INVESTIGATION INTO INTERFEROMETRIC SONAR SYSTEM ACCURACY

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The results of the accuracy measurements of phase differencing bathymetric sonar (PDBS) system in shallow waters are presented in the article. The measurement results were compared with the theoretical calculations for sonar system accuracy and international standards for hydrographic surveys. The proposed formulas enable to assess a priori sonar system performance using system quality factor (SQF), which takes into account influence of variable environmental conditions and auxiliary sensors on depth accuracy in a real-life scenario. The proposed SQF can be used in survey planning process to predict the swath width.

INTRODUCTION

A phase differencing bathymetric sonar (PDBS), commonly referred as an interferometric sonar, has been used for obtaining sea bathymetry for more than 25 years [1, 2, 3]. Although initially it was used mainly for ocean measurements [4], it has become a valuable tool for coastal surveys. It has the advantage over multi-beam echo sounder (MBES) of providing wider swath width especially in shallow waters (up to 12 times water below the transducer). This greatly reduces time necessary to obtain the full coverage [5] and allow to convey survey further from hazardous features and the shore line. The construction of PDBS has developed over the years by incorporating more receivers and separating projectors from hydrophones as well as using advanced signal processing techniques [6, 7]. Although sole interferometric sonar is proven to be an accurate tool [8, 9, 10] there are still means needed to assess the overall sonar system performance, as it is a combination of multiple sensors and operates in a dynamically changing environment, in relation to international and national standards or other systems. The article develops the idea of quality factor (QF) proposed by X. Lurton [11, 12, 13] to provide a simple way of predicting sonar system performance.

1. BASICS OF ACOUSTIC INTERFEROMETRY

PDBS operates on similar basics to radar interferometry [14]. In its simplest form it combines signals from two receivers A and B to derive direction of arrival γ (DOA), relative to the interferometer axis, from the phase difference between them (Fig. 1.). The phase shift $\delta\hat{\varphi}$ is estimated form the formula:

$$\delta\hat{\varphi} = \arg\left(E\left\{s_A \cdot s_B^*\right\}\right) + n \cdot 2\pi, \quad n = \ldots -2\, -1, 0, 1, 2, \ldots . \tag{1}$$

where s_A is the signal received by the hydrophone A and s_B* is a complex conjugate of the signal received by hydrophone B.

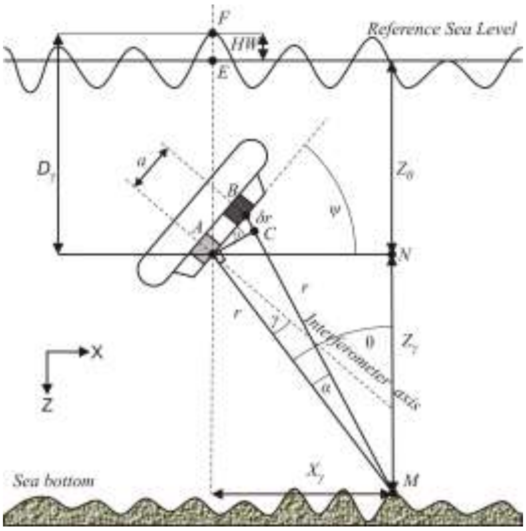

Fig.1. PDBS operating principles.

The distance between the receivers *a* plays a crucial role in the operation of PDBS. If it is grater than half wavelength the resolved angle is ambiguous (*n* can be different than zero as there is more than one interference fringe along the array aperture) [15] and one of various methods should be used to overcome this issue [16]. For high frequencies though, it is impossible to achieve such a small separation, that is why phase unwrapping is performed before further calculations. In general, the larger the baseline the better angular accuracy can be achieved [17], but it cannot be enlarged indefinitely due to constraints described in section 2. If we estimate the phase shift and convert it to distance according to the formula:

$$\delta r = \frac{\delta\hat{\varphi}}{k} = \delta\hat{\varphi} \cdot \frac{\lambda}{2\pi} = \delta\hat{\varphi} \cdot \frac{c}{2\pi f} , \tag{2}$$

were *c* is the sound speed, *k* is the wavenumber and *f* is the frequency. We can calculate DOA from the triangle ABC (Fig. 1): *

$$\sin\gamma \approx \frac{\delta r}{a} = \frac{\delta\hat{\varphi}}{k \cdot a} = \delta\hat{\varphi} \cdot \frac{c}{2\pi a f} , \tag{3}$$

$$\gamma \approx \arcsin\left(\frac{\delta\hat{\varphi}}{k \cdot a}\right) = \arcsin\left(\delta\hat{\varphi} \cdot \frac{c}{2\pi \cdot a \cdot f}\right) . \tag{4}$$

Similarly to multibeam echosounders (MBES), sound speed *c* at the array face is crucial for calculating DOA. The sound velocity probe situated near the array is used to provide

* For large *r* the angle *α* goes to zero and rays MA and MB are almost parallel at the array face which justifies the approximate formula.

so-called beam angle correction. Because the beam is transmitted in the direction perpendicular to the vessel motion the Doppler effect can be neglected.

The distance r is calculated from two-way time-of-flight t for which the estimation of γ is computed and sound propagation speed (constant in the first approximation):

$$r = \frac{c \cdot t}{2} . \tag{5}$$

The depth determination is accomplished by knowing the exact attitude of the array (tilt ψ, instantaneous drought D_γ, roll, pitch and yaw). Depth should be related to a certain reference sea level be calculating the height of water (HW) for the moment of measurement (tide and heave corrections). Position of the sounding is determined in a similar way from simple geometric relations. In a real-life scenario there should be a sound velocity profile measured and the ray tracing algorithm used to obtain more accurate range estimation.

2. MAIN SOURCES OF PDBS ERRORS

There are five primary sources of errors in PDBS DOA determination [17, 18, 19, 20]:

1) additive noise;
2) baseline decorrelation;
3) shifting footprint effect;
4) multipath;
5) volume reverberation.

Additive noise may have many sources. In the case of high-frequency acoustics additive noise can be mainly attributed to thermal noise in water, electrical noise in the electronic equipment and the carrier noise (water flow, engine etc.). Sea water noise is not the primary source of errors [17] however care should be taken in supplying high-quality AC for the equipment. Electromagnetic compatibility issues can severely degrade the sonar performance.

Interference of many scatters within a single footprint causes disturbance in the reflected wavefront. If the receivers are to closely spaced the resulting DOA error due to baseline decorrelation can be significant. On the other hand, increasing the separation causes phase ambiguity that needs to be resolved. Shifting (or sliding) footprint effect is a source of decorrelation of signals since at a given measurement time slightly different parts of footprint contribute to the signals received by A and B. This effect is particularly evident for DOA far from the interferometer axis, and in the case of large separation between receivers (greater than wavelength). Multiple reflected signals may reach the receivers particularly in the shallow water and harbour areas. Signals reflected from sea bottom, sea surface and piers or wharf interfere with the direct signal degrading the sonar performance. Volume reverberation is generally of a lesser concern. However, care should be taken to avoid surveying shortly after a period of high sea states or heavy rainfall because air bubbles may negatively affect the sonar performance.

Most of the above errors can be minimised by increasing the number of receivers, tilting the array and by employing advanced signal processing techniques [5, 7, 20]. Nevertheless, there is a residual uncertainty which can be assessed.

3. PDBS ACCURACY

Taking into account three of the aforementioned sources of errors, excluding multipath and reverberation, sonar DOA accuracy can by calculated from the following formula, under the assumption that ψ is exactly known [7]:

$$\delta\theta = \cdot\frac{\lambda}{2\pi\cdot M_B\cdot a\cdot\cos(\psi)\cos(\theta-\psi)}\cdot\sqrt{\left(\frac{1}{(N-1)M_s\cdot d_{eq}}\right)\cdot\left(1+\frac{N}{(N-2)M_s\cdot d_{eq}}\right)}\,, \tag{6}$$

where θ is the angle of incidence (Fig. 1), N is the number of snapshots used to obtain one sounding. M_s is the number of subarrays, M_B is the number of receivers between the centres of subarrays and d_{eq} is the equivalent SNR calculated from the formula [17]:

$$d_{eq} = \frac{1}{\frac{1}{d_{ext}}+\frac{1}{d_{sf}}+\frac{1}{d_{bd}}}\quad , \tag{7}$$

where:

d_{ext} – output SNR after beamforming,
d_{sf} – equivalent shifting footprint SNR,
d_{bd} – equivalent baseline decorrelation SNR,

$$d_{ext} = 10^{\frac{SL-NL-2TL+BL+AG}{10}}\quad , \tag{8}$$

$$d_{sf} \approx \frac{cT}{2a\left|\sin(\theta-\psi)\right|}-1\ , \tag{9}$$

$$d_{bd} = \frac{\nu}{1-\nu}\ , \tag{10}$$

$$\nu = \frac{\sin\eta}{\eta}\ , \tag{11}$$

$$\eta = \frac{ka}{H}\cdot\frac{cT}{4}\frac{\cos\theta}{\tan\theta}\cos(\theta-\psi)\ . \tag{12}$$

A theoretical curve for GeoSwath Plus system parameters [21] is presented in the Fig. 2. It is evident, that shifting footprint effect has the greatest influence on PDBS accuracy and that the best achievable accuracy is can be obtained near the interferometer axis. The tilt of the array by 60° allows the effect to be minimized for a wider range of angles.

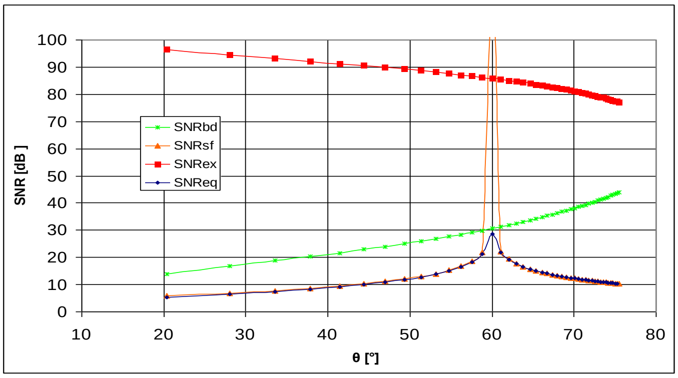

Fig. 2. SNR of external noise, baseline decorrelation, shifting footprint, and equivalent SNR as a function of angle of incidence. Assumptions for calculations: Tilt angle ψ=60°, depth below transducer 7,5 m; attenuation 0,8 dB/m, array gain 50 dB, bottom reflection -30 dB, source level 210 dB, along track beam width 0,5°, pulse length 50μs,thermal noise level 81,5 dB, a=0,012 m, frequency 500 kHz, sound speed 1500 m/s [21].

4. SONAR SYSTEM ACCURACY

In hydrographic research applications surveying system accuracy is of the biggest concern. The International Standard S-44 5-th edition [22] states that the system as a **whole** should be capable of delivering certain depth and position accuracy depending on the water depth and Order of the survey (see Tab. 1).

Tab. 1. Minimum Standards for Hydrographic Surveys [22].

Order	**Special**	**1a**	**1b**	**2**
Maximum allowable TVU 95% Confidence level	**a = 0.25 m** **b = 0.0075**	a = 0.5 m b = 0.013	a = 0.5 m b = 0.013	a = 1.0 m b = 0.023
Maximum allowable THU 95% Confidence level	**2 m**	5 m + 5% of depth	5 m + 5% of depth	20 m + 10% of depth

The Total Vertical Uncertainty (TVU) is computed from the formula:

$$\mathrm{TVU} = \sqrt{a^2 + (b \cdot d)^2} \quad , \qquad (13)$$

where:

a - represents that portion of the *uncertainty* that does not vary with depth;
b - is a coefficient which represents that portion of the *uncertainty* that varies with depth;
d -is the depth in meters.

We can divide the sources of system errors into four main domains:

1) sonar errors;
2) auxiliary sensors errors;
3) system setup errors;
4) environmental influence.

Sonar errors for PDBS were described in section 2. A typical system configuration for PDBS consists of:

- transducer heads (port and starboard);
- Processing Unit (PU);
- Motion Reference Unit (MRU);
- dual antenna GNSS receiver (GPS and/or GLONASS, preferably with PPS synchronization and RTK mode);
- Sound Velocity Probe (beam angle correction);
- Sound Velocity Profiler (CDT, STD, or SVP);
- The equipment set technical specifications for a performance limit on the accuracy.

System setup errors should be understood as:

- errors of measurement of relative sensors positions;
- errors of alignment of sensors relative to the vessel axes (although some errors might by minimised by proper calibration);
- errors of centre of gravity determination (crucial for proper attitude determination);
- signals synchronization errors.

Environmental conditions additionally limit the achieved accuracy. Apart from those already mentioned, the environmental influence is also attributed to:

- spatial and temporal changes in the sound speed profile;
- bottom and sea surface properties;
- constant changes in the sea level (waves i.e. surface waves, tides, seiches);
- marine life.

The above list is by no means comprehensive but its purpose is to underline the need of overall system performance analysis.

5. SONAR SYSTEM ACCURACY MEASUREMENT

Research was carried to determine the accuracy of GeoSwath Plus system in the port of Gdynia on the 29th of May 2015. A flat area of mean depth of 8,3 metres was surveyed several times to obtain the reference DTM with a grid cell size of 0,25x0,25 m. Then each survey line, after initial filtering of outliers (see Fig. 4 and 5.), was compared to the DTM. Standard deviation and average difference were calculated for 2m strips oriented parallel to the survey line. Results are presented in Fig. 3.

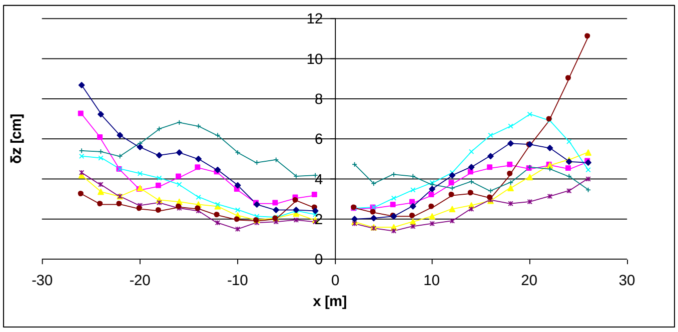

Fig. 3. Standard deviation root-mean squared with mean difference from DTM as a function of cross track distance, mean depth =8,3m.

Fig. 4 shows several important issues about interferometric sonar data acquisition. Firstly, if the soundings are not range gated we can observe noise up to the range equal to the depth below the transducer, as there is no real signal reflected from the bottom. Secondly, there are sparse outliers that can be attributed to errors in phase unwrapping or multipath. What is more the online processing of the data generated images similar to Fig. 4 and Fig. 5, where the 'butterfly' pattern can be observed in accordance to the quantitative results above and theoretical formulas indicating gradual degradation of accuracy as a function of range and angle of incidence.

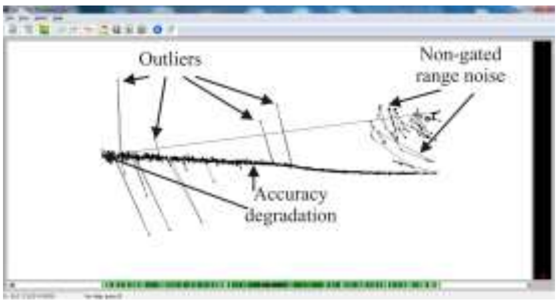

Fig. 4. Sample raw data from portside head (QINSY® 8.1).

Fig. 5. Sample sonar system swath (QINSY® 8.1).

Subsequently, logarithmic system quality factor [13] for mean depth accuracy was calculated as a function of the angle incidence (Fig.6):

$$SQF = \log\left(\frac{Z_\gamma}{\delta z(\theta)}\right) . \qquad (14)$$

The results of the research were compared with the theoretical quality factor QF for PDBS which can be calculated from the formula (12) by substituting *δz(θ)* in equation by:

$$\delta z_t(\theta) = Z_\gamma \tan\theta \cdot \delta\theta \ , \tag{15}$$

$$QF = \log\left(\frac{Z_\gamma}{\delta z_t}\right) . \tag{16}$$

From the Fig. 6, it is evident that QF overestimates the system quality factor as it does not take into account other sources of errors than sonar alone. A formula is proposed for estimating theoretical SQF:

$$SQF = \log\left(\frac{Z_\gamma}{\sqrt{\delta z_t^{\ 2} + \delta_{HW}^{\ 2} + \left[\delta\psi \cdot Z_\gamma \cdot \tan(\theta)\right]^2}}\right) . \tag{17}$$

After applying values of standard error values of MRU for roll and heave (0,02° and 0,03 m respectively) the resulting SQF matches more closely the results of the research. The remaining discrepancy is associated with the error sources not accounted in the equation (especially multipath).). For angles from 20° to ψ the errors of MRU are the main contributors the total depth error ie. PDSS depth errors are more than 3 times smaller compared to them (which is equivalent to approximately 5% of total error).

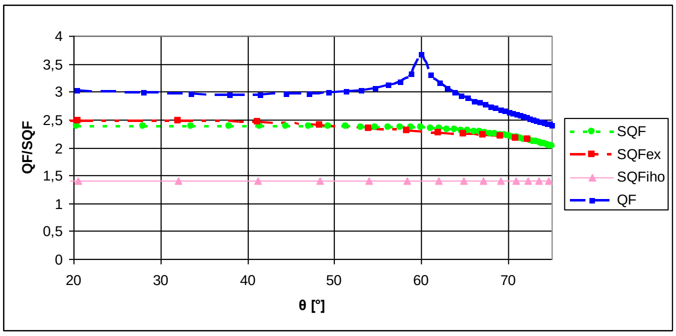

Fig. 6. Comparison of QF and SQF against IHO standards (adjusted to the RMS value) for the depth of 8,3 m.

Equation (17) might be further expanded to the form:

$$SQF = \log\left(\frac{Z_\gamma}{\sqrt{\delta z_t(\theta)^2 + (a \cdot \delta_{HW})^2 + \left[b \cdot \delta\psi \cdot Z_\gamma \cdot \tan(\theta)\right]^2}}\right), \tag{18}$$

where *a* and *b* are empirical parameters providing curve fit to the experimental results.

6. CONCLUSIONS AND FURTHER RESEARCH

Accuracy of the system performance is of the greatest concern in hydrographic research which has to fulfil the requirements of the Order of the survey. The proposed formulas allows to assess the in field system performance based on characteristics of the sonar and auxiliary sensors. The proposed approach also allows calculating the swath width of the desired accuracy, related to the survey depth, which can be helpful in planning survey lines and achieving better survey efficiency.

Although quite simple the proposed formulas seems to fit quite well to the real data. Further research will be carried to validate this approach for different depths and bottom types. Also a model of multipath will be employed to fit better real-life conditions.

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