Pacific Hake Integrated Acoustic and Trawl Survey Methods

Prepared by:
Fleischer, G.W., Ressler, P.H., Thomas, R.E., de Blois, S.K.,
Hufnagle, L.H. and Dezhang Chu

NOAA Fisheries, Northwest Fisheries Science Center (NWFSC)
Fishery Resource Analysis and Monitoring Division Acoustics Team

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Introduction and Background

Scientists from the United States (NOAA Fisheries) and Canada (Department of Fisheries and Oceans - DFO) jointly conduct biannual acoustic surveys of Pacific hake, *Merluccius productus*, along the west coasts of both countries. The age-specific estimates of total population abundance derived from the surveys are a key data source for the joint US-Canada Pacific hake stock assessment and ultimately act as the foundation for advice on international harvest levels. These integrated acoustic and trawl surveys, used to assess the distribution and biology, in addition to the status and trends in abundance of Pacific hake, were historically conducted triennially by the Alaska Fisheries Science Center (AFSC) beginning in 1977 and annually along the Canadian west coast since 1990 by DFO, Pacific Biological Station (PBS) scientists. The triennial surveys in 1992, 1995, 1998, and 2001 were carried out jointly by AFSC and DFO.

The NOAA mandate to develop national and regional protocols for acoustic-based surveys did not consider joint international programs such as the Pacific hake acoustic survey. The protocols listed below pertain strictly to the US portion of the survey. Our Canadian collaborators are aware of the protocol mandate and will be party to the results for their consideration. However, the procedures and standards adopted for the joint Pacific hake survey and listed herein are not to be construed as applicable for the survey practices beyond NOAA and do not necessarily signify acceptance and approval by the sovereign of Canada. However, the details of the procedures and practices by the DFO listed in Kieser et al. (1998, 1999) show the established compatibility of technique across the entire survey.

Methods

Following 2001, the responsibility of the US portion of the survey was transferred to Fishery Resource Analysis and Monitoring (FRAM) Division scientists at the Northwest Fisheries Science Center (NWFSC). A joint survey conducted by FRAM and PBS scientists in 2003 marked not only the change in the US participants but also a change to a newly-adopted biennial survey regimen specifically adopted to improve the overall future assessment capability for this species by an increased frequency of coast-wide surveys.

The surveys are performed in the summer months (June-September) targeting aggregations of Pacific hake along the continental shelf and break with a geographic coverage that ranges generally from central California to north of Queen Charlotte Sound (36°30’N - 54°30’N). The cruise tracks are executed starting from the southern extent of the survey area as series of parallel line transects that were generally oriented east-west and spaced at the established 10-nm interval, traversed sequentially in an alternating, or boustrophedonic, fashion. In summer, movements of Pacific hake are believed to be nominal and the stock fully available to the survey (Nelson and Dark 1985). Trawl samples are used to classify the observed backscatter layers to species and size composition and to collect specimens of Pacific hake and other organisms. The number and locations of trawl sets are not pre-determined – other than an allowance for an expected total number of tows for each area based on past surveys – but are dependent on the occurrence and pattern of backscattering layers observed at the time of the survey. Our goal is to obtain catches that were representative of the species composition and the size distribution of organisms detected acoustically in as many areas as was feasible within the constraints of vessel logistics, time, and focusing on the target species Pacific hake. As such, coverage by trawling is not systematic but adaptive and individual tows did not require a standardized effort.

Our acoustic estimates of fish abundance are derived from the accepted application of echo integration theory where the range-compensated measure of calibrated volume backscattering is assumed to be directly proportional to fish density (Burczynski, 1979; Foote, 1983a). Calculations of the echo integral (mean volume backscattering strength) are made over a specific volume in the vertical direction of a depth stratum in a defined region and Geostatistical methods applied to obtain biomass. In our application, the integrator output is averaged for the hake backscatter regions within 'cells' defined by 10-m vertical depth strata along 0.5-nm horizontal intervals. Values of mean area backscatter from the EK500/EK60 echosounder, termed nautical area scattering coefficient (m2/nm2) and denoted as s_A (MacLennan et al. 2002), were calculated along with related variables by the SonarData® (currently Myriax Software Pty. Ltd., GPO Box 1387, Hobart TAS 7001, Australia) Echoview software. Estimates of density of Pacific hake are derived from scaling the measured area backscattering for each cell within each echo integration interval by the expected backscattering cross section of hake for that area. The density is scaled by weight at length to determine biomass density, which is then kriged to provide an overall biomass estimate.

The equipment and survey techniques have evolved over the history of the integrated hake acoustic and trawl survey. Improvements in both, especially the rapid and continuous technological advances in the echo sounding systems, have advanced the capabilities of the survey. The NWFSC inherited this current state of survey operations from the AFSC with the transfer of the survey responsibility. For the purposes of these regional protocols, only the most recent operational and procedural elements of the joint Pacific hake survey are considered. The reader should note that the protocols detailed below pertain to acoustic data collected with SIMRAD EK60 (previously EK500) quantitative echo sounding systems (SIMRAD, 1996). 18 kHz, 38 kHz, 70 kHz, 120 kHz, and 200 kHz split-beam transducers are mounted on the centerboard of the NOAA Ship *Bell M. Shimada*, while 38 kHz and 120 kHz transducers are mounted on a hydraulic ram on the CCGS *W.E. Ricker*, with the 38 kHz system the primary data source for quantitative Pacific hake backscatter measurements.

Protocol 1 – Calibration and System Performance

Calibration

The calibration process characterizes system parameters relative to expected standard values and is conducted to (1) ensure that the echosounder and transducer components are operating properly, to (2) document the system performance over time (i.e., among survey periods), and to (3) allow inter-echosounder comparisons. The practice of calibration is essential to ensure accurate quantitative surveys.

Techniques

Issues to consider for the calibration procedure include that (1) the calibration should be conducted in as near the range of environmental conditions (e.g., water temperature and salinity) expected during the ensuing survey as possible, (2) water depths must be sufficient to exceed near-field limitations and system limitations for the sounder frequencies to be calibrated, (3) the vessel needs to be anchored a) in a location that is calm and sheltered, avoiding areas with inclement weather or strong tidal currents to minimize the effects of surge that can hamper the ability to properly locate the suspended sphere in the sound beam, and b) in an area with few or no fish. Given the above considerations, which collectively are all difficult to fully satisfy, past experience indicates the calibrations for the west coast survey should be conducted at the following locations:

- Port Susan, Puget Sound, Washington (48° 9’ N, 122°7’ W)
- Elliot Bay, Puget Sound, Washington (47° 62’ N, 122° 37’ W)
- Departure Bay, near Nanaimo, British Columbia, Canada (49°12’N, 123°58’ W)
- Barkley Sound, near Ucluelet, British Columbia, Canada (48°55’ N, 125°30.5’ W)
- Prince Rupert, British Columbia, Canada (54°19’ N, 130°19’ W)

Another calibration site that may be used, but is less favorable due to depth limitations, protection from surge, and the presence of fish is:

- Monterey Bay, Monterey, California (36°37’ N, 121°53’ W)

A successful calibration must be completed prior to embarking on the survey. An additional calibration immediately after the survey is also strongly encouraged, but is not required if and only if the initial calibration indicated a continued history of acceptable system performance, and regular *in situ* performance measures did not indicate any system irregularities (see System Performance section below). Calibrations during the survey are helpful for ensuring the system performance, but may be difficult to complete due to the combination of lack of suitable sites on the west coast and time constraints.

The method of calibration used for all acoustic surveys by the NWFSC employs a standard target whose acoustic scattering properties are known following the procedure of Foote et al. (1987). The target is a solid metal copper or tungsten carbide sphere which is suspended below the transducer. The appropriate sphere is suspended on 3

Spectra (fishing) lines below the transducer – either manual or mechanical adjustments are made to the individual lines to move the sphere relative to the transducer.

- A 38.1-mm tungsten carbide sphere with 6% cobalt binder is used as the primary reference target for the 38 kHz system, the primary frequency currently used for hake biomass estimate. The 38.1-mm sphere can also be used for calibrating the echosounders at other frequencies (70, 120, and 200 kHz)
    - Spheres machined to the appropriate diameters for other frequencies may be employed (64-mm copper sphere is used for 18 kHz echosounder, see manufacturer's guidelines for each additional frequency).
    - A 60-mm copper sphere can also be used as the reference target for 38 kHz.
- Ensure a minimum of 15 m distance between the transducer and sphere for the 38 kHz system as recommended by the manufacturer.
- Soak spheres in ultrasonic cleaner for approximately 1 hour to ensure clean surface.
- Conduct calibrations at each unique set of sounder settings to be used in the survey.
- Conduct calibration for each frequency separately.
- Log the calibration results and all supporting information into cruise log.

Each calibration will follow the manufacturer's operational procedures. Refer to the manufacturer's manual (SIMRAD, 1996) for details on preparations and transducer maintenance, specific reference target to use, system settings, data recording, data editing, and updating the transducer parameters.

- Collect calibration backscatter data on the acoustic axis.
- To measure beam pattern, move the sphere slowly throughout the beam to collect calibration backscatter data evenly in all quadrants of the beam.
- Record the raw backscatter for both the on- and off-axis sessions for archive.
- Include correction (reduction) of range between transducer and sphere as detailed by manufacturer (SIMRAD, 1996).
    - For the 38 kHz transducer operating at a 1.024 ms pulse width and a 3.8 kHz bandwidth, the range correction is 0.30 m (SIMRAD, 1996).

The decision to use the current calibration information to update the system parameters is based on both the guidance provided by the manufacturer and the level of confidence in the calibration values as judged by the scientist. *Failure to update at this point is not critical to the success of the survey as any corrections to these values can be implemented in the post survey analysis.* The judgment by the chief scientist is to be based on the degree the full suite of conditions listed initially in this section were met during the calibration.

Prior to each calibration session, measurements of the physical environmental conditions need to be made to document temperature and salinity conditions. These variables are necessary to calculate the ambient sound speed. If the duration of the calibration is greater than several (4-5) hours, it is recommended that at least one other measure of temperature and salinity be made to ensure consistency in sound speed during the session. If the measurements are found to be significantly different, update values as appropriate.

- Speed of sound will be calculated from the ambient water temperature, salinity and depth using the SIMRAD EK60 echosounder software.
- Apply those measures from the depth stratum immediately surrounding the sphere.
  - The use of the immediate area around the sphere, which is the standard practice, rather than use of the entire water column for this calculation has been criticized. With this issue unresolved, we recommend avoiding areas with severe clines in temperature or salinity for the calibration.

Error

Errors associated with calibrations are indicative of the overall system precision.

- Tolerance for error in the 38 kHz system calibration should be ± 0.2 dB for on-axis target strength measurements (Foote, 1983b; MacLennan and Simmonds, 1992).

Considerations

Measured values should fall within the above tolerance. If not, the source of the error should be identified and corrected. System performance tests (see below) should be performed in an attempt to determine if the problem is with the transducer or transducer cable. If this does not reveal the source of the problem, then a full set of diagnostics must be completed on the echo sounder to determine the source of the problem.

- The survey should not continue until the problem is rectified.

<u>System Performance</u>

System performance procedures are used to evaluate the echo sounder and transducer performance during a survey. These procedures are intended to provide periodic monitoring and evaluation of the system performance to ensure continued data quality during the survey. System performance addresses the internal electronics and processors, transducer, and cable. It does not consider interference introduced from external sources (see Performance Degradation section).

Techniques

Since calibrations cannot be practically performed on a daily basis, measurements of test values and passive noise values need to be completed once a day.

- Passive noise values will be conducted on a daily basis. Refer to manufacturers manual (SIMRAD, 1996) for details on procedures. Logistically, these procedures can only be completed when data collection is not critical, as the echo transmissions need to be turned off.
- Log all results and supporting information into cruise log.
- During periods of data collection, inspect individual target locations on TS Menu. Individual echoes should appear in all quadrants.

Error

Degraded system performance will directly affect backscattering measurements. Systematic errors include a change in transducer sensitivity that can be tracked by periodic and regular tests as described above. Random errors may also be present, but are more difficult to detect. Every effort should be made to monitor whether system performance is found to change consistently, or vary considerably, over time.

Considerations

Follow the manufacturer's detailed guidelines for system performance.

- Survey operations must be suspended until system performance is rectified if test values range out of manufacturer's tolerances.
- To minimize the potential loss of survey time from failed or failing systems, backup components (e.g., echo sounder unit, cables, and processors) should be kept in stock and ready for deployment. Failed transducers are less likely, but pose a serious logistical problem that will usually require time in dry dock to replace.

Protocol 2 -- Volume Backscattering Measurements

<u>Data Collection</u>

The AFSC and NWFSC has in the past used SIMRAD EK500 echo sounders, but currently use SIMRAD EK60 echo sounders. Abundance estimation is based on data collected at 38 kHz. See Calibration section for settings derived from calibration of the sounder and transducer. Other 38 kHz frequency settings are as follows:

- Pulse duration (τ) = 1.024 ms (SIMRAD's recommended value, which is considered a "medium" value)
- Two-way integrated beam pattern (ψ) = -21.0 dB (supplied by SIMRAD; value is specific to individual 38 kHz transducers)
- Absorption (α) = 9.855 dB/km
- Sound speed (c) = 1480.6 m/s

The sound speed and absorption settings are based on a compromise between previous AFSC survey sound speed settings and DFO Canada sound speed settings. All echo sounder parameter values are saved in the EK60 *.raw* file format.

Software

Acoustic data have been logged with SonarData (currently Myriax Software Pty. Ltd., GPO Box 1387, Hobart TAS 7001, Australia) EchoLog 500 and in the future may be logged with SonarData EchoLog60. Acoustic data are logged onto a PC and are backed up at the end of each day. The echo sounder firmware version is recorded on the calibration sheets and is included in the daily export file of echo sounder parameters.

The version of the post-processing software used to analyze the data should be the 2nd most recent validated (non beta) version of SonarData Echoview to ensure backward compatibility. The post-processing version is included as a field in the *Integration Settings* table in the survey database. When upgrading versions, a reference set of data should be analyzed with both versions and the s_A values (see definition of s_A in Protocol 3) compared to ensure that no significant change has occurred to the echo integration algorithm.

GPS

A GPS receiver(s) on the vessel sends navigation data to the echosounder where the data are logged with each ping. Mapping of the planned vessel route and recording of the actual vessel track are accomplished with a navigational software package (e.g. Nobletec, Seaplot or SIMRAD CM-60). Vessel speed and direction are also available with this software. Position data and vessel speed are monitored in real time.

Oceanographic Data

Conductivity-temperature-depth (CTD) casts may be conducted regularly during cruises, according to standard oceanographic procedures (Emery and Thomson, 1997) and relevant manufacturer guidelines. In general, these salinity and temperature profiles are not used to perform in-cruise updates of sound speed and sound absorption. Rather, single representative sound speed and absorption values are used for the entire survey. As sound speed and absorption may vary rapidly within a transect both in horizontal and vertical distance in the water column, updating sound speed based upon a local profile may generate more variability than it would reduce and is not currently logistically feasible. Our survey values of 1480.6 m/s sound speed and 9.855 dB/km attenuation coefficient for 38 kHz are a compromise between values obtained from DFO Canada and the AFSC historical oceanographic data.

Detection Probability

The NWFSC does not set a data collection S_v threshold. The post-processing S_v threshold is set to –69 dB. The areas surveyed by the NWFSC range from shallow water through the shelf break to deeper water, covering depths from <50 m to greater than 1500

m. However, the data are only analyzed to a depth of 500 m, as the vast majority of hake are believed to be distributed at depths of less than 500 m. The assumption is made that at this depth hake are above the noise threshold for their entire geographic range.

Acoustic Dead Zones: Near surface and near bottom

A fixed depth of 11 m for the *CCGS Ricker* and 14 m for the NOAA Ships Miller Freeman and *Bell M. Shimada* are used as the surface offsets. These values are derived from the location of the transducer on the centerboard below the water surface plus a 5 m buffer zone for the transducer's near field. The surface offset may vary from ship to ship based upon the depth of the transducer; of greatest importance is to leave a buffer zone for the transducer's near field. An constant offset of 0.5 m above the sounder-detected bottom is used as the bottom offset. Near bottom dead zone corrections are not applied to echo integration data.

Vessel Noise and Avoidance

According to measured underway noise signatures of the *Miller Freeman* and the *Ricker* (Ken Cooke, DFO, Alex De Robertis, AFSC, personal communication), both vessels exceed the ICES radiated noise recommendations for fisheries survey vessels given by Mitson (1995). However, it is assumed that the radiated noise of these vessels does not significantly affect hake detection probability.

Passive noise levels are routinely measured while underway during surveys as a measure of internal system performance, ideally during offshore cross-transects in deep water (> 1,000 m; see Protocol 1, Calibration and System Performance). Unusual noise levels can also indicate problems external to the system, such as noise from a damaged propeller or an object entangled in the propeller (e.g., rope, kelp) or noise from other shipboard equipment (e.g., generators, compressors, other acoustic gear).

Multiple scattering and shadowing (extinction)

The NWFSC has not observed the conditions that would indicate the need to correct for attenuation at high fish densities.

Considerations

Remediation

Under ideal circumstances, a volume backscattering threshold would not need to be used, as a threshold is a purposeful bias of the backscatter. This bias usually implemented to provide an improved signal to noise ratio, but can also have unintended consequences. Consideration should be given to the possibility that using a consistent threshold may not always yield consistent survey results.

See also Protocol 4, Sampling.

Improvements

Four new noise reduced Fisheries Survey Vessels (FSV) have been built for NOAA. These new noise reduced vessels are expected to meet ICES recommended noise standards (Mitson, 1995), reducing the potential for vessel noise to affect fish behavior and bias survey results. NOAA Ship *Bell Shimada* is one of these noise-reduced ships that is being be used by the acoustics team of the NWFSC. Limited Inter-Vessel Comparisons (IVC) of *Miller Freeman* and *Bell M. Shimada* have been conducted and analysis is underway. Previous IVCs between *Miller Freeman* and *Oscar Dyson* (same FSV class vessel) have been inconclusive.

<u>Classification</u>

Some terminology associated with echograms are visually represented in Figure 1.

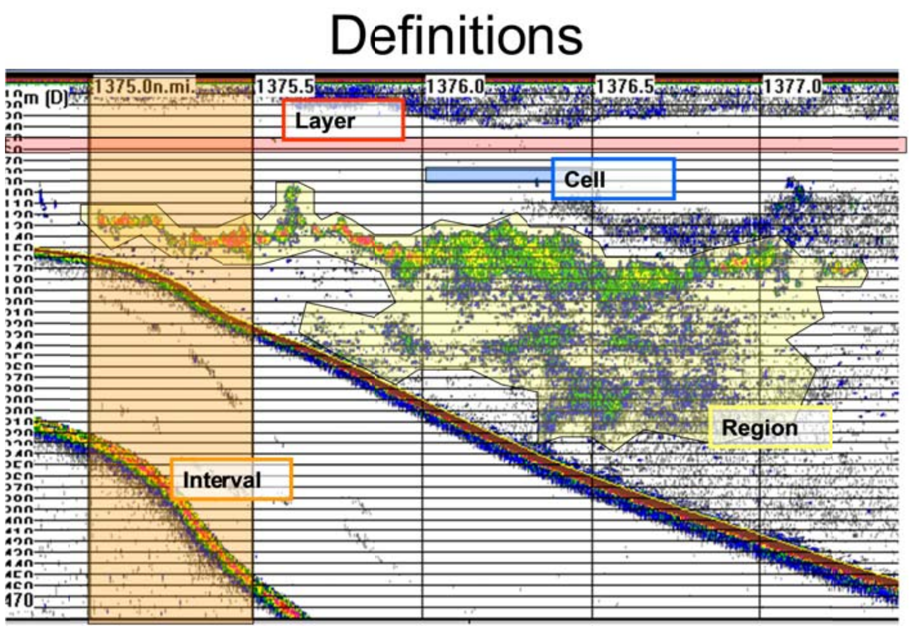


Figure 1. Definitions of echogram terminology

Techniques

Single Frequency

As described previously, the NWFSC uses a 38 kHz system as the primary system in its survey assessment of adult hake, age 2 and up. Young-of-year (YOY) and age-1 hake are classified separately. Information about YOY and age-1 hake is collected during the survey; however, the survey design is geared towards adult hake. Experienced operators primarily use the visual characteristics of these 38 kHz echograms together with catch composition data from trawl hauls.   Starting in 2011, information is also available from an underwater camera attached to the inside of the net near the codend to classify the backscattering layers. Regions are hand-drawn in Echoview around areas interpreted to be hake or other species of interest.

For regions when the associated haul was not 100 % hake, expert judgment was used to determine when a region should be classified as a mixture of species. There are several reasons why a haul might contain other species but the backscatter in the region of interest would be primarily hake. Primary reasons include the net catching other species on the way down to (or up from) the layer of Pacific hake, and the presence in the haul of bladderless fish. Mixed species regions are rare, for instance in 2011, only five regions on two transects were classified as mixed species, rockfish and hake.

A general rule of thumb used by the acoustics team is that if there is between 20% and 80% of hake in the trawl, then the associated regions should be strongly considered to be classified as a mix of species. The percent mix used is by weight of fish that are in the water column that have swimmbladders or other strong sound reflectors. This rule of thumb is interpreted by each chief scientist

When hake are below 20%, or above 80% of the weight of the trawl, the judgment is usually on a case-by-case basis, although frequently trawls with less than 20% hake will not be classified as hake and trawls above 80% hake will be classified as pure hake. However there is considerable room for expert judgment. For instance, if there is a large region associated with a trawl that caught 15 % hake mixed with rockfish, which have somewhat similar catchabilities, and the reviewer cannot parse out different regions to assign to hake and rockfish, the reviewer might choose to assign a mixed species to that region. On the other hand, if there is 15% hake in a trawl mixed with myctophids and euphausiids, since the reviewer knows that myctophids and euphausiids have a much lower catchability in the trawl than hake, then the reviewer would either choose to mark that region as myctophids and euphausiids, or find a way to try to assign myctophid/euphausiid-specific regions and hake-specific regions.

For most regions that we classified as a mixture of species, for which there are no reliable TS-length relations available but have similar scattering mechanisms and target strengths such as rock fish, the s_A (defined in Eq. 1) attributed to Pacific hake was apportioned from the total s_A based on the biomass catch proportion of acoustically detectable species (i.e., excluding bladderless or bottom-dwelling fish since their contribution to acoustic backscattering is assumed negligible). This direct ratio or "slider" method (analogous to Eq. 9.4 or 9.11 in Simmonds and MacLennan 2005) assumes equal trawl catchability and identical backscattering properties between Pacific hake and other species:

$$\frac{B_i^{acoust}}{B_{tot}^{acoust}} = \frac{s_{A_i}}{s_{A_{tot}}} = \frac{B_i^{trawl}}{B_{tot}^{trawl}}, \tag{1}$$

s_A= Nautical Area Scattering Coefficient (*NASC*) = $4\pi(1852)^2 s_a$ (m^2/nm^2)

s_a = area scattering coefficient (m^2/m^2), the integrated backscatter from an area

where $s_{A_{tot}}$ is the s_A resulting from all species of the mixture while s_{A_i} is the s_A resulting from species *i*. B_{tot}^{acoust} and B_i^{acoust} are the acoustically estimated total biomass and biomass of species *i*, respectively. B_{tot}^{trawl} and B_i^{trawl} are the total biomass and biomass of species *i* obtained directly from the trawl sampling. Since the relation between B_{tot}^{acoust} and $s_{A_{tot}}$ is assumed the same as that of hake, from the measured acoustic quantity $s_{A_{tot}}$, we can determine B_{tot}^{acoust}, hence the hake biomass will be

$$B_{hake}^{acoust} = B_{tot}^{acoust} \frac{B_i^{trawl}}{B_{tot}^{trawl}} . \qquad (2)$$

However, for hake mixed with smaller size species with more complicated scattering mechanisms such as myctophids and jelly fish, the scattering mechanisms (gas-bearing, fluid-like, etc.) are not understood very well. In addition, there is no quantitative catchability analysis available for these species with the midwater Aleutian Wing Trawl (AWT) used in our hake survey. As a result, it is extremely hard to partition the species acoustically based on the trawl data. Using a -69 dB threshold partially addresses this issue, fortunately hake in general aggregate strongly in mono-specific aggregations.

Unlike most other contaminant species in the net, the TS-length relationship of Humboldt squid is known. For regions that we classified as a mixture of Humboldt squid and hake, the s_A attributed to hake was apportioned from total s_A using the number of squid and Pacific hake in the tow and the TS-length relationship for each species. Species mixes with Humboldt squid and Pacific hake have occurred to date only in the 2009 survey. Details of the apportioning of Humboldt squid and Pacific hake using the TS-length relationships are described in Appendix A.

A qualitative comparison of the 38 kHz echograms with those at a lower frequency (e.g. 18 kHz) and those at higher frequencies (e.g. 120 and 200 kHz) can also assist in the process. At present, no quantitative analysis of multi-frequency data is used to aid in judging the presence of Pacific hake.

Multiple Frequency

Multiple discrete frequency and broadband acoustical data offer potential ways of classifying backscatter from targets of interest, since the scattering from different kinds of fish, for example, may have a different acoustical signature across multiple frequencies. This is an active area of research, and the success of the technique depends heavily on the kinds of organisms present, the frequencies available, and the goals of the survey. Multi-frequency techniques have been used to classify fish and plankton, but these techniques have not yet become reliable and robust enough to be a part of regular NWFSC surveys.

Biological Sampling

Mid-water and near-bottom scattering layers are sampled with trawl gear. Net openings and fishing depth are monitored with a net sounder system. Catch rates are visually monitored with the net sounder and the trawl is retrieved when the scientist overseeing fishing operations determines that an appropriate amount of fish has been sampled. Catches are completely sampled, unless they are too large, in which case they are sub-sampled. To scale backscatter data to estimates of abundance, length data from the target species are aggregated into analytical strata based on patterns of the backscattering layers, geographic proximity of hauls, and similarity in size composition of associated catch data. Age structure (i.e. otolith) samples from the trawl catches are grouped into age-length keys for conversion of abundance-at-length estimates to abundance-at-age. When Pacific hake are captured along with significant quantities of non-target fish species, the backscattering is partitioned based on catch weight proportions of the two species. See Numerical to Biomass Density in Protocol 4, Sampling.

Underwater video and camera systems are a potential alternative to trawling for the purposes of identifying backscattering organisms, collecting size data, and documenting behavior. Potential drawbacks are the relatively short range of view and the possible behavioral reaction of fish to the artificial lights necessary for the operation of the cameras. Also, video or still camera sampling does not provide a direct means of collecting age data. NWFSC does not currently use underwater video to classify echo sign as a primary operation. Using a camera mounted inside the net which would eliminate some of these issues, such as behavioral avoidance of fish to lights, is an active area of research. This technology could potentially be used for refining backscatter proportioning in the future. However, at least some trawling will continue to be necessary even after this technology is fully implemented as a part of the survey.

Bottom Tracking

Echosounders and post processing software have algorithms to identify and track the seabed in the echogram display. This function is very important because non-biological scattering associated with the bottom return must be completely excluded. The performance of these algorithms varies with bottom type, slope, and ship motion. The minimum bottom detection level is set at – 45 dB. This value is written to the sounder settings file. The maximum depth for bottom detection is at least 1000 m, and can be changed by the user depending on conditions.

The NWFSC uses a 0.5 m offset above the sounder-detected bottom (acoustic dead zone) to exclude scattering from the seafloor. This 0.5 m offset must be manually checked during post processing. When the sounder bottom detection is incorrect, the 0.5 m offset line is adjusted manually to approximate a 0.5 m offset from true bottom.

Oceanographic Data

Temperature profiles are routinely collected during trawl sites using a temperature depth profiler attached to the headrope of the trawl. These profilers are calibrated by the manufacturer and also compared to the data gathered with the ship's CTD.

Error

Sources of error include departure from the assumption of the representation of the size distribution of the source of backscatter and the selectivity of the trawl gear, which could produce unrepresentative catch proportions, age-length data, and misidentification of acoustic scattering.

Incorrect bottom tracking could result in the inclusion of bottom energy or exclusion of near bottom fish backscatter, depending on where the bottom detection is drawn.

Considerations

Remediation

Proper gear maintenance, deployment, and processing procedures should be followed to maximize the quality of the trawl data for classification of the acoustic data.

Bottom tracking settings should be optimized and the resulting traces checked for accuracy.

Oceanographic equipment should be maintained and calibrated according to the manufacturers specifications. It is good practice to compare the performance of trawl mounted sensors to those on oceanographic CTD packages.

Improvements

Bottom tracking algorithms and post-processing software continue to improve.

Alternative techniques, such as underwater video, still cameras, acoustic cameras (e.g. DIDSON), may be used to judge the performance of traditional trawling techniques or to augment the data gathered by trawling. Other techniques usually have potential drawbacks and biases, however; there is no panacea for the problem of correctly classifying the acoustic data.

As of 2011 the NWFSC began routinely placing a camera in most trawls to provide additional information that can be optionally used in trawl interpretation.

Multi-frequency and broadband acoustics provide another future means of improving classification and acoustic biomass estimates. These techniques are currently under development.

Performance Degradation

Definition & Importance

"Performance degradation is the reduction in echo sounder performance due to mechanical, biological, or electrical processes.

Degradation in echo sounder performance can be caused by acoustical, vessel, and electrical noise, bio-fouling of the transducer face, excessive transducer motion, and bubble attenuation. Performance degradation differs from system performance in that the causes of performance degradation are external to the echo sounder, whereas 'system performance' concerns the echo sounder electronics.

Routine monitoring of data by scientific personnel during data collection is necessary to ensure a high standard of data quality." (NOAA Protocols for Fisheries Acoustics Surveys and Related Sampling)

Techniques

Noise

Video displays of echograms are constantly monitored for the appearance of acoustical noise. Examining the display while the sounder is in passive mode may also be useful in identifying external sources of acoustical noise. A common source of acoustical noise is a result of the bridge sounder or ADCP being out of sync with the EK60. If the source of the noise can be identified as another piece of shipboard gear, the offending gear should be either shut down (preferably) or synchronized with the EK60.

Small amounts of noise are edited during post processing. In the event of serious noise, the position is determined where the noise began to affect the data. The chief scientist will decide either to continue or lose those data, or to re-start the transect prior to the position of the noise. The choice will depend on whether the data loss appeared to be significant. If data loss is determined not to be significant and the survey is continued, the area of noise will be designated as "bad data," and will yield a zero data point at the position.

Electrical noise can result from grounding problems or other pieces of electrical equipment. As with acoustical noise, electrical noise is often manifested in the data display or in unusual system diagnostic values (see Protocol 1, Calibration and System Performance). To resolve, ensure proper grounding of the sounder, use an uninterruptible power supply and/or "clean" ship's power, and shut off offending equipment if it can be identified. Additional remediation methods during the cruise and in post-processing are the same as those given above for acoustical noise.

Bubble Attenuation

Bubbles are strong sources of scattering. Bubbles can both lead to increased signal attenuation and also be a source of misclassified backscattered energy on an echogram (scattering from bubbles could be confused with scattering from fish). Bubbles near the sea surface are often associated both with vessel speed and sea state. Transducers should be located so as to minimize the effects of 'bubble sweep down'. In rough seas, vessel speed may have to be reduced or operations suspended to preserve data quality (see Protocol 4, Sampling). If scattering from bubbles can be reliably identified on the echogram, it can be identified and disregarded in post-processing. This will not correct for attenuation of the transmitted signal, however. The NWFSC does not apply a post-processing correction for signal attenuation due to bubbles.

Transducer Motion

As with bubble attenuation, transducer motion is associated with vessel motion, placement of the transducer, and sea state, thus many of the same considerations and remediation methods apply. "Dropouts" on an echogram are a typical manifestation of transducer motion. As with bubble attenuation, if transducer motions become excessive, reduction of vessel speed or suspension of operations may be considered to preserve the quality of the data (see Protocol 4, Sampling).

Bio-fouling

Bio-fouling refers to biological growth (e.g. barnacles) on the face of the transducers. The effects of bio-fouling can be identified by unusual calibration results or system performance measures (see Protocol 1, Calibration and System Performance). Transducer faces should be inspected and cleaned if necessary before the beginning of a survey or field season.

Error

Noise, bubble attenuation, excessive transducer motion, and bio-fouling will degrade system performance and lower the signal to noise ratio of the data and any resulting biomass estimates.

Considerations

Remediation

If possible, the above sources of reduced performance should be avoided by proper planning and setup, troubleshooting and elimination of noise problems encountered during the survey, or post-cruise processing to remove or otherwise account for the problem, as described in each section above. The error resulting from issues that reduce sounder performance should be well understood.

Improvements

If applicable, motion sensor data may be used to correct acoustic measurements.

Data Management

Acoustic Data

Raw data files and .ev files are logged, written to an external hard drive, and live viewed with Echoview software. File size is limited to 10 MB to facilitate file handling and data transfer. Raw data files are copied to a second external hard drive at the end of each transect or at the end of a day's operation to ensure that two shipboard copies of the raw data exist. This copy of the raw data is judged with Echoview and saved on both external hard drives. Raw data, .ev files, and judged data are stored on DVDs or other types of storage devices such as portable hard drives. A total of three copies of the data are thus created.

Upon completion of the survey all data are uploaded to a server in the Seattle FRAM facility. Duplicate copies of raw data, .ev files, and judged files are archived to the Newport FRAM and Nanaimo DFO facilities such that, overall, raw data from the survey reside in three separate physical locations.

Biological Data

Data from catch processing and haul operations are recorded to PCs using the ship's Fisheries Scientific Computing System (FSCS) during a survey. Catch, haul, length, and specimen files should be backed up routinely onto external hard drives or networked servers. Files can also be burned onto CD or DVD for added redundancy. Upon survey completion, these files are permanently archived onto an Oracle server at the Seattle FRAM facility after undergoing a battery of error checks.

Oceanographic Data

Vertical profiles of temperature and salinity collected with conductivity-temperature-depth (CTD) systems and temperature and depth profile data collected from portable, micro-bathythermographs are recorded to PCs during a survey. Ocean current velocity profile data from Acoustic Doppler Current Profilers (ADCP) are also written to a PC. Oceanographic data is backed up routinely onto external hard drives or networked servers during a survey. Data can also be burned onto CD or DVD for added redundancy. Upon survey completion, all files are downloaded to a server in the Seattle FRAM facility. An Oracle-based database for oceanographic data has yet to be developed. Currently, post-cruise quality control/quality assurance procedures and analysis of these data are done in collaboration with partners in the oceanographic field, e.g. at Oregon State University and/or DFO, Institute of Oceanographic Sciences.

Protocol 3 – Target Strength (TS)

Models

The backscattering characteristics of detected Pacific hake, required to scale the measured volume backscattering (see Protocol 2), are predicted by applying an empirically derived TS-length relation to the appropriate size distribution of sampled fish. *In situ* measurements are not used owing to the combination of depth (distance from the transducer) and the rather high densities Pacific hake aggregations typically exhibit during survey conditions (see Techniques section and Improvements section, below).

- The Traynor (1996) relation of backscattering to fish size for Pacific hake at 38 kHz is given as

$$TS_{dB} = 20 \log L - 68 , \tag{3}$$

where TS_{dB} is target strength in decibels and L is fish fork length in centimeters.

The following are conventions to be followed:

- Target strength (TS), the logarithmic form of the measured differential backscattering cross section (σ_{bs}), is given as:

$$TS \equiv 10 \log_{10}(\sigma_{bs}) \quad \text{dB} \quad \text{re } 1\,\text{m}^2 \tag{4}$$

in Maclennan et al. (2002).

- The differential backscattering cross section and the backscattering cross section (σ_b) used in radar are related by:

$$\sigma_b = 4\pi\sigma_{bs} , \tag{5}$$

where the 4π term must be included in the scaling of volume backscattering by σ_{bs} when applied to nautical area scattering coefficient (m^2/nm^2), denoted as s_A (Maclennan et al., 2002).

Techniques

The expected backscattering cross section (σ_{bs}) for a given assemblage of Pacific hake is based on the empirical relation suggested by Traynor (1996) as:

$$\sigma_{bs} = \sum_{i} f_{ij} 10^{\{[-68+20\log L_{ij}]/10\}} \tag{6}$$

for the frequency *f* of length *L* of the length class *i* in composite catch sample *j* .

Validation

To date, the empirical equation reported by Traynor (1996) represents the best understanding of *in situ* backscattering properties of Pacific hake that relates target strength to fish length at 38 kHz. This work represents an extension of initial *in situ* measurements on Pacific hake made by (Williamson and Traynor, 1984). These and other studies that attempt to define the *in situ* target strength characteristics of Pacific hake (e.g. Hamano et al., 1996) all suffer from the ability to find appropriate day and nighttime concentrations of hake at moderate depths. Recent publication by Henderson and Horne (2007) suggested that a TS regression relation that predicts TS values a few dB lower than those predicted by Traynor's empirical model. However, their measurements were conducted exclusively during nighttime while our acoustic surveys are conducted only during daytime. In addition, more recent studies indicated that *in situ* TS of hake were more consistent with Traynor's predictions than those of Henderson and Horne. Additional *in situ* TS measurements are needed before any changes in TS model are made.

Error

Error in the predicted TS values will affect the overall uncertainty in the derived abundance estimates. While this error will never be eliminated, the degree of variability in backscattering characteristics should be recognized in view of the resulting level of tolerance of error based on survey goals. Under typical survey conditions, MacLennan and Simmonds (1992) suggest error in TS may range 0 – 50%, which at the upper end, may contribute extensively to the overall error budget.

One source of potential error in predicted TS from application of the Traynor (1996) equation is the inability to incorporate effects on backscattering from changes in behavior and vertical distribution of Pacific hake. The conditions that characterized the hake during the acquisition of the *in situ* measurements and used to develop the relation must necessarily be assumed to be the same for subsequent application in any given survey – deviations from those behaviors present in the fish used in developing the relation (e.g., tilt angle distributions) and those encountered during a survey will induce errors in the length-specific predicted TS values. Moreover, this relation also assumes that backscattering cross section is proportional to the square of the fish length (Foote, 1987), which may not necessarily be a viable assumption (McClatchie et al., 1996). The latter feature of the TS-length model has implications for the accuracy to which the relation can predict TS, especially beyond the narrow size range of hake used in the Traynor (1996) equation.

Another consideration regarding bias in the derived TS from fish size distribution is whether the assumption is representative across all length classes for sampled Pacific hake. Net selectivity is typically asymptotic, with smaller fish proportionately less represented in the trawl catches. If the younger fish are indeed a significant proportion of the backscatter, but are not represented in the catch, appropriate compensation by weighting in the size distributions will be needed. There is evidence of variable catchability of Pacific hake acoustic survey (Helser et al., 2004), but this pattern incorporates other features of the survey (e.g., availability, sampling bias) beyond simple net selectivity.

Considerations

Remediation

In the event that the currently accepted TS-fish length relation for Pacific hake is deemed incorrect or not as accurate as a successor, an analysis will be undertaken to determine the effects of the past practices on Pacific hake population estimates.

Improvements

A combination of *in situ*, *ex situ,* and modeling experiments are currently underway and are designed to investigate and compare measured and predicted target strength measurements from a wide range of sizes of Pacific hake. The results of this work will shed additional light on the reliability of the currently accepted TS-length relation, including hake target strength variation as a function of tilt. If needed, the problem of remotely determining the *in situ* orientation distribution of fish may be assessed by an inferential method (Foote and Traynor, 1988). This method, which couples an understanding of swimbladder morphology and fish TS values measured at multiple frequencies, may provide a general method for determining the parameters of the tilt angle distribution *in situ*. Key to advancing this research is the capability to place transducers of different frequencies closer to the hake, either through drop transducer systems or autonomous underwater vehicles.

<u>Data Collection</u>
Not Applicable

<u>Detection Probability</u>
Not Applicable

<u>Classification</u>
See Protocol 2

Performance Degradation

See Protocol 2

Protocol 4 – Sampling (A_i, D_i)

Survey Design (A_i)

Definition & Importance

The design of any acoustic fisheries survey is critical to the accuracy and precision of the resulting estimate of abundance and distribution. There is no single optimum design to achieve all possible survey objectives, so a given design becomes the result of a series of strategic choices (MacLennan and Simmonds, 1992; Simmonds et al., 1992; Rivoirard et al., 2000). The goal of the joint US-Canadian survey for Pacific hake is to "determine the distribution, biomass, and length-at-age composition of the exploitable portion of the [hake] population" (Nelson and Dark, 1985) in support of analysis and management of the stock. The current design of the survey is based upon knowledge of the biology of the fish and the historical distribution of the stock, past survey coverage, statistical considerations, and logistical constraints. The sampling design includes the assumption that the survey area (A_i) encompasses the entire range of the recruited stock and that the stock is available to the survey techniques at the time of the survey.

Techniques

Broadly speaking, the survey measures S_v at 38 kHz along east-west oriented transects spaced at 10 nautical miles (nmi) along the U.S. and Canadian west coasts. The equivalent quantity of S_v in linear domain, a.k.a. the mean backscattering cross section per unit volume s_v, is integrated over depth into 0.5 nmi long intervals by 10 m thick depth strata, and then converted into units of backscatter per unit area $(s_A, \mathrm{m}^2/\mathrm{nm}^2)$; see definition in Protocol 2). The s_A or *NASC* numbers will be converted to abundance, then biomass density $(\mathrm{kg/nm}^2)$ using information from midwater and bottom trawls. The biomass density will then be used to generate biomass distribution using geostatistics (for more detailed descriptions of estimating biomass distribution, see Biomass Density to Biomass Distribution, below). Estimates of age-specific biomass for individual cells are summed for each interval, transect, and ultimately into a total coast-wide estimate. Basic oceanographic information is also collected during the survey, including regular CTD profiles.

The survey takes place in the summer months (between June and September), when adult hake are found at the northern extent of their annual coastal migration along the continental shelf and slope (Alverson and Larkins, 1969; Bailey *et al*., 1982). Typically, the survey stretches from near Monterey, CA (36°30'N) to Queen Charlotte Sound, B.C. (54°30'N), extends from about 50 m of water nearshore to water depths of 1500 m or more, and requires about 65-75 days to complete, including coverage of both U.S. and Canadian waters. The survey had been a triennial effort until 2003, when a biennial schedule was implemented (see Introduction).

In terms of transect layout, the Pacific hake survey has employed both zig-zag and parallel transect designs in the past. Currently, a systematic design using parallel transects traversed in a boustrophedonic fashion with a random start location is employed. In 2011 in areas of Canada where the shelf break is not at 90°to traditional east-west transects the design was modified to allow for diagonal transects, which cross perpendicular to the shelf break as recommended by Simmonds *et al* (1992). These modified transect s are at approximately a 60 ° angle to the US transects. The transits between lines are not used in the analysis. This design is recommended for "the most precise estimate of abundance," particularly if it is important to determine the geographical distribution of the stock as well as the abundance (MacLennan and Simmonds, 1992; Simmonds *et al*., 1992; Rivoirard *et al*., 2000). For each survey, a preliminary transect layout is constructed based upon historical transect locations and recent reports from commercial boats. The first transect of the survey is randomly located within a zone at the southern end of the survey area, and then subsequent transects are subsequently positioned at the standard 10 nmi spacing. If adult hake are found on this first transect, additional lines are added to the south to bracket the southern extent of adult hake. The 10 nmi spacing is finer than the 13.5-18.9 nmi (25-35 km) decorrelation distance estimated for Pacific hake using geostatistical techniques (Dorn 1997). A time budget for the survey plan is developed using a conservative survey speed along the preplanned route, allowing extra time for a typical amount of trawling effort, port calls and crew changes, and possible delays for bad weather or mechanical problems.

As a matter of procedure, the northward extent and turn points of these preplanned transects may be adjusted during the survey. If hake are observed on the most northerly planned transect, the survey is extended northward with more transects until no more hake are seen. Transects have been extended as far north as Cape Spencer, AK, 58° N (Wilson et al., 2000). Similarly, if hake are observed at the preplanned inshore end of the transect, the ship will proceed inshore as far as safety allows to find the beginning of the detected hake shoal before starting the transect, while at the offshore end, the ship will extend the transect as far offshore as necessary to find the end of the detected shoal (Fleischer et al., 2008). The preceding extensions of survey area and transects are not attempts to adaptively allocate survey effort, but rather a procedure to locate the boundaries of the population and ensure that the assumption of complete survey coverage is met (Simmonds et al., 1992; Rivoirard et al., 2000) and are made only in order to find the boundaries of hake shoals already detected on the preplanned transects. It should be noted that adaptive surveys are not recommended for surveys of distribution and abundance, unless the goal is locating commercially fishable aggregations, because the approach may result in a biased stock estimate (MacLennan and Simmonds, 1992; Rivoirard et al., 2000).

Due to the diel migratory behavior of Pacific hake (Alverson and Larkins, 1969; Stauffer, 1985), only daytime S_v data are used for the hake biomass estimate: during the daytime, the animals form distinct, mostly isotypic, shoals in midwater, while at night hake disperse and migrate to the surface, along with many other species of fish and plankton. This dispersed and mixed nighttime condition makes accurate classification of the hake S_v and trawl sampling of candidate shoals difficult. Nighttime hours (sunset to sunrise) have been used instead to conduct other research, including *in situ* target strength research, or to make oceanographic or other ancillary scientific measurements (see Oceanographic Data, below)

Midwater or bottom trawls are made during survey operations in order to classify the observed S_v and to gather the length and age data needed to scale the acoustic data into units of biomass (see Numerical Density to Biomass Density, below). The locations of these trawl deployments are not systematic, but rather depend on the local acoustic observations, recent and anticipated trawl effort, and other logistical constraints (time available for trawling, time required to process the catch, weather and sea conditions, etc.). Due primarily to logistic and time constraints, not all scattering aggregations can be sampled. Typically, two or three trawl sets are made per day during the survey.

Survey speed along transects ranges from 9-12 knots, depending on the vessel and prevailing sea conditions. Consistent vessel speed and heading are maintained while on transect. When sounding is interrupted for trawling or at the end of the daytime survey effort, the position of this break is recorded and data collection is later resumed at that point with the vessel underway at normal survey speed.

Vessel position is determined by using Global Positioning System (GPS) fixes. These fixes serve as the primary geographic reference for all data and events.

In rough seas, survey speed may need to be reduced to maintain data quality and safe shipboard operations. The chief scientist, in consultation with the Captain of the vessel, must balance the need to maintain data quality, the need to make progress on completing the survey, and safety considerations when deciding whether to alter or suspend survey operations.

Error

Uncertainty, randomness, systematic bias

The national protocol document notes that:

> "[t]he survey design (timing and location) should consider potential systematic changes in detection probability. If systematic changes in detection probability are discovered, either a change in the survey design is required or analyses should be conducted to determine a correction factor." (NOAA Protocols for Fisheries Acoustics Surveys and Related Sampling)

As mentioned previously, a major assumption made in this survey is that the entire stock is available to the survey effort. Potential bias includes incomplete coverage of the population.

The Geostatistical technique of kriging allows for biomass calculations with estimates of sampling variance. The reader should note that this section addresses potential sources of error in the acoustic survey design and sampling, not in the stock assessment modeling process.

Considerations

Remediation

If it is found that the survey design is in some facet inappropriate (e.g., ill timed, deficient in geographic coverage, or the acoustic technique used is found not to be robust across full range of conditions employed) a new survey design must be considered. However, changes in design must include a strategy for considering the potential impacts on the complete survey time series as on future surveys. As an example, the survey design by the Pacific hake survey underwent changes in 1992 and 1995: the survey was expanded offshore and further northward, and previous data points in the survey time series were back-corrected for this expansion in the assessment (Dorn et al., 1994; Dorn, 1996; Wilson and Guttormsen, 1997). The revision of the design was done based on an accumulation of new information about stock distribution (more northerly and offshore) to ensure more complete coverage of the population.

Understanding the uncertainty associated with the coast wide Pacific hake biomass estimate is an area of current research. One initial approach that has already been attempted is to apply the technique of Jolly and Hampton (1990) in a post survey stratification scheme that treats each transect as a sampling unit (Fleischer et al., 2008). In this way, a mean and variance for biomass in each stratum and for the total biomass was estimated, however the error associated with the point estimate propagated by this technique did not consider measurement errors.

Improvements

The annual hake migration is known to be sensitive to oceanic phenomena such as the El Niño southern oscillation, with adult hake migrating much further north during warmer years (Dorn, 1995). This implies that environmental data might help model the distribution of the stock during a given year or reveal that survey selectivity is related to environmental conditions. Currently, efforts are underway to determine if oceanographic variables can help improve the design of the survey. Also, the potential impact of changes in survey design will be explored through simulation modeling.

Stratifying the sampling design is advantageous if there are predictable patterns in hake concentrations. Since the variance in fisheries data often increases with the mean, a stratified sampling effort can reduce the variance in the final estimate (MacLennan and

Simmonds, 1992). A geostatistical analysis of spatial variability may suggest ways to stratify the survey effort accordingly, thereby reducing the variance of the total population estimate (Simmonds et al., 1992; Rivoirard et al., 2000).

In the future, autonomous underwater vehicles (AUVs) may be used to augment sampling conducted by the acoustic survey vessel.

Biomass Density to Biomass and Abundance Distribution(D_i)

Definition & Importance

The age-specific population number and biomass estimates of Pacific hake used for stock assessment modeling are ultimately based on the measured acoustical energy. The conversion from calibrated echosounder output to units of biomass relies upon data obtained from trawl sampling during the survey. More specifically, the needed information includes the distribution of fish lengths and ages in trawl samples and relationships between fish length, target strength, weight, and age (MacLennan and Simmonds, 1992). See also Protocol 3, Target Strength.

Techniques

During echogram judging, each hake region is assigned a haul that is deemed to be the most representative of the length-frequency of the hake in that region based on the depth and appearance of the echosign and compared to the echosign that was fished on in nearby hauls. Pairwise Kolmogorov-Smirnov goodness of fit tests (Campbell, 1974) were performed to help classify the hauls into strata based on their length frequency. For each length stratum, a composite average length distribution is generated from trawl data using Equation 8.9 in MacLennan and Simmonds (1992). Equal weight assigned to each haul, taking no account of differences in the total catch. See also Protocol 2, Volume Backscattering Strength.

The relation used to relate target strength to length for Pacific hake is TS=20*log(length)-68 as given by Traynor (1996) given in Eq. (3). The form of the equation implies a dependence of target strength on the square of fish length and is the same as that used for many fishes; *in situ* target strength data have been used to determine the intercept value for Pacific hake and validate the equation (Traynor, 1996). Previous to the 1995 survey, a TS-to-biomass conversion value of –35 dB/kg was used, but after this a TS-length relation was used instead and the survey time series was back-corrected for this change in the stock assessment analysis (Dorn et al., 1994; Dorn, 1996; Wilson and Guttormsen, 1997).

An allometric equation, used to convert length to weight, is established for each survey using measurements of individual fish lengths and weights of subsamples from the fish collected during the survey (see Protocol 2, Volume Backscattering Measurements). Typically the equation used is of the transformed form log weight = log a + b * (log fork length). The ‘a’ and ‘b’ parameters are determined by linear regression. However, empirical estimates of the length-weight relation are used unless the sample sizes in each length bin are too low (less than 5 fish).

Error

Uncertainty, randomness, systematic bias

The TS-length relation is a major source of uncertainty.

Considerations

Remediation

Efforts are ongoing to collect and analyze *in situ* measurements of Pacific hake target strength and length in order to evaluate the currently used TS-length relation.

Improvements

De Robertis et al. (2004) suggested that when developing a weight-length relation from a relatively large set of data from an acoustic survey (ca. 100 – 1000 fish), use of the empirical mean weight for each 1 cm length class was less biased than reliance on predicted values from the fitted exponential regression to untransformed data or a linear regression to log-transformed data. Both types of regression analysis tended to not fully capture variations in the changes in weight-at-age and in this particular case overestimated the weight of larger fish and underestimated the weight of smaller fish in a reanalysis of AFSC acoustic survey data.

<u>Oceanographic Data</u>

Definition & Importance

These data are secondary in importance to the acoustic data. Oceanographic data are needed to constrain hydrographic conditions encountered in the survey (e.g., sound speed and sound absorption). They also represent fundamental environmental measurements characterizing the dynamic habitat of the Pacific hake.

Techniques

The primary source of these data is conductivity-temperature-depth (CTD) profiles. Also, acoustic Doppler current profilers (ADCPs) are used to collect data on ocean currents while underway. Expendable bathythermographs (XBTs), underway flow-through collection of temperature and salinity near the surface, and satellite measurements of ocean properties represent additional sources of near-surface environmental data.

The number and location of oceanographic samples should be chosen to provide assurance that proper sound speed and absorption values have been used and to support research on the environmental factors affecting Pacific hake distribution and abundance, taking into account available ship time.

Sampling should follow ship-specific procedures, instrument-specific instruction from the manufacturers of the oceanographic equipment, and protocols developed to facilitate post-cruise processing and analysis of the data to accepted oceanographic standards (Emery and Thomson, 1997). For data management procedures for oceanographic data, see Data Management under Protocol 2.

Error

Uncertainty, randomness, systematic bias

While useful information is immediately available from these oceanographic instruments, post-cruise calibration QA/QC procedures by a trained analyst (Emery and Thomson, 1997) are usually required for quantitative work.

Considerations

Remediation

Oceanographic data should be processed post-cruise by a trained analyst if they are to be used for quantitative work.

Improvements

AUV and satellite remote sensing technologies offer major routes of future expansion of the collection of concomitant oceanographic data.

Further details of sampling procedures are given in the technical memoranda describing the 2003 hake survey (Fleischer et al., 2008).

EchoPro Software Package

Dr. Dezhang Chu developed the EchoPro software using geostatistics, specifically kriging, to calculate the biomass estimate. The newly developed software package EchoPro, is a Graphic Unser Interface (GUI) driven Matlab (Mathworks, 3 Apple Hill Drive Natick, MA 01760, http://www.mathworks.com/

Biomass Estimate using Geostatistics

Introduction

Historically, hake biomass (age 2+) and variability were estimated from the survey data using a stratified random transect design following Jolly and Hampton (1990). These design-based estimates did not account for spatial correlation of the data or patchiness of hake distributions and assumed that there was no hake biomass beyond the ends of each transect. In addition, estimates of variability were uncertain and likely biased because some sources of uncertainty could not be accounted for. In 2010 the survey analysis method was transitioned to kriging and historical data was reanalyzed. Kriging is now the standard method for calculating the hake biomass estimate from biomass density.

Geostatistical methods were originally developed for spatially structured mining data and are a collection of numerical and mathematical techniques used to analyze observations that are correlated in space (Journel and Huijbregts 1992). Kriging is a geostatistical method and a local estimator used to interpolate a spatially distributed quantity in an unobserved location and was considered to be suitable to estimate fish abundance and precision by an ICES Study Group (Anon, 1993). Kriging has been used in many cases to estimate the abundance and variance of fish stocks surveyed using acoustic techniques (Petitgas, 1993; Rivoirard et al. 2000; Mello and Rose 2005; Simmonds and MacLenann, 2005). A brief description of the theoretical background is provided in Appendix B.

Methods of estimating fish biomass distribution that are based on random sampling theory do not make any assumptions about spatial correlation, and assume that the observations are independent samples. However, due to its nature, hake biomass distribution is believed and has been verified to follow the intrinsic hypothesis, thus is correlated. The spatial correlation must therefore be accounted for to appropriately estimate the biomass and the variance.

There are several advantages of applying geostatistical techniques (i.e., kriging) to the biomass estimate of Pacific hake from the Integrated Acoustic and Trawl Survey (IATS).

1) It provides the hake biomass and associated sample variance estimates simultaneously and properly accounts for spatial correlation along and between transects.
2) It provides biomass estimates in the area beyond and between transect lines but within correlation distance; assuming an **Intrinsic Model** (Petitgas 1993).
3) It provides maps of hake biomass and variance that take into account the inhomogeneous and patchy hake distribution.
4) It provides more flexibility in survey transect design, such as allowing transects to remain more or less perpendicular to the coastline or to zigzag up the coast, which is likely a more efficient sampling scheme.

In order to estimate abundance and biomass using geostatistics we need to introduce a new quantity, the biomass density, which can be expressed as:

$$\hat{\rho}^{X,I} = \frac{s_A^{X,I}(s)}{4\pi\langle\sigma_{bs}\rangle_s}\hat{W}, \tag{7}$$

where $s_A^{X,I}(s)$ is the Nautical Acoustic Scattering Coefficient (*NASC*) number on transect *X* for interval *I*, associated with hake stratum *s* exported from Echoview directly, $\langle\sigma_{bs}\rangle_s$ is the averaged differential backscattering cross section in stratum *s*, and $\hat{W}$ is the length-weight key (a conversion from length distribution to biomass) according to the hake length distribution in stratum *s*. The hake biomass distribution can be estimated using geostatistics (kriging). Theoretically speaking, we could estimate the abundance and biomass of hake based on the length, age, and sex- structured quantity $\hat{\rho}_{a_k,l_i}^{X,I}(male, female)$ directly using geostatistics method and obtain the corresponding abundance and biomass distribution maps. However, due to the total number of length and age classes, as well as different sex, the computation time will be too long to be realistic. Therefore, we take $\hat{\rho}^{X,I}$ as the input values for kriging (geostatistics analysis) and derive kriged biomass density $\hat{\rho}(\mathbf{x}_L)$, where $L = 1, 2, \cdots, N_g$ and N_g is the total number of kriging grids, removing length, age, and sex specific information.

We are able to provide the biomass distribution (kriging map) and the total biomass estimate by

$$\begin{aligned} \hat{B}(\mathbf{x}_L) &= \hat{\rho}(\mathbf{x}_L)A_L \\ \hat{B}_{tot} &= \sum_{L=1}^{N_g}\hat{B}(\mathbf{x}_L) \end{aligned}, \tag{8}$$

where N_g is the number of the grid points in the survey region but can include some locations beyond the transect lines, and $A_L = 2.5\times2.5 = 6.25$ nmi^2 is a constant area on which the biomass density is assumed to be a constant throughout the survey region. The primary stratification scheme we have been using is the post-cruise clustering method aided by pairwise Kolmogorov-Smirnov goodness of fit test (Campbell, 1974), which allows multiple strata within the same interval. However, since this allows for overlapping strata, it is not possible to provide precise length, age, and sex- structured biomass estimates using geostatistics.

If we were to use a stratification scheme either pre- or post-cruise where strata are defined based on their geographic regions, we should be able to provide more desirable length, age, and sex- structured kriged biomass and abundance estimates. However, it should be noted that such stratification does not allow overlaps of strata at the same geographic location such as two different strata at the same location but at different depths such as juvenile and adult hake layers. In other word, each data location on transect X at interval I must correspond to a unique stratum.

In this hypothetical scenario, the estimated biomass density at age class a_k and length class l_i at the geographic location (grid point), $\mathbf{x}_L = \{lat, lon\}_L$, is

$$\hat{\rho}_{a_k,l_i}^{male,\,female}(\mathbf{x}_L) = R_{male,\,female}^{s}\hat{\rho}(\mathbf{x}_L)Q_{ki}^{s}. \tag{9}$$

where $R_{male,\,female}^{s}$ is the proportion of the male or female hake in stratum s, Q_{ki}^{s} is the length-age key in stratum s, i.e. the proportion of hake at age class a_k for length class i where i = 1, 2, N_l, and k = 1, 2, … N_a . N_l and N_a are the number of length and age classes, respectively. The corresponding biomass at the location $\mathbf{x}_L$ averaged over an area A_L is then

$$\hat{B}_{a_k,l_i}^{male,\,female}(\mathbf{x}_L) = \hat{\rho}_{a_k,l_i}^{male,\,female}(\mathbf{x}_L)A_L. \tag{10}$$

The accumulative length, age, and sex- structured biomass can be obtained by summing $\hat{B}_{a_k,l_i}^{male,\,female}(\mathbf{x}_L)$ over all grid points

$$B_{a_k,l_i}^{\Sigma male,\,female} = \sum_{L=1}^{N_g} R_{male,\,female}^{s}\hat{B}_{a_k,l_i}^{male,\,female}(\mathbf{x}_L). \tag{11}$$

Similarly, the corresponding kriged length, age, and sex- structured abundance is

$$N_{a_k,l_i}^{\Sigma male,\,female} = \sum_{L=1}^{N_g} R_{male,\,female}^{s}\hat{B}_{a_k,l_i}^{s}(\mathbf{x}_L)/W_i. \tag{12}$$

Data preparation

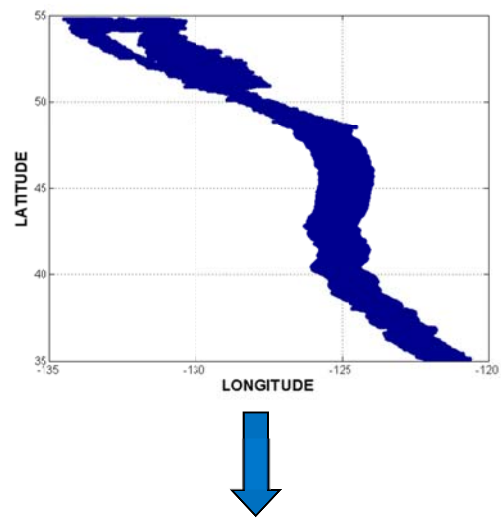
The Nautical Acoustic Scattering Coefficient (*NASC*) is a quantity that measures the acoustic backscattering intensity from a vertically integrated unit area(m^2/nm^2). As there could be multiple fish aggregation regions at the same interval (Vessel Log distance) that have different biological properties, (e.g., juvenile versus adult hake, hake mixture versus hake only) it is more logical to "krige" on the integrated biological quantity that is derived from the *NASC* value, **hake biomass density** (biomass/unit area, or kg/nm^2) rather than on the acoustic quantity – the depth-integrated *NASC*. The kriging software is based on the EasyKrig Toolbox developed by Dezhang Chu and is posted on the website (ftp://globec.whoi.edu/pub/software/kriging/easy_krig/V3.0.1/) and is part of the EchoPro software package. The theoretical background of kriging is provided in Appendix B. The input data files required by the kriging software are:

- Raw total hake biomass density file – this is a list of biomass per unit area at discrete locations along the transects with 0.5 nm spacing (most of the data are zeros since often there were no hake observed along the transect).
- Mesh grid file – this is the table of mesh grids on which the estimated biomass density is generated with the kriging software. The grid size is 2.5 nm by 2.5 nm.

It is well known that hake are normally found along the isobaths near the continental shelf break, i.e., that correlation length is longer along the isobaths than across the isobaths. To reflect these characteristics of the Pacific hake spatial distribution, the following coordinate transformation is performed:

$$Lon_{Trans}(i, lat) = Lon_{Orig}(i, lat) - Lon_{200m}(lat) + Lon_{Ref}\,, \tag{13}$$

where $Lon_{Orig}(i, lat)$ and $Lon_{Trans}(i, lat)$ are the original and transformed longitude values of the i^{th} datum or mesh grid point (function of latitude), respectively. $Lon_{200m}(lat)$ is the longitude of the 200 m isobath (function of latitude), and Lon_{Ref} is an arbitrary scalar, or a reference longitude (e.g., the mean longitude of the 200 m isobath). Figure 1 shows an example of the transformation to the mesh grids used in our biomass estimate. With such a transformation, the anisotropic signature of the hake distribution can be approximately characterized by two perpendicular (principal) correlation scales: one is along the isobaths and the other is across the isobaths. The aspect ratio of the hake spatial distribution is defined as the ratio of the two length scales.



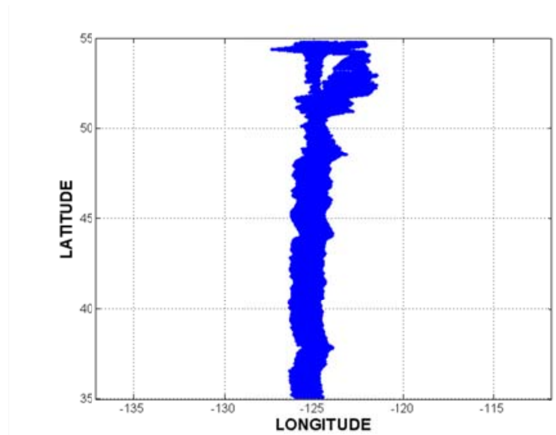


Figure 2**.** Coordinate transformation of the mesh grids used for Pacific hake acoustic survey. Two plots are the original mesh grids (left) and the transformed mesh grids (right), with $Lon_{Ref} = -125^o$ or 125^o W.

Semi-Variogram and correlogram

The semi-variogram defined in Appendix B Eq. (B3) is the key of the kriging processing. The choice of semi-variogram model and corresponding model parameters was initially determined by least-square fit and refined by visual fit. There are a number of commonly used semi-variogram models: spherical, Gaussian, exponential, general exponential-Bessel, etc. The exponential model was chosen due to its simplicity (fewer parameters) and the quality of fit (Fig. 3). The exponential model is defined by (Deutsch and Journel, 1992; Kitanidis, 1997):

$$\gamma(h) = \gamma(\infty)[1 - \exp(-h/L)], \tag{14}$$

where L is the *length scale* and $\gamma(\infty)$ is the *sill*, the value of the semi-variogram when $h \to \infty$ and is finite if $\gamma(h)$ is stabilized as $h \to \infty$. For a finite $\gamma(\infty)$, we can use a more familiar quantity to describe the **Intrinsic Model**: a correlation function, or a correlogram, which is a correlation function normalized by its variance,

$$\rho(h) = \frac{C(h)}{\sigma^2} = \frac{C(0)}{\sigma^2} - \frac{\gamma(h)}{\sigma^2} = \rho(0) - \frac{\gamma(h)}{\sigma^2}, \tag{15}$$

where σ^2 is the variance assuming a zero mean, i.e., $\mu_h = 0$ or $\mu_h << \sigma$. The semi-variogram at zero lag, $\gamma(0)$, is called the *nugget* and may not be zero, i.e., $\gamma(0) \neq 0$. For a non-zero $\gamma(0)$, Eq. (14) can be modified to

$$\gamma(h) = [\gamma(\infty) - \gamma(0)][1 - \exp(h/L)] + \gamma(0), \tag{16}$$

and Eq. (15) will be

$$\rho(h) = \rho^*(0) - \frac{\gamma^*(h)}{\sigma^2}, \tag{17}$$

with

$$\rho^*(0) = \rho(0) - \gamma(0)/\sigma^2 \qquad \text{and} \qquad \gamma^*(h) = \gamma(h) - \gamma(0) \tag{18}$$

Note that when the nugget, $\gamma(0)$, approaches $\gamma(\infty)$, the semi-variogram will be a constant, indicating a completely random distribution that has no correlation at all.

In computing the semi-variogram, the longitude and latitude of each datum (lon, lat) are first transformed to a latitude-independent distance coordinate system, (x, y) with x in the longitude direction and y in the latitude (isobaths) direction. This is performed by assuming that the earth is a perfect oblate spheroid, and then converting it to an isotropic system by compressing the y-axis (latitude) to the same length scale of the x-axis with the aspect ratio determined by fitting the semi-variogram.

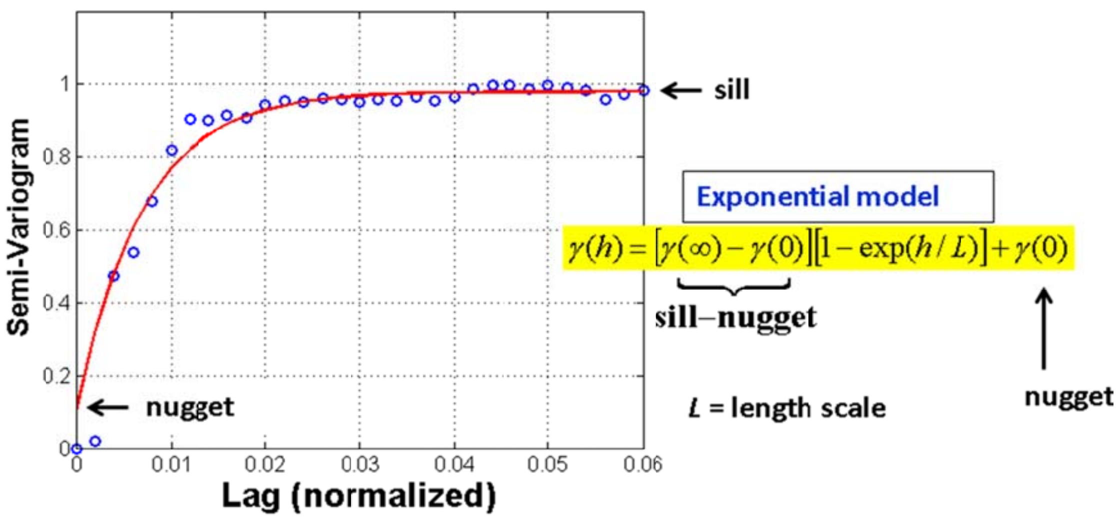


Figure 3. Illustration of the parameters used by an exponential semi-variogram.

Kriging

To avoid numerical difficulties associated with solving a huge linear equation system [either Appendix B Eq. (B8) or (B9)], we chose a moving localized kriging scheme, i.e., instead of using all the acoustically measured data points to estimate the value at a specified location, we use only those that are within the search radius centered at that specified location. This radius is larger than $4L_{corr}^{lon}$ in longitude direction and $20L_{corr}^{lat}$ in latitude direction (along isobath), where L_{corr}^{lon} is the 3-dB correlation length in longitudinal direction defined as

$$C(L_{corr}^{lon}) = \frac{\sqrt{2}}{2} C(0) \approx 0.707\, C(0) \tag{19}$$

which leads to $L_{corr}^{lon} = \frac{\ln 2}{2} L \approx 0.35\, L,$ where $\ln(x)$ is the natural log function and L is the length scale given in Eq. (14). The correlation length scale in latitude is then the product of the aspect ratio and L_{corr}^{lon}, i.e., $L_{corr}^{lat} = R_{aspect} L_{corr}^{lon}$.

Biomass estimate and Coefficient of Variance (CV)

The total biomass estimated with geostatistics can be calculated by

$$\hat{B}_{tot} = \sum_{L=1}^{N_g} \hat{\rho}(\mathbf{x}_L) A_L, \tag{20}$$

where N_g is the total number of grids of the kriging region and A_L is the area (nmi^2) of grid region L. In our application, $A_L = 2.5 \times 2.5 = 6.25$ nmi^2 is a constant throughout the survey region. The averaged CV from kriging is

$$CV = \frac{1}{N_L} \sum_{L=1}^{N_L} \frac{\sigma_L(\mathbf{x}_L)}{\hat{\rho}(\mathbf{x}_L)}, \tag{21}$$

where $\sigma_L(\mathbf{x}_L)$ is given in Appendix B Eq. (B10).

Modifications to Protocols

Changes to operational protocols will be at the discretion of the NWFSC Science Director who may approve such changes directly or specify a peer review process to further evaluate the justification and impacts of the proposed changes.

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Appendix A

Procedures of processing hake/Humboldt squid mix trawls for 2009 Integrated Hake Acoustical and Trawl Survey

I. Trawl data collected by US Acoustics Team

Available data: (a) Total catch weights and numbers of hake and Humboldt squid
(b) Sub-sampled individual hake length and weight

A. Humboldt Squid Length-Weight Relation

Obtain length-weight regression coefficients of the Humboldt squid from the trawls that have length and weight measurements for individual Humboldt squid (trawls 16 and 18) with non-linear least square algorithm (a function in Matlab)

The obtained regression relation is:

$$W = \beta L^{\alpha}, \tag{A1}$$

where $\alpha = 3.01$ and $\beta = 3.046 \times 10^{-5}$ kg. L is the Humboldt squid mantle length in cm.

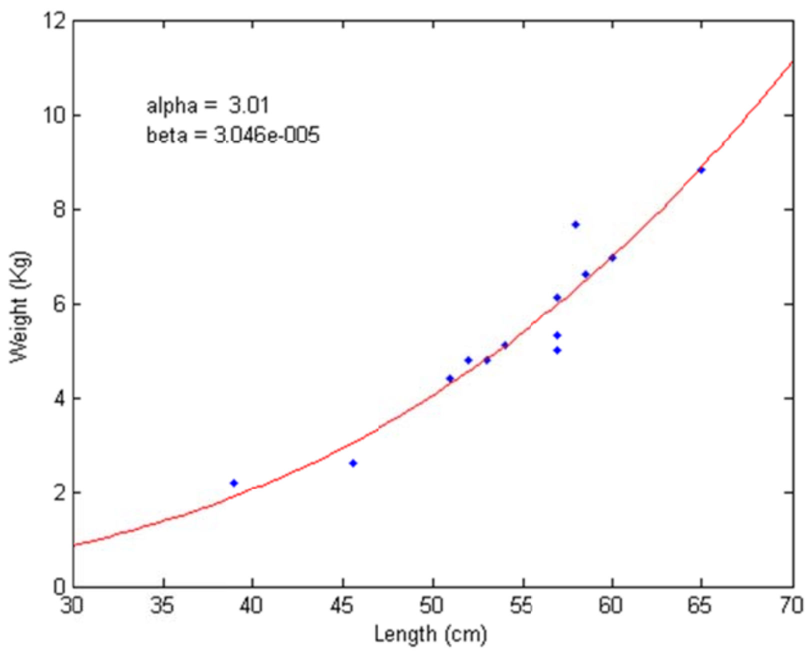

Figure A1. Length-Weight regression curve of Humboldt squid based on the 2009 trawl data.

B. Hake Target Strength

For each mix trawl, since we have individual hake length data, we can determine the average differential backscattering cross section of hake at 38 kHz (we need to performance average in linear domain):

$$\bar{\sigma}_{bs} = < 10^{TS/10} >, \tag{A2}$$

where $TS = 10 \log_{10} L - 68$ and L is hake fork length in cm.

C. Humboldt Target Strength

We can determine the average differential backscattering cross section of Humboldt squid at 38 kHz using the regression equation given by Benoit-Bird *et a*l. (2008):

$TS = 20 \log_{10} L - 62$,(A3)

where again L is the Humboldt squid mantle length in cm. The average differential backscattering cross section can be easily calculated by using Eq. (A2). Since we don't have the squid length for the mix trawls, we can get the "average" length from the regression relation given by Eq. (A1)

$$L = \left(\frac{W}{\beta} \right)^{1/\alpha}. \tag{A4}$$

The average weight of individual Humboldt squid is obtainable since the trawl data have the total weight and number of the caught Humboldt squid from the trawl.

D. *NASC* Ratio

The total backscattering contribution from all the hake and Humboldt squid can be obtained by simply multiplying the backscattering cross section and the number of individuals since we have the total and numbers of hake and Humboldt squid:

$$\begin{aligned} \sigma_{tot}^{hake} &= n_{hake} \bar{\sigma}_{bs}^{hake} \\ \sigma_{tot}^{humboldt} &= n_{humboldt} \bar{\sigma}_{bs}^{humboldt} \end{aligned}. \tag{A5}$$

The ratio of the backscattering coefficients in (A5) represents the ratio of the *NASC* values, which can be used for handling mix-catch trawls.

What is desired for the database is the ratio of percent of hake and squid to apportion the *NASC* into. That is, we want to know R^{hake} and $R^{humboldt}$, where

$$R^{hake} = \frac{NASC^{hake}}{NASC^{hake} + NASC^{humboldt}}, \quad \text{(A6)}$$

and

$$R^{humboldt} = \frac{NASC^{humboldt}}{NASC^{hake} + NASC^{humboldt}}, \quad \text{(A7)}$$

with

$$R^{hake} + R^{humboldt} = 1.$$

$NASC^{hake}$ for an area represented by the haul is $\frac{\sigma_{tot}^{hake} n^{hake} \overline{H}}{V_{haul}}$, where V_{haul} is the volume of the haul, and $\overline{H}$ is the average height of the area. ($NASC$=s_A, $s_a = s_v \overline{H}$, s_v=$\sigma_{tot}^{hake}/V_{haul}$, $s_A = 4\pi 1852^2 s_a$). Hence,

$$R^{hake} = \frac{4\pi 1852^2 n^{hake} \overline{\sigma}_{bs}^{hake} \frac{\overline{H}}{V_{haul}}}{4\pi 1852^2 \left(n^{hake} \overline{\sigma}_{bs}^{hake} + n_{humboldt} \overline{\sigma}_{bs}^{humboldt}\right) \frac{\overline{H}}{V_{haul}}}, \quad \text{(A8)}$$

or

$$R^{hake} = \frac{n^{hake} \overline{\sigma}_{bs}^{hake}}{n^{hake} \overline{\sigma}_{bs}^{hake} + n_{humboldt} \overline{\sigma}_{bs}^{humboldt}} = \frac{\overline{\sigma}_{bs}^{hake}}{\overline{\sigma}_{bs}^{hake} + (n_{humboldt} / n^{hake}) \overline{\sigma}_{bs}^{humboldt}}. \quad \text{(A9)}$$

$\overline{\sigma}_{bs}^{hake}$ and $\overline{\sigma}_{bs}^{humboldt}$ can be calculated from Eqs. (A2) and (A3), respectively. Since we assume the ratio of $n_{humboldt}$ to n^{hake} from the region of interest is the same as that from the trawl catch, R^{hake} can be determined uniquely.

Similarly, $R^{humboldt}$ can be determined by

$$R^{humboldt} = \frac{n_{humboldt} \overline{\sigma}_{bs}^{humboldt}}{n^{hake} \overline{\sigma}_{bs}^{hake} + n_{humboldt} \overline{\sigma}_{bs}^{humboldt}}. \quad \text{(A10)}$$

E. Biomass Determination

$NASC^{hake}$ and $NASC^{humboldt}$ values for the entire aggregation region can be uniquely determined by solving Eqs. (A6) and (A7):

$$NASC^{hake} = \frac{R^{hake}}{R^{hake} + R^{humboldt}}, \quad \text{(A11)}$$

and

$$NASC^{humboldt} = \frac{R^{hake}}{R^{hake} + R^{humboldt}}. \tag{A12}$$

The total numbers of hake and Humboldt squid in the aggregation can then be computed using Eqs. (27b) and (28b). Note that s_A is the same as *NASC*. The corresponding biomass of hake and Humboldt squid can be obtained using Eqs. (29) and (30).

II. Trawl data collected by Canada Acoustics Team

Available data: (a) Total catch weights of hake and Humboldt squid
(b) Sub-sampled individual hake length and weight for some trawls and length only for other trawls

A. Use the length-weight regression coefficients of the Humboldt squid obtained from US survey.
B. Get $\bar{\sigma}_{bs}^{hake}$ of hake the same way as for the US survey (Step B).
C. The average weight and length of individual Humboldt squid is obtained from the US Humboldt squid catch data, and the average length is calculated using Eq. (A4). The average differential backscattering cross section of Humboldt squid ($\bar{\sigma}_{bs}^{humboldt}$) can be calculated by using Eq. (A2). In addition, the approximate or estimated total number of Humboldt squid ($n_{humboldt}$) from the catch can be determined since we have the total catch weight of the Humboldt squid.
D. Two types of sub-sampled hake data:
   a. For trawls sub-sampled hake length and weight data are available, get average weight of individual hake directly from the data and get the estimated total scattering contribution using Eq. (A5).
   b. For each trawl that has only length data: (i) first find all the trawls within the same stratum but have both length and weight measurements for sub-sampled hake catch; (ii) find the length-weight regression coefficients as in (1); (iii) compute the average weight using the regression coefficients from the average length obtainable from the trawl data; (iv) get total number of hake caught by the trawl (n_{hake}); (v) obtain the total backscattering contribution from all the hake and Humboldt squid by using Eq. (A5).
E. The same as for the US survey.

Appendix B

Background of Kriging Technique

Kriging is a technique that provides the Best Linear Unbiased Estimator of the unknown quantities (Journel and Huijbregts, 1978; Kitanidis, 1997). It is a local estimator that can provide the interpolation and extrapolation of the originally sparsely sampled data that are assumed to be reasonably characterized by the Intrinsic Statistical Model (ISM). An ISM does not require the quantity of interest to be stationary, i.e., its mean and standard deviation are independent of position, but rather that its covariance function depends on the separation of two data points only:

$$\mathrm{E}[\ (\mathrm{z}(\mathbf{x}) - \mathrm{m})(\mathrm{z}(\mathbf{x}+\mathbf{h}) - \mathrm{m})\ ] = C(h), \tag{B1}$$

where $\mathrm{z}(\mathbf{x})$ is the quantity to be kriged, m is the mean of $\mathrm{z}(\mathbf{x})$, and $C(h)$ is the covariance function with lag h, with h being the distance between two samples at $\mathbf{x}$ and $\mathbf{x}+\mathbf{h}$:

$$h = \|\ \mathbf{x} - (\mathbf{x}+\mathbf{h})\ \| = \sqrt{(x_1 - x_1')^2 + (x_2 - x_2')^2 + (x_3 - x_3')^2}. \tag{B2}$$

Another way to characterize an ISM is to use a semi-variogram,

$$\gamma(h) = 0.5^*\ \mathrm{E}[\ (\mathrm{z}(\mathbf{x}) - \mathrm{z}(\mathbf{x}+\mathbf{h})\ )^2] \tag{B3}$$

The relation between the covariance function and the semi-variogram is

$$\gamma(h) = C(0) - C(h). \tag{B4}$$

The *kriging* method finds a local estimate of the quantity at a specified location, $\mathbf{x}_L$. This estimate is a weighted average of the N adjacent observations:

$$\hat{z}(\mathbf{x}_L) = \sum_{\alpha=1}^{N} \lambda_\alpha z(\mathbf{x}_\alpha) \tag{B5}$$

The weighting coefficients λ_α can be determined based on the minimum estimation variance criterion:

$$E\left\{\left[z(\mathbf{x}_L) - \hat{z}(\mathbf{x}_L)\right]^2\right\} = C(0) - 2\sum_\alpha \lambda_\alpha C(\|\mathbf{x}_\alpha - \mathbf{x}_L\|) + \sum_\alpha \sum_\beta \lambda_\alpha \lambda_\beta C(\|\mathbf{x}_\alpha - \mathbf{x}_\beta\|) \tag{B6}$$

subject to the normalization condition

$$\sum_{\alpha=1}^{N} \lambda_\alpha = 1 \tag{B7}$$

Note that we don't know the exact value at $\mathbf{x}_L$, but we are trying to find a predicted value that provides the minimum estimation variance. Differentiating Eq. (B6) with respect to λ_α results in

$$\begin{aligned} &\sum_{\beta=1}^{N} \lambda_\beta C_n(\|\mathbf{x}_\alpha - \mathbf{x}_\beta\|) - \mu = C_n(\|\mathbf{x}_\alpha - \mathbf{x}_L\|) \\ &\sum_{\beta=1}^{N} \lambda_\beta = 1 \end{aligned} \tag{B8}$$

where μ is the Lagrangian coefficient. In addition, we have replaced the covariance function with the normalized covariance function [normalized by $C(0)$]. Equivalently, by using Eq. (B4), the kriging equation can also be expressed in terms of the semi-variogram as

$$\begin{aligned} &\sum_{\beta=1}^{N} \lambda_\beta \gamma_n(\|\mathbf{x}_\alpha - \mathbf{x}_\beta\|) + \mu = \gamma_n(\|\mathbf{x}_\alpha - \mathbf{x}_L\|) \\ &\sum_{\beta=1}^{N} \lambda_\beta = 1 \end{aligned} \tag{B9}$$

where we have used the normalized semi-variogram, i.e., the semi-variogram normalized by $C(0)$ as we did in deriving Eq. (B8).

Having obtained the weighting coefficients (λ_β) and the Lagrangian coefficient (μ) by solving either Eq. (B8) or Eq. (B9), the kriging variance, Eq. (A6), can be expressed as:

$$\begin{aligned} \sigma_L^2 = E\left\{\left[z(\mathbf{x}_L) - \hat{z}(\mathbf{x}_L)\right]^2\right\} &= C(0) + \mu - \sum_\alpha \lambda_\alpha C(\|\mathbf{x}_\alpha - \mathbf{x}_L\|) \\ &= \mu + \sum_\alpha \lambda_\alpha \gamma(\|\mathbf{x}_\alpha - \mathbf{x}_L\|) - \gamma(0) \end{aligned} \tag{B10}$$

The above equations are the basis of the kriging software package.