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DEVELOPMENT OF ACOUSTIC TECHNIQUES FOR ASSESSMENT OF ORANGE ROUGHY *HOPLOSTETHUS ATLANTICUS* BIOMASS OFF NAMIBIA, AND OF METHODS FOR CORRECTING FOR BIAS

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Orange roughy form dense spawning aggregations in specific small areas in deep water on the Namibian shelf between late June and early August each year. The biomass in three such areas, where most commercial fishing occurs (the Johnies, Frankies and Rix Quota Management Areas, or QMAs) has been assessed acoustically each year since 1997. Acoustic estimates of the aggregated portion of the biomass (the only component that can be assessed reliably using acoustics) were obtained for all three QMAs in 1997 and 1998, but only for Frankies in 1999 owing to increased problems with target identification as the biomass declined. The methodology developed for these surveys, including the equipment used, survey design, target identification, data processing and error analysis are described. Some important biases that should be corrected for when estimating absolute abundance of orange roughy acoustically are addressed. Individual sources of error were quantified as well as possible, and input to an error model that simulated the error process and produced probability density functions of absolute biomass, from which the mean absolute biomass and its standard error could be computed for each survey, effectively correcting for identified sources of bias and quantifying the overall uncertainty. The correction factors ranged from 1.58 to 1.71 and the *CV*s increased by factors of 1.2–2.1. Target strength uncertainty and negative bias attributable to the dead zone close to the bottom were considered to be the most serious errors. The acoustic estimates indicate a substantial decline in orange roughy biomass in all three QMAs since 1997, in accord with indices from contemporaneous swept-area surveys and the catch rate of the commercial fleet. Acoustic estimates have already been used extensively to manage the resource and are likely to remain important in the future.

Key words: acoustics, deep-water fisheries, orange roughy, survey

The orange roughy *Hoplostethus atlanticus* is a long-lived, slow-growing trachichthyid fish, that has a worldwide distribution at depths of 500–1 500 m. There are major stocks off New Zealand and smaller stocks southeast of Australia, along the Mid-Atlantic Ridge, on the Namibian shelf and in the southern Indian Ocean.

The fish aggregate densely on or close to the bottom during the austral winter, between late June and early August off New Zealand (Clark 1995), Australia (Koslow *et al.* 1994) and Namibia (Boyer *et al.* 2001a). The aggregations are often associated with bottom features such as pinnacles and canyons, although the fish occasionally also form plumes extending more than 100 m above the bottom. It is believed that the formation of dense aggregations is related to spawning, in that the behaviour is well synchronized and at the same time each year, although not all individuals spawn annually (Bell *et al.* 1992, Clark and Tracey 1994). Aggregations are found throughout the year, however, but at lower densities outside of the spawning season. This aggregating behaviour, combined with low productivity, makes orange roughy stocks highly vulnerable to overfishing.

Exploration for orange roughy in Namibia started in 1994 and, within a year, several aggregations had been discovered, suggesting that the stock was large enough to support a viable fishery (Boyer *et al.* 2001a). During 1996 more than 13 000 tons were caught by the single company then operating in the fishery, and it became clear that the fishery was to become a major contributor to the Namibian fisheries sector. The exploratory phase of the fishery ended at the end of 1996, when two additional companies were given licences to fish in the established fishing areas. By that time, four commercially viable grounds (subsequently designated as Quota Management Areas, or QMAs, for management purposes) had been found, three of which (Johnies, Frankies and Rix) are on the shelf-break off central Namibia, and the fourth (Hotspot) is off northern Namibia, on the southern edge of the Walvis Ridge (Boyer *et al.* 2001a). No further high-density areas have been discovered, despite extensive exploration, but it is possible that such areas do exist within the Namibian Exclusive Economic Zone. A full description of the Namibian orange roughy fishery, including critical biological parameters, is provided by Boyer

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et al. (2001a), and Branch (2001) gives a general overview of the biology, fisheries and management of orange roughy worldwide.

In 1995, the Namibian Ministry of Fisheries and Marine Resources instituted a comprehensive monitoring scheme for orange roughy. A proactive research programme, including annual surveys of the main commercial grounds, was planned in 1996 and started in 1997, with the initial aim of obtaining an absolute estimate of virgin biomass, knowledge of which was considered crucial for assessment and management of the stock. Thereafter the surveys were intended to be used in a relative sense, to monitor changes in abundance. Surveys were favoured above traditional catch-rate-based models of stock reduction, because the latter require a number of years of commercial catch data and would probably be highly biased owing to the extremely patchy distribution of the species (Kirchner and McAllister in press).

Several different survey methods were considered. Surveys of eggs and larvae, used to estimate orange roughy biomass off Australia (Koslow *et al.* 1995) and New Zealand (Zeldis 1993), were rejected because they tend to be very imprecise as a result of the aggregating behaviour of the fish; also, Namibia did not have the technical capacity or expertise to conduct such surveys. Swept-area bottom trawl surveys, based on the methodology developed for orange roughy surveys off New Zealand (see Francis 1984) were considered worth attempting, and were subsequently introduced. However, it was appreciated that such surveys would probably also be imprecise because of the highly aggregated nature of the population, and that they would only give relative estimates of biomass (Francis 1992, Clark 1996) because the catchability coefficient for orange roughy would be highly uncertain and difficult to estimate.

Acoustic survey techniques offered an attractive, cost-effective alternative. Such techniques can be applied to orange roughy because their aggregating behaviour makes them acoustically detectable despite their low target strength (low because their swimbladder is filled with wax esters) and deep habitat (Clark 1996, Kloser 1996, Kloser *et al.* 1997). Although there are numerous problems involved, largely associated with the depth at which the fish live, their closeness to the bottom and low target strength, the method offered the prospect of absolute estimates because the errors are, to some extent, potentially quantifiable. It was also an advantage that there was a body of literature and experience in acoustic surveys of orange roughy off Australia and New Zealand (e.g. Do and Coombs 1989, Elliott and Kloser 1993, Bulman and Elliott 1994, Clark 1996, Kloser 1996) that could be drawn upon in planning and implementing the surveys. Finally, Namibia, although a developing country, had access to the acoustic equipment and vessels (both research and commercial) and acoustic expertise needed for the surveys.

This paper describes the development of the acoustic survey programme from 1997 to 2000, presents those estimates of orange roughy biomass that are considered valid, and discusses in some depth the sources of error, and the ways in which allowance was made for them.

METHODOLOGY

The general approach to the Namibian surveys was to adapt methods used in acoustic surveys of orange roughy off Australia (e.g. Kloser 1996, Kloser *et. al.* 1997) and, to a lesser extent, New Zealand, (e.g. Do and Coombs 1989, Clark 1996) to local conditions and capacity. Information on orange roughy behaviour off Australia and New Zealand (M. R. Clark, NIWA, Wellington, New Zealand, pers. comm., R. J. Kloser, CSIRO, Hobart, Tasmania, pers. comm.) was also helpful in determining the initial survey strategy. Full descriptions of the methods, including biological and acoustic sampling protocols, survey design, data analysis and results are available in the relevant survey reports (Huse *et al.* 1997, Dalen *et al.* 1998, Staalesen *et al.* 1999, Boyer *et al.* 2001b), but they are summarized here for convenience.

General description of surveys

As very little was known of the distribution and aggregating behaviour of orange roughy off Namibia prior to the surveys, it seemed sensible to attempt a survey of the QMAs and to ignore the fact that part of the stock could appear outside them. It was accepted that this would introduce a negative bias were not all the population to spawn every year (e.g. Bell *et al.* 1992) or if there are still undiscovered spawning areas outside the QMAs, and that such biases could be large. For example, Bell *et al.* (1992) found that the non-spawning proportion of the orange roughy population off south-eastern Australia varied considerably from year to year, and that it could be as large as 45%.

As commercial catch data suggested that the abundance in the northernmost QMA, Hotspot, is much smaller than in the QMAs to the south, it was decided in the interests of cost-effectiveness to restrict the surveys to the other three QMAs, at least initially. (Subsequent catch data have justified this decision and to date Hotspot has not been surveyed.) The other

Table I: Vessels used for the acoustic surveys and some critical parameters of the sampling equipment

Parameter	1997	1998	1999
Vessel used to collect acoustic data	*Dr Fridtjof Nansen*	*Dr Fridtjof Nansen*	*Dr Fridtjof Nansen*
Echo-sounder	SIMRAD EK500	SIMRAD EK500	SIMRAD EK500
Frequency (kHz)	38	38	38
Acoustic software	EK500 Version 4.01	EK500 Version 5.30	EK500 Version 5.30
Transducer gain (dB)	27.50	27.54	27.48
Pulse duration (ms)	1.0	1.0	1.0
Beam width (degrees)	6.8	6.8	6.8
Sound velocity (m s^{-1})	1 500	1 500	1 500
Absorption coefficient (dB km^{-1})	10	10	10
S_V threshold (dB)	-76	-76	-76
Vessel(s) used for species identification	*Southern Aquarius*	*Emanguluko*	*Emanguluko* and *Hurinus*
Trawl type	New Zealand "Arrow" with 20 mm codend liner	New Zealand "Arrow" with 20 mm codend liner	New Zealand "Arrow" with 20 mm codend liner
Wingtip-to-wingtip distance (m)	20	15	15
Headline height (m)	6	5–6	6

three QMAs were all surveyed acoustically in 1997, 1998 and 1999. At Johnies and Rix, where orange roughy tend to be concentrated in a single area, estimates were made for the whole QMA as a unit, but at Frankies, where the fish tend to aggregate in three distinct areas (Three Sisters, Frankies Flats and 21 Jump St) estimates were sometimes made for each area separately, then combined to give an estimate for the whole QMA. In 2000, only the Frankies and Rix QMAs were surveyed acoustically because of time constraints and the difficulty experienced in the two previous years in obtaining usable acoustic estimates at Johnies.

The surveys were conducted largely during the second half of July each year when, according to biological data from commercial samples, spawning peaks (Boyer *et al.* 2001a). Survey duration varied between 2 and 3 weeks. The vessel used from 1997 to 1999 was the R.V. *Dr Fridtjof Nansen*, a 58 m research stern trawler operated by the Institute of Marine Research on behalf of the Norwegian Agency for Development Cooperation (NORAD) and in cooperation with the Food and Agricultural Organization of the United Nations. As the vessel has neither the equipment nor expertise for deep-water trawling of orange roughy, and because it does not have the capacity to handle the large catches that are occasionally made, acoustic target identification in the surveys was done mainly by supporting commercial orange roughy trawlers that used standard deep-water fishing gear with small-meshed (20 mm) codend liners. In 2000, the survey, including all target identification hauls, was done from a commercial vessel, F.V. *Conbaroya Cuarto* (operated by Coastal Marine Industries, Lüderitz). (The results from that survey are still being analysed and are not presented here, although the methodology employed is discussed briefly.) The commercial vessels used for target identification between 1997 and 1999 were F.V. *Southern Aquarius* (Gendor Fishing), F.V. *Emanguluko* (Glomar Fisheries) and F.V. *Hurinis* (Atlantic Sea Products). All three companies are registered and based in Walvis Bay.

Table I summarizes the role of the vessels in each survey and specifications of the sampling equipment used.

Equipment

The surveys on *Dr Fridtjof Nansen* were made with a Simrad EK 500 echo-sounder, firing into an ES38B split-beam 38 kHz transducer, mounted on a protruding keel that could be lowered 2.5 m below the hull to reduce the effects of surface aeration. On *Conbaroya Cuarto*, a 38 kHz Simrad EK60 scientific sounder was used, firing into a ES38B transducer mounted in a fixed hull-mounted blister to reduce flow noise. Particular attention was paid to the suppression of electrical interference, often a problem when commercial vessels are used for acoustic survey work.

In 1997, a SIMRAD ES38D pressure-compensated split-beam transducer mounted on a remotely controlled towed body (FOCUS 400 Mk II, MacArtney A/S Underwater Technology, Esbjerg, Denmark) and interfaced to a SIMRAD EY500 portable echo-sounder, was used for a short period to examine the effects on the estimates of the height of the transducer above the orange roughy targets. The system was towed at a depth of about 380 m for almost 60 miles during the survey. The keel-mounted acoustic system was operated simultaneously, allowing acoustic data collected by the two systems to be compared.

Table II: Summary of the number of coverages of each QMA showing the sizes of the areas surveyed

Year	Area	Number of coverages	Area of initial broad survey (nautical miles^2)	Average area of final intensive surveys (nautical miles^2)
1997	Johnies	4	121	25
	Frankies – Three Sisters	4	410 (all three areas surveyed together)	8
	Frankies – Frankies Flats	3		11
	Frankies – 21 Jump St	3		5
	Rix	3	109	27
1998	Johnies	6	430	5
	Frankies – Three Sisters	4	407 (all three areas surveyed together)	24
	Frankies Flats	4		13
	Frankies – 21 Jump St	4		19
	Rix	8	214	28
1999	Johnies	7	323	47
	Frankies – Three Sisters	6	323 (all three areas surveyed together)	25
	Frankies Flats	4		33
	Frankies – 21 Jump St	2		35
	Rix	7	103	31

For each survey, the on-axis sensitivity of the sounder was estimated to within ±0.2 dB by sphere calibration (Foote *et al.* 1987) either shortly before or shortly after the survey. As an overall check on the system performance, an inter-calibration exercise with the R.V. *Welwitchia* (a 47 m research vessel operated by the Ministry of Fisheries and Marine Resources in Namibia, which carries similar acoustic survey equipment to *Dr Fridtjof Nansen*) was conducted during the 1999 survey. The methodology employed followed the general procedure recommended by Foote *et al.* (1987). The two vessels alternated the lead for almost 150 miles, keeping a distance of between 0.2 and 1.0 miles apart. Their acoustic systems were set up identically.

A Bergen Echo-Integrator (BEI) system, operating on a UNIX-based Workstation on *Dr Fridtjof Nansen*, was used to capture and analyse the acoustic data in 1997 and 1998. In 1999, most of the on-board analysis, and all analysis after the cruise, was done through ECHOVIEW (Version 1.50.30), a PC-based analysis system developed by Messrs SonarData Tasmania (Pty) Ltd, Hobart. On *Conbaroya Cuarto* all acoustic data capture and analysis was done through Version 1.51.20 of ECHOVIEW.

A Seabird SBE 911*plus* (Sea-Bird Electronics, Inc.) CTD (conductivity, temperature, depth) profiler with an attached oxygen sensor and a General Oceanics rosette was used to obtain vertical profiles of oceanographic data. At each QMA, samples were taken on an east-west transect across the centre of the main aggregation and on transects several miles to the north and south of that aggregation. Each line consisted of 3–5 stations spaced equally between the 500 and 1 000 m isobaths. The data from the profile at the centre of the QMA were used, *inter alia*, to calculate sound velocity and the sound absorption between the transducer and orange roughy targets.

Survey design and strategy

The highly concentrated and static nature of the aggregations called for a design in which effort is concentrated in small areas. Typically, surveys covered about 400 miles^2 initially. The survey area was usually reduced to 10–30 miles^2 as the distribution of aggregations was pinpointed (see Table II). For all surveys, each QMA was surveyed at least three times using systematic or random E-W transects (the direction of greatest expected change in density), effort being increasingly concentrated on areas of high abundance as the survey progressed, to improve precision.

The initial survey areas were pre-selected on the basis of commercial catch information earlier in the season and the results of surveys in previous years when available. The first one or two coverages covered the pre-selected area on transects spaced equally 1 or 2 miles apart, and were intended primarily to establish the general distribution of orange roughy in the area. In subsequent coverages, the area was narrowed down in both N-S and E-W directions to intensify sampling effort in the region where the highest densities had been recorded in the initial coverages. As many intensive coverages of the target area were then completed as time and circumstances allowed, transect spacing usually being reduced to 0.5 miles. On a number of occasions, a random transect design was used for the intensive coverages. Where a systematic coverage was repeated, the grids were usually displaced

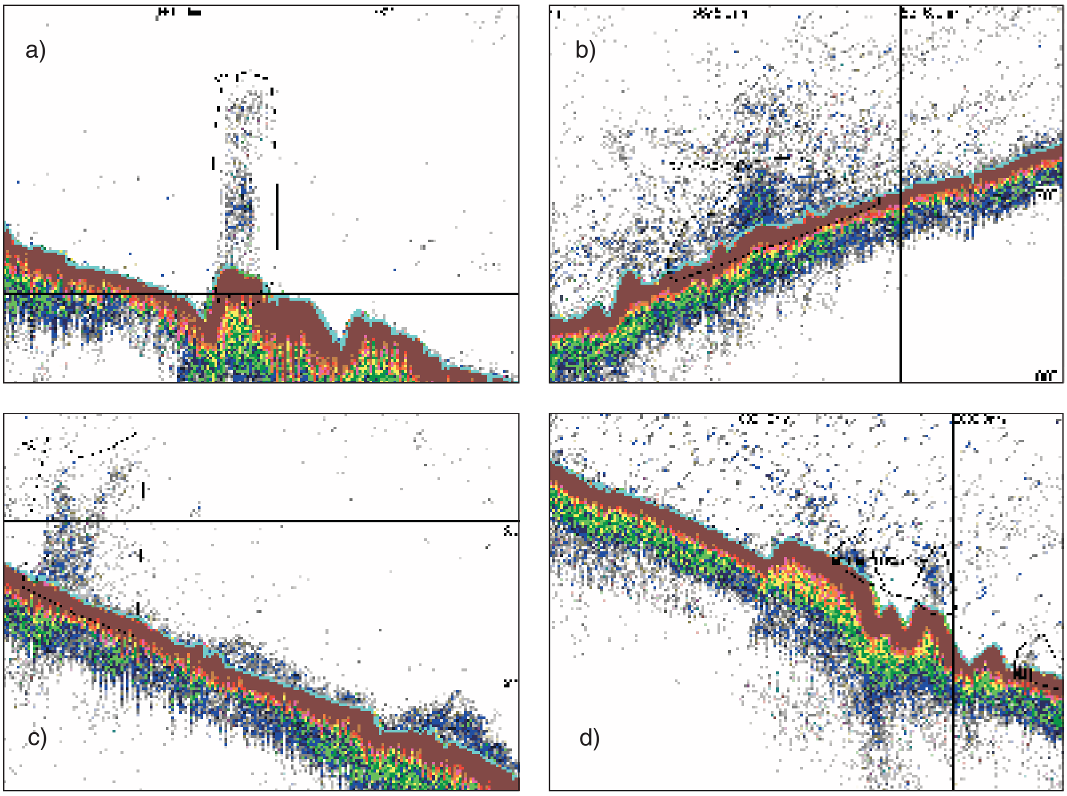

Fig. 1: Examples of echograms showing typical orange roughy aggregations – (a) plume lifting more than 100 m from the bottom, (b) mixed with other species, (c) a typical dispersion of other species downslope of the orange roughy aggregation, and (d) with hake upslope and in midwater around the orange roughy aggregation. S_V threshold set at -70 dB

by half a transect spacing to minimize the areas left unsampled. Typically, the distribution of the aggregations could be defined adequately after at most two broad coverages, each taking about a day to complete. A number of intensive coverages could usually be completed in a day.

Table II summarizes the number of coverages of each QMA and the range of areas surveyed during each survey. It will be noted that, in most cases, there is a substantial reduction in the areas surveyed in the initial broad and subsequent intensive coverages.

Target identification

Acoustic targets were identified on the basis of the characteristics of acoustic recordings, validated as far as possible by targeted bottom trawling either from a second vessel or, in 2000, from the survey vessel itself. Features examined were shape, density, definition, depth of aggregation and water depth, relation to bottom features and proximity to other similar aggregations within the same depth range. Figure 1 shows a number of aggregations classified as orange roughy, as well as a number of other acoustic targets considered not to be orange roughy.

The trawls were assumed to sample all species equally and without bias. As only the targeted acoustics method (see below) was used to estimate biomass, this assumption is not critical because the aggregations included in these estimates were assumed to contain only orange roughy. Of greater importance may have been the assumption that fish in that part of the aggregation above the trawl headrope, which were not sampled, were also orange roughy.

Where a second vessel was used to identify targets,

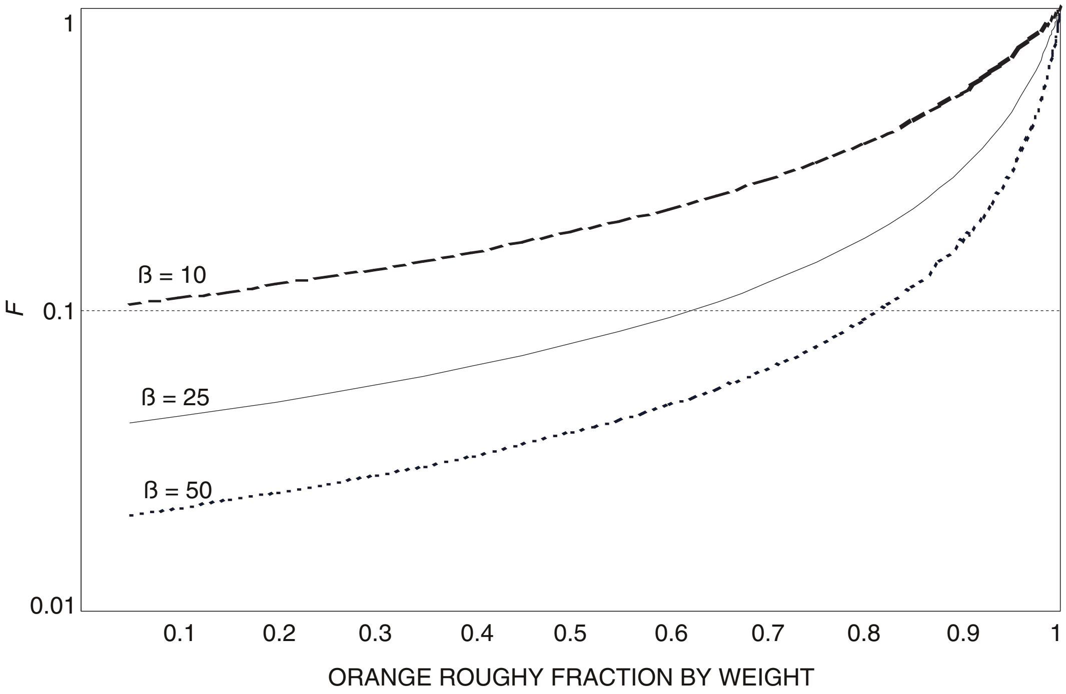

Fig. 2: Scaling-factors (*F*) for calculating the density of orange roughy in heterogeneous aggregations as a function of the proportion by weight of orange roughy in the aggregation, for three different ratios (β) of the mean backscattering strength of other species to that of orange roughy

every attempt was made to synchronize the vessels in time and space to maximize the chance of the catcher vessel sampling the target detected by the survey vessel, or one similar to it. However, problems often arose when the vessels became separated for operational reasons, or if the targets were small or changed in characteristic between the times of detection and attempted identification. When a single vessel was used, the usual strategy was to interrupt the survey and to make an identification haul almost immediately after detecting the target.

Over the study period, the ability to identify aggregations from a second vessel deteriorated because of the decreasing number of large, easily targeted aggregations, to the extent that, in 1999, an acoustic estimate could only be made at one QMA. Despite a large number (117) of targeted trawls by the catcher vessels conducted in the three QMAs, the only orange roughy targets that could be identified with any certainty were at Frankies. It was largely because of this fact that a commercial vessel capable of trawling for orange roughy was used for the survey in 2000.

DATA ANALYSIS

Biomass estimation methods

Biomass estimates for the QMAs were calculated from all coverages of the QMAs considered valid for biomass estimation. Coverages were discarded if the weather conditions were regarded as too poor, if the fish were unusually close to the seabed, or if there was great uncertainty concerning acoustic target identity. The following methods of estimating orange roughy biomass in the presence of echoes from other species were tried at various stages of the programme:

Targeted acoustics (1997–2000) — In this method, which is equivalent to the "school-based" acoustic method of Kloser *et al*. (2000), the biomass was estimated from the average backscattering intensity of well-defined aggregations, characteristic of orange roughy, assuming that no other species were present in the aggregations. All other targets were excluded, so the dispersed portion of the population was ignored.

Trawl-based acoustics (1997 and 1998) — Here, all acoustic targets possibly containing orange roughy were included. The contribution of the orange roughy to the backscatter was calculated from the species composition of nearby identification trawls and published estimates of the target strengths of the major species present. Aggregations typical of orange roughy were assumed to consist only of orange roughy, as in the targeted acoustics method. The allocation of trawls to dispersed targets was made either solely on the basis of their proximity to each other, or alternatively by also taking the physical characteristics of the targets into account (the so-called "scrutinized acoustics" method commonly used in acoustic surveys, MacLennan and Simmonds 1992).

Acoustics/swept area (1997 only) — In this method, targeted acoustic estimates of the aggregated component were added to estimates of dispersed orange roughy obtained from a contemporaneous swept-area survey on a commercial vessel. This method was not used after 1997 because of concerns that, owing to very different potential biases in the acoustic and swept-area estimates, it was inappropriate to combine them directly in this way.

The first two methods are both highly sensitive to errors in species composition, primarily because orange roughy do not possess gas-filled swimbladders, and therefore have low specific target strengths compared to most of the other species contributing to the backscatter. When other species are present, estimates of orange roughy biomass made on the assumption that there are no other species present, have to be scaled down by a factor F, given by

$$F = \frac{p_{ORH}}{\left(\beta + (1-\beta) p_{ORH}\right)} \quad ,$$

to account for the other species, where β is the ratio between the mean backscattering cross-section of orange roughy and that of the other species present, and p_{ORH} is the proportion by weight of orange roughy in the mixture. In Figure 2, F is plotted against p_{ORH} for β = 10, 25 and 50, covering the likely range of target strength ratios for the species typically found in orange roughy mixtures (e.g. hake *Merluccius* spp., deep-water sharks Squalidae, oreo dories Oreosomatidae, rattails Macrouridae). F is very sensitive to p_{ORH}, as well as to the value of β. As uncertainty in these parameters is likely to be large because of non-representative sampling by the trawl and the great uncertainty concerning the target strengths of the individual species commonly encountered, the trawl-based method was considered to be too unreliable to be used, and after 1998 it was discarded.

It is concluded, after attempting all the above methods, that valid acoustic estimates of orange roughy biomass can only be obtained by the targeted acoustic method, and then only when most of the population is aggregated into monospecific aggregations that can be identified with confidence as orange roughy. These conditions applied for enough of the 1997 and 1998 surveys for acoustic estimates to be made from a reasonable number of the coverages, but in 1999, when the aggregations were generally small and difficult to identify, the method could only be applied with any confidence at Frankies.

In order to ensure standardization in identification of targets and to reduce observer drift, the 1997, 1998 and 1999 survey data were rescrutinized entirely after the 1999 survey. These rescrutinized data are presented here.

In estimating biomass and sampling variance, the transects were taken as basic sampling units, as recommended by Jolly and Hampton (1990). The mean orange roughy density for a coverage was estimated from the mean area backscattering intensity:

$$\bar{S}_a = \frac{\sum_{i=1}^{n} \left(\bar{S}_a\right)_i L_i}{\sum_{i=1}^{n} L_i} \quad , \qquad (1)$$

where $(\bar{S}_a)_i$ is the mean area backscattering intensity for transect i, L_i the length of transect i, and n is the number of transects in the coverage. The sampling variance of $(\bar{S}_a)$ was estimated from the following expression, based on Jolly and Hampton (1990):

$$Var\left(\bar{S}_a\right) = \frac{n}{(n-1)} \frac{\sum_{i=1}^{n} L_i^2 \left[\left(\bar{S}_a\right)_i - \bar{S}_a\right]^2}{\left(\sum_{i=1}^{n} L_i\right)^2} \quad . \qquad (2)$$

This expression, which is appropriate for transects spaced randomly, was used for all calculations of sampling variance, even though the transects were evenly spaced in most cases. The consequence of this is that the sampling variance will tend to be slightly overestimated (Jolly and Hampton 1990).

The mean density of orange roughy in mass per unit area, $\bar{\rho}$, was estimated from $(\bar{S}_a)$ through the expression

$$\bar{\rho} = \frac{\bar{S}_a}{\bar{\sigma}_{kg}} \quad ,$$

where σ_{kg} is the mean backscattering cross-section per kg of orange roughy in the area, estimated from a pooled length distribution for the area through the equation

$$\bar{\sigma}_{kg} = \frac{4\pi 10^{0.1B_{20}} \sum_{j=1}^{M} m_j L_j^{2-\mathrm{b}}}{\mathrm{a} \sum_{j=1}^{M} m_j} \quad ,$$

where a and b are the coefficient and exponent respectively in a general orange roughy weight/length expression for the area, L_j the midpoint of length class j, and m_j is the number of orange roughy in that length-class. B_{20} is the constant in the target strength/length expression $TS = 20 \log L + B_{20}$.

As no measurements have yet been made on the target strength (TS) of orange roughy off Namibia, B_{20} values obtained elsewhere had to be used. Those chosen were *in situ* rather than *ex situ* estimates (e.g. those of McClatchie *et al.* 1999, McClatchie and Ye 2000), because the latter cannot be applied readily without some knowledge of the orientation of the fish with respect to the incident acoustic beam. B_{20} was initially taken from an *in situ* estimate of orange roughy TS obtained by Kloser *et al.* (1997) off Tasmania. They obtained an estimate of -50.0 dB for fish of mean length 35.8 cm, which gives a B_{20} value of -81.0 dB, some 2 dB lower than predictions from the *ex situ* work of McClatchie *et al.* (1999) and McClatchie and Ye (2000), which those authors attributed to avoidance reactions in the *in situ* experiments. Subsequently, the B_{20} value was corrected to -82.0 dB on the basis of information supplied by Kloser (pers. comm.). More recent *in situ* experiments on target strength on the Chatham Rise, conducted jointly by Kloser and Soule in 1998 (Kloser *et al.* 2000, M. A. Soule, formerly Marine & Coastal Management [MCM], Cape Town, pers. comm.), have suggested a target strength of -51.5 dB for a 33.5 cm orange roughy, which gives a B_{20} value of -82.02 dB, supporting this estimate. The estimate is further supported by independent *in situ* experiments on the Chatham Rise at the same time by McClatchie and Coombs (2000), who reported a value of -51 dB for fish of the same size. Those authors' caution regarding the uncertainty of this result should, however, be noted.

The orange roughy in the Australian and New Zealand experiments (35 and 33.6 cm standard length) were substantially larger than in the Namibian surveys, where the mean length was around 27 cm. Adjustment for length is done through the above equation, which assumes that the backscattering cross-section is proportional to L^2. The applicability and accuracy of the B_{20} estimate, and possible errors introduced through the adjustment for length, are discussed in the next subsection.

The estimates of the mean density for a coverage, and of the sampling variance of this estimate, were raised to the size of the area surveyed to give estimates of biomass and corresponding sampling variance. An overall biomass estimate for the QMA was obtained by simple averaging of the estimates for all coverages considered valid for biomass estimation. The *CV* of this average was obtained from the sum of the sampling variances in the individual estimates.

Estimation of error and correction for biases

The results of all surveys are subject to random and systematic error (biases). In cases where they cannot be estimated and corrected for, the biases are usually assumed to be small, or at least to be multiplicative constants so that estimates can be compared in a relative sense. One of the advantages of acoustic surveys is that systematic and random errors can often be quantified, at least to some extent, enabling a quantitative error analysis to be undertaken, so providing estimates of absolute abundance. Such an analysis has been attempted here by estimating the individual errors as well as possible as input to an error model that combined their effect through a Monte Carlo simulation process to give a probability density function (pdf) of the overall multiplicative factor to be applied to correct for error, and to estimate the absolute accuracy of the corrected estimate. In each run of the model, the values of the individual error factors were drawn randomly and independently from pdfs that were uniform between specified limits (the so-called "likely range" of the error) and decreased exponentially on either side of these limits to a specified minimum and maximum. In cases where a bias was assumed, and hence the pdf was not centred on 1, the model corrected for it. The sources of error considered are described below, not necessarily in order of importance.

CALIBRATION ERROR

The on-axis sensitivity of an echo-sounder can be determined to within ±0.2 dB (approx. 5%) by sphere calibration under good conditions (Foote *et al.* 1987). The likely range was taken as 10% and the maximum range as double this value. As the sounder was cali-

Table III: Mean dead zones and overall dead-zone correction factors for the 1997 and 1999 surveys, including and excluding (in parenthesis) the effect of transducer tilt

QMA	Year	Mean dead-zone height (m)	Correction factor
Johnies	1997	8.16	1.58 (1.34)
	1999	10.24	1.46 (1.27)
Frankies	1997	7.17	1.71 (1.43)
	1999	7.64	1.62 (1.29)
Rix	1997	6.08	1.30 (1.14)
	1999	11.03	1.67 (1.51)

brated for each survey, the effect of the error would have been random. In addition, there could have been a systematic error of up to 1 dB in the equivalent beam factor used in converting from echo intensity to backscattering strength (Simmonds *et al.* 1992), on the basis of which it was assumed that the maximum systematic uncertainty was ±25% (approx. 1 dB), and the likely range ±10%. Note that the error would have had little effect on relative estimates made from *Dr Fridtjof Nansen* but that, when comparing with estimates from another vessel (e.g. *Welwitchia* or *Conbaroya Cuarto*), errors in the beam factors of the vessels could introduce significant uncertainty. This is a penalty for changing survey vessel in the course of the time-series, and was one of the reasons that intercalibrations between vessels were carried out. A 20% difference detected in the intercalibration of *Dr Fridtjof Nansen* and *Welwitchia* in 1999 could well be largely attributable to errors in the assumed beam factors on the two vessels (see Results).

ABSORPTION COEFFICIENT

Because of the long range to the targets (typically about 700 m), corrections for error in the absorption coefficient (α) set up in the sounder (10 dB km^{-1}) were necessary. These were computed from calculations of the average absorption coefficient at 38 kHz between the surface and near bottom in the region of highest orange roughy density, using temperature and salinity measurements from CTD casts in Francois and Garrison's (1982) expression for α as a function of frequency, depth, temperature, speed of sound and pH (assumed to be 8.0). The correction factors were typically about 1.10. The maximum range of the error after correction was taken as ±5%, the stated accuracy of Francois and Garrison's expression. The likely range was taken somewhat arbitrarily as half the maximum range. The error was classified as systematic, because the same expression was used in all surveys.

WEATHER

The effects of aeration in bad weather were minimized by use of the protruding keel, and by discarding estimates when there were obvious signs of signal attenuation in the echo recordings. Nonetheless, even in the accepted coverages there would have been a variable negative bias in poor weather, which, according to data from MacLennan and Simmonds (1992), could have been as large as 1 dB at times. A maximum error of 25% and a minimum of 0 was therefore assumed. The likely range was taken to be 5 –10%, centred on 7.5%.

TARGET STRENGTH

Kloser *et al.* (2000) quote an uncertainty of ±0.5 dB (±12%) in their estimate of mean target strength of a 33.5 cm orange roughy. However, considering the reported uncertainties in the identification of targets in their experiments (Soule, pers. comm.) and that *in situ* estimates of orange roughy target strength made on the Chatham Rise at the same time by other authors were some 0.5 dB higher, and were probably equally uncertain (McClatchie and Coombs 2000), a value of ±1 dB (approx. ±25%) is considered to be more realistic as a likely range for the target strength. This range has been doubled as an estimate of the maximum error.

Extrapolation to fish of a smaller size through the L^2 dependency could have introduced further error. For example, if an L^3 dependency (which could be more appropriate) had been used, the estimated target strength of a 27 cm fish would have dropped by 1.2 dB, resulting in a 32% increase in any biomass estimate based on this value. As the exponent lies between 2 and 3 for most species on which experiments of target strength have been conducted (MacLennan and Simmonds 1992), correction for a bias of 10–20% was considered appropriate. This was done by centring the error pdf on 1.15 (likely range 1.10–1.20). The minimum value was taken as 1.0 (L^2 dependency) and the maximum as 1.3 (L^3 dependency). If the target strength/ length relationship for orange roughy remains more or less constant, errors introduced through the use of a single expression for all surveys (as in this case) will tend to be systematic.

DEAD ZONE

Fish close to the bottom will not be detected at a range greater than the distance from the transducer to the seabed on the beam axis. This is the so-called acoustic dead zone. It increases with, *inter alia,* water depth, proximity of the fish to the bottom, and the slope of

Table IV: Error factors applied to acoustic estimates of absolute abundance

Factor	Minimum	Likely range	Maximum	Nature
Calibration (on-axis sensitivity)	0.90	0.95–1.05	1.10	Random
Calibration (beam factor)	0.80	0.90–1.10	1.25	Systematic
Absorption coefficient	0.95	0.98–1.02	1.05	Systematic
Weather	1.00	1.05–1.10	1.25	Random, centred on 1.075
Target strength (experimental error)	0.50	0.75–1.25	1.50	Systematic
Target strength (length dependency)	1.00	1.10–1.20	1.30	Systematic, centred on 1.15
Dead zone (including bottom slope and transducer tilt)	1.10	1.30–1.70	1.90	Random, centred on 1.50
Non-homogeneous aggregations	0.50	0.85–0.95	1.0	Random, centred on 0.90

the bottom. In the case of orange roughy, which are often found close to the bottom in deep water on rough ground, the proportion missed in the dead zone can be substantial. For example, Kloser (1996) estimated that, in surveys of orange roughy off Tasmania with a hull-mounted transducer, roughly half the biomass would be undetected in the dead zone, which can be more than 30 m high in places.

Attempts to estimate, and correct for, this effect were made by adapting Ona and Mitson's (1996) expression for the height of the dead zone for a 38 kHz vertical beam striking a flat bottom. The method, described in detail in Hampton and Boyer (in prep.), essentially involves integrating the acoustic beam function within the main lobe of the beam over the volume bounded by the wave front and the seabed, allowing for the slope of the bottom and transducer tilt. (It was necessary to include the latter, because it was estimated from analysis of the asymmetry in echoes of single fish that the 38 kHz transducer on *Dr Fridtjof Nansen* is tilted forward by almost 5°, which has a significant effect on the dead zone – see Table III.) The integral is a measure of the energy effectively lost from the beam. The ratio between it and the equivalent integral for a flat bottom and vertical beam gives a correction factor to be applied to Ona and Mitson's estimate for the height of the dead zone. This height, which depends on water depth, bottom slope and direction of steaming, was estimated for all aggregations used in estimating biomass, and was used to correct the backscattering intensity from each aggregation on the assumption that the density of the aggregation in the dead zone was the same as that in the 1 m depth channel immediately above it. Recalculation of the biomass using the corrected aggregation backscattering intensities gave an overall correction factor for the survey. Table III lists mean dead-zone heights and the overall correction factor for the aggregations in the 1997 and 1999 surveys. (Data from the 1998 and 2000 surveys have still to be analysed.)

The correction factors are large (Table III) and in all cases the contribution of transducer tilt to the correction is substantial. Although not definitive, the results of the comparison between the towed and hull-mounted transducer in 1997 are consistent with a dead-zone effect of this order (see Results).

As the means were similar between years, it was decided to apply a constant correction of 1.50, and to set the likely range to the range of estimates in Table III (i.e. 1.30–1.70). The maximum range was set at double this (1.10–1.90).

NON-HOMOGENEITY OF AGGREGATIONS

Figure 2 shows that the targeted acoustic method will be positively biased if the aggregations contain even a small proportion of other species with swimbladders. Fortunately, catches indicate that the large, distinct aggregations (that contain most of the aggregated biomass) are almost monospecific, typically containing less than 0.5% of other species. From Figure 2, a scaling factor (F) of 0.9 was considered appropriate, applicable to an orange roughy proportion of 99.5% and a backscattering strength ratio (β) of 25. The limits on the likely range were placed at 0.85 and 0.95, and the minimum and maximum at 0.5 (equivalent to $\beta = 50$, $p_{ORH} = 0.98$) and 1.0 ($_{ORH} = 1$) respectively.

NON-AGGREGATED ORANGE ROUGHY

Bottom trawl catches in the QMAs outside the aggregations almost invariably contain some orange roughy, so the targeted acoustic method is clearly negatively biased. For reasons previously explained, it was not possible to estimate the dispersed component acoustically. Assuming a catchability coefficient of 1, research bottom trawl catches indicate that the dispersed component could be as large as the aggregated component, particularly on Johnies, where orange roughy tend to be more dispersed than in other QMAs, but because of great uncertainty regarding this, it was decided not to attempt any correction based on catch information.

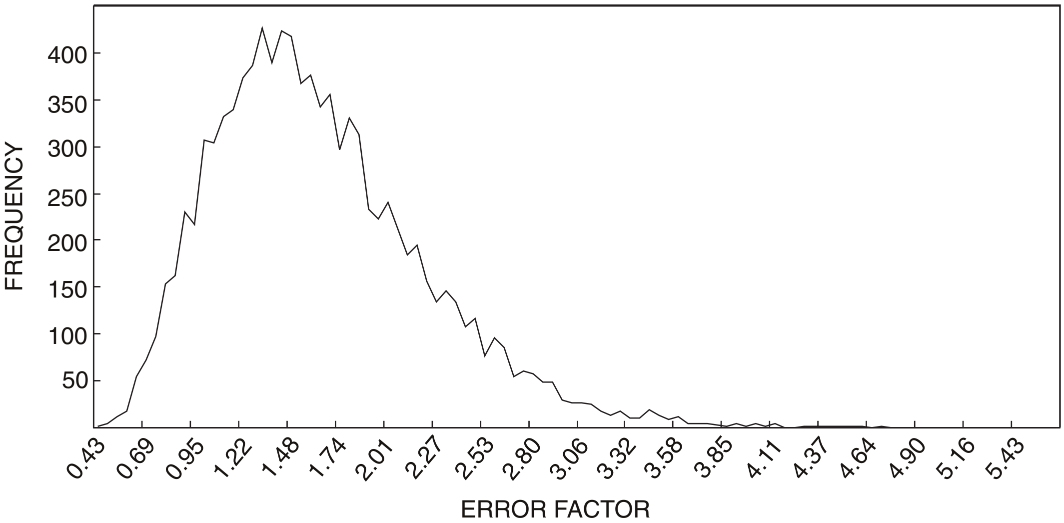

Fig. 3: An example of the probability density function of the overall error factor for a biomass estimate – Johnies in 1997

ORANGE ROUGHY OUTSIDE THE QMAs

As there is very little information on orange roughy abundance or distribution outside the Namibian QMAs surveyed, no correction could be applied for orange roughy spawning elsewhere or not moving onto the QMAs to spawn. Bell *et al.* (1992) noted that the proportion of the orange roughy stock that did not spawn in any given year was variable, and that it could be as high as 45%. No attempt was therefore made to expand the estimates for the QMAs over the whole population range to estimate overall population size. Rather, they should be regarded as estimates of the part of the population where practically all fishing takes place.

Table V: Mean error correction factor and *CV* of the overall error probability density functions for each QMA and year

QMA	Year	Mean correction factor	*CV* (%)
Johnies	1997	1.61	36.0
	1998	1.71	52.8
Frankies	1997	1.62	39.2
	1998	1.68	48.1
	1999	1.62	38.2
Rix	1997	1.58	32.5
	1998	1.60	34.4

SAMPLING ERROR

Acoustic sampling error was estimated formally from Equation 2. For each QMA, the error factor was modelled as log-normally distributed about unity, with a standard error equal to the standard error of the mean s_A for the QMA.

The inputs to the error model for all errors except the sampling error are summarized in Table IV, and an example of the pdf of the overall error factor for Johnies in 1997, resulting from 10 000 runs of the model, is shown to illustrate the output (Fig. 3). The means of the distributions for all surveys and all years are in the region of 1.58–1.71 (Table V). The *CV*s are between 1.2 and 2.1 times greater than the estimated sampling *CV*s. The results of applying these distributions to the acoustic estimates are given in the following section and in Table VI.

RESULTS

Distribution and aggregating behaviour

Aggregations of orange roughy were generally found in areas where commercial catches were made during the same period. Figure 4 gives an example of a typical distribution, in this case for the Johnies QMA in the 1997 survey. At Johnies the aggregations were found

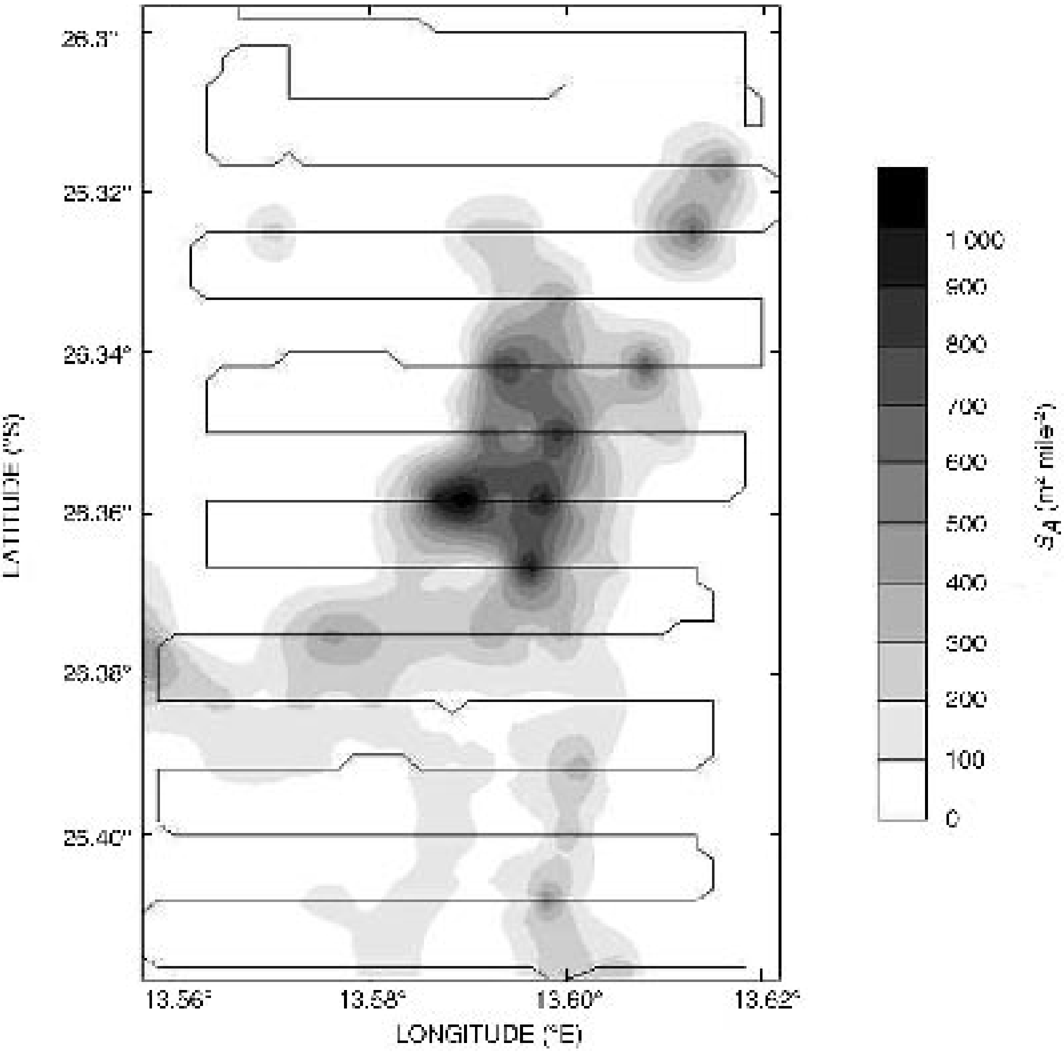

Fig. 4: Survey track and contour plot of orange roughy distribution from the second coverage of the Johnies QMA in 1997. The contouring was done through a kriging algorithm based on the isotropic variogram for this coverage (see Fig. 5; analysis conducted by J-O. Krakstad, NatMIRC, Swakopmund, Namibia)

primarily between the 630 and 680 m isobaths, whereas at Rix they were usually between 700 and 800 m deep. At Frankies, the aggregations became progressively deeper from north to south, at around 600 m on 21 Jump St, 650 m on Frankies Flats, and between 730 and 750 m deep on Three Sisters. Only at Johnies, where orange roughy were found several miles southwest of the core of the QMA in 1997 and 1998, were significant quantities found away from the areas fished heavily. (This area, known as "Strawberry Patch" was later added to the Johnies QMA after further exploration by commercial vessels.)

The individual aggregations themselves were generally between 0.1 and 1.0 miles in extent along the track, were usually discrete, and commonly occurred on the upper edge of a distinct bottom feature such as a gully or drop-off. Anisotropic variograms from a geostatistical analysis of the 1997 data performed by

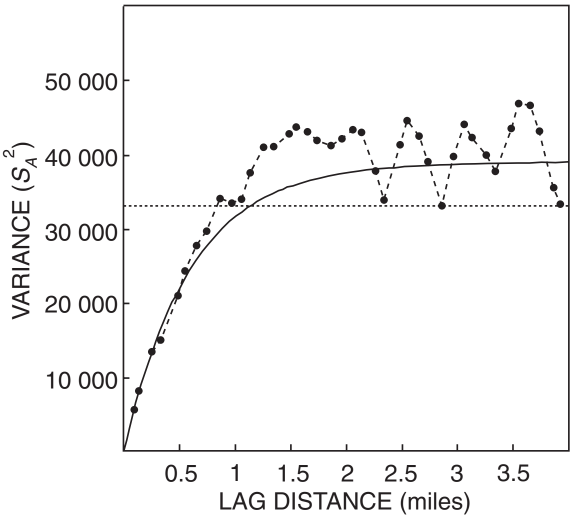

Fig. 5: Anisotropic variogram for the second coverage of Johnies in 1997 based on s_A values every 0.1 miles. An exponential spatial model was used in both cases (analysis conducted by J-O. Krakstad, NatMIRC, Swakopmund, Namibia)

Barange (1998), an example of which is shown in Figure 5, show autocorrelation ranges of between 0.5 and 2.0 miles. The nugget effect was zero for all variograms, indicating that individual aggregations were generally larger than the scale of sampling (0.1 miles). These observations all confirm a high degree of small-scale patchiness, as evident in Figure 4.

There was usually clear water between the orange roughy aggregations and surrounding midwater scattering layers (Fig. 1a, c). The vertical dimensions were highly variable. At times the fish were concentrated within a narrow band hard on the bottom, making acoustic assessment difficult, if not impossible (Fig. 1b, d); at others they formed plume-like aggregations extending more than 100 m off the bottom (Fig. 1a). The volume backscattering strength of the aggregations was always low as a consequence of the low target strength, seldom exceeding -52 dB even in the densest part of the aggregation. For an orange roughy target strength of -55 dB, this translates to a maximum volume density of approximately 2 fish m^{-3} or about 0.8 kg m^{-3}.

There were other mixed-species demersal scattering layers over a wide depth range on either side of the orange roughy aggregations (Fig. 1c, d). Bottom trawls almost always took a small proportion of orange roughy from these layers. Upslope (inshore), deep-water Cape hake *Merluccius paradoxus* dominated the demersal community. Offshore, oreo dories, rattails and deep-water sharks were mixed with a large and diverse variety of other deep-water species (see individual Cruise Reports for full species lists).

As the abundance of orange roughy in the QMAs declined over successive years (see below) the orange roughy aggregations on Johnies and Rix became less

Table VI: Targeted acoustic, research swept area and catch rate (*cpue*) estimates of orange roughy biomass population in the QMAs, 1997–1999, *CV*s (%) in parenthesis. Corrected estimates refer to the mean estimate after correction for biases (see Table V)

Year	QMA	Uncorrected acoustic estimate (tons)	Corrected acoustic estimate (tons)	Swept-area estimate (tons)	*Cpue* (relative to 1997)	Catch taken since previous survey (tons)
1997	Johnies	34 178 (21)	54 978 (36)	57 650 (27)	1	Not relevant
	Frankies	17 925 (25)	29 043 (39)	30 995 (37)	1	Not relevant
	Rix	21 579 (15)	34 164 (33)	No estimate	1	Not relevant
	Total	73 683 (12)	118 185 (22)	–		–
1998	Johnies	3 570 (43)	6 094 (53)	6 980 (25)	0.67	6 015
	Frankies	4 940 (38)	8 311 (48)	2 400 (60)	0.34	2 711
	Rix	7 572 (19)	12 088 (34)	No estimate	0.84	3 578
	Total	16 082 (17)	26 493 (25)	–		12 304
1999	Johnies	No estimate	–	2 137 (40)	0.27	1 219
	Frankies	1 782 (25)	2 890 (38)	3 055 (35)	0.11	616
	Rix	No estimate	–	1 006 (59)	0.36	2 997
	Total	–	–	6 198 (24)		4 832

distinct (see Fig. 1b). Trawls targeted on these aggregations usually contained a significant proportion of other species, although this may be attributable to the trawl missing the orange roughy aggregations because of their small size, and catching surrounding dispersed fish instead. It was frequently not possible to identify such aggregations.

Results of experiments

During the intercalibration between *Dr Fridtjof Nansen* and *Welwitchia* in 1999, 12 orange roughy aggregations were intercepted, all but one of which were clearly detected by both vessels. A linear regression of the s_A values showed that the *Welwitchia* values were 1.21 times greater than those from the *Dr Fridtjof Nansen,* with an R^2 of 0.93, indicating that the same targets were integrated and that the discrepancy between the systems was primarily the result of differences in system performance rather than sampling variability. The results are consistent with several previous intercalibration exercises between the same vessels on dispersed midwater scattering layers, which indicated discrepancies of a similar magnitude and sense between the two systems (Boyer *et al.* in prep.).

The most useful information from the deep-towed transducer was collected during a coverage of the Three Sisters ground on Frankies in 1997, where the estimate from the towed transducer (towed at 380 m) was about 1.4 times greater than that from the keel-mounted transducer. On that ground, where the bottom depth varies between 730 and 750 m, towing the transducer at 380 m effectively reduces the dead zone by between one-third and one-half, compared to the hull-mounted transducer, depending on transducer tilt, slope and direction of travel. The difference is therefore consistent with the estimated dead zone correction factor of 1.71 for the hull-mounted transducer on that ground (Table IV). The experiments cannot, however, be regarded as definitive, because the differences could have been partly an artefact of inter-transducer calibration errors and range-dependent errors introduced, for example, through errors in the absorption coefficient assumed.

Biomass estimates

Targeted acoustic estimates of biomass in the QMAs in 1997, 1998 and 1999 (Frankies only) are shown in Table VI. For reasons previously explained, the other acoustic estimates are not shown. In each case the estimate was averaged from all coverages of the QMA considered to be valid for biomass estimation. Also shown are the mean bias-corrected estimates and *CV*s obtained from the pdfs of the corrected biomass estimates, an example of which (from Johnies in 1997) is shown in Figure 3. The correction factor is between 1.58 and 1.71 for all surveys (Table V). Note that, in this case, the *CV* incorporates all sources of error modelled and is therefore somewhat larger than the *CV* for sampling error alone. Table VI shows swept-area estimates made at the same time over the same area, plus indices of catch rate within the QMAs for that year (after Boyer *et al.* 2001a) for comparison.

DISCUSSION

The acoustic estimates indicate a sharp decline in biomass in all three QMAs between 1997 and 1998. The estimate for Frankies in 1999, although less precise than indicated by the *CV* because of great uncertainty regarding target identity, is evidence that the biomass there was lower in 1999 than in 1997. These trends are also reflected in the swept-area estimates and *cpue* indices (Table VI). As these are essentially indicators of aggregated biomass, the fact that the acoustic estimates track them well increases confidence that the targeted acoustic method does provide a valid measure of aggregated biomass.

It is appreciated that, in many cases, the error estimates are themselves uncertain, in that the form and ranges assumed are often somewhat arbitrary. Nonetheless, it is believed that the error factors are realistic, and that the treatment does provide a defensible method of assessing their combined effect, which is far preferable to ignoring them or setting an error limit based on acoustic surveys of other species, where the problems are very different. Kloser *et al.* (2000) identified similar errors, with similar ranges, in an orange roughy survey of the Chatham Rise in 1998.

Table IV indicates that the greatest sources of error in the absolute acoustic estimates are uncertainty in target strength (including the uncertainty in its length-dependence) and in the correction for the dead-zone effect. Both errors will have less of an effect on relative estimates, but this does not obviate the need to estimate them as accurately as possible, because of the importance to management of the estimates as absolute, particularly the high estimate obtained in 1997.

The allowance made for target-strength uncertainty (potentially the largest source of error) is based on the reported uncertainty in a small number of experiments in one locality, which may not be indicative of the overall variability of orange roughy target strength and may not be strictly applicable to the species off

Namibia because, for example, of differences in behaviour and habitat there. There may also have been biases in the experiments that were not accounted for, and sources of variability (caused, *inter alia*, by behavioural effects and target identification uncertainties) not reflected in the reported error estimates. Therefore, whereas the error estimates given here are based on reports on the experiments, and allowance has been made for some additional uncertainty by widening the error limits, it is certainly possible that the error limits are still too narrow. Considerable further work is necessary to increase the confidence in the estimates, and in the estimates of their accuracy.

It is not intended at this stage to attempt target-strength studies off Namibia because of the complexities and expense of deep-towed systems needed for such studies (Kloser 1996). Improvement in this area will therefore depend on progress made in estimating orange roughy target strength elsewhere, for example off Australia and New Zealand, where such work is continuing (McClatchie *et al*. 1999, Kloser *et al.* 2000, McClatchie and Ye 2000). Whether any such results can be applied to Namibian orange roughy, which are generally much smaller, is unclear. Table III shows that the dead-zone error can be significantly reduced by minimizing transducer tilt. The correction method can be improved by incorporating information on the density structure close to the bottom, and other refinements discussed in Hampton and Boyer (in prep.). These measures are believed to be the most practicable and cost-effective way of addressing the problem of dead zones on the Namibian shelf where, unlike off Australia and New Zealand where deep-towed bodies are used to reduce the dead zone, the grounds tend to be relatively flat, with few slopes greater than 5° where the aggregations were found.

The motivation to assess the absolute errors as accurately as possible, and to incorporate them into the acoustic biomass estimate, was largely driven by the need to know the absolute abundance of orange roughy in the QMAs as accurately as possible. It was particularly important for management purposes to decide whether the decline in all indices between 1997 and 1998 was primarily caused by a reduction in population size brought about by fishing, or whether other factors such as changes in distribution or behaviour (perhaps in response to fishing activity) could have resulted in change in availability. This question has been addressed through two modelling exercises, in which the probability of the commercial catch between the surveys in 1997 and 1998 (12 800 tons) having caused such a decline has been computed, allowing for potential errors in the two surveys (Brandão and Butterworth 2000, McAllister and Kirchner in press). In that work, the accuracy of the estimates as absolute estimates was of primary concern. Both analyses suggested that the reduction in the biomass between 1997 and 1998 could not be accounted for by catches alone. Further speculation on this question is beyond the scope of this paper, and the reader is referred to Brandão and Butterworth (2000) and McAllister and Kirchner (in press).

Current assessment models for orange roughy require trends in abundance rather than absolute estimates (Boyer *et al.* 2001a), for which relative acoustic indices suffice. Nevertheless, future acoustic estimates will still need to be corrected for biases because these biases vary from survey to survey.

Potential error arising from uncertainty in target identity is not reflected in Table IV. As already explained, with declining abundance on the QMAs this has become a major source of uncertainty when a second vessel is used for target identification, even precluding estimates at times. Indications from the *Conbaroya Cuarto* survey in 2000 are that the problem can be reduced significantly by using a single vessel for surveying and target identification, making it possible to obtain usable estimates in circumstances when target identifications with a second vessel may be highly unreliable. The vessel needs to be both efficient at trawling orange roughy and sufficiently quiet at survey speed to be able to detect orange roughy at the maximum depth of interest (around 1 000 m). Hampton and Soule (2000) showed that the self noise of *Conbaroya Cuarto* at 38 kHz in good weather is between 50 and 55 dB re 1 μPa at 10 knots, more than adequate for detecting orange roughy aggregations in the QMAs. For work in bad weather, or on a noisier vessel, it might be necessary to resort to a shallow-towed transducer. In all, it would appear that the single-vessel approach is worth following and developing further for orange roughy surveys off Namibia, especially if the aggregations on the QMAs remain small and sparse.

Target identification could also be improved with better knowledge of aggregating behaviour, which is poorly understood at present. For example, a better understanding of the relationships between aggregations and bottom topography could enable orange roughy aggregations to be identified on the basis of their position in relation to bottom features.

Most aggregations extended far above the headrope of the trawl, so assuming that the fish assessed acoustically were the same as in the sample catch was critical to biomass estimation. However, this assumption was made with some confidence, particularly when the sample contained only orange roughy and the aggregation was obviously contiguous above and below the headrope height. Additionally, commercial fishers and scientists from the New Zealand orange roughy fisheries participated in the surveys and were able to confirm this assumption, based on their extensive experience of midwater trawling similar orange roughy targets elsewhere.

More needs to be known about the distributional and aggregating dynamics on a larger scale, to enable estimates made in the QMAs at one time of the year to be related to the size of the population as a whole. Until this can be done, management of the fishable part of the orange roughy stock in Namibian waters on the basis of estimates made only on the QMAs will remain highly problematic.

The role of, and strategy for, future acoustic surveys will depend on the management strategy used for the resource, which is still under development. One question being considered is whether it is necessary and cost-effective to conduct an acoustic survey every year, or whether less-frequent surveys would suffice. An alternative might be to monitor the biomass in small key areas throughout the fishing season from a commercial vessel equipped with the necessary acoustic equipment. This might obviate the need for a full-scale survey of all QMAs every year, and provide valuable information on aggregating dynamics over a large part of the year, at comparatively little cost.

In summary, an effective acoustic method has been developed over the past four years for estimating the biomass of aggregated orange roughy in the present QMAs during the spawning period. While many problems still need resolution, and further developments are likely, the present method, with the use of a single vessel for surveying and target identification, appears to be suitable for monitoring trends in aggregated biomass. Furthermore, the error model, with the present inputs (or refinements of them), permits defensible estimates of absolute biomass in the QMAs, and of the accuracy of such estimates, which are particularly useful when absolute levels of abundance are needed for management purposes.

Aspects of the methodology that have now become more or less standardized include acoustic hardware, processing methods and software, survey design, target classification and the treatment of error. The major problems still requiring attention, despite considerable progress, are the estimation and correction for dead-zone effects, and target identification, both of which can introduce large uncertainties. These are both problems that can be addressed with available expertise and equipment. On the other hand, owing to the technological difficulties and expense involved in making direct *in situ* estimates of orange roughy target strength (the other major source of uncertainty), progress is likely to depend on experiments conducted elsewhere, at least in the immediate future.

The original decision to opt for acoustic surveys as a means of estimating absolute biomass in the QMAs, and of monitoring changes in biomass there, has been justified. The results have already been used in recommending *TAC*s for the 1998, 1999 and 2000 seasons, and to support a recommendation to close the Frankies QMA to commercial fishing in 1999. It is expected that future assessment and management of the resource will continue to rely heavily on the results of acoustic surveys, primarily as relative assessments, but absolute estimates of biomass on the fishing grounds may still be required, particularly for assessing the impact of fishing on the stocks.

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