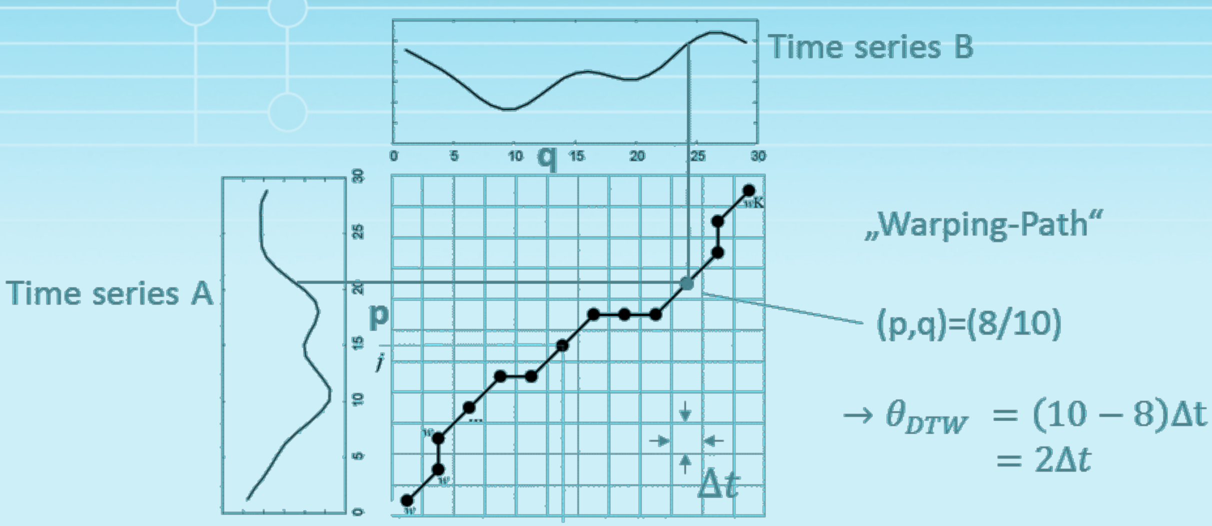
Dynamic Time Warping improves sewer flow monitoring



David Dürrenmatt

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What’s the matter?

Quality control of discharge measurements

Problem

- Flow meters show considerable errors under normal operating conditions in sewers.

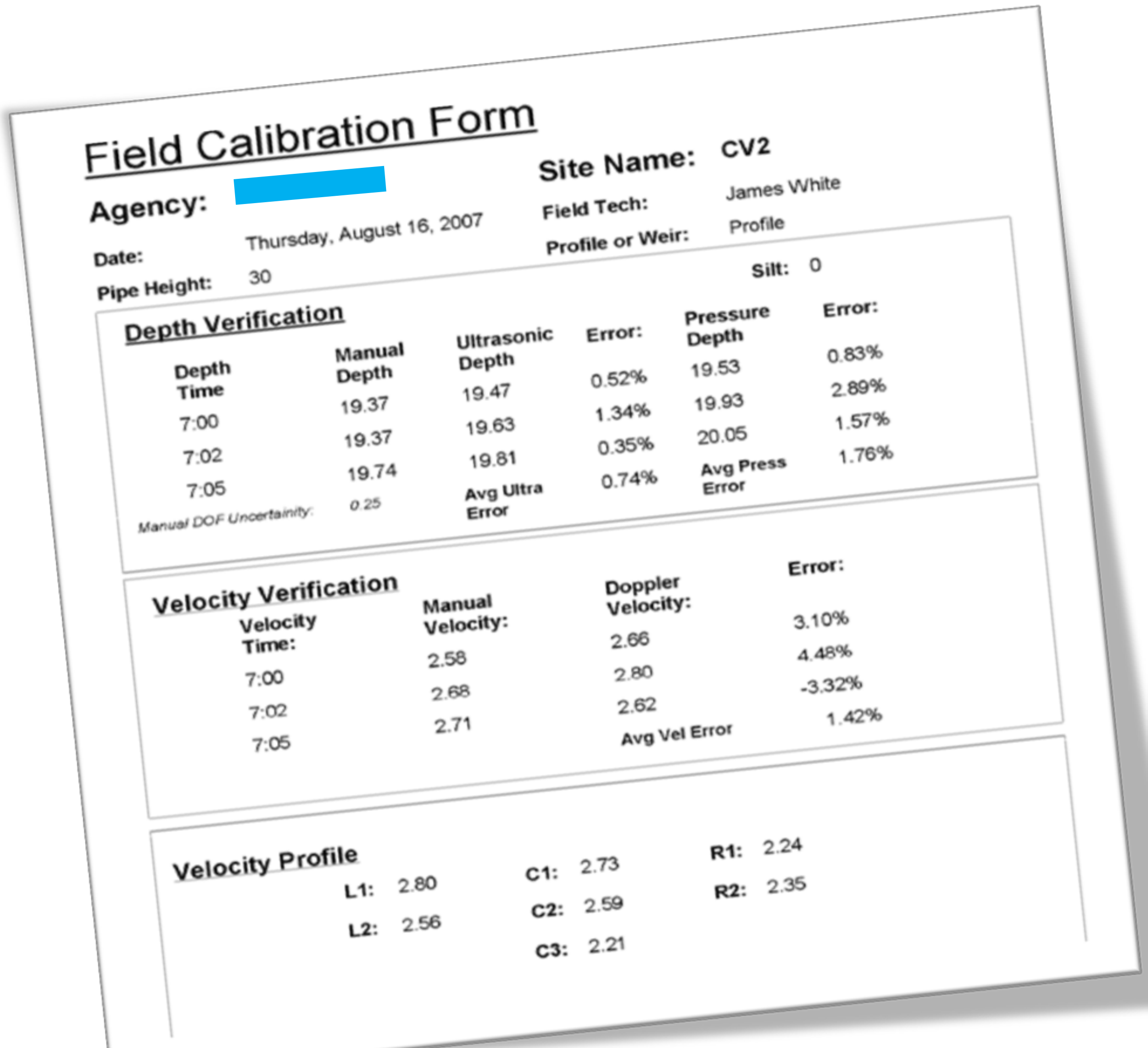
- Discharge
  - Ultrasonic flow meters: 10%
  - Tracer dilution methods: 6% to 16%
  - Venturi: 12% to 20%

- Ultrasonic velocity sensors
  - Single-point: 14 - 18%
  - Multi-point: 4 - 5%

Hoppe (2009), Smits (2008)

Quality control of discharge measurements

- Manual calibration in the lab or field is expensive.
- Usually only point calibration once per year or 3 months.
- During dry weather conditions!


Field Calibration Form

Agency:

Site Name: CV2

Field Tech: James White

Date: Thursday, August 16, 2007

Profile or Weir: Profile

Pipe Height: 30

Silt: 0

Depth Verification

Depth Time	Manual Depth	Ultrasonic Depth	Error:	Pressure Depth	Error:
7:00	19.37	19.47	0.52%	19.53	0.83%
7:02	19.37	19.63	1.34%	19.93	2.89%
7:05	19.74	19.81	0.35%	20.05	1.57%
Manual DOF Uncertainty:	*0.25*	Avg Ultra Error	0.74%	Avg Press Error	1.76%

Velocity Verification

Velocity Time:	Manual Velocity:	Doppler Velocity:	Error:
7:00	2.58	2.66	3.10%
7:02	2.68	2.80	4.48%
7:05	2.71	2.62	-3.32%
		Avg Vel Error	1.42%

Velocity Profile

L1:	2.80	C1:	2.73	R1:	2.24
L2:	2.56	C2:	2.59	R2:	2.35
		C3:	2.21		

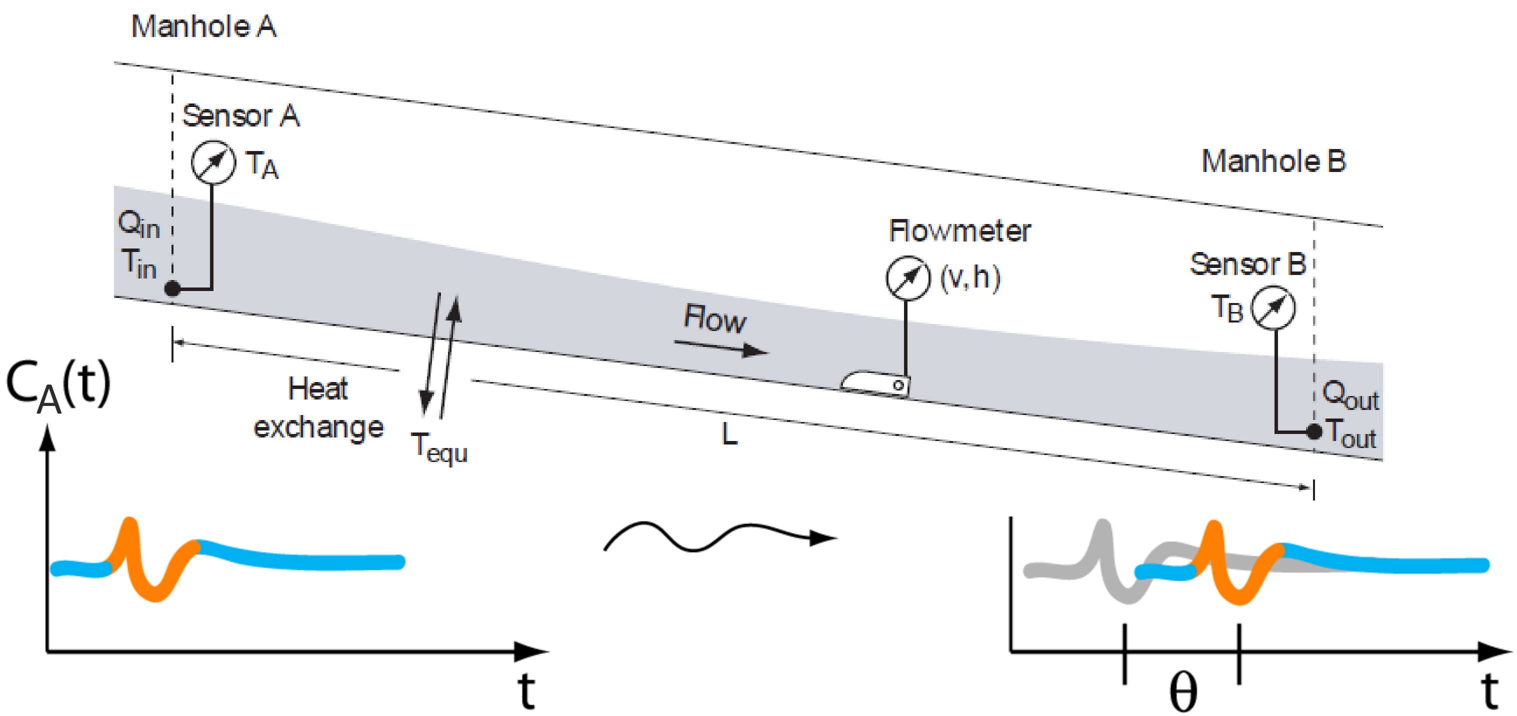
Quality control of discharge measurements

Create independent information on flow velocities

Idea

- Use "natural" tracers in wastewater to obtain independent information on average flow velocities

⇒ Time shift of characteristic patterns between 2 measuring locations A and B contains information on travel time θ.



Quality control of discharge measurements

Create independent information on flow velocities

Idea

- Use “natural” tracers in wastewater to obtain independent information on average flow velocities

⇒ Time shift of characteristic patterns between 2 measuring locations A and B contains information on travel time θ.

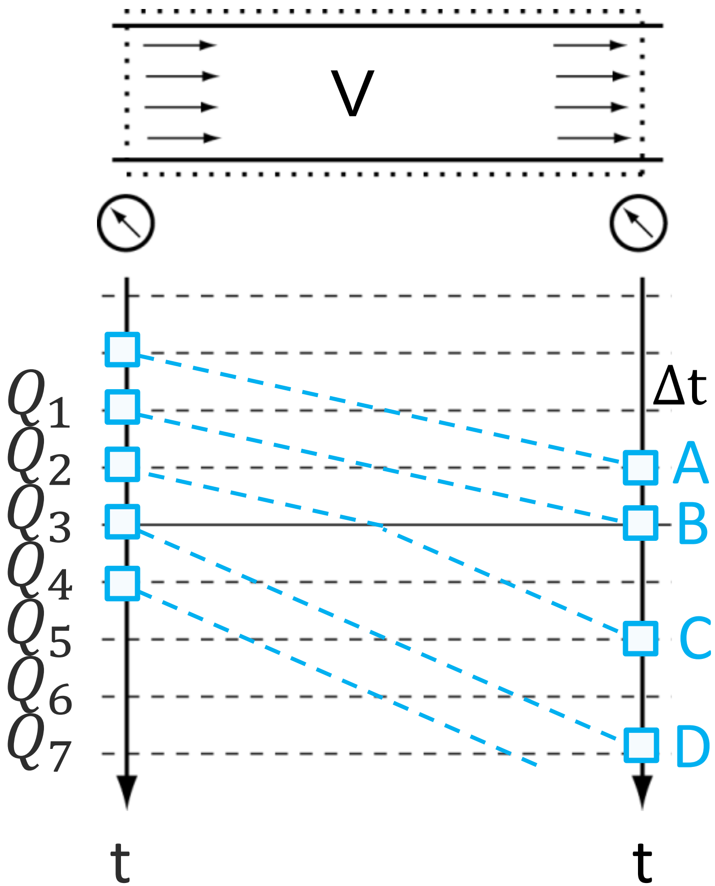
⇒ Length of the sewer section is obtained from map or field measurements.

$$v(t) \approx \frac{L}{\theta}$$

Methods

Ideal plug-flow reactor

Concept



$$\theta(t) = \frac{V}{Q(t)}$$

Equations:

Packet A: $2\Delta t \rightarrow \Delta t(Q_1 + Q_2) = V$

Packet B: $2\Delta t \rightarrow \Delta t(Q_2 + Q_3) = V$

Packet C: $3\Delta t \rightarrow \Delta t(Q_3 + Q_4 + Q_5) = V$

Packet D: $4\Delta t \rightarrow \Delta t(Q_4 + Q_5 + Q_6 + Q_7) = V$

…

Ideal plug-flow reactor

4 Equations:

$$\Delta t(Q_1 + Q_2) = V$$
$$\Delta t(Q_2 + Q_3) = V$$
$$\Delta t(Q_3 + Q_4 + Q_5) = V$$
$$\Delta t(Q_4 + Q_5 + Q_6 + Q_7) = V$$

Matrix notation: $AQ = b$ **with**

$$\boldsymbol{A} = \begin{pmatrix} 1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 1 & 1 \end{pmatrix},$$

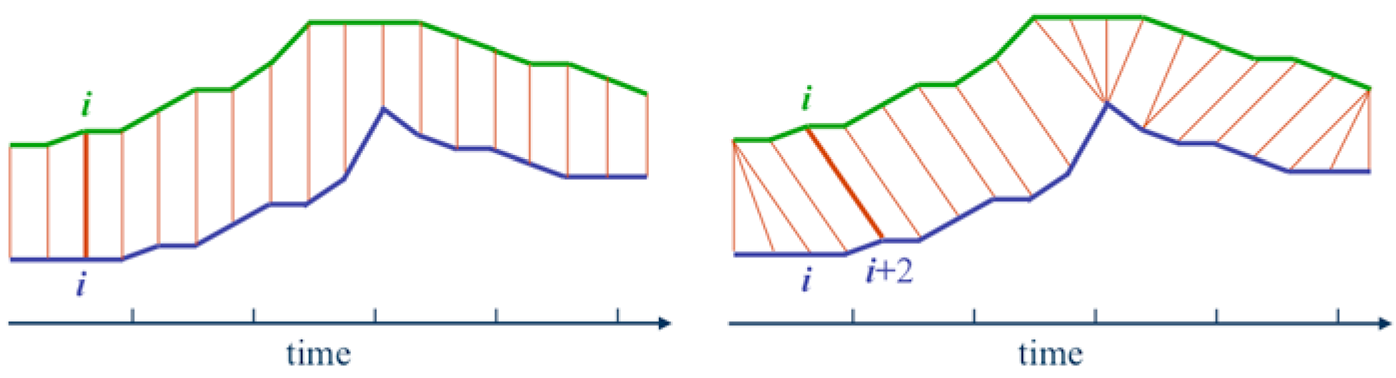
$\mathrm{Q} = (Q_1, Q_2, \ldots, Q_7)^T$ and $\mathrm{b} = \frac{V}{\Delta t}(1,1,1,1)^T$

How do we get the residence times of the water packets?

Dynamic Time Warping

- “Warps” two sequences non-linearly in the time domain so that the dissimilarity is minimized

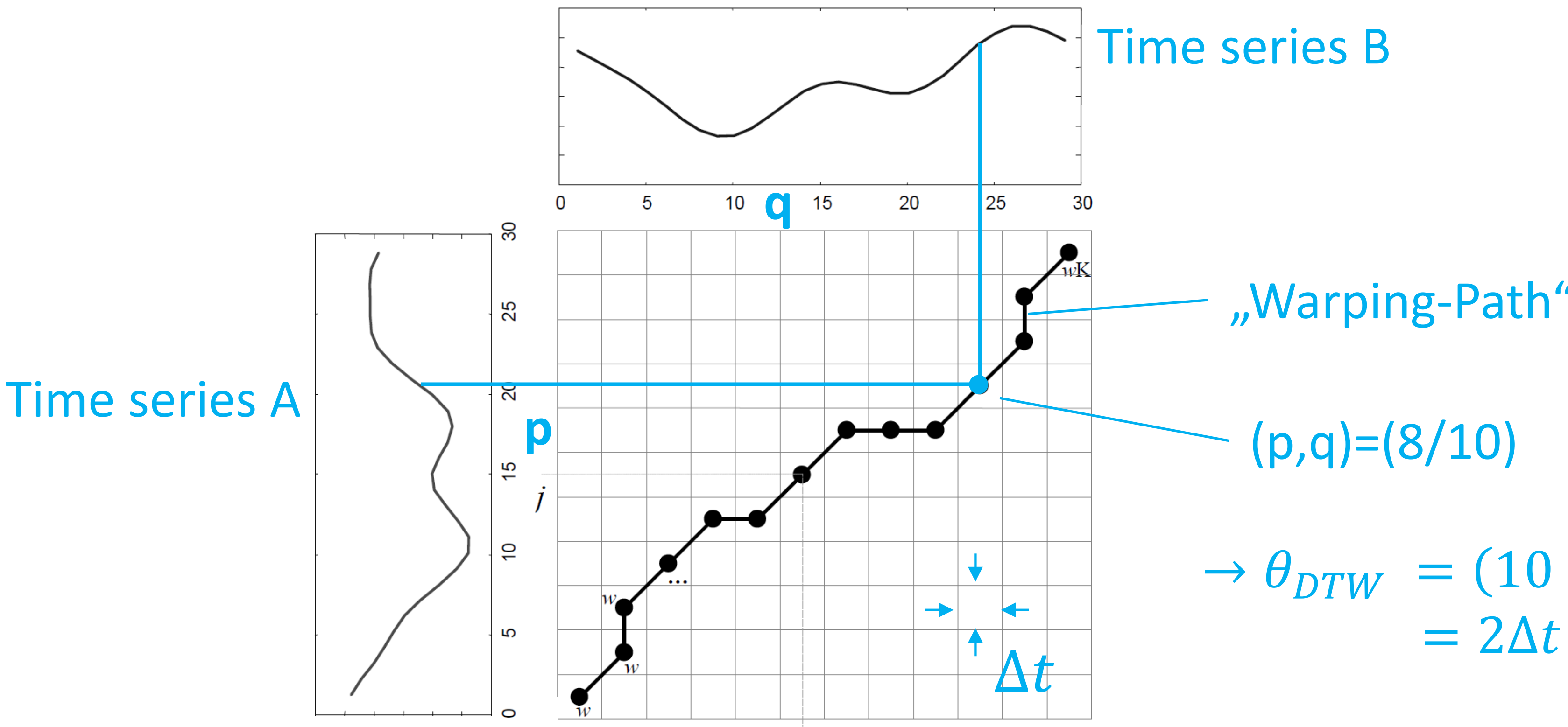
- Was originally developed for speech recognition
- Is a standard technique for non-linear pattern matching



- Has been used to successfully estimate flow distribution in hydraulic flow dividers at WWTPs.

Dürrenmatt (2011)

Dynamic Time Warping

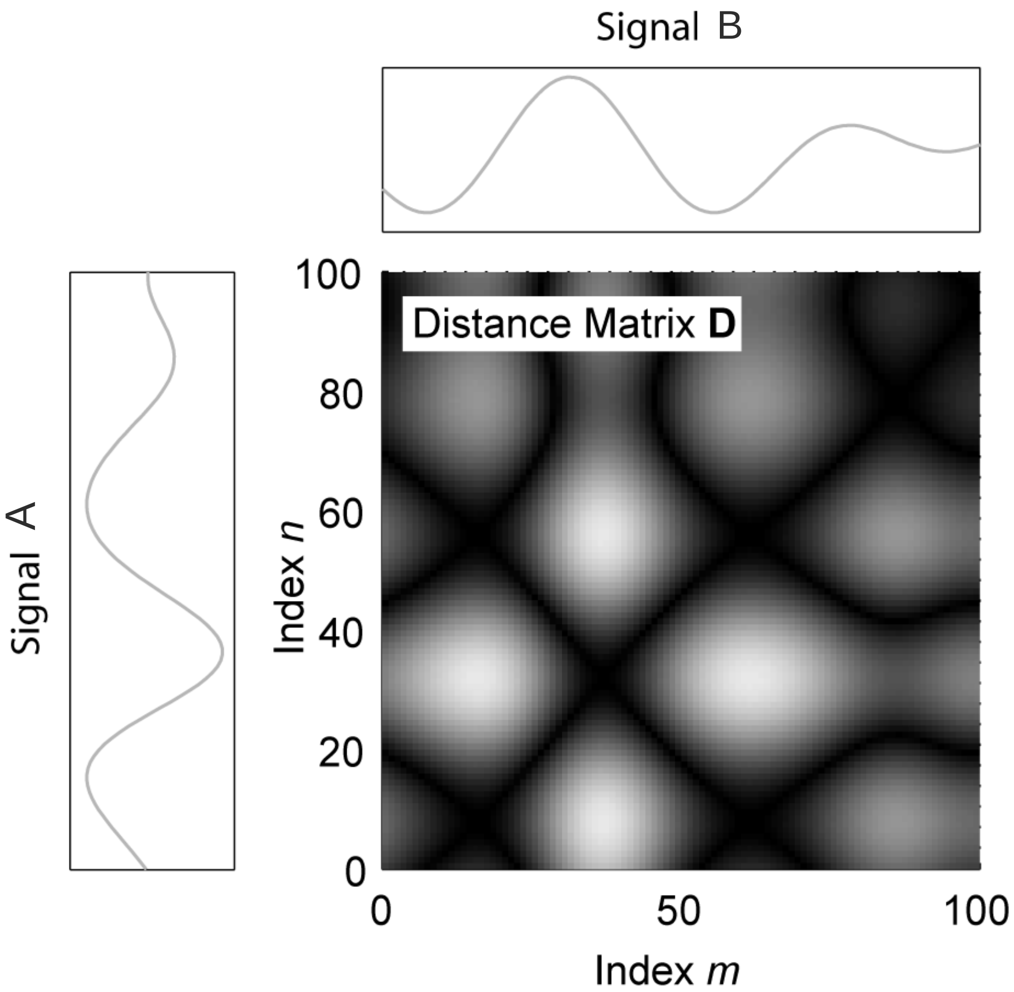


$$\rightarrow \theta_{DTW} = (10-8)\Delta t = 2\Delta t$$

$$d(A,B) = \sum_{w_k} D_{n,m}$$

(Keogh und Pazzani, 2000)

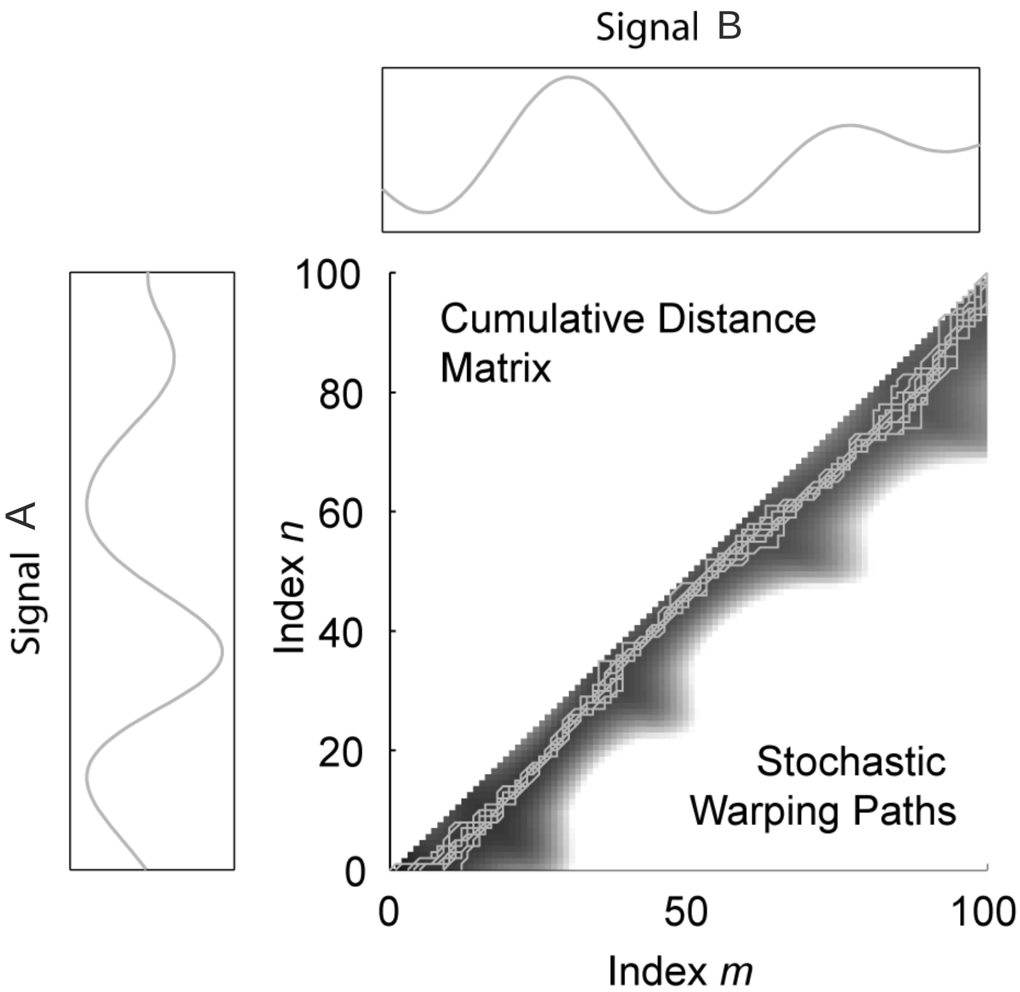
Dynamic Time Warping



Conditions for the warping path:

- Starts and ends in opposite corners
- continuous
- Steps are restricted
- Pattern appears first in A, then in B.

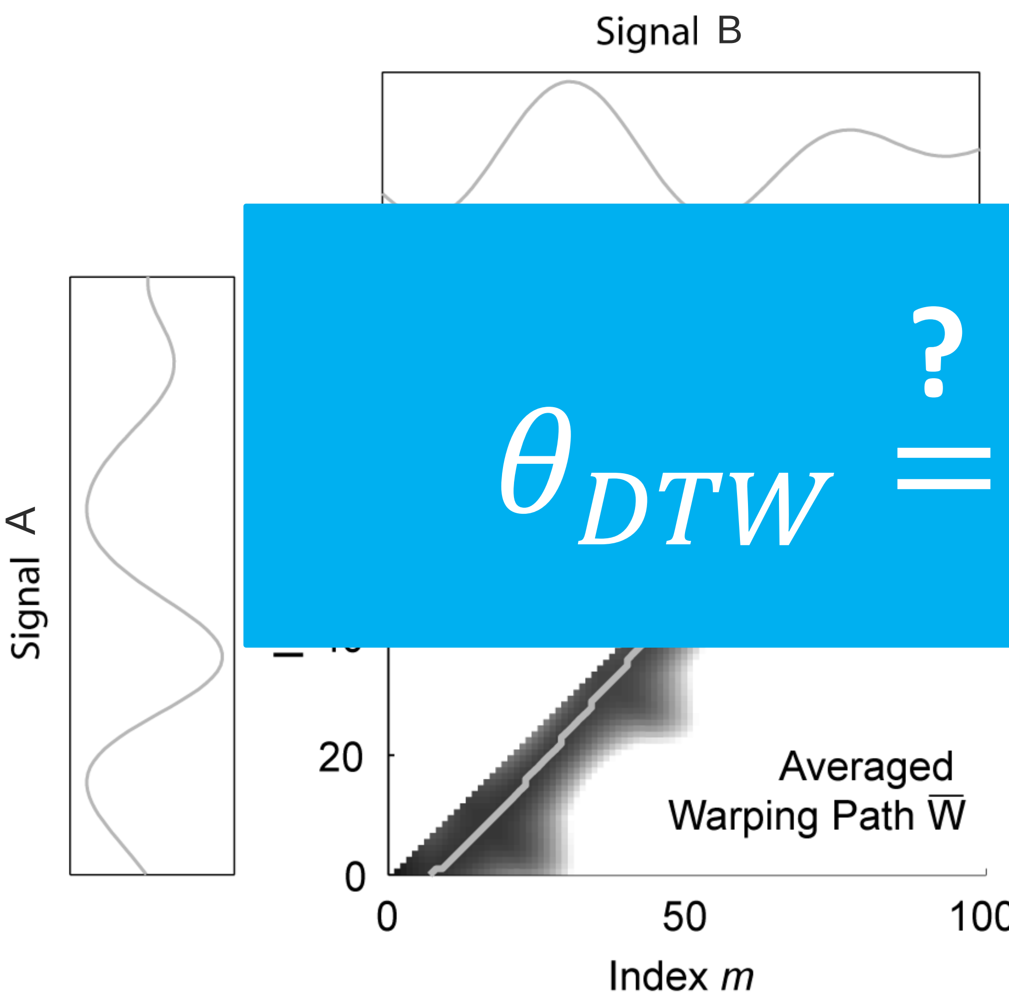
Dynamic Time Warping



Added stochasticity to avoid local optima:

1. Add noise to observations
2. Iterate computation of warping paths

Dynamic Time Warping



$$\theta_{DTW} \stackrel{?}{=} \theta$$

city to

na:

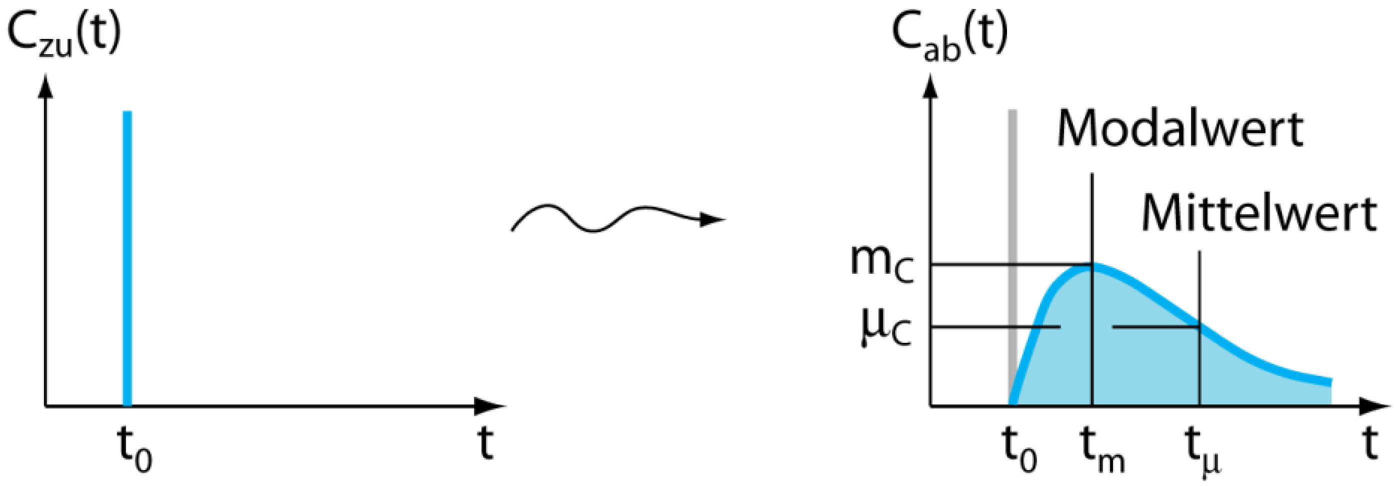
tation of warping paths

3. Compute average warping

… $\theta_{DTW} = \theta$?

- The estimated travel time does not equal the true travel time in real systems (Dispersion, Reaction).

Illustration: Tracer experiment



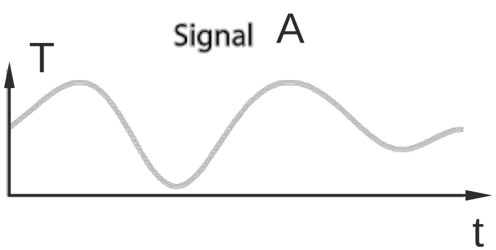
Error: $E = \frac{V}{t_\mu} - \frac{V}{t_m} \neq 0$ if $t_\mu \neq t_m$

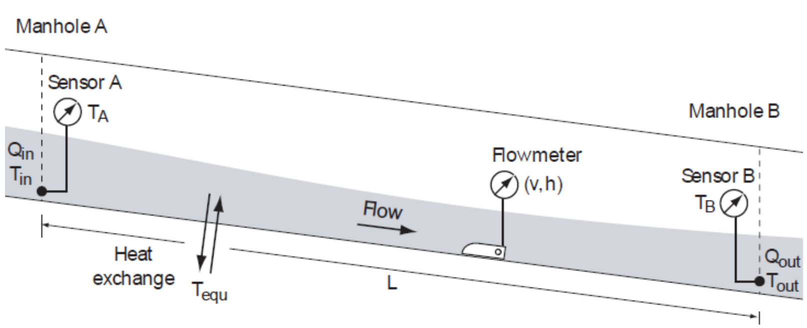
Numerical experiments

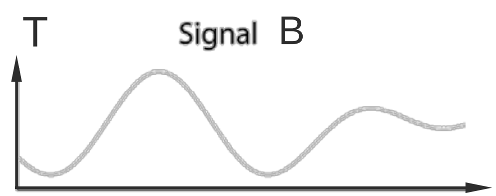
Numerical experiments

- Testing the method on virtual data to determine the field of application

- “Benchmark Simulation Environment”
  - Inflow generator (Discharge, Temperature)
  - Hydrodynamic heat transport model (Aquasim)
  - Sensor model (BSM 1, Class “A”)

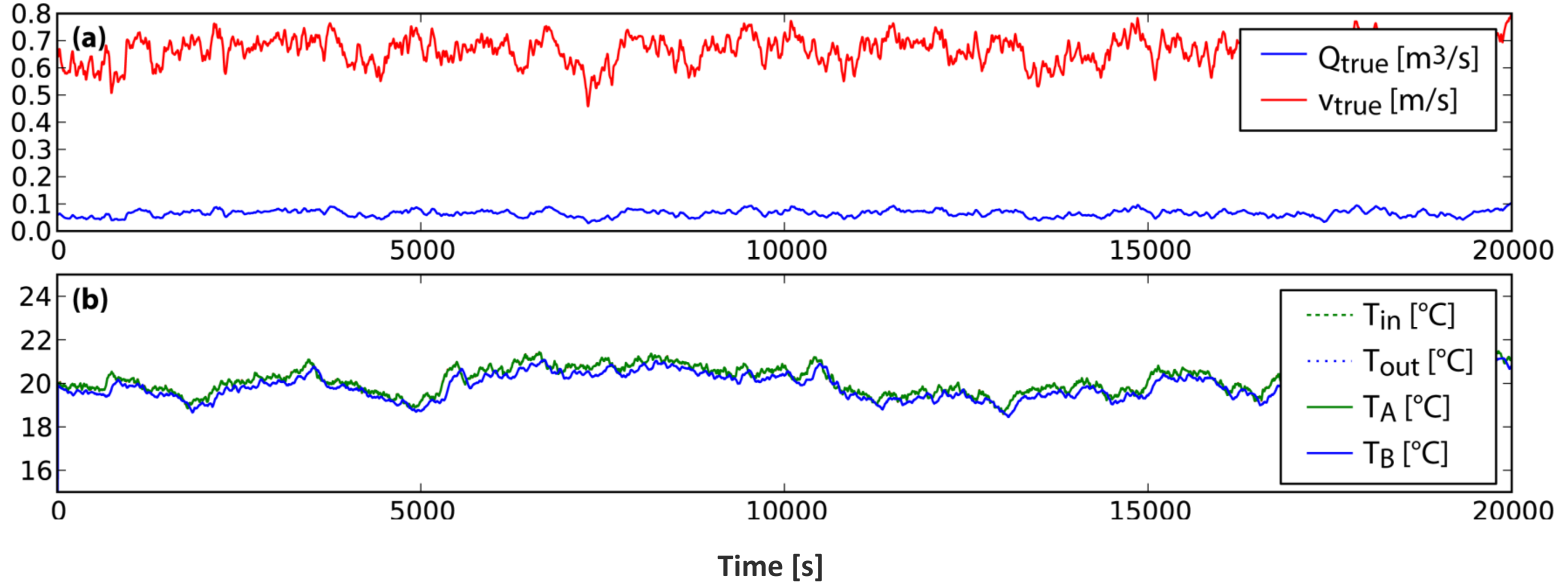






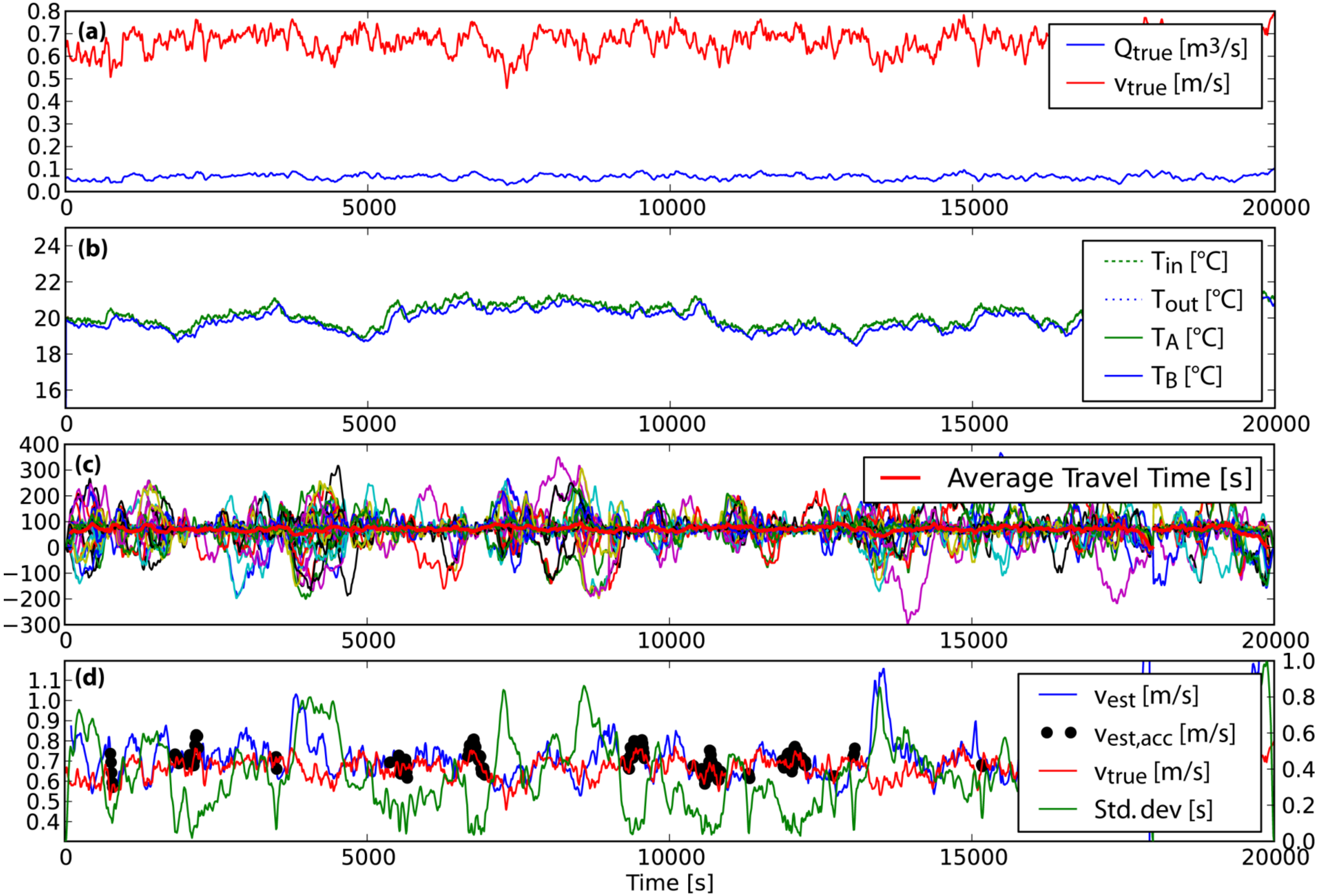
Results (1)

Example



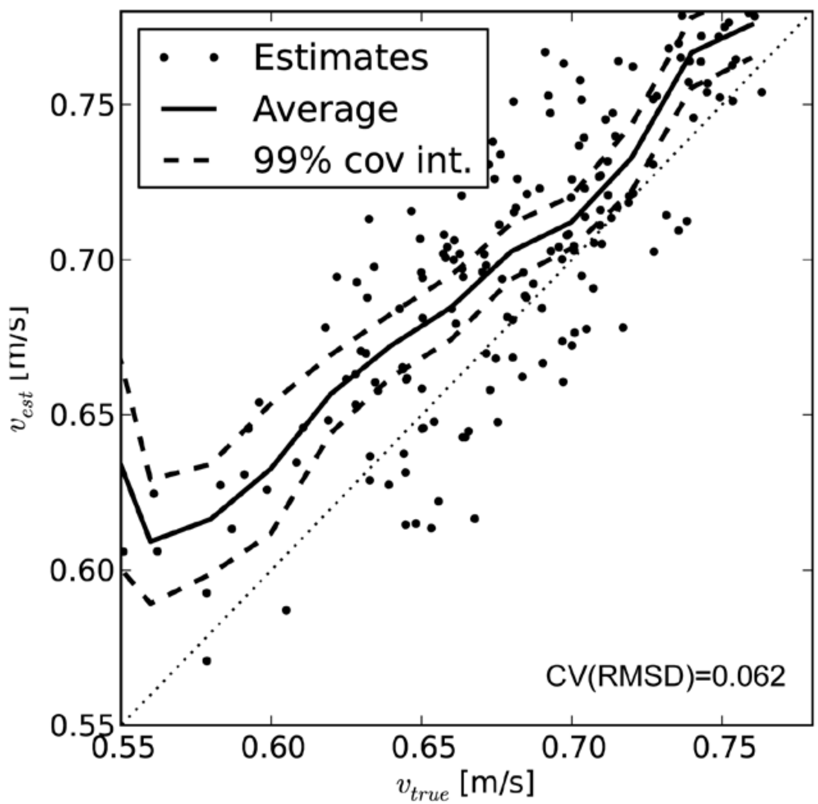
Results (1)

Example



Results (1)

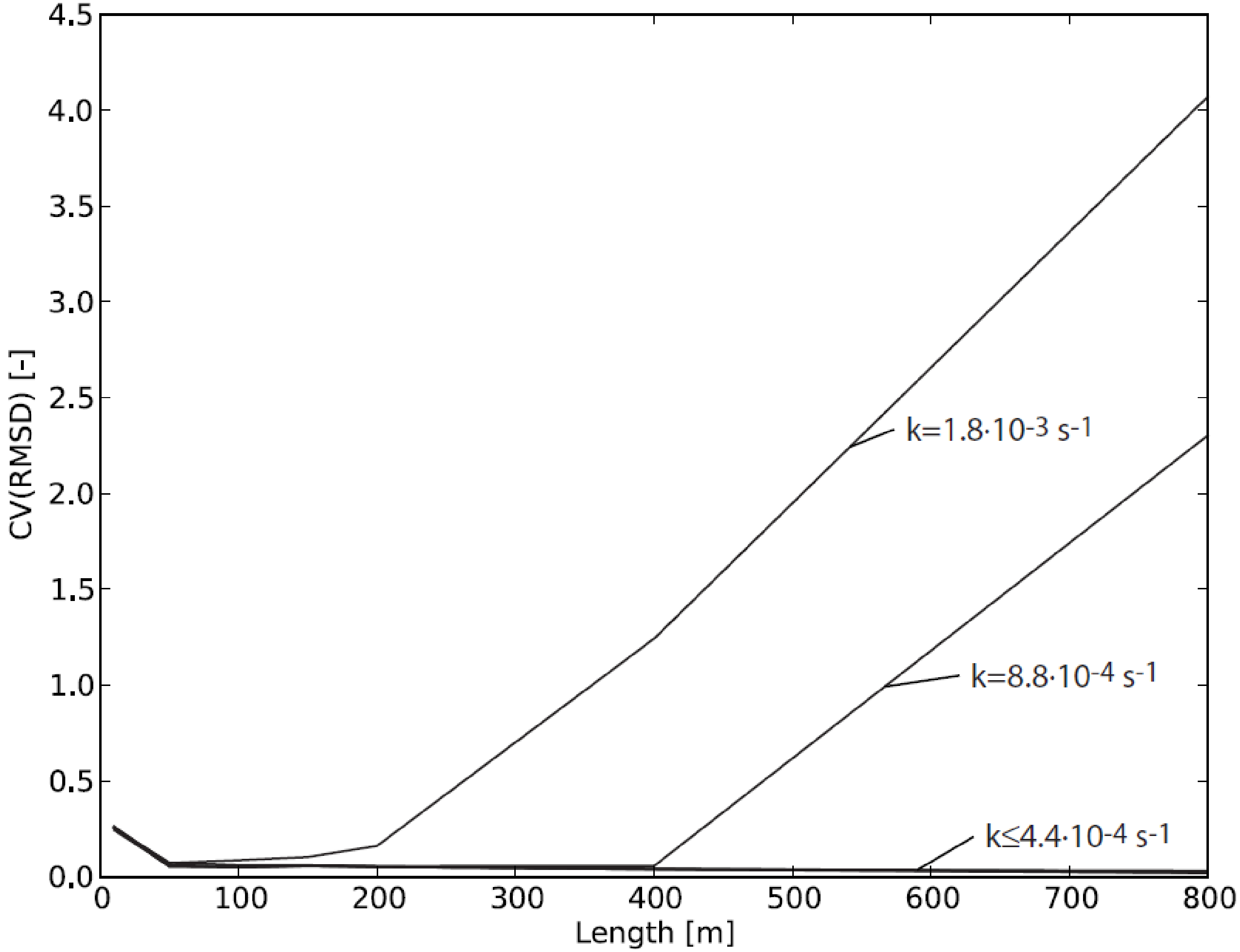
Accuracy of DTW velocity estimates



Confirms the theorectical considerations.

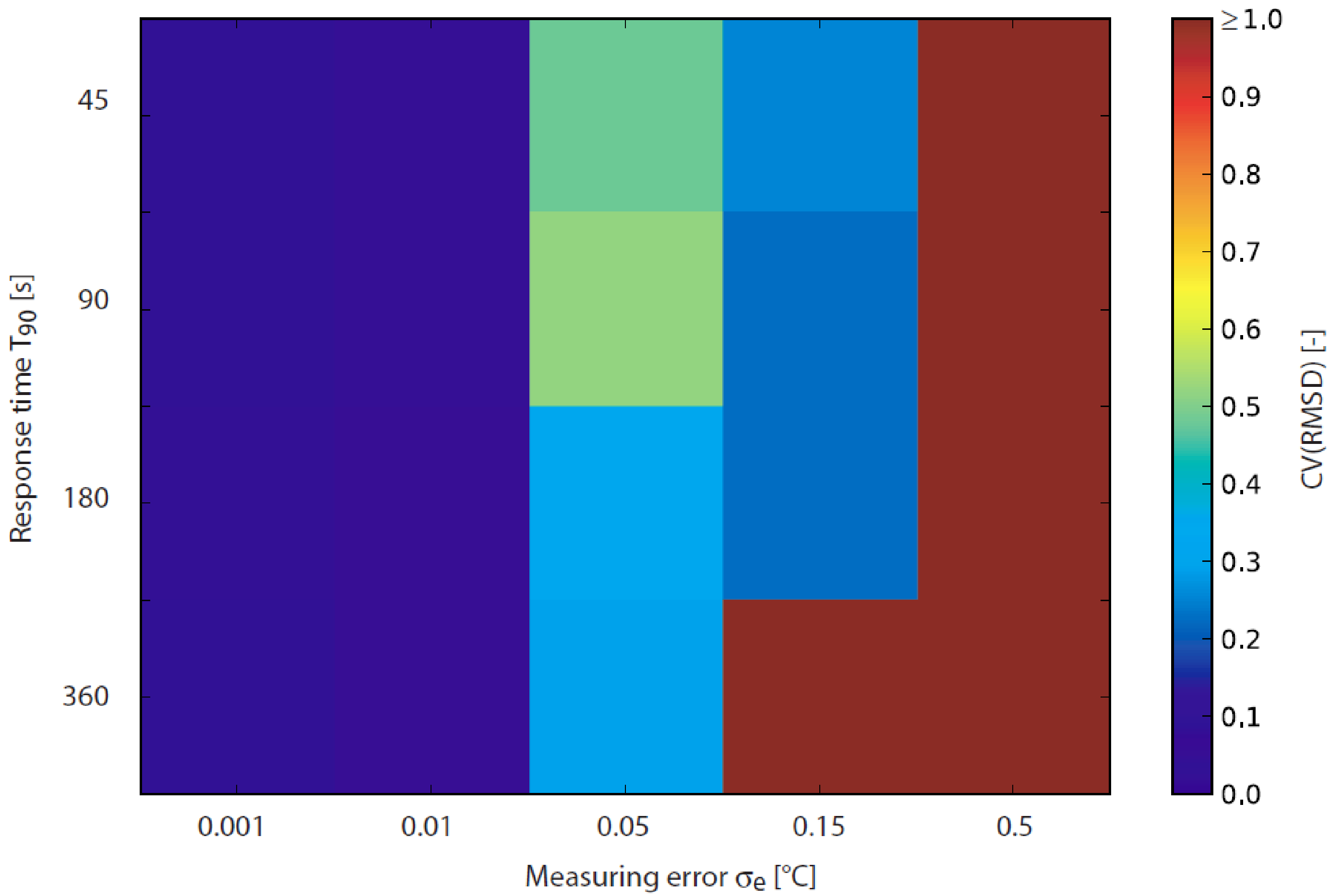
Results (2)

Dispersion and heat exchange



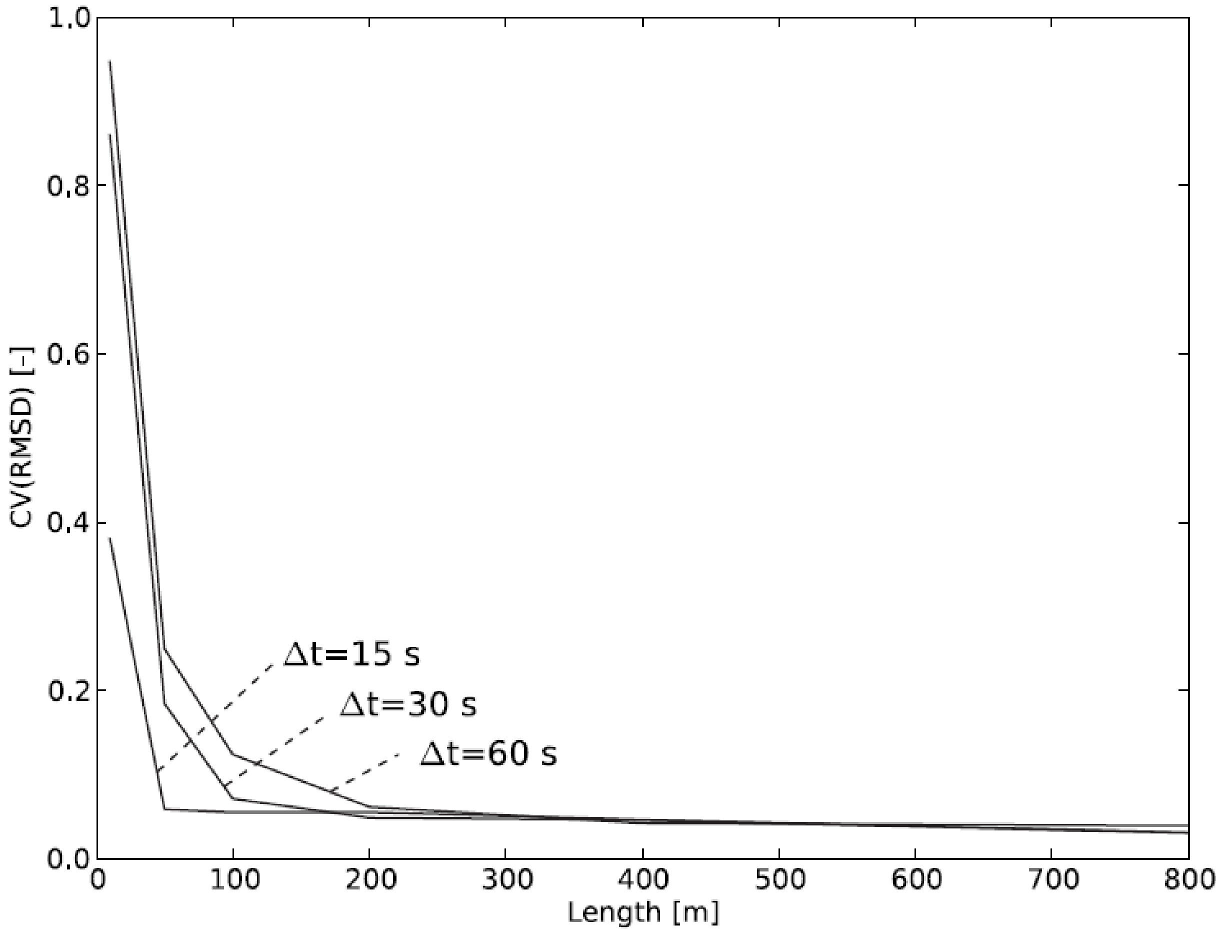
Results (3)

Sensor response time and error



Results (4)

Sampling frequency



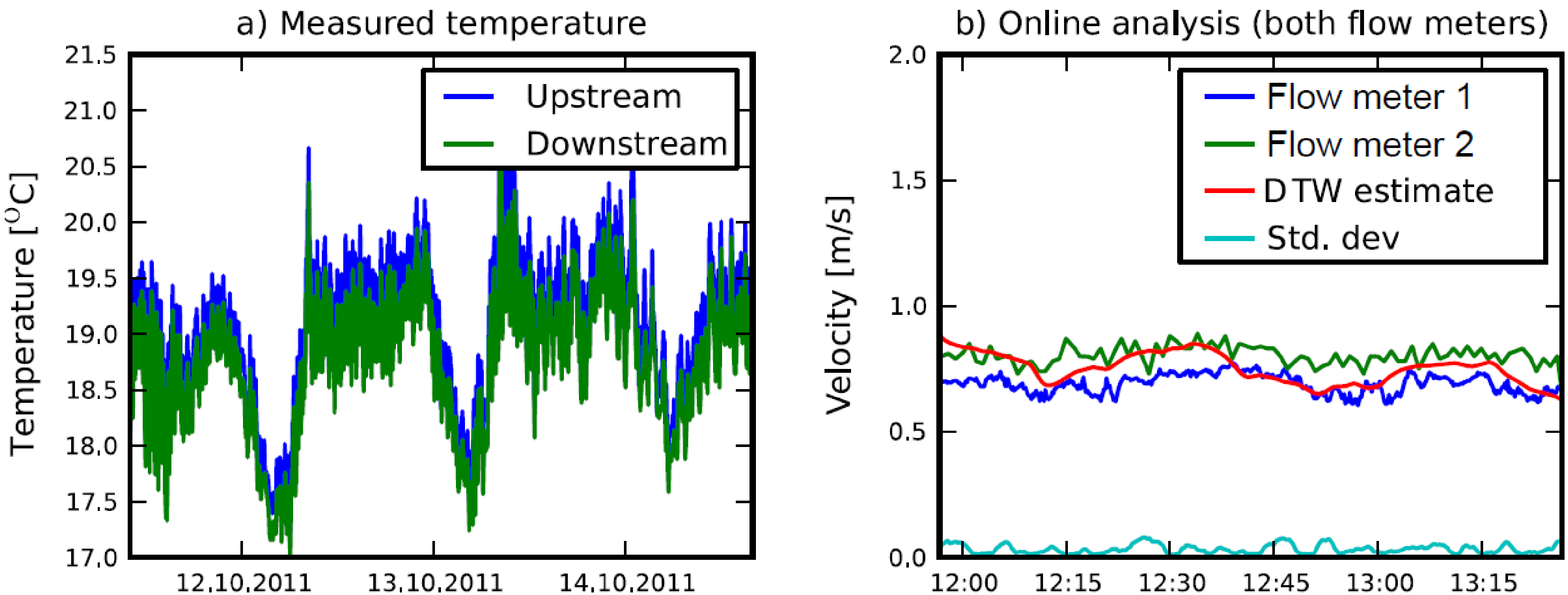
Application

Real-world case study

- Testing the performance of 2 flow meters
- Measurement campaign: 2 weeks
- 2x Onset TMC6-HD thermistor w. HOBO logger
  - Accuracy: 0.25 °C
  - Resolution: 0.03 °C
  - $T_{10/90}$: 30s (90%)

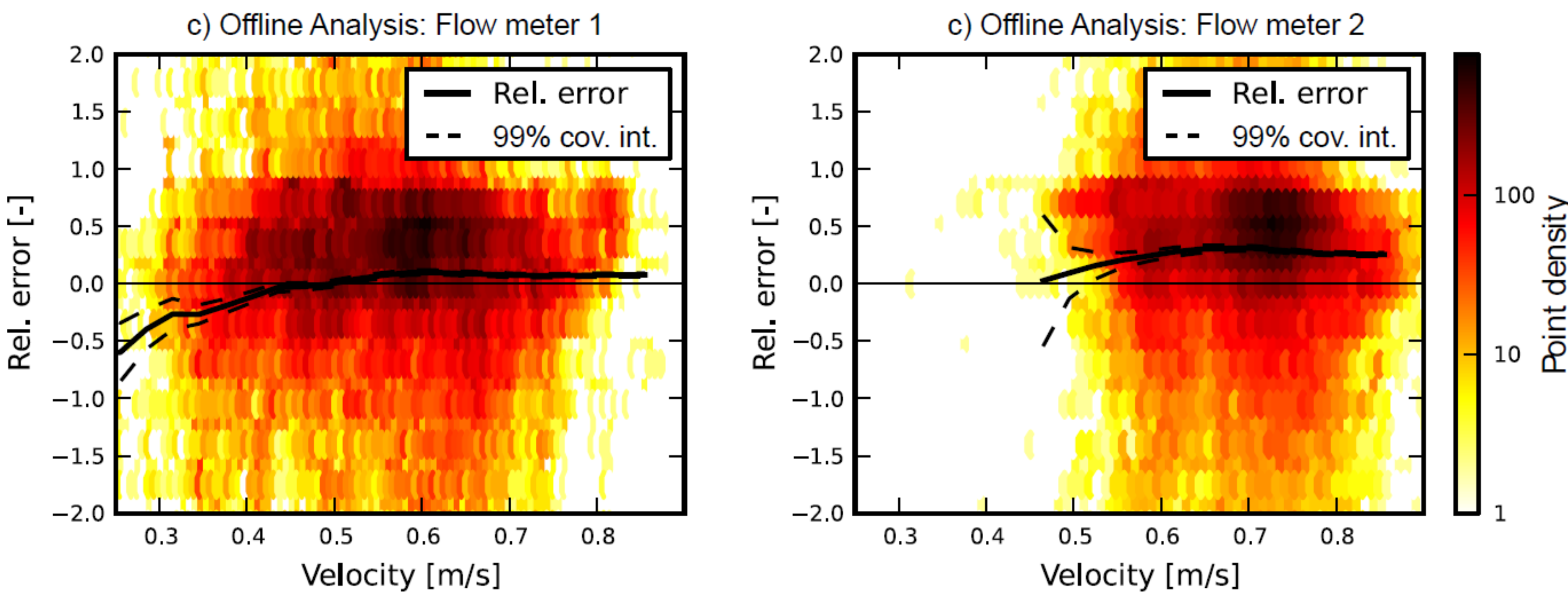
Results (5)

Online analysis



Results (6)

Offline analysis



This looks nice. But...

Discussion

- Pre-processing is important! High-pass filtering is better than normalization of the Temperature signals.
- Results chould be improved by using other or multiple tracers with near-conservative behaviour (e.g., Conductivity).
- Using a physically-based model for data analysis could also be promising.

Dürrenmatt, D.J., D. Del Giudice, J. Rieckermann et al., Dynamic time warping improves sewer flow monitoring (submitted to Water Research)

Discussion

Comparison to Cross-correlation with sliding windows

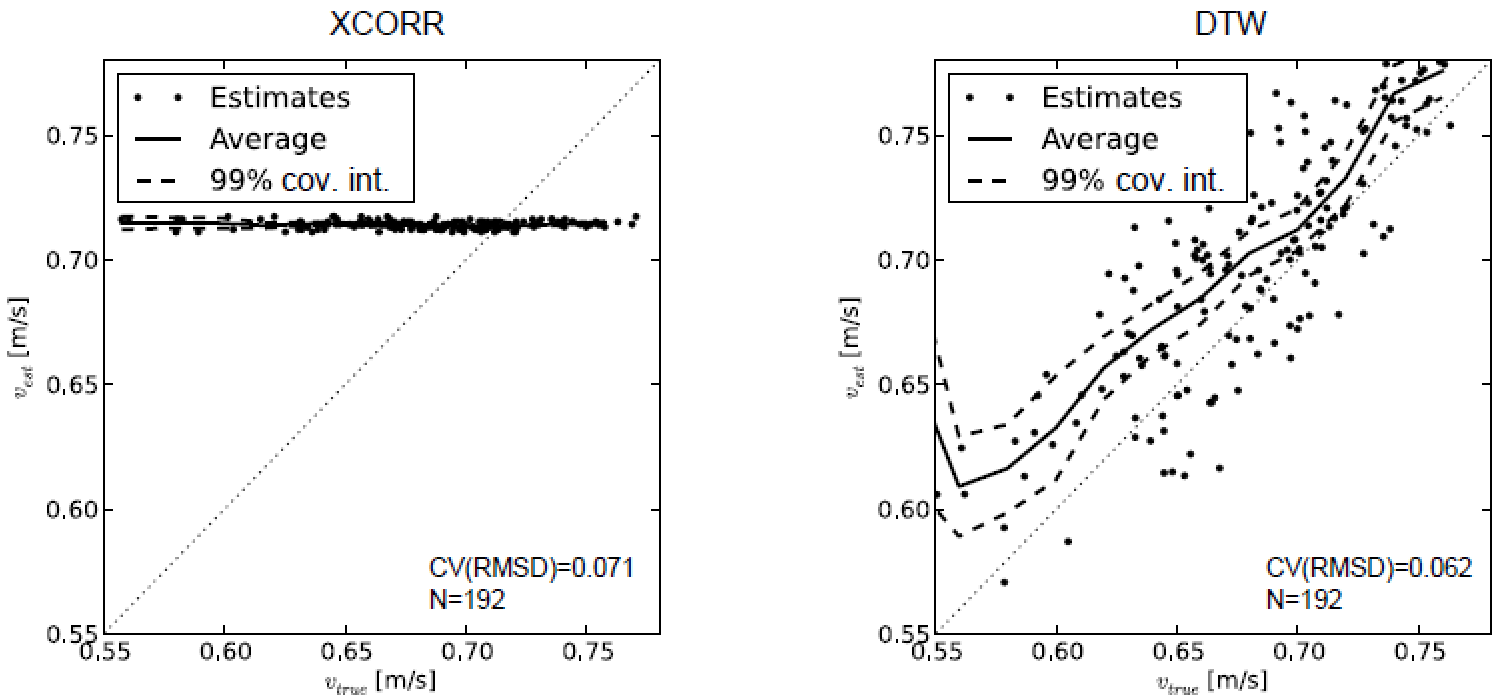


Figure B.6: Comparison of the estimated velocity v_{est} with the true velocity v_{true} for the XCORR (left) and DTW method (right). Accepted data points are indicated, as well as the weighted average with the 99% coverage intervals. For this figure, a total of N values within the 10% percentile of the standard deviation of the paths were accepted.

Conclusions

Conclusions

- Dynamic time warping (DTW) can retrieve sewer flow velocities from online measurements of wastewater quality.

- DTW extracts travel times from the temporal shift between upstream and downstream patterns by computing a non-linear warping path which maximizes the similarity between both patterns.

- The method is very well suited for the conditions found in typical sewer systems. Errors are estimated to less than 7.5%.

- The simple set-up and low experimental costs for sensors make it a practicable approach to diagnose sewer flow monitoring devices.