A comparison of bathymetry mapped with the Simrad ME70 multibeam echosounder operated in bathymetric and fisheries modes

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The Simrad ME70 multibeam echosounder was designed for quantitative fisheries research and is currently installed on Ifremer's fishery survey vessel (FSV) "Thalassa" and each of the new, quiet, NOAA FSVs. The ME70 has configurable beams and transmits in the range 70–120 kHz to provide calibrated, acoustic-backscattering data throughout the detection range (fisheries mode, FM). With optional hardware and software, the ME70 can also collect soundings that potentially meet International Hydrographic Organization's S–44 Order 1 standards (bathymetric mode, BM). Furthermore, with custom algorithms and software, bathymetric data can be obtained from the ME70 operating in FM, and volume backscatter can be sampled from the ME70 operating in BM. This flexibility allows data to be concurrently collected on fish and their seabed habitat. A method is described for processing the echo amplitude and phase data from multiple split-beams formed in FM to estimate seabed range, slope, and roughness. The resulting bathymetry is compared with that collected with the ME70 operating in BM in the same area of the Bay of Biscay. A proposal is made for software development to facilitate dual-use data processing.

Keywords: bathymetry, mapping, ME70, multibeam echosounder, NOAA FSV, split-beam.

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Introduction

Ifremer's fishery survey vessel (FSV) "Thalassa" and each of the new, quiet, NOAA FSVs (currently "Oscar Dyson", "Henry B. Bigelow", "Pisces", and "Bell M. Shimada") are equipped with Simrad ME70, multibeam echosounders. The ME70 was designed collaboratively by Simrad and Ifremer (Trenkel *et al.*, 2008) for quantitative acoustic surveys of marine organisms, particularly those residing near the seabed. Like a typical multibeam echosounder, the ME70 forms a fan of beams athwartships using an 800-element array. Unlike conventional multibeam echosounders, the ME70 allows split-aperture processing for any beam (e.g. Shirazi *et al.*, 1992; Shippey, 1997) in both alongship and athwartship planes (Demer *et al.*, 1999, 2009; Cutter and Demer, 2010) and field calibrations using standard-sphere techniques (Ona *et al.*, 2009). The beam directions can be automatically compensated to $\pm 10^\circ$ roll, $\pm 5^\circ$ pitch, and heave using data from an inertial-motion unit (IMU).

The ME70, operating in its standard fisheries mode (FM), provides calibrated volume-backscattering strength (S_v; dB re m^{-1}) and target strength (TS; dB re 1 m^2) data from water-column scatterers within the detection range and automated estimates of the seabed ranges using amplitude-based detections. These data provide observations of fish and plankton including the estimates of their distributions and abundances, and three-dimensional images of their aggregations and seabed habitat (Trenkel *et al.*, 2008). The FM uses ME70 software for system control and data input/output (I/O) and is user-configurable with adjustments to the number of beams (3–45), whether they are single-beam or split-aperture, their transmit frequency (70–120 kHz), overlap, and beam width (minimum 2°), steering, and swath angles. Depending on the configuration, the ME70 can achieve unmatched two-way sidelobe suppression to −70 dB in FM.

The ME70 installed on "Thalassa" (Trenkel *et al.*, 2008) is configured with an optional bathymetric module, so can also be operated in bathymetric mode (BM) to emulate a standard seabed-mapping multibeam echosounder. The BM has a relatively fixed configuration including: single-frequency (90 kHz) transmissions; 80 equidistant or equiangle beams, each with two pulse-duration options, providing up to 200 soundings per swath; and one-way sidelobe suppression to −17.5 dB (beams formed only during reception). Using a Simrad EM processor station and SIS software for system control and data I/O, as for the Simrad EM series multibeam echosounders, the BM estimates ranges to the seabed using amplitude detection with near-normal incidence and phase detection for more oblique (low-grazing) angles. If sound-speed profile data are input, the processor corrects range and location estimates for the effects of sound refraction. The ME70 with BM is designed to output data which could meet survey requirements that satisfy the International Hydrographic

Organization's (IHO) S–44 Order 1 standard (Kongsberg Maritime, 2003).

In terms of seabed mapping, the principal difference between the FM and the BM is the seabed-detection scheme, although there are other differences such as the number of beams, transmit power, and side-lobe suppression. Near-normal incidence, the sample corresponding to the seabed range, can be estimated accurately using the peak or centre-of-mass of the seabed echo, after filtering or thresholding to avoid spurious detections of the transmit pulse or strong water-column scatterers. However, for oblique angles caused by the orientation of the transducer, the beam direction, and the seabed slope, the phase differences between wavefronts received by different elements or portions of the receiver array (interferometric phase differences) can be used to estimate more accurately the range to the seabed. The moment when the phase difference is equal to zero indicates the range to the seabed at the centre of the beam. However, interferometric phase can be used to estimate multiple ranges to the seabed within each beam (Jin and Tang, 1996). The BM employs both strategies, dependent on incidence angle and echo properties, whereas the default method in FM is only peak-echo detection.

Note that the seabed-detection algorithms employed in BM can also be used with the FM data. Therefore, with custom algorithms and software, bathymetric data can be obtained from the ME70 operating in FM and S_v. *TS* can be sampled from the ME70 operating in BM (see Figure 1 for more details). This flexibility allows data on fish and their seabed habitat to be collected concurrently and efficiently.

Here, we demonstrate that the ME70 operating in FM can produce high-resolution bathymetry data that are equivalent to those produced by the ME70 operating in BM. Such processing allows the ME70 to collect data simultaneously and efficiently from marine organisms, their seabed habitat, and navigational-quality bathymetric maps, without the configuration limitations of the BM and the costs associated with the bathymetric option and the ship time needed to survey an area twice or more to collect both FM and BM data.

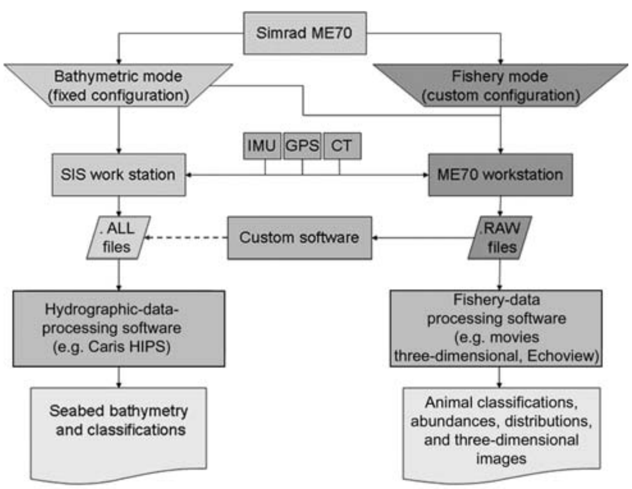

Figure 1. Data-processing sequence for the ME70 in BM and FM. Ancillary data are input from the IMU, global-positioning-system receiver, and conductivity and temperature profiler (CT). With custom algorithms and software to derive high-resolution bathymetry data from the raw files and to convert the results to all or GSF format, high-resolution bathymetric data can be obtained from the ME70 operating in FM. This flexibility allows data to be collected concurrently and efficiently on fish and their seabed habitat.

Methods

Data were collected with the ME70 with its transducer mounted on the hull of RV "Thalassa", in the Bay of Biscay, west of France, ca. 46°31.5′N 04°44.5′W, on 19 March 2008. Initially they were collected in BM, transiting from the southeast to the northwest, and then in the same area, in FM, from the northwest to the southeast. The common coverage area was 0.30 km^2, comprising a track ~1.7 km long and <0.2 km wide. In BM, the 80 beams provided a 120° swath and some 150 soundings per transmission. The FM was configured, for another investigation, to record to a depth of 232 m, with 21 beams from six transmission-pulse groups, each with one or four beams, with beam widths from 2.3° to 3.8° (Table 1), resulting in a narrower (~60°) swath (Figure 2). Note that the FM mode could have been configured with a swath width equivalent to that for the BM, and to collect data to a larger range, but this was not done out of consideration for other experiments. The pulse duration was 0.268 ms in BM and 1.024 ms in FM. Beam centre-frequencies in FM ranged from 71.9 to 118.1 kHz, and the frequency distribution was arranged with the highest frequency at the 0° beam, with frequency decreasing with increasing athwartships angle to achieve an "inverted V" pattern (Trenkel *et al.*, 2008). In BM, all beams have a centre frequency of 90 kHz.

Custom software was developed to emulate the BM data processing and to generate bathymetric data from the ME70 operating in FM; these data were then compared with the data from the ME70 operating in BM. A local Cartesian-coordinate system was defined from an origin x_0, y_0, z_0 at the centre of the transducer face and with positive values of x, y, and z along orthogonal axes pointing in the alongships, starboard, and downward-vertical directions. Ranges to the seabed measured in the centre of each beam $[r(\theta, t)]$, for each beam-steering angle θ and transmission time t, were estimated using amplitude detection near-vertical incidence angles (<8°), and phase detection for larger beam angles. Amplitude detection was by filtering the S_v dataseries to retain samples with ranges exceeding a specified minimum range, sufficient to avoid returns from the initial pulse, and values of $S_v \geq -50$ dB to define a contiguous set of candidate samples. The amplitude-detected range was the range corresponding to the centre-of-mass of the S_v values from candidate samples. For each beam, trigonometry was used to convert the estimated range to the seabed r to an uncorrected depth $z_u(\theta, t)$ by accounting for θ in the athwartships (y) direction. Beams were automatically steered to an angle equal to zero degrees in the alongships (x) direction. The local positions for the bottom detections x, y, z_u represented horizontal and vertical distances relative to x_0, y_0, z_0. The z_u values were then compensated for transducer depth, heave, and tidal elevation to estimate local positions with corrected depths (x, y, $z_{corr}(\theta, t)$). Then, using geographic position and course data from the global-positioning-system receiver, these were converted to global Easting (E; m) and Northing (N; m) coordinates, in zone 30 north of a Universal Transverse Mercator projection referenced to WGS–84, and depths (z). Although possible, these data were not compensated for the effects of sound refraction.

The bathymetric data from the ME70 in BM (.all format) were processed using standard methods and software. Specifically, CARIS Hydrographic Information Processing System (HIPS)

Table 1. Beam-configuration summary for the ME70 FM survey.

Beam	Frequency (Hz)	Beam direction (°)	Beam-width alongships (°)	Beam-width athwartships (°)	Angle-sensitivity alongships
1	71 943	−30.5	3.79	4.40	63.3
2	76 449	−26.2	3.57	3.98	67.3
3	80 956	−22.5	3.37	3.65	71.3
4	85 462	−19.0	3.19	3.37	75.2
5	89 969	−15.7	3.03	3.15	79.2
6	94 476	−12.7	2.89	2.96	83.1
7	98 982	−9.8	2.75	2.80	87.1
8	103 489	−7.1	2.63	2.66	91.1
9	107 995	−4.5	2.53	2.53	95.0
10	112 502	−2.0	2.42	2.43	99.0
11	118 057	0.4	2.31	2.31	103.9
12	114 755	2.7	2.38	2.38	101.0
13	110 249	5.1	2.47	2.48	97.0
14	105 742	7.7	2.58	2.60	93.1
15	101 235	10.4	2.69	2.74	89.1
16	96 729	13.2	2.82	2.90	85.1
17	92 222	16.2	2.96	3.08	81.2
18	87 716	19.3	3.11	3.30	77.2
19	83 209	22.8	3.28	3.55	73.2
20	78 702	26.5	3.46	3.87	69.3
21	74 196	30.5	3.68	4.27	65.3

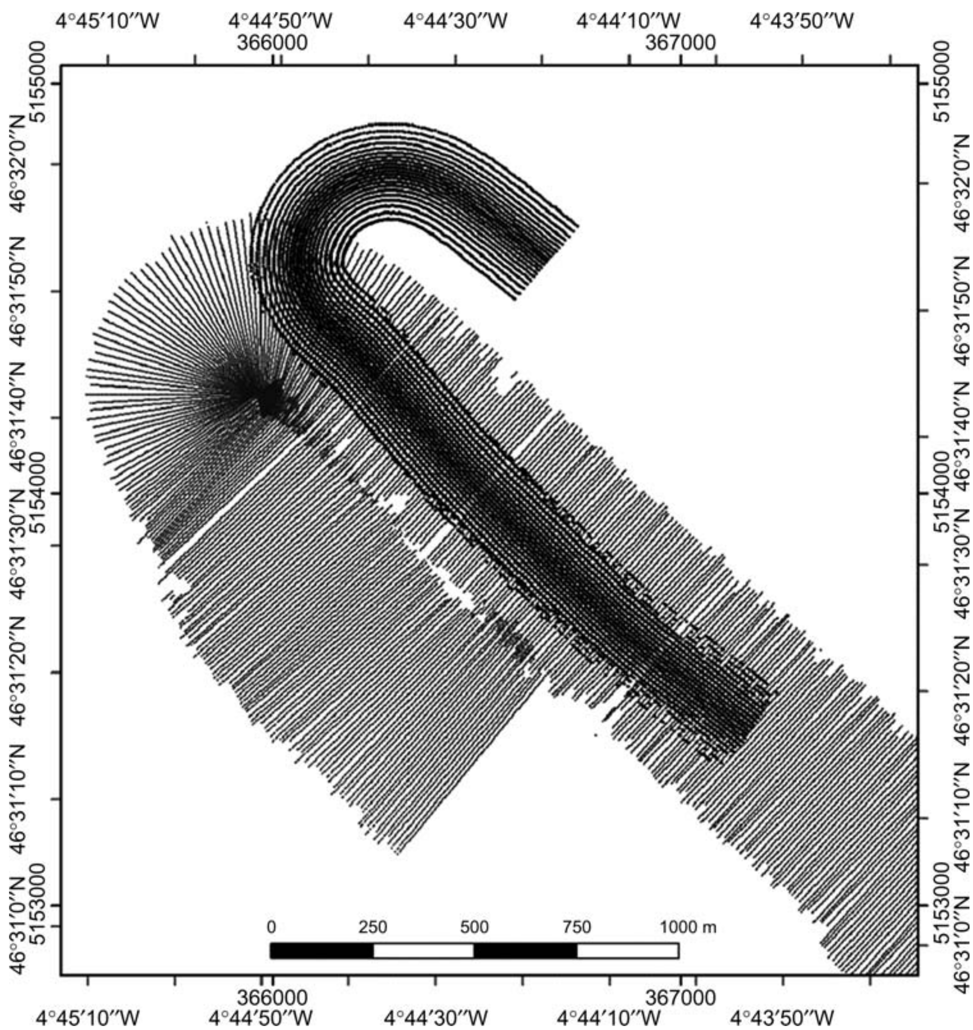

Figure 2. Locations of soundings from BM and FM, with the FM configured for a 60° swath width, and the BM configured for 120°. The whole numbers on the axes of this and subsequent Figures are the coordinate values, in units of metres, from a Universal Transverse Mercator projection.

software was used to remove outliers, examine the motion data, compensate for tidal elevation and refraction, merge data, create surfaces, and export the results for display and comparison in ESRI ArcMap GIS.

Bathymetric maps were generated for the same area using data from the ME70 operating in both BM and FM. The sampling coverage and bathymetric maps from BM and FM modes are compared in plan view (Figures 3 and 4). The bathymetry from each mode is also compared in perspective, viewed from the northwest at an elevation of 35°, after processing the FM data with amplitude detections (Figure 5a), then amplitude and phase detections of the seabed (Figure 5b). The quality of the FM solutions is evaluated by subtracting the BM and FM surfaces (Figure 6). Additionally, seabed slopes were estimated by differences in depths between neighbouring grid cells, for both the BM and FM data (Figure 7). Local roughness was estimated for both the BM and FM surfaces from the standard deviation (s.d.) of depth values within 15 × 15 m cells (Figure 8).

Results

The common survey area has a smooth, locally flat seabed with depths ranging from 204 to 232 m. This is fortuitous for comparisons and optimizations of the FM seabed-detection methods. The effective swath of the FM data is reduced as the depth approaches the maximum detection range of 232 m; this effect could be mitigated with another FM configuration having a greater swath width and larger maximum detection range. The maximum detection range of FM mode is, however, reduced compared with BM because of simultaneous transmissions of up to four beams, and beamforming at both transmission and reception.

The mean difference in the BM vs. FM depths is virtually zero. The principal differences are due only to the amplitude detection in the FM data at large incidence angles (Figure 5a). Even these differences are removed when using the amplitude and phase detection method with the FM data (Figure 5b). The remaining differences are believed to be residuals of uncompensated, or inaccurately compensated, motion artefacts, predominantly caused by heave, as well as navigational positioning errors. Heave artefacts in both FM and BM result from the internal filter of the motion sensor, and in the former, heave compensation only occurs at the time of transmission. The median depth of the area was 214 m, and the mean difference in depth between the BM and FM results was 0.54 m (s.d. = 0.37 m). The mean difference between FM and BM depths included a bias (0.54 m) that is

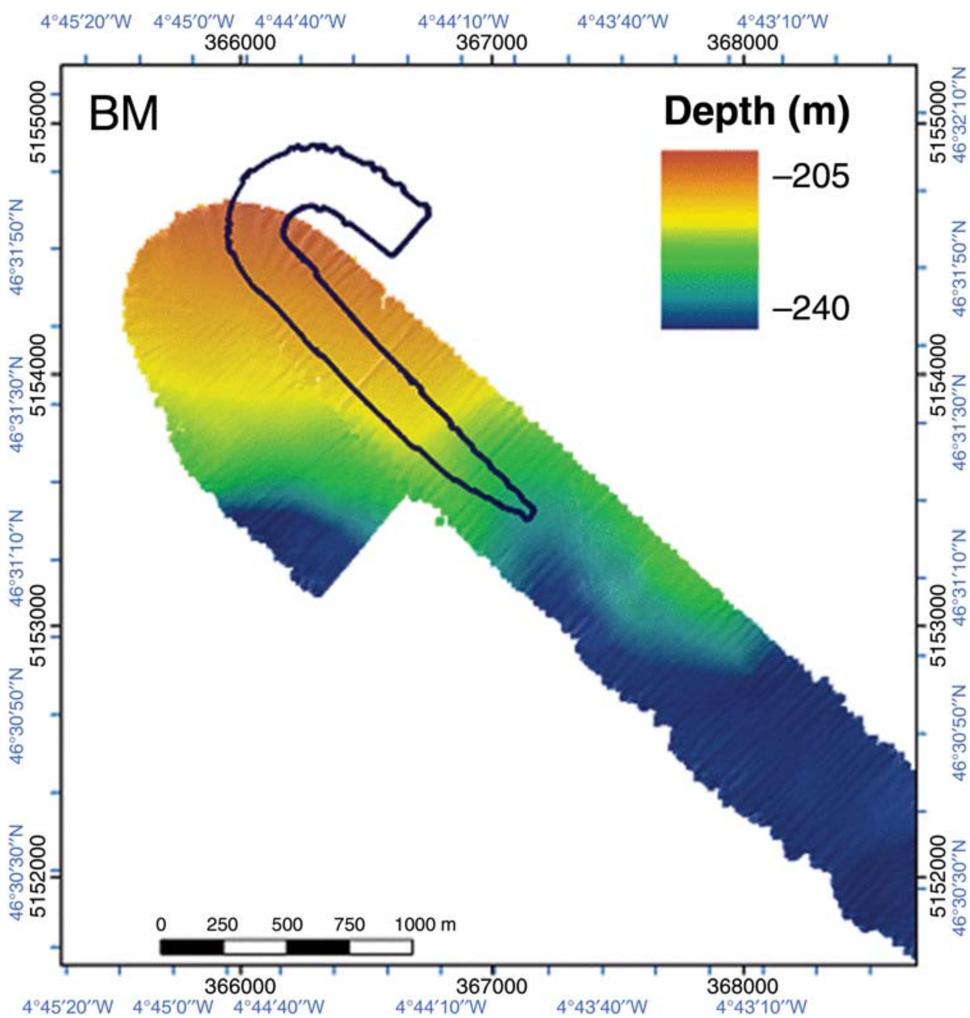

Figure 3. Plan view of the shaded relief bathymetric surface from the ME70 in BM, coloured by depth, and with the FM coverage outlined. The surface is a regular grid with 5 × 5 m grid cells, with values representing the median depth from 30-m neighbourhoods.

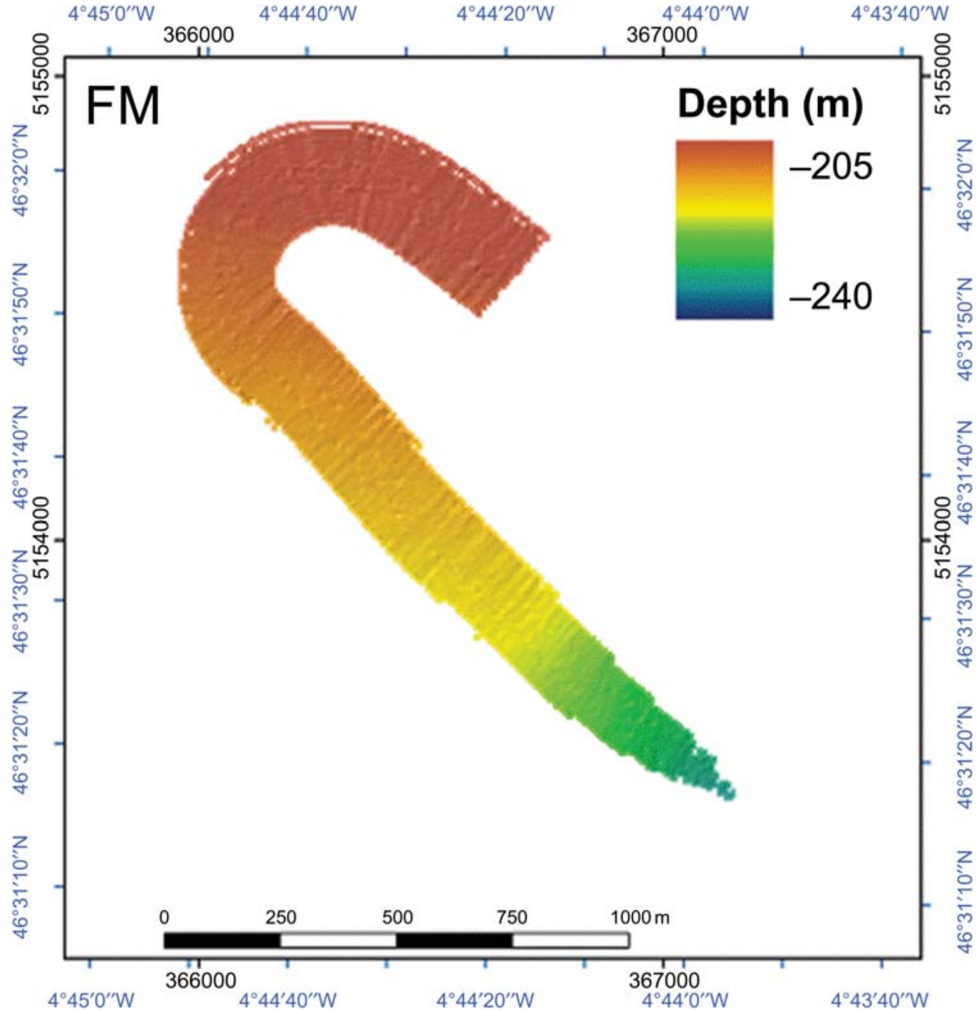

Figure 4. Plan view of the shaded relief bathymetric surface from the ME70 in FM, coloured by depth. The surface is a regular grid with 5 × 5 m grid cells, with values representing the median depth value from 30-m neighbourhoods.

believed to be related to position-data inaccuracy or imprecision, or to the estimation of tides. Without compensating for the bias, the difference between BM and FM depths was <1.6% for 100% of the common coverage area, with corresponding bathymetric grid cells, <0.65% for 99% of the area, <0.52% for 95% of the area, <0.46% for 90% of the area, and <0.27% for 50% of the area (Figure 6). The difference between BM and FM mean depths was <0.5%, which also corresponds to the accuracy of the BM mode, for 93% of the area. After accounting for the 0.54-m bias by adding it to the FM depth values, the difference between mean depths was −0.0047 m, and a test for equality of means for BM and FM depths showed no difference between sample means (pooled-variance, two-sample t-test, $t = -0.0414$, d.f. = 10 688, $p = 0.967$, 95% $CI = -0.228$ to 0.219 m). In other words, removing the bias resulted in a mean difference of −0.0047 m, and <0.11% of the mean depth. A pairwise comparison also showed no difference in depths ($t = -0.9287$, d.f. = 5344, $p = 0.353$, 95% $CI = -0.0147$ to 0.0053 m). Larger differences, of the order of 1.5 m, not accounting for the unresolved bias, which are apparent in the southeast portion of the area, are probably a combination of refraction, tidal effects, and positioning error.

The largest slopes (5–14°) are evident in the BM data (Figure 7a) as the seabed smoothly changes from shelf to slope. In the common survey area, the slopes are generally <2° (Figure 7b). Values of 2–3° are associated with detection artefacts, residual motion, and the shape of the seabed sloping downwards towards the southeast. Both the BM and FM results indicate that the large-scale slope is controlling the seabed roughness in this area (Figure 8). The local roughness is <10 cm for most of the common area, increasing to ∼1 m for the large depressions. Minor variation in the slope, and hence the roughness, is a result of residual motion artefacts in the BM results. The minor variation in the slope in FM results stems from the fixed angle used to switch from amplitude to phase detections.

Discussion

By employing standard amplitude- and phase-based seabed-detection methods, data collected in the BM and FM modes produce practically equivalent results for the relatively flat seabed of the study area. Although the comparison was only for bathymetry estimated for a relatively flat seabed, an analysis of FM and BM data from a rough seabed (not shown) demonstrated

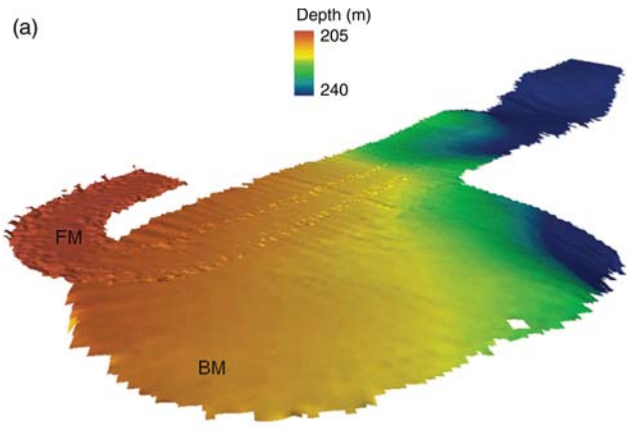

Figure 5. Perspective of the shaded relief bathymetric surfaces from the ME70 FM surface resulting from (a) amplitude detection only and the BM surface, and (b) amplitude detection used within 8° of normal incidence and phase detection used for incidence angles >8°, and the BM surface.

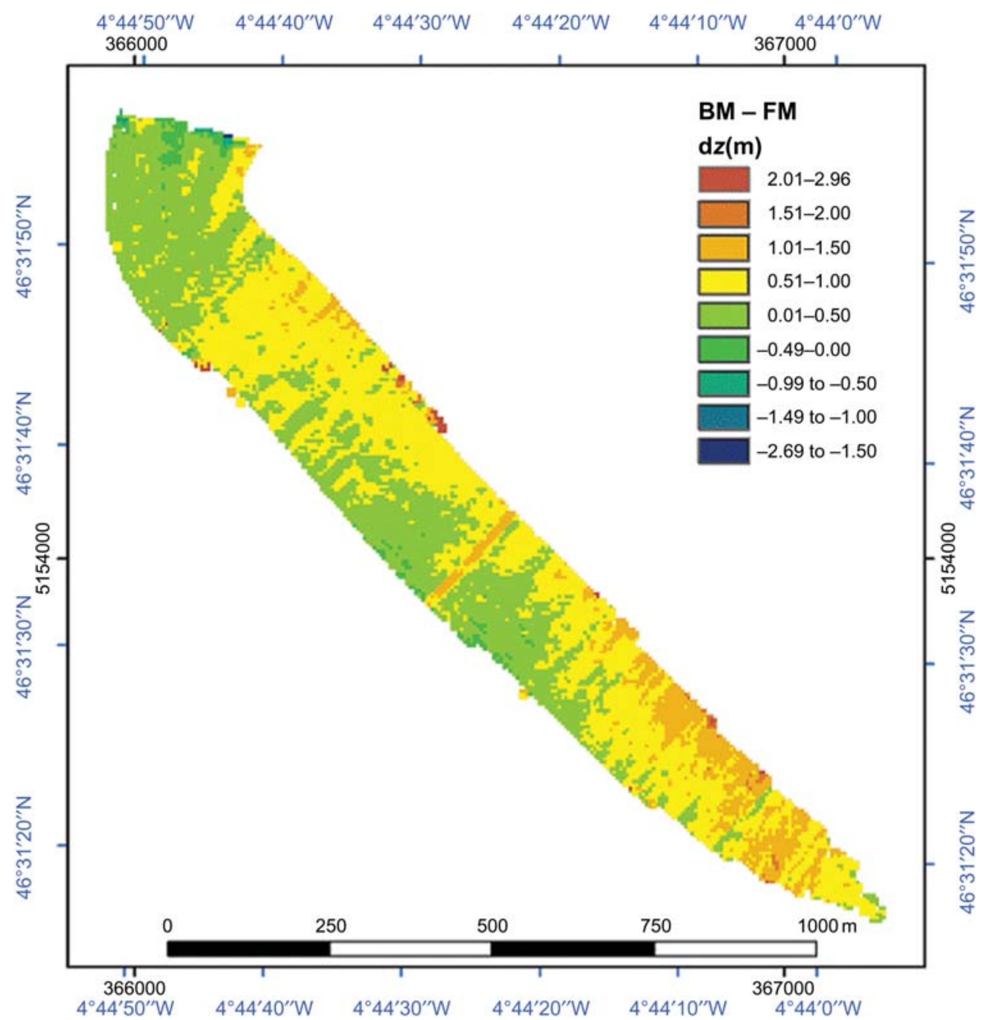

Figure 6. Difference in depths (dz; m) by grid cell between the BM and FM bathymetric surfaces, coloured by dz in intervals of 0.5 m. The mean difference was <50 cm for approximately half the area, and <1 m for ~95% of the area, for an area with a mean depth of 220 m.

that the results are practically equivalent for either rough or flat seabed when positioning data are accurate and precise for both datasets.

Possible limitations of the FM are the reduced pulse-repetition rate and number of beams, and the increased pulse duration. Generally, increased pulse duration diminishes the accuracy and

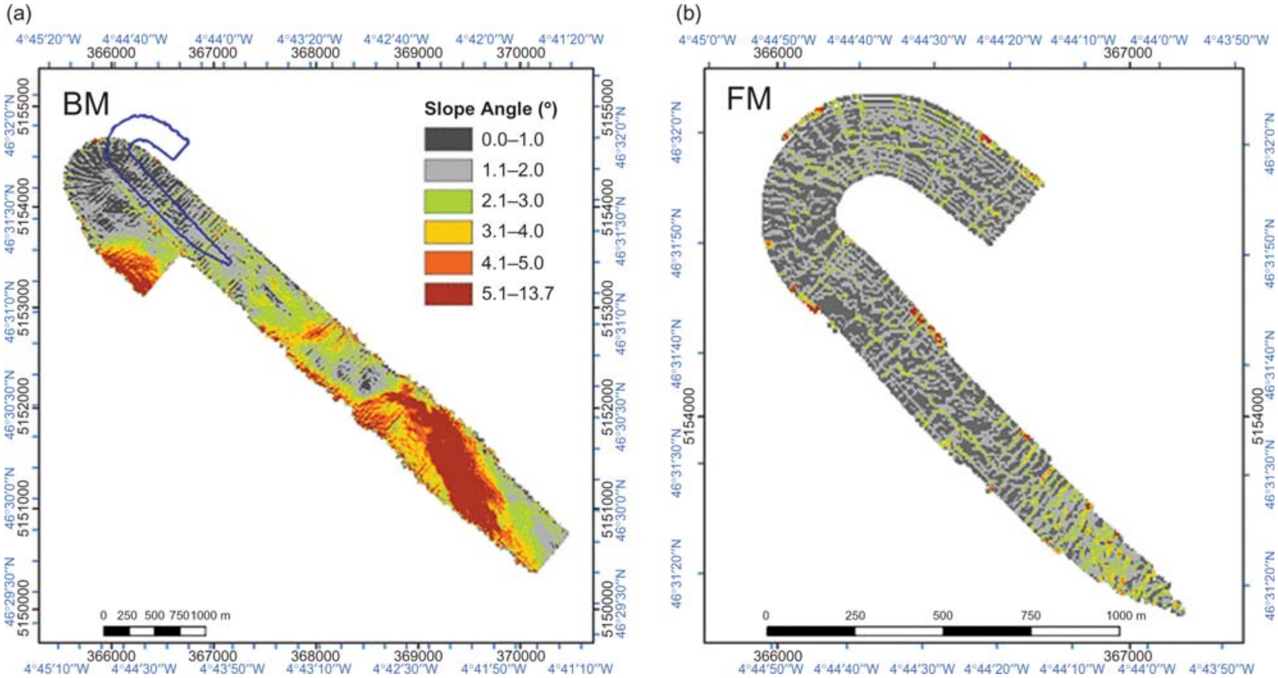

Figure 7. Seabed-slope angles estimated from the difference in elevations among neighbouring grid cells for (a) the BM, and (b) the FM surfaces. Colour classes indicate differences in slope angle at 1° intervals, from 0° to 5°, and one class for >5°. The mean slope for most of the common coverage area was <2°, and the slope values estimated from the BM and FM surfaces are virtually the same. Discrepancies stem from residual motion artefacts in the BM surface and where the change from amplitude to phase detection is in the FM surface.

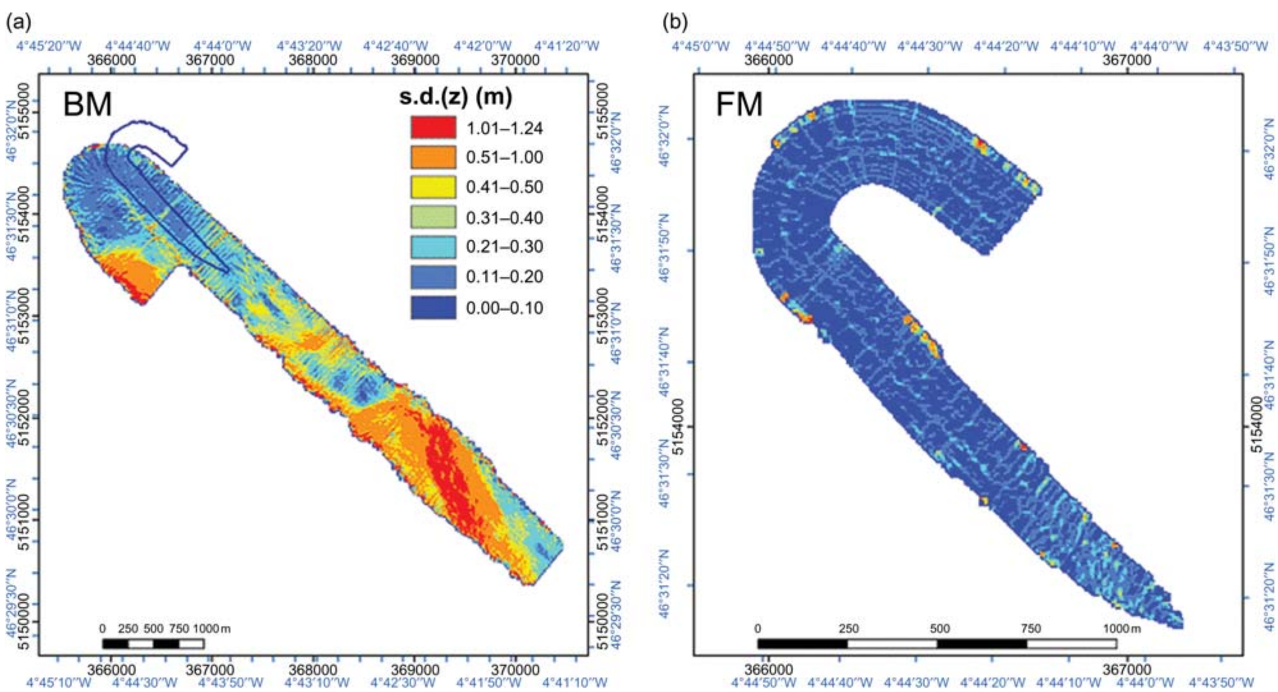

Figure 8. Seabed roughness as the standard deviation of data within 15-m neighbourhoods, estimated for each 5-m grid cell. The roughness was <20 cm for most of the common coverage area for (a) BM and (b) FM bathymetric surfaces.

spatial resolution of bottom-detection solutions from standard methods. However, a method introduced by Demer *et al.* (2009) and enhanced by Cutter and Demer (2010) holds the promise of overcoming these perceived limitations, at least for bathymetry, and provides multiple soundings per split-aperture beam. Nevertheless, software needs to be developed that uses conventional or new methods to process the ME70 FM data. For example, high-resolution bathymetric data could be generated from ME70

FM using a program that processes the data as shown here and also reformats the output into a standard format (e.g. .all format) for input into standard bathymetric data-processing software packages (e.g. Caris HIPS, Hypack, or Triton). Many such packages also include CUBE (Calder and Mayer, 2003), an algorithm for estimating seabed depths and the uncertainty in these estimates.

Such a program could evolve to incorporate improved methods for seabed detection and classification data. For example, the method of Bourguignon *et al.* (2009) uses models and information from multiple beams to determine the statistical probability of a detection. Alternatively, Statistical–Spectral Identification (SSID; Demer *et al.*, 2009) and Multifrequency Bi-planar Interferometric Imaging (MBI; Cutter and Demer, 2010) could be exploited; they use within-beam amplitude and phase information to provide more robust and high-resolution estimations of seabed range, slope, hardness, and roughness from echo amplitudes and phase differences. However, further analyses need to be conducted to configure FM for optimal application of the SSID and MBI methods, and comparison with the FM configured to emulate a bathymetric multibeam with many narrowbeams.

There are many advantages to collecting data with the ME70 in FM compared with BM. Beyond the additional costs of the bathymetric module and the need to survey areas in BM and then FM, the FM is much more configurable and offers two-way beamforming, which more than doubles the side-lobe suppression. The BM uses a single-frequency transmission, and beams are formed only during reception (one-way side-lobe suppression, e.g. −25 dB in the athwartships dimension through classical array weighting). In stark contrast, the acoustic cross-talk between beams is reduced approximately to 2–3 orders of magnitude in FM (reduced by ≤70 dB, depending on array weighting). This notable reduction is accomplished by two-way narrowbeams, side-lobe suppression, and frequency filtering. Consequently, the transmission and the reception of each beam have a unique bandwidth, and the sidelobe of the vertical beam is filtered in the main lobe of the steered beam. The FM also provides multifrequency operation for spectral classification of the water column and seabed scatterers (Demer *et al.*, 2009). Increased pulse duration, typically 2 ms for FM vs. 0.2 ms for BM for a swath of 120°, will, however, lead to averaged measurements for seabed backscatter in FM and reduced resolution for associated metrics for hardness measurements, which could be a limitation in this mode. Notwithstanding, new methods for higher resolution, sub-beam estimates of volume and surface backscatter (e.g. Cutter and Demer, 2010) could help rectify or even reverse this disparity.

Active beam steering is used by the ME70 to compensate for vessel motion. As only up to 45 beams can be formed in FM, such beams are commonly formed that are wider than BM beams to maximize coverage. During active steering, beams are deformed relative to the calibrated-beam shapes, and this can lead to errors in the volume-backscattering coefficients calculated using the calibration-beam model and gain adjustments. The effect and error are enhanced for greater beam-direction angles, away from the broadside of the planar-array transducer. To avoid this effect and potential error when using FM and a configuration with wide beams, motion compensation could be turned off so that the calibrations will remain accurate. It could then be applied in post-processing.

Conclusions

Accurate and precise bathymetry can be obtained from the ME70 operating in FM and BM. The differences between the BM and FM surfaces were <0.65% of depth at >200 m for 99% of the common survey area, after accounting for a 0.54-m bias. The differences were <0.25 and <0.5% of depth for 45 and 93% of the common area, respectively. Taking account of refraction, and with more accurate positioning data, the bias and these differences are likely to be less. Using different beam configurations in FM and alternative bottom-detection methods (e.g. Demer *et al.*, 2009; Cutter and Demer, 2010), the differences could be reduced further, the spatial resolution of the FM soundings could be improved beyond that provided by the BM or the FM configured with many narrowbeams, and the seabed could be characterized and classified.

The BM option is designed specifically for bathymetric mapping and includes processing hardware and software for computing bathymetry and seabed images in real time, and standard bathymetric-mapping products with post-processing. Raw data collected with the BM could also be used for some water-column studies not affected by high side-lobe levels, but there is currently no commercial post-processing software for this purpose.

For the ME70 operating in FM, there is also a lack of commercial post-processing software for both bathymetric-mapping and water-column studies. This situation can be easily mitigated for seabed studies with the development of software that implements the classical methods demonstrated here, or new methods (e.g. Bourguignon *et al.*, 2009; Demer *et al.*, 2009; Cutter and Demer, 2010) and reformats the output into a standard format (e.g. Generic Sensor Format, or Simrad .all) for input into standard bathymetric data-processing software. In addition to bathymetric data-processing tools for ME70 FM data, it is important that methods be developed to process the data for water-column studies. Ultimately, a software package would allow processing of the ME70 FM data for integrated analyses of marine animals and their seabed habitats.

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