Stokes intensity–variance relationship and how to determine it

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May 24, 2021

At its core, the temperatures as measured by Distributed Temperature Sensing (DTS) are determined by studying the ratio between the Stokes and anti-Stokes backscatter. This makes the uncertainty in these Stokes and anti-Stokes measurements one of the most important parts of determining the uncertainty of the calibrated DTS temperature. This is especially true when dealing with shorter integration times where nearly all uncertainty will originate from the (anti-)Stokes signals.

The uncertainty in the Stokes signals results from noise in the optical detectors, such as electrical noise and shot noise. As the entire fiber is sampled nearly instantaneously, there is barely any time difference between each measurement along the length of the fiber, and as such detector properties do not change appreciatively over the length of the fiber. However, the signal weakens along the length of the fiber due to attenuation. As the signal strength is not constant, the total noise level varies along the fiber. Some components of the noise are independent of the signal strength, such as Johnson–Nyquist (thermal) noise. Other parts can be signal strength dependent, such as shot noise, where the (absolute) amount of noise will increase with increasing signal strength, even as the signal-to-noise ratio is lower with stronger signals. This forces us to characterize the noise of our Stokes signals as a function of signal strength;

$$s_{St}^2 = f(P_{St}) \tag{1}$$

Where s_{St}^2 is the sample variance (arbitrary units^2), and P_{St} the Stokes signal intensity (arbitrary units).

1 Characterizing the variance function

To characterize the Stokes intensity–variance relationship, actual measurements of the (to be) used DTS interrogator are required. The analysis is performed on the raw Stokes data provided by the devices. For each time step, one or more sections at a constant temperature are required, as any deviations in the temperature cause deviations in the Stokes intensity, and thus would increase the apparent variance. Any small (linear) trends can be removed. For every section at each time step, the sample mean and sample variance can be computed. The more sections there are, with large Stokes intensity differences, the better it is for characterizing the intensity–variance relationship. All the sets of means and variances can be shown on a scatter plot;

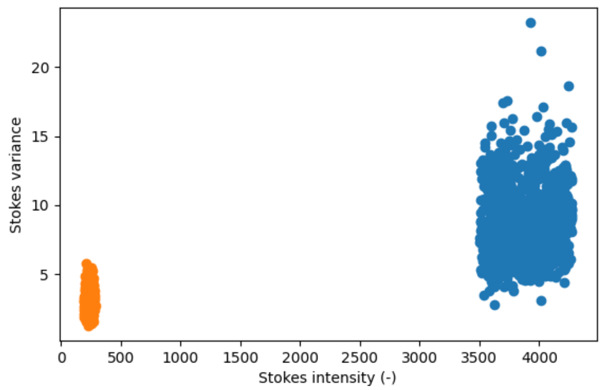

Figure 1: Scatterplot of the Stokes mean intensity and variance. In blue the reference section at the start of the cable, and in orange the reference section at the end of the cable (˜4500 m length). Integration time was 2.0 sections.

As this is based on samples, we can bin the samples to reduce the uncertainty;

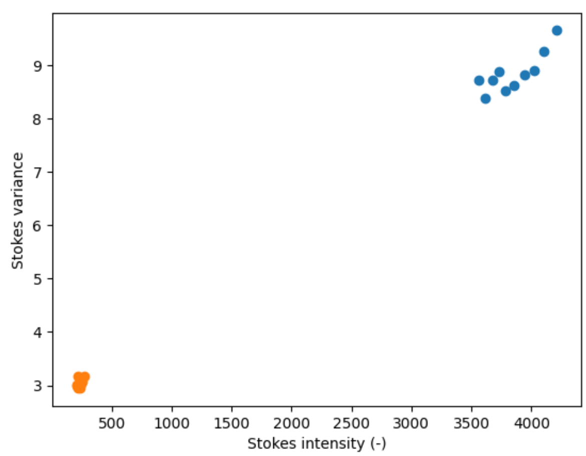

Figure 2: Same plot as Figure 1, but with binned data.

As you can see from Figure 2, the relationship seems to be linear. From multiple measurements done with Silixa Ultima-S and Ultima-M devices, we found that the relationship between the intensity and variance is linear, at least with the devices and intensity ranges studied. This gives us a linear relationship between the detected Stokes intensity and the variance;

$$s_{St}^2 \approx a \cdot P_{St} + b \tag{2}$$

where a and b can be determined during the calibration routines using a least squares optimization.

To generate the Stokes intensity–variance plots, and to immediately perform a linear regression using the binned data, *dtscalibration* has the following function built in;

```
ds.variance_stokes_linear(
   st_label='st', # In double ended mode either 'st' or 'rst'
                  #  are both fine to use
   sections=sections, # sections used for determining i.--var. relationship
   plot_through_zero=False,
   plot_fit=True
   )
```

2 Practical tips

For accurate estimates internal reference coils are very appropriate, as they are homogeneous in temperature, and only vary relatively slowly in temperature over time. Especially in double ended measurements the internal reference coils are good to look at, as they are both at the start (highest Stokes intensities) and end (lowest Stokes intensities) of the measurement.

Alternatively, having very long reference sections (many data points) will also aid in accurately characterizing the variance function, as each time step would provide a more accurate estimate of the variance, rather than having to aggregate many time steps together for sufficient information.

As the forward and backward channels use the same set of detectors for the Stokes signals, the variance–intensity relationship only has to be determined for the Stokes and anti-Stokes signals.

In measurements without much variation in intensity (e.g. just 100 – 200 meters of fiber), it is possible approximate the Stokes variances to be constant.

In case of medium length cables (1000 – 2000 meters) without a low-intensity reference section, some devices have a noise floor low enough that it is possible to fit the linear relationship through 0; requiring less information to calculate the variance function.