Instantaneous continental-shelf scale sensing of cod with Ocean Acoustic Waveguide Remote Sensing (OAWRS)

by

Ankita Deepak Jain

Submitted to the Department of Mechanical Engineering in partial fulfillment of the requirements for the degree of

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Signature redacted

Author ....... ........................

Department of Mechanical Engineering

May 22, 2015

Signature redacted

Certified by ....... ........................

Nicholas C. Makris
Professor
Thesis Supervisor

Signature redacted

Accepted by ............................

David E. Hardt
Chairman, Department Committee on Graduate Theses
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Abstract

Reported declines in the population of Atlantic cod have a potential to affect long-term ecological balance and the sustainability of the cod fishery along the US northeast coast. These assessments have led to severe fishing cuts over the past few years, have consequently threatened the centuries-old Atlantic cod fishery along the New England coast and put the livelihood of thousands of fishermen at risk. Amidst this fisheries crisis, calls by elected officials, environmental groups and fishing consortiums were made for an Ocean Acoustic Waveguide Remote Sensing (OAWRS) survey of the Gulf of Maine cod stock. Typically, cod stock assessments incorporate data collected from conventional acoustic and trawl line transect surveys that highly undersample the marine environment in space and time and lead to ambiguities in population estimates. The combination of conventional methods and OAWRS techniques, however, has been demonstrated to provide rapid and accurate fish stock assessments over ecosystem-scale areas for other species. In this thesis, the feasibility of accurately surveying cod stocks with OAWRS is theoretically assessed. These theoretical predictions are then experimentally verified by successfully sensing cod with OAWRS over ecosystem scales in the Nordic Seas.

Following direct requests by Massachusetts state officials to determine if OAWRS could be used to detect and survey the reported waning cod populations in coastal New England waters, we obtained measurements of typical aggregation densities and occupancy depths of spawning cod in Ipswich Bay from conventional echosounder surveys conducted in Spring 2011. Cod length distributions were also measured from which we estimated the swimbladder resonance frequencies of local cod via a harmonic oscillator model that includes the effects of damping, the cod’s swim bladder air volume at a given neutral buoyancy depth as well as changes to this volume for deviations from neutral buoyancy depth. The optimal frequency for OAWRS detection typically corresponds to that where the resonance peak is found. We showed that our theoretical estimates of cod swimbladder resonance matched very well with independent measurements of caged cod resonance from decades old Norwegian data. Using parabolic equation modeling of ocean waveguide propagation, the scattered level of typical spawning cod aggregations was estimated and compared with that from seafloor
scattering, which is a typical limiting factor in long range active sensing. Seafloor scattering was estimated via a Rayleigh-Born approach we developed, where the magnitude squared of seafloor scattering amplitude was empirically determined from thousands of measurements made during major OAWRS experiments along the US Northeast coast.

It was found that near cod swimbladder resonance (roughly 150-600 Hz), determined from the New England length and depth distribution data, OAWRS was capable of robustly detecting spawning cod aggregations from many tens of kilometers in range with high signal-to-noise ratios (SNRs) greater than 20 dB for typical spawning cod configurations in New England waters. Above the resonance frequency peak, it is possible to detect cod for typical shoaling densities because cod scattering reaches a plateau due to geometric scattering that is above the seafloor scattering trend for typical OAWRS frequencies. Well below the resonance peak, scattering from cod is expected to fall off rapidly and faster than seafloor scattering, and so provides important information about resonance behavior but can be difficult to probe given the very low frequencies involved. This theoretical feasibility study emphasized the need for a low frequency source that spans cod swimbladder resonance and helped demonstrate the potential for use of OAWRS for cod assessments over ecosystem scales.

To confirm our theoretical predictions on the OAWRS detection of cod and other keystone fish species, we designed, prepared and conducted a major oceanographic experiment in the Nordic Seas in the Arctic in the winter (February-March) of 2014 using three major research vessels, the US RV Knorr, the Norwegian RV Johan Hjort and the Norwegian FV Artus. The Nordic Seas 2014 experiment was conducted in difficult gale and hurricane force weather conditions along most of Norway’s western and northern coast. MIT’s OAWRS Source, obtained through a NSF-Sloan MRI grant, spanned the 800-1600 Hz range, and the receiver was ONR’s Five Octave Receiver Array (FORA). Unlike the declining trend of cod population in New England waters, cod population in the Nordic Seas has been thriving for many years and is currently at its healthiest recorded state. The experiment period was chosen such that it coincided with the peak spawning period of cod along the coastal Lofoten region in Norway where they congregate in high densities, as well as other keystone species that migrate from the ice-edge to spawn in some of the world’s largest mass migrations. In planning, we determined likely spawning grounds for cod, and other keystone species such as capelin, herring, and haddock using historic survey data collected along the Norwegian coast. With our calibrated model of fish swimbladder resonance and historic length distribution data from Norway, swimbladder resonance frequencies and target strengths of these fish species were estimated. We also determined optimal OAWRS ship tracks for remote detection of these species above seafloor scattering using waveguide propagation modeling. While the OAWRS frequencies were greater than those expected for cod swimbladder resonance, cod shoals over ten kilometers in length were robustly detected and successfully imaged from tens of kilometer ranges during the experiment. This produced the first instantaneous images of a vast cod shoal. It also confirmed our predictions that OAWRS can be used to remotely sense and survey cod populations. Our theoretical predictions suggest that the use of lower OAWRS frequencies near cod swimbladder resonance would lead to greater dynamic range in population density estimates. The Nordic Seas experiment provided the first look revealing the entire horizontal morphology of vast cod, capelin, haddock and Norwegian herring shoals. This was done with instantaneous OAWRS imaging.
The presence of multiple shoaling fish species during the Nordic Seas experiment provided us with a unique opportunity to study general shoaling behavior across species over ecosystem scales with OAWRS. For example, many pelagic and demersal fish species are known to undergo distant migrations for feeding, spawning and overwintering year after year. This suggests that migrating populations have an ability to efficiently sense their environment. By combining OAWRS estimates of fish scattering strength and population density obtained from simultaneous depth echo-sounding along line transects, areal population densities over entire shoals were determined. This enabled estimation of total shoal population, shoal aspect ratio, and shoal migration speed via cross correlation of population density over time. It was shown that across several species, as shoal population increased (tens of thousands to hundreds of millions of individuals), shoal aspect ratio also increased (roughly from one to ten). Single-celled organisms with higher aspect ratios have been shown to more efficiently and accurately detect chemical gradients at microscopic scales. The high-aspect ratio or elongated morphology of a large migrating fish shoal is consistent with the entire shoal serving the function of a biological antenna for efficient spatial and temporal sensing of mesoscale processes in the environment.

We also studied the evolution of air resonance power efficiency in the violin and its ancestors. We collected historical data, including samples from roughly 500 classical Cremonese violins from the renowned workshops of Amati, Stradivari and Guarneri, to establish historic time series of key design traits. We determined the primary physical mechanisms governing radiated air resonance power in the violin and its ancestors and used this knowledge to explain the evolutionary trends we discovered.

Thesis Supervisor: Nicholas C. Makris
Title: Professor
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Lofoten region transmission loss analysis: Range-depth transmission loss in dB re 1 m estimated along the shown path using RAM [13] at 1300 Hz averaged over 10 Monte Carlo simulations for different receiver and source depths. Each simulation uses a distinct set of sound speed profiles randomly picked from historic profiles every 500 m [14]. The y-axis represents water depth in meters and x-axis represents the range in km from the source/receiver.

Lofoten region transmission loss analysis: Range-depth transmission loss in dB re 1 m estimated along the shown path using RAM [13] at 1300 Hz averaged over 10 Monte Carlo simulations for different receiver and source depths. Each simulation uses a distinct set of sound speed profiles randomly picked from historic profiles every 500 m [14]. The y-axis represents water depth in meters and x-axis represents the range in km from the source/receiver.

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3-25 Averaged OAWRS scattered level $10 \log_{10} \left| \hat{\phi}_F \right|^2$ measured for the March 8 shoal at 00:16:49 UTC in the Lofoten area near Andenes at 955 Hz. Colors indicate measured scattered level in dB re 1 $\mu$ Pa. Solid black lines indicate bathymetric contours.

3-26 Estimated OAWRS scattering strength $SS_{fOAWRS}$ for the March 8 shoal at 00:16:49 UTC in the Lofoten area near Andenes at 955 Hz. Colors indicate the scattering strength in dB. Solid black lines indicate bathymetric contours.

3-27 Estimated OAWRS areal population density estimate $\hat{n}_a$ for the March 8 shoal at 00:16:49 UTC in the Lofoten area near Andenes. The mean areal population density across the shoal is found to be roughly 0.04 fish/m$^2$. Colors indicate the population density in fish/m$^2$. Solid black lines indicate bathymetric contours.
4-1 Gigantic migrating shoals spanning several kilometers were imaged in the
Atlantic Ocean and Nordic Seas environments. Shoal of (a) Atlantic herring
imaged on September 27, 2006 at 19:41 EDT along the northern flank of
Georges Bank in the Gulf of Maine during the 2006 OAWRS experiment [11];
(b) Northeast Arctic cod imaged on March 8, 2014 at 01:16 CET in the Lofoten
Area near Andenes; (c) Norwegian herring imaged on Feb 21, 2014 at 00:50
CET off the coast of Alesund; and (d) Barents Sea capelin imaged on Feb 27,
2014 at 05:45 CET in the Finnmark Area during the 2014 Nordic Seas OAWRS
experiment (Chapter 3). This is the first time any Northeast Arctic cod,
Norwegian herring or Barents Sea capelin shoals have been instantaneously
imaged showing the entire horizontal morphology of shoals formed by these
species. The moored OAWRS source is the coordinate origin in (a) located
at 42.00°N and 68.39°W. The towed OAWRS receiver ship is the coordinate
origin in (b) at 68.96°N 14.29°E; (c) at 62.61°N 4.95°E; and (d) at 71.29°N
25.78°E at the respective time-stamps. Solid black lines indicate bathymetric
contours.

4-2 OAWRS receiver array beampattern at 1335 Hz steered to broadside direction
and 65° from broadside. As the array is steered toward the endfire direction,
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4-3 OAWRS image of cod schools on March 5, 2014 at 18:01:39 UTC.

4-4 OAWRS image of a large cod shoal on March 7, 2014 at 00:16:49 UTC.

4-5 OAWRS image of a large capelin shoal on February 27, 2014 at 04:44:59 UTC.

4-6 OAWRS image of a small capelin school on February 28, 2014 at 09:17:59 UTC.
Shoal population versus aspect ratio measured for (a) Atlantic Herring in the Gulf of Maine during September-October 2006, (b) Cod and Haddock in Lofoten region, Norway; (c) Norwegian Herring in Alesund region, Norway; and (d) Capelin in Finnmark region, Norway during February-March 2014. For all species, as shoal population increased, shoal aspect ratio also increased. The length of the vertical tick marks represents the span of shoal population estimated over the two time instances used for estimating migration speeds shown in Figures 4-9-4-12. Similarly, the length of the horizontal tick marks represents the span of the shoal aspect ratio estimated over the two time instances. For more than 50% variation in shoal population, the larger population estimate is used.

4-8 Shoal migration speed versus population measured for (a) Atlantic Herring in the Gulf of Maine during September-October 2006, (b) Northeast Arctic cod in Lofoten region, Norway; (c) Norwegian Herring in Alesund region, Norway; and (d) Barents Sea capelin in Finnmark region, Norway during February-March 2014. Measured migration speeds are found to be consistent with typical fish swimming speeds of up to 3 body lengths/second. With the exception of Northeast Arctic cod, all species showed a decrease in migration speeds with increase in shoal population. The length of the vertical tick marks represents the span of shoal population estimated over the two time instances used for estimating migration speeds shown in Figures 4-9-4-12.
(a) Shoal contours showing migration speeds and directions for the Gulf of Maine Atlantic Herring shoal shown in Figure 4-1(a). The contours represent areal population densities at threshold values of 0.5 fish/m² for Atlantic herring. Blue curves represent shoal contours at the observation time of 19:41 EDT on September 27, 2006 and the red curves represent shoal contours after 105 minutes from the initial observation time. (b) Cross correlation coefficients $\rho(x, y)$ of shoal population density measured at the two instances as a function of spatial lag in x- and y-directions. The black circle identifies the location of the peak cross correlation coefficient and so determines the direction of migration relative to the origin (0,0). The shoal is found to migrate in the north-east direction towards Georges Bank at a speed of 0.36 m/s and has a high cross correlation coefficient of 0.85 over roughly two hours of migration.

(a) Shoal contours showing migration speeds and directions for the cod shoal in the coastal Lofoten region in Norway shown in Figure 4-1(b). The contours represent areal population densities at threshold values of 0.025 fish/m² for Northeast Arctic cod. Blue curves represent shoal contours at the observation time of 00:37 CET on March 8, 2014 and the red curves represent shoal contours after 32 minutes from the initial observation time. (b) Cross correlation coefficients $\rho(x, y)$ of shoal population density measured at the two instances as a function of spatial lag in x- and y-directions. The red circle identifies the location of the peak cross correlation coefficient and so determines the direction of migration relative to the origin (0,0). The shoal is found to migrate in the north-west direction towards the shelf at a speed of 0.28 m/s and has a high cross correlation coefficient of 0.7 over roughly forty minutes of migration.
4-11 (a) Shoal contours showing migration speeds and directions for the Norwegian herring shoal in the coastal region off the city of Alesund in Norway shown in Figure 4-1(c). The contours represent areal population densities at threshold values of 0.5 fish/m² for Norwegian herring. Blue curves represent shoal contours at the observation time of 00:50 CET on February 21, 2014 and red curves represent shoal contours after 141 minutes from the initial observation time. (b) Cross correlation coefficients \( \rho(x, y) \) of shoal population density measured at the two instances as a function of spatial lag in \( x \)- and \( y \)-directions. The red circle identifies the location of the peak cross correlation coefficient and so determines the direction of migration relative to the origin \((0,0)\). The shoal is found to migrate in the north-west direction at a speed of roughly 0.1 m/s and rotate in counter clockwise direction at a speed of 0.04 deg/min. The shoal has a high cross correlation coefficient of roughly 0.65 over two hours of migration.

4-12 (a) Shoal contours showing migration speeds and directions for the capelin shoal in the coastal Finnmark region in northern Norway shown in Figure 4-1(d). The contours represent areal population densities at threshold values of 4 fish/m² for Barents Sea capelin. Blue curves represent shoal contours at the observation time of 05:45 CET on February 27, 2014 and red curves represent shoal contours after 34 minutes from the initial observation time. (b) Cross correlation coefficients \( \rho(x, y) \) of shoal population density measured at the two instances as a function of spatial lag in \( x \)- and \( y \)-directions. The red circle identifies the location of the peak cross correlation coefficient and so determines the direction of migration relative to the origin \((0,0)\). The shoal is found to migrate in the north-east direction at a speed of 0.38 m/s and the shoal has a high cross correlation coefficient of 0.85 over roughly a half hour of migration.
Monopole and dipole components of radiated acoustic pressure spectrum as a function of frequency for a Stradivari 1717 violin estimated using the elastic volume flux analysis and estimated parameters given in Table 5.1. At frequencies above roughly 100 Hz, the monopole component dominates the total field, whereas for frequencies less than roughly 75 Hz, the dipole component dominates the total field. Both pressure spectra are normalized with respect to the maximum value of the monopole spectra. The air resonance peak is shown to occur at roughly 282 Hz. The estimated fall off of roughly 35 dB at 200 Hz from the radiated pressure spectrum level at air resonance is consistent with radiated sound pressure level measurements of violins in Refs [15–18]. Away from the air resonance peak, other sound radiation mechanisms may become important.
5-2 (a) Amplitude of total violin air volume flux, volume flux through f-holes, volume flux due to only top plate motion and volume flux due to only back plate motion at air resonance. The levels are normalized with respect to the total volume flux at air resonance from the violin \( \tilde{v}_{\text{max}} \); (b) Phase (in degrees) of volume flux from the violin, f-holes, top plate motion and back plate motion with respect to the phase of top plate forcing at air-resonance; (c) Radiated pressure spectrum level from the whole violin, only f-holes, only top plate and only back plate at air resonance. (d) Radiated pressure spectrum level from the whole violin, only f-holes, and violin structure comprising top and back plate motions at air resonance. The levels in (c) and (d) are normalized with respect to the total radiated pressure spectrum level from the violin at air resonance \( \tilde{P}_{\text{max}} \). All values are estimated for a Stradivari 1717 violin using the elastic volume flux analysis and parameters given in Table 5.1. At and near air resonance at 282 Hz, the radiated acoustic pressure spectrum level due to air flow through f-holes is greater by roughly two orders of magnitude than that from the violin structure. At and near air resonance, the air flow through f-holes is out of phase with that due to top and back plate motion, but the latter two are in phase with each other. The radiated field from the entire violin at air resonance comprises coherent addition of air volume fluxes or radiated pressure fields from the f-holes and the violin structure.

5-3 Time series of changes in f-hole length \( L_F \) (colored markers) measured from 470 Cremonese violins. The conductance of the two interacting violin f-holes is determined using the methods presented in Ref. [19].

5-4 Temporal variations in (a) air-cavity volume \( V \), (b) back plate thickness \( h^{\text{back}} \), (c) top plate thickness \( h^{\text{top}} \), (d) plate thickness near f-holes \( h^{\text{sh}} \), and (e) mean air cavity height \( h^a \) measured from 110 classical Cremonese violins (Section 5.3.3.0.1). Black lines in (a) and (e) represent 20-instrument running averages, and in (b)-(d) represent quadratic regression fits of available thickness data.
5-5 (a) The distribution of f-hole length fluctuations due to craftsmanship limitations minus the mean (gray bars) measured from 448 Cremonese violins (Figure 5-3), with the Gaussian distribution (black) that best fits the measured data. Standard deviation is roughly 1.9% of mean f-hole length over Cremonese period. (b) The distribution of air-cavity volume fluctuations due to craftsmanship limitations minus the mean (gray bars) measured from 110 Cremonese violins (Figure 5-4a), with the Gaussian distribution (black) that best fits the measured distribution. Standard deviation is roughly 2.7% of the mean air-cavity volume over the Cremonese period.

5-6 Acoustic air-resonance power efficiency grows as sound hole shape evolves over centuries through the violin's European ancestors to the violin. (a) Change in radiated acoustic air-resonance power for an elastic instrument $W_{\text{air-elastic}}$ (Eq. 5.41), rigid instrument $W_{\text{air-rigid}}$ (Eq. 5.39), and infinite rigid sound hole bearing wall $W_{\text{wall}}$ (Eq. 5.38) as a function of sound hole shape, where percentage change is measured from the circular sound hole shape. (b) Air-resonance frequency for elastic instrument $f_{\text{air-elastic}}$ (Eq. 5.40) and rigid instrument $f_{\text{air-rigid}}$ (Eq. 5.9) as a function of sound hole shape, normalized by $f_{\text{air-elastic}}$ for the circular opening (i). (c) Conductance $C$ [19] and perimeter length $L$ for different sound hole shapes of fixed sound-hole area, normalized to be unity for the circular opening (i). Shape overlap occurred between nearby centuries. Only sound hole shape is changed and all other parameters are held fixed and equal to those of the 1703 “Emiliani” Stradivari violin [20]. The conductance of the two interacting sound holes for each instrument is taken from Ref. [19]. Data sources are provided in Section 5.3.3.0.1.
5-7 Time series of change in total radiated acoustic power as a function of temporal changes of the purely geometric parameter of f-hole length during the Cremonese period. The estimated dependence via elastic volume flux analysis ($W_{\text{air-elastic}} \sim C^{1.7}$, Eq. 5.41, solid colored lines) is roughly the average of the upper ($W_{\text{wall}} \sim C^2$, Eq. 5.38, dashed black line) and lower ($W_{\text{air-rigid}} \sim C$, Eq. 5.39, solid black line) limiting cases. Colored lines and shaded patches respectively represent mean trends and standard deviations of $W_{\text{air-elastic}}$ for different workshops: Amati (blue), Stradivari (red), Guarneri (green), Amati-Stradivari overlap (blue-red) and Stradivari-Guarneri overlap (red-green). Percentage change is measured from the 1560 Amati workshop instrument. The conductance of the two interacting violin f-holes is determined from Eq. 5.26.

5-8 Time series of changes in (a) total radiated acoustic air-resonance power $W_{\text{air-elastic}}$ (Eq. 5.41, solid colored lines); (b) air resonance frequency $f_{\text{air-elastic}}$ (Eq. 5.40, solid colored lines) over the classical Cremonese period and (c) f-hole length $L_F$ (colored markers) measured from 470 Cremonese violins. Colored shaded patches in (a) and (b) represent standard deviations. Filled circles and error bars in (b) respectively represent the means and standard deviations of air resonance frequencies for each workshop for 26 surviving Cremonese violins (2 Nicolo Amati, 17 Antonio Stradivari, 7 Guarneri del Gesu) previously measured in the literature [21–23]. Black solid line in (b) represents rigid instrument air resonance frequency $f_{\text{air-rigid}}$ (Eq. 5.9). Two Northern Italian pitch standards, Mezzo Punto and Tuono Corista (SI Section 10), from the late 16th to late 17th centuries and common 17th to early 18th century French baroque pitches (black dashed lines) are also shown in (b). Percentage change in radiated power is measured from the 1560 Amati workshop instrument. Black line in (c) represents 10-instrument running average. The conductance of the two interacting violin f-holes is determined from Eq. 5.26. Data sources are provided in SI Section 5. *Documents suggest Tutto Punto to be the problematic pitch of the Cremonese organ in 1583 because it did not conform to dominant Northern Italian pitch standards of the time.
5-9 Time series of half power bandwidths (colored lines) at air-resonance frequency over the classical Cremonese period estimated from the elastic volume flux analysis. Estimates are based on measurements of f-hole length, air cavity volume, top and back plate thickness, plate thickness near f-holes and mean air cavity height (Figures 5-8c and 5-4) from 470 classical Cremonese violins. Colors and arrows represent different workshops: Amati (blue), Stradivari (red), Guarneri (green), Amati-Stradivari overlap (blue-red) and Stradivari-Guarneri overlap (red-green). Standard deviations are represented by colored patches. Half power bandwidth in combination with the air resonance frequency characterizes the air resonance peak.

5-10 Approximate components of temporal trends in (a) radiated acoustic power $W_{a-elastic}$ (Eq. 5.41) and (b) air resonance frequency $f_{a-elastic}$ (Eq. 5.40) over time due to f-hole length $L_F$ (blue), air cavity volume $V$ (red), top plate thickness $h_{top}$ (green), back plate thickness $h_{back}$ (magenta), plate thickness near f-hole $h_{sh}$ (brown) and mean air cavity height $h_a$ (yellow) estimated from elastic analysis. Mean trends and standard deviations are represented by colored solid lines and error bars, respectively. Percentage change in radiated power is measured from the 1560 Amati workshop instrument. Contributions from each parameter are isolated by holding all other parameters fixed at 1560 Amati workshop instrument values. The conductance of the two interacting violin f-holes is determined from Eq. 5.26. Input mean time series data are from Figs 5-8c and 5-4.
5-11 Measured evolution rates and thresholds distinguishing mutation origins as being consistent or inconsistent with accidental replication fluctuations from craftsmanship limitations. Mean evolution rates for (a) linear sound hole dimension and (b) estimated radiated acoustic power at air resonance. Below $N = 2$, corresponding to $E_{\text{CraftFluct}}$ (Eq. 5.42, lower dashed grey line), mutations likely arise within the range of accidental replication fluctuations due to craftsmanship limitations. Above $N \approx 4$, corresponding to $E_{\text{DesignPlan}}$ (Eq. 5.43, upper dashed grey line), mutations likely arise from planned design changes. All rates are based on a generational period of 0.1 year [20].

5-12 Sound hole shapes and violins made by Savart and Chanot in the early 1800’s [24–26]. While the Savart and Chanot instruments, which had notable design differences from classical violins, were unsuccessful, they were made for the violin repertoire, and were consistently referred to as violins by their creators and in subsequent literature [24–26]. In particular, Savart’s instrument is usually referred to as the “trapezoidal” violin and Chanot’s instrument is usually referred to as the “guitar-shaped” violin [25–27].
Reported humpback whale Stellwagen Bank song occurrence [28] shows large natural variations within and across years. Large natural variations in humpback whale song occurrence reported from single sensor detections at Stellwagen Bank [28] in time-dependent ambient noise within and across years are common in the absence of sonar. Line plots of reported single sensor daily humpback whale song occurrence at Stellwagen Bank in hours/day (A) for the entire year and (B) from September 15 to October 17, in 2006 and 2008 [28]. Many periods lasting roughly weeks where high song occurrence episodes are found in one year but not in another when no sonars are present are indicated by black arrows in (A). The reported reducing change in humpback whale song occurrence, to zero [28, 29], occurred in the “before” period while the OAWRS vessels were inactive and docked on the other side of Cape Cod from Stellwagen Bank, at the Woods Hole Oceanographic Institution, due to severe winds for days before OAWRS transmissions for active surveying began on September 26, 2006, as marked by the black arrow in (B). This shows that the analysis in Ref. [29] analysis violates temporal causality.
A-2 Quantifying large differences in the reported humpback whale song occurrence at Stellwagen Bank [28] across years. Difference in humpback whale song occurrence reported from single sensor detections at Stellwagen Bank [28] in time-dependent ambient noise across years exceeds that of the “during” period most of the time when no sonars are present. (A) Difference in mean humpback whale song occurrence at Stellwagen Bank over respective 11-day periods with 1-day increment in 2006 and 2008, (B) histogram of difference in mean humpback song occurrence over 11-day periods between 2006 and 2008 when no sonar is present, i.e. excluding the “during” period from September 26 to October 6. Periods when the difference in means of respective 11-day periods is greater than (red dots) and less than (blue dots) that of the “during” period are indicated in (A). The difference in means fluctuates randomly throughout the year, exceeding the “during” period 57.8% of the time (most of the time) when no sonars are present, indicating that there is nothing unusual about such differences, which are actually the norm.
Reported annual humpback song occurrence at Stellwagen Bank [28] are uncorrelated between years over 11-day periods. Annual humpback whale song occurrence reported from single sensor detections at Stellwagen Bank [28] in time-dependent ambient noise are uncorrelated over 11-day periods across years. (A) Correlation coefficient between 2006 and 2008 humpback whale song occurrence time series over 11-day period with 1-day increment (B) histogram of the correlation coefficient in (A). The correlation coefficient of the annual humpback whale song occurrence time series over 11-day periods across years obeys a random distribution peaking at zero correlation about which it is symmetric, showing that correlation in trend between years is random and quantitatively expected to be zero with roughly as many negative correlations as positive ones. The correlation coefficient between the humpback whale song occurrence across years smoothly transitions from negative values in the “before” period, showing no similarity or relation in trend between years just before the 2006 OAWRS survey transmission period, to some of the highest positive correlations obtained between years in the “during” period. This demonstrates high similarity and relation in trend between years during the 2006 OAWRS active survey transmission period, which contradicts the results of the study in Ref. [29].
Wind-dependence of mean detection range for single sensor at Stellwagen Bank [29], and OAWRS receiver array. The green shaded areas indicate the overall vocalizing humpback whale call rate densities (number of calls/[(min) (50 nmi)^2]) determined between September 22 and October 6, 2006 by our large aperture receiver array towed along several tracks (black lines). The mean detection ranges for the single sensor at Stellwagen Bank are in blue and for the OAWRS receiver array are in red, where Stellwagen Bank is marked by yellow shaded regions. These detection ranges are determined by the methods described in Section A.2 given a humpback whale song unit source level of approximately 180 dB re 1 μPa and 1 m which is the median of all published humpback whale song source levels [30–35]. The error bars represent the spread in detection range due to typical humpback whale song source level variations (Section A.2). Under (A) low wind speed conditions vocalizing whales are within the mean detection area for a single Stellwagen Bank sensor but for (B) higher wind speeds most vocalizing whales are outside the mean detection area of the same sensor, which results in reduction of detectable whale song occurrence by the single sensor [29] at Stellwagen Bank.
Wind-speed increase causes reduction in humpback song occurrence at Stellwagen Bank. Average wind speed increase from the “before” to the “during” period at Stellwagen Bank causes reduction in the percentage of time humpback whale songs are within mean detection range of a single Stellwagen Bank sensor. (A) Averaged wind speed measured at the NDBC buoy [36] closest to Stellwagen Bank over the “before,” “during,” and “after” 11-day periods; and (B) percentage of the time vocalizing humpback whales localized by our large aperture array are within the mean detection range of the single sensor [29] at Stellwagen Bank in the “before” and “during” periods, using waveguide propagation methods and whale song parameters described in Section A.2. Since the OAWRS experiment was conducted only up to October 6, 2006, the humpback whale source distribution in the “after” period was not measured and we do not investigate the percentage of time that humpback whales are within the mean detection range of the single sensor at Stellwagen Bank [29] for the “after” period. The triangles represent the mean wind speed and the solid ticks represent the standard deviation of the wind speed over the respective 11-day periods.

Humpback song occurrence rate is constant in the periods “before” and “during” OAWRS survey transmissions. The mean percentage of a diurnal cycle containing humpback whale song in the periods “before” and “during” OAWRS survey transmissions, as defined in Section A.3, remains constant, indicating the transmissions had no effect on humpback whale song over the entire passive 400-km diameter survey area of the Gulf of Maine including Stellwagen Bank.
Humpback song occurrence detectable by single sensor matches reported humpback song occurrence at Stellwagen Bank [29]. Average humpback whale song occurrence detectable by a single hydrophone at Stellwagen Bank in time-dependent ambient noise in the “before” and the “during” periods matches the reported humpback whale song occurrence by Risch et al. [29]. Using the measured wind speeds at Stellwagen Bank [36] (Figure A-5), the measured spatial distribution of vocalizing humpback whales [37], and constant song production rates (Figure A-6) measured by our large-aperture array, the detectable song occurrence over the “before” and “during” period are found to be within ±18% of the reported means [29], much less than the standard deviations of reported song occurrence [29], using waveguide propagation methods and whale song parameters described in Section A.2. Before and during OAWRS survey transmissions, this figure shows that reported variations in song occurrence at Stellwagen Bank [29] are actually due to detection range changes caused by wind-dependent ambient noise, through well established physical processes [38, 39].

Geometry for the implementation of the theoretical formulation for the scattered field in a standard Pekeris waveguide of a depth of 100 m for a monostatic point source-receiver located at the mid-water column. The total moments of the scattered field are calculated for a sector of an ocean bottom or seabed patch, extending over range $R_t$, depth $Z_t$ and azimuth $\theta_t$, containing volume inhomogeneities. The scattered field from the patch then effectively corresponds to the scattered field level measured from a given direction if a receiver array with an angular beamwidth of $\theta_t$ is used instead [40]. The sound speed, density and attenuation in the water column and in the sand bottom are $c_w, \rho_w, \alpha_w$ and $c_b, \rho_b, \alpha_b$, respectively, and (B) sound speed profiles measured on the New Jersey continental shelf (gray) are used for the simulations. The solid black line and horizontal tick marks indicate the mean sound speed profile and the standard deviations, respectively [40].

A-7

D-1
D-2 The modeled (A) total moments of the matched-filtered seafloor scattered field; (B) matched-filtered scattered field variance and its components; (C) range-averaged matched-filtered scattered field variance compared to the range-averaged variance at the center frequency or time-harmonic approximation; and (D) range-averaged variance term $\text{Term}_{\text{THVar}}^{\text{THVar}}(\text{r})$, $\text{Var}(\text{r})$, $\text{Covar}(\text{r})$, compared to its three components, monopole, dipole and cross terms at the center frequency. The source is assumed to be a linear frequency modulated (LFM) pulse centered on 415 Hz and with a bandwidth of 50 Hz. Computations are for a seabed patch extending from 2 km to 20 km in the range, 3° in the azimuth and 10 m in depth, in a Pekeris sand waveguide, as shown in Figure D-1. The cross range resolution of 3° is the typical angular resolution of the OAWRS receiver array [11, 40], and the range resolution, $\Delta r = c/2B$, is 15 m for sound speed $c = 1,500$ m/s and OAWRS bandwidth $B = 50$ Hz. The source and receiver are co-located at a depth of 50 m. Detailed derivations of the normalized broadband seafloor scattered field and its moments are given in Appendices C-C.1.

E-1 One of the first few OAWRS images in the Lofoten cod spawning area near Andenes on March 5, 2014 at 18:29 UTC. Several schools spanning a few hundred meters in dimensions were observed within 10 km of R/V Knorr. The gain setting used in (b) is different from that used in (a) to enhance the levels of imaged cod schools.

E-2 An OAWRS image showing cod shoals on the shallow bank on the east and deeper waters off the bank on the west on March 5, 2014 at 23:09 UTC. The gain setting used in (b) is different from that used in (a) to enhance the levels of imaged cod shoals.
E-3 A large offshore shoal, likely another gadoid species haddock, was imaged at 23:43 UTC on March 5, 2014 off the shelf in roughly 1000-1500 m deep waters. This shoal was roughly 25 km long and 1-4 km thick. The image also shows the same on and off-bank shoals shown in Figure E-2. We were not able to conduct an echosounder line transect survey through this large off shore shoal due to an upcoming storm in the region. The gain setting used enhances the levels in the shoal but also enhance the levels close to the source with no shoals. So, the region of high SPL near source has been blocked out in the image.

E-4 A large cod shoal spanning roughly 15 km in length and 1-4 km in width was observed at array broadside at 23:37 UTC on March 7, 2014 while a ship turn. Prior to this image, the shoal was directly at array endfire and so was not imaged with good resolution. The OAWRS image or scattering intensity map is not corrected for transmission loss, so higher levels are measured at closer ranges. Since the OAWRS receiver array beam width is narrowest at broadside and widest at the endfire of the array, the image shows good resolution near broadside but poor resolution with high scattered levels near the array endfire.
Another view of the same shoal in Figure E-4 roughly half an hour later imaged at 00:16 UTC on March 8, 2014 when the shoal was closer to array endfire. Due to the hurricane in the area, RV Johan Hjort could not reach the survey location in time to help with simultaneous depth echosounding for ground truth confirmation of this shoal. The only way for us to confirm that this was a cod shoal was to turn into the shoal placing poor resolution endfire beams in the direction of the shoal to confirm the presence of the shoal and its depth distribution with the RV Knorr's echosounder. This meant that we had to sacrifice good resolution OAWRS imagery at broadside as in Figure E-4. This image was taken just as RV Knorr started to turn into the shoal and the south-western tail of the shoal fell in the endfire direction. The OAWRS image or scattering intensity map is not corrected for transmission loss, so higher levels are measured at closer ranges. Since the OAWRS receiver array beam width is narrowest at broadside and widest at the endfire of the array, the image shows good resolution near broadside but poor resolution with high scattered levels near the array endfire.
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G-6 At-sea transmission loss modeling for the shown Path 1 and measured CTD sound speed profile on February 23, 2014 in the Lofoten area near Rost. 245

H-1 Volumetric and areal population density of a cod shoal from R/V Johan Hjort’s echosounder transect between 02:47 to 03:30 UTC on March 8, 2014. The red dashed line indicates the areal population density threshold. 248

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Chapter 1

Introduction

1.1 Motivation

The population of Atlantic cod in the Gulf of Maine has been reported to be declining rapidly over the past several decades [43–45]. Dwindling Atlantic cod populations have a potential to affect long-term ecological balance [46–48] and the sustainability of the cod fishery along the US northeast coast [49]. A recent report published by the National Oceanographic and Atmospheric Administration (NOAA) stated that the current Gulf of Maine cod stock was overfished and that rebuilding it may not be possible until 2018 and most likely until 2024 [43, 50–52]. These assessments [43, 50–52] have led to severe fishing cuts, threatened the centuries-old Atlantic cod fishery along the New England coast and consequently put the livelihood of thousands of fishermen at risk [53–55]. Typically, cod assessments incorporate data collected from conventional acoustic and trawl line transect surveys [56–60] that may lead to ambiguities in population estimates [58, 61, 62]. The combination of conventional methods and OAWRS techniques, however, has a potential for accurately estimating fish stocks over ecosystem-scale areas as has been demonstrated in the past for Atlantic herring [11, 63].

US Senator Kerry, US Congressman Tierney, a number of elected Massachusetts state officials, and representatives from coastal communities met with us on numerous occasions over a period of two years and requested us to assess the ability of OAWRS techniques
for groundfish sensing in the Gulf of Maine amidst the New England Fisheries crisis. In a US Senate hearing before the Subcommittee on Oceans, Atmosphere, Fisheries, and Coast Guard in Washington DC and in several letters by Senator Kerry to NOAA in 2011, urgent requests were made to allocate funds to study the effectiveness and applicability of OAWRS for ground fish assessments [53–55]. In this regard, we prepared a detailed report theoretically explaining the capabilities of OAWRS in detecting cod and other groundfish and proposed a plan for conducting an OAWRS experiment in Massachusetts state waters to confirm our predictions. This report was widely distributed among Massachusetts state officials. Subsequently, a bill was passed in Massachusetts to fund an OAWRS experiment but unfortunately the funds became available too late to actually conduct the experiment in the Spring of 2012. A later date was considered too late by Massachusetts officials to help alleviate the fisheries crisis in a timely manner.

1.2 Thesis Organization

A large part of this thesis presents quantitative analysis we performed to help Massachusetts state during the New England fisheries crisis. The results of our theoretical investigation were valuable for the potential sustained use of OAWRS techniques for cod assessments and emphasized the need for a low frequency OAWRS source for optimal remote sensing of cod over ecosystem scales. Chapter 2 of this thesis highlights the key points of that work. We find that Ocean Acoustic Waveguide Remote Sensing (OAWRS) is capable of instantaneously and robustly detecting spawning cod aggregations over wide areas spanning thousands of square kilometers for observed spawning cod densities and configurations in U.S. northeast continental shelf waters at cod swim bladder resonance frequencies. At swim bladder resonance, OAWRS can also be used to detect individual cod within a few kilometers of the OAWRS system. Such robust detections of cod are possible, because the cod scattering amplitude has a strong low frequency resonance peak spanning the roughly two-octave range of 150–600 Hz within water depths of roughly 100 m, in contrast to the relatively uniform seafloor scattering frequency dependence of roughly $f^{-4}$, which we find below roughly 2 kHz in U.S. northeast continental shelf environments. This cod resonance frequency range is also op-
timal for long-range ocean acoustic waveguide propagation, because it enables multimodal acoustic waveguide propagation with minimal acoustic absorption and forward scattering losses. Above the resonance frequency peak, it is possible to detect cod for typical shoaling densities because cod scattering reaches a plateau due to geometric scattering that is above the seafloor scattering trend for typical OAWRS frequencies. Well below the resonance peak, scattering from cod is expected to fall off rapidly and faster than seafloor scattering, and so provides important information about resonance behavior. The low swimbladder resonance frequencies of cod further emphasize the need for a low frequency OAWRS source for optimal long range sensing of cod.

A first confirmation of the theoretical predictions of OAWRS and imaging of spawning cod populations was made during an experiment conducted in the Nordic Seas in winter (February-March) of 2014, in collaboration with the Institute of Marine Research, Norway. During this experiment, oceanographic and acoustic measurements were made from three major research vessels the US Research Vessel (RV) Knorr, the Norwegian RV Johan Hjort and the Norwegian Fishing Vessel Artus. Unlike the declining trends in Atlantic cod stocks, Northeast Arctic cod, which is known to spawn along the coast of Norway has been thriving for the past many years. In fact, it is currently at its healthiest state yet and so this experiment provided us with an opportunity to remotely detect spawning cod populations. This focused, three week field experiment was designed to instantaneously image and continuously monitor the spawning behavior of cod, other keystone fish species capelin, herring and haddock, and the co-dependent behavior of their predators over continental shelf scales along the coast of Norway. During the experiment, several days were dedicated to monitoring each species in their specific spawning grounds, which enabled us to study any diurnal behavioral patterns over wide areas. In addition to the OAWRS survey, local ultrasonic fisheries echo sounding and trawl surveys were also conducted in OAWRS-guided fish aggregation hotspots to provide us with ground truth calibrations of species, fish body characteristics and depth distribution. Along most of the Norwegian coastline into the Barents Sea, measurements were taken over level continental shelf regions, shelf breaks, canyons and Fjords, which were well characterized with high resolution bathymetry. The details of this experiment, with a
focus on remote sensing of cod using OAWRS, are provided in Chapter 3.

The Nordic Seas experiment provided the first look revealing the entire horizontal morphology of vast cod, capelin, haddock and Norwegian herring shoals. This was done with instantaneous OAWRS imaging. This gave us a unique opportunity to study general shoaling behavior across multiple species over ecosystem scales with OAWRS. For example, most pelagic shoaling fish species have very specific spawning grounds where populations return year after year to spawn [64, 65]. Often these species undergo distant migrations to reach their spawning grounds. The three keystone fish species in the Nordic Seas environment, namely cod, herring and capelin, perform migrations during late winter from the Arctic to all along the coastal regions of Norway and Russia for spawning [66–68]. Such consistent migratory behavior indicates that fish populations likely have an ability to efficiently sense the environment in space and time that enables them to identify these specific spawning grounds and undergo spawning processes over very short time periods. During the Nordic Seas OAWRS experiment, a large diversity in fish shoal population, structure and dynamics was observed over mesoscales via ocean acoustic waveguide remote sensing of cod, herring and capelin in their respective spawning grounds. Such diversity has also been observed previously in the Gulf of Maine spawning Atlantic herring aggregations via OAWRS [11, 69]. In Chapter 4 of this thesis, one specific aspect of shoal morphology is investigated, i.e. shoal aspect ratio, and its relationship to the population of migrating shoals is quantified. This is done via estimation of fish shoal areal population density, shoal aspect ratio, speed and direction of coherently migrating fish shoals obtained from OAWRS imaging. It is shown that most populous fish shoals attain antenna-like shapes with high aspect ratios. Previous observations of single celled organisms have shown that high cell aspect ratios enable efficient and accurate detection of chemical gradients at microscopic scales. Our observations of high shoal aspect ratios are then consistent with the elongated shoal serving the function of a biological sensor or antenna for efficient environmental sensing.

Chapter 5 of this thesis presents a quantitative analysis of violin acoustics and the violin’s historic evolution over roughly eight centuries. The lowest dominant mode of vibration
of a violin, the air-resonance, has been empirically identified as an important quality discriminator between violins [27, 70, 71] and is functionally important because it amplifies the lower frequency range of a violin’s register [70–72]. At this frequency, acoustic radiation from a violin is monopolar [73] and can be determined by pure volume change [74–76]. The violin behaves as a simple harmonic oscillator at this frequency, which enables us to quantify the radiated acoustic power at air resonance as a function of various design parameters, including f-hole length. It has been shown that the acoustic conductance of arbitrarily shaped sound holes is proportional to the sound hole perimeter length and the coupling between compressible air within the violin and its elastic structure lowers the Helmholtz resonance frequency from that found for a corresponding rigid instrument by roughly a semitone [19].

As a result of the former, it is found that as sound-hole geometry of the violin’s ancestors slowly evolved over centuries from simple circles to complex f-holes, the ratio of inefficient, acoustically inactive to total sound-hole area was decimated, roughly doubling air-resonance power efficiency. F-hole length then slowly increased by roughly 30% across two centuries in the renowned workshops of Amati, Stradivari and Guarneri, favoring instruments with higher air-resonance power, through a corresponding power increase of roughly 60%. By evolution-rate analysis, these changes are found to be consistent with mutations arising within the range of accidental replication fluctuations from craftsmanship limitations with subsequent selection favoring instruments with higher air-resonance power. This work was a collaborative effort of various authors comprising: (1) acoustic conductance analysis of arbitrarily shaped sound holes; (2) historic evolution of sound hole shape from the 10th-18th centuries; (3) limiting case changes in radiated air resonance power and frequency due to the isolated effect of sound hole shape change; (4) elastic volume flux analysis of the violin to determine the effect of changes in key design parameters measured from roughly 500 Cremonese violins on air resonance power and frequency over the Cremonese period; and (5) sound hole shape and air resonance power evolution rates and mechanisms. The primary contribution of this thesis is towards the latter three points.

In this thesis, we also investigate the environmental impact of OAWRS survey and show that in the Fall of 2006, active OAWRS transmissions had no measurable effect on hump-
back whale songs [37]. During ocean acoustic waveguide remote sensing of spawning Atlantic Herring in the Gulf of Maine in Fall 2006, many species of vocalizing marine mammals were passively monitored. Among these, humpback whales that predominantly prey on Atlantic herring were one of the most vocally active species producing calls and songs [37]. An impact assessment made prior to the experiment revealed no effect of active transmissions on humpback whales and other marine mammals. Here, we re-investigate the impact of the OAWRS survey and again show that the singing behavior of humpback whales remained unchanged in the presence and absence of OAWRS source transmissions in Fall 2006. By combining passively measured whale song production rates, measured wind speed and ambient noise in the Gulf of Maine during the experiment, and long range acoustic waveguide propagation modeling, we show that passive song measurements at a single hydrophone are expected to show large fluctuations due to natural fluctuations in wind speed dependent detection ranges of a single hydrophone [37]. These fluctuations in whale song reception are often incorrectly mistaken for fluctuations in whale song production. The large array gain of our OAWRS receiver array, however, leads to nearly wind speed independent detection ranges, and so enabled the monitoring of whale song reception rates, and consequently whale song production rates, over a roughly 400-km diameter area in the Gulf of Maine [37].

1.3 Ocean Acoustic Waveguide Remote Sensing (OAWRS) System

The OAWRS system comprises a vertical moored or towed source array and a towed horizontal receiver array. The vertical source array sends a short, broadband acoustic pulse omni-directionally in horizontal azimuth roughly every minute and the scattered acoustic waves are continuously received on all receiver array elements. Using plane wave beamforming and temporal matched filtering, these measured returns are charted in azimuthal bearing and range with respect to the receiver array heading and center, respectively. The resulting image is an instantaneous snapshot of the distribution of scattered acoustic intensity in the ocean waveguide environment over the two-way signal travel time or range covered
by the signal in roughly a minute in all directions. However, in typical continental shelf or shallow water environments where detection ranges are typically much greater than the water depth, there exists an inherent ambiguity in charting of acoustic returns about the horizontal receiver array axis. So, acoustic returns from the left-half of the plane about the array axis overlap with those from the right-half of the plane. This ambiguity can often be removed by changing the array heading and identifying the real scatterer location as the one from which scattered returns do not change with change in array heading. Each pixel of the image corresponds to an OAWRS resolution footprint. The scattered acoustic intensity at each pixel equals the scattered intensity integrated over the corresponding OAWRS resolution footprint. The range resolution of OAWRS $\Delta r$, given by the mean sound speed divided by twice the signal bandwidth from the matched filter theory, is roughly 15 m. The azimuthal resolution in radians varies as the acoustic wavelength $\lambda$ divided by the projected array length $L \cos \theta$, where $L$ is the full array length and the azimuth angle $\theta$ is zero at broadside, which is normal to the array axis. At endfire, parallel to the array axis, the resolution becomes roughly radians. The cross-range resolution of each OAWRS pixel is then a product of pixel range and azimuthal resolution in the direction of the pixel.

The OAWRS acoustic scattering level charted in the horizontal space are converted to acoustic scattering strength by correcting for changes purely due to transmission loss and OAWRS source level variations [11, 40, 69, 77]. Once potential fish shoals are identified in OAWRS images, echo-sounders and trawl equipment are guided to these locations for ground truth confirmation. The depth distribution of fish obtained from echo-sounding data and fish body length information obtained from trawl sampling is used to estimate fish areal population density over localized regions beneath the echosounder. Here, areal fish population density from echo-sounding data is given by the integral of volumetric density over the entire water column. The estimated scattering strength and areal population density was then used to estimate fish target strength at all OAWRS source frequencies [11, 40, 69, 77]. This target strength frequency analysis provides key information about fish swim bladder size, which also helps determine the predominant species in mixed assemblages, via comparison with modeled target strength. Further, the target strengths are used to estimate areal popula-
tion density from OAWRS images over the entire shoal and delineate the areal span of the shoal. This is done by using sonar equation where OAWRS source level, transmission loss and target strength are known parameters [11, 40, 69, 77].
Chapter 2

The need for and feasibility of remotely sensing Atlantic Cod using OAWRS

2.1 Introduction

Reported declines [43–45, 50–52] in the population of Atlantic cod have led to calls for additional survey methods for stock assessments, specifically the use of Ocean Acoustic Waveguide Remote Sensing (OAWRS) in the Gulf of Maine [53–55]. Recently, OAWRS techniques have been shown to be capable of instantaneous wide-area sensing of marine life over thousands of square kilometers [11, 40]. Dwindling cod populations have a potential to affect long-term ecological balance [46–48] and the sustainability of the cod fishery along the U.S. northeast coast [49]. Cod assessments typically incorporate data collected from conventional acoustic and trawl line transect surveys [56–60] that may lead to ambiguities in population estimates [58, 61, 62]. The combination of conventional methods and OAWRS techniques, however, has a potential for accurately estimating fish stocks over ecosystem-scale areas [11, 63].

We were requested by the Massachusetts Senator's office and state officials [53–55] to assess the feasibility of detecting cod populations in New England waters using OAWRS amidst the Massachusetts fisheries crisis. In this regard, the primary contribution of this thesis work was towards a technical report that we submitted to the Massachusetts state where
we quantified the feasibility of detection of cod aggregations and other groundfish species above seafloor scattering, a primary limiting factor in long range active sensing. The key results of the report are valuable for the potential sustained use of OAWRS techniques for ground fish assessments over ecosystem scales and are presented in this chapter. Specifically, we assess the feasibility of OAWRS detection and enumeration of cod in typical continental shelf waveguide environments along the U.S. northeast coast. We do so by combining ocean-acoustic waveguide propagation modeling [11, 40] that has been calibrated in a variety of continental shelf environments for OAWRS applications with a model for cod scattering that matches well with measured data [2] for cod scattering.

Both OAWRS detection range and minimum detectable fish population density are limited by scattered returns from the seafloor in the same resolution cell as the fish. Efficient and reliable estimates of seafloor scattering are then necessary to determine OAWRS fish detection limitations. Here, we use a Rayleigh–Born volume scattering approach, where multimodal propagation effects, which appear only in the waveguide Green function, can be mathematically separated from seafloor scattering effects. Our approach differs from traditional investigations of seafloor scattering using free-space plane-wave approaches [38, 59], which often do not efficiently or effectively translate to multimodal propagation and scattering in an acoustic waveguide [78–80]. We estimate seafloor scattered returns by applying the Rayleigh–Born approximation to Green’s theorem [81]. From hundreds of measurements of seafloor scattering in continental shelf waveguide environments along the U.S. northeast coast, we determine key statistics of the Rayleigh–Born seafloor scattering amplitude for various source frequencies. We show that OAWRS techniques are capable of robustly detecting Atlantic cod above seafloor scattering at and near their swim bladder resonance frequencies. These frequencies also happen to be optimal for long-range propagation in an ocean waveguide. Away from the swim bladder resonance frequencies, OAWRS detection of cod can become less optimal, due to rapid decreases in the cod scattering amplitude.
2.2 Theory for Fish Sensing using OAWRS

2.2.1 Expected Scattered Intensity from Fish Aggregations

Within an OAWRS resolution footprint of area \( A(r_F) \) centered at the horizontal position \( r_F = (p_F, z_F) \), the expected square magnitude of the scattered field from a group of \( N \) scatterers, \( \langle |\Phi_F(r_F|r, r_0, f_c)|^2 \rangle \) at frequency \( f_c \) is proportional to the instantaneous, and can be expressed as [82]

\[
10 \log_{10} \langle |\Phi_F(r_F|r, r_0, f_c)|^2 \rangle = SL(f_c) + TLA(\rho_F, z_0, H, f_c) + 10 \log_{10} \left( \frac{S(f_c)}{k} \right) + 10 \log_{10} \langle n_a \rangle
\]

(2.1)

where \( SL \) is the source level, \( TLA \) is a transmission loss area term equal to the expected second moment of depth averaged propagation to and from the fish layer integrated over the resolution footprint of the OAWRS system, \( S(f_c) \) is the random scatter function of a fish in the group, \( k \) is the acoustic wavenumber, and \( \langle n_a \rangle = N/A(r_F) \) is the expected areal fish density within the spatially varying resolution footprint. The \( TLA \) term, a function of center depth \( z_0 \) and thickness of the fish layer \( H \), can be expressed as

\[
TLA(\rho_F, z_0, H, f_c) = 10 \log_{10} \chi(\rho_F, z_0, H, f_c)
\]

(2.2)

\[
\chi(\rho_F, z_0, H, f_c) = \int_{A(\rho_F)} A(\rho_F) \int_{z_F = z_0 - H/2}^{z_F = z_0 + H/2} \int_{c(r_w), d(r_w)} (4\pi)^4 \times \\
|G(r|\rho_F, z_F; f_c, c(r_w), d(r_w)) G(\rho_F, z_F|r_0; f_c, c(r_w), d(r_w))|^2 \times \\
P(c(r_w), d(r_w)) P(\rho_F, z_F) dz_F d^2 \rho_F dc(r_w) dd(r_w)
\]

(2.3)

where \( G(r|\rho_F, z_F; f_c, c(r_w), d(r_w)) \) and \( G(\rho_F, z_F|r_0; f_c, c(r_w), d(r_w)) \) are Green functions describing random waveguide propagation to and from the fish, \( P(c(r_w), d(r_w)) \) is the joint probability distribution of sound speed \( c \) and seawater density \( d \) in the water column at any
point \( r_w \) in the propagation path and \( P(\rho_F, z_F) \) is the probability of finding a fish at \((\rho_F, z_F)\). For a uniform distribution of fish within the OAWRS resolution footprint \( P(\rho_F, z_F) = \frac{1}{HA(\rho_F)} \), so that

\[
\chi(\rho_F, z_0, H, f_c) = \int_{A(\rho_F)} \int_{z_F = z_0-H/2}^{z_F = z_0+H/2} (4\pi)^4 \langle |G(\mathbf{r}|\rho_F, z_F; f_c, c(r_w), d(r_w))|^2 |\rho_F, z_F \rangle \ dz_F \ d^2 \rho_F \quad (2.4)
\]

where the conditional expectation is over the water column sound speed and density random variables.

The third term on the right hand side of Eq. 2.1 is defined as the target strength \((TS)\) corresponding to the expected scattering cross section of a fish in the group. Most fish contain a gas-filled buoyancy organ called the swimbladder that acts as a strong scatterer acoustic waves near its resonance. The target strength for a fish swimbladder is estimated using the Love model [1] described in Appendix B. Cod swimbladder resonance estimated using this model has an excellent match with measurements. Figure 2-1 shows the model-data comparison for swimbladder resonance made by Lovik & Hovem [2] and Sand & Hawkins [3] for juvenile cod. The deviation of measured resonance frequency behavior at low depths near the fish’s neutral buoyancy depth is apparently related to cod’s hearing mechanism [3].

### 2.2.2 Fish-to-Seafloor Scattering Ratio

For a given fish aggregation density of \( N \) fish in the water column per unit area, the second moment of total scattered field from all \( N \) fish [40, 82] is:

\[
\langle |\Phi_F(N)|^2 \rangle = N \langle |\Phi_F(1)|^2 \rangle \quad (2.5)
\]

where \( \Phi_F(1) \) is the scattered field from one fish per unit area. For the fish aggregation to be detectable, the expected magnitude squared of the scattered field from \( N \) fish, \( \langle |\Phi_F(N)|^2 \rangle \), should be greater than that from the seafloor, \( \langle |\Phi_S|^2 \rangle \), over the same area:
Figure 2-1: Excellent match between Love model [1] (Appendix B) estimates and measurements of cod swimbladder resonance frequency made by (a) Lovik and Hovem [2] and (b) Sand and Hawkins [3] for rapid descent of cod from its neutral buoyancy depth to deeper depths. The deviation of measured resonance frequency behavior at low depths near the fish’s neutral buoyancy depth is apparently related to cod’s hearing mechanism [3]. Rapid movement ensures that cod does not adapt itself to the new depth by adjusting the amount of gas in its swimbladder. Cod length and neutral buoyancy depths are provided in the respective figure titles. The major axis of cod swimbladder is assumed to be roughly 33% of cod body length. Flesh density and viscosity are assumed to be 1.071 kg/m³ and 50 Pa s, respectively.
Figure 2-2: (A) The distribution of cod body length derived from Gurshin et al. [4]. The estimated target strength of a cod at different depths following the body-length distribution in (A) measured during Ipswich Bay spring surveys conducted in May–June, 2011 [4, 5], for neutral buoyancy depths (B) at 70 m, (C) near the sea-surface and (D) at 300 m. Large variations in body lengths of cod during surveys are common and lead to variations in swim bladder resonance frequency and peak target strength for different fish depths in the water column. All depths are measured from the sea-surface. The target strength of cod is estimated using the Love model [1] (Appendix B).
\[ N \langle |\Phi_F(1)|^2 \rangle > \langle |\Phi_S|^2 \rangle \]  

or:

\[ \text{FSR} = \frac{N \langle |\Phi_F(1)|^2 \rangle}{\langle |\Phi_S|^2 \rangle} > 1 \]  

where FSR is the fish-to-seafloor scattering ratio. Then, the minimum required number of fish per unit area, \( N_{\text{min}} \), above which fish scattering is greater than seafloor scattering is:

\[ N_{\text{min}} = \frac{\langle |\Phi_S|^2 \rangle}{\langle |\Phi_F(1)|^2 \rangle} \]  

As a direct consequence of Equation (2.7), FSR decreases with decreasing fish aggregation density, and so, it becomes harder to detect less dense fish aggregations above seafloor scattering within a given OAWRS resolution footprint.

### 2.2.3 Derivation of Rayleigh–Born Seafloor Scattering Amplitude

The seafloor scattered field at center frequency, \( f_c \), can be written from Equation (C.5) as:

\[
\Phi_S(r_S|r_0, f_c) = (4\pi) \int \int \int_{V_S} [k^2 \Gamma_k(r_t) G(r_t|t_0, f_c) G(r|t_0, f_c)]
\]

\[ + \Gamma_d(r_t) \nabla G(r_t|t_0, f_c) \cdot \nabla G(r|t_0, f_c)] dV_t \]

where \( \Phi_S(r_S|r_0, f_c) \) is the seafloor scattered field for an OAWRS source located at \( r_0 \), a scattering seafloor region centered on \( r_S \) and an OAWRS receiver located at \( r \); \( \Gamma_k \) is the fractional change in seafloor compressibility; \( \Gamma_d \) is the fractional change in seafloor density; \( V_S \) is the volume of the scattering seafloor patch determined by the resolution footprint of
the sensing system; \( k = 2\pi f_c/c \) is the acoustic wavenumber; \( c \) is the sound speed; \( G(r_t|r_0, f_c) \) is the Green function from the source to the elemental patch centered on \( r_t \) within \( V_S \); and \( G(r|r_t, f_c) \) is the Green function from the patch to the receiver.

Since the mean scattered field from diffuse inhomogeneities in a fluctuating waveguide vanishes [83–86], the second moment of the seafloor scattered field is well approximated by its variance (Equations (C.17) and (C.18)):

\[
\text{Var}(\Phi_S(r_s|r, r_0, f_c)) = \langle (4\pi)^2 \iint_{V_S} V_c(r_s, z_t) k^4 \text{Var}(\Gamma_k) (|G(r_t|r_0, f_c)|^2|G(r|r_t, f_c)|^2) dV_t, \\
+ (4\pi)^2 \iint_{V_S} V_c(r_s, z_t) \text{Var}(\Gamma_d) (|\nabla G(r_t|r_0, f_c) \cdot \nabla G(r|r_t, f_c)|^2) dV_t, \\
+ (4\pi)^2 \iint_{V_S} V_c(r_s, z_t) k^2 \text{Covar}(\Gamma_k, \Gamma_d) \\
(2\Re\{G(r_t|r_0, f)G(r|r_t, f_c)\nabla G^*(r_t|r_0, f_c) \cdot \nabla G^*(r|r_t, f_c)\}) dV_t
\]

(2.10)

where \( V_c \) is the coherence volume of inhomogeneities and \( \Re\{\cdot\} \) represents the real part. Here:

(i) the integral term with waveguide Green functions sums monopole scattering contributions;
(ii) the integral term with the gradients of waveguide Green functions sums dipole scattering contributions; and (iii) the integral term with Green functions and their gradients contains cross terms. Since the integrals (ii) and (iii) are found to be proportional to the integral (i) in Section D, we define proportionality constants \( F_d \) and \( F_c \), such that:

\[
\text{Var}(\Phi_S(r_s|r, r_0, f_c)) = \langle (4\pi)^2 \iint_{V_S} k^4 V_c [\text{Var}(\Gamma_k) + F_d \text{Var}(\Gamma_d) + F_c \text{Covar}(\Gamma_k, \Gamma_d)] \\
+ (4\pi)^2 \langle |G(r_t|r_0, f_c)|^2|G(r|r_t, f_c)|^2 \rangle dV_t
\]

(2.11)

The variance of the seafloor scattered field can also be written as:

\[
\text{Var}(\Phi_S(r_s|r, r_0, f_c)) = \langle (4\pi)^2 \iint_{V_S} k^4 V_c [\text{Var}(\Gamma_k) + F_d \text{Var}(\Gamma_d) + F_c \text{Covar}(\Gamma_k, \Gamma_d)] \\
+ (4\pi)^2 \langle |G(r_t|r_0, f_c)|^2|G(r|r_t, f_c)|^2 \rangle dV_t
\]

(2.12)
where $S(f, r_t)$ is the scatter function of seafloor inhomogeneities contained within a single coherence volume centered on $r_t$ (Section C.1). Then, for relatively constant moments of fractional changes in seafloor density and compressibility across OAWRS spatial scales, we can write Equation (2.11) as:

$$\text{Var}(\Phi_S(r_s|r_0, f_c))$$

$$= \langle |A_S(f_c, \Gamma_k, \Gamma_d, V_c)|^2 \rangle \iiint_{V_s} (4\pi)^2 \langle |G(r_t|r_0, f_c)|^2 |G(r_t, f_c)|^2 \rangle dV_t$$

where the expected magnitude squared of the seafloor scattering amplitude per coherence volume is defined as:

$$\langle |A_S(f_c, \Gamma_k, \Gamma_d, V_c)|^2 \rangle = \frac{1}{V_c} \left\langle \left| \frac{S(f_c)}{k} \right|^2 \right\rangle$$

$$= k^4 V_c [\text{Var}(\Gamma_k) + F_d \text{Var}(\Gamma_d) + F_c \text{Cov}(\Gamma_k, \Gamma_d)]$$

which is a function of insonification frequency and seafloor properties, such as changes in seafloor density, compressibility and coherence length scale.

Detailed derivations of the broadband seafloor scattered field and its moments and approximations that enable efficient wide-area estimation of seafloor scattering using the Rayleigh-Born approach are provided in Appendices C-C.2.

### 2.3 Measured Distribution of Atlantic Cod in Massachusetts State Waters

We used cod body length distributions and aggregation densities measured during recent spring surveys conducted from New Hampshire during May–June, 2011, described in [4, 5]. The surveys were conducted just south of the Isle of the Shoals and entered the Gulf of Maine.
Cod Spawning Protection Area just a few nautical miles east of the northern Massachusetts coastline [7]. A scientific echo sounder with a 120-kHz split beam transducer produced range-depth images of cod aggregations [4, 5], as shown in Figure 2-3. Spawning aggregations imaged along the survey tracks were found to have areal population densities of roughly 0.01 cod/m² [4, 5]. Concurrent trawls found a mean cod length of roughly 66 cm (Figure 2-2) [4, 5]. The most dense cod aggregations were found within roughly 10 m of the seafloor, where the water depth varied between roughly 50 to 90 m (Figure 2-3) [4, 5]. These recent measurements of cod during spawning are used to provide examples of cod distributions, from which the feasibility of using OAWRS to detect cod aggregations is assessed. Since no cod were found in trawls during the Northeast Fisheries Science Center Georges Bank Atlantic Herring survey [87] that was conducted in conjunction with an OAWRS survey during the peak fall herring spawning in 2006, no ground truth experimental comparisons between OAWRS detections and known cod aggregations are available.

Figure 2-3: Echograms showing cod aggregations on (A,B) 28–29 May and (C,D) 18–19 June 2011, off the coasts of Massachusetts and New Hampshire in Ipswich Bay during the same University of New Hampshire surveys described in [4, 5]. The color bar shows the volume density in the number of cod/m³. Black regions represent seafloor sediment.
2.4 Seafloor Scattering Data Collection during OAWRS Experiments

We used OAWRS seafloor scattering data acquired in 2003 on the New Jersey continental shelf [14, 40] and in 2006 on the northern flank of Georges Bank in the Gulf of Maine [11, 88] (Figure 2-9). The areas investigated for study here had relatively constant bathymetry with sandy bottoms of mean density and sound speed, 1.9 g/cm$^3$ and 1700 m/s, respectively [80, 88, 89]. Hundreds of sound speed profile samples of the water column were taken during the experiments to allow accurate characterization of both the mean and randomly fluctuating components of the continental shelf waveguide. Here, by “scattered returns” we mean the OAWRS source signal that is scattered from a target, such as fish or seafloor, and received at the OAWRS horizontal receiver array, typically measured in decibel units (dB re 1 $\mu$Pa).

2.5 Experimental Estimation of Rayleigh-Born Seafloor Scattering Amplitude

The expected magnitude squared of the Rayleigh-Born seafloor scattering amplitude, $|A_s|^2$, is estimated by minimizing the mean squared error between the measured and modeled scattered field (Equation (2.13)) over range with respect to $|A_s|^2$. For the $m^{th}$ radial beam of the $j^{th}$ transmission, an estimate, $|A_s|^2_{m,j}$, is obtained by minimizing the sum of the mean squared error over $L$ OAWRS range resolution cells, so that:

$$\begin{align*}
|A_s(f_c)|^2_{m,j} = & \min_{|A_s|^2} \frac{1}{L} \sum_{i=1}^{L} \left| 10\log\left( \frac{|\Phi^j_{m,\text{data}}(r_i,|r_0, f_c)|^2}{p^2_{\text{ref}}} \right) - 10\log\left( \frac{\text{Var}(\Phi^j_m(r_i,|r_0, f_c))}{p^2_{\text{ref}}} \right) \right|^2 \\
\end{align*}$$

(2.15)

where $|\Phi^j_{m,\text{data}}(r_i,|r_0, f_c)|^2$ is the measured scattered field and $\text{Var}(\Phi^j_m(r_i,|r_0, f_c))$ is the variance of the modeled scattered field; a good approximation to the second moment of
the scattered field (Equations (C.17) and (C.18)), at the $i^{th}$ OAWRS range resolution cell centered on $r_s$, and $P_{ref}$, is $1 \mu Pa/Hz$ in water. The estimate of $\langle |A_s(f_c)|^2 \rangle$ for each source frequency, $f_c$, is then the mean of $|A_s(f_c)|^2_m$ over $M$ radial beams and $J$ transmissions:

$$\langle |A_s(f_c)|^2 \rangle = \frac{\sum_{j=1}^{J} \sum_{m=1}^{M} |A_s(f_c)|^2_m}{JM}$$  \hspace{1cm} (2.16)

We restrict our analysis to beams that are not contaminated by bio-clutter or ship noise and to regions that are within approximately 30 km of the receiver array (Figure 2-9). We have excluded the beams where the scattered returns from the seafloor fall below the local ambient noise in the same beam. Seafloor scattered returns can be distinguished from fish scattered returns in OAWRS images, because (i) they have different frequency dependence from fish scattered returns [11, 40, 88] and (ii) they are statistically stationary in time as opposed to non-stationary returns from fish aggregations [11, 40, 80, 88, 90].

Comparisons between the measured and modeled scattered field level in the New Jersey continental shelf and Georges Bank for various source frequencies are shown in Figures 2-10 and 2-11, respectively. We find that the mean modeled seafloor scattered level matches well (within one standard deviation) with the respective mean measured scattered level over a given resolution cell along the entire sensing range for most frequencies that have been used for OAWRS sensing in the past. The 1,325-Hz New Jersey continental shelf scattered field data (Figure 2-10C) may be contaminated by diffusely distributed scatterers in the water column that affect the range-dependence of the scattered field.

Using OAWRS measurements of long-range seafloor scattering in typical sandy continental shelf waveguide environments along the U.S. northeast coast, we estimate the magnitude squared of seafloor scattering amplitude per coherence volume (Figure 2-4) over the range of frequencies that are conducive for long-range waveguide propagation and where the scattering amplitude of fish aggregations is high due to swim bladder resonance. We find that seafloor scattering amplitude squared follows a roughly $f^{2.4}$ frequency dependence, varying
as $f^{2.7}$ in the New Jersey continental shelf and as $f^{2.1}$ in Georges Bank (Figure 2-4). At all source frequencies, the magnitudes of seafloor scattering amplitudes in the two continental shelf environments match well with each other (Figure 2-4), consistent with the similarity in sandy sediments found in these two regions [11, 40]. Seafloor scattering is modeled using a Rayleigh–Born approach in terms of the incoming Green function from an acoustic source to a seafloor scattering volume element, the Rayleigh–Born seafloor scattering amplitude and an outgoing Green function from the seafloor scattering volume element to a receiver, integrated over the entire scattering volume in the seafloor (Section 2.2.3). Multimodal propagation effects appearing in waveguide Green functions [81, 91] can be mathematically separated from seafloor scattering effects. In order to account for random fluctuations in the ocean waveguide, the moments of Green functions and their derivatives are calculated by Monte Carlo realizations over range- and depth-dependent sound speed structures [14, 88, 90].

Figure 2-4: Frequency dependence of the experimentally estimated magnitude squared of seafloor scattering amplitude, $|A_s|^2$ (Equation (2.14)), which is proportional to the scattering cross-section, in terms of a volume adjusted target strength defined as $T_{S_s} = 10 \log_{10} \left( \frac{|A_s|^2}{V_{ref} r^3_{ref}} \right)$, for the New Jersey continental shelf (gray circles) and Georges Bank environment (black circles) along with the respective standard deviations (solid tick marks). The overall frequency dependence of the magnitude squared of seafloor scattering amplitude per coherence volume for both environments is approximately $f^{2.4}$. In water, $V_{ref} = 1 \text{ m}^3$ and $r_{ref} = 1 \text{ m}$. 
Figure 2-5: (A) Distribution of cod spawning populations during the Industry-Based Survey for Gulf of Maine Cod conducted by the Massachusetts Division of Marine Fisheries in 2006 [6] with the typical OAWRS areal coverage of 100 km in 75 s and 50 km in 35 s. (B) Bathymetry of the region off the coast of Massachusetts and the typical OAWRS areal coverage of 100 km in 75 s and 50 km in 35 s. The Gulf of Maine cod spawning protection area [7] and May–June, 2011, University of New Hampshire Cod Survey area [4, 5] falls in the Ipswich Bay, off the coast of Massachusetts and New Hampshire. A towed receiver array typically employed in OAWRS moves along tracks that would run between the centers of the shown circles and produce effectively continuous overlapping imaging windows in between.
2.6 Feasibility of OAWRS Detection of Atlantic Cod Aggregations and Individuals

We find that at swim bladder resonance frequencies, robust detection and imaging of cod spawning aggregations with OAWRS is possible (Figures 2-3 and 2-2) in continental shelf waveguide environments along the U.S. northeast coast. Our analysis shows that scattered returns from bottom-dwelling spawning cod aggregations, which were observed by echosounders during recent spring surveys in Ipswich Bay [4, 5], with population densities of 0.01 fish/m², can be detected roughly 20–27 dB above seafloor scattered returns at swim bladder resonance, roughly 300 Hz in this case, when cod are neutrally buoyant close to the seafloor (Figures 2-6A,B). This spawning cod aggregation density is roughly 2–3 orders of magnitude larger than the minimum density necessary for OAWRS detection above seafloor scattering for ranges up to and beyond 30 km, as shown in Figure 2-6B. Similarly robust OAWRS detection is possible for cod spawning aggregations during mid-water column feeding [8, 9] up to 30 km and beyond, when probed at a swim bladder resonance frequency of roughly 200 Hz, for cod neutrally buoyant in the mid-water column (Figure 2-6C,D). Individually dispersed cod located in the mid-water column can also be robustly detected within a few kilometers using OAWRS when probed at the swim bladder resonance frequency (Figure 2-7). In the extreme case of cod being neutrally buoyant at the sea surface and, so, at their negative buoyancy limit anywhere in the water column [92–95], the swim bladder resonance frequency will increase and the cod scattering amplitude will decrease (Figure 2-2C), so that the fish-to-seafloor scattering ratio (FSR) (Equation (2.7)) will decrease by roughly 8 dB for the bottom dwelling case of Figure 2-6A,B and by roughly 5 dB for the mid-water column case of Figure 2-6C,D. The spawning aggregation density then would be roughly 1–2 orders of magnitude higher than the minimum density required for OAWRS detection above seafloor scattering, again enabling robust OAWRS detection. At spawning sites with denser cod aggregations [96], the FSR is expected to be higher, and so, the cod will be robustly detectable over a wider range of frequencies near swim bladder resonance. In the case of cod found in deeper Gulf of Maine waters located and neutrally buoyant close to the
seafloor [97], the swim bladder resonance frequency increases and cod scattering amplitude decreases (Figure 2-2D), so that the fish-to-seafloor scattering ratio (FSR) (Equation (2.7)) decreases. For example, this decrease is roughly 5–6 dB from that shown in Figure 2-6A for cod at 300 m of depth with a population density of 0.01 fish/m². This aggregation density then would be roughly 1–2 orders of magnitude higher than the minimum density required for OAWRS detection above seafloor scattering, again enabling robust OAWRS detection.

The scattering amplitude of Atlantic cod is modeled as a function of frequency using the Love model [1] for a given body length distribution and an occupancy depth in the water column. Our theoretical predictions of cod swim bladder resonance from the Love model [1] match well with past swim bladder resonance measurements of cod [2, 3] made at similar depths. The scattered field from cod are modeled using this scattering amplitude and the waveguide Green function determined by parabolic equation calculations given known water column and sediment sound speed structures and bathymetry and using the methods described in Appendix C of Jagannathan et al. [90]. Cod densities are assumed to be uniform within the resolution footprint of the OAWRS system. This is easily attained for OAWRS range resolution \( \Delta r = c/(2B) \), which is typically on the order of 15 m and set by the signal bandwidth, \( B \) [40]. It is also typically attained in cross-range \( \Delta S = R(\lambda/L) \) out to ranges of at least 30 km, where \( \Delta S \) typically is less than the roughly 1 km extent of spawning cod aggregations (Figure 2-3) [4, 98] for typical 128-element receiver arrays sampled at half-wavelength spacing [11, 40]. The seafloor scattering amplitude in the Ipswich Bay environment considered here is expected to be similar to that estimated in the New Jersey continental shelf and Georges Bank environments (Section 2.5, Figure 2-4), due to similar [99] sediment types.

Spawning cod aggregations in the coastal waters under investigation here have recently been shown to produce sounds in the 50–500 Hz frequency range [100, 101]. The fact that these cod sounds are in the same frequency range as our theoretical predictions of swim bladder resonance for spawning cod aggregations is expected, because the cod sound production mechanism involves stimulation of the swim bladder [102, 103], which produces the largest response at resonance. These cod sounds would not affect active OAWRS cod sensing, because their levels are well below active OAWRS scattered returns and are also incoherent.
with respect to OAWRS scattered returns, which reduces their effect as noise even further by the coherent matched filtering used in OAWRS detection and imaging [11, 40].

Figure 2-6: The Ocean Acoustic Waveguide Remote Sensing (OAWRS) fish-to-seafloor scattering ratio (FSR) (Equation (2.7)) as a function of frequency and the normalized scattered returns from cod vs. seafloor for various cod configurations in the water column of a depth of 80 m. The minimum population density required for OAWRS detection of cod at or near the swim bladder resonance is roughly $1 \times 10^{-4}$ cod/m$^2$ for bottom-dwelling cod and roughly $1 \times 10^{-5}$ cod/m$^2$ for mid-water column cod. Cod are assumed to be neutrally buoyant at the shallowest limit of their assumed occupancy depth range in each case. The aggregation density in (A)–(B) is 0.01 cod/m$^2$, similar to that observed during spawning in Ipswich Bay [4, 5], and in (C)–(D) is 0.001 cod/m$^2$, similar to that observed during feeding [8, 9]. The cod body length is assumed to follow the distribution measured during a recent Ipswich Bay spring survey in 2011, as shown in Figure 2-2. Methods for the estimation of FSR and the scattered returns are described in Sections 2.3 and 2.2.3.
Figure 2-7: The fish-to-seafloor scattering ratio (FSR) (Equation (2.7)) as a function of range for OAWRS detection of a single cod at the swim bladder resonance frequency. An individual cod can be detected at least 10 dB above the seafloor scattering when suspended at mid-water column within roughly 8 km of the source, but may not be detected when located on or very close to the seafloor when probed at the swim bladder resonance frequency. The cod is assumed to be neutrally buoyant at its occupancy depth in the water column. The cod is assumed to have a body-length distribution shown in Figure 2-2A. The seafloor is assumed to have a uniform depth of 80 m. The source and receiver are located at 50 m of depth. Methods for estimation of FSR are described in Section 2.3.

2.7 Discussion

A lower frequency OAWRS system [11, 40] spanning the cod swim bladder resonance frequencies may be used to continuously detect, monitor and enumerate cod populations and to quantitatively describe their temporal and spatial behavior. Widely separated population centers (Figure 2-5A) can be identified by the continuous spatial coverage of OAWRS imaging, but may be missed by conventional acoustic and trawl line transect approaches. A typical scenario for wide-area sensing using OAWRS is given in Figure 2-5, where almost the entire Massachusetts and New Hampshire coastal region, including the Gulf of Maine Cod Spawning Protection Area [7], can be surveyed in 75 s within the corresponding 100-km diameter OAWRS imaging window. The OAWRS coverage area in Figure 2-5B includes some of the prime spawning locations of Atlantic cod in the Gulf of Maine, where they are known to form dense aggregations [97, 104] that should be robustly detectable using OAWRS techniques. The OAWRS approach typically employs a towed receiver array that moves along
tracks and, so, produces hundreds of instantaneous overlapping imaging windows [11, 40]; some of these are shown in Figure 2-5B, where the centers of the circles correspond to the location of the tow ship when the image was formed. Since detection ranges in OAWRS typically span many tens to hundreds of water column depths, ocean depth is very shallow compared to the OAWRS sensing range in continental shelf environments [11, 40] and enables hundreds to thousands of propagating acoustic modes to fill the entire water column at OAWRS frequencies [38, 105-107]. Only at potential nulls within an eighth of the acoustic wavelength from potential pressure release surfaces at the water column’s upper and lower boundaries may fish detection become difficult to effectively impossible, as in any acoustic sensing system. Consistent application of National Oceanic and Atmospheric Administration (NOAA) guidelines on sound in the ocean [108] suggests that many ships with continuous engine noise, such as cruise ships, cargo vessels and whale-watching boats [109-111], should monitor for marine mammals within a few to tens of kilometers of the ship, but that OAWRS, which uses short, infrequent pulses of low duty cycle (roughly 0.01) and whose received sound pressure levels never exceed those of natural marine mammal vocalizations [112-114], should monitor for marine mammals within tens to hundreds of meters from the OAWRS source.

It may be possible to remotely classify cod by OAWRS spectral analysis, since they have such a strong response at their swim bladder resonance, which is not found in seafloor scattering. Ground truth from capture, as well as behavioral analysis to set the context would still likely be necessary, since a number of other species of large fish, such as haddock, hake and pollock [115], may have resonant responses in similar frequency ranges (Figure 2-8). It should, however, be possible to remotely distinguish cod from smaller groundfish species that have resonance responses at frequencies hundreds of Hertz greater than those of cod, as shown in Figure 2-8 for plaice and redfish. Cod surveys are typically conducted during the spawning season, when cod aggregations are largest and densest [7, 104], making concurrent ground truth verification possible by capture trawl. During off-spawning seasons, however, capture trawl may not be practical for the typical widely dispersed cod populations, so increasing the need for classification by remote techniques, such as OAWRS spectral analysis.
Figure 2-8: (A) The distribution of body lengths of some other groundfish species found along the coasts of Massachusetts and New Hampshire during spring 2005–2006 [6, 10]. (B) The estimated target strength of these fish species following the body-length distribution in (A), located between 70 m and 80 m in the water column and neutrally buoyant at 70 m. All depths are measured from the sea-surface. The target strength of the different species is estimated using the Love model [1] (Appendix B).
2.8 Conclusions

We find that Ocean Acoustic Waveguide Remote Sensing (OAWRS) is capable of instantaneously and robustly detecting spawning cod aggregations over wide areas spanning thousands of square kilometers for observed spawning cod densities and configurations in U.S. northeast continental shelf waters at cod swim bladder resonance frequencies. At swim bladder resonance, OAWRS can also be used to detect individual cod within a few kilometers of the OAWRS system. Such robust detections of cod are possible, because the cod scattering amplitude has a strong low frequency resonance peak spanning the roughly two-octave range of 150–600 Hz within water depths of roughly 100 m, in contrast to the relatively uniform seafloor scattering frequency dependence of roughly $f^{2.4}$, which we find below roughly 2 kHz in U.S. northeast continental shelf environments. This cod resonance frequency range is also optimal for long-range ocean acoustic waveguide propagation, because it enables multimodal acoustic waveguide propagation with minimal acoustic absorption and forward scattering losses. As the sensing frequency moves away from the resonance peak, OAWRS detection of cod becomes increasingly less optimal, due to a rapid decrease in cod scattering amplitude. In other environments where cod depth may be greater, the optimal frequencies for cod detection are expected to increase with swim bladder resonance frequency.

2.9 Author Contributions

This chapter comprises the work appearing in Ref. [116] co-authored by Ankita D. Jain, Anamaria Ignisca, Dong Hoon Yi, Purnima Ratilal and Nicholas C. Makris. The text was primarily written by ADJ and edited by NCM. Theoretical fish and seafloor scattering derivations appearing here were primarily done by ADJ and NCM. Associated theoretical derivations on seafloor scattering appearing in Ref. [117] were primarily done by AI, ADJ, PR and NCM. The OAWRS seafloor scattering data analysis was primarily done by ADJ, DHY and AI. Software to implement the analytic formulations presented here and in Ref. [117] were primarily developed by AI and ADJ.
Figure 2-9: Bathymetric map of (A) New Jersey continental shelf and (B) Georges Bank showing the location of the fan-shaped patches used for estimating the magnitude squared of the Rayleigh–Born seafloor scattering amplitude. The seafloor scattered field data from these patches was collected along several tracks (black lines) for the respective OAWRS source locations (black diamond) during the (A) 2003 OAWRS experiment for source location 1 (39.0563°N, -73.0365°E) and two receiver tracks extended between (39.08°N, -73.08°E) and (39.07°N, -72.97°E); and (39.09°N, -73.08°E) and (39.06°N, -72.97°E); and (B) 2006 OAWRS experiment for source location 1 (41.8901°N, -68.2134°E), source location 2 (41.9372°N, -68.1046°E), and source location 3 (42.0134°N, -67.829°E) and respective receiver tracks extended between (41.83°N, -68.35°E) and (41.81°N, -68.32°E); (41.98°N, -68.2°E) and (42.05°N, -68.0°E); and (42.05°N, -67.85°E) and (42.1°N, -67.89°E). The gray lines represent depth contours.
Figure 2-10: Comparison between the measured normalized seafloor scattering and the modeled normalized scattered level in the New Jersey continental shelf at (A) 415 Hz using 198 radial beams, (B) 925 Hz using 187 radial beams and (C) 1,325 Hz using 381 radial beams as a function of the total travel time (Section 2.5). The darker regions in the measured scattered field level indicate a higher density of data points. The standard deviation of the measured level (vertical tick marks) is calculated from all the data points that fall within the travel time corresponding to an OAWRS range resolution [11] seconds around a given travel time. The total travel time is the two-way travel time from the source to the seafloor and from the seafloor to the receiver.
Figure 2-11: Comparison between the measured normalized seafloor scattering and the modeled normalized seafloor scattering in the Georges Bank at (A) 415 Hz using 410 radial beams, (B) 575 Hz using 458 radial beams, (C) 735 Hz using 405 radial beams, (D) 950 Hz using 408 radial beams and (E) 1,125 Hz using 312 radial beams as a function of the total travel time (Section 2.5). The darker regions in the measured scattered level indicate a higher density of data points. The standard deviation of the measured level (vertical tick marks) is calculated from all the data points that fall within the travel time corresponding to an OAWRS range resolution [11] seconds around a given travel time. The total travel time is the two-way travel time from the source to the seafloor and from the seafloor to the receiver.
Chapter 3

Nordic Seas Experiment 2014:
Experimental Demonstration of
Remotely Sensing Cod using OAWRS

3.1 Introduction

A main objective of the Nordic Seas 2014 experiment relevant to this thesis was to confirm our theoretical predictions on ocean acoustic waveguide remote sensing of Northeast Arctic cod as they ended their migration from the polar ice edge and engage in spawning activities in the coastal Lofoten area [66]. Unlike the declining trend of cod population in New England waters, cod population in the Nordic Seas has been thriving for many years and is currently at its healthiest recorded state. The experiment period was chosen such that it coincided with the peak spawning period of cod along the coastal Lofoten region in Norway where they congregate in high densities, as well as other keystone species that migrate from the ice-edge [47, 118, 119] to spawn in some of the world’s largest mass migrations. Other keystone species in the Nordic Seas environment namely herring, capelin and haddock were also investigated.

Another objective of the Nordic Seas 2014 experiment relevant to this thesis was to de-
termine the group behavioral mechanisms of vast social groups or shoals of pelagic fish in the Nordic Seas Arctic Ecosystem that govern basic processes such as spawning, migration and response to variations in the ocean environment and whale predators. These mechanisms are essential to species survival but remain largely unknown due to the current lack of adequate space-time sampling of conventional survey methods for such vast social groups which typically extend contiguously over thousands of square kilometers and freely range over habitats many orders of magnitude larger [66]. Nordic fish migrations and spawning behavior are highly dependent on oceanographic and ice-edge conditions [66] that are currently in a state of flux due to rapid arctic warming trends [47, 118, 119]. This makes it essential to understand the basic animal group behavioral mechanisms [11, 120–123] governing these species so that accurate models and forecasts can be made of their future and that of their ecosystem and appropriate decisions can be made to help their conservation. The Nordic Seas Arctic Ecosystem is one of the most fertile and productive habitats in the world [124], but is currently undergoing increased pressures from rapid climate change associated with the retreat of the polar ice edge [119] which alters key oceanographic conditions upon which the pelagic fish species and their predators depend.

3.2 Technical Approach

The approach was to instantaneously image and continuously monitor the population distributions of entire cod shoals in their Arctic spawning grounds along the north-central coast of Norway known as the Lofoten region (tens of thousands of square kilometers) for the first time with Ocean Acoustic Waveguide Remote Sensing (OAWRS) [11, 40, 77]. This was part of a three week field experiment from February 17 to March 8, 2014 (Figure 3-1) which included the first uses of new NSF towable and portable OAWRS source and receiver arrays (Figure 3-12) to enable instantaneous continental-shelf scale imaging and continuous monitoring of fish and whale populations. This is because a single OAWRS transmission can instantaneously image roughly 100 km diameter in a 75-second inter-transmission period. To provide verification of areal fish population densities and species identification, OAWRS was used in conjunction with simultaneous measurements of fish populations by conventional
line transect methods that employ direct sampling with net and trawls as well as standard high frequency acoustics. For the experiment, Woods Hole Oceanographic Institution operated R/V *Knorr* was used to deploy the OAWRS source and receiver arrays, and Norwegian fishing vessel *Artus* and R/V *Johan Hjort* were used for conducting simultaneous trawl and conventional echosounding surveys.

Figure 3-1: Nordic Seas Experiment 2014 overview of cruise tracks. The focus of this chapter is on the modeling and measurements made in the Lofoten area, which is the prime spawning area for cod in the Nordic Seas.

### 3.3 Pre-cruise preparation

Experiment preparation comprised (1) determining general OAWRS survey region based on historic cod spawning hotspot locations; (2) designing OAWRS source waveforms based
historic fish length distribution and occupancy depths in the water column for optimal long range detection of cod aggregations; (3) OAWRS survey track design based on acoustic transmission loss modeling using historic sound speed measurements. Cod are known to congregate in dense aggregations during spawning in February-March, making them ideal candidates to study group behavioral dynamics over ecosystem scales.

3.3.1 Historic Cod Spawning Hotspot Locations

The coastal Lofoten region is a prime spawning location for Northeast Arctic cod that are known to undertake distant migrations to these spawning areas [66]. Traditionally, cod are demersal species, i.e. they spend most of their time close to the seafloor but they periodically migrate vertically in the water column especially during night time [66]. The most dense spawning aggregations of cod are found near the island of Rost located at (67.5 N, 12 E), surrounding continental shelf regions of roughly 100-250 m water deep and all the way up to the coastal regions near the city of Andenes at (69.3 N, 16.1 E). (Figure 3-2) [66].

3.3.2 Cod Swimbladder Resonance Modeling

The optimal sensing frequencies for cod depend on their acoustic scattering characteristics. Cod, like many other pelagic and demersal fish species, have a gas-filled buoyancy organ called the swim bladder. The swim bladder acts as a strong scatterer of acoustic waves due to the large impedance difference between the gas inside and the water medium surrounding it. At the swim bladder resonance frequency, which depends on swim bladder size and consequently fish size, the dynamic response of the swim bladder attains a maxima. So, acoustic waves are scattered most efficiently at swim bladder resonance, making it the optimal frequency for remote detection using OAWRS. Modeling of swimbladder resonance is then necessary to optimally sense fish aggregations. The multi-frequency OAWRS system also enables remote species identification [77].

Swimbladder resonance frequency and amplitude (the logarithm of the amplitude squared is known as target strength) are estimated using Love’s model for swimbladder resonance [1]
Figure 3-2: Spawning Northeast Arctic cod hotspots (red circles) measured during February-March of 2011-2013 using high frequency echosounders in the Lofoten region during annual surveys conducted by IMR. The image was taken from Ref. [12].
and are a function of historic fish body length distributions, fish occupancy depth, and the depth at which the fish are neutrally buoyant (Appendix B). Mature Northeast Arctic cod have body lengths typically in the range of 50 cm to over one meter [12]. For these typical cod length distributions, swimbladder resonance modeling indicates that the resonance peak occurs in the wide range of 250 to 1200 Hz (Figure 3-4). Then, for most optimal sensing of these three species, the OAWRS frequencies would need to span these swimbladder resonances.

Figure 3-3: For spawning cod, the mean cod body length is assumed to be 75 cm with a 20% standard deviation in body lengths in target strength modeling.

3.3.3 OAWRS Source Characteristics and Waveform Design

3.3.3.1 Mod-30 Source Array

The Mod-30 source array consists of eight elements of Mod-30 flextensional transducers (Figure 3-5). Each Mod-30 transducer was manufactured new. The eight Mod-30 transducers are housed in individual tow bodies that are connected together mechanically with inter-element links. The eight transducers are connected electrically by an inter-element array cable. The approximate length of the array is 275 3/8" (≈23') from top element to bottom element. There are two non-acoustic sensors that provide pitch, roll, heading, depth and temperature. They are located on the top and bottom of the Mod-30 array and are cabled
Figure 3-4: Estimated target strengths and swimbladder resonance frequencies as a function of occupancy depth of Northeast Arctic cod with body length distribution shown in Figure 3-3 and neutral buoyancy depths at 0 m or the sea surface, half the occupancy depths, and equal to the occupancy depths. Fish are assumed to be uniformly distributed in a 10 m layer in the water column, where the shallowest depth is the given occupancy depth.
to the transmit controller rack. A surface controller box provides power to the sensors and sends the ASCII data to the transmit controller software for display and logging.

![Figure 3-5](image)

Figure 3-5: A picture of the OAWRS Mod-30 towable source array containing 8 elements and spanning 7 m in length used during the Nordic Seas experiment.

### 3.3.3.2 Source Waveform Design

Based on estimated cod target strengths, source waveforms shown in Figure 3-6 are designed for the Nordic Seas experiment. Since the relative source power is expected to peak at 955 Hz and 1335 Hz, these two center frequencies are used as the workhorse frequencies, i.e. a source transmission for at these frequencies is sent out every minute. All other waveforms are sent out sequentially and the wavetrain is repeated over and over.

Cod are often known to perform rapid vertical migrations and are usually negatively buoyant in the water column [92, 94, 125, 126]. For a typical cod aggregation of mean body length of 75 cm and neutral buoyancy depth at the sea surface, swimbladder resonance frequencies of up to 1.2 kHz are expected for occupancy depths of roughly 150 m in the water column (Figure 3-4). The other extreme is when a cod aggregation is neutrally buoyant at its occupancy depth of roughly 10 m, in which case swimbladder resonance frequencies of roughly
250 Hz (Figure 3-4) are expected. In both these cases, the 955 Hz source waveform is optimal for cod detection due to its proximity to cod swimbladder resonance frequencies and its relatively higher source level that enables acoustic transmission over longer ranges without being limited by ambient noise.

Given the low swimbladder resonance frequencies of cod in the 250-500 Hz range for cod neutrally buoyant at half their occupancy depths or at their occupancy depths (Figure 3-4), typical of Nordic Seas cod, the OAWRS technique would have benefitted from a low frequency source such as the XF-4 array used in the 2003 OAWRS experiment conducted in the New Jersey Continental Shelf [40].

### 3.3.4 Transmission Loss Modeling in the Lofoten Region

Long range two-way transmission loss from the OAWRS source to fish location to OAWRS receiver was estimated using a US Navy standard parabolic equation Range-dependent Acoustic Model (RAM) that has been calibrated in a variety of environments [13]. This was a necessary step since the spawning grounds for cod had distinct geophysical, oceanographic and bathymetric properties. OAWRS survey tracks in the Lofoten region were designed to optimize long range transmission.

Transmission loss modeling requires the knowledge of vertical sound speed structure, bathymetry and sediment properties. For the pre-cruise preparation, historic sound speed profiles over the past ten decades, provided by IMR, were used for transmission loss modeling, along with available bathymetry and sediment databases. The historic sound speed profiles in the Lofoten region in February-March shown in Figure 3-7 are all upward refracting. Consequently, long range transmission loss modeling indicated that placing the source array deeper led to a more uniform insonification of the water column and so was suitable for detection of fish aggregations located throughout the water column. The depth dependence of the transmission loss from target to the OAWRS receiver array, which by means of reciprocity is equal to that from the receiver array center to the target, was relatively negligible as the receiver array depth was varied. Examples of some transmission loss runs in the Lofoten region are shown in Figures 3-8, 3-9 and 3-10.
Figure 3-6: OAWRS source waveforms used in the Nordic Seas experiment.
3.3.5 OAWRS Cod Survey Track Design

Based on transmission loss analysis and location of spawning hotspots for cod, we designed preliminary, place-holder OAWRS tracks in the Lofoten region as shown in Figure 3-11.

The actual tracks were developed during the experiment as always, to adapt to the developing conditions found at sea to fully exploit the intelligence, flexibility and adaptability of a research vessel directed in real time by human beings.

3.4 OAWRS Data Acquisition

Acoustic waveforms were transmitted from R/V Knorr's Mod-30 source array and echo returns were measured with the Five-Octave Research Array (FORA) also deployed from R/V Knorr as sketched in Figure 3-12. Typically, both source and receiver arrays were deployed at different depths.

The FORA is a 277-m, 396 channel nested acoustic array, divided into five acoustic apertures with frequency coverage up to roughly 4000 Hz. There are three main sections of the array:

- a cardiodal/triplet sub-array for left-right ambiguity at the head of the array;
- three conventional center nested sub arrays labelled high frequency (HF), mid frequency (MF) and low frequency (LF) apertures;
- an 88-m removable ultra low frequency (ULF) section at the tail of the array.
Figure 3-8: Lofoten region transmission loss analysis: Range-depth transmission loss in dB re 1 m estimated along the shown path using a US Navy standard parabolic equation model RAM [13] at 1300 Hz averaged over 10 Monte Carlo simulations for different receiver and source depths. Each simulation uses a distinct set of sound speed profiles randomly picked from historic profiles every 500 m [14]. The y-axis represents water depth in meters and x-axis represents the range in km from the source/receiver.
Figure 3-9: Lofoten region transmission loss analysis: Range-depth transmission loss in dB re 1 m estimated along the shown path using RAM [13] at 1300 Hz averaged over 10 Monte Carlo simulations for different receiver and source depths. Each simulation uses a distinct set of sound speed profiles randomly picked from historic profiles every 500 m [14]. The y-axis represents water depth in meters and x-axis represents the range in km from the source/receiver.
Figure 3-10: Lofoten region transmission loss analysis: Range-depth transmission loss in dB re 1 m estimated along the shown path using RAM [13] at 1300 Hz averaged over 10 Monte Carlo simulations for different receiver and source depths. Each simulation uses a distinct set of sound speed profiles randomly picked from historic profiles every 500 m [14]. The y-axis represents water depth in meters and x-axis represents the range in km from the source/receiver.
Figure 3-11: Tentative tracks for OAWRS survey in the Lofoten region based on spawning hotspots of cod and transmission loss analysis using historic sound speed profiles in the region.

Table 3.1: Specifications of FORA apertures

<table>
<thead>
<tr>
<th>Acoustic Apertures</th>
<th>Number of hydrophones</th>
<th>Hydrophone spacing (m)</th>
<th>Aperture length (m)</th>
<th>Design cut-off frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ULF</td>
<td>64</td>
<td>3.0</td>
<td>189</td>
<td>250</td>
</tr>
<tr>
<td>LF</td>
<td>64</td>
<td>1.5</td>
<td>94.5</td>
<td>500</td>
</tr>
<tr>
<td>MF</td>
<td>64</td>
<td>0.75</td>
<td>47.25</td>
<td>1000</td>
</tr>
<tr>
<td>HF</td>
<td>64</td>
<td>0.375</td>
<td>23.625</td>
<td>2000</td>
</tr>
<tr>
<td>Triplet</td>
<td>783</td>
<td>0.2</td>
<td>15.4</td>
<td>3750</td>
</tr>
</tbody>
</table>
Figure 3-12: Wide-Area Towed Monostatic Ocean Acoustic Waveguide Remote Sensing (OAWRS) equipment setup and configuration.

Figure 3-13: Setup of the Five Octave Research Array (FORA) showing different apertures and components.
Of the 396 channels, one is a self-noise channel and another is a desensitized hydrophone. There are 4 NAS suites and a depth sensor. Each NAS suite provides heading, pitch, roll, depth, and temperature information. The array can operate either horizontally towed or vertically suspended from a moored or drifting ship. Some operational limitations of the FORA include:

- Nominal operating speed = 4 knots
- Maximum operating speed = 7 knots
- Survival speed = 10 knots
- Maximum working depth = 500 m
- Survival depth = 1000 m
- Tow cable length = sufficient to achieve 200 m at 5 knots

3.5 OAWRS Received Data Processing

The data acquisition and processing computer systems use PC workstations running the LINUX operating system. All processing signal programs are written in C language and all graphics programs are written in MATLAB. We also use a graphics user interface programmed in Python that enables efficient and convenient OAWRS data processing. Data processing includes demodulation, decimation, beamforming, and matched filtering of frequency modulated signals. Once spatial maps of the distribution of acoustic intensity, which indicates target hotspot locations, are generated, these images are concatenated to produce movies showing the temporal and spatial evolution of fish populations and their behavior.

Let $p^{raw}(r_i, t)$ be the raw pressure time series received at the horizontal range of the $i$-th receiver element from the array center $r_i$ where $i = 1, 2, 3, \ldots N = 64$. For sub-aperture center frequency $f_c$, the band-pass filtered pressure time series $p^{band}(r_i, t)$ at the $i$-th element is

$$p^{band}(r_i, t) = p^{raw}(r_i, t) \ast h(t) \tag{3.1}$$

and in the frequency domain is

$$p^{band-passed}(r_i, f) = P^{raw}(r_i, f)H(f) \tag{3.2}$$
where \( h(t) \leftrightarrow H(f) \) are Fourier transform pairs of the band pass filter. Demodulation of \( P_{\text{band}}^{\text{pass}}(r_i, f) \) such that the range of received frequencies within \( f_c \pm BW_0/2 \) is now limited to within a bandwidth \( BW > BW_0 \) where \( BW_0 \) is the source bandwidth about zero is

\[
P_{\text{demod}}(r_i, f) = P_{\text{band-passed}}(r_i, f + f_c).
\]

(3.3)

Next, \( P_{\text{demod}}(r_i, f) \) is decimated from an original sampling rate of 8000 Hz down to 200 Hz and we obtain the received pressure field vector \( P(r) \) containing pressure values \( P(r_i, f) \) for all \( i \) receiver array elements. For a taper function vector \( T(r) \) containing the taper of all \( i \) elements \( T(r_i) \), the pressure field received on the receiver array is \( P(r)T(r) \) and its Fourier transform from the horizontal range along array axis to azimuthal angle domain is

\[
Q(s) = \tilde{P}(s) \ast \tilde{B}(s)
\]

(3.4)

where \( s = \sin \theta \), \( \theta \) is the horizontal azimuthal angle, \( \tilde{P}(s) \) is the Fourier transform of \( P(u) = \lambda P(r) \), where \( u \) is a dimensionless parameter equal to \( r/\lambda \), \( \tilde{B}(s) \) is the beampattern of the array. An example of the OAWRS receiver array steered at broadside is shown in Figure 3-14. Next, we beam form the received pressure and map them on to different horizontal azimuths. Time-domain beam forming encompasses steering the array in different directions \( s_j \) by applying a corresponding phase \( e^{j2\pi s_j u} \) along the length of the array. Then, the beam-formed pressure in the direction \( s_j \)

\[
Q(s - s_j) \Leftrightarrow P(u)T(u)e^{j2\pi u s_j}.
\]

(3.5)

A schematic flow chart of the data processing is also shown in Figure 3-15.
Figure 3-14: OAWRS receiver array beampattern at 1335 Hz steered to (a) broadside direction and (b) at 65° degrees off broadside.

3.6 Acquisition, Transmission and Correspondence Logs for Cod Survey

In this section, a day-to-day log of all activities including data acquisition, processing, source transmission and fish correspondence with R/V Knorr and R/V Johan Hjort are compiled for the cod portion of the OAWRS survey. All times are in UTC or GMT unless otherwise specified. All OAWRS images shown in this section are not corrected for transmission loss and show the received sound pressure level in dB re 1 μ Pa charted on the horizontal plane.

The actual ship tracks of R/V Knorr in the Lofoten region near Andenes are shown in Figure 3-16.
Figure 3-15: A flow chart showing the steps involved in acquired OAWRS acoustic data acquisition and processing starting with the raw pressure time series measured at all OAWRS receiver array channels to the final charted acoustic intensity in the horizontal plane.
Figure 3-16: A map of the Lofoten area bathymetry and overlain R/V Knorr track during the survey on March 5-7 near Andenes. The eastern portion of the tracks show R/V Knorr's shelter in the fjords near Andenes during hurricanes on March 6 and March 8.
### 3.6.1 March 5-6, 2014

We started data collection at 16:49 UTC. We observed multiple small schools starting from 17:07 UTC and were able to track them over roughly 1.5 hours until we turned around at the end of the track. These schools were migrating up north and then on to the bank at speeds of roughly 0.3-0.5 m/s consistent with swimming speed of cod schools. We observed a large shoal forming at 22:33 UTC near the northern end of the track. We cut through the shoal and observed a dense cod layer at 50 m depth with vertical extent of 20 m extending roughly 2 km using R/V Knorr’s echosounder between roughly 22:40 UTC and 23:34 UTC, which is consistent with OAWRS imaging. At 04:21, it was noted that since the dense fish layer broke apart and became scattered individuals, the imaged species was a larger gadoid species such as cod or haddock. There was, however, a less than 1% chance of the species being other than cod since other gadoid species rarely come to shallower regions to spawn in the Lofoten region [66]. The imaged species could not have been a pelagic species like herring or capelin because their shoals do not break apart as individuals. Moreover, the target strength of individuals from echosounder data after the shoal dispersed was consistent with that of larger gadoid fish. After ending transmissions at 00:50 UTC on March 6 due to bad weather, we looped over the imaged shoal and again confirmed the cod shoal with R/V Knorr’s echosounder. OAWRS images of these schools and shoal are shown in Appendix E.

On March 5-6 in the Lofoten area, we only had a few hours of operation due to an oncoming hurricane whose eye wall was approaching the area with 40+ knot winds and high seas. This hurricane was later named "Jorunn" by the Meteorological Institute of Norway (Figure 3-20). We proceeded to the fjords near Andenes to take shelter from the storm.

### 3.6.2 March 7-8, 2014

We returned back to the same location as March 5, which was now inside the eye of the hurricane, on March 7. We took advantage of the low wind speeds inside the hurricane eye to survey cod for a few more hours. We started data collection at 21:32 UTC. We observed some cod distribution from R/V Knorr’s echograms before we started transmission. It ap-
pears we went over a dense shoal that we later imaged in the process of formation before starting the track. Many small schools were observed within roughly 15 km range from RV Knorr. Some schools moved in the northern/northeastern direction and some in the western direction, again at speeds consistent with swimming speeds of cod.

At 23:37 UTC, we imaged a large shoal (Figures E-4) as R/V Knorr turned. This shoal was at the same location where we first observed cod distribution using RV Knorr's echogram before starting the track. We again imaged the shoal roughly half an hour later (Figure E-5) when we made another turn, and shoal appeared to have congregated into a denser aggregation than the one imaged half an hour earlier. The shoal also appeared to be migrating north-west. We turned into the shoal and cut through it and again observed it with R/V Knorr's echosounder (Figure 3-19). This was the only way to confirm the presence of cod given the time constraint due to an upcoming hurricane. A dense cod layer at roughly 70 m with vertical extent of roughly 30 m was observed over roughly 5 km. We started to lose the cod layer when water depth became deeper than 200 m between time 02:04 UTC and 02:14 UTC.

We determined the coordinates of four corners of a rectangular region to investigate at 01:05 UTC and gave them to RV Johan Hjort. RV Johan Hjort confirmed the dense cod layer extending roughly 1.5 nmi by its echosounder roughly an hour later at the locations we provided after we moved out of the area (Appendix H). Unfortunately, R/V Johan Hjort could not do a trawl due to high seas and hurricane winds of up to 50 knots. We ended data collection at 02:35 UTC. At 03:45 UTC R/V Knorr echosounder passed over the north eastern portion of the shoal we had just imaged and confirmed, just as we were fleeing the area. Cod were distributed between 60-120 m in the water column in a 125 m deep bathymetry.

The second wall of the hurricane eye was approaching towards our survey area and so we had to end transmissions at 02:35 UTC. This second eye wall brought 70 knot winds and 30 foot seas (Figures 3-20 and 3-21). The Norwegian coast guard directed us and other ships
Figure 3-17: A large cod shoal spanning roughly 15 km in length and 1-4 km in width was observed at array broadside at 23:37 UTC on March 7, 2014 while a ship turn. Prior to this image, the shoal was directly at array endfire and so was not imaged with good resolution.
Figure 3-18: Another view of the same shoal in Figure E-4 roughly half an hour later imaged at 00:16 UTC on March 8, 2014 when the shoal was closer to array endfire. Due to the hurricane in the area, RV Johan Hjort could not reach the survey location in time to help with simultaneous depth echosounding for ground truth confirmation of this shoal. The only way for us to confirm that this was a cod shoal was to turn into the shoal placing poor resolution endfire beams in the direction of the shoal to confirm the presence of the shoal and its depth distribution with the RV Knorr's echosounder. This meant that we had to sacrifice good resolution OAWRS imagery at broadside as in Figure E-4. This image was taken just as RV Knorr started to turn into the shoal and the south-western tail of the shoal fell in the endfire direction.
Figure 3-19: Excellent correspondence of a cod shoal between OAWRS imagery at 01:26:49 UTC on March 8, 2014 and conventional echosounding from R/V Knorr roughly 15 minutes later. This image was taken roughly an hour after the image in Figure E-5 when the shoal was further into the array endfire. We deliberately turned into the shoal, cut through it and observed it with RV Knorr's echosounder since RV Johan Hjort could not reach the Lofoten survey area in time to do simultaneous echosounder survey due to the hurricane. The hurricane weather conditions and calls from the Norwegian Coast Guard to leave the area only provided us with a few hours window to survey this cod shoal, and so this was the only way to confirm the presence of cod in the short time period. RV Johan Hjort, however, returned roughly an hour later and again confirmed it with its echosounder (Appendix H). This cod shoal was present before OAWRS transmission started at 21:32 UTC and lasted at least an hour after OAWRS transmissions ended at 02:35 UTC.
to immediately leave the area and find shelter. Due to the hurricane, RV Johan Hjort was not able to reach Lofoten on time and support us by conducting simultaneous echosounder line transect surveys, so we used RV Knorr's echosounder instead and confirmed cod shoals by directly passing over them. The weather conditions pushed the ability to operate at sea.

Figure 3-20: A satellite cloud image of hurricane "Jorunn" during the early hours of March 8, 2014 just when the storm hit the OAWRS survey location in Lofoten area near Andenes. (Image taken from Meteorological Institute of Norway news archives www.met.no).

### 3.7 Estimation of Areal Fish Population Density from OAWRS Images

Areal fish population density over wide areas in OAWRS images is empirically determined from echosounding data by matching the areal population density measured from echosounding and that from OAWRS images at the location where the two measurements are simultaneously made. In doing so, fish target strength at OAWRS frequencies $T_{S_{OAWRS}}$ is obtained at localized regions along transects across a shoal where simultaneous OAWRS and depth
Figure 3-21: Atmospheric pressure and wind direction measured on March 8, 2014 at 06:00 UTC, just after the storm passed the OAWRS survey location in Lofoten area near Andenes. (Image taken from Meteorological Institute of Norway news archives www.met.no).

Echosounding measurements are available. The averaged sound pressure level measured from OAWRS, $10 \log_{10} |\phi_F|^2$, and modeled transmission loss integrated over OAWRS resolution footprint, $TLA$, are used to obtain OAWRS scattering strength $SS_{OAWRS}$ over wide areas. Then, by extrapolating OAWRS target strength $TS_{OAWRS}$ over the entire fish shoal, assuming fish distribution and scattering characteristics follow stationary random processes, estimates of areal fish population density over the entire shoal are obtained.

The maximum likelihood estimate of $TS_{OAWRS}$ at OAWRS center frequency $f_{OAWRS}$

$$\hat{TS}_{OAWRS}(\rho_F, f_{OAWRS}) = 10 \log_{10} \left| \frac{S(f_{OAWRS})}{k} \right|^2$$

$$= 10 \log_{10} |\hat{\phi}_F(r_F | r, r_0, f_{OAWRS})|^2 - 10 \log_{10} \hat{\chi}(\rho_F, z_0, H, f_{OAWRS}) - SL(f_{OAWRS}) - 10 \log_{10} \hat{n}_a(\rho_F)$$

$$= SS_{OAWRS}(\rho_F, f_{OAWRS}) - 10 \log_{10} \hat{n}_a(\rho_F)$$  \hspace{1cm} (3.6)
is obtained from the invariance of the MLE [127] by evaluation of parameters at their corresponding MLEs in Eq. 2.1. The first two terms on the right hand side of Eq. 3.6 are estimated from OAWRS measurements of averaged intensity, typically over 5 transmissions and 2-range resolution cells, and modeled TLA (Eq. 2.2), respectively. The sum of the first three terms in Eq. 3.6 is the MLE of OAWRS scattering strength \( \tilde{\text{SS}}_{\text{OAWRS}} \).

The areal fish number density \( n_a \) is estimated from simultaneous depth echosounder along line transects across a shoal as

\[
10 \log_{10} n_a(\rho_F) = \tilde{\text{SS}}_{\text{Echo}}(\rho_F) - \tilde{T}_S_{\text{Echo}} \\
= 10 \log_{10}(s_a(\rho_F)) - \tilde{T}_S_{\text{Echo}} \\
= 10 \log_{10} \left( \int_{\text{Fish depth}} s_v(\rho_F) dz \right) - \tilde{T}_S_{\text{Echo}} 
\]

(3.8)

where \( \tilde{\text{SS}}_{\text{Echo}} \) is MLE of fish scattering strength at echosounder frequency \( f_{\text{Echo}} \), \( \tilde{T}_S_{\text{Echo}} \) is the MLE of target strength of an individual fish at echosounder frequency \( f_{\text{Echo}} \), \( s_a \) is the back scattered cross section per square meter at echosounder frequency \( f_{\text{Echo}} \), \( s_v \) is the volume back scattering strength measured from the depth echosounder at echosounder frequency \( f_{\text{Echo}} \), and \( z_{\text{Fish depth}} \) is the depth over which fish are distributed. Fish target strength at echosounder operating frequencies, \( T_{S_{\text{Echo}}} \), are typically different from the target strength at OAWRS frequencies \( T_{S_{\text{OAWRS}}} \). Estimates of \( T_{S_{\text{Echo}}} \) are made using an empirical relationship to fish body length \( L \) of the form \( \tilde{T}_S_{\text{Echo}} = a \log_{10} L + b \) at the echosounder frequencies.

At any given location within the shoal, the areal population density estimated from simultaneous echosounder measurements should be equal to the areal population density in OAWRS images. So by equating \( 10 \log_{10} n_a(\rho_F) \) in Eq. 3.8 from echosounder measurements to \( 10 \log_{10} n_a(\rho_F) \) in Eq. 3.7 at spatial locations \( \rho_F \) where concurrent OAWRS and echosounder measurements are available, the OAWRS target strength \( T_{S_{\text{OAWRS}}} (\rho_F, f_{\text{OAWRS}}) \) is estimated. This estimate of OAWRS target strength is then checked for consistency with
the Love model [1] for the observed fish occupancy depths from echosounder imagery, body length from trawl samples and expected neutral buoyancy depths from the knowledge of fish biology. The mean OAWRS target strength is then obtained by averaging over many independent OAWRS pixels within regions of statistically stationary fish populations.

Next, to estimate OAWRS areal number densities over the entire fish shoal, Eq. 2.1 is employed by combining all terms except $10 \log_{10} \bar{n}_a(p_F)$, and using the empirically estimated $\bar{S}_{fOAWRS}$ from OAWRS imagery and simultaneous echosounder data, as described above. Extrapolation of $\bar{S}_{fOAWRS}$ over wide areas in an OAWRS image where there are no simultaneous echosounder measurements can be done when the fish distribution and scattering follow stationary random processes.

An example of areal fish population density estimation for a cod shoal on March 7, 2014 is given below. The averaged OAWRS scattered level or log of OAWRS intensity $10 \log_{10} |\phi_F|^2$ over the span of the shoal is shown in Figure 3-25, where $f_{OAWRS} = 955$ Hz. The OAWRS scattering strength $S_{fOAWRS}$ is shown in Figure 3-26. Next, the OAWRS target strength of cod is estimated. This is done in a few different ways since the shoal was migrating and we did not have simultaneous areal density measurements from RV Johan Hjort’s high resolution fisheries echosounder. We did have echogram confirmation from RV Knorr, roughly 15 minutes after the last OAWRS image, at 01:40 UTC on March 8, 2015. RV Knorr’s echosounder (Knudsen 320B), however, is a low resolution seabottom profiler with a signal to noise ratio of only 10 dB. The measured levels from RV Knorr’s echosounder only within the shoal are calibrated using measurements from RV Johan Hjort’s echosounder data made at roughly similar time (between 03:10 to 03:25 UTC) and spatial location, an hour after the last OAWRS image. Then, RV Knorr’s calibrated areal density estimates obtained inside the shoal at an earlier time between 01:40 to 02:00 UTC and the OAWRS image at 01:26 UTC are used to estimate $< S_{fOAWRS} >$. All methods listed below result in values consistent to within 1.5 dB of each other with a mean of $< S_{fOAWRS} > = -26.7$ dB re 1 m.

1. Method 1: First, we match the peak areal population density measured from RV Johan Hjort’s echosounder and RV Knorr’s echosounder at similar locations inside the shoal.
at similar times to calibrate RV Knorr's volume backscattered levels. Then areal population densities simultaneously measured from RV Knorr's echosounder during the OAWRS survey are used to estimate $TS_{fOAWRS}$. Peak areal population density from RV Johan Hjort's echosounder was found to be 0.044 fish/m$^2$ at 03:15 UTC and (69.08E, 14.17N) on March 8. The peak volume backscattered level from RV Knorr's echosounder was found roughly 250 m away from peak areal density location measured from RV Johan Hjort echosounder as shown in Figure 3-22. RV Knorr recorded this peak back scattered level roughly 7 minutes before RV Johan Hjort recorded the peak areal population density inside the same portion of the shoal. The echosounder target strength was found to be $TS_{fEcho} = -29.65$ dB re 1 m at 38 kHz for mean measured cod length of $L = 78$ cm from trawl catches, estimated via the empirical relationship $TS_{fEcho} = 20 \log_{10} L - 67.5$ dB re 1 m at 38 kHz [128]. This method results in $TS_{fOAWRS} = -26.5 \pm 1.34$ dB re 1 m shown in Figure 3-22.

2. Method 2: First, we match the areal density measured by RV Johan Hjort’s echosounder with that measured by RV Knorr's echosounder at the same spatial location to calibrate RV Knorr’s volume backscattered levels. Then as in Method 1, areal population densities simultaneously measured from RV Knorr’s echosounder during the OAWRS survey are used to estimate $TS_{fOAWRS}$. RV Johan Hjort and RV Knorr crossed the same spatial location (69.08E, 14.17N) at 03:23 UTC and 03:14 UTC, respectively, on March 8, i.e. roughly 9 minutes apart. The areal density measured from Johan Hjort’s echosounder was 0.028 fish/m$^2$ at this spatial location. This method results in $TS_{fOAWRS} = -25.45 \pm 1.34$ dB re 1 m shown in Figure 3-23.

3. Method 3: We estimate $TS_{fOAWRS}$ using Love model [1]. Assuming mean cod length of $L = 78$ cm with standard deviation of 20% of the mean from trawl catches, neutral buoyancy depth close to the sea surface and measured occupancy depth between 50 to 80 m in the water column (Figure 3-19), cod target strength at 955 Hz OAWRS frequency is found to be $TS_{fOAWRS} = -28.2$ dB re 1 m as shown in Figure 3-24.

By extrapolating this mean OAWRS target strength of $TS_{fOAWRS} = -26.7$ over the entire shoal results in the OAWRS areal population density estimates $\bar{n}_a$ shown in Figure 3-27.
Figure 3-22: OAWRS cod target strength $T_{SfOAWRS}$ estimation using Method 1 where RV Knorr’s areal population density estimates are calibrated by matching the peak density measured in a similar location within the shoal and at similar time from those measured by RV Johan Hjort during their respective survey tracks in (a). The location of the peak areal density measurements made by RV Knorr and RV Johan Hjort are separated by roughly 250 m in space and 7 minutes in time. The measured levels from RV Knorr’s seabottom profiler echosounder within the shoal are calibrated using simultaneous measurements from RV Johan Hjort’s echosounder data. This results in $T_{SfOAWRS} = -26.5 \pm 1.34$ dB re 1 m using the OAWRS image at 01:26:49 UTC on March 8, 2015. Time in (a)-(c) represents the total elapsed time since the track start time given in the title of (a) for both ships. Colorbar in (c) represents volumetric density in fish/m$^3$ measured from RV Johan Hjort’s echosounder. Color in (d) represents location where cod were measured from RV Knorr’s echosounder. Range in (d) and (e) corresponds to the range between points α to ω in Figure 3-19.
Figure 3-23: OAWRS cod target strength $T_{SOAWRS}$ estimation using Method 2 where RV Knorr's areal population density estimates are calibrated by matching the areal density measured at the same location within the shoal at similar time from those measured by RV Johan Hjort. The location of the peak areal density measurements made by RV Knorr and RV Johan Hjort are separated by 0 m in space and 9 minutes in time. The measured levels from RV Knorr’s seabottom profiler echosounder within the shoal are calibrated using simultaneous measurements from RV Johan Hjort’s echosounder. This results in $T_{SOAWRS} = -25.45 \pm 1.34$ dB re 1 m using the OAWRS image at 01:26:49 UTC on March 8, 2015. Time in (a)-(c) represents the total elapsed time since the track start time given in the title of (a) for both ships. Colorbar in (c) represents volumetric density in fish/m$^3$ measured from RV Johan Hjort’s echosounder. Color in (d) represents location where cod were measured from RV Knorr’s echosounder. Range in (d) and (e) corresponds to the range between points $\alpha$ to $\omega$ in Figure 3-19.
The mean areal population density over the entire shoal is found to roughly 0.04 fish/m².

### 3.8 Experimental verification of theoretical predictions on the feasibility of remote sensing of cod using OAWRS

This experiment provided a first confirmation of the theoretical predictions of OAWRS of cod in continental shelf environments. This was possible despite the OAWRS source frequencies being much larger than the expected typical swimbladder resonance frequencies of cod in Nordic Seas environment as shown in Figure 3-4. The estimated aggregation densities of cod in the Nordic Seas environment were found to be much greater than those of New England cod. Nevertheless, the use of a lower frequency OAWRS source is still critical to optimally detect cod aggregations, especially for lower population densities than those observed during the experiment. Details on OAWRS of large cod shoals will be delineated in another thesis. The next chapter, however, focuses on the empirical observations of general
Figure 3-25: Averaged OAWRS scattered level $10 \log_{10} \left| \hat{\phi}_F \right|^2$ measured for the March 8 shoal at 00:16:49 UTC in the Lofoten area near Andenes at 955 Hz. Colors indicate measured scattered level in dB re 1 μ Pa. Solid black lines indicate bathymetric contours.
Figure 3-26: Estimated OAWRS scattering strength $SS_{OAWRS}$ for the March 8 shoal at 00:16:49 UTC in the Lofoten area near Andenes at 955 Hz. Colors indicate the scattering strength in dB. Solid black lines indicate bathymetric contours.
Figure 3-27: Estimated OAWRS areal population density estimate $\tilde{n}_a$ for the March 8 shoal at 00:16:49 UTC in the Lofoten area near Andenes. The mean areal population density across the shoal is found to be roughly 0.04 fish/m². Colors indicate the population density in fish/m². Solid black lines indicate bathymetric contours.
behavioral mechanisms of shoaling populations across species observed during the Nordic Seas experiment.

### 3.9 Cruise Participants

Experiment personnel comprised (1) the Principal Investigator and Chief Scientist Prof. Nicholas C. Makris, (2) graduate students and from Massachusetts Institute of Technology: Ankita D. Jain, Dong Hoon Yi, Wenjun Zhang, Byung Gu Cho, Guy M. Schory; (3) graduate students from Northeastern University advised by Prof. Purnima Ratilal: Delin Wang, Heriberto Garcia, Wei Huang, Alexander Bohn; (4) scientists from Institute of Marine Research, Norway: Olav Rune Godo, Gavin J. Macaulay, Matteo Bernasconi; (5) scientists from National Oceanographic and Atmospheric Administration, National Marine Fisheries Service: J. Michael Jech; (6) scientists from Naval Research Laboratory: Michael Collins; (7) scientists and technical staff from Forsvarets forskningsinstitutt (Norwegian Defence Research Establishment), Penn State, Einhorn Engineering and BAE; and (8) the crew of R/V Knorr, Artus and R/V Johan Hjort. Dong Hoon Yi helped with part of the cod analysis presented in this chapter.
Chapter 4

Most populous coherent mass migrations occur in highest aspect ratio antenna-shaped fish shoals

4.1 Introduction

Fish aggregations are known to undergo complex group behavior over ecosystem scales [11, 40, 129, 130]. Among these, spawning dynamics are key for survival and sustenance of fish species [65, 102]. Many pelagic fish species around the world have very specific spawning grounds where populations return year after year [64, 65], often undergoing distant migrations. Studies on fish aggregation dynamics often rely on extrapolations of fish population, behavior and morphology observed using conventional methods [131-134] that may significantly undersample the environment in space and time. This is because the coherence time scale of shoal processes, typically on the order of ten minutes [40], is much smaller than the time required to survey a shoal using traditional line-transect [57, 135] methods. Here we describe the behavioral dynamics of gigantic migrating fish shoals and relate these to likely environmental sensing mechanisms.

We show that most populous fish shoals attain antenna-like shapes with high aspect ra-
tios of up to ten. We do so by instantaneously imaging and monitoring the behavior of large fish shoals that span a few hundred meters to tens of kilometers in dimensions using Ocean Acoustic Waveguide Remote Sensing (OAWRS) in the Atlantic Ocean and Norwegian Sea (Figure 4-1). This is observed for several species undergoing spawning migrations, with shoal populations spanning several thousand to hundreds of millions. Previously, single-celled organisms with high aspect ratios have been shown to efficiently and accurately detect chemical gradients at microscopic scales. The observed elongated morphology of a large migrating fish shoal is then consistent with the entire shoal serving the function of a biological antenna for efficient spatial and temporal sensing of mesoscale processes in the environment.

4.2 Field Observations

We used OAWRS in combination with conventional methods to study the behavioral dynamics of migrating Norwegian herring, capelin, haddock and cod in the Nordic Seas in 2014 (Chapter 3) and Atlantic herring in the Gulf of Maine in 2006 [11] during their respective spawning periods and spawning grounds. All of these species are known to form large, dense shoals as part of their spawning process. Until now, cod, capelin, haddock and Norwegian herring shoals have been monitored using conventional echosounding surveys, but the inherent spatial and temporal undersampling has made it difficult to capture the entire horizontal shoal morphology. The Nordic Seas experiment, however, provided the first look revealing the entire horizontal morphology of a shoal formed by these species via instantaneous OAWRS imaging. Large populations of cod, herring, capelin and haddock are also known to perform distant migrations to favorable spawning locations. Specifically, Atlantic herring has been shown to form pre-spawning shoals along the northern flank of Georges Bank in the Gulf of Maine before migrating towards the bank to spawn during September-October [11, 136, 137]. Similarly, Norwegian herring, capelin, cod and haddock are known to migrate from the Arctic to congregate in dense aggregations along the coast of Norway from the North Cape to south-central Norway in January-March each year [66–68]. These species have body lengths in the range of few tens of centimeters to over a meter and so are representative of most pelagic shoaling species [138] that undergo complex spawning processes.
Figure 4-1: Gigantic migrating shoals spanning several kilometers were imaged in the Atlantic Ocean and Nordic Seas environments. Shoal of (a) Atlantic herring imaged on September 27, 2006 at 19:41 EDT along the northern flank of Georges Bank in the Gulf of Maine during the 2006 OAWRS experiment [11]; (b) Northeast Arctic cod imaged on March 8, 2014 at 01:16 CET in the Lofoten Area near Andenes; (c) Norwegian herring imaged on Feb 21, 2014 at 00:50 CET off the coast of Alesund; and (d) Barents Sea capelin imaged on Feb 27, 2014 at 05:45 CET in the Finnmark Area during the 2014 Nordic Seas OAWRS experiment (Chapter 3). This is the first time any Northeast Arctic cod, Norwegian herring or Barents Sea capelin shoals have been instantaneously imaged showing the entire horizontal morphology of shoals formed by these species. The moored OAWRS source is the coordinate origin in (a) located at 42.00°N and 68.39°W. The towed OAWRS receiver ship is the coordinate origin in (b) at 68.96°N 14.29°E; (c) at 62.61°N 4.95°E; and (d) at 71.29°N 25.78°E at the respective time-stamps. Solid black lines indicate bathymetric contours.
around the world. The use of OAWRS enabled us to unambiguously monitor the behavior of large shoals of cod, Norwegian herring, capelin and haddock in the Arctic for the first time. Excellent correspondence between OAWRS images and simultaneous echosounding was found for the imaged species (Appendix H).

4.3 Approach

4.3.1 Deconvolution of OAWRS images

An OAWRS image is formed by convolving the receiver array beam pattern with the incident scattered intensity from a target group over azimuthal angles spanning ±90° with respect to the receiver array axis. At long enough ranges, the array beam width can become greater than the target size, thereby diffusing or blurring the charted returns and inaccurately representing the span of the target group in the horizontal plane. In such situations, deconvolution of charted returns becomes necessary to delineate the true areal span of target groups. Here we use a maximum likelihood approach for spatial deconvolution of OAWRS images.

4.3.1.1 Theoretical Formulation

At a given range r, let the vector \( \mathbf{W} \) contain beam pattern convolved intensity measurements \( W_k \) at a steered direction \( \theta_k \) for \( k = 1, 2, 3, \ldots N \). Let the matrix \( \mathbf{B}(\sin \theta) \) contain the deterministic beam pattern \( B_{jk} \) and vector \( \mathbf{P}(\theta) \) contain the scattered pressure from a target group \( P_j \), which is to be estimated, at the azimuthal angle \( \theta_j \) for \( j = 1, 2, 3, \ldots, M \) and steering angle \( \theta_k \) where \( M \) is typically much greater than \( N \). We also define a scattered intensity vector \( \mathbf{S} \) from a target group containing intensities \( S_j = |P_j|^2 \). Then in the absence of noise, \( W_k = |\mathbf{P}(\theta) \ast \mathbf{B}(\theta)|_{\theta=\theta_k}^2 \). Assuming that \( W_k \) are measured from circular complex Gaussian random (CCGR) fields, the conditional probability distribution for \( \mathbf{W} \) given \( \mathbf{S} \) is the product of gamma distributions [139, 140]

\[
P(\mathbf{W}|\mathbf{S}) = \prod_{k=1}^{N} \left[ \frac{\mu_k}{\sigma_k(\mathbf{S})} \right]^{\mu_k} W_k^{\mu_k-1} \exp \left[ \frac{-\mu_k W_k}{\sigma_k(\mathbf{S})} \right] \Gamma(\mu_k)
\] (4.1)

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where $\mu_k$ is the SNR and $\sigma_k(S) = \langle W_k \rangle$ is the mean intensity at azimuthal angle $\theta_k$. In the presence of signal-dependent noise, however, the convolved intensity is $W = G + N$, where $g$ is the signal vector containing $g_k$ and $N$ is the signal-dependent noise vector containing $n_k$ at azimuthal angle $\theta_k$. Then

$$W_k = |g_k + n_k|^2 = \left(1 + \frac{1}{\mu_k}\right)^2 |g_k|^2$$

(4.2)

$$\langle W_k \rangle = \sigma_k(S) = \left(1 + \frac{1}{\mu_k}\right) \langle |g_k|^2 \rangle$$

(4.3)

where $*$ represents a convolution (Section 3.5 in Chapter 3). Further,

$$\langle |g_k|^2 \rangle = \langle |P(\theta) * B(\theta)|^2 \rangle = \sum_j \langle (P_j B_{jk})^2 \rangle = \sum_j \langle (P_j B_{jk})^2 \rangle$$

$$= \sum_j \langle P_j^2 \rangle B_{jk}^2 + 2 \sum_{j \neq l} \langle P_j P_l \rangle B_{jk} B_{lk}$$

$$= \sum_j \langle S_j \rangle B_{jk}^2$$

(4.4)

since $P_j$ and $P_l$ are independent of each other and follow CCGR statistics with zero mean such that $\langle P_j P_l \rangle = \langle P_j \rangle \langle P_l \rangle = 0$ and where $S_j = P_j^2$ is the source intensity from azimuth direction $\theta_j$. The log-transformed vector $L$ defined by $L_k = \ln(W_k/I_{ref})$, where $I_{ref}$ is the reference intensity, obeys the conditional distribution [140]

$$P(L|S) = \prod_{k=1}^{N} \left[ \frac{\mu_k}{\sigma_k(S)} \right]^{\mu_k} \exp \left[ -\frac{\mu_k \exp(L_k)}{\sigma_k(S)} + \frac{\sigma_k(S) \mu_k L_k}{\Gamma(\mu_k)} \right]$$

(4.5)

which is also the likelihood function, where vector $S$ contains source intensity $S_j$ for all azimuthal directions $\theta_j$ and $\sigma_k(S) = \sigma_k(S)/I_{ref}$. The log-likelihood function is then

$$\ln P(L|S) = \sum_{k=1}^{N} \mu_k \ln \left[ \frac{\mu_k}{\sigma_k(S)} \right] + \left[ -\frac{\mu_k \exp(L_k)}{\sigma_k(S)} + \mu_k L_k \right] - \ln \Gamma(\mu_k)$$

(4.6)

The value of $S$ for which the log-likelihood function attains its global maxima is the
maximum likelihood estimate of $S$,

$$\hat{S} = \arg \max_{\hat{S}} \left[ \ln P(\mathbf{L}|\mathbf{S}) \right].$$

which is also the value of $\hat{S}$ for which the derivative of $\ln P(\mathbf{L}|\mathbf{S})$ with respect to $S$ vanishes

$$\frac{d \ln P(\mathbf{L}|\mathbf{S})}{dS_j} = \sum_{k=1}^{N} -\frac{\mu_k}{\sigma_k(S)} \frac{d\sigma_k'(S)}{dS_j} + \frac{\mu_k W_k}{\sigma_k(S)^2} \frac{d\sigma_k'(S)}{dS_j} = 0 |_{S_j=\hat{S}_j},$$

is true for all $j$ where $\frac{d\sigma_k'(S)}{dS_j} = B_{jk}^2$. Let $C_{jk} = B_{jk}^2$, then in vector form Eq. 4.8 can be written as

$$\sum_{k=1}^{N} (C_k)^T \frac{\mu_k}{\sigma_k(S)} |_{S=\hat{S}} = \sum_{k=1}^{N} (C_k)^T \frac{\mu_k W_k}{\sigma_k(S)^2} |_{S=\hat{S}}$$

or

$$\left[ C^T \sigma_k'(S) \right] |_{S=\hat{S}} = \left[ C^T \nu C \right] |_{S=\hat{S}}$$

where $[i_\sigma]_{ij} = \delta_{ij} \mu_{ij}/\sigma^2_j$ are elements of a diagonal matrix, which by the invariance of the MLE is equal to $\delta_{ij}^2 \mu_k / W_k^2$, and $C_k$ is the $k$-th row of $C$. Since $\sigma'(S) = \nu \mathbf{C} S$, where $\nu_{ij} = \delta_{ij} (1 + 1/\mu_t)^2$ are the elements of another diagonal matrix, the MLE of $\mathbf{S}$ is

$$\hat{S} = \left[ C^T \nu \mathbf{C} \right]^{-1} C^T \nu C.$$

Typically, $\nu$, is not known a priori and so needs to be estimated. If the MLE of $\nu$ is $\hat{\nu}$, then by the invariance of the MLE $[127]$, $[\hat{\nu} \mathbf{C}]_{kl} = \delta_{kl} \mu_{kl} / W_k^2$, where $W_k$ is the MLE of $\sigma_k'(S)$. Then, by invariance [127] of the MLE,

$$\hat{S} = \left[ C^T \hat{\nu} \mathbf{C} \right]^{-1} C^T \hat{\nu} C.$$

When the solution of $\hat{S}$ is linear in $\mathbf{W}$, as in Eq. 4.11, the problem can be solved by performing a gradient descent. Except in the case of a square matrix $\mathbf{B}$, the solution (Eq. 4.12) is in general non-linear in $\mathbf{W}$ and finding the solution using gradient descent is not
possible due to local minima. Additionally, if $B$ is a square matrix, and consequently $C$ is a square matrix, then $\hat{S}$ simply becomes the solution to Eqs. 4.3 and 4.4 via matrix inversion or gradient descent since the problem is linear.

### 4.3.1.2 Implementation

The minimum number of source azimuthal directions $M$ required to unambiguously resolve the array beam pattern $B(s)$ in the horizontal plane is determined using the Nyquist criterion [141], where $s = \sin \theta$ is the sinusoid of the azimuthal angle. The array beam pattern is a continuous function that is sampled at $M$ points to transform it to a discrete function for deconvolution. For simplicity, let's assume the continuous beampattern $B_1(s) = \text{sinc}(s)$ as a result of a constant taper applied to the $J$ receiver array elements. This implies that the taper function $T(u)$ of the receiver takes the form of a rectangular window where $u = r/\lambda$, $r$ is the length along the array from the array center, $\lambda$ is the acoustic wavelength, and $B_1(s) \leftrightarrow T(u)$ are Fourier transform pairs. Then, in the $s$ domain, the square of the discretized beam pattern, i.e matrix $C$ in Eq. 4.11, is a product of (a) the square of a sinc function $B_1^2(s)$, the Fourier transform of a continuous rectangular window $T_1(u)$ spanning $-L/2\lambda$ to $L/2\lambda$ in the $u$ domain; (b) an infinite delta function series $B_2(s)$ with spacing $\Delta s$, the Fourier transform of another infinite delta function series $T_2(u)$ in the $u$ domain with spacing $\Delta u = 1/\Delta s$; and (c) a rectangular window $B_3(s)$ spanning -1 to 1 in $s$ or only real angles in $\theta$. Then, the Fourier transform of $B_1^2(s)B_2(s)B_3(s)$ in the $s$ domain is a convolution of the $[T_1(u) \ast T_1(u)] \ast T_2(u) \ast T_3(u)$ in the $u$ domain. This results in the function $[T_1(u) \ast T_1(u)] \ast T_3(u)$ appearing at every $1/\Delta s$ interval in the $u$ domain.

In order to avoid aliasing, the spacing between the functions $[T_1(u) \ast T_1(u)] \ast T_3(u)$ should be greater than two times the function bandwidth according to the Nyquist rate [141]. Then,

$$\frac{1}{\Delta s} > \frac{2L}{\lambda} + 1$$  \hspace{1cm} (4.13)

where $L = (J - 1)\lambda_0/2$ is the aperture length, $J$ is the number of receiver array elements and $\lambda_0 = c/f_0$ is the acoustic wavelength at the aperture cutoff frequency $f_0$. The bandwidth
of $T_3(u)$ is $1/2$, the bandwidth $T_1(u)$ is $L/2\lambda$, and so the bandwidth of $T_1(u) \ast T_1(u)$ is $L/\lambda$ and the bandwidth of $[T_1(u) \ast T_1(u)] \ast T_3(u)$ is approximately $L/\lambda + 1/2$. Then, the number of samples $M$ between $-1$ and $1$ in $B(s)$ is $2/\Delta s + 1$ and should be greater than

$$M = \frac{2}{\Delta s} + 1 > \frac{2(J-1)\lambda_0}{\lambda} + 3 = \frac{2(J-1)f}{f_0} + 3$$  \hspace{1cm} (4.14)

At exactly the cutoff frequency $f = f_0 = c/\lambda_0$, $M > 2(J - 1) + 3 = 129$. Below the cutoff frequency $M > a$ value less than 129. For example, at 1335 Hz with cutoff frequency of 2000 Hz, $M > 89$. In the illustrative examples shown in the next section, $M = 450$ is chosen for deconvolution of images at 1335 Hz.

Typically, the matrices $B$ and $C$ are approximately singular and this makes the numerical implementation of Eq. 4.11 difficult. So, an iterative scheme using gradient descent is used to determine $\hat{S}$ as given below

- Select a starting solution $\hat{S}$. The magnitude squared of a CCGR field is a reasonable starting point since it accurately depicts the embedded noise in the measurements. One could also start with a zero vector, but this will result in voids in the signal that could be several tens of dB below the signal level and inconsistent with observations.

- Determine $\ln P(L|\hat{S})$.

- For the $q$-th iteration, determine $\ln P(L|S_{trial,j})$ where the trial solution $S_{trial,j} = \hat{S} + [\delta_{ij}]$ for all $j$. Here $\delta_{ij}$ is the Kronecker delta function.

- Find the $j$ for which $\ln P(L|S_{trial,j})$ is the maximum and then set $\tilde{S} = \hat{S} + \alpha S_{trial,j} + \beta$, where $\alpha$ is a small number between 0 and 1 and $\beta$ is the magnitude squared of CCGR noise with maximum amplitude at least an order of magnitude smaller than $\alpha$. The addition of noise is done to avoid local solutions or maximas as in simulated annealing. This is the end of the $q$-th iteration.

The maximum likelihood estimate $\hat{S}$ is the one for which $\ln P(L|S)$ is the maximum over all iterations. At this value, the value in Eq. 4.4 will also converge to $W$. A total of 500 iterations were used and $\ln P(L|S)$ always attained a maxima well within the 500 iterations.
4.3.1.3 Illustrative Examples

This section presents a few illustrative examples of deconvolution of OAWRS images at center frequency 1335 Hz. At this frequency, the OAWRS receiver array beampattern $B$ has a beamwidth of approximately $3.5^\circ$ at broadside, i.e. steered at $0^\circ$ and increases as the array is steered towards the broadside direction (Figure 4-2).

![Graphs of OAWRS beampatterns at 1335 Hz](image)

(a) Steering angle $= 0^\circ$, plotted vs. $\sin(\theta)$
(b) Steering angle $= 65^\circ$, plotted vs. $\sin(\theta)$
(c) Steering angle $= 0^\circ$, plotted vs. $\theta$
(d) Steering angle $= 65^\circ$, plotted vs. $\theta$

Figure 4-2: OAWRS receiver array beampattern at 1335 Hz steered to broadside direction and $65^\circ$ from broadside. As the array is steered toward the endfire direction, the array beamwidth increases from that at broadside as can be seen in (c) and (d).

The examples of original OAWRS areal population density images and deconvolved images are taken from the Nordic Seas survey of capelin in the Finnmark region on February 27-28, 2014. All images have been averaged over 5 transmissions or pings and 2-range cells.
Figure 4-3: OAWRS image of cod schools on March 5, 2014 at 18:01:39 UTC.
Figure 4-4: OAWRS image of a large cod shoal on March 7, 2014 at 00:16:49 UTC.
Figure 4-5: OAWRS image of a large capelin shoal on February 27, 2014 at 04:44:59 UTC.
Scattering Strength
TL Fish Depth Avg.
10m to 100m
fora2014jd059t191759, 1335 Hz

Scattering Strength
TL Fish Depth Avg.
10m to 100m
fora2014jd059t191759, 1335 Hz

(a) Original OAWRS image

(b) Deconvolved image

Figure 4-6: OAWRS image of a small capelin school on February 28, 2014 at 09:17:59 UTC.

4.3.2 Estimation of shoal population, morphology and migration speed

A variety of fish species were imaged during the OAWRS experiments conducted in the Gulf of Maine in the Atlantic Ocean in 2006 and along the Norwegian coast in the Norwegian and Barents Seas in 2014. The estimated fish population densities are used to determine shoal population, shoal aspect ratios, and coherent migration speeds.

4.3.2.1 Shoal Population

Areal population density estimates are obtained from OAWRS images by estimating OAWRS fish target strength as described in Section 3.7. To reiterate, the OAWRS sound pressure levels charted in the horizontal space are converted to acoustic scattering strength maps by correcting for changes purely due to transmission loss and OAWRS source level variations [11, 40, 69]. The measured backscattered levels and depth distribution of fish obtained from simultaneous echo-sounding data, and fish body length information obtained from trawl sampling are used to estimate fish areal population density over localized regions beneath the echosounder. By matching OAWRS areal population density to areal population density from echosounder data, an estimate for OAWRS fish target strength over localized regions
within the shoal is obtained. The areal fish population density over the entire shoal is
obtained by extrapolating the OAWRS target strength estimate over the entire shoal and
subtracting it from the OAWRS scattering strength. The shoal population is then

\[ S = \int_{x,y} n_a(x, y) dx dy. \]  

which is the spatial integral of areal population density within a shoal. Typically, a shoal
is defined above a density threshold derived from OAWRS images and echosounder data
[11, 40]. For herring, a threshold density of 0.5 fish/m² is used [11]. For capelin and herring,
threshold densities are derived using conventional echosounder data such that greater than
90% of the shoal population is captured above the threshold as shown in Appendix H. This
results in a threshold density of 4 fish/m² for capelin and 0.025 fish/m² for cod.

4.3.2.2 Aspect Ratio

Aspect ratio is defined as the ratio of the major to minor axis of an ellipse. For an arbitrarily
shaped shoal, a least square fit is found between its contour and an ellipse. The directions of
the major and minor axes of the ellipse are found using principal component analysis. The
aspect ratio of the shoal is then given by the ratio of its major and minor axes of the ellipse.

For given points on a contour \((X, Y) \equiv (x_i, y_i)\) where \(i = 1, 2, 3, \ldots N\), the covariance matrix
is given by

\[
C = \begin{pmatrix}
\text{cov}(x - \langle x \rangle, x - \langle x \rangle) & \text{cov}(x - \langle x \rangle, y - \langle y \rangle) \\
\text{cov}(y - \langle y \rangle, x - \langle x \rangle) & \text{cov}(y - \langle y \rangle, y - \langle y \rangle)
\end{pmatrix}
\]

where \(\langle x \rangle\) and \(\langle y \rangle\) are respectively the means of the \(x\) and \(y\) coordinates of the contour.
The contour data points along the principal component axes \(\tilde{x}\) and \(\tilde{y}\) is then

\[
\begin{pmatrix}
\tilde{x} \\
\tilde{y}
\end{pmatrix} = I' \begin{pmatrix}
x \\
y
\end{pmatrix}
\]

where \(I\) is the eigenvector matrix with eigenvectors in columns.
Often, the imaged shoals do not have the principal axis that are simple, linear functions of \( x \) and \( y \) coordinates but have a non-linear principle axis such as an 'S' or 'U' shape. In these situations, the principle axis is linearized and the contour points are straighten out as per the steps below:

- Choose a dependent variable \( R \), which could be either \( X \) or \( Y \), such that the non-linear principle \( L \) axis has a one-to-one mapping with the dependent variable. This may require rotation of the OAWRS images or manual selection of the approximate center line in case of convoluted shapes.

- Estimate a polynomial of order \( p \), \( L = \sum_{n=1}^{p} a_n R^n \), that best fits the contour points \((X, Y)\) in the least squares sense. This polynomial is chosen as the principle axis.

- Estimate the the distance of the contour point \((x_i, y_i)\) from \( L \) equal to \( d_i \) and construct a distance array \( D = d_i \). The principle axis array is given by the length along the curve \( L = \equiv l_i \), where \( l_i \) is the point on \( L \) closest to \((x_i, y_i)\).

Once the new contour points \((L, D) = (l_i, d_i)\) are obtained, the aspect ratio of the shoal is estimated by determining the aspect ratio of an ellipse that best fits the contour points in the least squares sense.

4.3.2.3 Coherent Migration

A fish shoal is defined to be coherently migrating if the two-dimensional spatial cross correlation coefficient of the shoal population densities, where shoals undergo a rigid body motion comprising translation and rotation, at different time instances is greater than roughly 0.5. The cross correlation between two areal population density distributions \( n_1(x, y) \) and \( n_2(x, y) \) is given by

\[
R_{n_1,n_2}(\delta x, \delta y) = \int_{x,y} n_1(x, y)n_2(x + \delta x, y + \delta y)dx dy
\]

and the cross correlation coefficient at lag \( \delta x \) and \( \delta y \) is

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The migration displacement is given by the vector connecting the origin \((0, 0)\) and the spatial location at which the cross correlation attains a maxima \((\delta x_M, \delta y_M)\). The migration velocity is then

\[
\vec{v} = \left[ \frac{\delta x_M}{\Delta t}, \frac{\delta y_M}{\Delta t} \right]
\]

where \(\Delta t\) is the elapsed time between the two OAWRS snapshots.

Here, only those shoals are considered that have non zero migration speeds for time periods greater than roughly ten minutes, which is the typical coherence time scale of shoal dynamics observed in the past [40]. The average distance of migration is given by the distance between the origin and location of the peak cross-correlation coefficient of the areal population densities at the two time instances. The direction of migration is given by the unit vector from the origin towards the location of the peak cross-correlation coefficient of the areal population densities at the two time instances.

## 4.4 Results

We found that shoal population was highly dependent on shoal morphology. We focused only on coherently migrating shoals and their one morphological characteristic, namely its aspect ratio as a measure of its elongation (Section 4.3.2). We found that as shoal population increased, the aspect ratio of the shoal increased (Figure 4-7). This was consistently observed for all four species with distinct biological characteristics in distinct habitats, oceanography and geographical locations. The measured aspect ratios were found to span roughly 1, for small schools with lengths of roughly a few hundred meters, to 10, for gigantic shoals of lengths up to 25 kilometers. For all species, the maximum aspect ratio of these shoals were consistently found to be roughly 10, indicating a universality in shoal morphology across species. Maximum shoal populations, on the other hand, varied from roughly a million for
Northeast Arctic cod (Figure 4-7(b)) to tens of millions for Norwegian herring and Barents Sea capelin (Figures 4-7(c) (d)) in the Nordic Seas to hundreds of millions for Atlantic herring in the Atlantic Ocean (Figure 4-7(a)), potentially indicative of different spawning processes and regional spawning stock across species. Despite this large, orders of magnitude variation in shoal populations across and within species, shoals with aspect ratios greater than roughly ten were never found. This may indicate that there exists an upper bound on migrating shoal morphology within which a group of individuals maintains its coherence, and that increasing the shoal aspect ratio beyond a certain value results in disruption of rapid information transfer among the individuals within the shoal to maintain shoal structure. Shoal aggregation densities also varied across species, ranging from roughly 0.4-15 fish per square meter (fish/m²) for smaller fish such as herring and capelin (typically 10-30 cm body length), and 0.03-0.1 fish/m² for the larger cod (typically 60-120 m body length). This density variation is consistent with a spatial scaling of typical inter-fish distance of roughly one fish per body length within an aggregation [142, 143] across species.

The speeds of coherently migrating shoals were found to be roughly 0.1-1 m/s, consistent with typical fish swimming speeds of 1-3 body lengths/second (Figure 4-8). Shoal motion comprised a combination of linear translation and rotation, where even the maximum translation speeds were found to be consistent with these typical fish swimming speeds. These shoal migrations are inconsistent with shoal convergence wave speeds that are typically on the order of 3-6 m/s [11] and so are likely not a result of local population convergences and divergences within the shoal. The level of coherence for migrating shoals was quantified by the cross-correlation coefficient of shoal population densities over time periods greater than roughly ten minutes, which is the typical time scale of dynamic processes within a shoal [40]. Cross-correlation coefficients were found to be in the range of 0.6-0.9, indicating a high degree of coherence in shoal structure and population over time periods spanning roughly ten minutes to up to two hours (Figures 4-9-4-12 and Section 4.3.2). Moreover, more populous shoals were found to migrate slower than smaller shoals and schools (Figure 4-8). Some of these migrations were likely due to passive current drifts [144]. However, the large diver-
Figure 4-7: Shoal population versus aspect ratio measured for (a) Atlantic Herring in the Gulf of Maine during September-October 2006, (b) Cod and Haddock in Lofoten region, Norway; (c) Norwegian Herring in Alesund region, Norway; and (d) Capelin in Finnmark region, Norway during February-March 2014. For all species, as shoal population increased, shoal aspect ratio also increased. The length of the vertical tick marks represents the span of shoal population estimated over the two time instances used for estimating migration speeds shown in Figures 4-9-4-12. Similarly, the length of the horizontal tick marks represents the span of the shoal aspect ratio estimated over the two time instances. For more than 50% variation in shoal population, the larger population estimate is used.
sity observed in migration directions and speeds over spatial scales spanning a few hundred meters to tens of kilometers, which are typically smaller than the spatial scales over which oceanic currents operate, indicates that active swimming likely contributed to part of the migration (Section 4.3.2). Unlike previously observed shoal formation processes [11], the observed migrating shoals were found span and move across bathymetric contours indicating little preference to seafloor depths.

4.5 Conclusions

Past work on group behavioral dynamics has revealed that animal aggregations often take different shapes that offer certain advantages. For example, flying geese take a 'V' shape that helps reduce aerodynamic drag and enables prolonged flying [145] and schools of fish form varied shapes to avoid predators [146]. Similarly, elongated morphological patterns have been observed in the past in single-celled micro-organisms and have been linked with the ability to accurately sense spatial and temporal changes in chemical gradients [147–149]. In fact, most shape deformations of cells comprise elongation and bending in response to externally applied chemical gradients [148]. Theoretical modeling of gradient detection in eukaryotic cells also indicates that more slender cells shapes can detect gradients more efficiently in both space and time [147]. The high aspect-ratio shoals observed here are then consistent with the shoal serving the purpose of a biological sensor or antenna to detect mesoscale environmental gradients and help direct mass migrations towards optimal spawning grounds. So, this morphological structure is likely key to efficient mass spawning, and consequently, species survival.

Our observations of spawning shoal migrations show that (i) most populous shoals have the highest aspect ratios apparently to more efficiently sense their environment; (ii) shoals are able to maintain their coherent structure while migrating over time periods spanning roughly tens of minutes to a few hours; and (iii) typical shoal migration speeds are consistent with fish swimming speeds and inconsistent with fish convergence waves reported [11, 40] previously. The observed elongated morphology of fish shoals we observed is consistent with
Figure 4-8: Shoal migration speed versus population measured for (a) Atlantic Herring in the Gulf of Maine during September-October 2006, (b) Northeast Arctic cod in Lofoten region, Norway; (c) Norwegian Herring in Alesund region, Norway; and (d) Barents Sea capelin in Finnmark region, Norway during February-March 2014. Measured migration speeds are found to be consistent with typical fish swimming speeds of up to 3 body lengths/second. With the exception of Northeast Arctic cod, all species showed a decrease in migration speeds with increase in shoal population. The length of the vertical tick marks represents the span of shoal population estimated over the two time instances used for estimating migration speeds shown in Figures 4-9-4-12.
Figure 4-9: (a) Shoal contours showing migration speeds and directions for the Gulf of Maine Atlantic Herring shoal shown in Figure 4-1(a). The contours represent areal population densities at threshold values of 0.5 fish/m² for Atlantic herring. Blue curves represent shoal contours at the observation time of 19:41 EDT on September 27, 2006 and the red curves represent shoal contours after 105 minutes from the initial observation time. (b) Cross correlation coefficients $\rho(x, y)$ of shoal population density measured at the two instances as a function of spatial lag in $x$- and $y$-directions. The black circle identifies the location of the peak cross correlation coefficient and so determines the direction of migration relative to the origin $(0,0)$. The shoal is found to migrate in the north-east direction towards Georges Bank at a speed of 0.36 m/s and has a high cross correlation coefficient of 0.85 over roughly two hours of migration.
Figure 4-10: (a) Shoal contours showing migration speeds and directions for the cod shoal in the coastal Lofoten region in Norway shown in Figure 4-1(b). The contours represent areal population densities at threshold values of 0.025 fish/m² for Northeast Arctic cod. Blue curves represent shoal contours at the observation time of 00:37 CET on March 8, 2014 and the red curves represent shoal contours after 32 minutes from the initial observation time. (b) Cross correlation coefficients $\rho(x, y)$ of shoal population density measured at the two instances as a function of spatial lag in $x$- and $y$- directions. The red circle identifies the location of the peak cross correlation coefficient and so determines the direction of migration relative to the origin (0,0). The shoal is found to migrate in the north-west direction towards the shelf at a speed of 0.28 m/s and has a high cross correlation coefficient of 0.7 over roughly forty minutes of migration.
Figure 4-11: (a) Shoal contours showing migration speeds and directions for the Norwegian herring shoal in the coastal region off the city of Alesund in Norway shown in Figure 4-1(c). The contours represent areal population densities at threshold values of 0.5 fish/m² for Norwegian herring. Blue curves represent shoal contours at the observation time of 00:50 CET on February 21, 2014 and red curves represent shoal contours after 141 minutes from the initial observation time. (b) Cross correlation coefficients $\rho(x, y)$ of shoal population density measured at the two instances as a function of spatial lag in $x$- and $y$- directions. The red circle identifies the location of the peak cross correlation coefficient and so determines the direction of migration relative to the origin (0,0). The shoal is found to migrate in the north-west direction at a speed of roughly 0.1 m/s and rotate in counter clockwise direction at a speed of 0.04 deg/min. The shoal has a high cross correlation coefficient of roughly 0.65 over two hours of migration.
Figure 4-12: (a) Shoal contours showing migration speeds and directions for the capelin shoal in the coastal Finnmark region in northern Norway shown in Figure 4-1(d). The contours represent areal population densities at threshold values of 4 fish/m² for Barents Sea capelin. Blue curves represent shoal contours at the observation time of 05:45 CET on February 27, 2014 and red curves represent shoal contours after 34 minutes from the initial observation time. (b) Cross correlation coefficients ρ(x, y) of shoal population density measured at the two instances as a function of spatial lag in x- and y- directions. The red circle identifies the location of the peak cross correlation coefficient and so determines the direction of migration relative to the origin (0,0). The shoal is found to migrate in the north-east direction at a speed of 0.38 m/s and the shoal has a high cross correlation coefficient of 0.85 over roughly a half hour of migration.
the shoal behaving as a single entity to detect changes in environmental gradients across its length span and identify optimal spawning conditions and locations. These findings provide information of behavioral mechanisms that are essential to sustenance of species in a variety of marine ecosystems around the world.
Chapter 5

The evolution of air resonance power efficiency in the violin

5.1 Introduction

Acoustic radiation from a violin at its lowest frequency resonance is monopolar [73] and can be determined by pure volume change [74–76]. This lowest frequency resonance is also known as air cavity resonance and Helmholtz resonance [75, 76, 150]. Air cavity resonance has been empirically identified as an important quality discriminator between violins [27, 70, 71] and is functionally important because it amplifies the lower frequency range of a violin’s register [70–72]. It corresponds to the violin’s lowest dominant mode of vibration. Since most of the violin’s volume is devoted to housing the air cavity, the air cavity has an important effect on a violin’s acoustic performance at low frequencies by coupling interior compressible air with the violin’s elastic structure and air flow to the exterior via sound holes. In this chapter, we explain certain aspects of the violin’s historic design evolution that are important to acoustic radiation at its lowest frequency resonance.

Due to its long standing prominence in world culture, enough archaeological data exists for the violin and its ancestors to quantitatively trace design traits affecting radiated acoustic power at air cavity resonance across many centuries of previously unexplained change. By combining archaeological data with physical analysis, it is found that as sound hole geometry
of the violin’s ancestors slowly evolved over a period of centuries from simple circular openings of 10th century medieval f-holes to complex f-holes that characterize classical 17th-18th century Cremonese violins of the Baroque period, the ratio of inefficient, acoustically inactive to total sound hole area was decimated, making air resonance power efficiency roughly double. Our findings are also consistent with an increasing trend in radiated air resonance power having occurred over the classical Cremonese period from roughly 1550 (the Late Renaissance) to 1750 (the Late Baroque Period), primarily due to corresponding increases in f-hole length. This is based upon time series of f-hole length and other parameters that have an at least or nearly first order effect on temporal changes in radiated acoustic power at air cavity resonance. The time series are constructed from measurements of 470 classical Cremonese violins made by the master violin making families of Amati, Stradivari and Guarneri. By evolution rate analysis, these changes are found to be consistent with mutations arising within the range of accidental replication fluctuations from craftsmanship limitations and selection favoring instruments with higher air-resonance power, rather than drastic preconceived design changes. Unsuccessful 19th century mutations after the Cremonese period known to be due to radical design preconceptions are correctly identified by evolution rate analysis as being inconsistent with accidental replication fluctuations from craftsmanship limitations and are quantitatively found to be less fit in terms of air resonance power efficiency.

Measurements have shown that acoustic radiation from the violin is omni-directional at the air cavity resonance frequency [73]. These findings are consistent with the fact that the violin radiates sound as an acoustically compact, monopolar source [74–76], where dimensions are much smaller than the acoustic wavelength, at air resonance. The total acoustic field radiated from a monopole source can be completely determined from temporal changes in air volume flow from the source [74–76, 151, 152]. For the violin, the total volume flux is the sum of the air volume flux through the sound hole and the volume flux of the violin structure. Accurate estimation of monopole radiation at air resonance then only requires accurate estimation of volume flow changes [74, 75, 152, 153] rather than more complicated shape changes of the violin [16, 71, 72] that do not significantly affect the total volume flux. By modal principles, such other shape changes may impact higher frequency acoustic radi-
ation from the violin. Structural modes describing shape changes at and near air resonance have been empirically related to measured radiation, where modes not leading to significant net volume flux, such as torsional modes, have been found to lead to insignificant radiation [16, 71]. Since acoustic radiation from the violin at air resonance is monopolar [73], and so can be determined from changes in total volume flow over time, a relatively simple and clear mathematical formulation for this radiation is possible by physically estimating the total volume flux resulting from the corresponding violin motions that have been empirically shown [16] to lead to the dominant radiation at air resonance.

The effect of sound hole geometry on acoustic radiation at air resonance is isolated by employing a theory for the acoustic conductance of arbitrarily shaped sound holes. This is used to determine limiting case changes in radiated acoustic power over time for the violin due to f-hole length change alone. These limiting cases are extremely useful because they have exact solutions that are only dependent on the simple geometric parameters of sound hole shape and size, as they varied over time, and are not dependent on complex elastic parameters of the violin. Monopole radiation from the violin and its ancestors is then estimated at air resonance from elastic volume flux analysis. This elastic volume flux analysis leads to expected radiated power changes at air resonance that fall between and follow a similar temporal trend as those of the geometric limiting cases. The exact solution from rigid instrument analysis leads to a similar air resonance frequency temporal trend as elastic analysis but with an offset in frequency from measured values by roughly a semitone. Elastic volume flux estimation, on the other hand, matches measured air resonance frequencies of extant classical Cremonese instruments to roughly within a quarter of a semitone or a Pythagorean comma [154]. This indicates that rigid analysis may not be sufficient for some fine-tuned musical applications.
5.2 Analytical formulation of upper and lower limiting cases of radiated acoustic power change at air resonance over time

Here we derive analytical expressions for total radiated acoustic power from (a) an infinite rigid sound hole bearing wall, which corresponds to the upper limiting case of radiated acoustic power change over time; and (b) a closed rigid instrument with a sound hole, which corresponds to the lower limiting case. The frequency spectrum of total radiated pressure field from a monopole [74–76] at a receiver location \( \bar{r} \) is given as

\[
\hat{P}(\bar{r}, f) = \frac{(-j2\pi f)^2 \hat{m}(f)}{4\pi r} e^{jkr}
\]  

(5.1)

where \( \Delta \hat{P}(f) \) is the Fourier transform of \( \Delta P(t) \), \( (-j2\pi f)^2 \hat{m}(f) \) is the Fourier transform of mass flow rate \( \hat{m}(t) \) of the monopole source. The power spectral density [151] of acoustic radiation is

\[
S(f) = \frac{1}{T} \iint_{\rho_{\text{air}} c_{\text{air}}} \frac{\left| \hat{P}(\bar{r}, f) \right|^2}{\rho_{\text{air}} c_{\text{air}}} \, ds.
\]  

(5.2)

In this chapter, the total radiated acoustic power from the source is defined as the power spectral density, \( S(f) \), integrated over the half power bandwidth, \( \Delta f \), about a resonance peak at \( f_0 \)

\[
W = \int_{f_0-\Delta f/2}^{f_0+\Delta f/2} S(f) \, df.
\]  

(5.3)

5.2.1 Total acoustic field radiated from an infinite rigid sound hole bearing wall

An infinite rigid sound hole bearing wall with no air-cavity does not resonate. The spectrum of the radiated acoustic pressure field at a distance \( r \) from the sound hole in an infinite rigid wall [76, 151] is
\[ \tilde{P}_{\text{wall}}(\vec{r}, f) = \frac{(-j2\pi f)^2 \tilde{m}(f)}{2\pi r} e^{jkr} \]  

(5.4)

where \((-j2\pi f)^2 \tilde{m}(f)\) is the Fourier transform of mass flow rate \(\tilde{m}(t)\) through the sound hole, which is related to sound hole acoustic conductance by

\[ \tilde{m}(t) = C\Delta P \]  

(5.5)

where \(\Delta P\) is the applied pressure difference across the hole-bearing wall, for monopolar sound sources [74, 76, 150] like the violin at the air resonance frequency. The power spectral density [151] of acoustic radiation through the sound hole is then given by Eq. 5.2 where \(\tilde{P}(\vec{r}, f) = \tilde{P}_{\text{wall}}(\vec{r}, f)\) and the radiated acoustic power from an infinite sound hole bearing wall integrated over a frequency band \(\Delta f\) is given by

\[ W_{\text{wall}}^r = \frac{1}{T} \int_{\Delta f} \frac{(|\Delta \tilde{P}(f)|^2}{\pi \rho_{\text{air}} c_{\text{air}}} \, df \, C^2, \]  

(5.6)

where \(T\) is the averaging time, \(\rho_{\text{air}}\) is air density, \(c_{\text{air}}\) is the sound speed in air and only \(C\) changes with sound-hole shape.

### 5.2.2 Total acoustic field radiated from a rigid instrument with an air cavity and sound hole at Helmholtz resonance

A rigid instrument with a sound hole is a simple harmonic oscillator [150]. The spectrum of the total radiated pressure field is given by Eq. 5.1, where \((-j2\pi f)^2 \tilde{m}(f)\) is the Fourier transform of \(\tilde{m}(t)\), for displaced air volume through the sound hole \(q(t)\).

In a freely oscillating system

\[ \Delta P = (P_{\text{inside}} - P_{\text{outside}}) = -\rho_{\text{air}} c_{\text{air}}^2 \frac{q}{V} \]  

(5.7)

where \(\rho_{\text{air}} c_{\text{air}}^2\) is the bulk-modulus of the air inside the air-cavity of volume \(V\). Combining Eqs. 5.5 and 5.7, the equation of motion for the freely oscillating system is
\[ \ddot{q} + c_{air}^2 \frac{C}{V} \dot{q} = 0 \quad (5.8) \]

with Helmholtz or air resonance [76, 150] occurring at

\[ f_{\text{air-rigid}} = \frac{c_{\text{air}}}{2\pi} \sqrt{\frac{C}{V}} \quad (5.9) \]

Radiation damping is characterized by the damping coefficient \( 4\pi \zeta f_{H}^{\text{rigid}} \), where \( \zeta = \frac{1}{8\pi} C_{\text{air}}^{1/2} \) [76]. Under an externally applied pressure difference across the sound hole, \( p_1(t) \), the time-domain equation of motion for the forced system is

\[
\ddot{q} + \frac{c_{\text{air}}}{4\pi} \frac{C^2}{V} \dot{q} + c_{\text{air}}^2 \frac{C}{V} q = C \frac{p_{1}(t)}{\rho_{\text{air}}} \quad (5.10)
\]

and frequency-domain equation of motion for the forced system is

\[
-\omega^2 \dot{Q} - j\omega \frac{c_{\text{air}}}{4\pi} \frac{C^2}{V} \dot{Q} + c_{\text{air}}^2 \frac{C}{V} Q = C \frac{\tilde{P}_{1}(f)}{\rho_{\text{air}}} \quad (5.11)
\]

where \( q(t) \leftrightarrow \tilde{Q}(f) \) and \( p_1(t) \leftrightarrow \tilde{P}_1(f) \) re the time-frequency Fourier transform pairs and \( \omega = 2\pi f \). The spectrum of displaced air-volume through the sound hole is

\[
Q(f) = \frac{C \tilde{P}_1(f)}{4\pi^2 \left( f_{H}^{\text{rigid}}^2 - f^2 \right) - j \frac{c_{\text{air}}}{2} \frac{C^2}{V} f}. \quad (5.12)
\]

The spectrum of \( \tilde{m}(t) \) is \( \rho_{\text{air}} (-j2\pi f)^2 \tilde{Q}(f) \) and the power spectral density of the radiated pressure field (Eq. 5.2) from the sound hole in a rigid instrument is then

\[
S(f)^{\text{rigid}} = \frac{1}{T} \frac{\rho_{\text{air}} 4\pi^3 f^4}{c_{\text{air}}} \left| \tilde{Q}(f) \right|^2 \quad (5.13)
\]

where \( T \) is the same averaging time as in Eq. 5.2. The half-power bandwidth around the resonance peak at \( f_0 \) for a single degree of freedom damped harmonic oscillator [141, 155] is \( \Delta f_0 = 2\zeta f_0 \). Then from Eq. 5.9, the half-power bandwidth around the Helmholtz resonance peak is

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The total radiated acoustic power within the half-power bandwidth from a sound hole in a rigid instrument at Helmholtz resonance for constant $P_1$, corresponding to a system frequency response [141], is then

$$W_{air-rigid} = \frac{1}{T \rho_{air} c_{air}} \left| \tilde{P}_1 \right|^2 C^2 \int_{f = f_{air-rigid} - \Delta f_{air-rigid}/2}^{f = f_{air-rigid} + \Delta f_{air-rigid}/2} \frac{f^4}{\left[ (f_{air-rigid})^2 - f^2 \right]^2 + \left[ \frac{(f_{air-rigid})^2}{2 c_{air}} \right]^2} df$$

$$= \eta_{rigid} C$$

where

$$\eta_{rigid} = \frac{\left| \tilde{P}_1 \right|^2}{2\pi \rho_{air} T} \left[ I_1 \left( f_{air-rigid} + \Delta f_{air-rigid}/2 \right) - I_1 \left( f_{air-rigid} - \Delta f_{air-rigid}/2 \right) \right]$$

$$+ I_2 \left( f_{air-rigid} + \Delta f_{air-rigid}/2 \right) - I_2 \left( f_{air-rigid} - \Delta f_{air-rigid}/2 \right),$$

$$I_1(f) = \left[ \frac{1}{2\sqrt{R_1 R_2 (R_1 - R_2)}} \ln \left( \frac{1 + \sqrt{R_1 f}}{1 - \sqrt{R_1 f}} \right) - \frac{f}{R_1 (R_1 - R_2)} \right] \frac{C}{2 c_{air} (f_{air-rigid})^2} \frac{1}{f_{air-rigid}^2},$$

$$I_2(f) = \left[ \frac{1}{2\sqrt{R_2 R_1 (R_2 - R_1)}} \ln \left( \frac{1 + \sqrt{R_2 f}}{1 - \sqrt{R_2 f}} \right) - \frac{f}{R_2 (R_2 - R_1)} \right] \frac{C}{2 c_{air} (f_{air-rigid})^2} \frac{1}{f_{air-rigid}^2},$$

$$R_1 = \frac{1}{(f_{air-rigid})^2} - \frac{C^2}{8 c_{air}} \left( 1 + \sqrt{1 - \frac{16 c_{air}^2}{(f_{air-rigid})^2 C^2}} \right)$$

$$= \frac{C^2}{8 \pi^2 V}.$$
Taylor series expansion of the integrand in Eq. 5.15 about \( f = f_{\text{air-rigid}} \) yields

\[
\eta_{\text{rigid}} = \frac{1}{2\pi \rho_{\text{air}} T} \left( f_{\text{air-rigid}} - \left( f_{\text{air-rigid}} \right)^2 \right) + \frac{4c_{\text{air}}^2}{3C^2} \left( \frac{\Delta f_{\text{air-rigid}}}{f_{\text{air-rigid}}} \right)^2 + O \left[ \left( \frac{\Delta f_{\text{air-rigid}}}{f_{\text{air-rigid}}} \right)^3 \right]
\]

from which it is seen that to leading order \( \eta_{\text{rigid}} \) is independent of conductance \( C \) and air cavity volume \( V \). The second order term in Eq. 5.21 is approximately independent of \( C \) and \( V \). The exact solution of \( \eta_{\text{rigid}} \) in Eq. 5.21 is numerically found to be effectively constant with respect to conductance and air cavity volume, i.e. \( \eta_{\text{rigid}} \propto C^a \) and \( \eta_{\text{rigid}} \propto V^b \) where \( a, b \ll 0.001 \). This dependence can also be understood by noting that a first order approximation to the total radiated acoustic power in the half power band, the product of the peak spectral density at the resonance peak (Eq. 5.13) and the half power bandwidth (Eq. 5.14), is

\[
W_{\text{air-rigid}} \approx \frac{\left| \hat{P}_1 \right|^2}{2\pi \rho_{\text{air}} T} C
\]

which is proportional to \( C \).

5.3 Elastic structural dynamic and acoustic response of a violin at air resonance

In this section, the violin is modeled as a coupled harmonic oscillator and the total acoustic pressure field radiated from it is derived in terms of structural displacements and air-flow through f-holes.
5.3.1 Harmonic oscillation of violin elastic structure elastic structure coupled with compressible air and f-hole air flow at air resonance

At air resonance measurements have shown that the violin radiates sound as an omnidirectional or monopolar source [73], as has also been noted in Ref. [156]. Sound radiation at air resonance can then be determined from the total volume flux due to air volume flowing through the f-holes and violin body volume change. For the guitar, the lowest mode of vibration, that at air resonance, has been modeled [157, 158] by coupling the elastic deformation of the guitar with fluid compression within the air cavity using a fundamental harmonic oscillator approach. This work followed earlier suggestions of considering a similar harmonic oscillator approach for the violin [159]. It was found that the guitar's elastic body led to a significant lowering of the air cavity resonance frequency from that of a corresponding rigid instrument [160] given by the classical theory of a Helmholtz resonator [75, 76, 150]. A similar reduction in air cavity resonance frequency is experimentally found for a violin [19]. This similarity between guitar and violin results suggests rigid analysis is inadequate and elastic analysis, as was applied to the guitar [157, 158], is necessary to estimate the air resonance frequency of a violin to within a semitone.

At and in the vicinity of the air resonance frequency, it has been experimentally shown that roughly normal displacements of the top and back plate of the violin are primarily responsible for radiation of sound [16, 71]. This is consistent with measured monopole radiation at the air resonance frequency since monopole radiation results from pure volume change. The spectral peak at the air resonance frequency is a result of harmonic oscillation involving masses, stiffnesses, and damping components from the violin. Measurements across extant classical Cremonese violins [21–23] show the air resonance frequency to be remarkably stable, varying within only two-thirds of a semitone (≈ 4%) with a standard deviation of only one-third of a semitone (≈ 2%). This suggests that a stable physical mechanism is at work at air resonance. The harmonically oscillating structural elements of the violin that lead to sound radiation at air resonance have stiffnesses that have been identified in previous
studies [42] (Appendix I). In particular, at the air resonance frequency, the ribs and sound post correspond to nulls in the displacement field of the violin top and back plates [41, 71], and so these regions yield negligible contributions to both volume change and the resulting monopole radiation. The ribs and sound post, however, add stiffness to the violin top and back plates, which affects the displaced volume. The stiffness of an actual violin top plate, $K_{\text{top}}$, of thickness $h_{\text{top}} \approx 3$ mm with sound holes, curvature and structural support from the bass bar, sound post and ribs has been experimentally [42] determined through spectral analysis (Appendix I). The stiffness of an actual violin back plate, $K_{\text{back}}$, of thickness $h_{\text{back}} \approx 3.5$ mm with curvature and structural support from the sound post and ribs has been experimentally [42] determined through spectral analysis (Appendix I). Elastic coupling of the air cavity, with compressibility $1/\rho_{\text{air}}c_{\text{air}}^2$, to the violin structure plays an important role at air resonance, as does the combined conductance of the sound holes, $C$, which regulates volume changes due to air volume flow, $v_{\text{air}}$, through the sound holes. When the system is subjected to top plate forcing $F$ at the bridge, the resulting harmonic oscillation can be described using Newton's second law. The total structural volume change resulting from this oscillation can be determined via multiplication of equivalent displaced areas (Appendix I) $S_{\text{top}}$ and $S_{\text{back}}$ of the top and back plates at air resonance, which include the combined effects of the curved violin shape and non-linear modal displacement field, with associated time dependent normal displacements $x_{\text{top}}(t)$ and $x_{\text{back}}(t)$ of the top and back plates (Appendix I). The ratios of equivalent displaced area to total plate surface area for actual violin top and back plates at air resonance have been experimentally determined (Appendix I) from holographic measurements [41].

The air-resonance dynamics of $i = 1, 2, 3, \ldots N$ Cremonese violins beginning from Amati 1560 to Guarneri 1745 where $N = 485$ are analyzed. Known design parameters $C_i, V_i, h_{i,\text{top}}, h_{i,\text{back}}$ and $h_{i,\text{op}}$ from direct measurements or interpolation appear in Figs 5-8c and 5-4. Small variations in top plate thickness $h_{i,\text{top}}$ about $\bar{h}_{\text{top}}$ for the $i$-th violin lead to top plate stiffness $K_{i,\text{top}} = \bar{K}_{\text{top}} + \epsilon_{\text{top}} [h_{i,\text{top}} - \bar{h}_{\text{top}}]$ near air resonance where $\epsilon_{\text{top}}$ is the first order Taylor series coefficient. Similarly, back plate stiffness $K_{i,\text{back}} = \bar{K}_{\text{back}} + \epsilon_{\text{back}} [h_{i,\text{back}} - \bar{h}_{\text{back}}]$ near air resonance depends on plate thickness $h_{i,\text{back}}$, where $\epsilon_{\text{back}}$ is the first order Taylor series coefficient.
for small variations near \( \bar{h}^{\text{back}} \). The equivalent displaced top plate and back plate areas (I) that contribute to acoustic radiation via net volume change near air resonance are given by

\[
S_i^{\text{top}} = \xi^{\text{top}} A_i^{\text{top}} \quad \text{and} \quad S_i^{\text{back}} = \xi^{\text{back}} A_i^{\text{back}}
\]

where \( A_i^{\text{top}} = V_i / h_i^a \) and \( A_i^{\text{back}} = V_i / h_i^a \) are the total top and back plate areas. The displaced masses of the top and back plates near air resonance are then

\[
M_i^{\text{top}} = \rho_i^{\text{top}} h_i^{\text{top}} S_i^{\text{top}} \quad \text{and} \quad M_i^{\text{back}} = \rho_i^{\text{back}} h_i^{\text{back}} S_i^{\text{back}}.
\]

Damping factors at air resonance are determined such that the energy dissipated by the damping forces acting on the plates and air piston is equal to that acoustically radiated from plate oscillations and air flow through the sound holes. Specifically, the factor \( R_i^{\text{air}} \) is determined by equating the power dissipated by the damping force acting on \( v_i^{\text{air}} \) and that radiated from the monopole source due to air flow through sound holes. The top and back plate motion can be expressed as a sum of symmetric and asymmetric motions. Symmetric motion of the plates leading to volume change results in monopole radiation, from which a radiation damping factor for symmetric plate motion is derived. Similarly, asymmetric motion of the plates results in dipole radiation, from which another radiation damping factor for asymmetric plate motion is derived. The factors \( R_i^{\text{top}} \) and \( R_i^{\text{back-top}} \) are determined by adding the two damping forces on the top plate. Similarly, the factors \( R_i^{\text{back}} \) and \( R_i^{\text{top-back}} \) are determined by adding the two damping forces on the back plate. Here constants \( \rho_i^{\text{top}} \) and \( \rho_i^{\text{back}} \) are top and back plate densities, respectively. Viscous air flow damping at the sound hole is at least one order of magnitude smaller than radiation damping \([151]\) at air resonance and is negligible. In the guitar model \([157, 158]\), damping coefficients were empirically determined by matching modeled and measured sound spectra and/or plate mobility. The physical approach for determining the damping coefficients used here follows Lamb \([76]\), through a radiation damping mechanism. The Q-factors obtained here for the air resonance peaks and the corresponding half power bandwidth are within roughly 20% of those measured for violins \([16, 161]\), indicating that radiation damping is the dominant source of damping at the air resonance frequency.
Narrowband [127, 141, 162, 163] forcing $F(t) \approx F_0(t)e^{-j\omega_{i\text{air}}t}$ that is spectrally constant in the vicinity of the air resonance peak $\omega_{i\text{air}}$ is assumed where $F_0(t)$ is a slowly varying temporal envelope that is the same for each of the $i = 1, 2, 3, ... N$ violins. This allows narrowband approximations [127, 141, 162, 163] for the displacements $x_{i\text{top}}(t) \approx \chi_{i\text{top}}(t)e^{-j\omega_{i\text{air}}t}$, $x_{i\text{back}}(t) \approx \chi_{i\text{back}}(t)e^{-j\omega_{i\text{air}}t}$ and $v_{i\text{air}}(t) \approx \gamma_{i\text{air}}(t)e^{-j\omega_{i\text{air}}t}$, where $\chi_{i\text{top}}(t)$, $\chi_{i\text{back}}(t)$ and $\gamma_{i\text{air}}(t)$ are slowly varying temporal envelopes that are effectively constant at the center of the time window for the $i$-th violin. The harmonic oscillating system at air resonance for the $i$-th violin can then be described by

$$
\begin{pmatrix}
B_{11} & B_{12} & B_{13} \\
B_{21} & B_{22} & B_{23} \\
B_{31} & B_{32} & B_{33}
\end{pmatrix}
\begin{pmatrix}
x_{i\text{top}}(t) \\
x_{i\text{back}}(t) \\
v_{i\text{air}}(t)
\end{pmatrix}
= 
\begin{pmatrix}
F(t) \\
0 \\
0
\end{pmatrix}
$$

where

$$
B_{11} = M_{i\text{top}} \frac{d^2}{dt^2} + R_{i\text{top}} \frac{d}{dt} + \left[ K_{i\text{top}} + \frac{\rho_{i\text{air}} c_{i\text{air}}^2}{V_i} (S_{i\text{top}}')^2 \right]
$$

$$
B_{12} = R_{i\text{top-back}} \frac{d}{dt} + \frac{\rho_{i\text{air}} c_{i\text{air}}^2}{V_i} S_{i\text{top}} S_{i\text{back}}
$$

$$
B_{13} = \frac{\rho_{i\text{air}} c_{i\text{air}}^2}{V_i} S_{i\text{top}}
$$

$$
B_{21} = R_{i\text{top-back}} \frac{d}{dt} + \frac{\rho_{i\text{air}} c_{i\text{air}}^2}{V_i} S_{i\text{back}} S_{i\text{top}}
$$

$$
B_{22} = M_{i\text{back}} \frac{d^2}{dt^2} + R_{i\text{back}} \frac{d}{dt} + \left[ K_{i\text{back}} + \frac{\rho_{i\text{air}} c_{i\text{air}}^2}{V_i} (S_{i\text{back}}')^2 \right]
$$

$$
B_{23} = \frac{\rho_{i\text{air}} c_{i\text{air}}^2}{V_i} S_{i\text{back}}
$$

$$
B_{31} = \frac{\rho_{i\text{air}} c_{i\text{air}}^2}{V_i} S_{i\text{top}}
$$

$$
B_{32} = \frac{\rho_{i\text{air}} c_{i\text{air}}^2}{V_i} S_{i\text{back}}
$$

$$
B_{33} = \frac{\rho_{i\text{air}}}{C_i} \frac{d^2}{dt^2} + R_i \frac{d}{dt} + \frac{\rho_{i\text{air}} c_{i\text{air}}^2}{V_i},
$$

the acoustic conductance of f-holes, $C_i$, [19] for the $i$-th violin is given by
\[
C_i = \frac{0.185 L_i^F}{\left(0.192 + 1.053 \frac{h_{i}^{th}}{L_i^F}\right)},
\] (5.26)

\(L_i^F\) is the f-hole length as defined in Refs. [164, 165], \(h_{i}^{th}\) is the average top plate thickness near f-holes, which contributes a small nonlinear dependence in Eq. 5.26.

Estimates of parameters the \(K_{\text{top}}, K_{\text{back}}, \xi_{\text{top}}, \xi_{\text{back}}, \xi_{\text{top}}\) and \(\varepsilon_{\text{back}}\) at the air resonance frequency are obtained by comparing measured air resonance frequency data of Cremonese violins with the respective first real root of

\[
\begin{vmatrix}
D_{11} & D_{12} & D_{13} \\
D_{21} & D_{22} & D_{23} \\
D_{31} & D_{32} & D_{33}
\end{vmatrix} = 0
\] (5.27)

where

\[
D_{11} = -\omega^2 M_{i}^{\text{top}} - j\omega R_{i}^{\text{top}} + \left[K_{i}^{\text{top}} + \frac{\rho_{\text{air}} c_{\text{air}}^2}{V_i} (S_i^{\text{top}})^2\right]
\]

\[
D_{12} = -j\omega R_{i}^{\text{back-top}} + \frac{\rho_{\text{air}} c_{\text{air}}^2}{V_i} S_i^{\text{top}} S_i^{\text{back}}
\]

\[
D_{13} = \frac{\rho_{\text{air}} c_{\text{air}}^2}{V_i} S_i^{\text{top}}
\]

\[
D_{21} = -j\omega R_{i}^{\text{top-back}} + \frac{\rho_{\text{air}} c_{\text{air}}^2}{V_i} S_i^{\text{back}} S_i^{\text{top}}
\]

\[
D_{22} = -\omega^2 M_{i}^{\text{back}} - j\omega R_{i}^{\text{back}} + \left[K_{i}^{\text{back}} + \frac{\rho_{\text{air}} c_{\text{air}}^2}{V_i} (S_i^{\text{back}})^2\right]
\]

\[
D_{23} = \frac{\rho_{\text{air}} c_{\text{air}}^2}{V_i} S_i^{\text{back}}
\]

\[
D_{31} = \frac{\rho_{\text{air}} c_{\text{air}}^2}{V_i} S_i^{\text{top}}
\]

\[
D_{32} = \frac{\rho_{\text{air}} c_{\text{air}}^2}{V_i} S_i^{\text{back}}
\]

\[
D_{33} = -\omega^2 \frac{\rho_{\text{air}} c_{\text{air}}^2}{C_i} - j\omega R_{i}^{\text{air}} + \frac{\rho_{\text{air}} c_{\text{air}}^2}{V_i}
\] (5.28)

for each \(i^{th}\) Cremonese violin via the method of least squares. Twenty six air resonance frequency measurements corresponding to 26 extant Cremonese violins [21–23] are used.
Parameter ranges in the least squares estimate are constrained to be near independently measured values. Specifically, the parameters $\hat{K}_{\text{top}}$, $\hat{K}_{\text{back}}$, $\hat{\xi}_{\text{top}}$ and $\hat{\xi}_{\text{back}}$ are all constrained to have small first order variations, i.e. no more than roughly 33%, from empirical values determined from direct measurements by Jansson [41, 42] of an actual violin top plate with f-holes, curvature, bass bar, and effectively zero displacement at the location of the sound post and ribs (Appendix I) and a violin back plate with curvature, and effectively zero displacement at the location of sound post and ribs (Appendix I). The sum of the squared differences between measured and estimated air resonance frequencies

$$
\Psi = \sum_{i=1}^{N} s[i] \left| \omega_i^{\text{air-data}} - \hat{\omega}_i^{\text{air}} \left( C_i, V_i, h_i^{\text{top}}, h_i^{\text{back}}, h_i^{\text{sh}}, \hat{K}_{\text{top}}, \hat{K}_{\text{back}}, \hat{\xi}_{\text{top}}, \hat{\xi}_{\text{back}}, \xi_{\text{top}}, \xi_{\text{back}} \right) \right|^2
$$

is minimized with respect to parameters $\hat{K}_{\text{top}}$, $\hat{K}_{\text{back}}$, $\hat{\xi}_{\text{top}}$, $\hat{\xi}_{\text{back}}$ and $\xi_{\text{top}}$ and $\xi_{\text{back}}$ resulting in the least squares estimates

$$
\begin{bmatrix}
\hat{K}_{\text{top}} \\
\hat{K}_{\text{back}} \\
\hat{\xi}_{\text{top}} \\
\hat{\xi}_{\text{back}} \\
\hat{\xi}_{\text{top}} \\
\hat{\xi}_{\text{back}}
\end{bmatrix} = \left[ \arg \min \Psi \left( \hat{K}_{\text{top}}, \hat{K}_{\text{back}}, \hat{\xi}_{\text{top}}, \hat{\xi}_{\text{back}}, \xi_{\text{top}}, \xi_{\text{back}} \right) \right]
$$

where $i = 1, 2, ... N$ and $s[i] = 1$ the $i$-th violin if air resonance frequency data $\omega_i^{\text{air-data}}$ is available, otherwise $s[i] = 0$. These least squares estimates are also the maximum likelihood estimates because the measured air resonance frequencies are uncorrelated and have roughly the same variance across time, and so have minimum variance for large samples [127, 166].

Estimates for $\hat{K}_{\text{top}}$, $\hat{K}_{\text{back}}$, $\hat{\xi}_{\text{top}}$, $\hat{\xi}_{\text{back}}$, $\xi_{\text{top}}$ and $\xi_{\text{back}}$ are provided in Table 5.1. These least squares estimates are used to determine the air resonance frequency $\omega_i^{\text{air}}$ via Eq. 5.27 and $\hat{x}_i^{\text{top}}$, $\hat{x}_i^{\text{back}}$ and $\hat{\psi}_i^{\text{air}}$ via Eq. 5.24 in the vicinity of the air resonance peak given the violin design parameters of Figures 5-3 and 5-4 for the $i$-th violin.

The second and third eigenvalues, where $\omega_i^{\text{Mode-1}} < \omega_i^{\text{Mode-2}} < \omega_i^{\text{Mode-3}}$ and $\omega_i^{\text{Mode-1}} = \omega_i^{\text{air}}$ of the Eq. 5.24 system are also estimated from Eq. 5.27 for all $i = 1, 2, 3...N$ violins with the parameters of Table 5.1. The root mean squared error between the means of estimated first

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eigenvalues and those measured from classical Cremonese violins for each family workshop is roughly 1%. Over the entire Cremonese period, the second and third eigenvalue estimates are (i) within roughly 15% of those measured from a modern violin in Refs. [42] and [41]; and (ii) consistent with the range found for extant Cremonese violins [16, 21, 41, 42, 70–72, 159]. Air resonance frequency is found to be relatively insensitive to typical changes in plate stiffness and equivalent displaced areas. For variations in plate stiffnesses of roughly 33% and equivalent displaced areas of roughly 33%, the air resonance frequency varies only by roughly 2%. Mode 1, the air resonance frequency mode, is dominated by resonant air flow through the sound holes, where top and back plates move in opposite directions, and the back plate moves in the same direction as air flow through the sound hole. Mode 2 is mainly influenced by the top plate [16, 167]. Mode 3 is mainly influenced by the back plate [16, 167]. These basic coupled oscillator results are consistent with the dominant "A0," "T1" and "C3" motions that Jansson et al. [16, 71] empirically found to contribute significantly to sound radiation near air cavity resonance (Figs 2b, 4 and 6 of Ref. [16]). Other modes in this frequency range are due to torsional motions that do not lead to significant volume flux nor consequent monopole radiation. Jansson et al. [16] empirically found these torsional modes lead to only insignificant acoustic radiation. Reference [168] provides a translation of nomenclatures used by various authors for violin modes.

The effect of the "island" area between the sound holes is included in the least squares stiffness estimates and in those from the empirical measurements of Jansson [41, 42] as shown in Appendix I. While, dynamical effects associated with the "island" area [72, 159, 169] between the f-holes have been discussed in the context of violin performance in the 2-3 kHz frequency range, i.e. near the "bridge hill" [170, 171], empirical measurements [71] and numerical simulations [169] of violins with and without f-holes, and consequently with and without the "island," show that the effects of the “island” at air resonance on radiated power and the air resonance frequency are negligible, as shown in Appendix I. All of these findings are consistent with the fact that at the air resonance frequency only total volume change needs to be accurately resolved. An investigation of the evolution of violin power efficiency at frequencies much higher than the air resonance frequency is beyond the scope of the air
Dynamical effects of the "island" [72, 159, 169] between the sound holes are included and found to be negligible at air resonance by comparison of violins with and without "islands," i.e. with and without f-holes [71] (Appendix I), but they may become significant at higher frequencies [170, 171].

Table 5.1: Parameters estimated in elastic volume flux analysis.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \hat{K} )<em>{top} for ( h</em>{top} = 3 \text{ mm} )</td>
<td>( 6.92 \times 10^4 \text{ N/m} )</td>
</tr>
<tr>
<td>( \hat{K} )<em>{back} for ( h</em>{back} = 3.5 \text{ mm} )</td>
<td>( 2.75 \times 10^5 \text{ N/m} )</td>
</tr>
<tr>
<td>( \hat{c} )<em>{top} for top plate thickness variation near ( h</em>{top} )</td>
<td>( 1.10 \times 10^8 \text{ N/m}^2 )</td>
</tr>
<tr>
<td>( \hat{c} )<em>{back} for back plate thickness variation near ( h</em>{back} )</td>
<td>( 1.20 \times 10^8 \text{ N/m}^2 )</td>
</tr>
<tr>
<td>( \xi_{top} )</td>
<td>0.15</td>
</tr>
<tr>
<td>( \xi_{back} )</td>
<td>0.22</td>
</tr>
</tbody>
</table>

5.3.2 Acoustic field radiated from the violin at air resonance

Acoustic radiation from violin motion and air flow through sound holes at air resonance can be determined by solving the corresponding acoustic boundary value problem [13, 151] using Green’s theorem [151],

\[
\hat{P}(\vec{r}, f) = \int \int \left[ G(\vec{r}|\vec{r}_0, f) \vec{\nabla}_0 \hat{P}_T(\vec{r}_0, f) - \vec{\nabla}_0 G(\vec{r}|\vec{r}_0, f) \hat{P}_T(\vec{r}_0, f) \right] \cdot d\vec{S}_0
\]

(5.31)

where: \( f \) is frequency, \( \hat{P}(\vec{r}, f) \) is the spectrum of total radiated pressured field at a receiver located at \( \vec{r} \) with respect to the center of a horizontal violin; \( \hat{P}_T(\vec{r}_0, f) \) is the spectrum of total field at \( \vec{r}_0 \) on the surface \( S_0 \); \( G(\vec{r}|\vec{r}_0, f) \) is the free space Green function, which in the far field \( |\vec{r}| \ll |\vec{r}_0| \) is approximately \( G(\vec{r}|\vec{r}_0, f) = \frac{e^{ikr}}{4\pi r} e^{-jkr} \), \( k \) is the acoustic wavenumber vector; and \( d\vec{S}_0 = dS_0 \hat{n}_0 \) is an infinitesimal element of the integral surface, with surface nor-
Momentum conservation [74–76, 150] is used to determine gradients of $G(\vec{r}|\vec{r}_0, f)$ and $\vec{P}_T(\vec{r}_0, f)$ in Eq. 5.31.

The frequency spectrum of the radiated acoustic pressure in the far field from the violin body displacements, not including air flow through the sound hole, is then given by

$$P_{\text{structure}}(\vec{r}, f) \approx -\rho_{\text{air}} (2\pi f)^2 \left[ S_{\text{top}} \frac{\partial^2}{\partial \vec{r}^2} + S_{\text{back}} \frac{\partial}{\partial \vec{r}} \right] \frac{e^{jkr}}{4\pi r}$$

$$+ \left( -j(kh)\rho_{\text{air}} (2\pi f)^2 \frac{[S_{\text{top}}\frac{\partial}{\partial \vec{r}} - S_{\text{back}} \frac{\partial}{\partial \vec{r}}]}{2} \right) + (2\pi f) \frac{\vec{P}_{\text{top}}(f) + \vec{P}_{\text{back}}(f)}{c_{\text{air}}} \cos \theta \frac{e^{jkr}}{4\pi r}$$

$$+ j(kh) (2\pi f)^2 \frac{\vec{P}_{\text{top}}(f) + \vec{P}_{\text{back}}(f)}{2c_{\text{air}}} \cos^2 \theta \frac{e^{jkr}}{4\pi r}$$

Longitudinal Quadrupole

Monopole

Dipole

(5.32)

where $k = \omega / c_{\text{air}}$,

$$\vec{P}_{\text{top}}(f) = \frac{\omega}{12.6} \left[ k \left( S_{\text{top}} \right)^{1/2} \right] \rho_{\text{air}} c_{\text{air}} S_{\text{top}} \frac{\partial}{\partial \vec{r}}$$

$$\vec{P}_{\text{back}}(f) = \frac{\omega}{12.6} \left[ k \left( S_{\text{back}} \right)^{1/2} \right] \rho_{\text{air}} c_{\text{air}} S_{\text{back}} \frac{\partial}{\partial \vec{r}}$$

(5.33)

are the spectral amplitudes, i.e. Fourier transforms, of the fluid dynamic forces acting on the moving plates including added mass effects [74, 172][10, 12], $h$ is the separation between the plates, and $\theta$ is the angle between the receiver $\vec{r}$ and surface normal pointing outward from the top plate. The first and second dipole terms in Eq 5.32 are small compared to the monopole term because $kh \ll 1$, $\frac{\pi}{12.6} \left[ k \left( S_{\text{top}} \right)^{1/2} \right] \ll 1$ and $\frac{\pi}{12.6} \left[ k \left( S_{\text{back}} \right)^{1/2} \right] \ll 1$ at air resonance. The quadrupole term is small compared to the dipole terms for similar reasons. The field radiated due to violin structural motion at and near air resonance then is approximately monopolar

$$\vec{P}_{\text{structure}}(\vec{r}, f) \approx -\rho_{\text{air}} (2\pi f)^2 \vec{P}_{\text{structure}} \frac{e^{jkr}}{4\pi r}$$

(5.34)
where \( \tilde{u}^{\text{structure}} = S_{\text{top}} \tilde{x}_{\text{top}} - S_{\text{back}} \tilde{x}_{\text{back}} \) are in terms of Fourier transforms of the plate displacements determined in Section 5.3.1. The radiated field due to air flow through sound holes at and near air resonance is also approximately monopolar

\[
\tilde{F}_{\text{soundholes}}(r, f) \approx -\rho_{\text{air}}(2\pi f)^2 \tilde{u}^{\text{air}} e^{jkr(r - \frac{h_0}{2}\cos \theta)} \frac{e^{jr}}{4\pi r}
\]  

(5.35)

where \( h_0 \) is the vertical offset between the centers of volume changes caused by violin plate displacements and air flow out of the sound holes, and \( \tilde{u}^{\text{air}} \) is the Fourier transform of \( u^{\text{air}} \). The total radiated field from the violin then is

\[
P_{\text{elastic}}(r, f) \approx -\rho_{\text{air}}(2\pi f)^2 \tilde{u}^{\text{air}} e^{jkr(r - \frac{h_0}{2}\cos \theta)} - \rho_{\text{air}}(2\pi f)^2 \tilde{u}^{\text{structure}} e^{jkr} \frac{e^{jr}}{4\pi r}.
\]  

(5.36)

At frequencies near and below air resonance where \( kh_0 \ll 1 \), Eq. 5.36 can be expressed as a sum of monopolar and dipolar components

\[
P_{\text{elastic}}(r, f) \approx \left[ -\rho_{\text{air}}(2\pi f)^2 \tilde{u}^{\text{air}}(f) + \tilde{u}^{\text{structure}}(f) \right] e^{jkr} \frac{e^{jr}}{4\pi r} + j\rho_{\text{air}}(2\pi f)^2 \left( \frac{kh_0}{2} \right) \left[ \tilde{u}^{\text{air}}(f) - \tilde{u}^{\text{structure}}(f) \right] \cos \theta \frac{e^{jr}}{4\pi r}.
\]  

(5.37)

For Cremonese violins at and near the air resonance frequency, the monopole field in Eq. 5.37 is found to dominate the total field from the least-squares estimates of plate displacements and sound hole air flow given in Section 5.3.1. This is consistent with the experimental findings of Ref. [73] and the monopole radiation assumption in a number of musical acoustics applications [157, 168, 169, 173, 174]. At frequencies well below air resonance, that the volume change caused by violin plate displacements is approximately balanced by air flow out of the sound holes. This leads to a net dipole field given by Eq. 5.37, which dominates the total field from the least-squares estimates of Table 5.1 and use of general low frequency rather than narrow band time dependencies in Eq. 5.24 of Section 5.3.1, due to the cancellation of air volume flow from sound holes and that due to plate displacements.
This is consistent with the experimental findings and discussion of Ref. [156]. Although the monopole and dipole components are determined by using the same parameters estimated at air resonance (Table 5.1) for frequencies smaller than air resonance, they are found to be consistent with measurements of radiated pressure field from violins [15–18]. For example, at roughly 200 Hz, a roughly 30-35 dB fall in radiated pressure spectrum level from that at air resonance has been measured in Refs. [15–18]. This is consistent with a similar fall off of roughly 35 dB shown in Figure 5-1. Away from the air resonance peak, other sound radiation mechanisms may become important.

Figure 5-1: Monopole and dipole components of radiated acoustic pressure spectrum as a function of frequency for a Stradivari 1717 violin estimated using the elastic volume flux analysis and estimated parameters given in Table 5.1. At frequencies above roughly 100 Hz, the monopole component dominates the total field, where as for frequencies less than roughly 75 Hz, the dipole component dominates the total field. Both pressure spectra are normalized with respect to the maximum value of the monopole spectra. The air resonance peak is shown to occur at roughly 282 Hz. The estimated fall off of roughly 35 dB at 200 Hz from the radiated pressure spectrum level at air resonance is consistent with radiated sound pressure level measurements of violins in Refs [15–18]. Away from the air resonance peak, other sound radiation mechanisms may become important.
At and near air resonance, the radiated acoustic field is dominated by that due to air flow through f-holes and is at least two orders of magnitude greater than the field radiated from the violin structure as shown in Figure 5-2(a). The radiated pressure from the violin structure comprises that due to top plate and back plate motion (Figure 5-2 (c),(d)), which are coherently added with their respective phases shown in Figure 5-2(b). Near air resonance, the air flow through f-holes is approximately out of phase with the air flow due to top plate motion and back plate motion as shown in Figure 5-2(b), but the latter two are approximately in phase with each other. So the f-hole, top plate and back plate components of volume flux and radiated pressure spectrum level shown in these figures need to be considered carefully along with their respective phases in order to correctly assess their respective contributions to the total radiated field from a violin at air resonance.

For the violin, which radiates as a monopole at air resonance (Eq. 5.1), the total radiated acoustic power in half-power bandwidth at air resonance is then given by Eq. 5.3, with \( \tilde{v}(f) = \tilde{v}_{\text{air}}(f) + \tilde{v}_{\text{structure}}(f)\) and \( \tilde{v}_{\text{structure}}(f) = S_{\text{top}} \tilde{x}_{\text{top}}(f) + S_{\text{back}} \tilde{x}_{\text{back}}(f)\) where \( \tilde{v}_{\text{air}}(t) \leftrightarrow \tilde{v}_{\text{air}}(f)\), \( \tilde{x}_{\text{top}}(t) \leftrightarrow \tilde{x}_{\text{top}}(f)\), \( \tilde{x}_{\text{back}}(t) \leftrightarrow \tilde{x}_{\text{back}}(f)\), and \( \tilde{P}(\tau, f) \leftrightarrow \tilde{P}(\tau, f)\) are Fourier transform pairs [141], \( \tilde{v}_{\text{air}}(t), \tilde{x}_{\text{top}}(t)\) and \( \tilde{x}_{\text{back}}(t)\) are estimated from Eq. 5.24, and \( f_{\text{air}} = f_{\text{air-elastic}} \) from Eq. 5.40. This leads to the time series of air resonance frequency and power shown in Fig 5-8a-b. Empirically obtained dependencies of the air resonance frequency and power on violin design parameters over the entire Cremonese period are given in Eqs. 5.40 and 5.41, respectively. Time series of estimated air-resonance frequency and half power bandwidth about the resonant peak, determined from Eq. 5.2, characterize the resonance peaks estimated for each violin in the time series [175]. Wood densities are taken to be \( \rho_{\text{top}} = 400 \text{ kg/m}^3 \), \( \rho_{\text{back}} = 600 \text{ kg/m}^3 \) [71] and air densities and sound speeds are taken to be \( c_{\text{air}} = 340 \text{ m/s} \) and \( \rho_{\text{air}} = 1 \text{ kg/m}^3 \) [176].

5.3.3 Data collection

5.3.3.0.1 Violin design parameter data

Sound hole shapes of the violin and its prominent European ancestors were obtained from contemporary iconography or extant instruments showing: (a) circular sound holes for the
Figure 5-2: (a) Amplitude of total violin air volume flux, volume flux through f-holes, volume flux due to only top plate motion and volume flux due to only back plate motion at air resonance. The levels are normalized with respect to the total volume flux from the violin \( v_{\text{max}} \); (b) Phase (in degrees) of volume flux from the violin, f-holes, top plate motion and back plate motion with respect to the phase of top plate forcing at air-resonance; (c) Radiated pressure spectrum level from the whole violin, only f-holes, only top plate and only back plate at air resonance. (d) Radiated pressure spectrum level from the whole violin, only f-holes, and violin structure comprising top and back plate motions at air resonance. The levels in (c) and (d) are normalized with respect to the total radiated pressure spectrum level from the violin at air resonance \( P_{\text{max}} \). All values are estimated for a Stradivari 1717 violin using the elastic volume flux analysis and parameters given in Table 5.1. At and near air resonance at 282 Hz, the radiated acoustic pressure spectrum level due to air flow through f-holes is greater by roughly two orders of magnitude than that from the violin structure. At and near air resonance, the air flow through f-holes is out of phase with that due to top and back plate motion, but the latter two are in phase with each other. The radiated field from the entire violin at air resonance comprises coherent addition of air volume fluxes or radiated pressure fields from the f-holes and the violin structure.
10th Century Medieval fithele [177, 178]; (b) semi-circular sound holes for 12th-13th century lyras [178–180]; (c) c-holes for 13th-16th century Medieval and Renaissance rebecs [177, 180]; (d) the addition of taper, circular end nobs and central cusps to c-holes in vihuela de arco’s and viols of the 15th-17th centuries [177, 178, 181]; (e) classical Cremonese f-holes of the 16th-18th centuries [177–179, 182, 183]; and (f) decorative rosettes in the lute [184, 185] and the harpsichord [186]. Time series of design parameters in Figures 5-3 and 5-4, that have an at least or nearly first order effect on temporal changes in radiated acoustic power at air resonance, are based on measurements of 470 classical Cremonese violins. To construct these time series we made measurements of f-hole lengths of 338 violins from images in Ref. [20]. Measurements of f-hole lengths and characteristic lengths for air-cavity volume estimation of 110 violins [19] were taken from existing measurements in technical drawings and images in Refs. [164, 165, 187–192]. Mean air cavity heights were determined from characteristic length measurements for air-cavity volume estimation of 110 violins [19]. We reduced average plate thickness data of 22 violins from existing thickness maps in Refs. [187, 193]. Eleven of the 470 classical Cremonese violins used to generate Figures 5-3 and 5-4 coincide with the 26 classical Cremonese violins (2 Nicolo Amati, 17 Antonio Stradivari, 7 Guarneri del Gesu) for which acoustic air resonance frequencies have been reported [21–23] and shown in Figure 5-8b. Of these measurements, the mean air-resonance frequency of the Guarneri data is greater by roughly 2/3rd of a semitone from that of the Stradivari and Amati data, which is consistent with the elastic analysis of Section 9. For Stradivari violins "Betts" 1704, "Titian" 1715 and "Wilmotte" 1734, all six design parameters and air resonance frequency measurements [21–23] are available. Air resonance frequency estimates from elastic analysis match well, to within a fifth of a semitone and 1.4% RMS error, with measurements for these three instruments (Table 5.2).

During the Cremonese period, each master maker produced roughly 10 violins per year on average [20], indicating a generational-period of roughly 0.1 year. The sound hole perimeter lengths of violins made by Savart and Chanot are determined from available technical drawings and images in references [24–26].
Table 5.2: Measured air resonance frequency of Stradivari violins "Betts" 1704, "Titian" 1715 and "Wilmotte" 1734 matches well with (1.4% RMS error) estimated air resonance frequency using elastic volume flux analysis and design parameter measurements.

<table>
<thead>
<tr>
<th>Violin name</th>
<th>$L_F$ (mm)</th>
<th>$V$ (cm$^3$)</th>
<th>$h_{\text{top}}$ (mm)</th>
<th>$h_{\text{back}}$ (mm)</th>
<th>$h_{\text{sh}}$ (mm)</th>
<th>$h_{\text{a}}$ (mm)</th>
<th>$f_{\text{air-elastic}}$ (Hz)</th>
<th>$f_{\text{air-elastic}}$ (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;Betts&quot; 1704</td>
<td>70.7</td>
<td>1981</td>
<td>2.59</td>
<td>2.98</td>
<td>2.64</td>
<td>39.16</td>
<td>276</td>
<td>272</td>
</tr>
<tr>
<td>&quot;Titian&quot; 1715</td>
<td>73.77</td>
<td>1972</td>
<td>2.6</td>
<td>3.01</td>
<td>2.67</td>
<td>37.38</td>
<td>275</td>
<td>277.2</td>
</tr>
<tr>
<td>&quot;Wilmotte&quot; 1734</td>
<td>71.0</td>
<td>1920</td>
<td>2.47</td>
<td>3.03</td>
<td>2.54</td>
<td>39.43</td>
<td>274</td>
<td>278.6</td>
</tr>
</tbody>
</table>

Figure 5-3: Time series of changes in f-hole length $L_F$ (colored markers) measured from 470 Cremonese violins. The conductance of the two interacting violin f-holes is determined using the methods presented in Ref. [19].
5.3.3.0.2 Fluctuations and statistics of violin design parameter measurements and radiated acoustic power estimates

The f-hole length fluctuations, determined from measurements of 448 violins over the Cremonese period, are found to approximately follow a Gaussian distribution about local mean f-hole length (Figure 5-5a). The fluctuations about the local mean are determined by subtracting a running average with a one year window from the f-hole length time series and binned into a histogram (Figure 5-5a). Local f-hole length fluctuations follow a consistent probability distribution that is independent of the local mean throughout the Cremonese period (Figure 5-3). The standard deviation of f-hole length due to craftsmanship fluctuations is roughly 1.9% of the mean f-hole length over the Cremonese period. Air-cavity volume fluctuations, determined from measurements of 110 violins, are found to approximately follow a Gaussian distribution about the mean air-cavity volume with a measured standard deviation of roughly 2.7% of the mean air-cavity volume over the Cremonese period (Figure 5-5b); fluctuations in top plate thickness, back plate thickness and plate thickness near f-holes, determined from measurements of 22 violins, have measured standard deviations of roughly 9% of their respective mean thicknesses over the Cremonese period (Figure 5-4b-d); and mean air cavity height fluctuations, determined from measurements of 110 violins, have a measured standard deviation of roughly 2.6% of the mean height over the Cremonese period (Figure 5-4e).

5.4 Evolution of Sound Hole Shape from the 10th to the 18th Century and Its Effect on Radiated Air Resonance Power of the Violin and Its European Ancestors

Upper and lower limiting cases are determined by exact solutions for the changes in radiated acoustic power over time due solely to changes in the purely geometric parameter of sound hole shape for the violin and its ancestors (Fig 5-6a, Sections 5.2.1 and 5.2.2). These are
Figure 5-4: Temporal variations in (a) air-cavity volume $V$, (b) back plate thickness $h_{\text{back}}$, (c) top plate thickness $h_{\text{top}}$, (d) plate thickness near f-holes $h_{\text{sh}}$, and (e) mean air cavity height $h_{\text{a}}$ measured from 110 classical Cremonese violins (Section 5.3.3.0.1). Black lines in (a) and (e) represent 20-instrument running averages, and in (b)-(d) represent quadratic regression fits of available thickness data.
Figure 5-5: (a) The distribution of f-hole length fluctuations due to craftsmanship limitations minus the mean (gray bars) measured from 448 Cremonese violins (Figure 5-3), with the Gaussian distribution (black) that best fits the measured data. Standard deviation is roughly 1.9% of mean f-hole length over Cremonese period. (b) The distribution of air-cavity volume fluctuations due to craftsmanship limitations minus the mean (gray bars) measured from 110 Cremonese violins (Figure 5-4a), with the Gaussian distribution (black) that best fits the measured distribution. Standard deviation is roughly 2.7% of the mean air-cavity volume over the Cremonese period.

compared with the radiated power changes over time at air resonance from elastic volume flux analysis (Section 5.3) (Fig 5-6a). To isolate the effect of sound hole geometry in Fig 5-6a-c, all cases have constant forcing amplitude over time, are normalized to the circular sound hole case, and have all other parameters including sound-hole area and air cavity volume fixed over time. Here we will quantify the isolated effect of the shape of this sound hole on the air resonance frequency and the acoustic power radiated at this resonance frequency.

The upper limiting case corresponds to the radiated power change of an infinite rigid sound hole bearing wall. To reiterate, the exact analytical solution for total power in a frequency band $\Delta f$ is given by

$$W_{\text{wall}} = \frac{1}{T} \int_{\Delta f} \frac{\Delta \hat{P}(f)}{\pi \rho_{\text{air}} c_{\text{air}}} df \ C^2,$$

which is proportional to $C^2$. The lower limiting case corresponds to the radiated power change of a rigid instrument with a sound hole and air cavity where the exact solution for
the total power in the half-power bandwidth around the Helmholtz resonance [75, 76, 150] frequency is given by

$$W^{\text{rigid-air}} = \eta^{\text{rigid}} C,$$  \hspace{1cm} (5.39)

which is proportional to $C$ since the exact form of $\eta^{\text{rigid}}$ is shown (Eq. 5.21) to be approximately independent of sound hole shape, conductance and cavity volume (Section 5.2.2). The corresponding rigid instrument Helmholtz resonance [75, 76, 150] frequency is given in Eq. 5.9 and is proportional to $\sqrt{C}$. 

In the case of elastic volume flux analysis (Section 5.3.1 and SI Sections 3-4), derived from classical Cremonese violin measurements, the air resonance frequency $f^{\text{air-elastic}}$ is found to be approximately

$$f^{\text{air-elastic}} \approx \kappa V^{-0.6} (h^{\text{back}})^{0.1} (h^{\text{top}})^{0.01} (h^a)^{0.2} C^{0.5}$$  \hspace{1cm} (5.40)

and the total power in the half-power bandwidth about the air resonance frequency is found to be approximately

$$W^{\text{air-elastic}} \approx \beta V^{-0.8} (h^{\text{back}})^{0.6} (h^{\text{top}})^{-0.2} (h^a)^{-0.9} C^{1.7}$$  \hspace{1cm} (5.41)

where $\kappa$ and $\beta$ are empirically determined constants, $h^{\text{back}}$, $h^{\text{top}}$ and $h^a$ are respectively the back plate thickness, top plate thickness, and mean air-cavity height, which are all assumed constant over time, and only $C$ changes over time in Fig 5-6a-b to isolate the effect of sound-hole shape change.

The power change curves in Fig 5-6a can be distinguished by their dependencies on sound hole conductance (Fig 5-6c), where the upper limiting case has power change proportional to $C^2$ (Eq. 5.38), the lower limiting case to $C$ (Eq. 5.39), and the elastic instrument case to $C^{1.7}$ (Eq. 5.41). The expected dependencies on sound hole conductance are in the $C^1 - C^2$ range, with elastic analysis falling roughly in the middle of the limiting cases determined by exact analytic solutions.
Figure 5-6: Acoustic air-resonance power efficiency grows as sound hole shape evolves over centuries through the violin’s European ancestors to the violin. (a) Change in radiated acoustic air-resonance power for an elastic instrument $W_{\text{air-elastic}}$ (Eq. 5.41), rigid instrument $W_{\text{air-rigid}}$ (Eq. 5.39), and infinite rigid sound hole bearing wall $W_{\text{wall}}$ (Eq. 5.38) as a function of sound hole shape, where percentage change is measured from the circular sound hole shape. (b) Air-resonance frequency for elastic instrument $f_{\text{air-elastic}}$ (Eq. 5.40) and rigid instrument $f_{\text{air-rigid}}$ (Eq. 5.9) as a function of sound hole shape, normalized by $f_{\text{air-elastic}}$ for the circular opening (i). (c) Conductance $C$ [19] and perimeter length $L$ for different sound hole shapes of fixed sound-hole area, normalized to be unity for the circular opening (i). Shape overlap occurred between nearby centuries. Only sound hole shape is changed and all other parameters are held fixed and equal to those of the 1703 “Emiliani” Stradivari violin [20]. The conductance of the two interacting sound holes for each instrument is taken from Ref. [19]. Data sources are provided in Section 5.3.3.0.1.
When compared to the exact solutions of the limiting cases, elastic analysis, which involves more parameters (Section 5.3.1), still yields a similar increasing trend in power change over time due to geometric changes in sound hole shape alone (Fig 5-6a). The elastic instrument dependence follows a trend that is roughly the average of the upper and lower limiting cases (Fig 5-6a). If only sound hole shape varied, these results are consistent with roughly a doubling of power as sound hole geometry of the violin's prominent European ancestors slowly evolved over the centuries from simple circular openings of 10th century medieval f-holes to complex f-holes that characterize classical 16th-18th century Cremonese violins of the late Renaissance and Baroque period (Fig 5-6(i)-(vi)). This doubling (Fig 5-6a) is due to a gradual morphing to more slender shapes that enables sound hole conductance to increase by roughly 50% through triplication of perimeter length for the same sound hole area (Fig 5-6c).

The rigid instrument resonance frequency $f^{\text{air-rigid}}$ (Eq. 5.9) follows a similar dependence on sound hole shape as that of elastic analysis but offset by roughly 6% (Fig 5-6b), which is experimentally confirmed in Ref. [19]. While this may seem to be a small inconsistency, 6% corresponds to roughly a semitone [154], which suggests that idealized rigid instrument analysis may lack the accuracy needed for some fine-tuned musical pitch estimates.

The resulting air resonance power and frequency dependencies shown in Fig 5-6a-b indicate that linear scaling of a violin, or related instrument, by pure dilation will not lead to an instrument with linear proportional scaling in resonance frequency or power at air cavity resonance. This suggests that historic violin family design may have developed via a relatively sophisticated nonlinear optimization process.

The explanation for how and why violin family sound hole evolution occurred is intimately connected to the fact that the acoustic source amplitude, via temporal changes in air flow through the sound hole, is directly proportional to sound hole perimeter length $L$ near the air resonance frequency, rather than area, as described in detail in Ref. [19]. Our findings from the archaeological record (Fig 5-6i-vi) indicate that the ratio of inefficient to total sound-hole area was gradually reduced over the centuries by increasing aspect ratio and geo-
metric complexity, as exhibited by the introduction of semi-circular sound holes [178–180] in 12th-13th century lyras (Fig 5-6ii), and then c-holes [177, 180] in 13th-16th century Medieval and Renaissance rebecs (Fig 5-6iii-iv). Through this series of shape changes alone, sound hole perimeter length gradually grew, providing greater conductance, greater air volume and mass flow rates over time, and higher radiated power for the same sound hole area at the air resonance frequency. The intertwined evolutionary trends of decreasing acoustically inactive sound-hole area by increasing sound hole perimeter length and conductance to increase radiated power efficiency continued with the addition of taper, circular end nobs and central cusps in vihuela de arco’s and viols [177, 179, 181] of the 15th-17th centuries (Fig 5-6v), and the classical Cremonese f-holes [177–179, 182, 183] of the 16th-18th centuries (Fig 5-6vi).

The gradual nature of sound hole shape changes from the 10th to the 16th century in the violin’s ancestors to the violin is consistent with incremental mutation from generation to generation of instruments. The steady growth of power efficiency across the centuries is consistent with a selection process favoring instruments with higher power efficiency at air resonance.

5.5 Time Series Analysis over the Classical Cremonese Period (16th to 18th Centuries)

Over the classical Cremonese period, exact solutions for upper (~ C^2, Eq. 5.38) and lower (~ C^1, Eq. 5.39) limiting cases on radiated acoustic power change over time (Fig 5-7) due purely to variations in the geometric parameter of f-hole length (Fig 5-8c) are compared with those determined from elastic volume flux estimation (~ C^{1.7}, Eq. 5.41) (Fig 5-7). As a control, all other parameters than f-hole length are again held fixed over time, including the forcing. Similar increasing trends are found for all cases (Fig 5-7). So, elastic analysis, which involves more parameters (Section 5.3.1, SI Sections 3-4) all of which are held fixed except for f-hole length in Fig 5-7, still yields similar trends as exact solutions based on purely geometric violin parameters.
Figure 5-7: Time series of change in total radiated acoustic power as a function of temporal changes of the purely geometric parameter of f-hole length during the Cremonese period. The estimated dependence via elastic volume flux analysis ($W_{\text{air-elastic}} \sim C^{1.7}$, Eq. 5.41, solid colored lines) is roughly the average of the upper ($W_{\text{wall}} \sim C^2$, Eq. 5.38, dashed black line) and lower ($W_{\text{air-rigid}} \sim C$, Eq. 5.39, solid black line) limiting cases. Colored lines and shaded patches respectively represent mean trends and standard deviations of $W_{\text{air-elastic}}$ for different workshops: Amati (blue), Stradivari (red), Guarneri (green), Amati-Stradivari overlap (blue-red) and Stradivari-Guarneri overlap (red-green). Percentage change is measured from the 1560 Amati workshop instrument. The conductance of the two interacting violin f-holes is determined from Eq. 5.26.
We next estimate the change in acoustic radiated power over time (Fig 5-8a) as a function of the temporal variations of six parameters (Fig 5-8c and 5-4) that have an at least or nearly first order effect on temporal changes in radiated acoustic power at air cavity resonance, by elastic analysis for constant forcing over time. These parameters are measured from 470 extant classical Cremonese violins. They are: air cavity volume (Fig 5-4a), which affects air cavity compression; mean plate thicknesses (Fig 5-4b,c), which affect masses and stiffnesses; plate thickness at the f-holes (Fig 5-4e), which affects acoustic conductance \[75\]; mean air-cavity height (Fig 5-4d), which affects overall stiffnesses; and f-hole length (Fig 5-8c), which affects acoustic conductance. The empirically observed modal motions that generate the effectively monopolar acoustic radiation at air resonance \[16, 71\], purely through changes in volume flux, are described by physical analysis involving these measured parameters in Section 5.3.1. Increasing sound hole length, for example, increases conductance and mass flow, but it also increases radiation damping. This lowers the resonance maxima but increases peak bandwidth (Figure 5-9) sufficiently to increase total power integrated over the spectral peak (Sections 5.2.1, 5.2.2 and 5.3). By making the back plate thicker and denser than the top plate, back plate motion and body volume change is reduced. This leads to less coherent cancellation between mass outflow from the sound hole and violin body contraction, and consequently higher radiated power at air resonance. This is because at the air resonance frequency the top and back plates move towards each other, air cavity volume decreases, forcing air volume out of the sound hole so that positive mass outflow from the sound hole is then partially canceled by negative mass outflow from the violin body contraction, in the observed omnidirectional or monopolar radiation (Section 5.3). Keeping the top plate lighter, on the other hand, enables it to be more responsive to direct forcing at the bridge and drive more air mass through the sound hole. For fixed air cavity volume, increasing mean air cavity height increases stiffness. Reducing top plate thickness at the f-holes reduces air flow resistance and so increases conductance.

By comparison of Fig 5-7 and 5-8a, we find that estimated power changes due to the temporal variations of all six parameters (Fig 5-8a) primarily follow the estimated power variations due to the isolated temporal effects of f-hole length variation alone (Fig 5-7). This can also be seen by noting that the total change in radiated power over the Cremonese
Figure 5-8: Time series of changes in (a) total radiated acoustic air-resonance power $W_{\text{air-elastic}}$ (Eq. 5.41, solid colored lines); (b) air resonance frequency $f_{\text{air-elastic}}$ (Eq. 5.40, solid colored lines) over the classical Cremonese period and (c) f-hole length $L_F$ (colored markers) measured from 470 Cremonese violins. Colored shaded patches in (a) and (b) represent standard deviations. Filled circles and error bars in (b) respectively represent the means and standard deviations of air resonance frequencies for each workshop for 26 surviving Cremonese violins (2 Nicolo Amati, 17 Antonio Stradivari, 7 Guarneri del Gesù) previously measured in the literature [21-23]. Black solid line in (b) represents rigid instrument air resonance frequency $f_{\text{air-rigid}}$ (Eq. 5.9). Two Northern Italian pitch standards, Mezzo Punto and Tuono Corista (SI Section 10), from the late 16th to late 17th centuries and common 17th to early 18th century French baroque pitches (black dashed lines) are also shown in (b). Percentage change in radiated power is measured from the 1560 Amati workshop instrument. Black line in (c) represents 10-instrument running average. The conductance of the two interacting violin f-holes is determined from Eq. 5.26. Data sources are provided in SI Section 5. *Documents suggest Tutto Punto to be the problematic pitch of the Cremonese organ in 1583 because it did not conform to dominant Northern Italian pitch standards of the time.
Figure 5-9: Time series of half power bandwidths (colored lines) at air-resonance frequency over the classical Cremonese period estimated from the elastic volume flux analysis. Estimates are based on measurements of f-hole length, air cavity volume, top and back plate thickness, plate thickness near f-holes and mean air cavity height (Figures 5-8c and 5-4) from 470 classical Cremonese violins. Colors and arrows represent different workshops: Amati (blue), Stradivari (red), Guarneri (green), Amati-Stradivari overlap (blue-red) and Stradivari-Guarneri overlap (red-green). Standard deviations are represented by colored patches. Half power bandwidth in combination with the air resonance frequency characterizes the air resonance peak.
period estimated from elastic volume flux analysis with all six parameters is roughly 60% ± 10% (Fig 5-8a), and that the conductance contribution via \( C_{1.7} \propto L_{f}^{0.7} \) from f-hole length changes alone of roughly 30% (Eq. 5.26) leads to a similar 58% ± 5% power change over the Cremonese period (Fig 5-7), with a very similar trend. We find that these results are consistent with a selection process favoring instruments with higher acoustic power at air resonance during the classical Cremonese period. The increases in estimated power and measured f-hole length over the classical Cremonese period are found to be relatively steady and gradual beginning from the Nicolo Amati period until the Guarneri period. During the Guarneri period more dramatic increases in both occurred. By examining individual contributions of the six parameters (Fig 5-10a), it is again found that temporal changes in estimated acoustic power are dominated by temporal changes in f-hole length. The next largest contribution to estimated power comes from clear increases in back plate thickness during the Stradivari and Guarneri periods, which is still roughly a factor of two less than the contribution from f-hole length increases (Fig 5-10a). These observations and trends have clear design implications.

Mean air resonance frequencies estimated from elastic analysis match well, to within an eighth of a semitone corresponding to a roughly 1% RMS error, with mean measured air resonance frequencies of classical Cremonese violins for each family workshop (Fig 5-8b). Rigid instrument analysis leads to a similar air resonance frequency temporal trend as elastic analysis (Fig 5-8b), suggesting that the elastic resonance frequency trend is dominated by variations in sound hole length and instrument volume. This is consistent with the finding that the effects of all other parameters are small on the overall resonance frequency temporal trend (Fig 5-10b), even though they play an important role in fine tuning the absolute resonance frequency. Rigid instrument analysis, however, results in offsets of roughly a semitone between estimated and measured Cremonese air resonance frequencies (Fig 5-8b), and so may not be sufficient for some fine-tuned musical applications. These observations and trends also have clear design implications. Increases in f-hole length (Fig 5-8c) were apparently tempered by a gradual increasing trend in cavity volume (Fig 5-4a) that effectively constrained the air resonance frequency (Eq. 5.40) to vary within a semitone of traditional pitch conventions (Figs 5-8b, 5-10b), and within a range not exceeding the resonance peak’s.
Figure 5-10: Approximate components of temporal trends in (a) radiated acoustic power $W_{air-elastic}$ (Eq. 5.41) and (b) air resonance frequency $f_{air-elastic}$ (Eq. 5.40) over time due to f-hole length $L_F$ (blue), air cavity volume $V$ (red), top plate thickness $h_{top}$ (green), back plate thickness $h_{back}$ (magenta), plate thickness near f-hole $h_{sh}$ (brown) and mean air cavity height $h_a$ (yellow) estimated from elastic analysis. Mean trends and standard deviations are represented by colored solid lines and error bars, respectively. Percentage change in radiated power is measured from the 1560 Amati workshop instrument. Contributions from each parameter are isolated by holding all other parameters fixed at 1560 Amati workshop instrument values. The conductance of the two interacting violin f-holes is determined from Eq. 5.26. Input mean time series data are from Figs 5-8c and 5-4.
half power bandwidth, roughly its resolvable range.

5.6 Sound Hole Shape and Air Resonance Power Evolution Rates and Mechanisms

A theoretical approach for determining whether design development is consistent with evolution via accidental replication fluctuations from craftsmanship limitations and subsequent selection is developed and applied. Concepts and equations similar to those developed in biology for the generational change in gene frequency solely due to random replication noise and natural selection [194, 195] are used. The formulation, however, includes thresholds for detecting changes in an evolving trait that are inconsistent with those expected solely from replication noise due to random craftsmanship fluctuations, and so differs from biological formulations. The expected evolution rate threshold $E_{\text{CraftFluct}}$ is defined as the difference from the mean of the expected maximum value of the evolving random trait variable, taken from the expected selection pool of population $N$ containing the most recent generations, divided by the mean time between each generation, assuming randomness and mutation solely due to random replication noise. So, the evolution rate threshold, $E_{\text{CraftFluct}}$, for a given trait $t$, such as f-hole length, below which trait evolution rates are consistent with accidental trait replication fluctuations from craftsmanship limitations is defined as

$$E_{\text{CraftFluct}} = \frac{\max_N(t) - \langle t \rangle}{T_g}.$$  

(5.42)

Here $\max_N(t)$ represents the maximum value of the trait $t$ taken from a selection pool of population $N$ containing the most recent generations, $\langle t \rangle$ is the expected value of $t$, and $T_g$ is the mean generational period. Equation 5.42 reduces to that for expected generational change in gene frequency due to replication error and natural selection obtained by Price [194] when only the sample with the largest trait value is selected for replication. Another evolution rate threshold, $E_{\text{DesignPlan}}$, above which trait evolution rates are likely to be inconsistent with
accidental replication fluctuations from craftsmanship limitations is defined as

\[ E_{\text{DesignPlan}} = \frac{\sqrt{\langle \nu^2 \rangle} - \langle \nu \rangle^2}{T_g}. \]  

(5.43)

This corresponds to an increase of one standard deviation in the value of the trait \( \nu \) over consecutive generations. Two evolving design traits of the Cremonese violins are examined here, f-hole length and radiated acoustic power at air resonance. Their statistics are described in Section 5.3.3.0.2.

For measured rates below the theoretical threshold \( E_{\text{CraftFluct}} \) (Eq. 5.42), mutations arise well within the range of accidental replication fluctuations from craftsmanship limitations while for those above the threshold \( E_{\text{DesignPlan}} \) (Eq. 5.43), mutations likely arise from planned design changes. All evolution rates for linear sound hole dimension (Fig 5-11a) and air resonance power (Fig 5-11b) are found to fall at least an order of magnitude below an expected evolution rate threshold set for a selection pool population of at least \( N = 2 \) instruments, the minimum whole number population enabling selection, since \( N = 1 \) leads to no selection and trendless random walk. All measured evolution rates are then consistent with mutations arising from replication noise due to random craftsmanship fluctuations before the 19th century. All measured evolution rates require very small and easy to attain minimum generational selection pool populations of between 1 and 1.12 instruments. Evolution rates exceeding the replication noise standard deviation per generational period, \( E_{\text{DesignPlan}} \) (Eq. 5.43), which corresponds to \( N = 4 \) for the given noise distribution, are more likely to be due to planned design alterations, but none above even the \( N = 2 \) threshold were found up to and including the Cremonese period. For the late Guarneri period, measured f-hole length and estimated power evolution rates dramatically increase (Fig 5-11). This is consistent with a significant increase in preference for instruments with longer f-holes and higher power or a significant increase in the mean selection pool population available compared with past generations. If lower evolution rates are associated with more stable evolutionary niches characterized by low environmental pressure for change, then the Stradivari period would be most stable and the Guarneri the least based on Fig 5-11, which is consistent with historical evidence [37,
Figure 5-11: Measured evolution rates and thresholds distinguishing mutation origins as being consistent or inconsistent with accidental replication fluctuations from craftsmanship limitations. Mean evolution rates for (a) linear sound hole dimension and (b) estimated radiated acoustic power at air resonance. Below $N = 2$, corresponding to $E_{\text{CraftFluct}}$ (Eq. 5.42, lower dashed grey line), mutations likely arise within the range of accidental replication fluctuations due to craftsmanship limitations. Above $N \approx 4$, corresponding to $E_{\text{DesignPlan}}$ (Eq. 5.43, upper dashed grey line), mutations likely arise from planned design changes. All rates are based on a generational period of 0.1 year [20].
Figure 5-12: Sound hole shapes and violins made by Savart and Chanot in the early 1800's [24–26]. While the Savart and Chanot instruments, which had notable design differences from classical violins, were unsuccessful, they were made for the violin repertoire, and were consistently referred to as violins by their creators and in subsequent literature [24–26]. In particular, Savart’s instrument is usually referred to as the “trapezoidal” violin and Chanot’s instrument is usually referred to as the “guitar-shaped” violin [25–27].

In unsuccessful evolutionary offshoots, relatively drastic and temporally impulsive changes to sound hole shape (Fig 5-12) and violin design were made by Savart and Chanot in the early 1800s by well documented preconceptions [24–26]. Their respective evolution rates in sound hole perimeter length and power are so large that they are inconsistent with random craftsmanship fluctuations, leaving planned design change as the likely possibility (Fig 5-11). The air resonance power efficiencies and conductances of the Savart and Chanot sound holes are significantly lower than those of the classic violin f-holes: Savart and Chanot sound holes (Fig 5-12) have perimeter lengths that are lower by roughly 34% and 30% (Fig. 5-11a), and air resonance powers that are lower by roughly 23% and 17% (Fig 5-11b), than those of classical Cremonese violin f-holes (Fig. 5-6vi), and are a regression to sound hole shapes of the 14th-15th centuries (Fig 5-6a) in terms of air resonance power. These results are consistent with the classical Cremonese violin makers taking the conservative approach of letting inevitable random craftsmanship fluctuations, or small planned changes of magnitude consistent with those of such random fluctuations, be the source of mutations that led to evolution by subsequent selection and replication. This approach avoids the potential waste
of implementing flawed preconceptions that exceed those of inevitable craftsmanship fluctuations. Savart and Chanot were scientists rather than professional violin makers. They apparently were freer to take the far riskier approach of gambling with the implementation of drastically different sound hole shapes based on preconceptions. Such gambling could produce much greater changes in efficiency in a short time. Unfortunately, the conductance theory here shows them to have been less efficient than the f-hole in terms of power efficiency at air resonance.

5.7 Conclusions

It is found that as the ratio of inefficient, acoustically inactive to total sound-hole area was decimated, radiated acoustic power efficiency from air-cavity resonance roughly doubled as sound-hole geometry of the violin’s ancestors slowly evolved over nearly a millennium from simple circles of the 10th century to the complex f-hole of the 16th-18th centuries. It is also found that f-hole length then followed an increasing trend during the classical Cremonese period (16th-18th centuries) in the renowned workshops of Amati, Stradivari and Guarneri, apparently favoring instruments with correspondingly higher air-resonance power. Temporal power trends due solely to variations in sound hole geometry over roughly a millennium, determined from exact analytic solutions for equivalent rigid violins and infinite rigid sound hole bearing plates, are found to be similar to those determined from elastic volume flux analysis. Resonance frequency and power changes over the classical Cremonese period were then also estimated by elastic volume flux analysis including the variations of other violin parameters as well as f-hole length. This was done by constructing time series of f-hole length, air cavity volume, top and back plate thickness, plate thickness near f-holes and mean air cavity height from measurements of 470 classical Cremonese violins. The resulting temporal trend in radiated power is dominated by the effect of variations in f-hole length alone. This trend is similar to that obtained by exact analytic solutions for equivalent rigid violins and infinite rigid f-hole bearing plates, where only f-hole length is varied. The resulting resonance frequency estimates from elastic analysis match measured resonance frequencies from extant classical Cremonese violins to within a quarter of a semitone, roughly a Pythagorean comma.
Rigid analysis, which only depends on f-hole length and cavity volume, leads to the same resonance frequency trend but with an offset of roughly a semitone. This indicates that elastic analysis is necessary for fine-tuned musical pitch estimates. Evolution rate analysis was performed on the time series of measured f-hole length and estimated air resonance power. The corresponding evolution rates are found to be consistent with (a) instrument-to-instrument mutations arising within the range of accidental replication fluctuations from craftsmanship limitations and subsequent selection favoring instruments with higher air-resonance power, rather than (b) drastic preconceived design changes from instrument-to-instrument that went beyond errors expected from craftsmanship limitations. This suggests evolutionary mechanisms by either (i) a conservative approach where planned mutations avoided changes of a magnitude that exceeded those inevitable from normal craftsmanship error, or (ii) purely random mutations from craftsmanship limitations and subsequent selection. The former is consistent with a practical and economical innovation strategy to minimize waste.

5.8 Author Contributions

This chapter comprises the work appearing in Ref. [19] co-authored by Hadi T. Nia, Ankita D. Jain, Yuming Liu, M-Reza Alam, Roman Barnas and Nicholas C. Makris. Sections 5.2 and 5.3 were written by ADJ, YL and NCM and the rest of the text was written by NCM. Work on evolution rates, evolution rate thresholds and mutation analysis was primarily done by ADJ and NCM. Work on elastic and rigid vessel modeling was primarily done by YL, ADJ and NCM. Acquisition and reduction of Cremonese violin data was primarily done by ADJ and RB. Acoustic radiation theory was primarily derived by ADJ, YL and NCM.
Appendix A

Environmental Impact Considerations for OAWRS Survey

A.1 Introduction

During OAWRS of spawning Atlantic Herring in the Gulf of Maine in Fall 2006, many species of vocalizing marine mammals were localized. Among these, humpback whales that predominantly prey on Atlantic herring were one of the most vocally active species producing calls and songs [37]. In this chapter, we show that during the OAWRS survey of spawning herring on Georges Bank in the Fall 2006, humpback whale song occurrence was unaffected by sonar transmissions.

Passive acoustic survey methods employing hydrophones at fixed locations [196–210] or mobile platforms [211, 212] have been widely used to detect, localize, track and study the behavior [196–204, 208–210] and abundance [199, 205–207] of whales. With our array situated on the northern flank of Georges Bank from September 19 to October 6, 2006 [11, 69], vocalizing whales could be detected and localized over most of the Gulf of Maine, a roughly 400-km diameter area, including Georges and Stellwagen Banks, and so vocalization behavior could be monitored over an ecosystem scale [37]. This was possible because a large-aperture, densely-sampled, coherent hydrophone array was used, which had orders of magnitude higher array gain [38, 106, 213–216] than previously available in acoustic whale sensing. Roughly
2000 humpback whale vocalizations per day were detected and were used to determine the corresponding whale locations [37] over time via a synthetic aperture tracking technique [217–219] and the array invariant method [220].

The distribution of the vast majority of vocalizing humpback whales was found to coincide with the primary time and location of Atlantic herring during their peak annual spawning period. During daylight hours, herring were found to be dispersed on the seafloor in deeper waters over wide areas of Georges Bank's northern flank [11]. At sunset, they would then rise and converge to form dense and massive evening shoals, which migrated to the shallow waters of Georges Bank for spawning, following a regular diurnal pattern [11]. Humpback whale vocalization behavior followed a similarly strong diurnal pattern, temporally and spatially synchronous with the herring shoal formation process, with vocalization rates roughly ten times higher at night than during daylight hours. At night, most humpback whale vocalizations originated from concentrated regions with dense evening herring shoals, while during daytime, their origins were more widely distributed over areas with significant but diffuse pre-shoal herring populations [37]. These vocalizations are comprised of: (i) non-song calls, dominated by repetitive downsweep “meows” which apparently have not been previously observed; and (ii) songs [197]. The repetitive non-song calls were highly diurnal and synchronous with the herring shoal formation process, consistent with hunting and feeding behavior [37]. In contrast, songs occurred at a constant rate with no diurnal variation, and are apparently unrelated to feeding and the highly diurnal herring spawning activities.

Before and during OAWRS survey transmissions [11, 69], we measured constant humpback whale song occurrence, indicating these transmissions had no effect on humpback whale song. In addition, our data shows no humpback whale vocal activity originating from Stellwagen Bank, which had negligible herring populations [221, 222], but vocalizing humpbacks located near Georges Bank, which had dense and decadally high herring populations [221], could be heard at Stellwagen Bank. These results are consistent with previous observations of humpback whale feeding activity in the Gulf of Maine and Stellwagen Bank which show humpback whales leave Stellwagen Bank for other regions plentiful in herring for feeding.
during the herring spawning season [223]. Our data analysis indicates that the change in humpback whale song occurrence reported at Stellwagen Bank [29] is consistent with wind-dependent noise [38, 214, 224, 225] limiting the single-hydrophone measurements [29] to a small wind-speed-dependent fraction of the singing humpback whales and songs detected by our densely sampled, large aperture, coherent array. These findings are all consistent with the constant humpback whale song occurrence rates before and during OAWRS survey transmissions found with our wide-area towed array measurements.

A.2 Model for detectable humpback whale song occurrence

Detectable humpback whale song occurrence for a coherent sensor array can be quantified in terms of local wind-speed-dependent ambient noise for a given spatial distribution of vocalizing humpback whales. The humpback whale song occurrence depends on the presence of at least one singing humpback whale inside the mean wind-dependent detection range of the sensor array. The percentage of time in a day over which a humpback whale is within the mean detection area and is singing corresponds to the measured daily humpback whale song occurrence rate.

The detection range [38, 214, 216, 225, 226], \( r_d \), is defined as the range from the center of the array at which signals, in this case humpback whale songs, can no longer be detected above the ambient noise, and is the solution of the sonar equation [38, 106, 213–215],

\[
NL(v) + DT - AG = RL(r_d(v)) = SL - TL(r_d(v)),
\]

where \( NL(v) \) is the wind-speed-dependent ambient noise level, \( v \) is the wind speed, \( DT \) is the detection threshold, \( RL \) is the received sound pressure level due to a humpback whale song source level \( SL \) undergoing a transmission loss of \( TL(r_d(v)) \) at range \( r_d(v) \) for some given source and receiver depths, and \( AG \) is the array gain equal to \( 10\log_{10} N_0 \) for a horizontal
array, where \( N_0 \) is the number of coherent sensors spaced at half wavelength [38, 106, 213–215]. The capability of sensor arrays with high array gain such as ours to detect sources orders of magnitude more distant in range than a single sensor is standard, well established and well documented in many textbooks [38, 106, 213–215, 218]. The array gain of our coherent horizontal OAWRS receiver array is 18 dB, which enables detection of whale vocalizations in an ocean acoustic waveguide [38, 213, 215, 218] up to either two orders of magnitude lower in SNR or two orders of magnitude more distant in range than a single hydrophone [38, 106, 213–215, 218], which has zero array gain [38, 106, 213–215, 218], by direct inspection of Equation (A.1). We set the detection threshold, DT, such that the sum of signal and noise is detectable at least 5.6 dB [113, 227–229] above the noise. The ambient noise and the received signal are filtered to the frequency band of the source. Further, the wind-speed-dependent ambient noise level is modeled as

\[
NL(v) = 10 \log_{10} \left( \frac{\alpha v^n + \beta}{1 \mu \text{Pa}^2} \right)
\]

where \( n \) is the power law coefficient of wind-speed-dependent ambient noise, \( \alpha \) is the waveguide propagation factor [230] and \( \beta \) corresponds to the constant baseline sound pressure squared in the frequency band of the source. The coefficients \( n, \alpha \) and \( \beta \) are empirically obtained by minimizing the root mean square error between the measured and the modeled ambient noise level as a function of measured wind speed during the OAWRS experiment in the Gulf of Maine [11]. Our estimate of \( n \) in the frequency range of the observed humpback song units is consistent with past ambient noise measurements in high shipping traffic regions [231–234]. (A value of \( n \approx 3 \) would have been consistent with wind-dependent ambient noise with no significant shipping component [235–237] but a value of \( n \approx 3 \) was not obtained.) The noise levels obtained for Stellwagen Bank are consistent with those reported in Ref. [29]. The noise level at Stellwagen Bank is then hind cast using available local wind speed data from National Oceanographic and Atmospheric Administration (NOAA) buoys located at Stellwagen Bank [36].
A standard parabolic equation model of the US Navy and the scientific community, Range-dependent Acoustic Model (RAM)[91, 107, 213, 238, 239], that takes into account range-dependent environmental parameters is used to calculate the transmission loss $TL(r_d(v))$ from the whale location to the sensor in a highly range-dependent continental-shelf environment in the Gulf of Maine including Stellwagen Bank. The model uses experimentally measured sound speed profiles acquired during the OAWRS 2006 experiment [69] and standard bathymetry data for the Gulf of Maine [240]. Expected transmission loss [241] is determined along any given propagation path from source to receiver by Monte-Carlo simulation over range-dependent bathymetry [240] and range-dependent sound speed structures measured from oceanographic data [14, 69, 77, 242]. An estimate of detection range $\hat{r}_d(v)$ for a given humpback whale song unit source level can be obtained from Equation (A.1) by a minimum mean squared error method. Higher transmission loss occurs in shallower waters due to more intense and pervasive bottom interaction [38, 106, 213–215]. Transmission loss in deeper waters is typically significantly lower due to upward refraction [38, 213] which leads to far less intense and pervasive bottom interaction, as is the case in the deeper waters surrounding Georges Bank [38, 106, 213–215]. Highly directional transmission loss may then occur when there are large depth variations about a receiver. Indeed, this effect makes the detection range of whales in directions to the North of our receiver and Georges bank much greater than in directions to its South where the relatively shallow waters of Georges Bank are found (Figure A-4). The fact that we localized the sources of many whale calls at great distances along shallow water propagation paths on Georges Bank in directions where transmission loss was greater and found negligibly small vocalization rates much closer to the receiver in the deeper waters north of Georges Bank where transmission loss was much less greatly emphasizes the finding that the vocalization rates originating from north of Georges Bank were negligibly small. This indeed is expected based on general behavioral principles [223] since the whales' dominant prey was on Georges Bank, where the majority of whale vocalizations originated [37], and not in the deeper waters to the North, as we note in Ref. [37]. This is also consistent with the historical distribution of humpback whales in the Gulf of Maine during the fall season [243]. The ranges and propagation paths from deep to shallow waters between our receiver array and Stellwagen Bank are very similar to those between our
receiver array and the distant whale call sources localized along Georges Bank (Figure A-4). The corresponding transmission losses have negligible differences. The fact that we localized the sources of many whale calls on Georges Bank but found negligibly small vocalization rates originating from Stellwagen Bank in the “before” or “during” periods, then emphasizes the fact that vocalization rates originating from Stellwagen Bank were negligibly small in these periods. As noted in Ref. [37] and Section A.3, this is consistent with the well documented findings that humpback whales migrate away from Stellwagen Bank where herring stocks have collapsed to feed at other locations that support large herring aggregations such as Georges Bank [223]. Our transmission loss calculations with the standard RAM parabolic equation model have been extensively and successfully calibrated and verified with (1) thousands of one-way transmission loss measurements made during the same 2006 Gulf of Maine experiment discussed here at the same time and at the same location [69, 244]; (2) thousands of two-way transmission loss measurements made from herring shoal returns and verified by conventional fish finding sonar and ground truth trawl surveys during the same 2006 Gulf of Maine experiment discussed here at the same time and at the same location [11, 63, 69]; (3) roughly one hundred two-way transmission loss measurements made from calibrated targets with known scattering properties during the same 2006 Gulf of Maine experiment discussed here at the same time and at the same location [245]; and (4) thousands of one-way transmission loss measurements made during a past OAWRS experiment conducted in a similar continental shelf environment [14].

We find that the humpback whale song source levels measured from more than 4,000 song units recorded during the same 2006 Gulf of Maine experiment discussed here at the same time and at the same location approximately follow a Gaussian distribution and are in the range 155 to 205 dB re 1 μPa and 1 m [37] with a mean of 179.8 dB re 1 μPa and 1 m and a median of 179.4 dB re 1 μPa and 1 m. The high array gain [38, 106, 213–216] of our densely sampled, large aperture coherent OAWRS horizontal receiver array used here enables detection of whale songs two orders of magnitude lower in SNR than a single hydrophone, which has no array gain. Our measurements of humpback whale song source levels then have a high dynamic range and span the wide range of published source levels [30–34, 204],

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except for those in Ref. [35], which appear to be anomalously low compared to the rest of the literature as has been previously noted in Ref. [204]. The mean and median of our measured source levels match very well (within 0.6 dB) with the median of all published humpback whale song unit source levels of 180 dB re 1 μPa and 1 m [30–35]. Our song unit source levels are determined given our estimated whale positions and waveguide propagation modeling. Results in Figures A-5 and A-7 are computed using our measured whale positions and the median of all published humpback song source levels of 180 dB re 1 μPa and 1 m [30–35], which has negligible difference from our measured median and mean song source levels, for the range of measured humpback singing depths of 2 m to 25 m [34, 246]. Results in Figures A-5 and A-7 are insensitive to variations in whale position variations within the errors we report for our measured whale positions in Ref. [37], and so are insensitive to the whale position errors of our measurement system. Insensitivity here means the measured to modeled song occurrence match is within ± 18% as in Figure A-7.

The total humpback whale song occurrence in a day detectable by a sensor in varying wind speeds is

\[ T_{\text{song}} = \int_0^{T_{\text{day}}} S(t) \, dt, \]  

\hspace{1cm} (A.3)

where

\[ S(t) = \begin{cases} 
1 & \text{if } \hat{r}_d(v(t)) \geq \min(r_i(t)) \forall i \\
0 & \text{if } \hat{r}_d(v(t)) \min(r_i(t)) \forall i
\end{cases} \]

\( i = 1, 2, ..., N_w, \) \( N_w \) is the total number of singing whales, \( v(t) \) is the measured wind speed, \( r_i(t) \) is the range of the \( i^{th} \) singing humpback whale from the sensor at time \( t \), and \( T_{\text{day}} \) is the full diurnal time period of 24 hours. The detectable humpback whale song occurrence rate is then

\[ SR_{\text{detectable}} = \frac{T_{\text{song}}}{T_{\text{day}}}. \]  

\hspace{1cm} (A.4)
A.3 Humpback whale song occurrence is unaffected by sonar transmissions during Fall 2006 in the Gulf of Maine

Before and during OAWRS survey transmissions [11, 69], we measured a constant humpback whale song occurrence rate, as shown in Figure A-6, indicating no change of humpback song related to these transmissions over the entire survey area in the Gulf of Maine, a roughly 400-km diameter area, including Georges and Stellwagen Banks. Additionally, we find that the humpback whale song occurrence rate from Stellwagen Bank was constant before and during OAWRS survey transmissions, indicating no change of humpback song at Stellwagen Bank related to these transmissions. These direct measurements contradict the conclusions of Ref. [29].

To investigate this contradiction, we first follow the standard practice of checking for the bias [247, 248] of a statistical test by applying the test to control data where no stimulus is present to determine the false positive outcome rate [249–251]. We show that the statistical test in Ref. [29] false-positively finds whales react to sonar 98–100% of the time over a yearly period when no sonars are present using available annual humpback whale song occurrence data [28] from the same set of single sensors as those used at Stellwagen Bank [29]. For example, when the statistical test is applied to annual humpback whale song occurrence data published in Ref. [28], with 2006 as the test year and 2008 as the control year, it false-positively finds whales react to sonar: (1) 100% of the time over the year before the “during” period; and (2) 98% of the time over the year when the “during” period is excluded from the test, as described in Ref. [37]. Here the “during” period is defined as the 11-day period from September 26 to October 6 with active OAWRS survey transmissions, the “before” period is the 11-day period before the “during” period, and the “after” period is the 11-day period after the “during” period following the usage in Ref. [29]. When applied to the same humpback whale song occurrence data reported in Ref. [29] over the 33-day period from September 15 to October 17 for 2008 and 2009, with either of these two years as the test
year and the other as the control year, the statistical test false-positively finds humpback whales respond to sonar 100% of the time when no sonar is present, as described in [37], indicating a self-contradiction in the approach of Ref. [29]. No meaningful conclusions can be drawn from a statistical test with such high bias.

An explanation for the severe bias in the statistical test of Ref. [29] becomes evident upon inspection of the annual humpback whale song occurrence time series published in Ref. [28]. Very large natural variations within and across years are common in the humpback whale song occurrence time series when no sonars are present, as can be seen in Figure A-1. There are many periods lasting roughly weeks where high song occurrence episodes are found in one year but not in another, when no sonars are present (Figure A-1). For the majority of the time, greater than 57%, the difference in the song occurrence across years when no sonars are present exceeds that of the “during” period (Figure A-2), indicating that there is nothing unusual about such differences, which rather than “alterations” [29] are actually the norm. The statistical test used in Ref. [29] is overwhelmingly biased because it mistakes natural variations in humpback whale song occurrence 98-100% of the time for changes caused by sonar when no sonar is present, lacks any true positive confirmation and so lacks the statistical significance to draw the conclusions in Ref. [29].

The reported reducing change in humpback whale song occurrence, to zero [28, 29], occurred in the “before” period (Figure A-1) while the OAWRS vessels were inactive and docked on the other side of Cape Cod from Stellwagen Bank at the Woods Hole Oceanographic Institution due to severe winds days before OAWRS transmissions for active surveying began on September 26, 2006. This reduction then could not have been caused by OAWRS transmissions unless temporal causality was violated. Moreover, the annual humpback whale song occurrence time series are uncorrelated over 11-day periods across years, and the correlation coefficient obeys a random distribution peaking at zero correlation about which it is symmetric (Figure A-3), showing that correlation in trend between years is random and quantitatively expected to be zero with roughly as many negative correlations as positive ones. In fact, the correlation coefficient between the humpback whale song occurrence across years smoothly transitions from negative values in the “before” period, showing no similarity
Figure A-1: Reported humpback whale Stellwagen Bank song occurrence [28] shows large natural variations within and across years. Large natural variations in humpback whale song occurrence reported from single sensor detections at Stellwagen Bank [28] in time-dependent ambient noise within and across years are common in the absence of sonar. Line plots of reported single sensor daily humpback whale song occurrence at Stellwagen Bank in hours/day (A) for the entire year and (B) from September 15 to October 17, in 2006 and 2008 [28]. Many periods lasting roughly weeks where high song occurrence episodes are found in one year but not in another when no sonars are present are indicated by black arrows in (A). The reported reducing change in humpback whale song occurrence, to zero [28, 29], occurred in the “before” period while the OAWRS vessels were inactive and docked on the other side of Cape Cod from Stellwagen Bank, at the Woods Hole Oceanographic Institution, due to severe winds for days before OAWRS transmissions for active surveying began on September 26, 2006, as marked by the black arrow in (B). This shows that the analysis in Ref. [29] analysis violates temporal causality.
Figure A-2: Quantifying large differences in the reported humpback whale song occurrence at Stellwagen Bank [28] across years. Difference in humpback whale song occurrence reported from single sensor detections at Stellwagen Bank [28] in time-dependent ambient noise across years exceeds that of the "during" period most of the time when no sonars are present. (A) Difference in mean humpback whale song occurrence at Stellwagen Bank over respective 11-day periods with 1-day increment in 2006 and 2008, (B) histogram of difference in mean humpback song occurrence over 11-day periods between 2006 and 2008 when no sonar is present, i.e. excluding the "during" period from September 26 to October 6. Periods when the difference in means of respective 11-day periods is greater than (red dots) and less than (blue dots) that of the "during" period are indicated in (A). The difference in means fluctuates randomly throughout the year, exceeding the "during" period 57.8% of the time (most of the time) when no sonars are present, indicating that there is nothing unusual about such differences, which are actually the norm.
or relation in trend between years just before the 2006 OAWRS survey transmission period, to some of the highest positive correlations obtained between years in the "during" period (Figure A-3). This demonstrates high similarity and relation in trend between years during the 2006 OAWRS active survey transmission period.

Figure A-3: Reported annual humpback song occurrence at Stellwagen Bank [28] are uncorrelated between years over 11-day periods. Annual humpback whale song occurrence reported from single sensor detections at Stellwagen Bank [28] in time-dependent ambient noise are uncorrelated over 11-day periods across years. (A) Correlation coefficient between 2006 and 2008 humpback whale song occurrence time series over 11-day period with 1-day increment (B) histogram of the correlation coefficient in (A). The correlation coefficient of the annual humpback whale song occurrence time series over 11-day periods across years obeys a random distribution peaking at zero correlation about which it is symmetric, showing that correlation in trend between years is random and quantitatively expected to be zero with roughly as many negative correlations as positive ones. The correlation coefficient between the humpback whale song occurrence across years smoothly transitions from negative values in the "before" period, showing no similarity or relation in trend between years just before the 2006 OAWRS survey transmission period, to some of the highest positive correlations obtained between years in the "during" period. This demonstrates high similarity and relation in trend between years during the 2006 OAWRS active survey transmission period, which contradicts the results of the study in Ref. [29].
It is well known that wind speed variation can lead to severe detection range limitations in passive sensors, especially a single sensor that has zero array gain [38, 214, 216, 226]. Wind speeds varied from calm to near-gale conditions within a period of a few hours or days, many times over the 33-day period under examination, as is common for Fall in Stellwagen Bank [36]. These natural wind speed variations must have significantly changed the local wind-dependent noise level according to known physics [38, 39]. Since noise "can have a tremendous, if not a dominating, influence on the detection range of any sonar system" [225], the dramatic changes in wind speed at Stellwagen Bank must have led to dramatic changes in the detection range of single sensors deployed there. The range at which signals, in this case humpback whale songs, can no longer be detected because they become indistinguishable from ambient noise is the detection range from the sensor. Since ambient noise is wind speed dependent, so is the detection range (Figure A-4), and so is humpback whale song occurrence measured at that sensor if variations in wind speed cause the detection range to pass through the range of the singing humpback whales (Figure A-5). In this case even if a whale sang at a constant rate, song occurrence measured at the sensor (Figure A-7) would vary with local wind noise (Figure A-5).

Using the measured wind speeds at Stellwagen Bank [36], and the measured spatial distribution and constant rates of singing humpback whales determined by our large aperture array, we determine the song occurrence detectable by a single hydrophone at Stellwagen Bank, as shown in Figure A-7. We find it to match the song occurrence reported in Stellwagen Bank [29] in the "before" and "during" periods with high accuracy, within ±18% of the reported means, which is much less than the standard deviation of the humpback whale song occurrence reported at Stellwagen Bank [29]. This match shows that the variation in reported song occurrence from the "before" to "during" period is due to detection range limitations of the single sensor at Stellwagen Bank from wind-dependent ambient noise, and is not due to the song production rate, which we show to be constant. The constant song production and occurrence rates in the "before" and "during" periods measured by our large aperture array are unaffected by wind noise because the array gain was sufficiently high to make the detection range well beyond the range of the vocalizing whales for all wind conditions (Figure A-4). Our data shows no humpback whale vocal activity originating
Figure A-4: Wind-dependence of mean detection range for single sensor at Stellwagen Bank [29], and OAWRS receiver array. The green shaded areas indicate the overall vocalizing humpback whale call rate densities (number of calls/[(min) (50 nmi)^2]) determined between September 22 and October 6, 2006 by our large aperture receiver array towed along several tracks (black lines). The mean detection ranges for the single sensor at Stellwagen Bank are in blue and for the OAWRS receiver array are in red, where Stellwagen Bank is marked by yellow shaded regions. These detection ranges are determined by the methods described in Section A.2 given a humpback whale song unit source level of approximately 180 dB re 1 μPa and 1 m which is the median of all published humpback whale song source levels [30–35]. The error bars represent the spread in detection range due to typical humpback whale song source level variations (Section A.2). Under (A) low wind speed conditions vocalizing whales are within the mean detection area for a single Stellwagen Bank sensor but for (B) higher wind speeds most vocalizing whales are outside the mean detection area of the same sensor, which results in reduction of detectable whale song occurrence by the single sensor [29] at Stellwagen Bank.
Figure A-5: Wind-speed increase causes reduction in humpback song occurrence at Stellwagen Bank. Average wind speed increase from the “before” to the “during” period at Stellwagen Bank causes reduction in the percentage of time humpback whale songs are within mean detection range of a single Stellwagen Bank sensor. (A) Averaged wind speed measured at the NDBC buoy [36] closest to Stellwagen Bank over the “before,” “during,” and “after” 11-day periods; and (B) percentage of the time vocalizing humpback whales localized by our large aperture array are within the mean detection range of the single sensor [29] at Stellwagen Bank in the “before” and “during” periods, using waveguide propagation methods and whale song parameters described in Section A.2. Since the OAWRS experiment was conducted only up to October 6, 2006, the humpback whale source distribution in the “after” period was not measured and we do not investigate the percentage of time that humpback whales are within the mean detection range of the single sensor at Stellwagen Bank [29] for the “after” period. The triangles represent the mean wind speed and the solid ticks represent the standard deviation of the wind speed over the respective 11-day periods.
from Stellwagen Bank in either the "before" or "during" periods, but vocalizing humpback whales located near Georges Bank could be heard at Stellwagen Bank during low wind noise conditions (Figure A-4). In high wind noise, the single sensor mean detection range at Stellwagen Bank is too short to include the regions with measured singing humpback whales, but in low wind noise, it is large enough to include the regions with measured singing humpback whales as shown in Figure A-4, making the mean song detection rate at Stellwagen Bank higher in lower wind noise. Noise from near gale force winds in the last 3 days of the “before” period, for example, caused a significant drop in the detection range of the single sensor and the corresponding significant drop in the song occurrence rate at Stellwagen Bank [28] while the OAWRS vessels were inactive and docked at the Woods Hole Oceanographic Institution. Since the OAWRS experiment was conducted only up to October 6, 2006, the vocalizing humpback whale distribution in the “after” period was not measured and we do not investigate the song occurrence for that period.

Figure A-6: Humpback song occurrence rate is constant in the periods “before" and “during" OAWRS survey transmissions. The mean percentage of a diurnal cycle containing humpback whale song in the periods “before" and “during" OAWRS survey transmissions, as defined in Section A.3, remains constant, indicating the transmissions had no effect on humpback whale song over the entire passive 400-km diameter survey area of the Gulf of Maine including Stellwagen Bank.
Figure A-7: Humpback song occurrence detectable by single sensor matches reported humpback song occurrence at Stellwagen Bank [29]. Average humpback whale song occurrence detectable by a single hydrophone at Stellwagen Bank in time-dependent ambient noise in the “before” and the “during” periods matches the reported humpback whale song occurrence by Risch et al. [29]. Using the measured wind speeds at Stellwagen Bank [36] (Figure A-5), the measured spatial distribution of vocalizing humpback whales [37], and constant song production rates (Figure A-6) measured by our large-aperture array, the detectable song occurrence over the “before” and “during” period are found to be within ±18% of the reported means [29], much less than the standard deviations of reported song occurrence[29], using waveguide propagation methods and whale song parameters described in Section A.2. Before and during OAWRS survey transmissions, this figure shows that reported variations in song occurrence at Stellwagen Bank [29] are actually due to detection range changes caused by wind-dependent ambient noise, through well established physical processes [38, 39].

It has been previously shown that due to collapse of the herring stock at Stellwagen Bank, humpback whale populations drastically decline at Stellwagen Bank during the herring spawning period and correspondingly increase at other locations where spawning populations are large [223]. Moreover, in the Fall of 2006, herring populations were negligible in the Massachusetts Bay and Cape Cod area, including Stellwagen Bank [222], but in contrast were decadally high in the Georges Bank region [221], consistent with the theory that humpback whales migrate to locations with large spawning herring aggregations [223]. Indeed, it has been previously shown by OAWRS in Ref. [11] and by annual NEFSC acoustic echosounding
and trawl surveys in Refs. [252] and [253] that this peak annual herring spawning period occurred from the last week of September to the first week of October 2006 on Georges Bank. Based on the results of Ref. [223], it should then be expected that the Stellwagen Bank humpback whale population would be low at this time and the population at Georges Bank would be high, as has been confirmed in Ref. [37] for vocalizing humpback whales.

It is recommended by the National Academy of Sciences (NAS) that “A comprehensive noise impact assessment would include additional specific data regarding both sound levels and sources throughout the area for which impacts are being assessed [254].” Such an impact assessment should include “all aspects of the acoustic environment” [255] to avoid the problem another impact assessment had of being evaluated as “misrepresentative of the existing soundscape [254].” Here the soundscape of anthropogenic noise sources at Stellwagen Bank, from highest to lowest intensity or loudest to most quiet is delineated in Tables A.1 and A.2, following these NAS recommendations, where it is seen that the reported OAWRS transmissions fell at the quietest end of the noise spectrum when audible. Shipping traffic, on the other hand, contributes most to the anthropogenic component of mean acoustic intensity at Stellwagen Bank by many orders of magnitude. Most anthropogenic sources of underwater noise listed in Tables A.1 and A.2 continuously operate [256, 257] over a wide range of frequencies audible to whales, i.e. tens to hundreds of Hertz [38, 225, 257, 258], and result in received levels that may exceed the currently recommended NOAA guideline of 120 dB re 1 μPa received level [259–263] in water for continuous noise [108] for a range of whale distances (Table A.1). Even the maximum OAWRS received sound pressure level reported at Stellwagen Bank [29] is orders of magnitude lower than the current 160 dB NOAA guideline for short duration signals such as the OAWRS 1-2 seconds duration pulse, and significantly lower than the 120 dB guideline for even continuous sources [108] which OAWRS is not. The maximum received acoustic intensities of OAWRS signals reported at Stellwagen Bank [29] are the same as those of a quiet wooded forest or a quiet room with no conversation [264], whereas the acoustic intensities received at Stellwagen Bank from shipping traffic are often the same as those of a busy roadway or a busy airport runway [217, 264].
Table A.1: Typical anthropogenic noise sources at Stellwagen Bank.

<table>
<thead>
<tr>
<th>Continuous anthropogenic noise source</th>
<th>Source level in dB re 1 µPa and 1 m</th>
<th>Frequency in Hz</th>
<th>Source range in km for received level above 120 ( a ) dB re 1 µPa</th>
<th>Source range in km for received level between 88-110 ( b ) dB re 1 µPa</th>
<th>Acoustic intensity in Watts/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cruise ship</td>
<td>219 [109]</td>
<td>10 to &gt;1,000</td>
<td>&lt;100</td>
<td>160 to &gt;200</td>
<td>5,000</td>
</tr>
<tr>
<td>Cargo vessel</td>
<td>192 [38, 110]</td>
<td>10 to &gt;1,000</td>
<td>&lt;10</td>
<td>30-200</td>
<td>10</td>
</tr>
<tr>
<td>Research vessel</td>
<td>166-195 [109]</td>
<td>40 to &gt;1,000</td>
<td>&lt;6</td>
<td>2-130</td>
<td>0.025-20</td>
</tr>
<tr>
<td>Outboard motor boat</td>
<td>176 [258, 266]</td>
<td>100 to &gt;1,000</td>
<td>&lt;2</td>
<td>3-20</td>
<td>0.25</td>
</tr>
<tr>
<td>Whale watching boat</td>
<td>169 [111]</td>
<td>100 to &gt;1,000</td>
<td>&lt;1</td>
<td>3-25</td>
<td>0.05</td>
</tr>
</tbody>
</table>

\( a \) Recommended received pressure level in the NOAA guideline for continuous-type sources [108]. \( b \) Range of received pressure level at Stellwagen Bank single sensor of OAWRS impulsive signal [29], of roughly 1-2 seconds duration and at least 75 seconds spacing between impulses. Source ranges are determined at the frequencies with maximum humpback whale vocalization energy, using the waveguide propagation methods described in Section A.2. Humpback whale vocalizations are known to have source levels in the range of 175 to 188 dB re 1 µPa and 1 m [30–32, 204], and have been reported to go up to 203 dB re 1 µPa and 1 m [269]. All data shown in the table is for sources and measurements in water where \( L_{s,water} = L_w + 171 \) based on the sound speed and density of water, \( L_w \) is the power level in dB re 1 Watt, and \( L_{s,water} \) is the source level in dB re 1µPa and 1 m. Underwater noise from a typical low flying jet airplane [217] can lead to underwater sound pressure levels exceeding 120 dB re 1µPa in water at ranges less than 5 kilometers.
Table A.2: Received mean intensity of typical anthropogenic noise sources at Stellwagen Bank.

<table>
<thead>
<tr>
<th>Continuous anthropogenic noise source</th>
<th>Received level in water in dB re 1 μPa (or corresponding mean intensity in Watts/m²) 500 m away from an anthropogenic noise source over a minute or longer</th>
<th>How many decibels higher (or times greater) the mean intensity of the given anthropogenic noise source over a minute or longer at 500 m is than that reported for OAWRS at Stellwagen Bank [29]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cruise ship</td>
<td>177 (0.33)</td>
<td>85 (300,000,000)</td>
</tr>
<tr>
<td>Cargo vessel</td>
<td>147 (0.00033)</td>
<td>55 (300,000)</td>
</tr>
<tr>
<td>Research vessel</td>
<td>121-144 (0.0000083-0.00017)</td>
<td>29-52 (750-150,000)</td>
</tr>
<tr>
<td>Outboard motor boat</td>
<td>131 (0.0000083)</td>
<td>39 (7,500)</td>
</tr>
<tr>
<td>Whale watching boat</td>
<td>124 (0.0000017)</td>
<td>32 (1,500)</td>
</tr>
</tbody>
</table>

*Whale watching vessels [270] are allowed to approach humpback whales at ranges much less than 500 m according to NOAA Whalewatching Guidelines [271].
A.4 Conclusions

Before and during OAWRS survey transmissions, we measured constant humpback whale song occurrence and production rates over our entire survey area roughly 400-km in diameter covering most of the Gulf of Maine, including Stellwagen Bank, indicating the transmissions had no effect on humpback whale song production rate. Using annual humpback whale song occurrence reported from single sensor detections at Stellwagen Bank [28] in time dependent ambient noise, we show the statistical test in Ref. [29] for assessing the response of humpback whales to sonar transmission false positively finds humpback whales respond to sonar 98-100% of the time when no sonars are present. With this and the lack of any true positive confirmation for the statistical approach in Ref. [29], the analysis lacks the statistical significance to draw the conclusions in Ref. [29]. The statistical test in Ref. [29] mistakes natural variations in whale song reception, from such factors as natural variations in whale distributions [272], singing behavior [196, 197], and ambient noise, for changes caused by sonar 98-100% of the time when no sonar is present. Before and during OAWRS survey transmissions, we find that the variations in song occurrence at Stellwagen Bank reported at Stellwagen Bank [29] are consistent with the natural phenomena of detection range fluctuations caused by wind-dependent ambient noise, through well established physical processes [38, 39]. Misinterpretation of natural phenomenon from flawed analytic methods such as biased testing and neglect of physical laws can have seriously negative consequences [273–277].

A.5 Author Contributions

This chapter comprises the work appearing in Ref. [37] co-authored by Zheng Gong, Ankita D. Jain, Duong Tran, Dong Hoon Yi, Fan Wu, Alexander Zorn, Purnima Ratilal and Nicholas C. Makris. The text was primarily written by NCM. Work on detectable humpback song occurrence and wind-noise estimation was primarily done by ADJ, DHY and NCM. Work on statistical test in Ref. [29] and humpback whale time series analysis was primarily done by DHY, ADJ, ZG and NCM. Work on humpback whale localization, whale call characterization and song source level estimation was primarily done by ZG, DT, FW, AZ, PR and NCM.
Work on humpback whale call - herring areal population density correlation was primarily done by ZG, ADJ, DHY, PR, and NCM.
Appendix B

Low frequency target strength modeling

In the range of OAWRS frequencies spanning few hundred to few thousand Hertz, the fish swimballer acts as a compact scatterer and radiates acoustic waves omnidirectionally. In this respect, a model for acoustic scattering from the typically spheroidal shaped fish swimbladders was developed by Love [1] that has shown to provide accurate estimates of swimbladder resonant scattering [11, 40, 69, 77].

Fish swimbladder target strength (TS) at low frequencies is given by

\[ TS = 10 \log_{10} \left( \frac{\Sigma}{4\pi} \right) \]  \hspace{1cm} (B.1)

and the total scattering cross section \( \Sigma \) is directly proportional to the square magnitude of the fish scatter function \( S(f) \) and the acoustic wave number via

\[ \Sigma = 4\pi \left| \frac{S(f)}{k} \right|^2 \]  \hspace{1cm} (B.2)

which depends on swimbladder shape and material properties of the surrounding fish. According to Love’s model [1], a US Navy standard, the backscattering cross section, related to the total scattering cross section by \( \Sigma_{bs} = \Sigma/4\pi \), is given by

\[ \Sigma_{bs} = \frac{r^2}{f^2 \eta^{-2} + \left( \frac{r^2}{f^2} - 1 \right)^2} \]  \hspace{1cm} (B.3)

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where \( r \) is the equivalent swimbladder radius (m), \( f \) is the insonifying frequency (Hz), \( f_0 \) is the swimbladder’s resonance frequency (Hz), and \( \eta \) is a dimensionless damping factor. For swimbladders that can be approximated as prolate spheroids, the resonance frequency is given by

\[
f_0 = \frac{1}{2\pi r} \sqrt{\frac{3\gamma P}{d_f}}
\]  

(B.4)

where \( \kappa \) is the dimensionless swimbladder correction factor that Weston [278] obtained using Strasberg’s solution for scattering from an oblate spheroid [279], \( \gamma = 1.4 \) is the ratio of the specific heats of air, \( P \) is the ambient pressure (Pa), and \( d_f \) is the fish flesh density (kg/m\(^3\)) (e.g. for Atlantic herring \( d_f = 1071 \) kg/m\(^3\); [280]). The damping factor \( \eta \) is obtained from

\[
\frac{1}{\eta} = \frac{2\pi f_0^2 f}{f_0 c} + \frac{\xi}{\pi r^2 f_0 d_f}
\]

(B.5)

where \( c \) is the speed of sound in water (m/s) and \( \xi \) is the viscosity of the fish flesh (Pa s) (e.g. empirical value for Atlantic herring: \( \xi = 50 \) Pa s; [280]).

The swimbladder correction term [278] is

\[
\kappa = \frac{\sqrt{2}(1 - \epsilon^2)^{1/4}}{\epsilon^{1/3}} \left\{ \ln \left[ \frac{1 + \sqrt{1 - \epsilon^2}}{1 - \sqrt{1 - \epsilon^2}} \right] \right\}^{-1/2}
\]

(B.6)

where the eccentricity \( \epsilon \) is the ratio of the minor to major axis of a prolate spheroid.

The volume of the swimbladder is assumed to follow Boyle’s Law so that

\[
P_0 V_0 = P_z V_z
\]

(B.7)

where \((P_0, V_0)\) are the ambient pressure and volume at zero depth, and \((P_z, V_z)\) are the pressure and volume at any depth \( z \). For a prolate spheroid, volume is related to the semimajor axis \( a \) and semi-minor axis \( b \) by

\[
V(z) = \frac{4}{3} \pi a^2(z) b
\]

(B.8)

Fish TS is then modeled by assuming the prolate spheroid swimbladder has a major axis
that is a constant percentage of total fish length, usually 15 to 33% [280, 281]. Swimbladder volume is assumed to only change through variation in minor axis [282–284] due to physical constraints in fish anatomy. Given fish length and depth distribution, target strength can be parameterized by a single parameter, swimbladder volume or equivalently neutral buoyancy depth.
Appendix C

Analytical Formulation of Rayleigh–Born Volume Scattering from Seafloor

We consider an ocean waveguide consisting of a water layer, located between an air half-space above and a bottom half-space below (Figure D-1). We let \( (x, y, z) \) be the coordinates of a Cartesian coordinate system with its origin at the air-water interface and the positive \( z \)-axis pointing towards increasing depth in the water column and the seafloor. We place the source at \( r_0 = (x_0, y_0, z_0) \), the receiver at \( r = (x, y, z) \) and the center of the inhomogeneity at \( r_t = (x_t, y_t, z_t) \).

To derive the broadband scattered field from random volume inhomogeneities, we use the Rayleigh–Born approach [79–81, 285]. The inhomogeneous Helmholtz equation for a single-frequency, time-independent acoustic field, \( \Phi_t(r_t, f) \), in the presence of volume inhomogeneities is given as:

\[
\nabla^2 \Phi_t(r_t, f) + k^2 \Phi_t(r_t, f) = -k^2 \Gamma_\kappa(r_t) \Phi_t(r_t, f) - \nabla \cdot [\Gamma_d(r_t) \nabla \Phi_t(r_t, f)]
\]

where \( \Gamma_\kappa \) is the fractional change in medium compressibility:

\[
\Gamma_\kappa(r_t) = \frac{\kappa(r_t) - \bar{\kappa}}{\bar{\kappa}}
\]
\( \Gamma_d(t) = \frac{d(r_t) - \bar{d}}{d(r_t)} \)  

\( \bar{\kappa} \) and \( \bar{d} \) are the mean compressibility and density in the region, respectively \([80, 81]\), \( f \) is the frequency, \( \omega = 2\pi f \) is the angular frequency, \( c \) is the sound speed and \( k = \omega/c \) is the acoustic wave number.

Applying Green’s theorem \([81]\) to Equation (C.1), we obtain the scattered field, \( \Phi_S(r_s | r, r_0, f) \), from inhomogeneities within a volume, \( V_s \), centered on \( r_s \). This region extends along the entire seafloor depth, over the sonar resolution angle in the azimuth and over multiple sonar resolution cells in the range. The scattered field is then given as:

\[
\Phi_S(r_s | r, r_0, f) = \iiint_{V_s} [k^2 \Gamma(\kappa(r_t)) \Phi_t(r_t, f) G(r | r_t, f)
\]

\[
+ \Gamma_d(r_t) \nabla \Phi_t(r_t, f) \cdot \nabla G(r | r_t, f)] dV_t
\]

Green function \( G(r | r_t, f) \) describes the propagation from the location of the inhomogeneity to the receiver, and \( \Phi_t(r_t, f) \) is the total field at the location of the inhomogeneity. The total field can be expressed as the sum of the incident field, \( \Phi_i(r_t | r_0, f) \), and the scattered field, \( \Phi_S(r_t, f) \) \([81]\):

\[
\Phi_t(r_t, f) = \Phi_i(r_t | r_0, f) + \Phi_S(r_t, f)
\]

We normalize the source level by letting \( \Phi_i(r_t | r_0, f) = (4\pi)G(r_t | r_0, f) \). For small fluctuations in density and compressibility, we approximate the total field at the location of the inhomogeneity by the incident field using the Born approximation \([81]\), i.e., the total field, \( \Phi_t \), can be approximated by the incident field, \( \Phi_i \), in Equation (C.3). Then, the scattered field at the receiver is:
We derive the scattered field for a source that transmits a broadband waveform, \( q(t) \), with Fourier transform \( Q(f) \) and bandwidth \( B \) around the center frequency, \( f_c \), by applying the matched filter [82] to Equation (C.5). Using Fourier synthesis, the time-domain matched filtered scattered field is:

\[
\Phi_S(r_s|r_0, f) = (4\pi) \iiint_{V_S} |k^2\Gamma_\kappa(r_t)G(r_t|r_0, f)G(r|r_t, f)| \\
+ \Gamma_d(r_t)\nabla G(r_t|r_0, f) \cdot \nabla G(r|r_t, f)] dV_t
\]

\[
\phi_S(r_s|r_0, t) = (4\pi) \int_{f_c-B/2}^{f_c+B/2} \iiint_{V_S} |k^2\Gamma_\kappa(r_t)G(r_t|r_0, f)G(r|r_t, f) | \\
+ \Gamma_d(r_t)\nabla G(r_t|r_0, f) \cdot \nabla G(r|r_t, f)] \\
\times \frac{1}{\sqrt{E_0}} |Q(f)|^2 e^{-i2\pi f(t-t_M)} dV_t df
\]

where \( t_M \) represents the time delay of the matched filter and \( E_0 = \int |Q(f)|^2 df \) is the source energy.

### C.1 Full Analytical Expressions for the Total Moments of the Matched Filtered Scattered Field

Here, we derive full analytical expressions for the total moments of the matched filtered scattered field in terms of the statistical moments of fractional changes in compressibility and density and in terms of Green functions and their gradients in a randomly fluctuating ocean waveguide. We assume the bottom inhomogeneities to vary randomly in space, following a stationary random process within the region, \( V_5 \), considered. In addition, we assume the fluctuations in the bottom properties to be independent from the fluctuations in the ocean waveguide. Therefore, we can treat the random variables, \( \Gamma_\kappa \) and \( \Gamma_d \), as independent from the medium’s Green function [80]. Then, following Equation (C.6), the mean matched filtered
scattered field can be expressed as:

$$\langle \phi_S(r_s|r, r_0, t) \rangle = (4\pi) \int_{f_c - B/2}^{f_c + B/2} \int_{f_c - B/2}^{f_c + B/2} \int_V \langle k^2 \langle \Gamma_\kappa(r_t) \rangle \langle G(r_t|r_0, f)G(r|r_t, f) \rangle \rangle \rangle \langle G(r_s|r_0, f)G(r|r_t, f) \rangle \rangle \langle G^*(r'_t|r_0, f')G^*(r|r'_t, f') \rangle \rangle$$

\( + \langle \Gamma_d(r_t) \rangle \langle \nabla G(r_t|r_0, f) \cdot \nabla G(r|r_t, f) \rangle \rangle \times \frac{1}{\sqrt{E_0}} |Q(f)|^2 e^{-i2\pi f(t-t_M)} \ dV_t \ df \)

The magnitude of the square of the mean matched filtered scattered field, then, is:

$$|\langle \phi_S(r_s|r, r_0, t) \rangle|^2 = (4\pi)^2 \int_{f_c - B/2}^{f_c + B/2} \int_{f_c - B/2}^{f_c + B/2} \int_V \langle k^2 \langle \Gamma_\kappa(r_t) \rangle \langle G(r_t|r_0, f)G(r|r_t, f) \rangle \rangle \langle G^*(r'_t|r_0, f')G^*(r|r'_t, f') \rangle \rangle$$

\( + \langle \Gamma_d(r_t) \rangle \langle \nabla G(r_t|r_0, f) \cdot \nabla G(r|r_t, f) \rangle \rangle \times \frac{1}{E_0} |Q(f)|^2 |Q(f')|^2 e^{-i2\pi(f-f')(t-t_M)} \ dV_t \ dV'_t \ df \ df' \)

and the second moment of the scattered field is:

$$|\langle \phi_S(r_s|r, r_0, t) \rangle|^2 = \langle \phi_S(r_s|r, r_0, t_M)\phi_S^*(r_s|r, r_0, t_M) \rangle$$

\( = (4\pi) \int_{f_c - B/2}^{f_c + B/2} \int_V \langle k^2 \langle \Gamma_\kappa(r_t) \rangle \langle G(r_t|r_0, f)G(r|r_t, f) \rangle \rangle \langle G^*(r'_t|r_0, f')G^*(r|r'_t, f') \rangle \rangle \times \frac{1}{\sqrt{E_0}} |Q(f)|^2 e^{-i2\pi f(t-t_M)} \ dV_t \ df \)

\( + \langle \Gamma_d(r_t) \rangle \langle \nabla G(r_t|r_0, f) \cdot \nabla G(r|r_t, f) \rangle \rangle \times \frac{1}{\sqrt{E_0}} |Q(f)|^2 e^{-i2\pi f(t-t_M)} \ dV_t' \ df' \)

which can be written as:
To model the statistics of the density and compressibility variations, we use a delta correlation function and assume the parameters to be correlated in all three dimensions within a coherence volume [80]; let:

$$\langle \Gamma_\kappa(r_t)\Gamma_\kappa(r'_t) \rangle = V_c(r_S,z_t)(\langle \Gamma_\kappa^2(r_t) \rangle - |\langle \Gamma_\kappa(r_t) \rangle|^2)\delta(r_t-r'_t) + \langle \Gamma_\kappa(r_t) \rangle \langle \Gamma_\kappa(r'_t) \rangle$$

Similarly:

$$\langle \Gamma_d(r_t)\Gamma_d(r'_t) \rangle = V_c(r_S,z_t)\text{Var}(\Gamma_d(r_t))\delta(r_t-r'_t) + \langle \Gamma_d(r_t) \rangle \langle \Gamma_d(r'_t) \rangle$$

$$\langle \Gamma_\kappa(r_t)\Gamma_d(r'_t) \rangle = V_c(r_S,z_t)\text{Covar}(\Gamma_\kappa(r_t),\Gamma_d(r_t))\delta(r_t-r'_t) + \langle \Gamma_\kappa(r_t) \rangle \langle \Gamma_d(r'_t) \rangle$$

$$\langle \Gamma_\kappa(r'_t)\Gamma_d(r_t) \rangle = V_c(r_S,z_t)\text{Covar}(\Gamma_\kappa(r_t),\Gamma_d(r_t))\delta(r_t-r'_t) + \langle \Gamma_\kappa(r'_t) \rangle \langle \Gamma_d(r_t) \rangle$$
Then, Equation (C.10) becomes:

\[
\langle |\phi_S(r_s|r_0,t)|^2 \rangle = (4\pi)^2 \int_{-B/2}^{B/2} \int_{-B/2}^{B/2} \int_{V_S} \int_{V_S} \int_{V_S} V_c(r_s,z_t) \times \left[ k^2 k'^2 \text{Var}(\Gamma_\alpha) \delta(r_t - r'_t) \langle G(r_t | r_0, f) G(r_t, f) G^*(r'_t | r_0, f') G^*(r'_t, f') \rangle \\
+ \text{Var}(\Gamma_d) \delta(r_t - r'_t) \langle \nabla G(r_t | r_0, f) \cdot \nabla G(r_t, f) \times \nabla G^*(r'_t | r_0, f') \cdot \nabla G^*(r'_t, f') \rangle \\
+ k^2 \text{Covar}(\Gamma_\alpha, \Gamma_d) \delta(r_t - r'_t) \langle G(r_t | r_0, f) G(r_t, f) \nabla G^*(r'_t | r_0, f') \nabla G^*(r'_t, f') \rangle \right] \\
\times 1 \frac{1}{E_0} |Q(f)|^2 |Q(f')|^2 e^{-i2\pi(f-f')(t-t_M)} \, dV_t \, dV'_t \, df \, df'
\]

After integrating one of the delta functions over the volume, \(V_S\), in the first term of Equation (C.15), the full expression for the matched filtered total second moment is:

\[
\langle |\phi_S(r_s|r_0,t)|^2 \rangle = (4\pi)^2 \int_{-B/2}^{B/2} \int_{-B/2}^{B/2} \int_{V_S} \int_{V_S} \int_{V_S} V_c(r_s,z_t) \times \left[ k^2 k'^2 \text{Var}(\Gamma_\alpha) \delta(r_t - r'_t) \langle G(r_t | r_0, f) G(r_t, f) G^*(r'_t | r_0, f') G^*(r'_t, f') \rangle \\
+ \text{Var}(\Gamma_d) \delta(r_t - r'_t) \langle \nabla G(r_t | r_0, f) \cdot \nabla G(r_t, f) \times \nabla G^*(r'_t | r_0, f') \cdot \nabla G^*(r'_t, f') \rangle \\
+ k^2 \text{Covar}(\Gamma_\alpha, \Gamma_d) \delta(r_t - r'_t) \langle G(r_t | r_0, f) G(r_t, f) \nabla G^*(r'_t | r_0, f') \nabla G^*(r'_t, f') \rangle \right] \\
\times 1 \frac{1}{E_0} |Q(f)|^2 |Q(f')|^2 e^{-i2\pi(f-f')(t-t_M)} \, dV_t \, dV'_t \, df \, df'
\]
The total variance can be expressed in terms of the total second moment and the squared of the mean field as:

$$\text{Var}(\phi_S(r_s|r_0,t)) = \langle |\phi_S(r_s|r_0,t)|^2 \rangle - \langle \phi_S(r_s|r_0,t)^2 \rangle$$ (C.17a)

which can be further expanded as:

$$\text{Var}(\phi_S(r_s|r_0,t)) = (4\pi)^2 \int_{f_e-B/2}^{f_e+B/2} \int_{f_e-B/2}^{f_e+B/2} \int_{V_s}^{V_s} V_c(r_s,z_t) \times \left[ k^2 \text{Var}(\Gamma_\kappa) \langle G(r_t|r_0,f)G(r_t,f)G^*(r_t'|r_0,f')G^*(r_t',f') \rangle 
+ \text{Var}(\Gamma_d) \langle \nabla G(r_t|r_0,f) \cdot \nabla G(r_t,f) \rangle \times \nabla G^*(r_t'|r_0,f') \cdot \nabla G^*(r_t',f') \rangle 
+ k^2 \text{Covar}(\Gamma_\kappa, \Gamma_d) \langle G(r_t|r_0,f)G(r_t',f') \nabla G^*(r_t|r_0,f) \cdot \nabla G^*(r_t',f') \rangle 
+ k^2 \text{Covar}(\Gamma_\kappa, \Gamma_d) \langle G^*(r_t|r_0,f')G^*(r_t',f') \nabla G(r_t|r_0,f) \cdot \nabla G(r_t',f') \rangle 
\times \frac{1}{E_0} |Q(f)|^2 |Q(f')|^2 e^{-i2\pi(f-f')(t-t_M)} dV_t df df' + (4\pi)^2 \int_{f_e-B/2}^{f_e+B/2} \int_{f_e-B/2}^{f_e+B/2} \int_{V_s}^{V_s} V_c(r_s,z_t) \times \left[ k^2 \text{Covar}(\Gamma_\kappa(r_t)) \langle \Gamma_\kappa(r_t') \rangle \langle G(r_t|r_0,f)G(r_t,f)G^*(r_t'|r_0,f')G^*(r_t',f') \rangle \right]$$
\[ + \langle \Gamma_d(r_t) \rangle \langle \Gamma_d(r'_t) \rangle \langle \nabla G(r_t|r_0,f) \cdot \nabla G(r|r_t,f) \rangle \times \nabla G^*(r'_t|r_0,f') \cdot \nabla G^*(r|r'_t,f') \rangle \]
\[ + k^2 \langle \Gamma_x(r_t) \rangle \langle \Gamma_d(r'_t) \rangle \langle \nabla G(r_t|r_0,f) G(r|r_t,f) \nabla G^*(r'_t|r_0,f') \cdot \nabla G^*(r|r'_t,f') \rangle \]
\[ + k^2 \langle \Gamma_x(r'_t) \rangle \langle \Gamma_d(r'_t) \rangle \langle \nabla G^*(r'_t|r_0,f') G^*(r|r'_t,f') \nabla G(r_t|r_0,f) \cdot \nabla G(r|r_t,f) \rangle \]
\[ \times \frac{1}{E_0} |Q(f)|^2 |Q(f')|^2 e^{-i 2 \pi (f-f')(t-t_m)} \, dV_t \, dV'_t \, df \, df' \]

\[- (4 \pi)^2 \int_{f_c-B/2}^{f_c+B/2} \int_{f_c-B/2}^{f_c+B/2} \int_V s \int_V s \int_V s \]
\[ \times \left[ k^2 k^2 \langle \Gamma_x(r_t) \rangle \langle \Gamma_x(r'_t) \rangle \langle \nabla G(r_t|r_0,f) \cdot \nabla G(r|r_t,f) \rangle \langle \nabla G^*(r'_t|r_0,f') \cdot \nabla G^*(r|r'_t,f') \rangle \right. \]
\[ \times \langle \Gamma_d(r_t) \rangle \langle \Gamma_d(r'_t) \rangle \langle \nabla G(r_t|r_0,f) \cdot \nabla G(r|r_t,f) \rangle \langle \nabla G^*(r'_t|r_0,f') \cdot \nabla G^*(r|r'_t,f') \rangle \]
\[ + k^2 \langle \Gamma_x(r_t) \rangle \langle \Gamma_d(r'_t) \rangle \langle \nabla G(r_t|r_0,f) G(r|r_t,f) \nabla G^*(r'_t|r_0,f') \cdot \nabla G^*(r|r'_t,f') \rangle \]
\[ + k^2 \langle \Gamma_x(r'_t) \rangle \langle \Gamma_d(r'_t) \rangle \langle \nabla G^*(r'_t|r_0,f') G(r|r'_t,f') \nabla G(r_t|r_0,f) \cdot \nabla G(r|r_t,f) \rangle \]
\[ \times \frac{1}{E_0} |Q(f)|^2 |Q(f')|^2 e^{-i 2 \pi (f-f')(t-t_m)} \, dV_t \, dV'_t \, df \, df' \]

\[ = \text{Term}_{\text{MF}}^{\text{Var}(\Gamma_x), \text{Var}(\Gamma_d), \text{Covar}(\Gamma_x, \Gamma_d)} + \text{Term}_{\text{MF}}^{\langle \Gamma_x, \Gamma_d \rangle} \]

Although Equation (C.17b) represents the full expression for the matched filtered total variance, we show in Section D that the last integral term of the variance Equation (C.17b) is negligible, so that the variance can be approximated by the first integral term as:

\[ \text{Var}(\phi_S(r_s|\mathbf{r}, r_0, t)) \quad (C.17c) \]

\[ = (4 \pi)^2 \int_{f_c-B/2}^{f_c+B/2} \int_{f_c-B/2}^{f_c+B/2} \int_V s \int_V s \int_V s \]
\[ \times \left[ k^2 k^2 \text{Var}(\Gamma_x)(G(r_t|r_0,f) G(r|r_t,f) G^*(r'_t|r_0,f') G^*(r|r'_t,f')) \right. \]
\[ + \text{Var}(\Gamma_d) \langle \nabla G(r_t|r_0,f) \cdot \nabla G(r|r_t,f) \rangle \times \nabla G^*(r'_t|r_0,f') \cdot \nabla G^*(r|r'_t,f') \rangle \]
\[ + k^2 \text{Covar}(\Gamma_x, \Gamma_d) \langle G(r_t|r_0,f) G(r|r_t,f) \nabla G^*(r'_t|r_0,f') \cdot \nabla G^*(r|r'_t,f') \rangle \]
\[ + k^2 \text{Covar}(\Gamma_x, \Gamma_d) \langle G^*(r'_t|r_0,f') G^*(r|r'_t,f') \nabla G(r_t|r_0,f) \cdot \nabla G(r|r_t,f) \rangle \]
\[ \times \frac{1}{E_0} |Q(f)|^2 |Q(f')|^2 e^{-i 2 \pi (f-f')(t-t_m)} \, dV_t \, df \, df' \]

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C.2 Time Harmonic Approximation to the Matched Filtered Scattered Intensity

In this section, we present a computationally efficient approximation to the matched filtered scattered intensity derived in Appendix C.1. Starting with Equation (C.5) for the time harmonic scattered field, where $V_s$ now represents the resolution cell of the imaging system, we follow a procedure similar to the one used in Appendix C.1 and find that the time harmonic total variance is:

$$\text{Var}(\Phi_S(r_s|r, r_0, f)) = (4\pi)^2 \iiint_{V_s} V_c(r_s, z_t)$$

$$\times [k^4 \text{Var}(\Gamma_\alpha) \langle |G(r_t|r_0, f)|^2 |G(r_t, f)|^2 \rangle$$

$$+ \text{Var}(\Gamma_\delta) \langle |\nabla G(r_t|r_0, f)| \cdot \nabla G(r_t, f)|^2 \rangle$$

$$+ k^2 \text{Covar}(\Gamma_\alpha, \Gamma_\delta) \{2\Re\{G(r_t|r_0, f)G(r_t, f)\nabla G^*(r_t|r_0, f) \cdot \nabla G^*(r_t, f)\}\} \, dV_t$$

$$+ (4\pi)^2 \iiint_{V_s} \iiint_{V_s} [k^4 \langle \Gamma_\alpha(r_t) \rangle \langle \Gamma_\alpha(r_t') \rangle \langle G(r_t|r_0, f)G(r_t, f)G^*(r_t'|r_0, f)G^*(r_t', f) \rangle$$

$$+ \langle \Gamma_\delta(r_t) \rangle \langle \Gamma_\delta(r_t') \rangle \langle \nabla G(r_t|r_0, f) \cdot \nabla G(r_t, f) \times \nabla G^*(r_t'|r_0, f) \cdot \nabla G^*(r_t', f) \rangle$$

$$+ k^2 \langle \Gamma_\alpha(r_t) \rangle \langle \Gamma_\delta(r_t') \rangle \langle G(r_t|r_0, f)G(r_t, f)\nabla G^*(r_t'|r_0, f) \cdot \nabla G^*(r_t', f) \rangle$$

$$+ k^2 \langle \Gamma_\alpha(r_t') \rangle \langle \Gamma_\delta(r_t) \rangle \langle G^*(r_t'|r_0, f)G^*(r_t', f)\nabla G(r_t|r_0, f) \cdot \nabla G(r_t, f) \rangle \, dV_t \, dV_t'$$

$$- (4\pi)^2 \iiint_{V_s} \iiint_{V_s} [k^4 \langle \Gamma_\alpha(r_t) \rangle \langle \Gamma_\alpha(r_t') \rangle \langle G(r_t|r_0, f)G(r_t, f)G^*(r_t'|r_0, f)G^*(r_t', f) \rangle$$

$$+ \langle \Gamma_\delta(r_t) \rangle \langle \Gamma_\delta(r_t') \rangle \langle \nabla G(r_t|r_0, f) \cdot \nabla G(r_t, f) \rangle \langle \nabla G^*(r_t'|r_0, f) \cdot \nabla G^*(r_t', f) \rangle$$

$$+ k^2 \langle \Gamma_\alpha(r_t) \rangle \langle \Gamma_\delta(r_t') \rangle \langle G(r_t|r_0, f)G(r_t, f)\nabla G^*(r_t'|r_0, f) \cdot \nabla G^*(r_t', f) \rangle$$

$$+ k^2 \langle \Gamma_\alpha(r_t') \rangle \langle \Gamma_\delta(r_t) \rangle \langle G^*(r_t'|r_0, f)G^*(r_t', f)\nabla G(r_t|r_0, f) \cdot \nabla G(r_t, f) \rangle \, dV_t \, dV_t'.$$

$$= \text{Term}_{TH}^{\text{Var}(\Gamma_\alpha, \text{Var}(\Gamma_\delta), \text{Covar}(\Gamma_\alpha, \Gamma_\delta))} + \text{Term}_{TH}^{\langle \Gamma_\alpha, \langle \Gamma_\delta \rangle \rangle}$$

In Section D, we show, using Monte Carlo simulations in a standard Pekeris waveguide, that the matched filtered scattered intensity derived in Equation (C.17c) can be approximated by the first term of the total time harmonic variance, also given by Galinde et al.,
\[ \begin{align*} \text{Var}(\Phi_S(r_s|r, r_0, f)) &= \text{Monopole}_{TH} + \text{Dipole}_{TH} + \text{Cross}_{TH}, \tag{C.18c} \\
\text{where,} \\
\text{Monopole}_{TH} &= (4\pi)^2 \iiint_{V_S} V_c(r_s, z_t) k^4 \text{Var}(\Gamma_\kappa) \langle |G(r_t|r_0, f_c)|^2 |G(r_t|r_t, f_c)|^2 \rangle dV_t, \\
\text{Dipole}_{TH} &= (4\pi)^2 \iiint_{V_S} V_c(r_s, z_t) \text{Var}(\Gamma_d) \langle |\nabla G(r_t|r_0, f_c) \cdot \nabla G(r_t|r_t, f_c)|^2 \rangle dV_t, \\
\text{Cross}_{TH} &= (4\pi)^2 \iiint_{V_S} V_c(r_s, z_t) k^2 \text{Covar}(\Gamma_\kappa, \Gamma_d) \\
&\quad \langle 2 \Re \{G(r_t|r_0, f) G(r_t|r_t, f_c) \nabla G^*(r_t|r_0, f_c) \cdot \nabla G^*(r_t|r_t, f_c) \} \rangle \rangle dV_t \tag{C.18d} \end{align*} \]
Appendix D

Effective Estimation of Scattering from the Seafloor Field over Wide Areas

We provide expressions for the mean, variance and second moment of the matched filtered scattered field in Appendix C.1. We show that the total broadband seafloor scattered field can be approximated very well by the field at the center frequency of the source signal (Figure D-2) for a typical broadband OAWRS signal [11, 40] transmitted in a standard Pekeris waveguide [105] (Figure D-1). This significantly reduces the total computation time of the scattered field over ecosystem scales to a small fraction of the time required to estimate the full field scattered level using the broadband signal. This is especially useful for planning experiments, where actual oceanographic parameters, such as range-dependent sound speed structure, are different from those expected, and experiment parameters, such as source-receiver depth configurations, may need to be modified on-site to optimize detection over long ranges.

We find that the second moment of the broadband field (Equation (C.16)) has a dominant contribution from the variance of the broadband field (Equation (C.17b)), as shown in Figure D-2A. This is expected, because the mean field scattered from diffuse inhomogeneities vanishes in a fluctuating waveguide [83–86]. This variance can be further approximated by terms containing the second moments of seafloor properties (Equation (C.17c)), such as fractional changes in density and compressibility (Figure D-2B). This is because the mean fractional changes in density and compressibility of sandy sediments in the environments we
consider (Figure 2-9) are known to be small compared to their respective second moments [80]. The broadband variance terms that depend on second moments of seafloor properties can be further approximated by the corresponding terms evaluated at the center frequency (Equations (C.18a) and (C.18c)), as shown in Figure D-2C, when the signal bandwidth is small compared to the center frequency. In addition, we find that this approximation to the variance at the source center frequency can be further decomposed into three terms that are all proportional to each other (Figure D-2D): (a) a monopole scattering term that depends on the variance of fractional changes in seafloor compressibility; (b) a dipole scattering term that depends on the variance of fractional changes in seafloor density; and (c) a cross term that depends on the covariance of fractional changes in seafloor compressibility and density (Equation (C.18d)).

In order to account for random fluctuations in the ocean environment, we vary the sound speed profile with the range [14]. The sound speed profiles used for this environment are selected from the measured sound speed profiles during the 2003 OAWRS experiment in the New Jersey continental shelf [40], and the Green functions are computed using the parabolic equation model, RAM [91]. We consider a monostatic geometry with a single-element source and receiver. The transmitted waveform is a one second-long linear frequency modulated (LFM) pulse [11, 40]. The corresponding matched filtered range resolution, \( \Delta r \), is then \( \Delta r = c/2B \), where \( c \) is the reference sound speed and \( B \) is the source bandwidth. We use the statistics of fractional changes in density and compressibility as estimated by Galinde et al. [80] at the source center frequency of 415 Hz and a bandwidth 50 Hz for the New Jersey continental shelf to model the seafloor-scattered field level.
Figure D-1: (A) Geometry for the implementation of the theoretical formulation for the scattered field in a standard Pekeris waveguide of a depth of 100 m for a monostatic point source-receiver located at the mid-water column. The total moments of the scattered field are calculated for a sector of an ocean bottom or seabed patch, extending over range $R_t$, depth $Z_t$ and azimuth $\theta_t$, containing volume inhomogeneities. The scattered field from the patch then effectively corresponds to the scattered field level measured from a given direction if a receiver array with an angular beamwidth of $\theta_t$ is used instead [40]. The sound speed, density and attenuation in the water column and in the sand bottom are $c_w$, $\rho_w$, $\alpha_w$ and $c_b$, $\rho_b$, $\alpha_b$, respectively, and (B) sound speed profiles measured on the New Jersey continental shelf (gray) are used for the simulations. The solid black line and horizontal tick marks indicate the mean sound speed profile and the standard deviations, respectively [40].
Figure D-2: The modeled (A) total moments of the matched-filtered seafloor scattered field; (B) matched-filtered scattered field variance and its components; (C) range-averaged matched-filtered scattered field variance compared to the range-averaged variance at the center frequency or time-harmonic approximation; and (D) range-averaged variance term 
\[ \text{Term}_{\text{TH}}^{\text{TH}} \] compared to its three components, monopole, dipole and cross terms at the center frequency. The source is assumed to be a linear frequency modulated (LFM) pulse centered on 415 Hz and with a bandwidth of 50 Hz. Computations are for a seabed patch extending from 2 km to 20 km in the range, 3° in the azimuth and 10 m in depth, in a Pekeris sand waveguide, as shown in Figure D-1. The cross range resolution of 3° is the typical angular resolution of the OAWRS receiver array [11, 40], and the range resolution, \( \Delta r = c/2B \), is 15 m for sound speed \( c = 1,500 \) m/s and OAWRS bandwidth \( B = 50 \) Hz. The source and receiver are co-located at a depth of 50 m. Detailed derivations of the normalized broadband seafloor scattered field and its moments are given in Appendices C–C.1.
Appendix E

OAWRS Survey of Cod and Haddock: Examples

In this appendix, preliminary OAWRS images of cod in the Lofoten area near Andenes are shown. Throughout the experiment, multiple gain settings were used to identify and delineate shoals in OAWRS images. Examples of how altering gain settings helps OAWRS imagery of cod shoals are also shown here. Since the OAWRS images or sound pressure level maps shown here are not corrected for transmission loss, higher levels are measured at closer ranges. The high levels at close ranges do not necessarily correspond to fish distributions. So, transmission loss correction is needed to generate OAWRS scattering strength maps to identify fish hotspots. Since the OAWRS receiver array beam width is narrowest at broadside and widest at the endfire of the array, the images show good resolution near broadside but poor resolution with high scattered levels near the array endfire.

In typical continental shelf or shallow water environments where detection ranges are typically much greater than the water depth, there exists an inherent ambiguity in charting of OAWRS acoustic returns about the horizontal receiver array axis. So, acoustic returns from the left-half of the plane about the array axis overlap with those from the right-half of the plane. This ambiguity is removed by changing the array heading and identifying the real scatterer location as the one from which scattered returns do not change with change in array heading.
Figure E-1: One of the first few OAWRS images in the Lofoten cod spawning area near Andenes on March 5, 2014 at 18:29 UTC. Several schools spanning a few hundred meters in dimensions were observed within 10 km of R/V Knorr. The gain setting used in (b) is different from that used in (a) to enhance the levels of imaged cod schools.
Figure E-2: An OAWRS image showing cod shoals on the shallow bank on the east and deeper waters off the bank on the west on March 5, 2014 at 23:09 UTC. The gain setting used in (b) is different from that used in (a) to enhance the levels of imaged cod shoals.
Figure E-3: A large offshore shoal, likely another gadoid species haddock, was imaged at 23:43 UTC on March 5, 2014 off the shelf in roughly 1000-1500 m deep waters. This shoal was roughly 25 km long and 1-4 km thick. The image also shows the same on and off-bank shoals shown in Figure E-2. We were not able to conduct an echosounder line transect survey through this large off shore shoal due to an upcoming storm in the region. The gain setting used enhances the levels in the shoal but also enhance the levels close to the source with no shoals. So, the region of high SPL near source has been blocked out in the image.
Figure E-4: A large cod shoal spanning roughly 15 km in length and 1-4 km in width was observed at array broadside at 23:37 UTC on March 7, 2014 while a ship turn. Prior to this image, the shoal was directly at array endfire and so was not imaged with good resolution. The OAWRS image or scattering intensity map is not corrected for transmission loss, so higher levels are measured at closer ranges. Since the OAWRS receiver array beam width is narrowest at broadside and widest at the endfire of the array, the image shows good resolution near broadside but poor resolution with high scattered levels near the array endfire.
Figure E-5: Another view of the same shoal in Figure E-4 roughly half an hour later imaged at 00:16 UTC on March 8, 2014 when the shoal was closer to array endfire. Due to the hurricane in the area, RV Johan Hjort could not reach the survey location in time to help with simultaneous depth echosounding for ground truth confirmation of this shoal. The only way for us to confirm that this was a cod shoal was to turn into the shoal placing poor resolution endfire beams in the direction of the shoal to confirm the presence of the shoal and its depth distribution with the RV Knorr’s echosounder. This meant that we had to sacrifice good resolution OAWRS imagery at broadside as in Figure E-4. This image was taken just as RV Knorr started to turn into the shoal and the south-western tail of the shoal fell in the endfire direction. The OAWRS image or scattering intensity map is not corrected for transmission loss, so higher levels are measured at closer ranges. Since the OAWRS receiver array beam width is narrowest at broadside and widest at the endfire of the array, the image shows good resolution near broadside but poor resolution with high scattered levels near the array endfire.
Appendix F

At-sea Sound Speed Profile Measurements and Transmission Loss Analysis in the Lofoten Region near Andenes

F.1 At-sea Sound Speed Profile Measurements

In-situ measurements of sound speed profiles were made using eXpendable BathyThermograph (XBT) and Conductivity-Temperature-Depth (CTD) probes throughout the experiment period.
Figure F-1: Locations and times of XBT probe drops in the Lofoten region near Andenes between March 5-8, 2014.
Figure F-2: Sound speed profiles measured from XBT probe drops in the Lofoten region near Andenes between March 5-8, 2014.
Figure F-3: Continued: Sound speed profiles measured from XBT probe drops in the Lofoten region near Andenes between March 5-8, 2014.
Figure F-4: (a) Locations and times of CTD probe drops and (b) measured sound speed profiles in the Lofoten region near Andenes between March 5-8, 2014.

F.2 At-sea Transmission Loss Analysis

Although the in-situ sound speed measurements were similar to the historic sound speed profiles provided to us, we performed transmission loss analysis as and when new XBT or CTD sound speed data was collected. This section provides some key sound speed measurements and corresponding source and receiver transmission loss modeling for various paths in each of the survey sites.
Figure F-5: At-sea transmission loss modeling for the shown path and all measured CTD sound speed profiles on March 7, 2014 in the Lofoten area near Andenes.
Figure F-6: At-sea transmission loss modeling for the shown path and all measured CTD sound speed profiles on March 7, 2014 in the Lofoten area near Andenes.
Appendix G

Ocean acoustic waveguide remote sensing of cod in the Rost region during the Nordic Seas Experiment

The ship tracks of R/V Knorr in the Lofoten region near Rost are shown in Figure G-1.

G.0.1  February 23-24, 2014

We started passive data collection at UTC and active transmissions at 09:50 UTC. The first features appear at 10:30 UTC. These features, as we realize on February 24, follow bathymetric contours that are aligned with cliffs of slopes roughly 0.05-0.1. Line transects with R/V Knorr’s echosounder many hours later across the cliffs reveal dense cod aggregations located close to the cliffs. The scattered levels measured were found to be very consistent with those due to cod considering the historically high densities of cod measured in the area from Norwegian acoustic surveys. We are yet to fully analyze the effect of local bathymetric changes on scattered returns in comparison to scattering from cod.

Some features were seen around the ship, and could be identified at endfire, or as diffused blast out region around the source. We stopped transmitting at 18:00 UTC due to bad weather.
Figure G-1: A map of the Lofoten area bathymetry and overlain tracks of R/V Knorr during the survey on February 23 near Rost and March 5-7 near Andenes.
G.1 At-sea Sound Speed Profile Measurements

In-situ measurements of sound speed profiles were made using eXpendable BathyThermograph (XBT) and Conductivity-Temperature-Depth (CTD) probes throughout the experiment period.

G.2 At-sea Transmission Loss Analysis

Although the in-situ sound speed measurements were similar to the historic sound speed profiles provided to us, we performed transmission loss analysis as and when new XBT or CTD sound speed data was collected. This section provides some key sound speed measurements and corresponding source and receiver transmission loss modeling for various paths in each of the survey sites.
Figure G-2: Locations and times of XBT probe drops in the Lofoten region near Rost on February 23, 2014.
Figure G-3: Sound speed profiles measured from XBT probe drops in the Lofoten region near Rost on February 23, 2014.

Figure G-4: (a) Locations and times of CTD probe drops and (b) measured sound speed profiles in the Lofoten region near Rost on February 23, 2014.
Figure G-5: At-sea transmission loss modeling for the shown Path 1 and measured CTD sound speed profile on February 23, 2014 in the Lofoten area near Rost.
Figure G-6: At-sea transmission loss modeling for the shown Path 1 and measured CTD sound speed profile on February 23, 2014 in the Lofoten area near Rost.
Appendix H

Correspondence between Simultaneous Echosounding and OAWRS Imagery of Cod, Capelin and Herring Shoals

During the Nordic Seas OAWRS survey, excellent correspondence was obtained between OAWRS imagery and conventional echosounding line transects through cod, capelin and herring shoals.

RV Johan Hjort passed over the same shoal imaged by OAWRS in the Lofoten area on March 8, 2014 (Figure E-5) at 02:47:23 UTC. Although the shoal was migrating and had moved north of the location shown in Figure E-5, RV Johan Hjort registered cod distribution in the shoal that was very similar to the one observed by RV Knorr's echogram in Figure 3-19 several minutes after the OAWRS image in Figure E-5. The depth distribution of cod measured by R/V Johan Hjort and estimated areal population densities for echosounder target strength at 38 kHz $T_{SE,\text{Echo}} = -29.65$ dB re 1 m for mean measured cod body length of 78 cm is shown in Figure H-1. The threshold shoal areal population density above which roughly 90% of the shoal population is captured by echosounder data is found to be 0.024 fish/m$^2$ (Figure H-8).
Figure H-1: Volumetric and areal population density of a cod shoal from R/V Johan Hjort's echosounder transect between 02:47 to 03:30 UTC on March 8, 2014. The red dashed line indicates the areal population density threshold.

Figure H-2: Areal population density threshold for a cod shoal (red dashed line) derived from R/V Johan Hjort's echosounder transect between 02:47 to 03:30 UTC on March 8, 2014.
The Norwegian FV Artus simultaneously passed over the same shoal imaged by OAWRS in the Alesund region on Feb 21, 2014 at 01:50 UTC shown in Figure 4-1. This correspondence is shown in Figure H-3. Herring target strength was found to be $T_{SEh} = -37$ dB re 1 m for mean measured body length of 34.8 cm at 38 kHz. The threshold shoal areal population density is found to be roughly 0.5 fish/m$^2$, consistent with that obtained previously [11, 69].

RV Knorr passed over the shoal shoal imaged by OAWRS in the Finnmark region on Feb 27, 2014 at 03:26 UTC shown in Figure 4-1, indicated by the segment b-b* in Figure H-7. Capelin target strength was found to be $T_{SEc} = -50$ dB re 1 m for mean body length of 17 cm at 38 kHz. The areal population density threshold from shoal density estimates from echosounder data (Figure H-7) is found to be roughly 4 fish/m$^2$. 


Figure H-3: Excellent correspondence of the long herring shoal between (a) OAWRS imagery at 01:52 UTC on February 21, 2014 and (b) conventional echosounding from Norwegian fishing vessel Artus. There is also excellent correspondence of bathymetric contours and seabed depth by Artus. The OAWRS image is not corrected for transmission loss.
Figure H-4: Volumetric and areal population density of a capelin shoal from FV Artus’ echosounder transect along the d-d* segment shown in Figure H-3 on February 21, 2014. The red dashed line indicates the areal population density threshold.

Figure H-5: Areal population density threshold for a herring shoal (red dashed line) derived from FV Artus’ echosounder transect shown in Figure H-4 UTC on February 21, 2014.
Figure H-6: Excellent correspondence of capelin shoals between (a) OAWRS imagery at 02:33 UTC on February 27, 2014 and (b) conventional echosounding from R/V Knorr. The OAWRS image is not corrected for transmission loss.
Figure H-7: Volumetric and areal population density of a capelin shoal from R/V Knorr’s echosounder transect b-b* shown in Figure H-6 on February 27, 2014. The red dashed line indicates the areal population density threshold.

Figure H-8: Areal population density threshold for a capelin shoal (red dashed line) derived from RV Knorr’s echosounder transect shown in Figure H-7 UTC on February 27, 2014.
Appendix I

Estimation of violin plate stiffnesses and equivalent displaced areas

At the air resonance frequency, given violin plate mode shapes $\Phi^{\text{top}}(x, y)$ and $\Phi^{\text{back}}(x, y)$ for normal displacements, where each function is normalized such that peak displacement is unity, integration over the total plate surface area leads to equivalent displaced areas

\[ S^{\text{top}} = \int_{A^{\text{top}}} \Phi^{\text{top}}(x, y) \, dx \, dy \]  
(I.1)

and

\[ S^{\text{back}} = \int_{A^{\text{back}}} \Phi^{\text{back}}(x, y) \, dx \, dy \]  
(I.2)

because $S^{\text{top}}x^{\text{top}}$ yields the total oscillating volume due to top plate motion and $S^{\text{back}}x^{\text{back}}$ yields the total oscillating volume due to back plate motion for displacement amplitudes $\chi^{\text{top}}$ and $\chi^{\text{back}}$.

Jansson has measured the fundamental resonance of the top plate [41, 42] at frequency, $f^{\text{top-violin}}$, for a violin top plate with f-holes, ribs, bass bar, curvature and sound post in a complete violin [42]. Similarly, Jansson has measured the fundamental resonance frequency of a back plate, $f^{\text{back-violin}}$, with ribs, curvature and sound post in a complete violin [42]. At $f^{\text{top-violin}}$, the oscillating top plate mass $M^{\text{top}}_{\text{top-violin}}$ that responds to plate stiffness $K^{\text{top}}$ is determined from holographic measurements (Fig 14a of Ref [42]) assuming the mean
Table I.1: Independent estimates of the ratio of equivalent to total area for the top plate $\xi^{\text{top}}$ and back plate $\xi^{\text{back}}$ at the air resonance frequency are obtained via Eqs. S16-S17, where $\Phi^{\text{top}}(x, y)$ and $\Phi^{\text{back}}(x, y)$ are determined for violin top and back plates from Jansson’s holographic measurements [41]. These values are within 10% of those independently estimated in Section 5.3.1 (Table 5.1) from classical Cremonese violin data.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Estimated from Jansson’s empirical measurements [41]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\xi^{\text{top}}$</td>
<td>0.16</td>
</tr>
<tr>
<td>$\xi^{\text{back}}$</td>
<td>0.24</td>
</tr>
</tbody>
</table>

Table I.2: Independent estimates of structural stiffnesses $\tilde{K}^{\text{top}}$ and $\tilde{K}^{\text{back}}$ from Jansson’s measurements of violin top and back plates [42]. These values are within 10% of those independently estimated in Section 5.3.1 (Table 5.1) from classical Cremonese violin data.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Estimated from Jansson’s empirical measurements [41, 42]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tilde{K}^{\text{top}}$</td>
<td>$7.2 \times 10^4$ N/m for $f^{\text{top-violin}} = 480$ Hz [42]</td>
</tr>
<tr>
<td>$\tilde{K}^{\text{back}}$</td>
<td>$2.5 \times 10^3$ N/m for $f^{\text{back-violin}} = 505$ Hz [42]</td>
</tr>
</tbody>
</table>

measured total top plate area for Cremonese violins and $\bar{h}^{\text{top}} \approx 3$ mm [42]. Top plate stiffness $\tilde{K}^{\text{top}}$ is then approximated as $M^{\text{top-air}}^{\text{top}} (2\pi f^{\text{top-violin}})^2$. Similarly at $f^{\text{back-violin}}$, the oscillating back plate mass $M^{\text{back-violin}}$ that responds to plate stiffness $\tilde{K}^{\text{back}}$ is determined from holographic measurements (Fig 14a of Ref [42]) assuming the mean measured total back plate area for Cremonese violins (Fig 5) and $\bar{h}^{\text{back}} \approx 3.5$ mm [42]. Back plate stiffness $\tilde{K}^{\text{back}}$ is then approximated as $M^{\text{back-air}}^{\text{back}} (2\pi f^{\text{back-violin}})^2$.

Dynamical effects of the "island" [72, 159, 169] between the sound holes are included and found to be negligible at air resonance by comparison of violins with and without "islands," i.e. with and without f-holes [41, 42, 71], but they may become significant at higher frequencies [170, 171]. The stiffness of a violin top plate without an "island," i.e. without f-holes, is found to be roughly $2.4 \times 10^3$ N/m greater than that of a plate with an "island" from empirical measurements of the top plate modal frequency by Jansson [71]for top plate equivalent displaced area obtained from Table I.1. The stiffness of the top plate with bass bar, sound post and ribs but without f-holes is then greater than the stiffness of the top plate with f-holes, bass bar, sound post and ribs by less than 5% (Table I.2). This increase in stiffness of a plate without an "island" yields a less than a 0.5% increase in air resonance.
frequency and a less than 2% increase in air resonance power of a violin, from that of a plate with an "island" from our coupled elastic analysis. So at air resonance, the "island" effect is negligible. Numerical simulations of violin structural modes by Gough [169] indicate a less than 5% increase in the breathing mode frequency and less than 10% increase in bending mode frequency of a violin without "island" compared to that with an "island." This increase in modal frequencies of a violin without an "island" yields a less than 1.5% increase in air resonance frequency and less than 3% increase in air resonance power of a violin, from that of a violin with an "island," again making the "island" effect negligible at air resonance. All of these findings are consistent with the fact that at the air resonance frequency only total volume change needs to be accurately resolved.
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