ANALYSIS OF MULTI-FREQUENCY BACKSCATTERING SIGNALS FOR SEDIMENT CONCENTRATION MEASUREMENTS

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ABSTRACT

Multi-frequency backscattering technologies are used commonly for sediment concentration measurements in combination with calibration data to ensure consistent quality of the measurement data. The calibration is conducted by taking water samples and has to be repeated when the grain size composition is changing otherwise the calibration is not valid anymore.

A detailed model based on the typical SONAR equation has been developed which allows to determine the sediment concentration of non-cohesive suspended sediments without any calibration needs. The model runs in real-time and calculates the suspended sediment concentration (SSC) and mean grain size simultaneously and estimates the particle size distribution (PSD) based on the backscatter signal strength of 4 ultrasonic frequencies ranging from 0.5 MHz to 4 MHz. The analysis can be done at a fixed distance or along the acoustic path of the ultrasound signals up to a profiling range of 2 m. The range will be sequenced into cells and the parameters PSD, mean grain size and SSC can be determined for each measurement cell.

INTRODUCTION

For the management of dams, reservoirs and hydro power plants sediment concentration measurements are becoming more and more important in particular with increased erosion topics. Real-time measurements are challenging since the necessary re-calibration of those instruments like optical backscattering, turbidity probes or acoustic backscattering can only be done subsequently. This increase the risk that the amount of total suspended solid/sediments are under- or overestimated. In addition knowledge of the actual mean grain size is important for deciding on preventive abrasion measures. In most cases this parameter can only be obtained during laboratory analysis.

The simplified SONAR equation introduced and described by [2, 4, 6] and for near bed measurements mainly by Thorne and others [1] is also the basis for the approach described in this paper.
A thorough trimming of the transducers and determination of transducer and electronic related functions have to be conducted under standard measurement conditions to derive the correct signal strength conversion from measured mV to dB as described in [9].

Four frequencies - normally from 500kHz to 4MHz – have been used for particle radii ranging from 2µm to 1mm, considering the acoustic sensitivity versus particle size for each applied frequency [1, 7, 9].

Acoustic backscatter technology has the general advantage of collecting data over a wider spatial range of the water column, known as profiling, compared to point measurements, e.g. achieved by optical or laser based methods.

**MEASUREMENT CONCEPT**

The newly developed method is using the theory of sound propagation and the SONAR equation (eq.1) to estimate SSC. The simplified SONAR equation [8] can be written in the following form:

\[
EL = SL + C - 20\log(\eta R) - 2\alpha R + 10\log\left(\psi \frac{c\tau}{2}\right) + BS_v
\]

where \( EL \) is the echo level (dB), \( SL \) is the source level (dB), \( C \) is a coefficient related to the transducer (dB), \( R \) is the range from the source to the targets (m), \( \eta \) is the near-field correction, \( \alpha = (\alpha_w + \alpha_s) \) is the attenuation coefficient (dB/m) due to water and sediments, \( \psi \) is the equivalent aperture (solid angle, in steradians) of the transducer(s), \( c \) is the velocity of the acoustic wave (m/s), \( \tau \) is duration of the transmitted signal (s), \( BS_v \) is volume backscattering strength (dB).

Combining the knowledge of sound propagation with equation (1) and ultrasonic backscatter principles led to a set of equations which can be solved by applying at least 3 different frequencies into the water column [7, 9].

As described in [7] the calculation of suspended sediment concentration (SSC) using multifrequencies is following the flow chart in Figure 1.
Input: S, T, Z, pH, SL, EL, open angle, pulse duration for 4 transducers, Range (distance to the bin).

Assume SSC

EL from Eq. (1)

No

Compare Echo Levels (EL)

Yes

Record SSC

Stop

Fig. 1: Simplified flow chart for estimation of SSC using multi-frequencies [7]

The coefficient $\alpha_w$ depends on the input salinity (S), temperature (T), pH, and depth (Z) of the measured location while the coefficient $\alpha_s$ and the function $BS_v$ depend on SSC, PSD, and the frequency. For accurate simulation of SSC and PSD, accurate models for $\alpha_s$ and $BS_v$ in equation (1) are required as proposed in [3, 5, 7].

SSC values can be estimated by multi-frequency backscatter responses along different bins of the water column applying the new model iteratively for different parameters as well as for different bins along the acoustic beam of the transducers. Depending on the strength of the transducers and the sediment concentration, profiling of the water column up to 2m can be realized, mainly limited by the 2 & 4MHz frequencies due to their higher absorption coefficients.

TECHNOLOGY

The four transducers are mounted into one transducer head as shown in Figure 2.
Fig. 2: Transducer Head with 0.5, 1, 2 and 4 MHz transducers

Pulses will be sent continuously, averaged and the absolute dB is calculated [2, 7, 9]. These dB values are sent to the model which calculates the SSC, mean grain size and estimates the PSD.

In Fig 3 a working prototype of the user interface for data acquisition is shown. At the current stage every 5 minutes a data point is computed based on several hundred raw data measured per frequency.

Fig. 3: User Interface of the software prototype

For dealing with an arbitrary PSD, the PSD has been divided into various sub-classes as shown in Figure 4. The values from the individual sub-classes will be combined and used to achieve the total $\alpha_s$ and $\text{BS}_v$ in eq. 1.
MEASUREMENT ENVIRONMENT

At the current stage, the new approach is tested under laboratory conditions to ensure stable measurement parameters. Analyzing the performance of the new technology requires a quasi-homogenous sediment concentration over a spatial water column with known particle size composition. Such stable environment has been achieved by setting up a water column in a measurement tube as shown in Figure 5.
A current controlled pump (capable to pump high concentrations of sediments) combined with a fixed set of inlet nozzles ensures a stable flow with well mixed sediments in the water column.

Water samples can be taken at the outlet valves to check the homogenous distribution of the SSC [7] over the measurement range.

Sand has been sieved for various size classes in order to mix well defined PSD for testing the new measurement approach.

RESULTS

Suspended Sediment Concentration

Figures 6 presents the comparison between known and measured SSC using the described approach as illustrated in Figure 1, with sub-classes of PSD, for various PSD as listed in Table 1 and 2.

![Fig. 6: Measured SSC [g/l] of original white sand but with different PSD, as listed in Table 1 and Table 2 [9]](image-url)
Table 1: Percentage of sub-classes in Experiment A [9]

<table>
<thead>
<tr>
<th>SSC (g/l)</th>
<th>Below 150µm (%)</th>
<th>Between 150µm and 250µm (%)</th>
<th>Bbve 250µm (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.18</td>
<td>0</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>2.35</td>
<td>0</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>3.53</td>
<td>0</td>
<td>100</td>
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<tr>
<td>4.71</td>
<td>0</td>
<td>100</td>
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<td>5.88</td>
<td>0</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>7.06</td>
<td>0</td>
<td>83.3</td>
<td>16.7</td>
</tr>
<tr>
<td>8.24</td>
<td>0</td>
<td>71.4</td>
<td>28.6</td>
</tr>
<tr>
<td>9.41</td>
<td>0</td>
<td>62.5</td>
<td>37.5</td>
</tr>
</tbody>
</table>

Table 2: Percentage of sub-classes in Experiment B [9]

<table>
<thead>
<tr>
<th>SSC (g/l)</th>
<th>Below 150µm (%)</th>
<th>Between 150µm and 250µm (%)</th>
<th>Bbve 250µm (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.18</td>
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<tr>
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<tr>
<td>9.41</td>
<td>37.5</td>
<td>62.5</td>
<td>0</td>
</tr>
</tbody>
</table>

For both measurements ExpA&ExpB, the Pearson correlation coefficient for SSC data is $r > 0.99$ with a p-value $< 0.001$. The average SSC deviation over the measurement range between experiment and simulation is ±12% for ExpA and ±6% for ExpB [9].

Particle Size Distribution (PSD)

Results from measurements using mixtures of different sand classes and concentrations are shown in Figures 7&8.
Fig. 7: Estimated PSD over 8 sand size classes for a SSC of 914 [mg/l]

Fig. 8: Estimated PSD over 8 sand size classes for a SSC of 1,371 [mg/l]

The main focus of the algorithm illustrated in Figure 1 is the calculation of the suspended sediment concentration (SSC) and the mean particle size whereas the PSD is an estimation as a secondary output:

The deviation of the mean grain size presented in Figure 7 is < 1% and in Figure 8 < 8%. The differences in the single sand classes between known and estimated percentages of the PSD might be higher.
Profiling

The new measurement concept has also been tested for its profiling capabilities.

In general the distance or maximum profiling range is defined by the applied frequencies. E.g. an Acoustic Doppler Current Profiler (ADCP) operating at 600 kHz can have a range up to 75m. The absorption coefficient is greater for higher frequencies which results in profiling ranges of app 25m for 1MHz, app 5m for 2MHz and 2m for app 4MHz [10]. Using ultrasonic frequencies in the range of 0.5 – 4.0MHz therefore will limit the profiling range to app 2m.

Moreover the size of the measurement cell can be selected depending on the resolution requirements.

In the Figures 8 & 9 results are shown varying the profiling range from 20cm to 30cm and the measurement cell size between 1.5cm (Fig. 8) and 3cm (Fig. 9).

![Fig. 8 & 9: Results of the SSC measurements in dependence of the measurement cell size: 1.5cm (left) and 3.0cm (right). For each cell size the profiling range, which is the center of the measurement cell, was moving from 20cm to 25cm to 30cm](image)

The larger deviations between the SSC at a distance of R=30cm compared to the SSC measured at R=20cm or 25cm is mainly caused by the in-homogenous sediment concentration at the bottom side of the measurement tube (Figure 5 and [7])

CONCLUSION AND OUTLOOK

The good comparison of SSC between know and measured values, as shown in Figure 6 confirm the workability of the concept described in [7] and [9] and illustrated in Figure 1.
The underlying algorithm of Figure 1 calculates the mean grain size as well and the results in Figures 7 and 8 are within the expected tolerances of ± 10%. The derived particle size distribution is a reasonable good estimation and following the trend of the true (known) particle size distributions.

The next steps are the expansion of the concept to lower concentrations < 0.5 g/l and starting field tests outside the laboratory environment in order to gain more experience, stabilizing the measurement equipment and testing the algorithm.

ACKNOWLEDGMENT

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REFERENCES