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Untangling fiber optic Distributed Temperature Sensing

Getting the right temperature, and getting there smoothly

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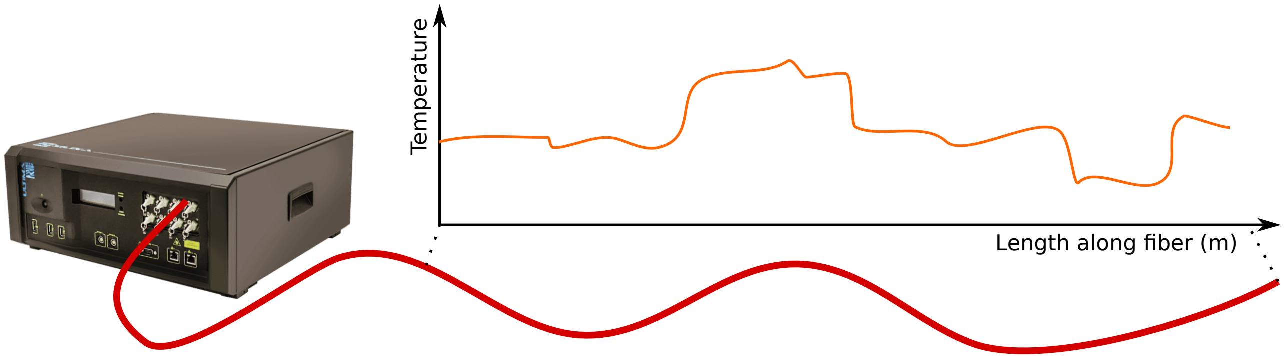
What is Distributed Temperature Sensing?

Distributed Temperature Sensing using fiber optic cables is a promising technique, capable of filling in critical gaps between point observations and remote sensing[1].

By firing a laser into a fiber optic cable, and analyzing the backscattered light, you can measure the temperature along the entire cable.



While DTS only directly measures the fiber temperature, it has been used to make spatially distributed observations of air temperature, wet bulb temperature[2], wind speed[3], and more. Of particular interest for the flux community, the spatially distributed nature of DTS allows us to place point observations within a spatial context, highlighting missing physics and linking processes across scales[4].

Problems with DTS

While DTS is a powerful technique, allowing distributed measurements at large scales or densities, there are some drawbacks:

- **Every setup is unique**, and deployment requires a large investment of time. Fiber types will differ, layouts vary per setup, and the calibration setup can vary as well.
- **A robust calibration** along the entire fiber **is required**, to turn the raw data into meaningful temperatures.
- In long term installations data can exceed terabytes
- With **complex setups** the temperature along the length of the fiber will have to be translated into a **2D or 3D physical coordinate system**.

A DTS setup measuring air temperature, wind speed and wind direction in 3D.

It contains 200m of fiber inside an 8mx8mx3m volume.

Photo: Karl Lapo

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Tools

To make using DTS easier, we have developed **two tools to manage DTS setups**. Both are written in **Python**, and make extensive use of the scientific data packages already available.

By using xarray, working with large multidimensional datasets is a breeze. Arrays are labeled and linked to coordinates, allowing efficient analysis. The datasets are also easily saved to and loaded from netCDF files.

xarray

The package ‘**dtscalibration**’ focuses on **calibration of raw data**, with the most advanced calibration routines to date.

‘**pyfocs**’ is designed to **streamline large setups**; archiving and analyzing continuously incoming data.

dtscalibration

dtscalibration is a **python tool for calibration** distributed temperature sensing data. It is able to load raw DTS data from most manufacturers, and supports many calibration features.

It can calibrate in the standard **single- and double-ended setups**, and uses **time integration** of calibration parameters. This allows for a better estimation of parameters, and can reduce the number of required reference sections.

The most novel feature of the package is that it reports the **confidence intervals** of the calibrated temperature. This allows users to know the uncertainty of the temperature data, to use this in their analysis, and propagate it to their final results.

dtscalibration is available on github.com/dtscalibration/python-dts-calibration, along with **example notebooks** to teach users how to use it. A very basic 5 line example is shown below:

```
from dtscalibration import read_silixa_files
ds = read_silixa_files('/home/dts_files/*.xml')
ds.sections = {'Cold': [slice(10., 20.)],
               'Warm': [slice(25., 35.)]}
ds.calibration_single_ended()
```

- Import the package

- Load the files

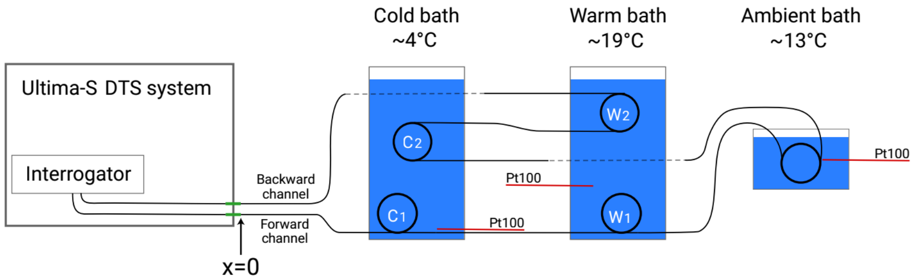
- Define calibration baths

- Calibrate!

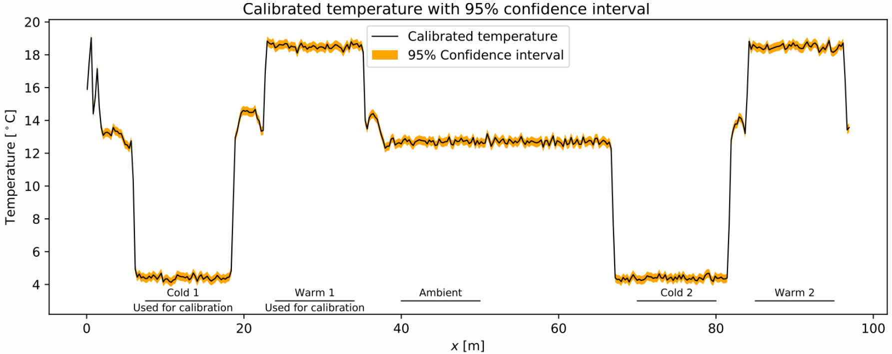
dtscalibration: confidence intervals

In *dtscalibration* the standard uncertainty is calculated along the entire cable. It is based on the **uncertainty of the raw signal** (Stokes and anti-Stokes), and the calibration **parameter estimation**. With this information we can determine the uncertainty along the cable, and through time.

This allows the user to calculate the confidence intervals of the temperature.



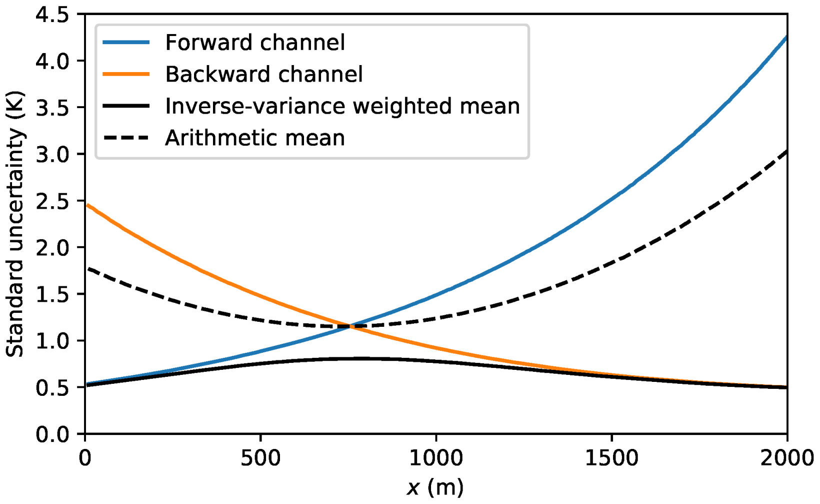
Example calibration setup, with multiple temperature baths and validation sections



The 95% confidence intervals for the example setup.

dtscalibration: weighted least squares

One of the other features is a **weighted least-squares calibration**, this will improve the temperature estimate as, e.g., calibration sections with a weaker signal are given a lower weight. Weighted calibration also allows computation of a weighted temperature in a double-ended setup, which provides the lowest uncertainty along the entire cable.



Comparison of uncertainty in a double-ended setup

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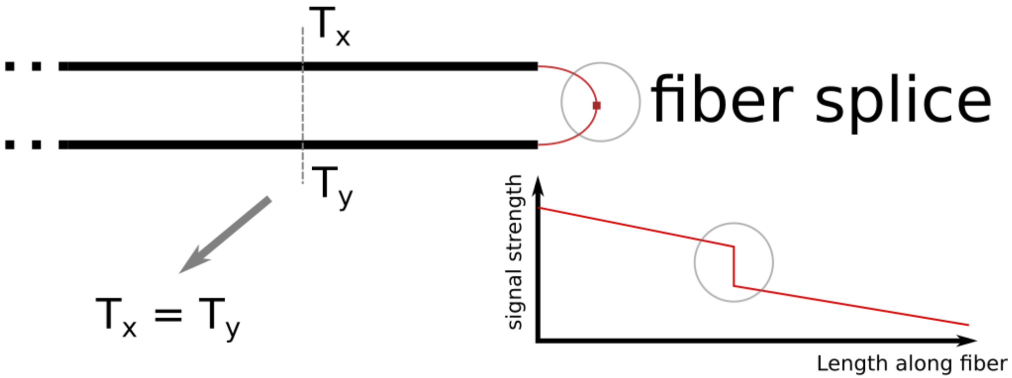
dtscalibration: advanced routines

When a calibration bath fails, measurements can be recovered by **fixing calibration parameters** to a previously determined value. The temperature scale parameter *y* is perfect for this as it generally does not change for a specific fiber.

Lastly, as splices cause a drop in signal strength they generally should be avoided between calibration bath. Sometimes they are necessary though, and splices within a setup are not an issue if enough information is available to correct for this. With *dtscalibration*, locations with **(asymmetric) step losses** can be added to the fiber, and corrected for. **Matching temperature sections** can be employed to do this.



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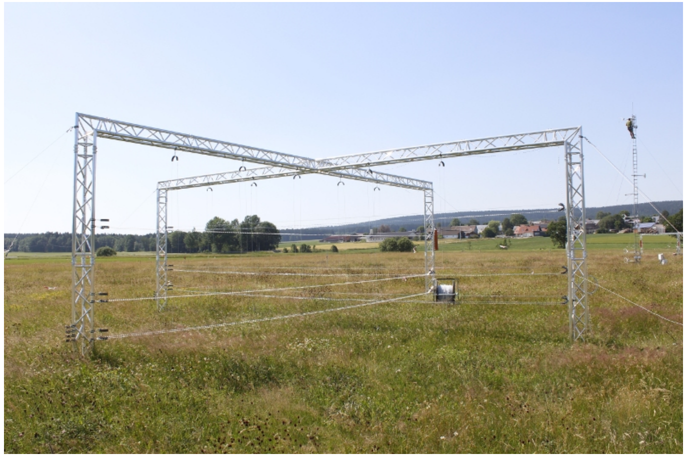
pyfocs

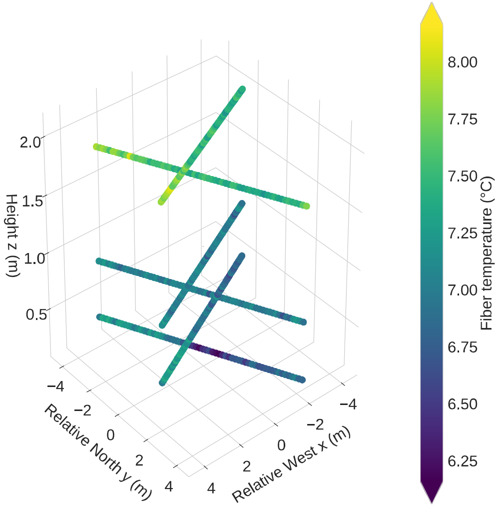
pyfocs is a tool for managing **larger, long term installations**. After defining the configuration files, it can **automate**:

- checking data integrity
- calibration
- physically mapping the data
- calculating other parameters from the calibrated temperature (e.g. wind speed)

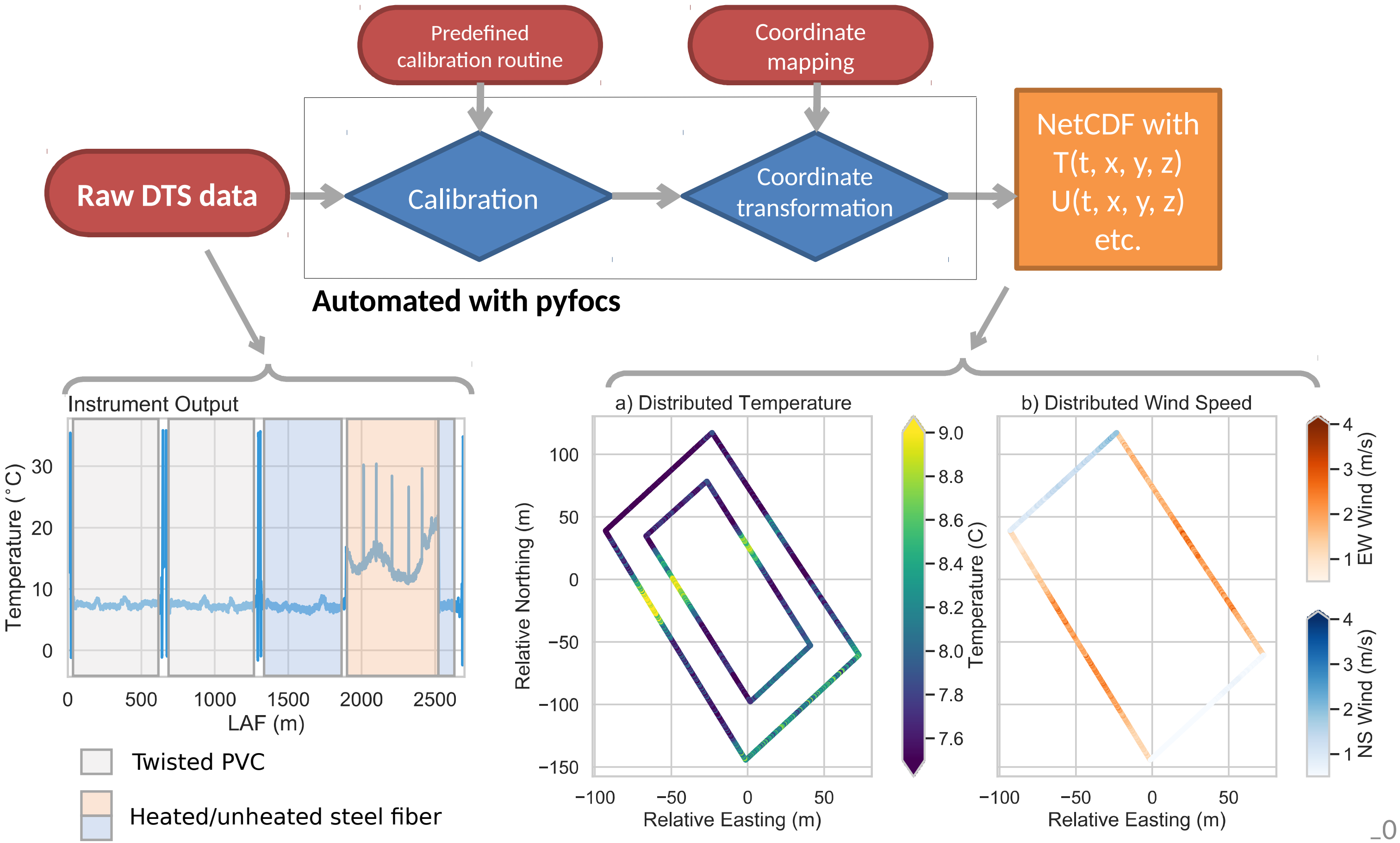
It incorporates ‘dtscalibration’ at its core, allowing it to robustly calibrate any DTS configuration.

pyfocs is available on github.com/klapo/pyfocs





pyfocs schematic overview



Conclusion

Both tools are open-source and hosted on GitHub, allowing for everyone to check the code and suggest changes. By sharing our tools, we hope to make the use of fiber optic DTS in geosciences easier and open the door of this new technology to non-specialists.

dtscalibration:

GitHub repository: github.com/dtscalibration/python-dts-calibration/
Contact: B.Schilperoort @ tudelft.nl

confidence intervals for DTS:

des Tombe, B., Schilperoort, B., and Bakker, M.: **Estimation of Temperature and Associated Uncertainty from Fiber-Optic Raman-Spectrum Distributed Temperature Sensing**, Sensors, 20, 2235, doi:10.3390/s20082235, 2020

pyfocs:

GitHub repository: github.com/klapo/pyfocs
Contact: Karl.Lapo @ uni-bayreuth.de

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