Improving spatial resolution of interferometric bathymetry in multibeam echosounders

Gerard Llort-Pujol[a], Christophe Sintes[a] and Xavier Lurton[b]

[a]ENST-Bretagne, Dpt ITI, CS 83818, 29238 Brest Cedex 03, France
[b]Institut Français de Recherche pour l'Exploitation de la Mer, NSE/AS, BP 70, 29280 Plouzané, France
lurton@ifremer.fr

Most multibeam echosounders used in seafloor mapping perform the interferometry method for bathymetry measurement, based on the zero-crossing of the phase difference between two sub-arrays. In this approach, only one sounding is computed per formed beam, and the spatial resolution is linked to the beam footprint extent. Using the whole content of the phase-difference signal vs. time makes it possible to ideally get a bathymetry data sampled at the very resolution of the digitized signal. However, this approach compels the phase difference to be unambiguous. Indeed, when the phase difference is determined through the argument operator, the resulting value is truncated within a 2pi-length interval. To tackle this hitch, this paper presents and compares techniques to remove the phase ambiguity based upon interferometry, cross correlation and high-resolution methods. Figures are illustrated by results obtained on a shipwreck, enhancing the difficulties of each removal technique.

1 Introduction

Many underwater applications such as pipeline tracking or seafloor cartography demand for high-resolution bathymetry at the lowest possible surveying cost. To this end, multibeam echosounders have taken an important role due to their potentiality of measuring a large quantity of bathymetric soundings per ping from a single emitted signal with full-swath coverage. In order to profit from this amount of available information, several direction-finding techniques can be then regarded such as an amplitude-based detection, a phase-based detection (interferometry) [1] or a complex detection (high resolution methods) [2]. In this paper, we focus our attention on interferometry due to its quick, accurate water-depth measurement compared to the other two techniques [3].

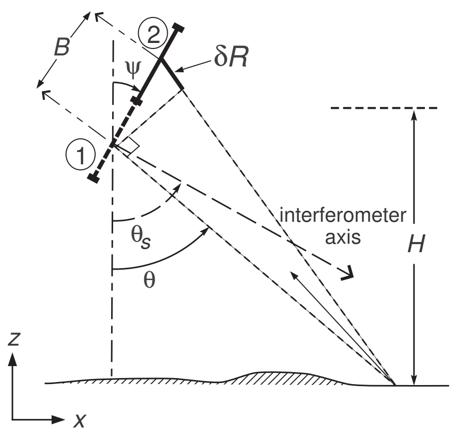

Figure 1: Multibeam interferometry geometry.

1.1 Interferometric principle

In order to triangulate an echo, interferometry estimates its spatial coordinates from the phase delay produced when the backscattered wavefront reaches two close receivers at different instants of time. This phase delay is estimated from the phase difference $\Delta\varphi$ between the signals s_1 and s_2 received by each interferometric antenna.

$$\Delta\varphi = arg\{s_1 s_2^*\} \tag{1}$$

with s_2^* denoting the complex conjugate signal s_2. Unfortunately, the resulting phase value after evaluation of the argument operator is truncated within the interval $]-\pi, +\pi]$. Consequently, a counter of phase rotations m is introduced to compensate for this truncation. Thus, the phase difference can be geometrically related to the optical propagation-path delay δR from Fig. 1:

$$\Delta\varphi + 2\pi m = \frac{2\pi}{\lambda}\delta R = \frac{2\pi B}{\lambda}\sin(\theta_s - \theta) \tag{2}$$

where B stands for the spacing between the two receivers, commonly called *baseline*, λ the acoustic wavelength, θ the wavefront direction of arrival (DOA) of target, θ_s the beam pointing angle (complementary to ψ), and $m \in \mathbb{Z}$. The ambiguity of the estimated phase difference produces some phase discontinuities as shown in Fig. 2. It is important to note that Eq. (2) is valid only under a non-dispersive medium hypothesis in which both phase and group velocities of the wave are linearly linked.

1.2 High-potential spatial resolution

The bathymetry consists in estimating the slant range, or time of arrival (TOA), and the direction of arrival (DOA) of seafloor echoes on the multibeam array. Then, the across-track distance and water depth composing the sounding coordinates can be determined by trigonometry. The bathymetric principle of interferometry is stated in Eq. (2) with the apparition of three terms: the ambiguous phase difference $\Delta\varphi$, the 2π rotation counter m, and an absolute delay, corresponding to the sine. Notice in the last term that when a target reaches the echosounder with a direction equal to the beam pointing angle, i.e. $\theta = \theta_s$, the sine term cancels out, resulting in a null phase difference. Consequently, many current interferometry-based methods aims at detecting the zero-phase difference instant, pointed in Fig. 2, defining the slant range of the target. Nonetheless, this procedure, providing a unique sounding per beam, represents a waste of potential information. Indeed, the phase ramps are composed of many useful phase samples, the total number being dependant on parameters such as the beam angle, sample rate, seafloor profile or SNR. Thus, as introduced in [1], it is certainly possible to take into account an important number of soundings per beam and still fulfill current survey accuracy standards such as the International Hydrographic Organization standards [3].

However, in order to retrieve the absolute delay, which leads to the DOA estimation, it is necessary to estimate the number of rotations m. This paper is devoted to this task, and proposes four possible solutions: the unwrapping algorithm, the cross-correlation function, the

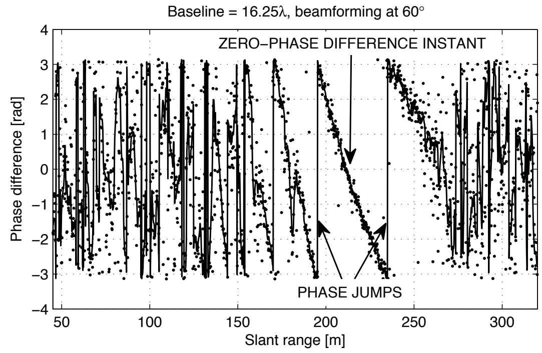

Figure 2: Raw (dotted line) and filtered (in solid line) phase differences between two close receivers, 16.25λ apart, on a flat sea bottom, 110m depth.

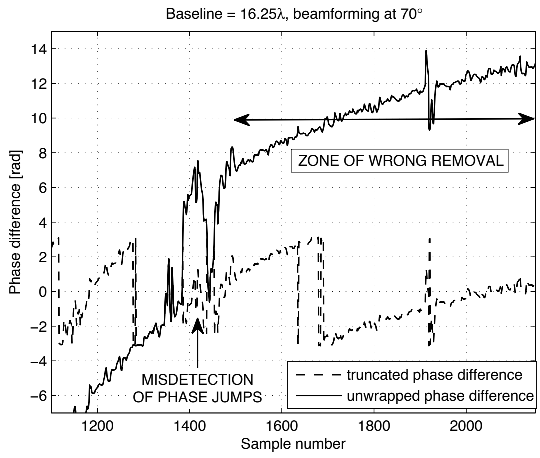

Figure 3: Evidence of the potential error propagation affecting a wrong unwrapping process.

MUSIC algorithm or the Vernier method.

Finally, see in Fig. 2 that only some phase samples contains bathymetric information; notice the clear phase ramps around 210-meter range and the random behavior of the rest. So, multibeam interferometry requires techniques to select the useful phase samples for every beamforming. The present paper does not deal with this topic, but information can be found in [1]. We will assume throughout this paper that the interval of useful phase samples has been bounded, and the issue is to remove the 2π-phase ambiguity. Thus, the following section describes techniques to deal with this problem, presenting their assets and drawbacks. The final part is devoted to the comparison between methods, and proposes a quickest combination of removal techniques. The illustrative examples were obtained from data sets collected with a 300-kHz EM3002 multibeam echosounder.

2 Phase ambiguity removal

When one aims at considering several phase samples per beam, it is absolutely necessary to determine the number of phase rotations m introduced in Eq. (2). Even in the case of a unique phase ramp, phase discontinuities may come up due to an increase of noise or simply, a relief discontinuity or the detection of different echoes within a beam. Therefore, the following subsections propose different solutions to estimate m.

2.1 Unwrapping technique

The unwrapping technique [4] is the most common removal procedure due to its quick application. When the interferometric signal phase is assumed to be continuous between consecutive samples, the intuitive way to remove the phase ambiguity is to detect phase jumps. Thus, a phase jump is identified by the presence of an abrupt discontinuity amplitude close to 2π. One solution to detect high transitions between two adjacent samples is to use a differential operator. When the absolute value of a transition reaches a given threshold (generally π [4]), the algorithm recognizes the discontinuity and increases the rotation counter. This procedure is extremely simple and only requires a threshold detection and a $\pm 2\pi$ addition. Therefore, the resulting algorithm has a low computation time cost, very attractive for quick removals.

Nonetheless, two important drawbacks limit the performance of the unwrapping procedure. The first one concerns the error propagation throughout the sonar swath as shown in Fig. 3. When an unwrapping error occurs, any successive sample will be wrongly unwrapped, too. The illustrative example in Fig. 3 corresponds to a set of short discontinuities that the unwrapping procedure does not achieve to compensate for. The resulting phase difference is then a complete disorder.

The second drawback concerns the relative reference of the resulting unwrapped phase. Indeed, the unwrapping process is carried out from an arbitrary starting point, so the resulting unwrapped phase is 2π vertically shifted depending on this starting point, even if the final shape is the same. The appropriate vertical shift is crucial to find the correct DOA estimation. Therefore, without an absolute reference, it is impossible to correctly estimate the slant range and the arrival angle.

In conclusion, the unwrapping technique can be used to remove the phase ambiguity when the continuity between contiguous phase samples, i.e. the absence of short phase discontinuities, is guaranteed. Then, an additional algorithm is required to provide the absolute reference.

2.2 Cross-correlation function

Interferometry is based upon the arrival-time delay between two sensors. Since these two sensors receive roughly the same signal, a way to estimate the time delay is to compare the received signals, checking the instant when they are the most similar. The cross correlation $R(k)$ between signals provides this instant, and is computed in its discrete form as

$$R_{s_1 s_2}(k) = \frac{1}{2L+1} \sum_{n=-L}^{L} s_1(n) s_2^*(n-k) \qquad (3)$$

where L is the length of a sliding window around the sample k under consideration. The amplitude of this function increases with the similarity between the signals s_1 and s_2, reaching its maximum value at k_0 as shown in Fig. 4.

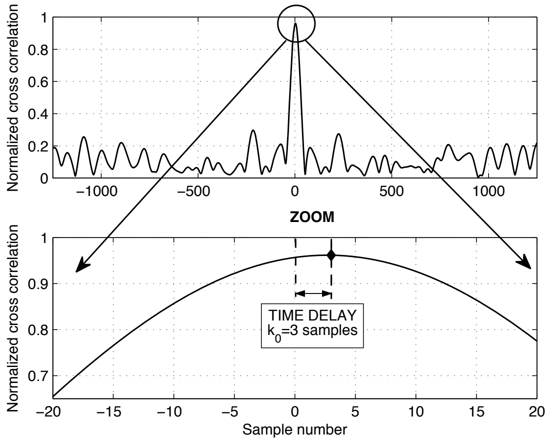

Figure 4: Normalized signal cross-correlation $R_{s_1s_2}(k)$ between two received signals using a DFT approach.

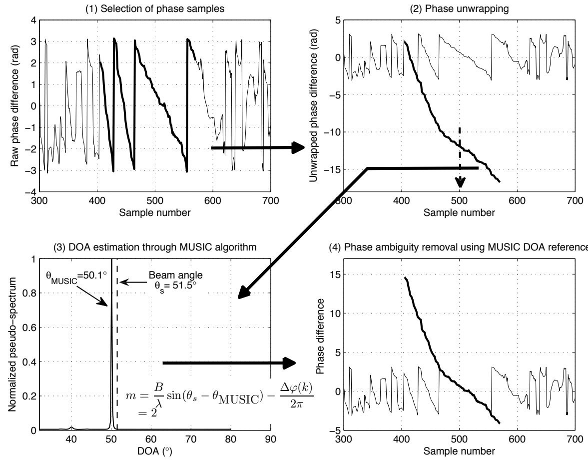

Figure 5: Phase ambiguity removal procedure using MUSIC algorithm (beamforming at 51.5°).

A quick way to compute Eq. (3) is to work in the frequency domain and determine the cross-correlation function from the conjugate product of their Discrete Fourier transforms (DFT). The result is a correlation spectrum such as Fig. 4 where the peak defines the time delay between receivers. Then, this time delay must be transformed into a phase delay in order to estimate the phase rotation counter.

The performance of the cross correlation is limited by two parameters: the maximum detectable delay, corresponding to the wavelength, and the maximum signal delay, defined by the baseline length. Furthermore, the computation of Eq. (3) entails some drawbacks. Thus, the use of a $2L$-length sliding window increases the measurement accuracy, but to the detriment of resolution. Moreover, the cross-correlation computation for each sample of the phase difference entails a significant time cost. Nonetheless, the main drawback of this technique concerns the sensor specifications: in order to properly perform the cross correlation function, it is necessary to use sensors with a relative wide bandwidth ($\Delta f/f$). As the DFT of a wideband signal is closer to a Dirac form than the DFT of a narrowband signal, the correlation peak is easier to detect from a close-to-Dirac signal than otherwise. Unfortunately, the use of relative wide bandwidths involves rather expensive sensors.

2.3 MUSIC algorithm

The MUSIC algorithm [5] is a high-resolution method [6] that aims at estimating the DOA of a backscattering signal at a given instant of sampling time. The detection principle is based on the decomposition of the covariance matrix of the observed sensor outputs into eigenvectors associated to either noise or signal subspace.

Let us denote $A(\theta)$ as a steering vector:

$$\begin{aligned} A(\theta) &= \left[\, a(\theta_1)\,, \cdots, a(\theta_p)\,\right] && (4) \\ a(\theta_k) &= [e^{j\psi_{1,k}} \quad e^{j\psi_{2,k}} \ \cdots \ e^{j(M-1)\psi_{M,k}}]^T && (5) \end{aligned}$$

with $\psi_{i,k}(f)$ denoting the phase of the arrival signal k at i-th sensor, M the number of sensors, and p the number of signal sources to be detected. Then, due to the orthogonality between the noise and signal subspaces [5], the scalar product between the eigenvectors associated with the noise subspace, v_n, and a given steering vector $a(\theta)$ will give null values for those angles θ_k corresponding to the arrival signal:

$$a^*(\theta_k)v_n = 0 \tag{6}$$

Eq. (6) provides a power pseudo-spectrum from which the DOAs are estimated either by locating its null values or, alternatively, by searching the maxima of the inverse spectrum. Thus, the MUSIC localization function $g_{\text{MSC}}(\theta)$ is written as

$$g_{\text{MSC}}(\theta) = \frac{1}{\sum_{k=p+1}^{M} |v_k^* a(\theta)|^2} \tag{7}$$

Although the computation of the MUSIC inverse pseudo-spectrum entails an important time-cost [3], it can be occasionally performed in order to provide the absolute reference required by the unwrapping technique. Thus, the proposed MUSIC-based removal procedure begins with unwrapping the phase difference from an arbitrary starting point. Here, we assume that the analyzed phase difference is continuous and that no abrupt phase discontinuity is present in the analyzed interval [1]. This condition guarantees a good phase unwrapping. Then, an instant of sampling time k is selected to apply MUSIC. Here, we propose to consider the sample with the highest SNR and the lowest variance, thus entailing trustful performance. The DOA estimation provided by MUSIC, θ_{MUSIC}, is then transformed into a phase-difference value from Eq. (2), and the number of phase rotations, m_{MUSIC}, is estimated as follows:

$$m_{\text{MUSIC}}(k) = \frac{B}{\lambda}\sin(\theta_s - \theta_{\text{MUSIC}}(k)) - \frac{\Delta\varphi(k)}{2\pi} \tag{8}$$

where θ_s stands for the beam pointing angle. A sketch of this procedure is shown in Fig. 5 where the sharp peak of the MUSIC pseudo-spectrum makes the phase ambiguity removal easier.

The main advantage of a MUSIC-based removal concerns the highly-reliable absolute reference, required to unbias the unwrapped phase difference. On the other

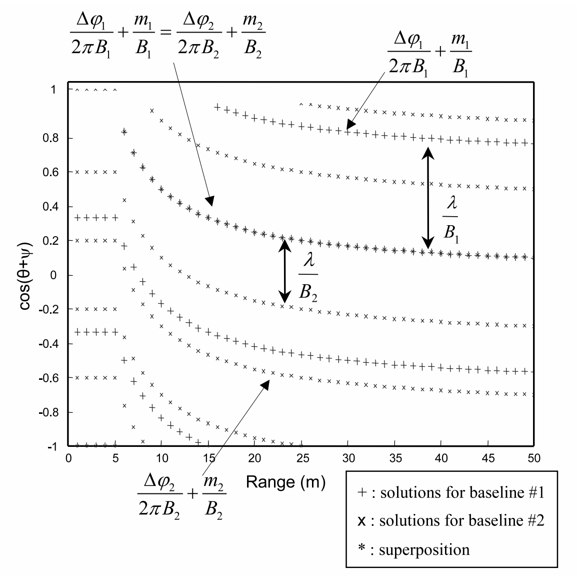

Figure 6: Vernier concept sketch, showing the superposition between curves when the equality (9) is reached.

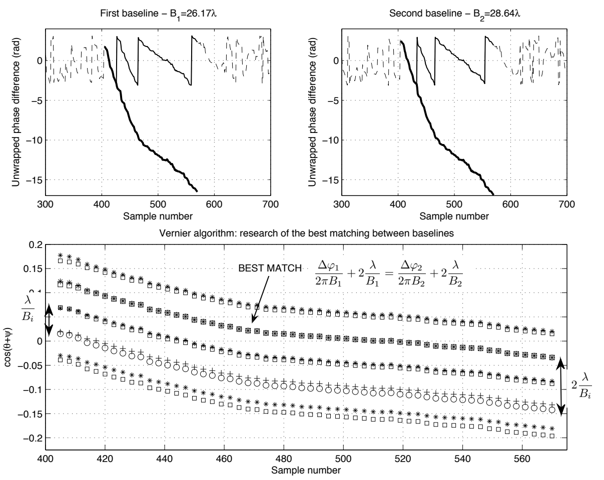

Figure 7: Vernier-based ambiguity removal for the same phase difference as in Fig. 5.

hand, it cannot be performed several times per beam due to its high computational time-cost.

In conclusion, the combination of a MUSIC-based removal together with a preliminary unwrapping allows a reliable ambiguity-phase removal with a bearable computational time-cost. This reliability, however, is subject to the right estimation of both data covariance matrix and the number of sources to be detected .

2.4 Vernier method

The Vernier method [7] requires at least two aligned pairs of receivers with different baseline to determine the number of phase rotations. This configuration allows this method to provide an unambiguous, referenced phase. The Vernier method is based on Eq. (2), where the number m of 2π rotations is to be estimated. When m is unknown, a family of solutions exists for each couple of sensors, corresponding to m possible wavefronts. Yet, the physical wavefront coming from the sea bottom with an angle θ, is unique and common to both couples if the two receivers are aligned. Thus, the Vernier principle is based on the existence of a couple (m_1,m_2) that verifies the following equality:

$$\frac{\Delta\varphi_1\lambda_1}{2\pi B_1}+m_1\frac{\lambda_1}{B_1}=\cos(\theta+\psi)=\frac{\Delta\varphi_2\lambda_2}{2\pi B_2}+m_2\frac{\lambda_2}{B_2} \quad (9)$$

Equation (9) is the general expression of the Vernier removal condition. See then that this method can be carried out either in the frequency domain (using one couple of sensors with different carrier frequencies) or in the spatial domain (using two couples of sensors with different baselines but with the same carrier frequency). Examples shown throughout this paper are obtained using the second solution due to the sonar specifications.

Fig. 6 illustrates an example of the Vernier removal procedure, introducing two important concepts: 1) superposition between phase differences, corresponding to the equality defined in Eq. (9), and 2) copies or clones of the initial phase difference. These copies are created when increasing or decreasing the phase rotation counter m, involving multiple $\pm\lambda/B$ phase-difference shifts (i.e. vertical shifts in Fig. 6).

Note that this illustrative example corresponds to a 5-meter depth, ideal noiseless flat sea bottom. In practice, the collected data do not allow a perfect superposition due to noise. Consequently, a small error ε between the phase differences of each couple of receivers remains:

$$\varepsilon(k)=\frac{\Delta\varphi_1(k)\lambda}{2\pi B_1}+m_1\frac{\lambda}{B_1}-\frac{\Delta\varphi_2(k)\lambda}{2\pi B_2}-m_2\frac{\lambda}{B_2} \quad (10)$$

Then, the Vernier solution is given by the couple of natural values (m_1,m_2) that minimizes this error $\varepsilon(k)$.

Several procedures can be regarded in order to remove the phase ambiguity [7]. Under the assumption of phase continuity introduced in Section 2.3, a possible procedure consists first, in unwrapping the phase difference before removing the phase ambiguity according to the minimal distance between curves. Fig. 7 show the Vernier results compared to the MUSIC-based removal represented in Fig. 5. The upper plots depict the smoothed phase differences of each couple and their corresponding unwrapped form. In this case, the starting point of the unwrapping process was the first sample of the analyzed interval, but it can be arbitrarily chosen. The lower plot shows the copies of the unwrapped phase difference for different values of m_1 and m_2 and the best superposition that leads to the correct phase removal.

In conclusion, the Vernier-based removal together with a preliminary phase unwrapping represents a quick, reliable process that provides a phase difference referenced to an absolute value. Its rapidity lies on the simple required algebraic operations.

3 Comparison between methods

The necessity of removing the 2π-phase ambiguity leads to the estimation of the rotation counter m of each phase sample. The unwrapping technique, in spite of being a quick solution, does not provide an absolute-referenced value. Thus, two quick, reliable solutions can be regarded, namely the MUSIC algorithm and the Vernier

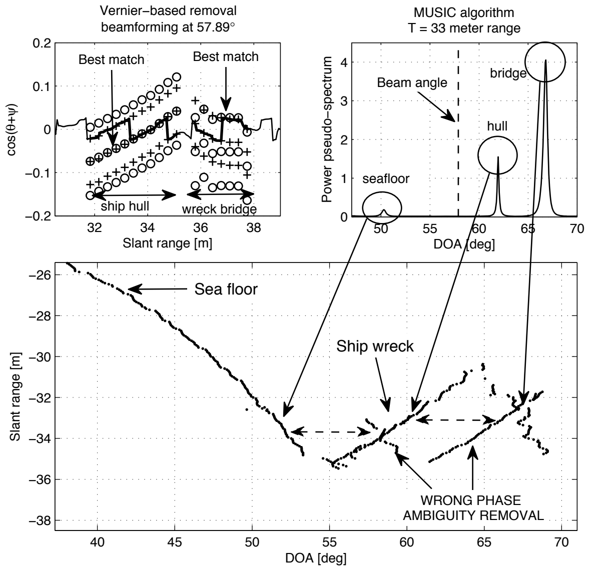

Figure 8: Complex ambiguity removal due to the presence of several detected signals for a shipwreck inspection, 20-meter depth (300-kHz Kongsberg EM3002 multibeam echosounder).

method. The first solution demands the selection of the snapshot where MUSIC is applied, the estimation of the covariance matrix, its eigen-decomposition, and the estimation of the number of sources. Concerning the Vernier-based solution, in addition to a second couple of interferometers, it demands two cross products, an additional smoothing of the second phase difference and the computation of a distance-error between samples. See then that the Vernier-based removal is faster and simpler (from an algebraic point of view) than a MUSIC-based removal.

The significant drawback of using MUSIC to remove the phase ambiguity comes up when several signals reach the echosounder at the same time, resulting in a pseudo-spectrum with several high, sharp peaks. Then, the problem consists in knowing which arrival angle corresponds to the phase sample. Remember that an interferometer can only detect one target per snapshot, while MUSIC is theoretically able to detect $M - 1$ uncorrelated sources per snapshot [6]. An illustrative example of this problem is shown in Fig. 8, depicting a DOA estimation as a function of the slant range, obtained from a 20-meter shipwreck survey. At 33-meter range, three echoes corresponding to the sea floor, hull and bridge of the shipwreck reach the antenna. Thus, according to the selected peak, the phase ambiguity is differently removed, resulting in a different DOA estimation as pointed in the lower plot. In this particular case, the peak associated with the nearest DOA to the beam pointing angle yields the correct ambiguity removal. This criterion, however, is not always true and it may happen that the strongest peak leads to the correct removal. Therefore, the problem with MUSIC is a matter of management of the multiple target detection rather than the fact of detecting them.

Conversely, the Vernier method does not need any information about the scene, and removes the ambiguity regardless of the position in the swath. Thus, each phase sample only corresponds to a unique arrival source. In Fig. 8, the phase ambiguity of two intervals of the phase difference are independently removed, each one corresponding to two different targets, namely the shipwreck hull and bridge. As the target detected by each sensor at sampling time is assumed to be the same, the superposition is evaluated between phase ramps describing the same object. Therefore, multibeam interferometry only detects the wreck hull at a 33-meter range. Nonetheless, thanks to the beamforming procedure, interferometry achieves to detect the seafloor, hull and bridge inside different beams as shown in Fig. 8.

4 Conclusion

Multibeam interferometry allows one to access to a large number of useful bathymetric soundings per beam. The result is an increase of independent information per ping and a richest target description as shown in Fig. 8. The availability of this amount of information, however, is subject to the phase ambiguity removal. Here, we have presented several techniques that, correctly applied, can lead to quick removals. Thus, the combination of a phase unwrapping followed by a MUSIC detection allows a reliable solution due to the good statistics of MUSIC. However, the detection of multiple targets may complicate the task. The other combination, consisting in phase unwrapping before Vernier removal is not concerned by the multiple-target problem and provides a quicker procedure as it uses simple algebraic operations. Furthermore, the Vernier solution can be also implemented without any priori unwrapping step [7].

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