REAL-TIME CONCENTRATION AND GRAIN SIZE MEASUREMENT OF SUSPENDED SEDIMENT USING MULTI-FREQUENCY BACKSCATTERING TECHNIQUES

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ABSTRACT

A new approach has been developed based on the typical SONAR equation but requiring 4 measurement frequencies in the range of 0.5, 1, 2 and 4 MHz. This method overcomes the need of taking sediment samples for (re-)calibration of the instrument due to changing particle size distributions. An iterative model has been implemented which estimates the particle size distribution and suspended sediment concentration simultaneously using the backscatter signal strength of the frequencies at different distances from the transducers. The instrument has been optimized to measure particle size ranges from 20µm - 1000µm and sediment concentrations from 0.0g/l to 50g/l. Measurements e.g. using white sand with a grain size of 50 – 600µm are showing very good results with the sediment laboratory analysis with a Pearson correlation coefficient of $r > 0.99$ over the range of 0g/l – 50g/l. The mean accuracy of the mean grain size estimation is at the current status < ±16%, whereas the mean accuracy of the estimation of the suspended sediment concentration is < ±10%.

INTRODUCTION

Sediment measurements of rivers and reservoirs are playing a key role in the management of dams and hydro power plants. Due to changing particle size distributions, real-time measurements are challenging since the re-calibration of the instruments like optical backscattering, turbidity probes or Acoustic Backscattering can only be done subsequently. This causes the risk that actual data are over or under estimating the amount of total suspended solid/sediments which can result in non-optimal management of the water intake. Moreover the knowledge of the actual mean grain size is important for deciding on preventive abrasion measures. In most cases this parameter can only be obtained after laboratory analysis.
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.
In addition a plurality of model defined sediment particle size distributions are determined in controlled experiments and used as an input for the model implementation.

There are various methods in place of which acoustic backscatter (ABS) applications have been gaining increasing acceptance and usage over the past two decades (Thorne and Hanes, 2002). ABS 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.
However, acoustic backscatters from single frequency profiling instruments also require calibration using turbidity measurements or sediment analysis in laboratories (Sontek, 1997). This makes on-line measurements more expensive and time-consuming.

In order to extract relatively accurate parameters of suspended sediments, parameters like particle size distribution (PSD) and suspended sediment concentrations (SSC), without the continuous (re-)calibration of the backscatter signals, more appropriate frequencies are required (Thorne and Hanes, 2002). Four frequencies - normally from 500 kHz to 5 MHz – have recently been used for particle radii ranging from 2 µm to 1 mm, considering the acoustic sensitivity versus particle size for each applied frequency (Thorne et al, 2011; Skripalle et al, 2012).

1. MEASUREMENT CONCEPT

Most of the existing empirical models for estimating the backscattering strength are based on the simplified SONAR equation (Sontek, 1997; Deines, 1997; Guerrero et al, 2011) or the work done by Thorne and others (AQUATEC, 2012). However, there is still a significant difference between measurements and simulations applying these models when the SSC is larger than 1.0 g/l (Thorne et al, 2011), which is a very small value compared to those usually measured near the bed or monitored for waste water, reservoir, hydro power or industrial water applications.

The newly developed method is using the theory of sound propagation and the SONAR equation (eq.1) to estimate SSC. The simplified SONAR equation (Lurton, 2004) can be written in the following form:

$$EL = SL + C - 20\log(\eta R) - 2\alpha R + 10\log\left(\psi \frac{c\tau}{2}\right) + BS_v \qquad (1)$$

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), η is the near-field correction, $\alpha = (\alpha_w + \alpha_s)$ is the attenuation coefficient (dB/m) due to water and sediments, ψ is the equivalent aperture (solid angle, in steradians) of the transducer(s), c is the velocity of the acoustic wave (m/s), τ 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.

As described in Skripalle et al (2012) the calculation of suspended sediment concentration (SSC) using multi-frequencies is following the steps shown in the flow chart in Fig. 1.

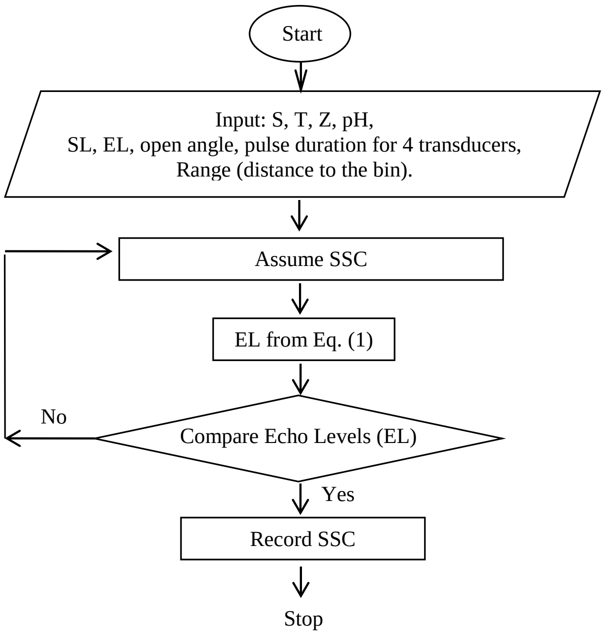

Figure 1: Simplified flow chart for estimation of SSC using multi-frequencies (Skripalle et al 2012)

The coefficient α_w depends on the input salinity (S), temperature (T), pH, and depth (Z) of the measured location while the coefficient α_s and the function BS_v depend on SSC, PSD, and the frequency. For accurate simulation of SSC and PSD, accurate models for α_s and BS_v in equation (1) are required as proposed in Skripalle et al (2012), Guererro et al (2011) or Thorne and Hanes (2002).

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 of several meters can be realized.

2. MEASUREMENT TECHNOLOGY

To achieve the required accuracy of SSC of <±10% an own transducer specific initial configuration measurement has been defined to allow very accurate conversion from the received electrical signal to dB levels. This approach is necessary to compensate performance variations of industrial manufactured ultrasonic transducers, which are typically in the range of ±3dB to ±6dB.

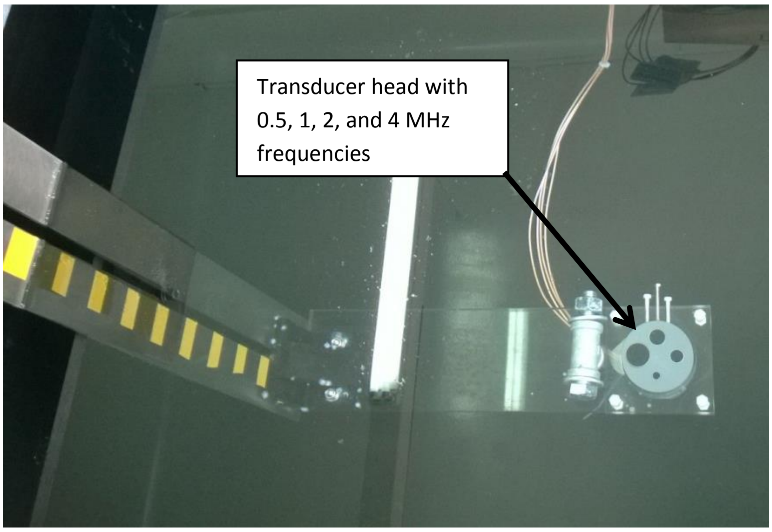

Figure 2: Setup for determining acoustic characteristics of the transducers.

The transducers are horizontally submersed in the water, as shown in Fig. 2, and transmit signals upward and receive the signals reflected back from the water surface. Based on the reflected signals, acoustic characteristics like the sensitivity of the transducers are obtained.

In addition pluralities of defined sediment particle size distribution functions are determined in controlled experiments and have been implemented for iterative model runs.

The typical measurement bin size is 2.5 cm to 5 cm, with a standard measurement range of 1m to 7m (up to 2 MHz only), depending on the temperature and suspended sediment concentration.

3. EXPERIMENTS AND RESULTS

3.1. Initial experiments

Benchmark measurements for suspended sediments are very challenging to conduct. The main task is the setup of a water column with a stable, homogenous and known sediment concentration. Test equipment as shown in Fig. 3 has been developed and tested intensively by taking samples at different bins in the water column and running sediment laboratory analysis for comparison.

Figure 3: Setup of experiments.

For estimating SSC, the present study used α_s and BS_v of white sand, which has a “bell-shape” PSD, as shown in Fig. 4. The simulation and experimental values for SSC up to 50 g/l are presented in Fig. 5 and for the mean grain size in Fig. 6 approving the new approach, as shown in Fig. 1, for both measurement set ups: 3 Transducers – 0.5, 1.0 & 2.0 MHz and 4 Transducers – 0.5, 1.0, 2.0 & 4.0 MHz.

In Fig. 5, the values on the x-axis are referring to the known amount of SSC, where a defined mass of sediments has been put in the defined water volume (here 17 liters) and are plotted as a red dotted reference line. The measurement results on the y-axis of Fig. 5 and Fig. 6 are calculated based on the received backscatter signals and the simulation approach as shown in Fig. 1.

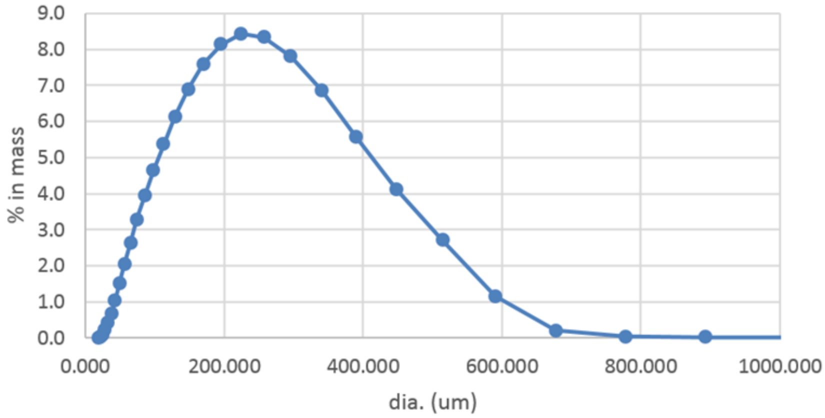

Figure 4: Particle size distribution of the white sand.

The Pearson correlation coefficient of SSC for both, 3 & 4 transducers, is $r > 0.99$ with p-values < 0.001. The average SSC deviation between experiment and simulation is ±15% for 3 transducer measurements and ±9% for the 4 transducer application (see Fig. 5).

The mean grain size (median radius of PSD shown in Fig. 4) is 117 µm and plotted as the red dotted reference line in Fig. 6. The average deviation of the mean grain size is ±26% for 3 transducer measurements and < ±16% for 4 transducer measurements.

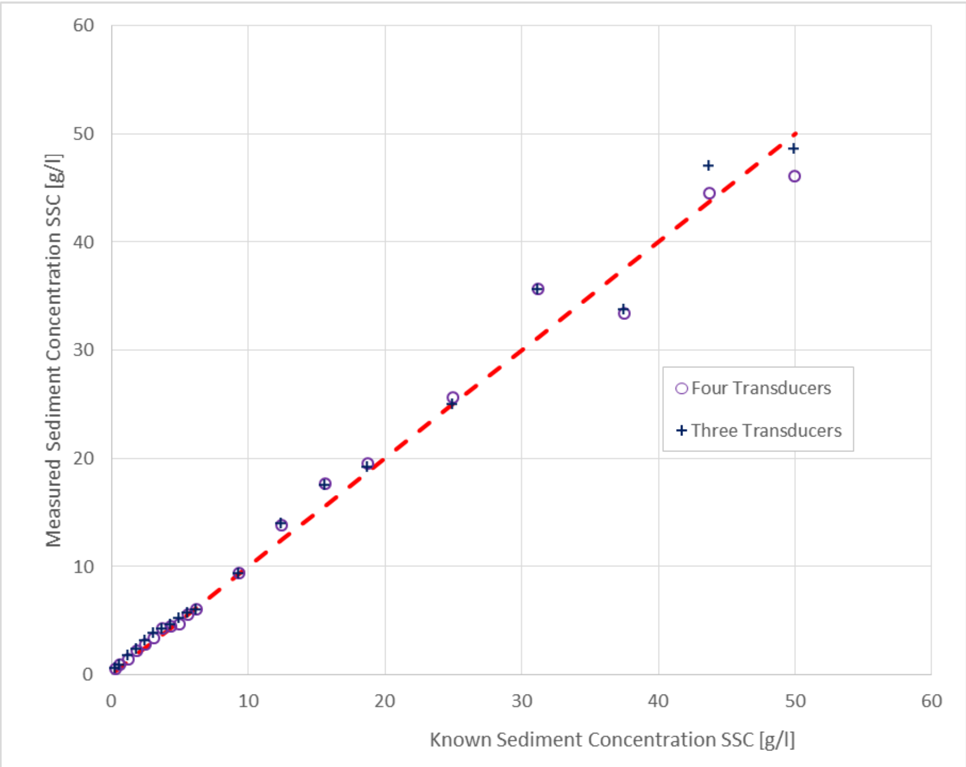

Figure 5: SSC [g/l] measurements of white sand using three and four transducers

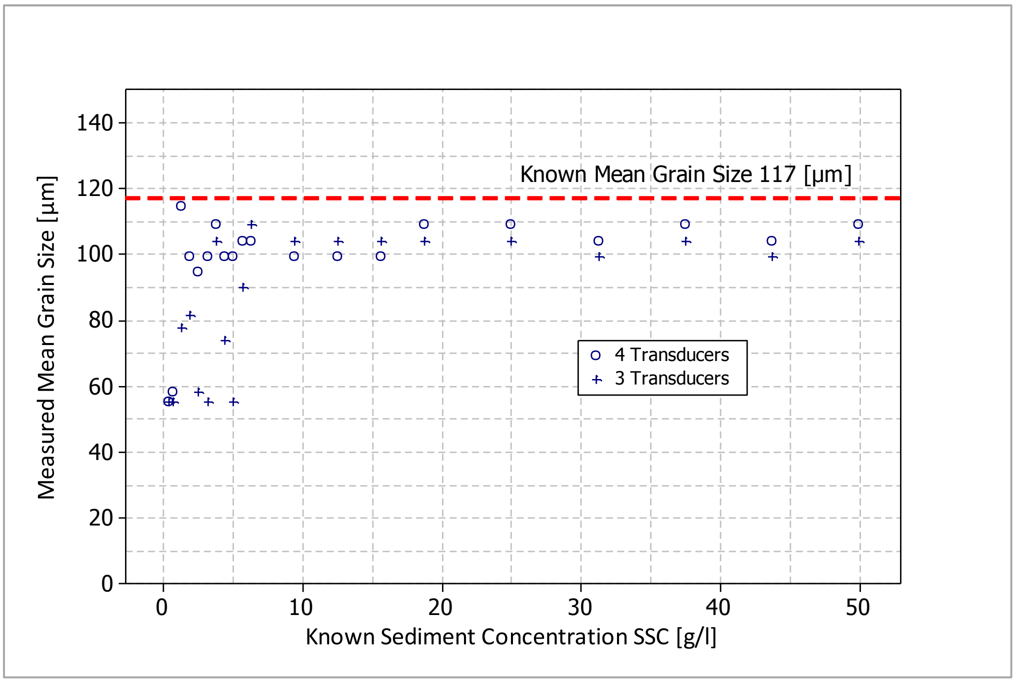

Figure 6: Measurements of the Mean Grain Size applying for three and four transducers

The new approach has been tested using larger sand with a different "bell-shape" PSD than the white sand PSD as shown in Fig. 4. The same α_s and BS_v of the white sand as in previous tests were applied (see Fig. 5). The results for a 3 transducer measurements (0.5, 1.0 & 2.0 MHz) as presented in Fig. 7 are showing a large difference between the known and measured SSC. This comparison indicates that models for α_s and BS_v are not the same for different PSD and the concept has to be further improved.

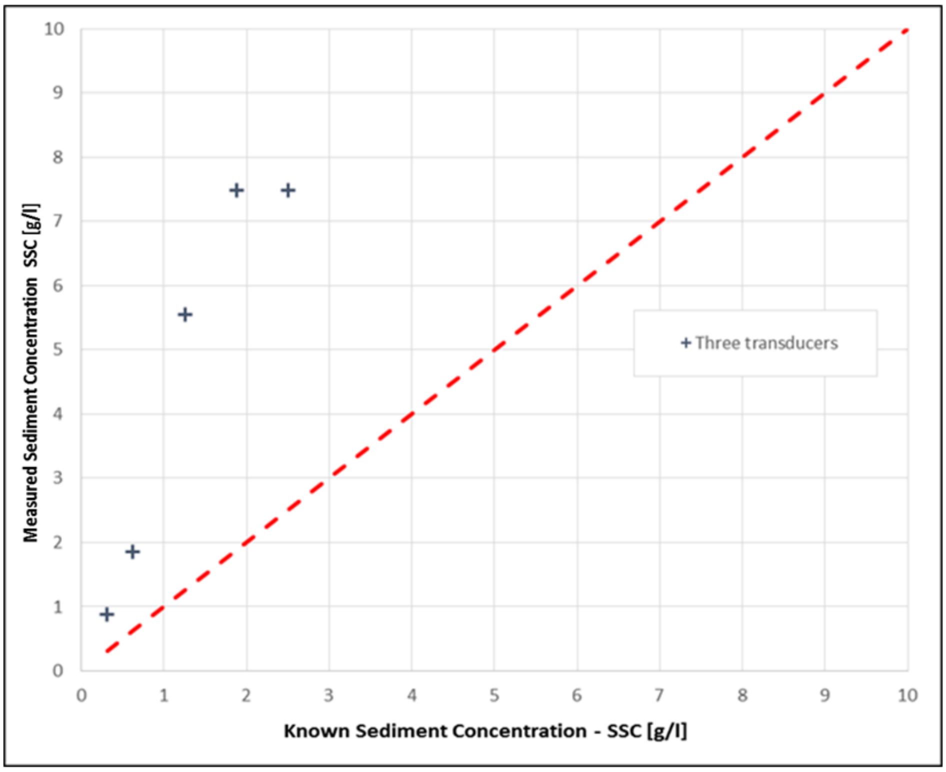

Figure 7: SSC [g/l] measurements of large sand

3.2. Improved PSD modeling and Results

For dealing with an arbitrary PSD, the PSD has been divided into sub-classes as shown in Fig. 8: below 150µm, between 150µm and 250µm, and above 250µm. The values from the individual sub-classes will be combined and used to achieve total α_s and BS_v.

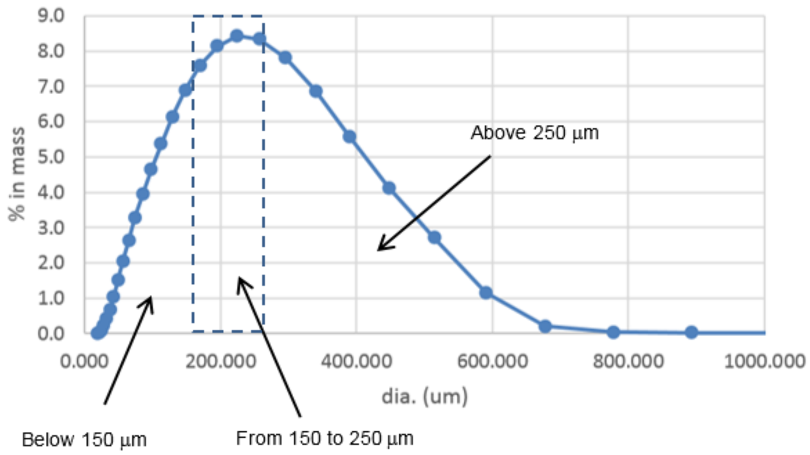

Figure 8: Particle size distribution of the white sand and three sub-classes.

Figure 9 presents the comparison between known and measured SSC using the described approach as illustrated in Fig. 8, with sub-classes of PSD, for various PSD (Table 1 and 2).

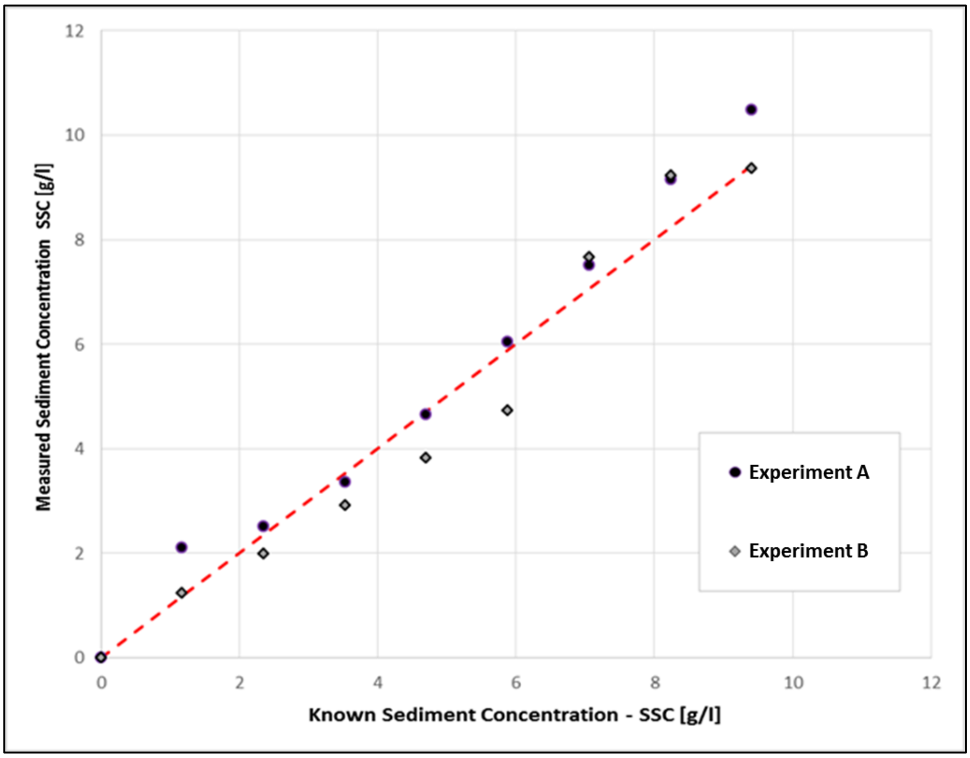

Figure 9: Measured SSC [g/l] of original white sand but with different PSD, as listed in Table 1 and Table 2.

Table 1: Percentage of sub-classes in Experiment A

SSC (g/l)	below 150µm (%)	between 150µm and 250µm (%)	above 250µm (%)
1.18	0	100	0
2.35	0	100	0
3.53	0	100	0
4.71	0	100	0
5.88	0	100	0
7.06	0	83.3	16.7
8.24	0	71.4	28.6
9.41	0	62.5	37.5

Table 2: Percentage of sub-classes in Experiment B

SSC (g/l)	below 150µm (%)	between 150µm and 250µm (%)	above 250µm (%)
1.18	100	0	0
2.35	100	0	0
3.53	100	0	0
4.71	75.0	25.0	0
5.88	60.0	40.0	0
7.06	50.0	50.0	0
8.24	42.9	57.1	0
9.41	37.5	62.5	0

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.

CONCLUSION AND OUTLOOK

The good comparisons of SSC between know and measured values, as shown in Fig. 5 and Fig. 9, confirm the workability of the concept described in Skripalle et al (2012) and as illustrated in Fig. 1. However, the results shown in Fig. 7 indicate that the values of α_s and BS_v are not the same for different PSD; for arbitrary PSD, combined values for α_s and BS_v from individual sub-classes must be applied. The results also demonstrate that the 4 transducer approach (0.5, 1.0, 2.0 and 4.0 MHz) provides more stable data for the simulation algorithm and achieves a higher accuracy for SSC and Mean Grain Size compared to the 3 transducer measurements using 0.5, 1.0 and 2.0 MHz.
Compared to the previous work (Skripalle et al. 2012) significant improvements of the measurement concept have been developed: determination of acoustic characteristics of the transducers (see Fig 2), solution for handling arbitrary PSD by dividing the PSD into sub-classes, verification and proof of measurement concept under standardized conditions with homogenous suspended sediment concentrations.
The next steps are the expansion of the concept to a broader range of particle sizes from 20µm - 1000µm, investigation of very low concentrations < 0.5 g/l, profiling along different bins and stabilized calculation of the particle sizes percentage per PSD sub-class.

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