CASE STUDY: SOP AND PMD MEASUREMENTS ON AERIAL FIBER UNDER TYPICAL WIND GUST CONDITIONS

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This document reports and analyzes states of polarization (SOP) and polarization mode dispersion (PMD) measurements on aerial fiber under moderate to severe wind conditions. The measurement and analysis methods are based on works published by David S. Waddy, Liang Chen and Xiaoyi Bao[1].

Tests were carried out on an installed communication cable, located in the Montmagny area in Quebec, Canada (special thanks to Larry Bernier of Telus for his keen collaboration in allowing us to access the site).

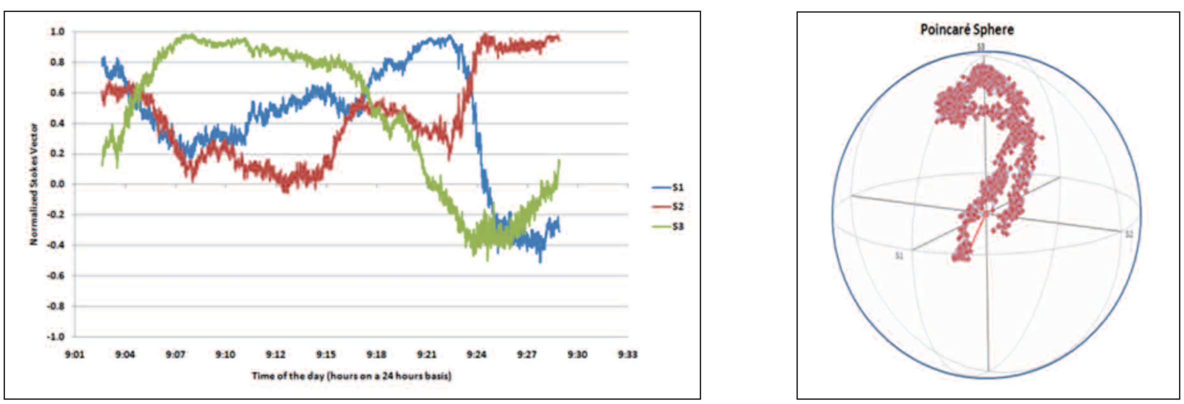
The tests were conducted using EXFO's FTB-5700 Single-Ended Dispersion Analyzer; the robustness of the unit was evaluated in terms of its capability to measure PMD on aerial cables under windy conditions.

Measurement of SOP Dynamics—Behavior under Windy Conditions

SOP Dynamics—Relatively Constant Wind Conditions

The first part of the test was performed under relatively constant wind conditions (without significant wind gusts) on the first fiber loop, which is the loop perpendicular to the St. Lawrence River (see Geographical Location, Figure 15). The Stokes parameters show some noise and slow variations.

The state of polarization (SOP) behavior of that first measurement displays a slow shift in the three components of the Stokes vector with relatively little noise. The projection of the SOP vectors taken every second on the Poincaré sphere shows a relatively smooth random walk-like pattern, as shown in Figure 1.



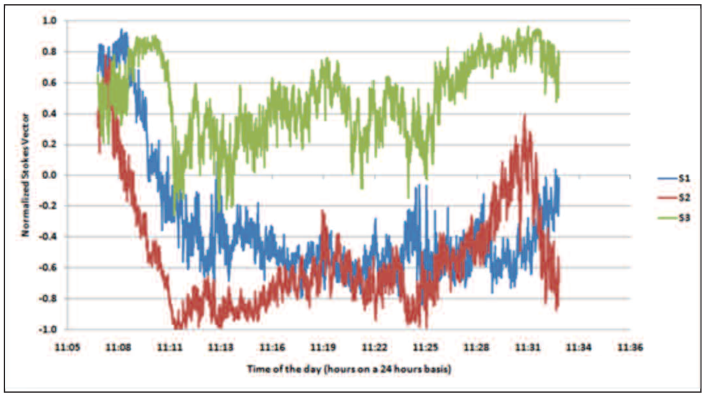
a) Measured Stokes unit vectors components ***b) Stokes vector projection***

Figure 1. State of polarization of aerial fiber under mild to moderate wind conditions (without wind gusts)

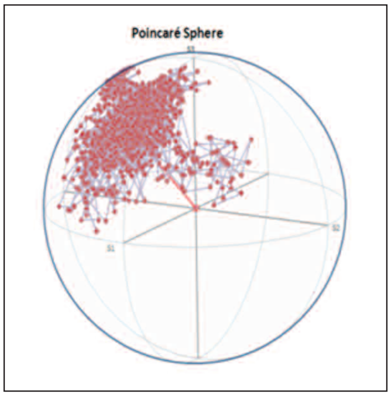
On average, the Stokes vector rotation rate is of 40 degrees per second; a peak of 516 degrees per second is also observed.

Later that day, the instantaneous noise on the Stokes unit vector components increased by a significant amount but the large variation was still relatively slow and not very frequent, as shown in Figure 2. The projection of the Stokes vector on the Poincaré sphere illustrates a tightly packed concentration area.

[1] *Waddy, David S., Liang Chen and Xiaoyi Bao, On the Dynamics of Polarization Mode Dispersion, Fiber Optics Group, Department of Physics, University of Ottawa, Canada, 2002.*



a) Measured Stokes unit vectors components



b) Stokes vector projection

Figure 2. State of polarization of aerial fiber under moderate wind conditions (with some wind gusts)

The large noise-like behavior of the Stokes vector components shown in Figure 2 indicates a significant increase in the stress induced by the wind on the aerial optical cable. This noise-like structure comes from very small but numerous changes in mode coupling.

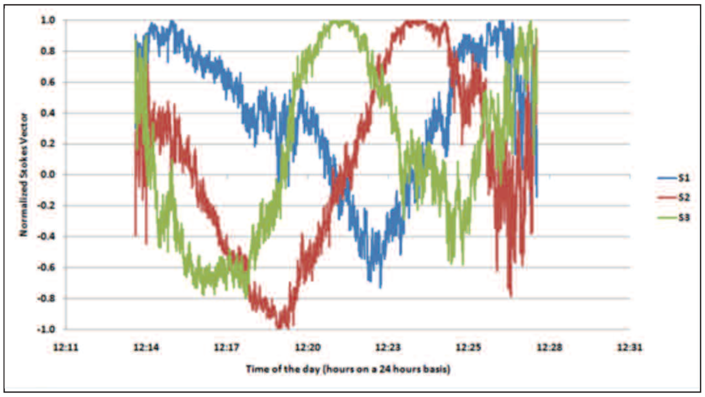
SOP Dynamics—Wind Gust Conditions

Wind Gust

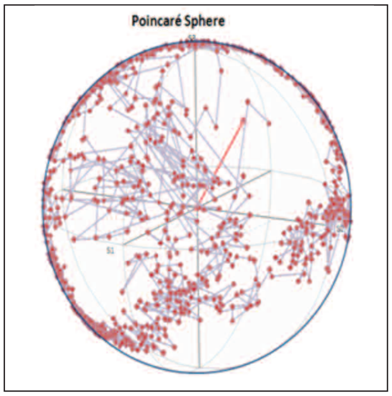
A wind gust is defined as a sudden, brief increase in the speed of the wind. According to U.S. weather observing practice, gusts are reported when the peak wind speed reaches at least 16 knots (30 km/h or 18 mph) and the variation in wind speed between the peaks and lulls is at least 9 knots (17 km/h or 10 mph). The duration of a gust is usually less than 20 seconds.

(Source: http://www.srh.noaa.gov/graphical/definitions/defineWindGust.html)

Wind gusts have much more impact on the dynamic behavior of the Stokes vector, as shown in Figure 3. Constant wind tends to induce rapid, white noise-like rotation of the Stokes vector, while wind gusts generate slow rotations of large amplitude of the Stokes vector.



a) Measured Stokes unit vectors components



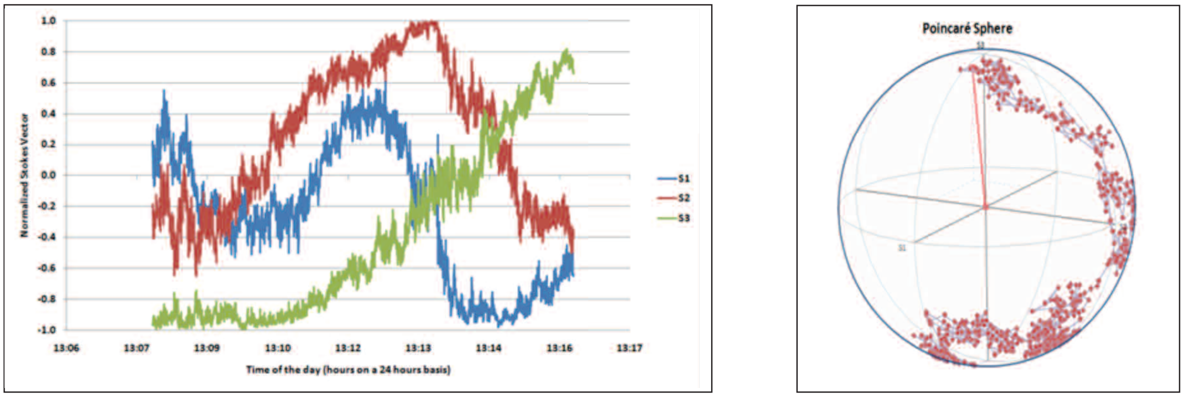
b) Stokes vector projection

Figure 3. State of polarization of aerial fiber under strong wind conditions (strong wind gusts)

This measurement was acquired on the same 70 km loop as the previous one. Wind was then characterized by strong wind gusts that trigger very large amplitude Stokes vector component oscillations within a 10- to 15-minute period.

At that point, a large amount of wind power was transferred to the entire structure of the link composed of poles and cables. All possible modes of oscillations were excited and several stress factors were induced on the fiber loop.

The next measurements were acquired on the 90 km extended loop. (For details, refer to Appendix A. Description of the Aerial Cable)



a) Measured Stokes unit vectors components　　*b) Stokes vector projection*

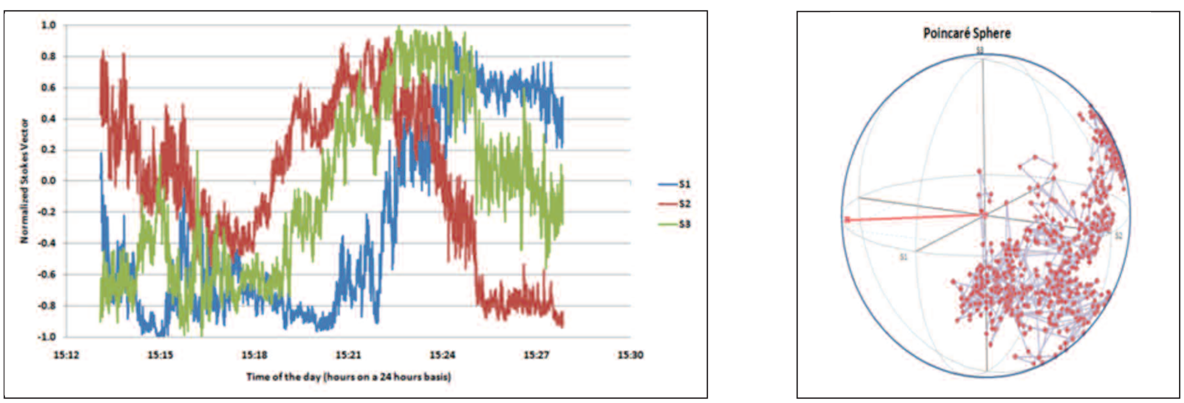
Figure 4. State of polarization of aerial fiber under strong wind conditions (strong wind gusts)

The added cable length being perpendicular to the first fiber span, the interaction with the wind covered all possible axes of interferences. The distribution of the Stokes vectors on the Poincaré sphere was somewhat less disperse but traveled from one pole to the other, indicating a strong effect on the phase between the two polarizations.

The maximum Stokes vector instantaneous rotation rate was significantly reduced compared to the previous measurement but was still close to 1000 degrees per second.

Around 3 p.m., the wind was still strong and there were noticeable wind gusts. The line structure, poles and cable were loaded with energy and all possible modes of oscillation were excited to their maximum.

As a result, there was a maximum scrambling of the polarization modes with high-amplitude, high-frequency Stokes vectors rotation due to interferences of an extremely large number of mechanical oscillations along the cable as well as a strong low frequency due to resonance at the pole structure level and cable oscillation like residual fiber galloping.



a) Measured Stokes unit vectors components　　*b) Stokes vector projection*

Figure 5. State of polarization of aerial fiber under strong wind conditions (moderate wind gusts)

The maximum rate of the instantaneous rotation was still impressively high, peaking at 1346 degrees per seconds.

Stokes Vector Instantaneous Rate of Rotation

The rotation rate of the Stokes vector components has often been mentioned as the parameter preventing PMD measurement; Figure 6 represents a histogram of each of the five measurements taken from the aerial fiber.

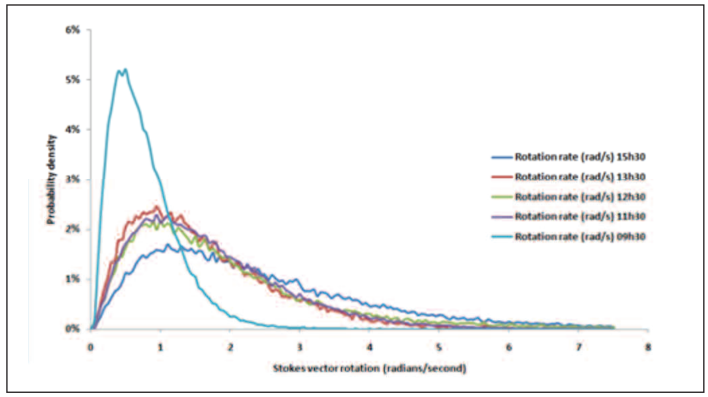


Figure 6. Instantaneous Stokes vector rotation rate

Observation Summary

The transfer of mechanical energy from the wind to the pole and cable structure of an aerial cable increased gradually from calm to strong wind conditions. All resonant modes—from low-frequency ones (due to a large flexible structure) to high-frequency ones (caused by a rigid and light structure)—were excited, which led to noise in the form of Stokes vector rotations to large amplitude and low frequency.

Acting as mechanical impulses on a low-damping mass-spring resonant system, wind gusts are the most effective means of energy transfer from the wind to the pole and cable structure of the aerial cable.

Attempts to predict the impact of the wind on the Stokes vector instabilities when dealing with an aerial cable must include a good evaluation of the mechanical resonant characteristics of the installation. Resonance frequencies, as well as the coupling efficiency between the wind and the pole and cable structure, can greatly influence the result.

Measurements performed during the first half of the day, after a relatively calm night, resulted in mild perturbations on the Stokes vector. If wind conditions were to persist, more and more energy would be transferred to the cable and pole structure, increasing the instability of the Stokes vector. This instability always appears under two frequency ranges: high frequency of relatively low amplitude (resembling white noise) and low frequency with fairly large amplitudes.

FTB-5700 Single-Ended Dispersion Analyzer—Performance under Windy Conditions

Basic Measurement Principles

The basic measurement principles are explained in detail in several reference works. [2]

Pre-Scan or Scale Selection

During the pre-scan, the FTB-5700's scale-selection method scans through different wavelength spacing for the pair of wavelengths. Based on specific proprietary criteria, it selects the best optical frequency spacing for measuring the PMD.

Once the optimal optical frequency spacing is found, the FTB-5700 measures the PMD.

The scale-selection method is extremely robust and will find the proper scale under the most severe wind conditions. If the Stokes vector's wind perturbations are too large, the FTB-5700 will display that information instead of providing an erroneous PMD value.

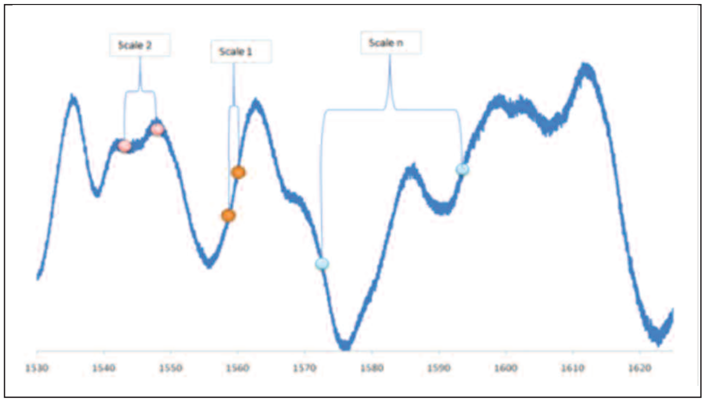


Figure 7. Signal intensity projection of the Stokes vector on the FTB-5700 principal axis

PMD Measurement and Wind-Induced Rotation of the Stokes Vector

The method calculates the slope defined by a pair of wavelengths or optical frequency. When the fiber-optic cable (buried or aerial) is stable, the Stokes vector corresponding to each wavelength of the pair is projected with a fixed value on the principal axis of polarization of the FTB-5700 polarizer.

The timing between the pair of wavelengths depends on the initial PMD estimation made at the pre-scan phase.

Figure 8 shows the first wavelength of the measurement pair, represented by a brown circle before the 1560 nm mark, and the second wavelength, represented by an ellipse to show the rotation effect of the corresponding Stokes vector due to wind-induced rotation of the fiber's polarization state.

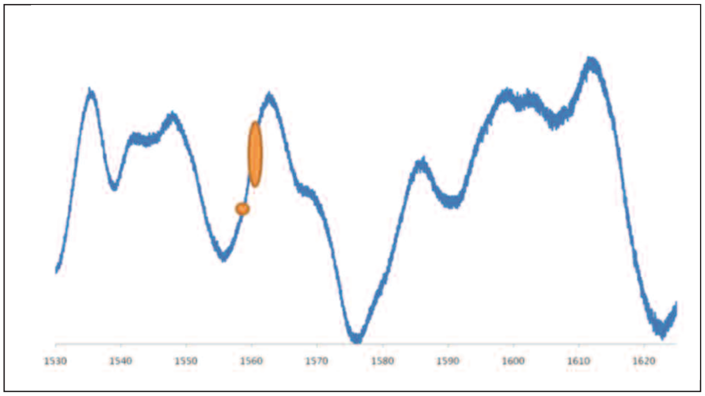


Figure 8. Uncertainty on the second wavelength due to wind-induced rotation of the Stokes vector

The FTB-5700 measurement method removes random fluctuation and only keeps the correlated values between both wavelengths. This is possible since there is a very large number of repeated measurements on both wavelengths for a given measurement point.

[2] *Chen, H., N. Cyr, B. Ruchet, M. Leclerc, and G.W. Schinn. Novel Technique for PMD Measurements of Installed Fibers Using Random Polarization Scrambling and a Tunable OTDR,* EXFO Electro-Optical Engineering Inc., Quebec, Canada.

Cyr, N., H. Chen and G.W. Schinn. Random-Scrambling Tunable POTDR for Cumulative-PMD Measurement of Installed Fibers, EXFO Electro-Optical Engineering Inc., Quebec, Canada.

Chen, Hongxin. Theory of Input and Output Randomly Sate of Polarizations Scrambling Analysis Method for Polarization Mode Dispersion Measurement Apply to the end-to-end and single-end measurement configurations, EXFO Electro-Optical Engineering Inc., Quebec, Canada, 2008.

Correlation between Wind and FTB-5700 Measurement

Stokes Vector Rotation for 200 ms Measurement Time

The FTB-5700's time gap between the two wavelengths needed to perform a calculation varies between 100 ms and 300 ms.

Figure 9 shows the statistics for 200 ms under mild wind conditions, without significant wind gusts. These measurements were taken on June 25, 2008, around 9 a.m., near Montmagny, on the 70 km aerial fiber loop.

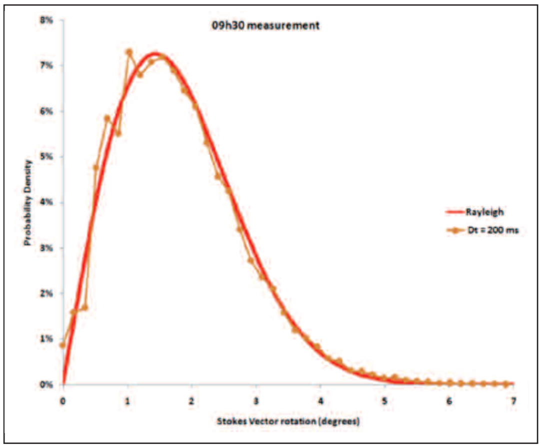


Figure 9. Stokes rotation statistics for measurement 200 ms apart

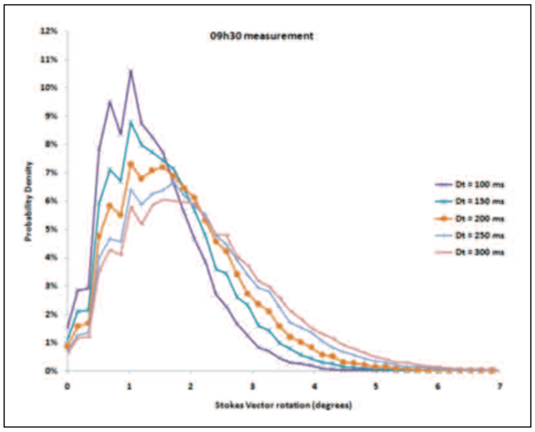


Figure 10. Stokes rotation statistics for measurement 200 ms apart

A Rayleigh distribution[3]–the red trace–fits the probability density of the normalized histogram obtained from the experimental data.

The Rayleigh distribution applies to any measurement time difference, as shown in Figure 10, where the profile is given for Δt of 100 ms, 150 ms, 200 ms, 250 ms and 300 ms.

The Rayleigh distribution is computed simply by calculating the average value of the Stokes vector's rotation angle for a given Δt. It can also be computed from the standard deviation as proposed in the publication On the Dynamics of Mode Dispersion; it is, however, less stable.

[3] *In probability theory and statistics, the Rayleigh distribution is a continuous probability distribution. It can arise when a two-dimensional vector (e.g., wind velocity) has elements that are normally distributed, are uncorrelated, and have equal variance. The vector's magnitude (e.g., wind speed) will then have a Rayleigh distribution. The distribution can also arise in the case of random complex numbers whose real and imaginary components are independent and identically distributed Gaussian. In that case, the absolute value of the complex number is Rayleigh-distributed. The distribution was so named after Lord Rayleigh. (Source: Wikipedia)*

FTB-5700 Performance under 11:30 Wind Conditions

Measurement Accuracy under Increasing Wind Gusts

The reference PMD measurement established with the FTB-5500B PMD Analyzer (using the generalized interferometric method, which is known and recognized for its robustness under wind conditions), was 3.692 ps on the 70 km aerial loop. The PMD value, as measured by the FTB-5700, is 3.72 ps and is in agreement with the reference method.

Figure 11 shows the noise associated with 800 states of polarization measurements. The two horizontal lines at about ±0.25 give the acceptance limits of a good measurement. As illustrated, the FTB-5700 was working in a very secure mode with a more than acceptable margin in terms of signal to noise.

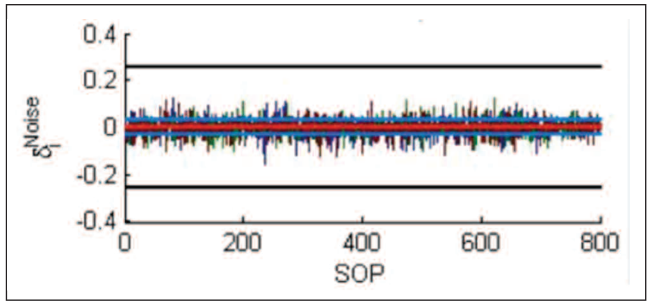


Figure 11. Measurement noise on the FTB-5700

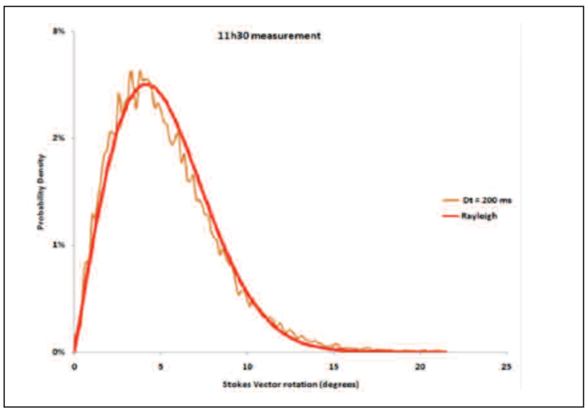


Figure 12. Stokes rotation statistics for measurement 200 ms apart

Figure 12 shows the probability density distribution for the angle of rotation of the Stokes vector.

Again, the normalized histogram fits very well with the Rayleigh probability density function.

This result indicates that the method implemented in the FTB-5700 is accurate and robust even when a significant number of events correspond to the Stokes vector rotation above 10 degrees.

Measurement Accuracy under Severe Wind Gusts

The reference PMD measurement established with the FTB-5500B was set at 4.233 ps on the 90 km aerial loop. The PMD value as measured using the FTB-5700 was 4.01 ps and shows a very good agreement with the reference method.

Figure 13 shows the noise associated with the measurement of 800 states of polarization. The two horizontal lines at about ±0.25 give the acceptance limits of a good measurement. As illustrated, the FTB-5700 was working in a relatively secure mode with an acceptable margin in terms of signal to noise.

We did not reach the limits of the FTB-5700 method; based on these results, we expect the unit to be able to work under wind conditions about twice as severe as those experienced on the afternoon of June 25, 2008, in Montmagny.

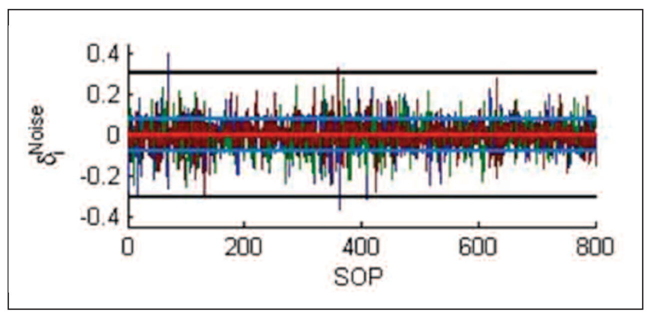


Figure 13. Measurement noise on the FTB-5700

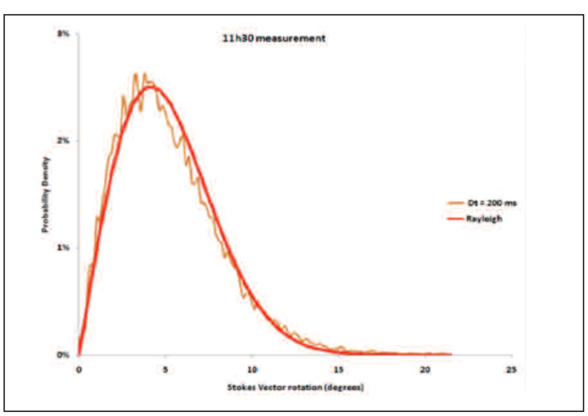


Figure 14. Stokes rotation statistics for measurement 200 ms apart

The fit of the Rayleigh distribution on the Stokes vector's rotation is not as good as before, as shown in Figure 14. This is due to the sample being too small in comparison with the amplitude of the high and low frequency fluctuation shown in Figure 5. State of polarization of aerial fiber under strong wind conditions (moderate wind gusts).

Appendix A. Description of the Aerial Cable

Geographical Location

The aerial cable measured is located near the St. Lawrence River, in the Montmagny area, near Quebec City. The fiber-optic cable shares electrical and standard communication cables, all mounted on standard wood poles.

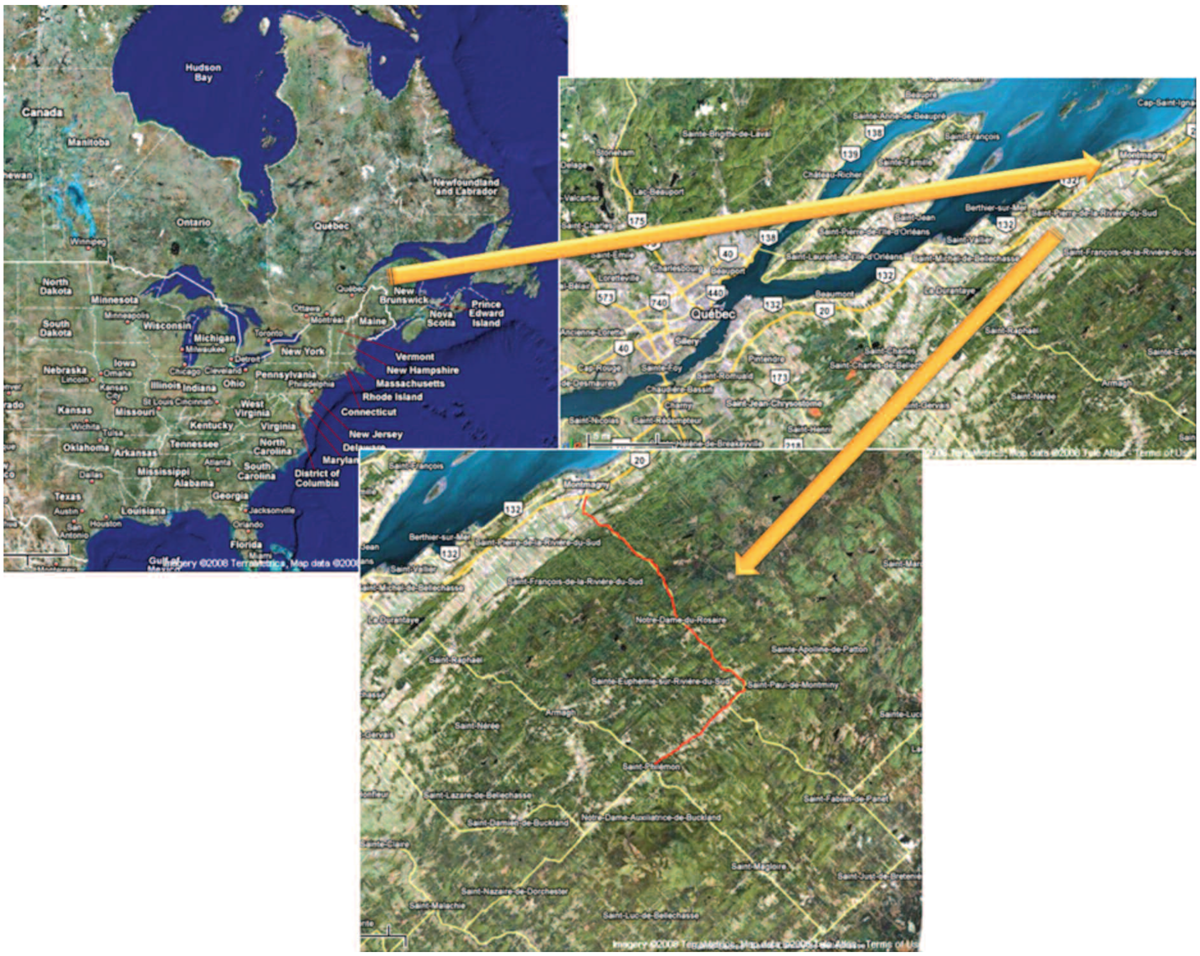


Figure 15. Location of the aerial cable

Wind Conditions

June 25, 2008, was a windy day both in Quebec City and in the Montmagny area. According to AccuWeather.com, the wind was predicted to be between 8 km/h and 16 km/h (5 and 10 mph) with wind gusts between 24 km/h and 32 km/h (15 and 20 mph) for the St. Lawrence River Estuary, near Montmagny.

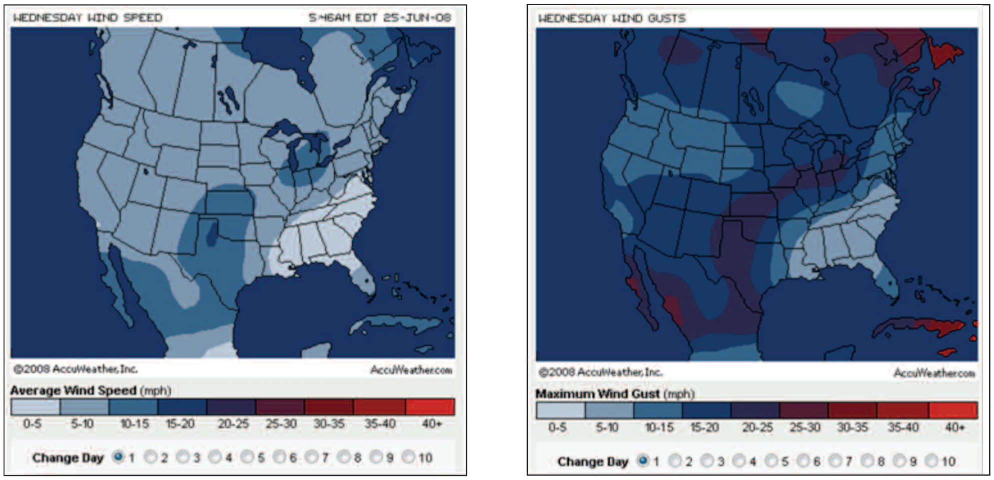


Figure 16. OTDR trace of the first round trip aerial fiber (measured with an AXS-100)

The observed wind conditions confirmed the AccuWeather.com prediction. The wind was in the lower range when the first measurement was taken, and it gradually increased to well above the predicted value; there were strong wind gusts between 11 a.m. and 2 p.m. After 2 p.m., the wind speed decreased gradually but remained relatively strong for the rest of the day.

Wind conditions for that series of tests are considered representative of the average wind statistics for North America, as reported in 0.

Wind Speed Statistics–North America (see Appendix B). We thus believe that this test covers the most probable wind conditions.

Appendix B. Wind Speed Statistics—North America

Statistics about monthly and annual average wind speed for the USA can be found at http://finder.geocommons.com/overlays/download/182.csv. A good fit to data is obtained using the Weibull probability distribution with a scale factor of 15.4 km/h and a form factor of 4.6.

The average wind speed for the 275 cities included in these statistics is 14.8 km/h with a standard deviation of 4.3 km/h.

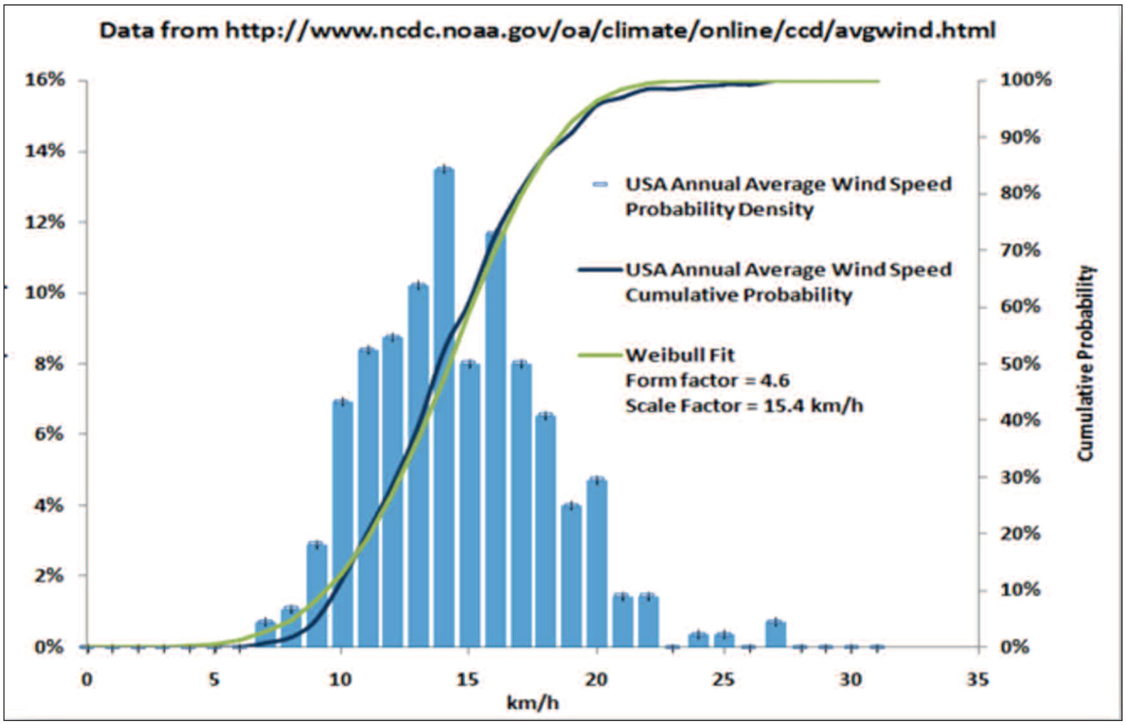


Figure 17. Annual average wind speed statistics for USA

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