Retrieving suspended-sediment concentrations from acoustic backscatter signals

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Measuring suspended-sediment concentrations

- Interest in measuring suspended-sediment fluxes : environmental issues, flood risk, erosion, dam management, etc.

- Flux estimates → **Suspended-sediment concentration (SSC)** + Flow velocity

Historically : water samples

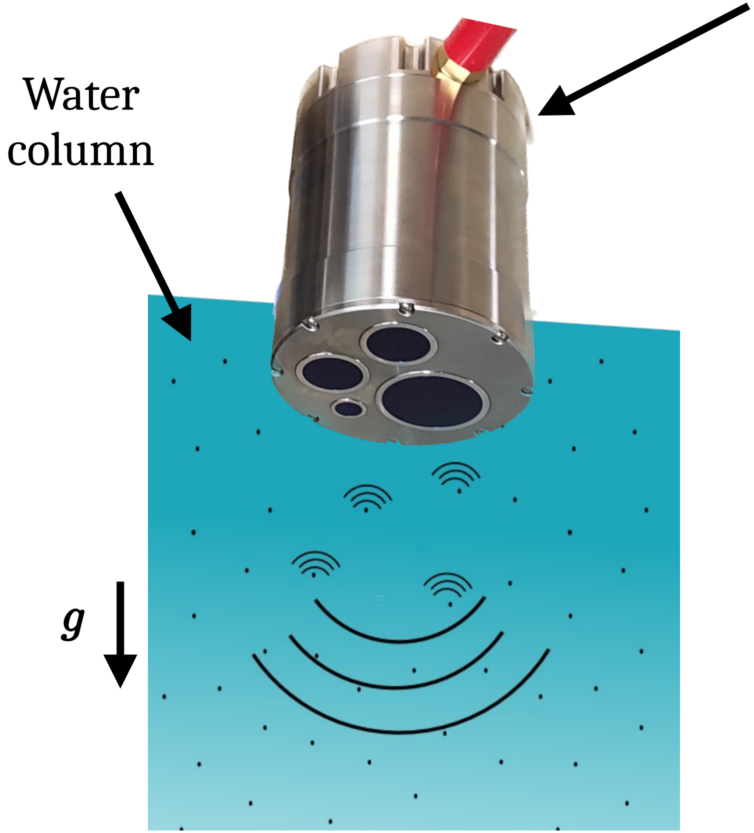
Niskin bottle

- Simple
- Direct measurement
- Works well !

- Time-consuming
- Difficult during floods
- Limited number of measurements
→ **poor spatial and temporal resolutions**

Alternative : SSC from **acoustic backscatter signals**

Working principle



Acoustic Backscatter System (ABS) = multiple acoustic sources

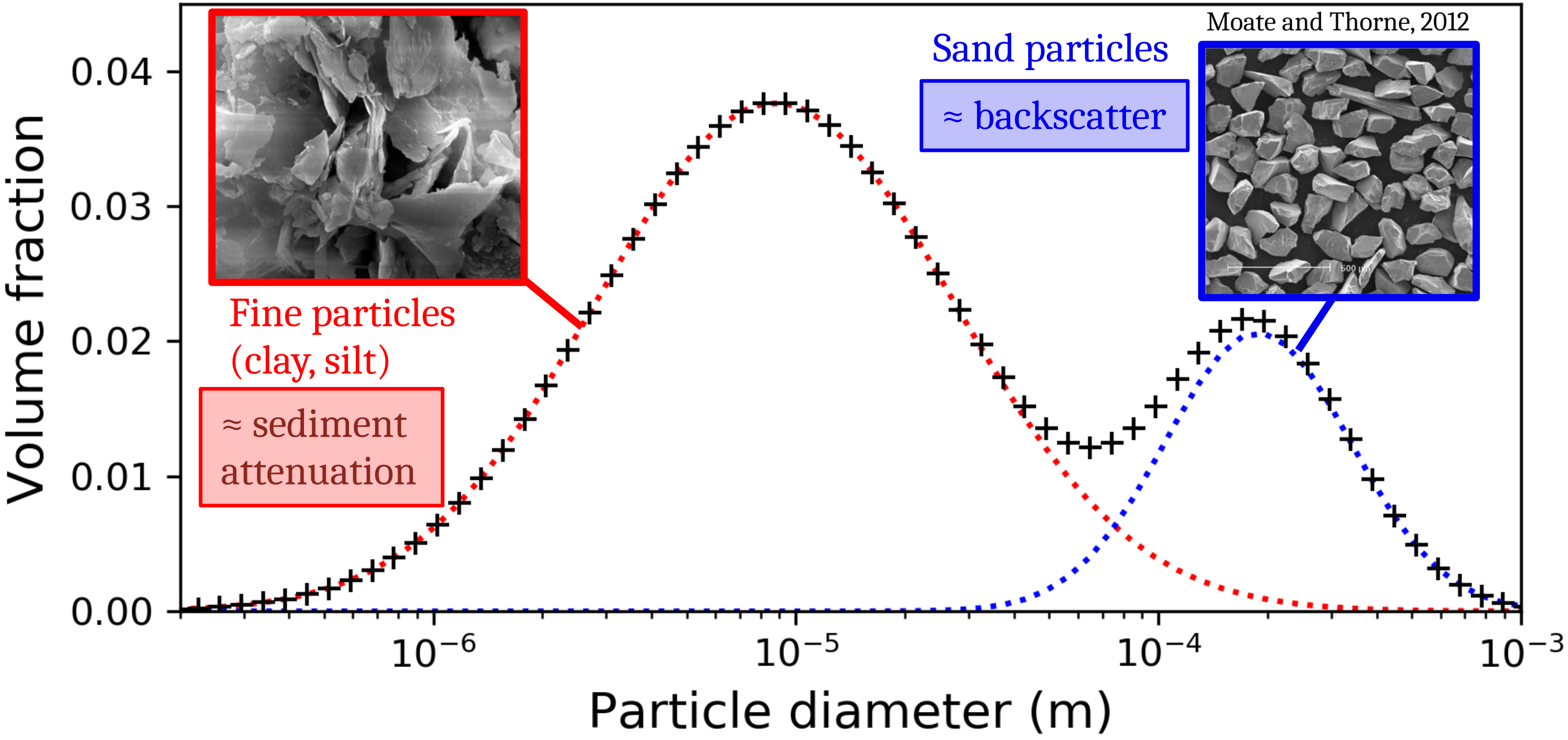
- Wavetrains (=pings) at different frequencies (~ MHz)
- Two main processes :

1. **Acoustic backscatter** : echo from the suspended sediments
   → depends on SSC and grain size distribution
2. **Acoustic attenuation** : loss of energy caused by the fluid and the suspended sediments
   → depends on SSC, grain size and fluid viscosity

→ **Indirect measurement** of the SSC from the voltage recorded by the ABS

Suspended sediments sizes

We often observe **multi-modal particle size distributions (PSD)** in large rivers (Agrawal and Hanes, 2015):



Relating the ABS voltage to the SSCs

Sonar equation relating the **time-averaged ABS voltage** to the **backscatter** and **attenuation** properties of the sediments (Vergne *et al.*, *Water Resources Research*, 2019):

$$\sqrt{\overline{V(r)^2}} = \frac{k_t k_s}{r} \sqrt{M_s(r)} \exp\left(-2\left[\alpha_w + \alpha_f(r)\right] r\right)$$

r : distance to the ABS

k_t : instrument-specific calibration constant

k_s : sediment (**sand**) backscatter constant (depends on PSD only)

M_s : sand concentration

α_w : sound attenuation coefficient due to water

α_f : Sound attenuation coefficient due to (**fine**) sediments

$$\rightarrow \alpha_f(r) = \frac{1}{r} \int_0^r \zeta M_f(r') \mathrm{d}r'$$

Fine sediment attenuation constant (depends on PSD only) [ζ]

Fine sediment concentration [$M_f(r')$]

Retrieving M_s and M_f → **Acoustic inversion :**

1. Model sand backscatter constant k_s (**assumed constant**)
2. Estimate fine sediment attenuation constant ζ (**assumed constant**)

   } Water samples (PSD + SSC) + hydroacoustics

3. Dual-frequency technique to obtain M_s on the acoustic path (Hurther *et al.*, *Coastal Engineering*, 2011)
4. Estimate the acoustic attenuation α_f on the acoustic path
5. Compute M_f from α_f

→ Development of a free open-source software implementing this acoustic inversion algorithm

AcouSed software

- **<u>Acou</u>**stic Backscattering for Concentration of Suspended **<u>Sed</u>**iments in Rivers (Moudjed *et al.*, 2024)

  → Open-source software (GPLv3) to make acoustic inversion-based measurements broadly available

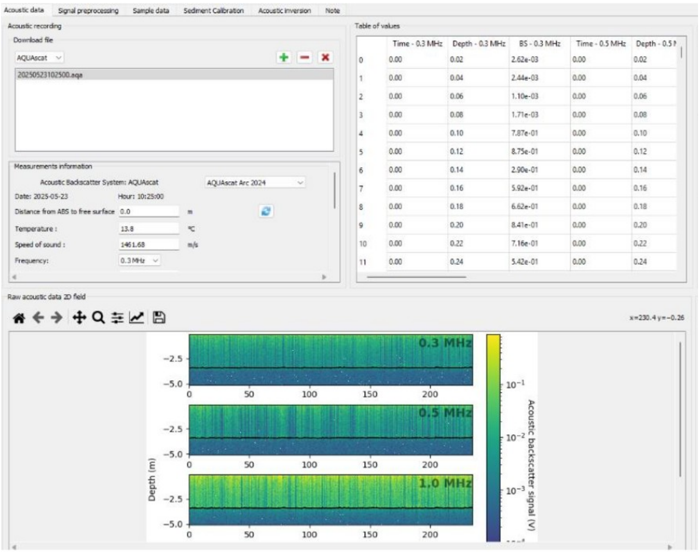
- GUI (Graphical User Interface):

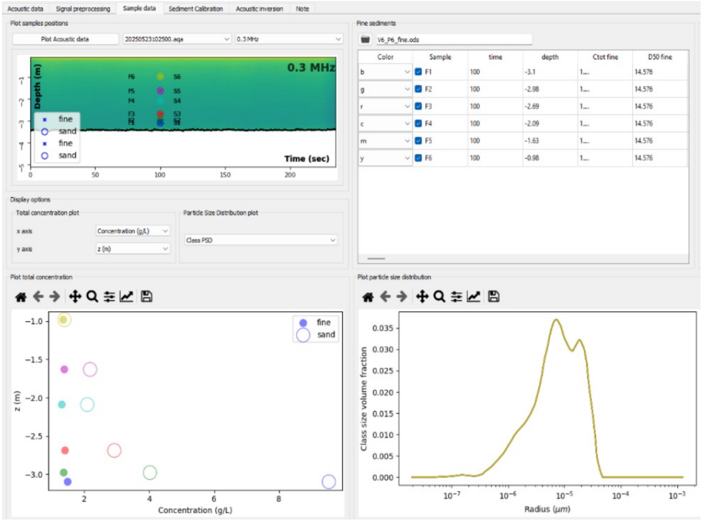
  - Raw acoustic signals import and pre-processing (e.g. filtering, spatio-temporal windowing, etc.).

  - Read fine and sand samples (PSD + concentrations)→ model the backscattering constant k_s, then infer the attenuation constant ζ.

  - Compute the sand and fine concentrations M_s and M_f + export to a .csv file

→ **Still under development, but already used for the analysis of field campaigns.**





Example : measuring sand concentrations on the Rhône River during a dam flushing event (APAVER 2025)

Master’s thesis of Jeanne FOUILLET

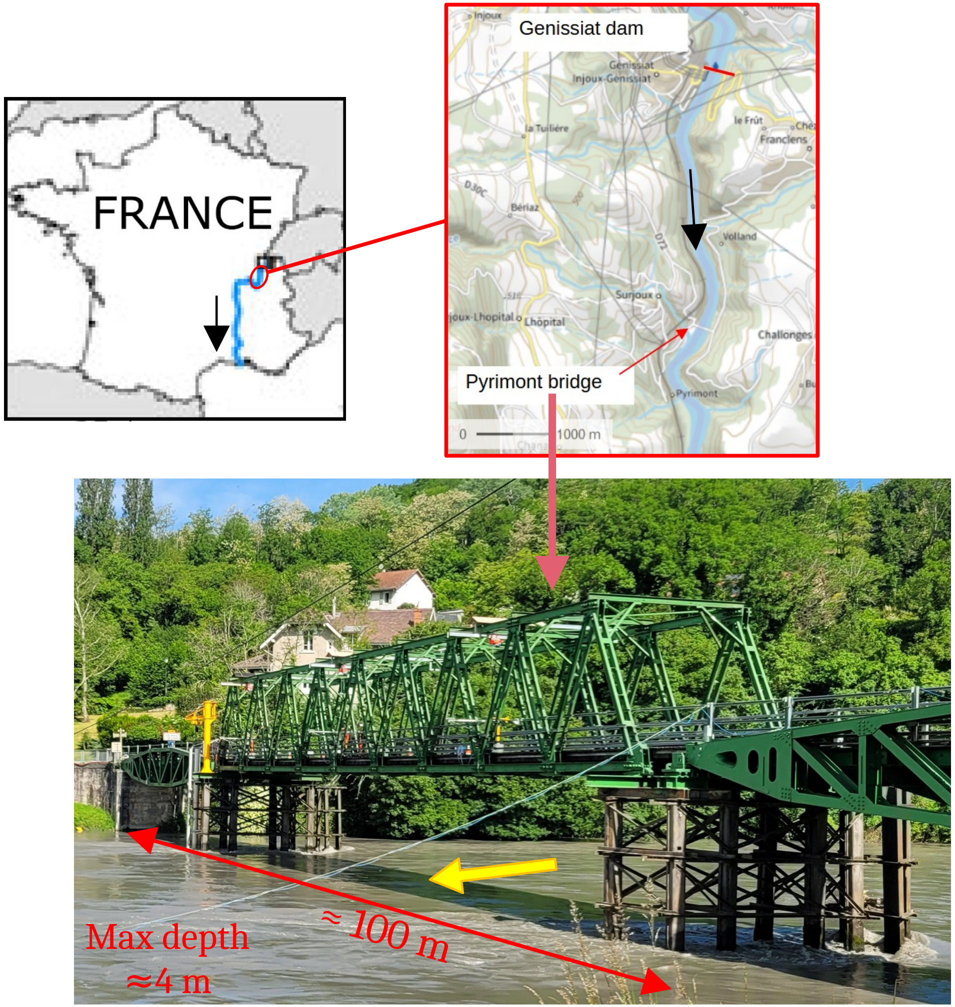
Aim: To assess the ability of ABS-based measurements to map the suspended-sand concentration in a river environment

Study site and conditions

- May 2025 → Flushing of Verbois and Chancy-Pougny Dams (Rhône River, Switzerland)

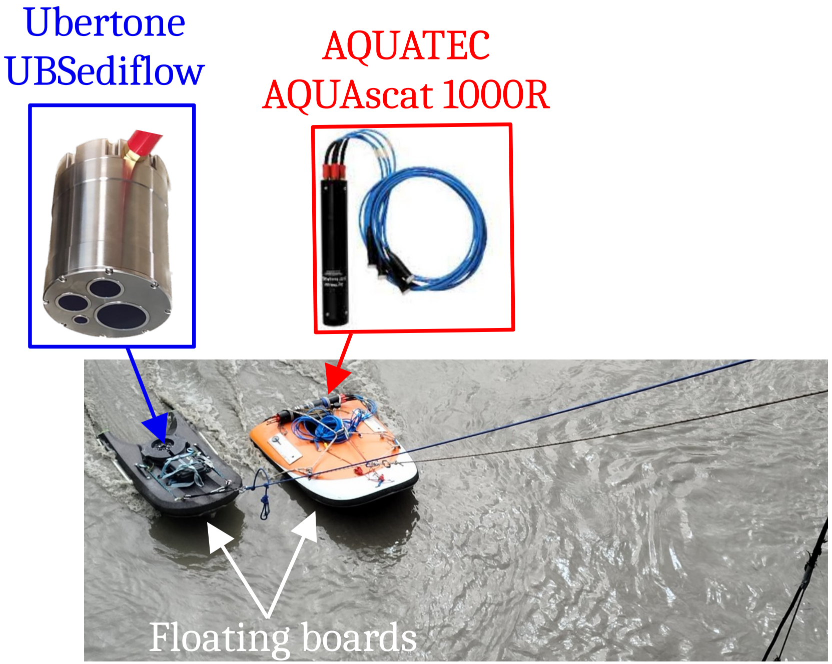
- Five-day measurement (19th to 23rd of May) campaign at Pyrimont Bridge (France) ≈ 3.6 km downstream of Génissiat Dam

- Flow and sediment conditions :
  - Discharge ∈ [450, 570] m^3/s
  - Total SSC (sand + fine) → **up to 11 g/L**



Instruments and measurements

- Two multifrequency ABS mounted on floating boards operated from the bridge.
- Acoustic wave frequency ∈ [0.5, 4.0] MHz, ping emission rate of 20 Hz.
- Sampler → for reference SSC + sediments' PSDs (in-lab analysis)
- ABS → Two configurations :
  a) Fixed position in space → **vertical profile of sand concentration**
  b) Moving accross the river cross section → **map of sand concentration**



Particle Size Distributions

- Fine and sand PSD constant in the cross section (and over time) ?

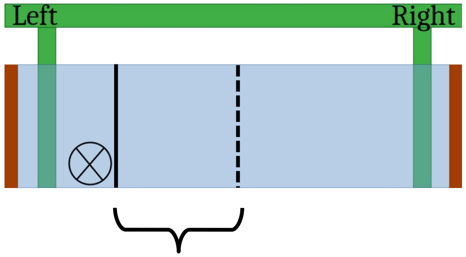
- **Sand (diameters > 63 µm):**

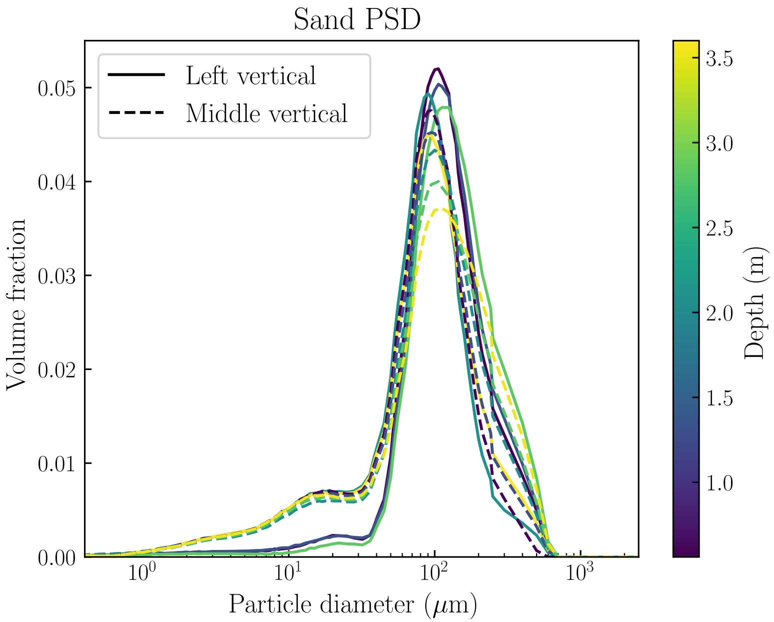
  - On a given day : d_{50} → varies at most by 15 % in the cross section, approx. same for d_{90}.
  - BUT larger variations (> 20 %) between different days.

- **Fine sediments :**

  - Marginal variations of d_{50} (< 10 %) during the whole campaign.

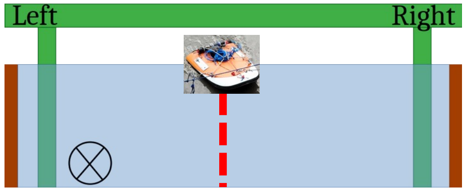
OK to assume constant scattering (k_s) and attenuation (ζ) properties in the cross section **BUT** must be re-evaluated each day.
→ **Combine acoustic signals with samples on a vertical**





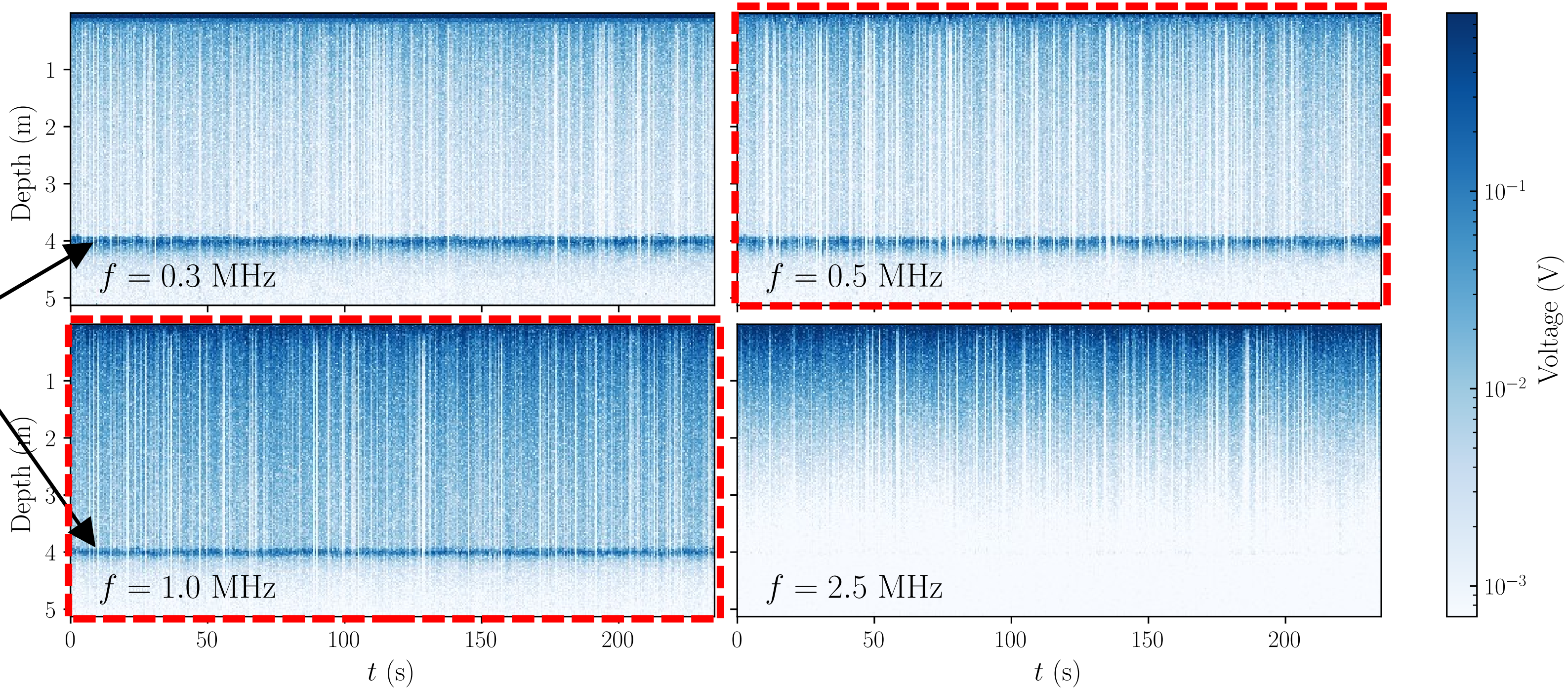
Fixed ABS position (middle vertical)

(AQUAscat data from the 22nd of May 2025, 13:15 [UTC])



Raw signals :

Strong echo from riverbed



Increasing frequency : better signal-to-noise ratio BUT reduced range due to sound attenuation !

→ **Best compromise** : 0.5 and 1.0 MHz

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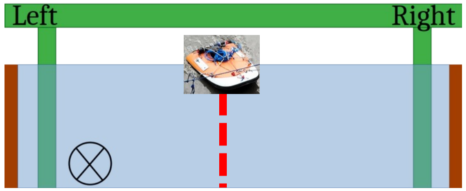


Sediment calibration → Estimating k_s and ζ for f = 0.5 and 1.0 MHz

$$\sqrt{\overline{V(r)^2}} = \frac{k_s k_t}{r}\sqrt{M_s(r)}\,\exp\left[-2\alpha_w r - 2\zeta\int_0^r M_f(r')\mathrm{d}r'\right]$$

1. Average in time the signals

2. For each transducer, from the sonar equation :

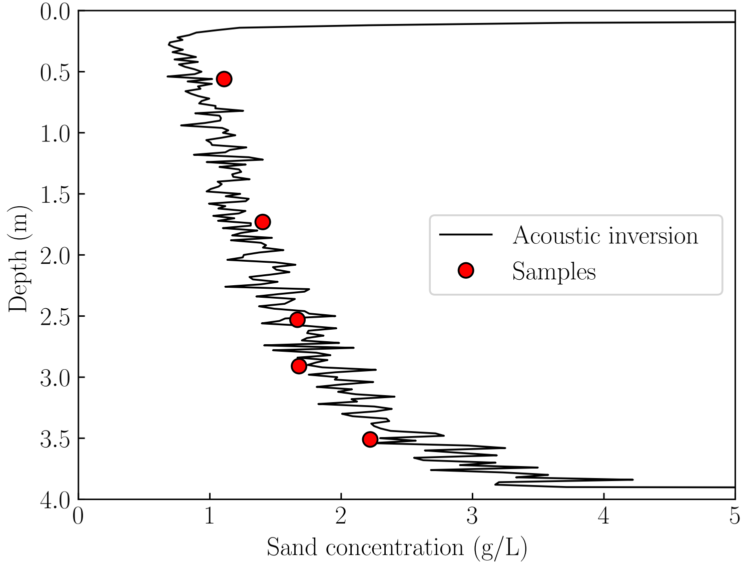
Semi-emprical model of Moate and Thorne (*Cont. Shelf Res.*, 2012) (sand PSD from samples)

$$\zeta = \frac{1}{\int_0^r M_f(r')\mathrm{d}r'}\left(\frac{1}{2}\log\left[\frac{k_s k_t}{r\sqrt{\overline{V(r)^2}}}\sqrt{M_s(r)}\right] - \alpha_w r\right)$$

Estimated from samples

3. **Check** : combine the signals recorded by the two transducers to obtain M_s.

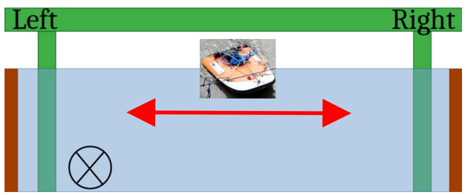
Time averaged profile obtained from the inversion of the 0.5 and 1.0 MHz acoustic signals

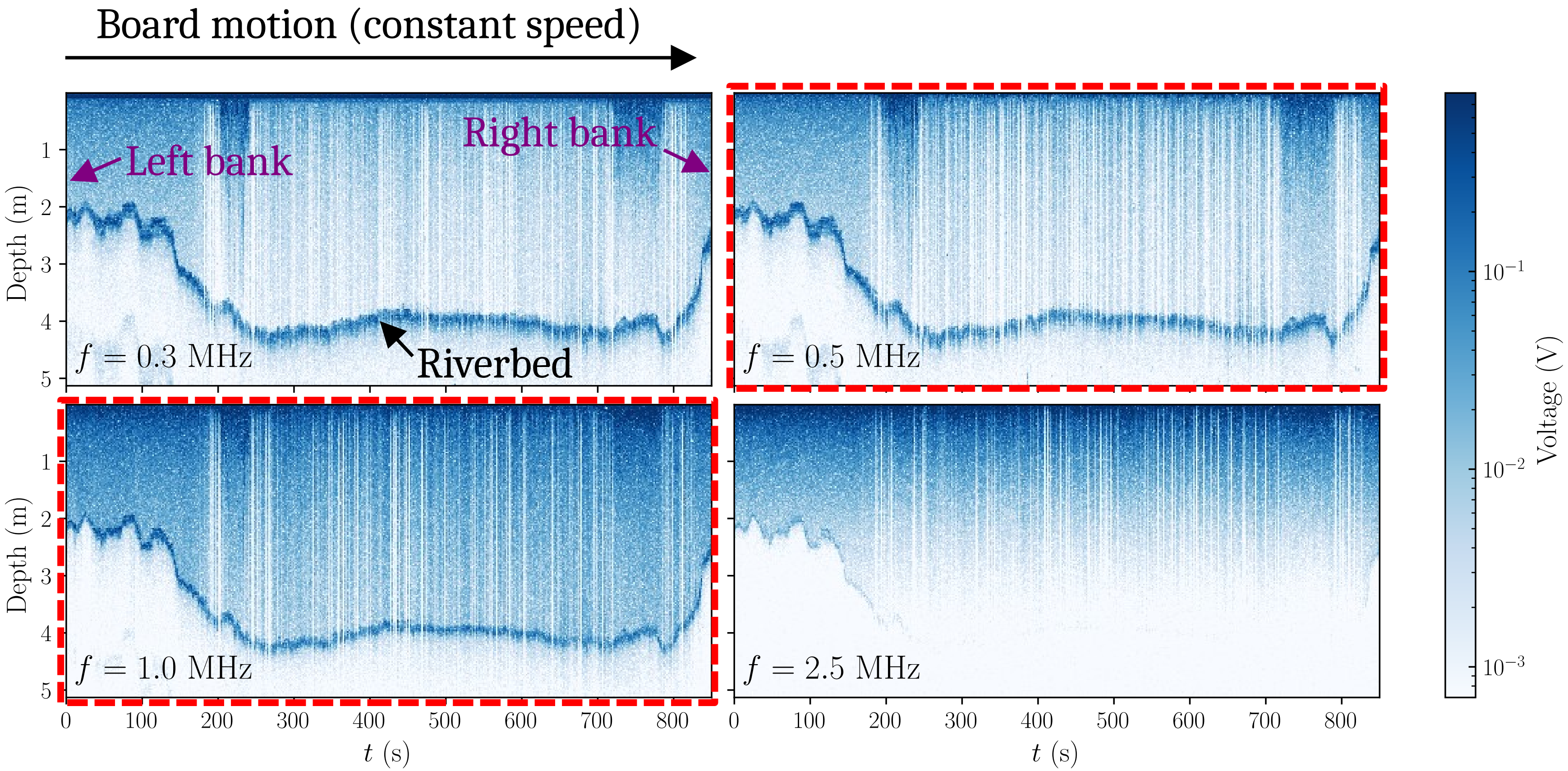


Error <10 % on a vertical

Map of sand concentration in the cross section

(AQUAscat data from the 22nd of May 2025, 14:05 [UTC])





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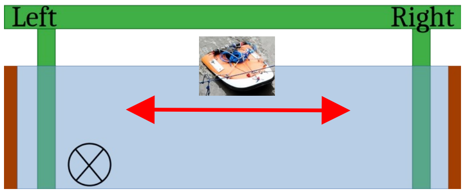
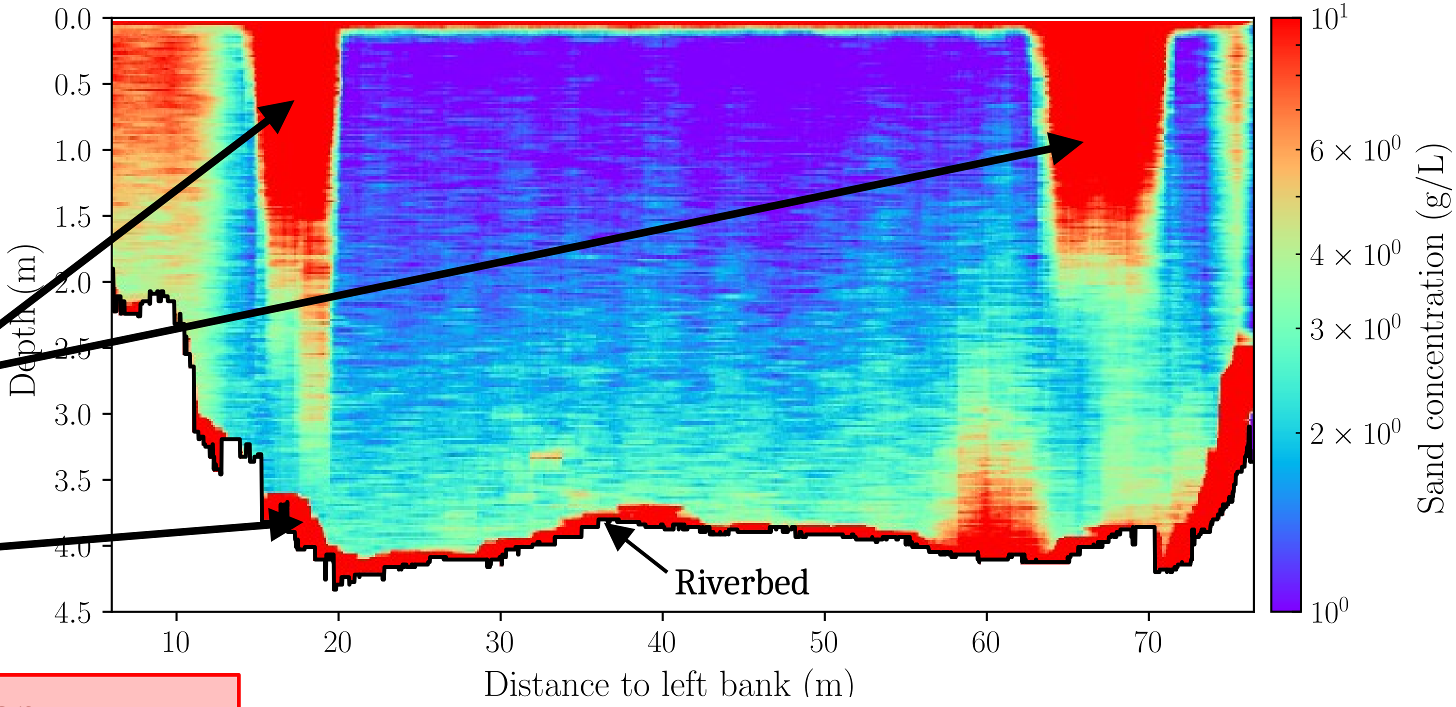


- Larger concentrations **in the lower half** and at the **banks**
- **Spurious signals** caused by bubbles (+ turbulence ?) forming at the piers.

- Echo of the riverbed **overshadows** suspended-sand-related signals there

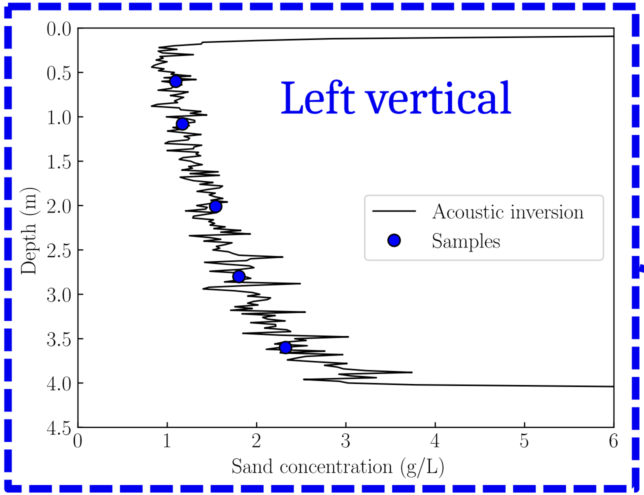


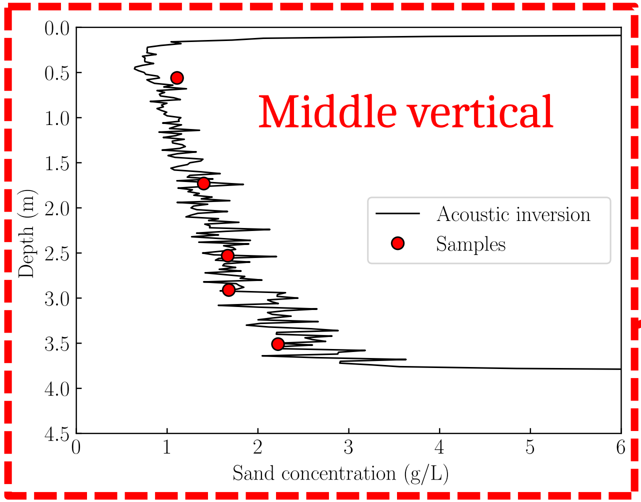
Transect obtained from the inversion of the 0.5 and 1.0 MHz acoustic signals. Each vertical profile is time-averaged over 5 seconds.

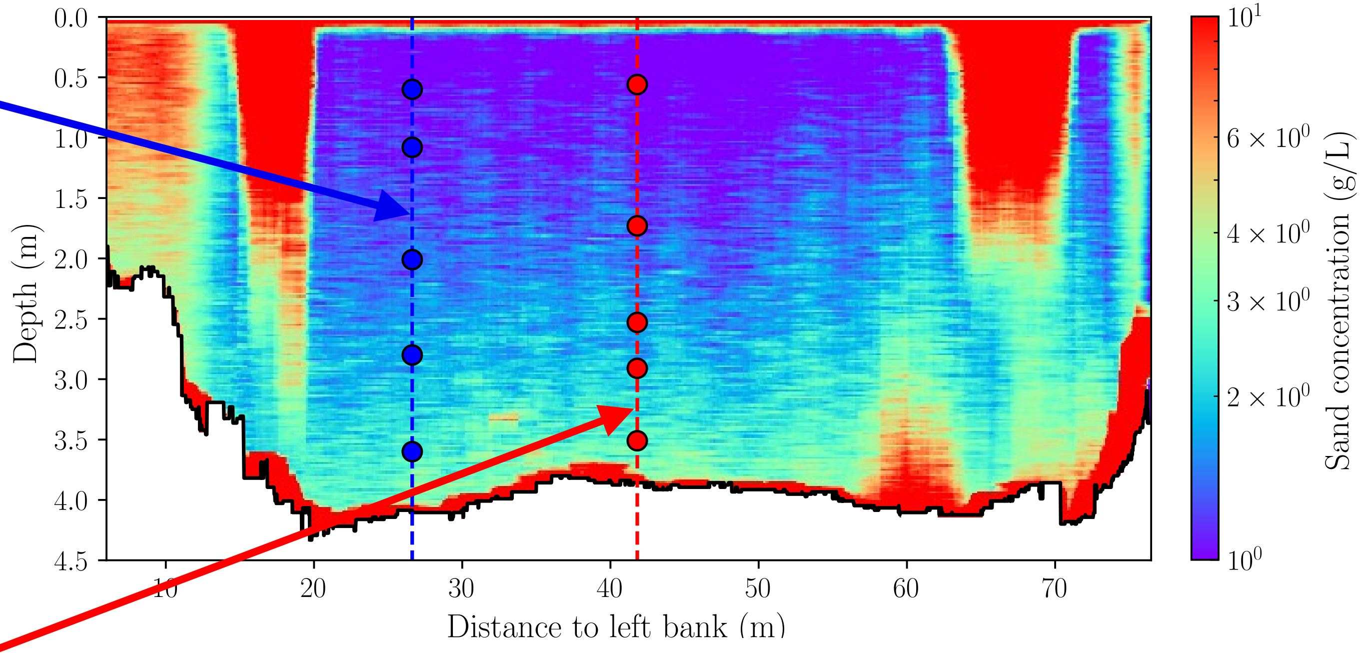
Quantitative sand concentration estimates in **most of the cross section !**

Map of sand concentration in the cross section

(AQUAscat data from the 22nd of May 2025, 14:05 [UTC])







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Conclusion and outlook (1/2)

- Hydroacoustic measurement of suspended sand concentrations
  - Acoustic backscatter System (ABS) → **active sonar**
  - → **Higher spatio-temporal resolution than samples**

- Method deployed on-site during a flushing event on the Rhône River:
  - **Quantitative** and **qualitative** agreement with samples
  - Map of suspended sand concentrations in **most of the river cross section**
  - Sensitivity to backscatterers other than suspended sediments (e.g. bubbles)
  - Still relies on samples (sediment calibration **needed each day**)

Conclusion and outlook (2/2)

- Rather complex method: numerous steps (preprocessing, sediment calibration, inversion, etc.)
  - Development of the open-source software code *AcouSed* (Moudjed *et al.*, 2024)
  - **Still under development** (stabilising the code, adding further pre/post-processing capabilities, etc.)
- **Currently:** joint project with INRAE, CNR and Ubertone
  - Permanently-installed ABS (UBSediflow) on the Rhône River in Lyon for monitoring suspended sediment concentrations
  - <u>**Aims:**</u> to reduce the dependency on samples + to move towards “real-time” monitoring