Distributed Temperature Sensing (DTS) calibration with confidence intervals

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Introduction

[Why?] The temperature can be measured with DTS on a sub-meter scale along a fiber-optic cable of several kilometers. The measurement precision varies along the fiber and over time due to: attenuation of the laser pulse, laser power, and acquisition time. The precision and confidence intervals should therefore be calculated for each measurement and communicated with the calibrated temperature .

[Physics] A laser pulse is shot from a DTS device through the fiber and is scattered back by inhomogeneities in the fiber. Most of the scattered light has the same wavelength as the emitted laser, and a small part has different wavelengths. The detectors in the DTS device measure backscatter at two distinct wavelengths: Stokes and anti-Stokes wavelengths. Their intensity is temperature dependent, so that the temperature can be estimated at the point of the reflection along the fiber.

[Parameter estimation] The Stokes and anti-Stokes measurements are related to temperature by calibrating to fiber sections with a known temperature. In practice, these fiber sections are submerged in water baths with a measured temperature. The Stokes and anti-Stokes measurements are weighted with their uncertainty, so that:

- Measurements with a stronger signal weigh in more
- Covariance matrix between the estimated parameters can be used for error propagation and estimation of the confidence intervals.

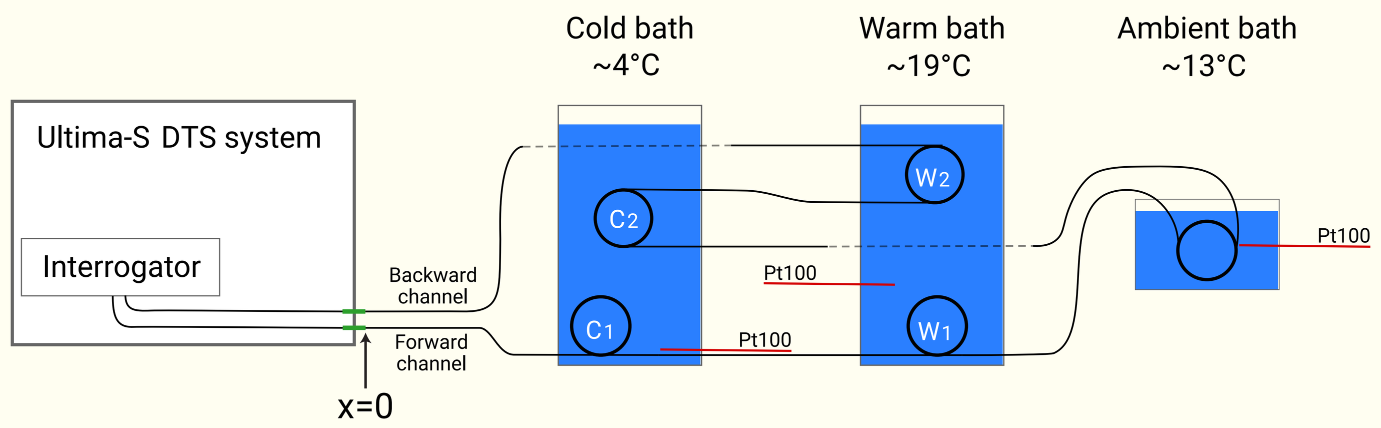
[Confidence intervals] Estimate confidence intervals from:

- Noise in the Stokes and anti-Stokes measurements. Normal distribution.
- Uncertainty in the parameter estimation. Multi-variate Normal distribution; with covariances.

These sources of uncertainty are propagated to the estimated temperature with a Monte Carlo procedure by drawing many samples from the distributions and evaluate the temperature for each sample. The 2.5 and 97.5 percentiles are used for the 95% confidence interval.

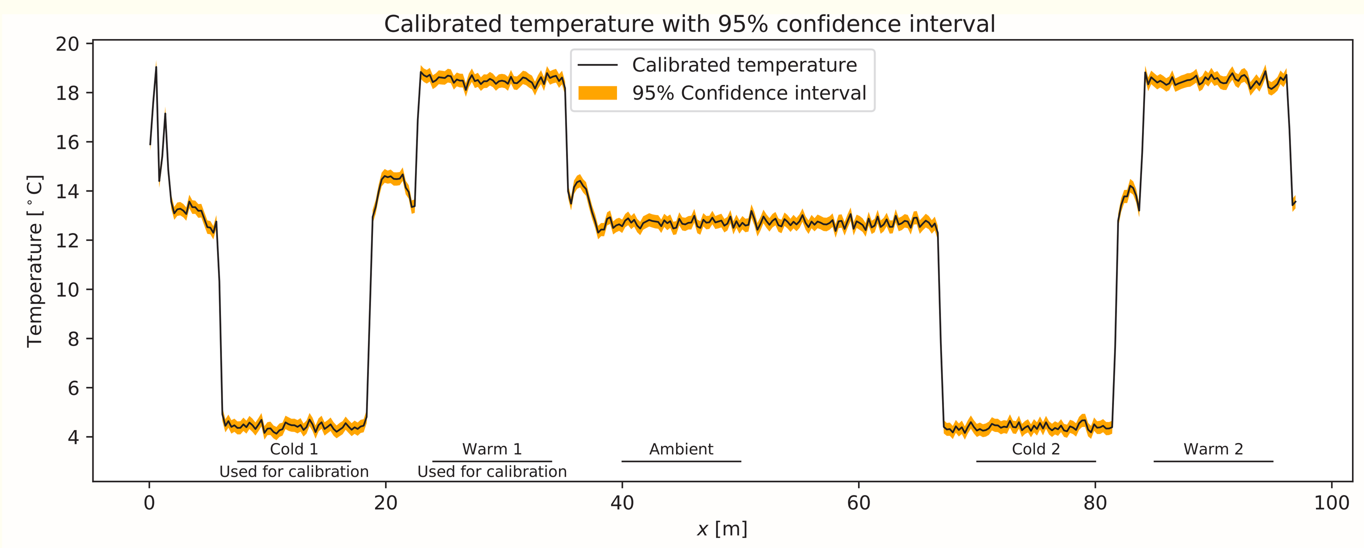
Example

[Setup] Measurements were made with reference fiber sections of three different temperatures:



The temperature of the three baths is measured with external temperature sensors. The Stokes power and anti-Stokes power were measured 1000 times in one day with an acquisition time of 2 seconds. Measurements were made in the forward and backward direction to perform a double-ended calibration.

[Result]



How to calibrate in style

[Setup] Install `dtscalibration` via the command line (https://github.com/dtscalibration)

```
! pip install dtscalibration
```

Import the package in your Python script

```
import dtscalibration
```

[Load data] Files may be loaded with:

- `read_silixa_files()`, read Silixa measurement files.
- `read_sensornet_files()`, read Sensornet measurement files.
- `open_datastore()`, load from a netCDF file or OPeNDAP url.

```
opendap_url='https://opendap.tudelft.nl/thredds/dodsC/data2/uuid/71b5c3c2-4105-4f4f-bd1e-d7c56732a665/calibrated1000x2sec.nc'
ds = dtscalibration.open_datastore(opendap_url)
```

The DataStore contains the Stokes and anti-Stokes measurements of the forward and backward channel. In addition, it contains temperature measurements of the cold, warm, and ambient water baths.

Neighboring measurement locations are correlated because the laser pulse has a finite width. The correlation is removed by omitting measurement locations so that the distance inbetween is larger than the spatial resolution of the DTS-device.

```
ds = ds.isel(x=slice(None, None, 2))
ds.sections = {'Cold': [slice(7.5, 17.)],
               'Warm': [slice(24., 34.)]}
```

[Calibration] The variance in the Stokes and anti-Stokes measurements are required for weighted least squares calibration and to calculate the confidence intervals. They are estimated by fitting an equation through the measurements, that assumes the temperature is constant along a reference section but may vary over time.

```
st_var, resid = ds.variance_stokes(st_label='ST')
ast_var, _    = ds.variance_stokes(st_label='AST')
rst_var, _    = ds.variance_stokes(st_label='REV-ST')
rast_var, _   = ds.variance_stokes(st_label='REV-AST')
```

The temperature along the forward channel, the backward channel, and the weighted average of the forward and backward channel (`ds.TMPW`), are calculated with double-ended calibration. Calibration is performed to the sections that were defined earlier.

```
ds.calibration_double_ended(
    st_var=st_var,
    ast_var=ast_var,
    rst_var=rst_var,
    rast_var=rast_var,
    store_tmpw='TMPW',
    method='wls',
    solver='sparse')
```

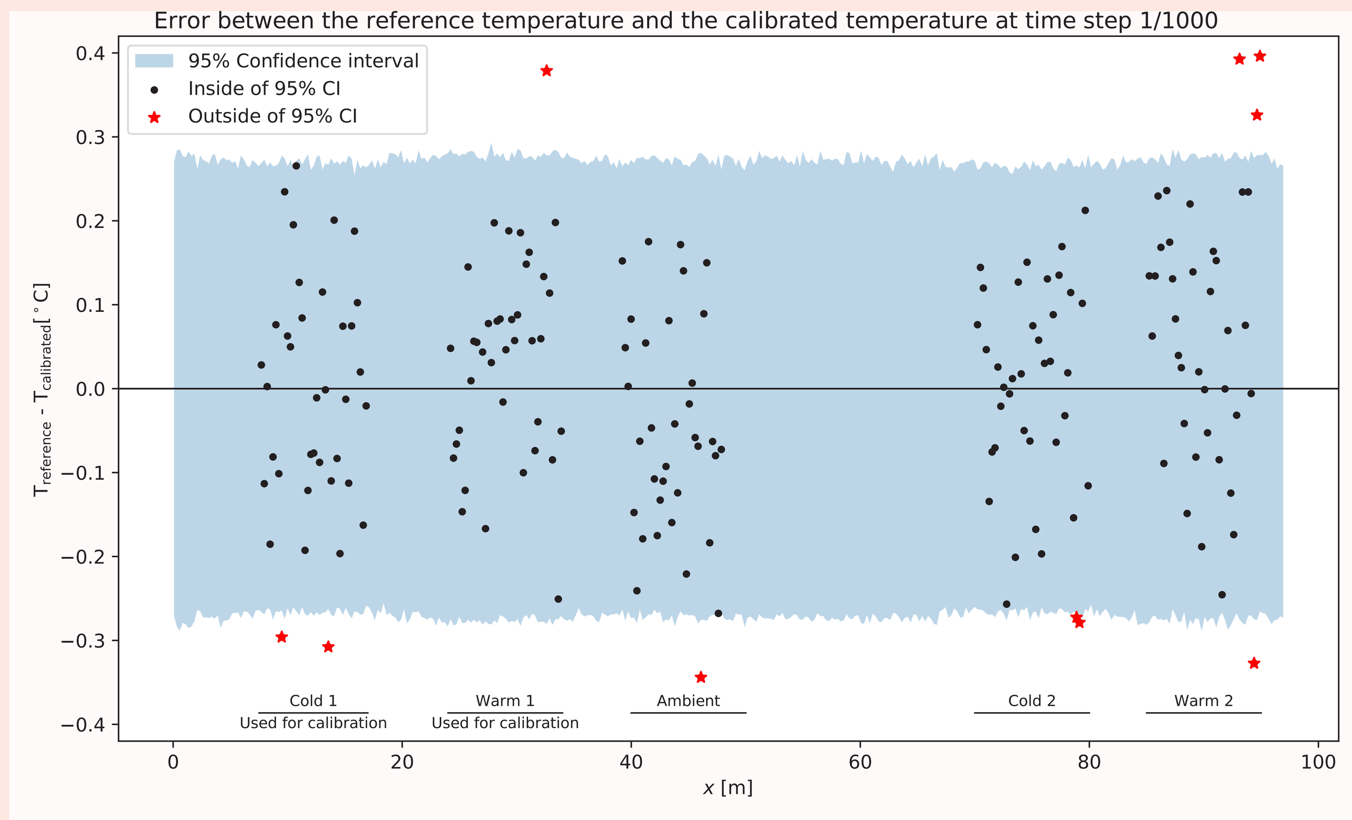
[Confidence intervals] We have calculated everything needed to estimate the confidence intervals. The 2.5 and 97.5 percentiles are used for the 95% confidence interval and is estimated with:

```
ds.conf_int_double_ended(
    st_var=st_var,
    ast_var=ast_var,
    rst_var=rst_var,
    rast_var=rast_var,
    conf_ints=[2.5, 97.5],
    mc_sample_size=5000)
```

The 95% confidence interval is different for each point along the fiber and varies over time. The calculation is performed in parallel and in chunks so that gigabytes of data can be processed on a personal computer.

Results and Conclusion

[Single time step] The real temperature is known along the reference sections, measured with external sensors, so that we can verify the confidence intervals. The error between the reference and the calibrated temperature for a single time step is plotted below. We expect 5% of the measurements to fall outside of the 95% confidence interval (red star):



The 95% confidence interval becomes narrower if the acquisition time is increased.

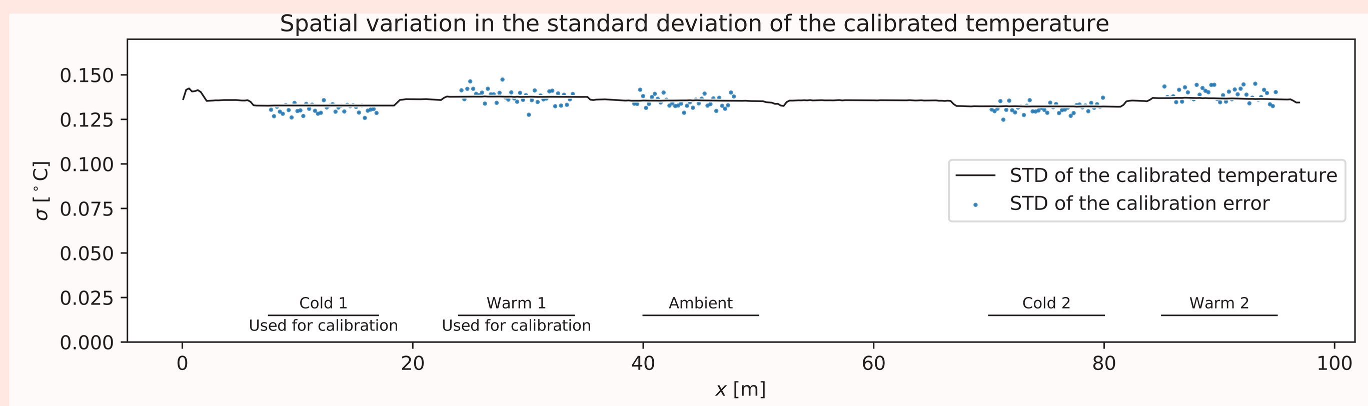
[Multple time steps]

Fraction of the reference temperature within the 95% confidence interval of the calibrated temperature for 1000 time steps

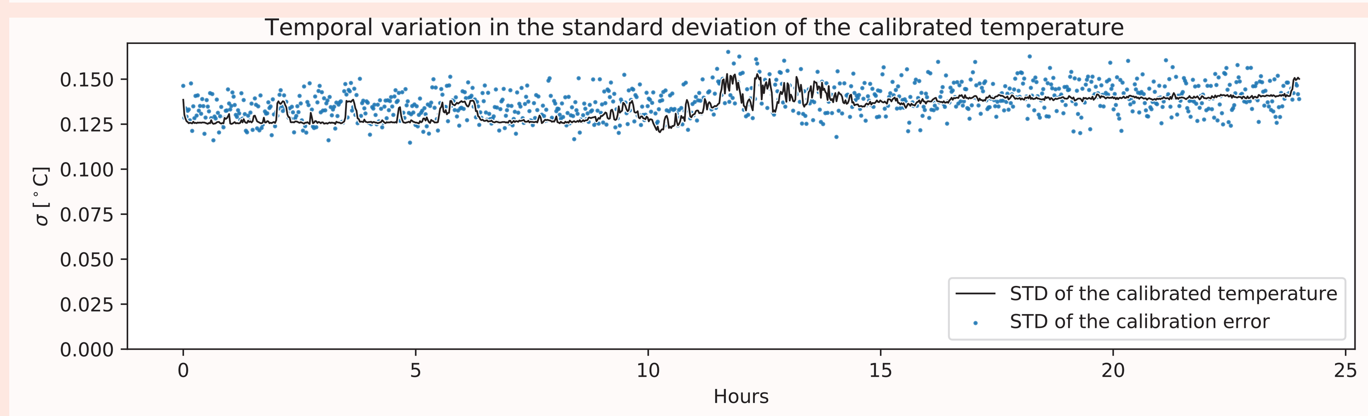
Cold 1	Warm 1	Ambient	Cold 2	Warm 2	Total
95.4%	94.5%	93.6%	94.9%	93.6%	94.4%

The uncertainty in the calibrated temperature (prediction) can also be expressed with the estimated standard deviation (STD), which is calculated directly from the Monte Carlo set. Similar values are expected for the standard deviation of the error and the standard deviation of the calibrated temperature.

[Spatial variation]



[Temporal variation]



The temporal variation is a result of the fluctuating laser strength. An increase in the number of measurements and the Monte Carlo sample size result in a smaller spread of the standard deviation of the error (not shown here).

[Conclusion] Concluding remarks:

- The suggested approach provides a good estimate for the confidence intervals of the calibrated temperature
- In a succesful calibration the uncertainty introduced by the parameter estimation is small compared to the unceratinty introduced by the (anti-) Stokes detectors.

The Python package `dtscalibration` together with documentation and many example is available at https://github.com/dtscalibration .

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