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AN UNCERTAINTY ASSESSMENT OF THE EFFECT OF USING FM PULSES ON MBES DEPTH MEASUREMENTS

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Abstract: *The most recent generation multi-beam echosounders (MBES) allows to transmit Frequency Modulated (FM) signals, in addition to the more conventional Continuous Wave (CW) pulses. In this contribution, the effect of using these FM pulses for bathymetric measurements is investigated. Advantage of using FM signals is that measurements can be taken at long ranges, due to the use of long pulse lengths combined with matched filtering at reception. However, it is found that using FM pulses results sometimes in a loss of the quality of the depth measurements. An important contributor to the errors when using FM signals is the Doppler frequency shift of the received signal, inducing errors in the matched filtering and beamsteering. The latter, however, also holds when using CW signals. A second contributor is the baseline decorrelation, resulting from not having an infinitely small footprint. Due to the larger pulse lengths of the FM signals, also the footprint is larger and consequently the effect of baseline decorrelation is more pronounced for FM signals. Here, we consider a situation of relevance for measurements in the Dutch North Sea (water depth of 50 m and ship dynamics corresponding to a typical winter season sea state). For this case, the uncertainty induced by the Doppler frequency shift, both for CW and FM signals, is found to contribute significantly to the MBES total error budget. The effect of baseline decorrelation depends fully on the signal shape and parameters.*

Keywords: *multibeam echosounder,baseline decorrelation,bathymetric uncertainty, Doppler effect*

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1. INTRODUCTION

The modern Multi-Beam Echo-Sounders (MBES) are able to not only transmit continuous wave (CW) signals, but also frequency modulated (FM) pulses. In contrast with the expectations, using the FM pulse has resulted in noisier depth measurements compared to their CW counterpart ([1] and [2]). Potential sources for this phenomenon are the Doppler effect (affecting both the beamsteering and matched filtering) and baseline decorrelation ([3] and [4]). The former stems from the constant movement of the ship affecting the received signal. The latter is due to the slightly different received signals at the two subarrays, used for determining the phase difference of the received signals in the interferometry step, reducing the coherence between the signals and negatively affecting the quality of the phase estimates. The effect of baseline decorrelation has been studied specifically in [2] and expressions were derived for quantifying the uncertainty in the MBES depth measurements due to the baseline decorrelation for CW and FM pulses. It was found that the errors in the estimation of the phase difference due to the baseline decorrelation is higher for FM than CW signals, indicating that the baseline decorrelation is a factor potentially contributing to a degradation in the quality of the depth measurements when switching to FM.

In the present contribution, we have extended the analysis to a shallow water configuration of relevance to the marine environment typically encountered on the Dutch Continental Shelf, and a high frequency MBES (200-400 kHz). We have considered the two error types identified and compared them to the total uncertainty inherent to MBES depth measurements to investigate whether a degradation on bathymetric measurements due to the use of FM pulses is expected for these type of environments. Knowledge regarding these uncertainties is not only of importance for the planning of bathymetric surveys, but also when using the bathymetric measurements for morphological studies and for discriminating different types of sediment ([5], [6]).

2. MODELING THE IMPACT OF FM SIGNALS ON DEPTH UNCERTAINTIES

The only difference between processing of the CW and FM pulses is that matched filtering is applied at reception for the FM signals. This is done by correlating the, potentially Doppler-affected, received signal and a replica of the transmitted FM signal. Small mismatches in emitted and received signals that are due to Doppler shifts, do not change the general output of the matched filtering and the amplitude, however, the maximum of the matched filter output is shifted in time (range-Doppler coupling) ([7]). The maxima of the matched-filtered signals y_a and y_b on subarrays a and b (see Fig. 1) read as

$$t_{y_a}^{shift} = -\frac{v_e + v_r + v_\alpha}{c} f_c \frac{T}{B} \text{ and } t_{y_b}^{shift} = -\frac{v_e + v_r - v_\alpha}{c} f_c \frac{T}{B} \quad (1)$$

where v_e and v_r are the speeds of the array centre at emission and reception as projected on the beam direction, respectively. v_α is the rotation speed which in this contribution is assumed to be zero. c and f_c indicate the speed of sound in the water and centre frequency of the signal. B and T are the signal bandwidth and pulse duration, respectively. The average of these two time shifts is the expected shift in the estimate of the two-way-travel time. By applying the error propagation law, the following expression is derived for the resulting uncertainty in the depth ([8])

$$\sigma^2_{d,t_{arv,\mathrm{Doppler}}} = (\frac{c}{2}\cos P\cos\theta)^2\sigma^2_{t_{arv,\mathrm{Doppler}}} = (\cos P\cos\theta)^2(f_c\frac{T}{\sqrt{2B}})^2\sigma^2_{v_r} \qquad (2)$$

where $\sigma^2_{d,t_{arv,\mathrm{Doppler}}}$ is the depth uncertainty induced by the Doppler effect . P and θ are the pitch and beam angle with respect to the depth axis, respectively. $\sigma^2_{v_r}$ indicates the uncertainty in the transducer speed at reception (here it is assumed that the uncertainty at reception is equal to that of transmission).

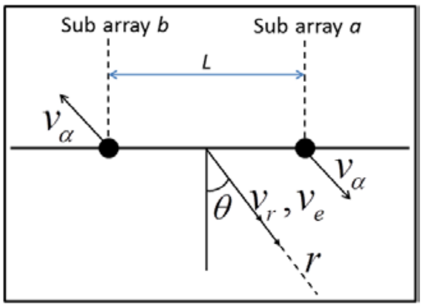

Fig. 1: Geometrical configuration considered. The figure is based upon figures from [2].

The Doppler effect also introduces an error in the beamforming, as the delays applied consider the frequency of the signal without the presence of the Doppler. Thus, the time delays applied do not take the speed of the transducer into consideration, i.e. instead of the full $c+v_r+v_\alpha$ and $c+v_r-v_\alpha$ on the sub arrays *a* and *b*, respectively, only the speed of sound *c* is considered. This results in a difference between the steering angle aimed for and that obtained (θ_s) as ([2])

$$\delta\theta_s = \theta_s - \theta = \sin^{-1}[\sin\theta(1-\frac{v_r}{c})] - \theta \approx -\frac{1}{\sqrt{1-\sin^2\theta}}\frac{v_r}{c}\sin\theta = -\frac{v_r}{c}\tan\theta \qquad (3)$$

This error is equal for CW and FM signals. The error in the beamsteering due to the Doppler effect induces an error in the bathymetry.

As mentioned before, for the interferometry step the difference between the phases of the two signals as received at the subarrays is determined as a function of time. The time corresponding to the null phase difference is the two way travel time. The two signals arrive from slightly different angular directions and hence decorrelation occurs which is referred to as the baseline decorrelation ([2]). As the signal footprint gets larger (resulting in a more directional backscattered signal) the decorrelation increases. The coherence coefficient (μ), see [2], [4] and [9], can be used to quantify the effect of the baseline decorrelation on estimates of the phase difference ([10]). The uncertainty in the estimates of the phase difference results in an uncertainty in the estimation of the zero crossing and depth measurements. The former is inversely proportional to the slope of the line fitted through the phase measurements over *N* number of samples ([11]).

3. RESULTS

To quantify the depth uncertainty induced by the Doppler effect and baseline decorrelation, we considered a water depth of 50 m, of relevance for the Dutch environment. The EM2040c was considered with centre frequency of 300 kHz and large bandwidth (20 kHz). The distance between the two interferometers was assumed to be 34 cm. To derive the speeds at the transmission and reception, use is made of positioning data acquired in the North Sea (Cleaver Bank area) in 2013, see Fig. 2. This area is located at a ~160 km distance North-West of the Dutch coast and is one of the most studied areas of the Dutch part of the North Sea. Due to the rough sea state during the data acqusition, the projected speed on the beam direction varies significantly.

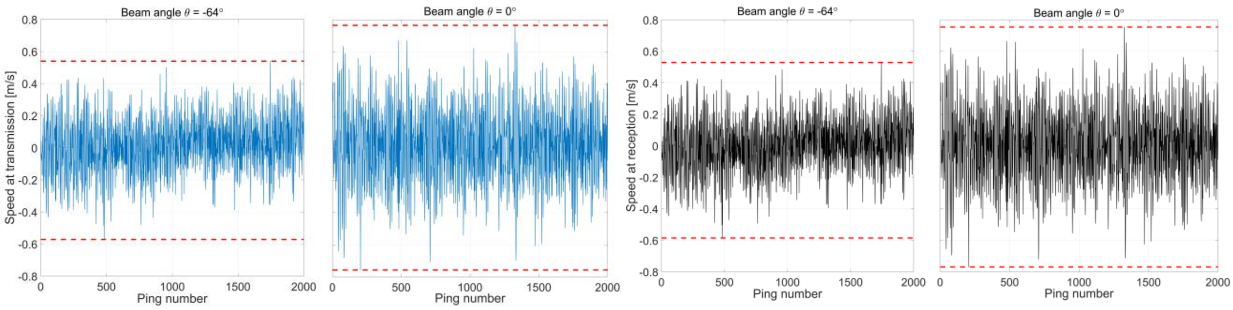

Fig. 2:Projected Speed at transmission (left) and reception (right) for two beam angles for 2000 pings. The horizontal red dashed lines indicate the maxima and minima of the speeds.

Shown in Fig. 3 are the bathymetric uncertainties (random vertical uncertainty, RVU) due to the use of FM and CW pulse shapes. The constant movement of the MBES transducer induces an error in the beamsteering irrespective of the signal type (the black dashed curve). When the FM signal is used, an error in the estimation of the travel time occurs due to the matched filtering, see the blue dotted-dashed curve in the right frame of Fig. 3. The combined effect for the FM pulse is also shown by the red curve. Increase in the pulse length and bandwidth result in increase and decrease in the error due to the Dopplerized matched filter respectively. However, changing the pulse length and bandwidth do not affect the error due to the beamsteering.

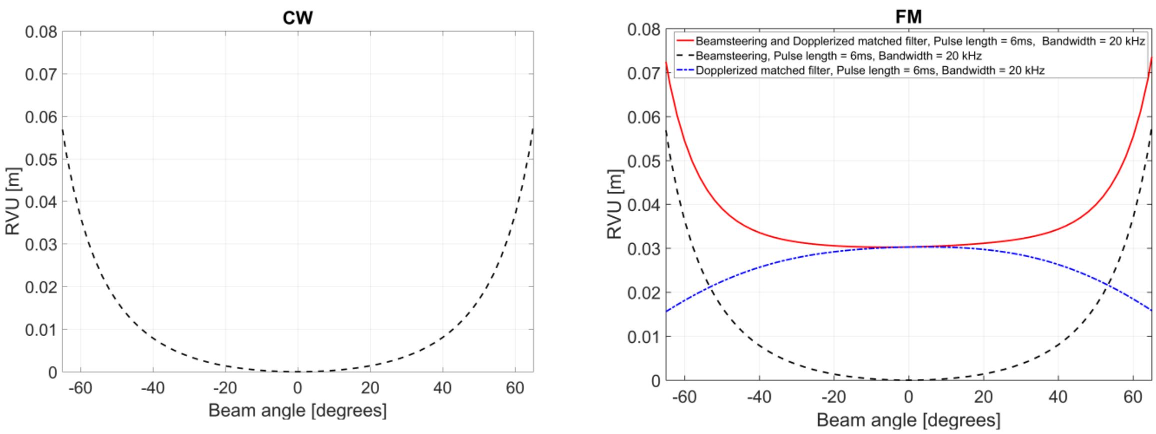

Fig. 3: Depth uncertainty due to the Doppler effect shift for CW (left) and FM (right) pulse. The bandwidth and pulse length of the FM pulse are assumed to be 20 kHz and 6 ms, respectively.

Shown in Fig. 4 is the final depth uncertainty due to the baseline decorrelation for CW and FM pulses with different specifics. For the CW pulse (right frame), the standard deviation increases with an increase in the pulse length. With regards to the two FM pulses (left frame) with equal bandwidths and differing pulse length, the standard deviation coincides due to the equal pulse lengths of the two matched filtered signals, see the squared pink and dotted dashed curves in left frame of Fig. 4. Widening the bandwidth of the FM pulse decreases the standard deviation due to the decrease in effective pulse length. It is seen that the effect of baseline decorrelation on the depth uncertainty fully depends on the pulse shape. It is not solely a matter of the pulse type employed.

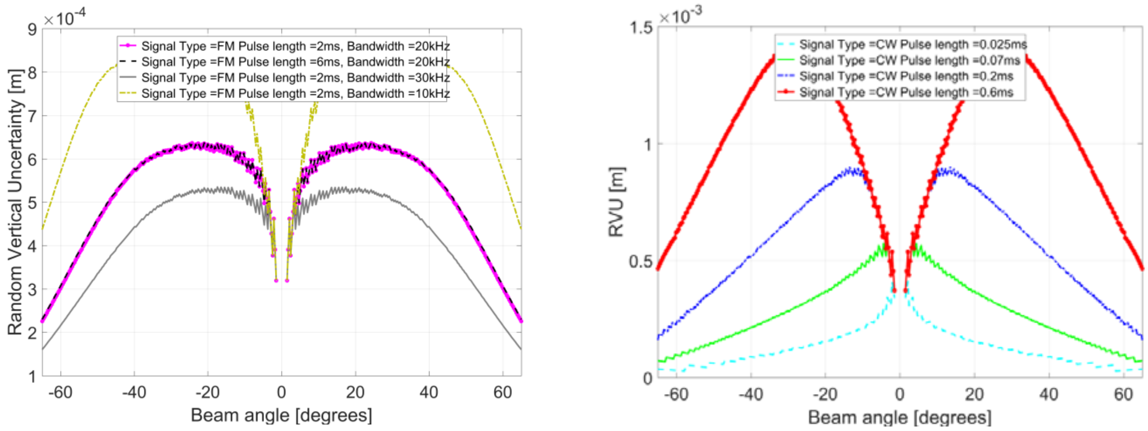

Fig. 4. Predicted bathymetric uncertainty due to the baseline decorrelation foe FM (left) and CW (right) pulses with different specifics.

To compare the magnitude of the uncertainties induced by the Doppler effect and baseline decorrelation to those inherent to the MBES, use has been made of the approach presented by [8]. The comparison between the total RVU (excluding errors induced by heave and water level variation) for EM2040c for a water depth of 50 m and those induced by the Doppler effect in case of using FM and CW pulses has revealed that the latter contributor is nearly 100% and 80% of the total error budget, respectively. Hence, taking the Doppler effect into consideration results in obtaining a more realistic description of the uncertainty.

While the vertical uncertainty induced by the Doppler effect has not been taken into consideration in the depth uncertainty prediction model introduced by [8], the model does contain a term reflecting the effect of baseline decorrelation without taking the pulse shape into account. The comparison between the depth uncertainties derived from the approach taken in [8] and those based on the baseline decorrelation has shown that in general using the former results in an overestimation of the depth uncertainties.

4. CONCLUSION

Here, the effect of the Doppler and baseline decorrelation on the depth uncertainties has been investigated for both CW and FM pulses and compared to the total MBES uncertainty. The vertical errors induced by the Doppler effect due to the beamsteering and Doppler-range coupling are significant. Taking them into consideration allows one to derive a more realistic description of the uncertainty. The depth uncertainty induced by the baseline decorrelation fully depends on the pulse shape. Models for depth uncertainty prediction do account for the baseline decorrelation, however, they do not take the pulse shape into consideration. We have used the expression that does account for this issue and have compared the results to those obtained without taking pulse shape into consideration. It was found that, in general, the latter approach overestimates the uncertainty.

5. ACKNOWLEDGEMENTS

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