Article

A QUALITY ESTIMATOR OF ACOUSTIC SOUNDING DETECTION

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IFREMER

Abstract

Swath sonar bathymetry accuracy depends on the intrinsic performance of acoustic signal processing. We propose here a quality factor, quantifying the accuracy associated with every sounding computation. This descriptor is derived from simple models either for amplitude (variance of the centre-of-gravity instant of a fluctuating bell-shaped envelope) or for interferometric phase (local variance for a number of processed samples). The purpose is to attach to each individual sounding an objective quality level that is sonar independent, and directly applicable in bathymetry processing, either in data editing, or as an input parameter to statistical post-processing. This concept is illustrated by examples from experimental data.

Résumé

La précision des sonars bathymétriques dépend des performances intrinsèques du traitement des signaux acoustiques. Nous proposons ici un facteur de qualité, quantifiant la précision associée à chaque calcul de sonde. Ce descripteur est obtenu à partir de modèles simples soit pour l'amplitude (variance du centre de gravité d'une enveloppe fluctuante) soit pour la phase Interférométrique (variance locale pour un nombre donné d'échantillons). L'objectif est d'affecter à chaque sonde individuelle un niveau objectif de qualité valide quel que soit le sonar, et applicable directement dans le traitement bathymétrique, soit pour l'édition des données, soit comme paramètre d'entrée d'un post-traitement statistique. Ce concept est illustré par des exemples de données expérimentales.

Resumen

La exactitud de la batimetría obtenida por sonar de sector depende del rendimiento intrínseco del procesado de señales acústicas. Proponemos aquí un factor de calidad, cuantificando la exactitud asociada al cálculo de cada sondeo. Este descriptor se deriva de modelos sencillos para la amplitud (variación del instante del centro de gravedad de una envoltura fluctuante campaniforme) o para una fase interferométrica (variación local para un número de muestras procesadas). El objetivo es atribuir a cada sondeo individual un nivel de calidad objetivo que sea independiente del sonar y directamente aplicable en el procesado de la batimetría, al editar los datos o bien como un parámetro de entrada para el posprocesado estadístico. Este concepto está ilustrado mediante ejemplos de datos experimentales

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1. Introduction

Multibeam echosounders (MBES) and interferometric sidescan sonars (ISSS, based on phase difference measurement)) provide a large number of sounding values per ping, obtained from the detection, inside each beam (MBES) or at each time sample (ISSS), of the seafloor impact location from either amplitude or phase processing (Lurton, 2010). The accuracy of this determination depends on many factors associated with either the environment of the sonar and its ancillary sensors such as sound speed or motion (Hare, Godin and Mayer, 1995; Hare, 1995) or to the intrinsic quality of the received acoustic signal and its processing (Lurton, 2003). Although crucial, this latter issue is the less well known, and is often treated as confidential by manufacturers, although some manufacturers have attempted to provide both sonar uncertainty models and real-time quality factors..

It is proposed here that the bathymetric detection from acoustic signals can be associated with a quality factor, describing the measurement performance associated with each sounding computation. Such a concept is expected by users of seafloor-mapping sonars, who need it for data quality estimation during field survey operations, for bathymetry data editing, and for post-processing (particularly the creation of digital terrain models). In this approach, the measurement quality should be directly available under an objective quantified form with a universal character (meaning that the quality descriptor should be the same – at least that its values are directly comparable-, whatever the sonar type, model and brand). Several attempts in this direction have already been made by sonar manufacturers (Reson 2007, Kongsberg 2008). Unfortunately, none has been really conclusive, for two main reasons:

- Usually the descriptor addresses the signal rather than the sounding itself, which is not what the user really needs; even an excellent estimation of the signal -to-noise ratio is only a step towards the expected sounding accuracy, involving a series of modelling steps (Lurton 2003).
- The signal- or sounding-quality estimation often includes some heuristic parts linked to one particular model of sonar, hence providing results valid only for a single configuration.

Hence the need for a universally accepted descriptor has not been fulfilled by these attempts.

The Quality Factor (*QF*) proposed in this paper is simply defined as the logarithm value of the relative depth error estimated directly from the signal used for detection. It is based on elementary models either for amplitude (the variance, in the time domain, of the centre-of-gravity instant of a bell-shaped envelope with fluctuating amplitude) or for interferometric phase (obtained from the local phase fluctuation variance, accounting for the number of processed samples). For one sounding, the uncertainty model is computed using the local characteristics of the actual signal and detection method used. The end goal of this approach is to assign to any sounding an intrinsic quality level valid whatever the sonar considered, and usable directly in the bathymetry processing, either for data flagging and selection, or as an input parameter to post-processing software such as CUBE (Calder 2003).

Thanks to the possibilities of recording intermediate data (signals at the beamformer output) in modern swath bathymetry sonars, the Quality Factor could be computed for a number of practical configurations. Comparisons have been conducted between the proposed *QF* and the estimated bathymetry accuracy, estimated from the statistical sounding value variance computed from an ideal terrain model. This process makes it possible to prove good agreement between the *QF* computed value and the objective uncertainty estimated according to the classical method used as an acceptance test for swath bathymetry sonars.

2. Sounding detection methods

For a huge majority of bathymetry sonars, each sounding value is actually computed by a basic operation (see Lurton 2003; for convenience, most notations are the same in this reference and in the present paper) applied to series of signal samples at the receiving channel output:

- Centre of gravity of the amplitude envelope, for the maximum amplitude instant method (MAI) in MBES;
- Zero-phase difference instant estimation (ZDI), for phase processing in MBES;
- Phase difference direction (PDD) estimation, for ISSS.

In all cases, a sounding computation is obtained from the estimation of a couple (range R, angle θ), or rather (time t, angle θ); see ***Fig.1*** for illustration and notation definition. These measured quantities are then converted into the space coordinates of the impact point geometrically referenced to the sonar arrays, accounting for refraction of the propagation paths; the georeferenced coordinates of the sounding are finally obtained by accounting for the sonar navigation and attitude. The sounding accuracy is hence a combination of the uncertainties caused by acoustical signal detection, refraction by sound speed variations, uncertainties in navigation and motion measurements, and installation geometrical parameters; see a detailed analysis in (Hare, Godin and Mayer 1995) and (Hare 1995). Only the phenomena linked to acoustical signal processing are considered here.

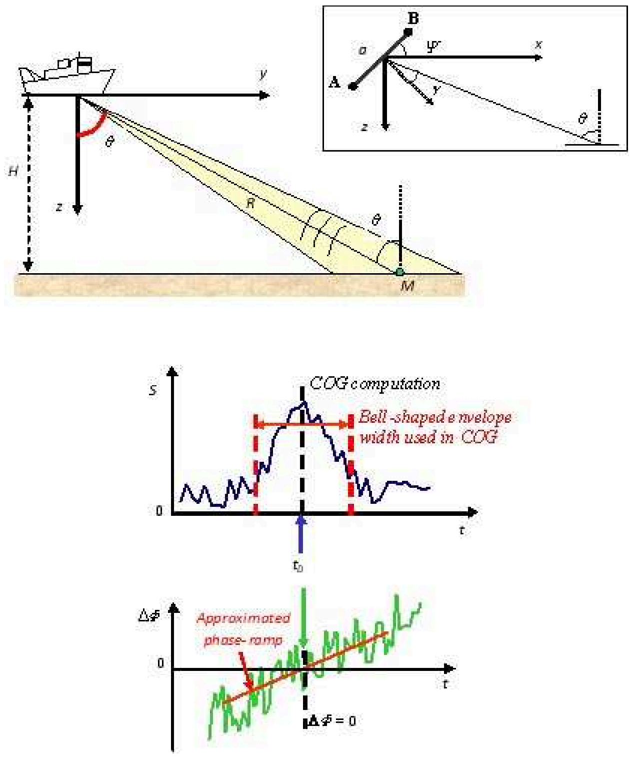

Figure 1. Multibeam sounding geometry (*top*) and notation definition, with a detailed view of the phase-difference measurement case. Arrival time detection by amplitude processing (*center*) (computation of the center of gravity of the bell-shaped envelope) and by interferometric phase (*bottom*) (detection of the zero-phase crossing instant of the phase ramp).

2.1. Amplitude detection

In beams incident at steep angles onto the seafloor, time detection is obtained from the amplitude envelope of the received signal. The most commonly applied processing consists in computing the centre of gravity of the time signal envelope (Fig.1). The accuracy is hence given by the time standard deviation of the COG of a bell-shaped signal perturbed by noise.

In the simplest case where the received time signal is a square window of duration T, assuming a Rayleigh-distributed amplitude, the COG instant variance (Ladroit *et al.* 2010) can be expressed as:

$$\delta t_D^2 = \frac{4-\pi}{\pi} \frac{N(N+2)T^2}{12(N+1)} \qquad (1)$$

where N is the number of statistically-independent samples used in the COG computation.

In the more realistic case of a bell-shaped received signal, it is possible to change Eq.(1) into the more general shape :

$$\delta t_D^2 = B^2 \frac{4-\pi}{\pi} \frac{N(N+2)T^2}{12(N+1)} \approx 0.0228 B^2 N T^2 \qquad (2)$$

where B is a constant depending on the bell shape and on the width considered for the COG computation (Ladroit *et al.* 2010); this width can be defined e.g. by computing the second order moment of the envelope (see 3.2.1). The approximate form in Eq.(2) is valid for high values of N (an accuracy of 5% over δt_D is obtained beyond N=8). Note that T is the transmitted pulse duration for a CW signal; for a chirp, T should be replaced by $1/W$, where W is the modulated bandwidth.

2.2. Phase detection

2.2.1. Detection of the zero-phase instant

In oblique- and grazing-incidence beams of MBES, detection generally consists in searching for the instant of null phase difference (Fig.1 and Fig.2) between the signals at the output of two sub-arrays forming beams in the nominal steering direction (Lurton 2003). This detection is blurred by the fact that the phase difference *vs* time is usually not a smooth line, but is strongly perturbed by noise. The dependence of phase variance on the signal to noise ratio (SNR) is given by :

$$\delta\Delta\Phi^2 \approx \frac{D-\gamma+\ln d}{d} \qquad (3)$$

where d is the power SNR at the input of the phase-difference processing, $D \approx 3.1484$ and $\gamma \approx 0.5772$; this expression is valid for a Rayleigh-fluctuating echo with a sufficiently high SNR.

The fluctuation level of the individual phase-difference values is normally quite high (for instance, a 10 dB SNR should provide a 40° standard deviation of the phase difference). It is usually improved by averaging a number N of complex signal samples prior to the phase value computation. Then the phase difference variance after averaging becomes:

$$\delta\Delta\Phi_N^2 = \frac{1}{(N-1)d} + \frac{N}{2(N-1)(N-2)d^2} \approx \frac{1}{Nd} \qquad (4)$$

considering that the N samples are statistically independent; the approximate form in $1/Nd$ comes for sufficiently high values of SNR d and sample number N. The derivations of formulas (3) and (4) are detailed in (Lurton and Augustin 2010).

The zero-phase difference instant is obtained by matching the fluctuating phase ramp with a straight line, or better with a second-order polynomial; this fitted ideal shape is then used for determining the zero (or possibly other phase angle) crossing within each beam. Statistically, this is equivalent to decreasing the fluctuation rate according to the number of samples used in this processing (Fig.2), equivalently to the averaging process of a random variable. Practically, fitting the phase ramp over N_A samples decreases the effective measurement variance by a factor $1/N_A$.

$$\delta\Delta\Phi_{N_A}^2 \approx \frac{\delta\Delta\Phi_N^2}{N_A} \tag{5}$$

Hence the higher the sample number N_A, the better the detection accuracy - with the disadvantage that the resolution is then degraded, raising the risk that small-size features may not be detected (Lurton and Augustin 2008).

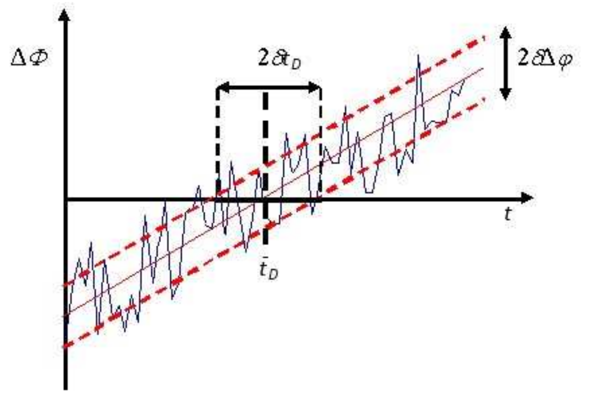

Figure 2. Arrival time uncertainty associated with phase-difference fluctuations. The time standard deviation is given by the projection of the phase-difference uncertainty onto the time axis.

2.2.2. Angle measurement from the phase difference

In an ISSS, the measurement uncertainty is to be considered as an angle error measured at a given instant. The relation between the measured phase difference and the incoming signal angle is given by the fundamental relation of interferometry :

$$\Delta\Phi = \frac{2\pi}{\lambda} a \sin\gamma \tag{6}$$

where a is the interferometer spacing, λ is the acoustical wavelength, and angle γ is referenced to the baseline axis (see Fig.1 for illustration and notation definition).

The angle error $\delta\gamma$ (equal to $\delta\theta$) corresponding to an uncertainty $\delta\Delta\Phi$ in the phase-difference value is hence given by:

$$\delta\gamma = \frac{\lambda}{2\pi a \cos\gamma}\delta\Delta\Phi \tag{7}$$

This last result illustrates the well-known observation that the phase-derived arrival angle estimation is better for large baselines, and directions close to the interferometer axis.

It is clear from the above that the angle accuracy will be improved by a decrease of the measured phase difference noise (given by Eq.(3) for elementary samples), which can readily be obtained by averaging over a number of consecutive samples, as given by Eq.(4). However in current ISSS, it is often chosen to limit (or possibly to omit) this averaging operation, and to provide raw estimates from individual samples, whose filtering is left to post-processing operations.

2.3. Sounding accuracy

The resulting sounding accuracy can be defined, in the general case, by the following relation (Lurton 2003):

$$\frac{\delta H}{H} = \frac{\delta t}{t} + \tan\theta.\delta\theta \tag{8}$$

Practically, time and angle are not estimated jointly: only one is, the other being fixed. In MBES, the measured quantity is the time of arrival, at a fixed angle (given by the beam steering angle), and Eq.(8) simplifies into :

$$\frac{\delta H}{H} = \frac{\delta t}{t} \tag{9}$$

For an ISSS, an angle measurement is performed at fixed values of time from the phase difference estimation, and the corresponding depth error writes:

$$\frac{\delta H}{H} = \tan\theta.\delta\theta \tag{10}$$

In both cases a residual component of the other parameter may be found (angle for MBES, time for ISSS) but it can usually be neglected.

Although the depth error is normally the main cause of concern in bathymetry data quality, the sounding location error in the horizontal transverse direction y is also to be considered:

$$\frac{\delta y}{y} = \frac{\delta t}{t} + \frac{\delta\theta}{\tan\theta} \tag{11}$$

However this aspect is not considered in the following. Similar developments to the depth error analysis proposed here can be readily derived in this respect.

3. The Quality Factor

3.1. Definition

For each one of the three bathymetry methods presented above (MAI, ZDI and PDD), an estimation of the relative depth error can be obtained directly from the corresponding modelling, parameterised by the local characteristics of the signal.

The purpose of the *QF* concept proposed here is hence to provide an *a priori* estimate of the sounding accuracy, based on the actual characteristics of the processed signal obtained from elementary observations and computations. **3**

The fundamental definition of the Quality Factor (noted q_F and *QF*) is given by:

$$q_F = \frac{H}{\delta H} \tag{12}$$

or, in a more convenient way, in logarithmic values:

$$QF = \log(q_F) = \log\left(\frac{H}{\delta H}\right) \tag{13}$$

With this definition, the *QF* value is greater for high-quality measurements, which is coherent with the concept of a quality descriptor. It takes typical values of 2 and 3 for relative depth errors of respectively 1% and 0.1%.

It can be inferred from Section 2 above that the practical computation of *QF* is dependent on the type of sonar considered; the various cases are developed below.

3.2. Multibeam amplitude processing

For amplitude-detected soundings from an MBES, the *QF* expression comes from the model presented in section 2.1, namely Eq.(2):

$$q_F = \frac{H}{\delta H} = \frac{t_D}{\delta t_D} \approx \frac{t_D}{0.15\, BT\sqrt{N}} \tag{14}$$

where t_D is the estimated detection instant, N is the number of independent time samples, T is the transmitted pulse duration, and B is the factor depending on the envelope shape.

3.2.1. Effective signal width

As evoked above, several definitions can be used for the processed width of the bell-shaped echo. A fall-off rate (typically –10 dB) is often considered. In order to improve the processing robustness, we preferred to consider a width N defined as twice the second-order moment of the normalized form $a(t)$ of the received time signal $s(t)$.

$$N = N_S / N_T$$
$$= 2 f_s \sqrt{\int_0^{+\infty} a(t)t^2 dt - \left(\int_0^{+\infty} a(t)tdt\right)^2} \Big/ N_T \tag{15}$$

with $$a(t) = s(t) \Big/ \int_0^{+\infty} s(t) \tag{16}$$

where the integrals are practically computed over a limited time window on the received echo. The number N of independent samples is expressed as a function of the number N_S of signal samples, and the number N_T of time samples inside the duration T. It was found that this approach is more effective than using an envelope fall-off rate, since it is less sensitive to the signal instantaneous fluctuations caused by multiplicative (Rayleigh-like) noise.

Using this width definition for simulations, we obtain the values of the B factor for several envelope types, given in Table I. Note that B is no longer unity in the case of the square window, since the definition of N given by Eq.(15) changes this value

Envelope Shape	*B* factor
Square window	$\sqrt{\sqrt{12}/2} \approx 1.32$
Sinc	1.04
Sinc²	0.96
Cos	1.05
Cos²	0.99

Table I.
Proportionality factor B giving the effective width of bell-shaped envelopes of various types, when using the width definition from Eq.(16).

3.2.2. Validity limit of the QF definition in amplitude

The *QF* definition provided here is valid only if the original signal fulfils sufficiently well the requirement of a "bell-shaped" envelope.

If this is not the case, the *QF* value, computed over too short a time interval without guarantee of the selection relevance, will be overestimated. Checking the bell-shape character is readily done by computing the normalized integration of the squared signal as a function of time over the analysis interval duration T_A:

$$Y(t) = \int_0^t s^2(t)dt \,/\, \int_0^{T_A} s^2(t)dt \qquad (17)$$

or $t \in [0, T_A]$. As a rule of thumb, the bell-shape criterion is admitted to be fulfilled if the difference $Y(0.7T_A)$-$Y(0.3T_A)$ is greater than 0.8.

This issue is particularly important if *QF* is used as an input for a post-processing algorithm such as CUBE (Calder 2003), where sounding values are weighted by their uncertainty: an erroneous high *QF* would cause the propagation of the value of this sounding in its adjacent nodes though its relevance is not as good as it seems. Also when using *QF* values for the choice between amplitude- or phase-detected sounding results, an inappropriate estimate of the amplitude *QF* may lead to a pointless elimination of phase-detected values : this is prone to happen at grazing angles where the bell shape is less pronounced while the phase difference processing is normally the best option.

3.3. Multibeam phase-difference processing

Phase fluctuations cause inaccuracy in the time detection applied in the ZDI method. Fig.2 illustrates the simple observation that the time detection δt_Φ uncertainty is given by the projection of the phase fluctuation onto the time axis, hence depending on the slope of the phase-ramp variation with time, it has to be increased by the uncertainty δt_T linked to the pulse duration T (Lurton & Augustin 2010). Hence the quality factor is defined as $q_F = t_D/\delta t_D$, where the detection time standard deviation is finally obtained as:

$$\delta t_D = \sqrt{\delta t_\Phi^2 + \delta t_T^2} \qquad (18)$$

$$\delta t_\Phi = \frac{\delta\Delta\Phi}{A\sqrt{N_A}}$$

$$\delta t_T = \frac{T}{\sqrt{12}}$$

where $\delta\Delta\Phi$ is the phase standard deviation measured over the effective part of the phase ramp used for curve fitting (featuring N_A statistically independent points); A is the phase-ramp slope; the$1/\sqrt{12}$ factor expresses the standard deviation of a uniformly distributed variable over the time duration T. Practically the phase-ramp is first to be matched with the approximated ideal curve, which provides the slope value A; the standard deviation $\delta\Delta\Phi$ is computed from the variations of the actual phase values around the ideal fitted ramp.

The phase-*QF* definition proposed for MBES is relevant provided that the null phase-difference detection is applicable over a long enough phase-ramp segment. This can be determined by analysing the number of time samples involved in this computation; typically a minimal number of 5 samples over the analysis interval is required. This defines the phase-detection applicability limit for beams at steep incidences.

3.4. Sidescan sonar interferometry

In ISSS processing, phase-difference fluctuations cause angle estimation uncertainty, which can be in turn expressed as a depth error, hence the quality factor comes as:

$$q_{F\Phi} = \frac{H}{\delta H} = \frac{1}{\tan\theta\ \delta\gamma} \qquad (19)$$

The angle measurement uncertainty $\delta\gamma$ can be expressed as the quadratic summation of two components $\delta\gamma_\Phi$ and $\delta\gamma_T$ linked respectively to the interferometric phase estimation noise and to the transmitted pulse duration:

$$\delta\gamma = \sqrt{\delta\gamma_\Phi^2 + \delta\gamma_T^2} \qquad (20)$$

$$\delta\gamma_\Phi = \frac{\lambda}{2\pi a\cos\gamma}\delta\Delta\Phi$$

$$\delta\gamma_T \approx \frac{cT}{2H\sqrt{12}}\frac{\cos^2\theta}{\sin\theta}$$

The phase component $\delta\gamma_\Phi$ is the one presented in Eq.(7). The pulse duration component $\delta\gamma_T$ given here is a first-order approximation, and can be improved by a more detailed derivation for small values of θ ; the $1\sqrt{12}$ factor expresses the standard deviation of a uniformly distributed variable over the angle sector spanned by the time duration T.

Practically the phase-difference standard deviation $\delta\Delta\Phi$ has to be estimated over a time interval surrounding the detection instant; this can be done conveniently by matching locally a linear phase-ramp segment on the actual data, similarly to what is done in ZDI processing (see Section 3.3).

Note that the differential phase may have been preliminarily processed (or not) by averaging over a number of time samples, depending on the details of the sonar receiver considered. Note finally that the *QF* definition provided here holds for the basic configuration of a simple interferometric measurement (with two receivers); it should be extended, in future works, to the case of more complex ISSS systems processing more than two receivers for an optimal combination of multiple angle estimations.

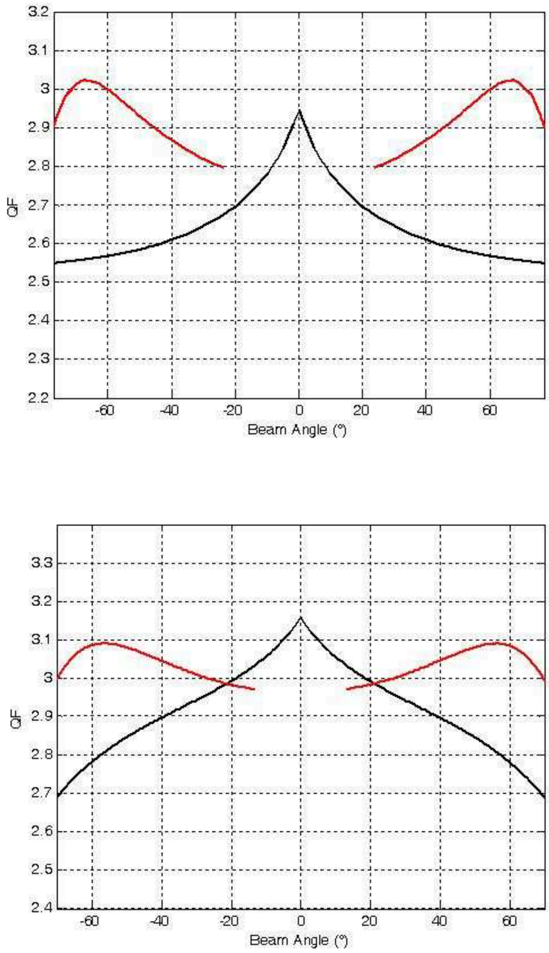

Figure 3. Example of *QF* computation over two simulated configurations. (*Top*) Shallow-water (30 m) high -frequency (100 kHz) case. (*Bottom*) Deep-water (2000 m) mid-frequency (24 kHz) case. These two configurations are close to the ones corresponding to the experimental results given in Fig.4. (*red is for phase processing, black is for amplitude*).

3.5. Simulation and first conclusions

The above models are used for simulating the computation of *QF* values as a function of the incident angle for two MBES configurations. Note that the two cases are very close to the configurations whose experimental results will be presented in Section 4.1.

The shallow-water case is a water depth of 25 m, a MBES at 100 kHz with 301 beams of 1.8°x 1.8° (beamwidth at –3 dB) over 152°, and a cylindrical array (neglecting in first approximation the beam aperture variation with steering angle).

The deep-water case is a 2000-m depth, a MBES at 24 kHz with 400 beams of 0.5° x 0.5° each (beamwidth at –3 dB) over 140°, and a flat horizontal array (hence causing an increase of the beam aperture with steering angle).

The *QF* values computed from these simulations are displayed in Fig.3. They make it possible to draw a number of first conclusions:

- Typical *QF* values are expected to range between 2.3 and 3.3 (i.e. relative depth errors of 0.5% to 0.05%);
- The amplitude *QF* is at its best at the normal from the seafloor; it then decreases as the incidence angles get more tilted from normal incidence;
- The amplitude *QF* either decreases continuously with incidence angle (for flat arrays with an increasing aperture of steered beams) or tends to a lower limit (for cylindrical arrays providing constant-aperture beams).
- The phase *QF* cannot be computed at normal incidences, where the interferometry processing is not applicable. It increases with the incidence angle, up to an optimal point, and then decreases at the swath extremities.
- The phase *QF* values, at their optimum, are as high or higher than the maximum value of the amplitude *QF*.

An intermediate regime with medium *QF* values is observed at the junction between the two regime (amplitude and phase)

All these preliminary conclusions regarding sounding quality are indeed in close compliance with practical field experiences of surveyors involved in MBES operation and data processing.

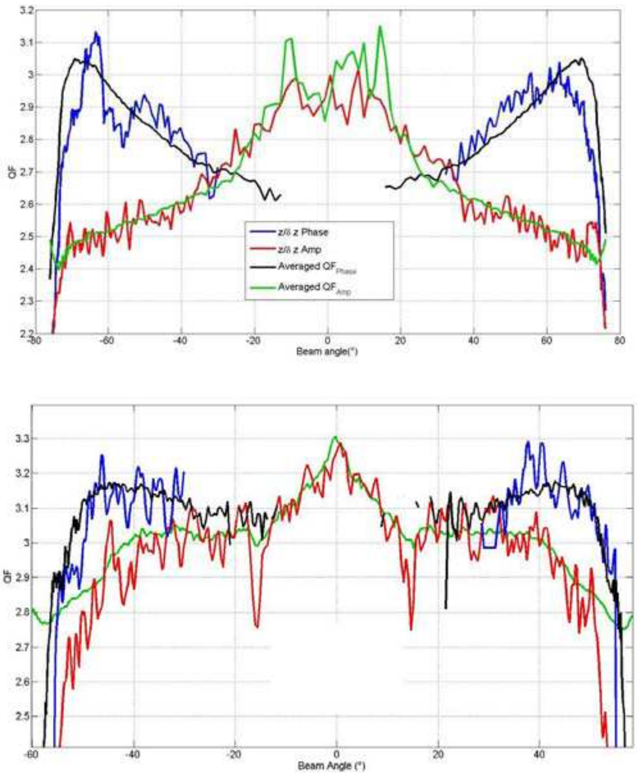

Figure 4. Comparison of the QF prediction and the actual sounding uncertainty, for a high-frequency shallow-water case (top) and a low-frequency deep-water case (bottom). The Quality Factor average predictions are presented for amplitude (green) and phase (black); the sounding uncertainty levels computed for amplitude (red) and phase (blue).

4. Validation over real data

4.1. Methodology

To compare the *QF* predictions with results obtained from actual bathymetry systems, we took advantage of the capacity of recent sonars to record data at the stage of raw signals (i.e. before the detection operations). This is made possible either as a dedicated optional module provided with the sonar, or by courtesy of the manufacturer providing experimental data.

On one side, the detected soundings delivered by the sonar are processed following the classical method used for bathymetry accuracy estimation. If a reference digital terrain model (DTM) is not available, then the soundings collected over a given area are used to generate it, by considering, as far as possible, multiple runs over the area and preferentially selecting the best-quality soundings (coming from MBES beams with moderate tilt). The obtained DTM is smoothed at a relevant scale, and the actual soundings are statistically compared to it, e.g., as a function of beam angle. This approach (that is the one classically used for checking the compliance of swath echosounders with accuracy requirements, e.g., during sea acceptance tests after installation) provides a reliable estimate of the actual sounding uncertainty. When possible, the two candidates for one sounding (in phase and amplitude) are considered.

In parallel with this, the raw signals are used for computing the *QF* values according to the formulas detailed in the above sections. Finally the results from the two methods are compared – the purpose being to check that the *QF* predictions are in good agreement with the sounding statistical uncertainties obtained from the bottom detection module.

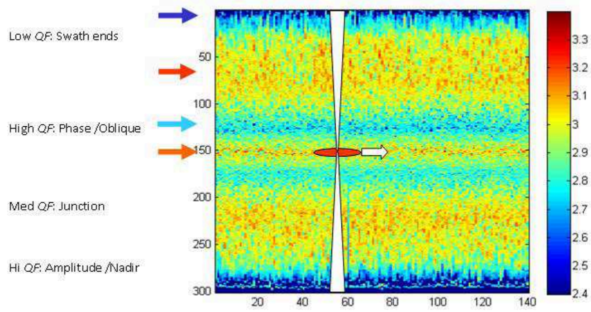

***Figure 5.** Map of the resulting quality factor (high-frequency shallow-water case presented in Fig.4) represented as a function of ping number (abscissa) and beam number (ordinate). This illustrates the stability of the various regimes observed in the (top) plot: good quality factor (2.8 to 2.9) around nadir, excellent values at oblique intermediate angles (3.0 to 3.1); medium values (2.7) at the junction between the two regimes (around 30°) and poor quality (2.6 and below) on the swath extremities.*

4.2. Multibeam echosounder

A first example of comparison is given in *Fig.4* (*top*). This was obtained in a shallow-water configuration (depth about 30 m) with a flat horizontal seafloor, which is a favourable case for estimating the sounding accuracy. The echosounder is a Reson Seabat 7111 installed onboard *RV Pourquoi pas?*. Its main characteristics are: 301 beams of width 1.8° × 1.8°; total aperture 152°; frequency 100 kHz; equidistant soundings.

The sounding uncertainties are plotted both for the amplitude and phase detection. They are compared to the result of the *QF* computation; the agreement obtained is very satisfactory.

A second example of comparison is given in ***Fig.4*** (*bottom*). This was obtained in 2200 meters of water on a flat seafloor, using a Reson Seabat 7150 at 12 kHz. Its main characteristics are: 880 beams of width 0.5°x 0.5°, total effective aperture 135°, equidistant soundings.

Here again the agreement is very good between the estimated fluctuations of the measured bathymetry and the predictions provided by the *QF* computation.

Fig.5 illustrates the variations of *QF* plotted in the horizontal plane. It makes clear the stability of the various regimes: high values of *QF* close to normal incidence and at intermediate oblique angles (where interferometry works at its best); low values at the swath ends (corresponding to the decrease in SNR); and a local minimum at the junction between the amplitude and phase detection modes.

Fig.6 presents an example of practical application of *QF* computation to the processing of data from a scene featuring a wreck over a flat shallow seafloor. It includes the bathymetry data obtained from the amplitude and the phase processing; the *QF* values computed for both detection modes; and finally the resulting bathymetry, obtained by retaining the sounding candidates presenting the highest *QF* values, displayed together with the resulting *QF* map. This example clearly illustrates the interest of the *QF* concept in the sounding detection process.

4.3. Interferometric sidescan sonar

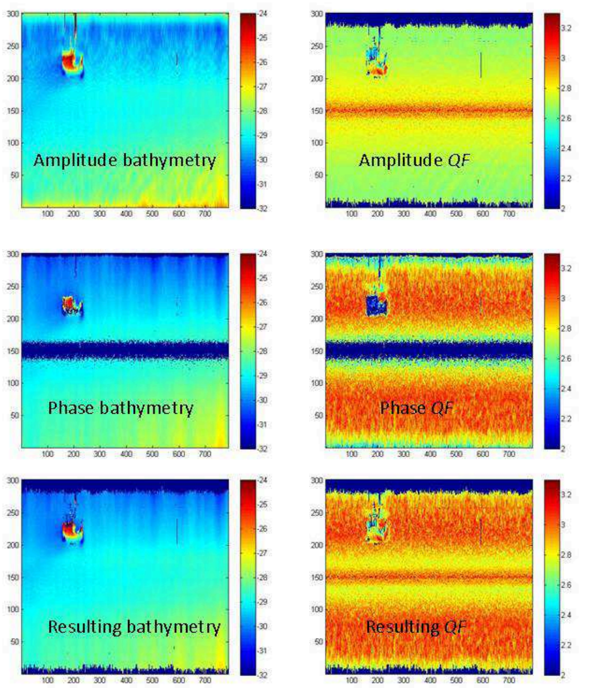

Figure 6. *Example of application of QF computation for the selection of soundings when both phase- and amplitude-detected candidates are in competition. The configuration is a high-frequency shallow-water case with a wreck present. The amplitude results (bathymetry and QF) are given in the top row ; the phase-difference detection results (bathymetry and QF) are in the central row; the lower row presents the resulting bathymetry and the corresponding quality factor.*

In this case the data made available by the manufacturer were the complex signals recorded from the receiving baselines. The sonar is a Klein series 5000, frequency 455 kHz, baseline spacing 4 wavelengths, pulse duration 0.2 ms; the signals were recorded over a flat sediment seafloor, at a sonar altitude of 9 m, with a sampling rate about 22 kHz.

The raw data were first used for computing the sounding values, using a classical process: the phase difference is computed between the baseline signals and unwrapped, then transformed into a signal arrival angle and finally the bathymetry values. The latter are filtered to obtain a smoothed terrain profile; a simple average over a square window was applied in this case. Finally, the local variance of the sounding values are computed from this smoothed bathymetry values.

The *QF* values are computed in parallel. Starting from the phase-difference values, a series of 30 samples is considered as a phase ramp (similarly to what is done in MBES processing) and fitted with a straight line; the phase variance around the ideal fitted phase ramp is then computed, and transformed into a depth uncertainty, which is completed by the term linked to the pulse duration. The resultant depth uncertainty is finally transformed into the *QF* value.

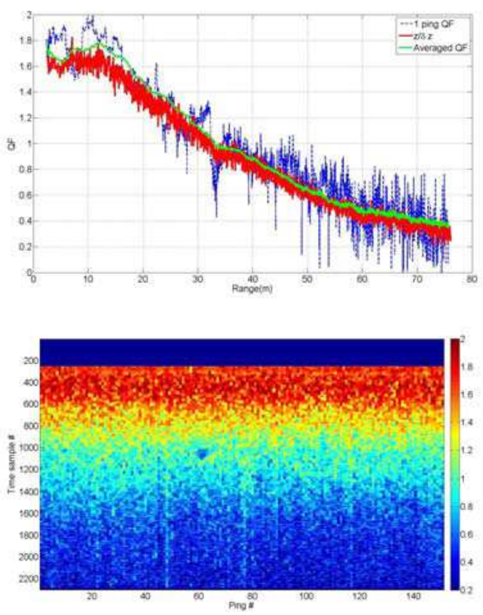

Figure 7. *Example of QF computation applied to an interferometric sidescan sonar (Klein 5000, frequency 455 kHz, baseline spacing 4 wavelengths, pulse duration 0.2 ms; signals recorded over a flat sediment seafloor, sonar altitude 9 m, sampling rate 22.5 kHz) .The upper plot presents the comparison between the estimated uncertainty in depth (red, log(z/dz)) and the QF prediction either averaged (green) or for one particular ping (blue). The second plot (bottom) depicts the computed QF plotted as a function of ping number (abscissa) and sample number in reception (ordinate).*

The comparison of these two processing results is given in ***Fig.7.*** It shows a very satisfactory agreement, in the sense that the *QF* values nicely describe the bathymetry fluctuations. This observation is not very surprising in itself considering that the bathymetry and the *QF* computations use the same formulas and input signals.

Also it is to be noticed that the *QF* values presented here (ranging from 0.3 to 1.8) are far poorer than the ones obtained with a MBES, and are characteristic of very inaccurate depth measurements. This should be tempered by the remark that absolutely no averaging has been applied in the processing; the phase-difference time samples have all been processed individually, which should normally not be the case in current situations, where some form of smoothing should occur, either over the individual soundings, or (better) over the input complex signal.

5. Conclusion: capabilities and limitations of the quality factor

The concept of a Quality Factor for individual soundings provided by swath bathymetry sounders has been proposed here for the most common configurations of modern sounding systems. Under this form, it shows a very good agreement between its estimates and the statistical results obtained from a classical analysis of the sounding uncertainty. The generality of the processing principles analysed here make it very versatile, independent of the sonar type, while of course depending on the details of the processing applied. In this respect, it is clear that the best option for its estimation is that manufacturers implement it in the bottom detection module, in order to provide it along with the sounding values as part of the output datagrams.

QF constitutes then a valuable and objective estimator of the local sounding quality. A major feature is that it gives direct access to the beam-by-beam bathymetric uncertainty (which for instance an estimation of the local SNR cannot provide directly). Based jointly on a model of the detection operations and on the received signal characteristics, it is an estimator of both the bottom-detection processing performance and the local signal quality.

One should keep in mind that *QF* only addresses the "acoustical component" of uncertainties in the sounding measurement process. The "global" bathymetry accuracy has to be completed by the components linked to ancillary sensors, vessel dynamics and environmental variables.

Moreover, *QF* is restricted to the simple configurations presented above, while the acoustical reality can be more complex. Several well-known issues in sonar bathymetry cannot be addressed, namely:

- ambiguities in phase-difference determination; this is one of the main problems met by ISSS. *QF* only estimates the quality of a correctly-unwrapped phase signal;
- the specular return influence close to normal incidence; a bottom detection biased by a strong specular signal may correspond to a high value of *QF*, which is hence inefficient for identifying such a problem;

similarly, external interferences from e.g. transmission from other sonar systems may be given excellent *QF* values (since they feature a very high SNR and a short duration); here again, *QF* is of no help for eliminating these unwanted signals.

The *QF* algorithm can be easily implemented in the standard bottom-detection software modules featured in the various bathymetry sonars; its computation time is negligible compared to the rest of the sounding detection operations. Its results are applicable to:

- the bottom detection algorithm, since it provides an objective criterion of choice between amplitude- and phase-determined candidate values for one given sounding (or, optionally, a weight that could be applied in an amplitude-phase blended detection solution);
- bathymetry data editing; once available in the datagrams, the *QF* values provide to the hydrographer a reliable tool for estimating the credibility of soundings, and help him in data cleaning (this suggests evolutions in post-processing software tools and in the training of hydrographers);
- quality control of bathymetry data; the locally-computed *QF* may be of interest for addressing objectively the trade-off between accuracy and resolution; bathymetry post-processing, in the case of high-density data; in such configurations, the statistical processing (Calder 2003) makes use of quality criteria for the measurement results, and *QF* can prove to be a very efficient input parameter for such an approach. In particular, this should enable multiple data sets from various sensors to be integrated (including e.g. both MBES and ISSS) in a single CUBE processing run.

Besides the ongoing works dedicated to refinements of the modelling and validation upon more experimental data, the next step in the *QF* development will be its transfer to sonar manufacturers for implementation in current bathymetry systems.

Hopefully this concept, once made operational, will prove to be a useful tool in bathymetry data acquisition and processing, especially given today's general trend toward the sounding density increase linked to progress in sonar technology, and the subsequent need for more automated methods of bathymetry data processing.

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References

Calder B. (2003) Automatic Statistical Processing of Multibeam Echosounder Data. *International Hydrographic Review*, Vol.4, No.1, pp53-68

Hare, R. (1995) Depth and position error budgets for multibeam echosounding, *International Hydrographic Review*, Vol.72, No.2, pp.37-69

Hare, R., Godin, A., & Mayer, L. (1995) Accuracy estimation of Canadian swath (multibeam) and sweep (multi-transducer) sounding systems. *Canadian Hydrographic Service Internal Report*

Kongsberg (2008) *Instruction Manual - EM series Multibeam Echosounders Datagram Formats*, pp 44 & 52

Ladroit Y., Lurton X., Augustin J.M & Garello R. (2010) Accuracy modelling of bathymetry measurement by amplitude processing for multibeam echosounders. *Canadian Hydrographic Conference*, Québec, Canada

Lurton X. (2010) *An Introduction To Underwater Acoustics – Principles and Applications*, 2nd ed., Springer-Verlag, Berlin

Lurton X. (2003) Theoretical Modelling of Acoustical Measurement Accuracy for Swath Bathymetric Sonars. *International Hydrographic Review*, vol.4, N°2, pp 17-30

Lurton X. & Augustin J.M. (2008) Interferometry for Bathymetry Sonars: Accuracy, Resolution and Quality Factor, *Shallow Survey'08*. University of New Hampshire, Portsmouth N.H.

Lurton X. & Augustin J.M. (2010) A Measurement Quality Factor for Swath Bathymetry Sounders. *IEEE Journal of Oceanic Engineering*, accepted for publication

Reson (2007) *SeaBat 7125 High-Resolution Multibeam Echosounder System Operator Manual*, pp 85-86

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Xavier Lurton received the PhD degree in Applied Acoustics from the University of Le Mans (France) in 1979. He was first for eight years with Thomson-Sintra ASM, mainly specializing in sound propagation modeling for naval applications. In 1989 he joined Ifremer in Brest as an R&D engineer for underwater acoustical applications to oceanography. He is now head of the Underwater Acoustics service of Ifremer, and in charge of technological research programs on advanced methods for seabed-mapping sonars, his current interests being both in seabed backscattering physics, sonar signal processing and engineering of sonar systems, especially multibeam echosounders. He has also been teaching underwater acoustics in French technical universities for many years.

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