# Determining the Rate of PMD Compensation in Deployed Aerial Optical Fibres Through SOP Monitoring

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***Abstract*—In this paper, statistical distributions for first order polarization mode dispersion (FO-PMD) and second order polarization mode dispersion (SO-PMD) are experimentally confirmed when measured using the FTB-5700 Single-Ended Dispersion Analyzer instrument for aerial optical fibres. We also determined the time scale over which to compensate FO-PMD in aerial fibres using the directional time drift autocorrelation function method. It is slightly higher than 390s for SOP measurements made on a particular windy and hot day. This is due to the fact that the changes of the PMD vector are known to be slower than the state of polarization (SOP) changes.**

***Index Terms*—Differential group delay (DGD), polarization mode dispersion (PMD), principal states of polarization (PSP), state of polarization (SOP).**

## I. INTRODUCTION

POLARIZATION-MODE DISPERSION (PMD) is one of the most critical limits in long-haul high-speed optical fibre communication systems with single channel bit rates. [1]-[5]. PMD originates from the small random bire-fringences that exist in the optical fibres that arise during the manufacturing process. This bire-fringence arises from small disturbances in the ideal cylindrical symmetry of the optical fibre core (intrinsic factors) and also stresses, twisting and bends that are external to the fibre (extrinsic factors). Bire-fringence leads to the existence of two orthogonal polarization modes which obey different dispersion relations and therefore have different group velocities [5]-[7]. Along the fibre, the random change of this bire-fringence leads to random coupling between the modes. The time disparity between the two orthogonal principal states of polarization (PSP) is called the differential group delay (DGD), $\Delta\tau$. The first-order PMD (FO-PMD), in vector form, is given by

$$\vec{\tau} = \Delta\tau\vec{p} \quad (1)$$

where $\vec{p}$ is the unit Stokes vector pointing in the direction of the fast PSP in Stokes polarization space and $\Delta\tau$ is the magnitude of the FO-PMD vector .

Available techniques to mitigate or compensate for PMD mainly target buried, ducted and submarine fibres [7]. This is because the PMD changes in such optical fibres are slow since the strain remains relatively constant and temperature fluctuations are minimal. The direct exposure of aerial optical fibres to the fluctuating environment makes the mitigation or compensation of PMD challenging because of their rapid changes in PMD.

State of Polarization (SOP) of a lightwave can be described by a three-dimensional Stokes vector that is positioned on the Poincaré sphere arbitrarily when measured at the output of an optical fibre. It describes the polarization state of light at a given wavelength. For a fixed input SOP, the output SOP changes will be due to changes in the PMD and mode coupling along the optical fibre length and time. So, when an aerial fibre is exposed to external mechanical stresses, it will lead to changes in the PMDs and SOPs.

In this paper, we investigate PMD and SOP changes in aerial fibres. This is of particular relevance in South Africa, as part of the backbone of the national grid includes long distances of aerial optical fibre between exchange stations. First we present the measurement of FO-PMD and second-order polarization mode dispersion (SO-PMD) in aerial fibres using the more robust and accurate FTB-5700 Single-Ended Dispersion Analyzer[1]. The PMD values obtained justify the accuracy of this measurement method for aerial fibres. Then we present the directional time drift autocorrelation function method in order to investigate the response time required for a PMD compensator to accurately track the PMD vector changes on the aerial optical network.

## II. STATISTICAL DISTRIBUTIONS OF FO-PMD AND SO-PMD

To develop effective PMD compensation techniques, it is important to measure and also characterize the probability density functions (pdfs) of random quantities such as the DGD. In this study, PMDs of the aerial optical fibre (ITU-T G.652) were measured during the month of June 2009 in the winter season using the FTB-5700 Single-Ended Dispersion Analyzer. The aerial fibre cable links two local Telkom Exchange transmission stations in Port Elizabeth, South Africa, and is exposed to dynamic environmental changes. Wind caused the optical fibre cable to gallop and oscillate mainly due to its direction and speed. This, together with temperature fluctuations, lead to the change in bire-fringence of the optical fibre. Since the aerial optical fibre was in a

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[1] We would like to acknowledge EXFO (EXPERTISE REACHING OUT) company for the loan of this instrument.

dynamic state, its PMD and SOP changed on short time scales.

The experimental set up was such that at one end of the looped fibre was the FTB-5700 and the other end was the open optical fibre. This is a single-ended measurement technique that uses the same principle as the polarization optical time-domain reflectometer (P-OTDR) that is based on measurement of the degree of polarization of the back scattered light as a function of distance in the fibre [4],[8].

The aerial optical fibres were exposed to severe vortex-induced oscillations. Vortex-induced oscillations are aerial optic fibre cable vibrations that are due to steady winds with a velocity range between 3 and 30 km/h and have a frequency range from 3 to 150 Hz [9]. During this period of our measurements, the winds were fairly steady with low speeds (mean speed of 18.7 km/h). In total, 224 PMD measurements were made at 30 minute intervals.

Fig. 1 shows a histogram of the FO-PMD coefficient values measured. These measurements were carried out at random times during this measurement period. The average FO-PMD coefficient of the optical fibre was 0.12 ps/√km with a standard deviation of 0.02 ps/√km. Both the Maxwellian and Gaussian probability density functions (pdfs) were fitted onto the histogram and clearly from Fig. 1, it indicates that the Gaussian is a better fit to the distribution as expected from theory [1]-[2],[10]-[11].

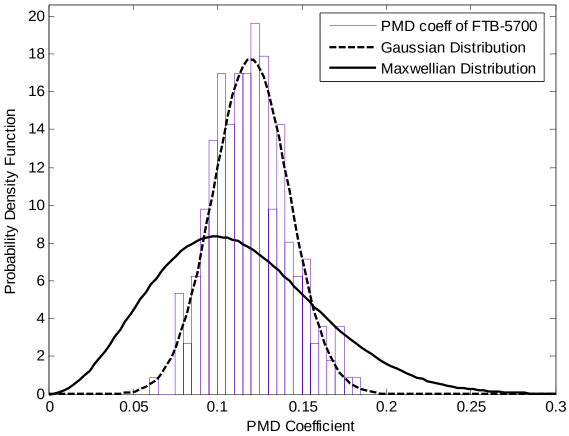


Fig. 1: The histogram of the FO-PMD coefficient values (ps/√km) obtained on measuring the aerial optic fibre (ITU-T G.652) from 8 to 23 June 2009 using the FTB-5700. The bin size is 25. Also shown are the Gaussian and Maxwellian distributions fittings.

Some researchers have used the traditional interferometric methods for PMD measurements [12],[13]. Brodsky *et al.* [12] made 950 and Mudau [13] made 150 000 PMD measurements for them to be able to get a Gaussian fit for the PMD statistics. However, in this study, we were able to get the Gaussian fit with only 224 PMD measurements using the FTB-5700 instrument. This justifies its robustness in accurately measuring the PMD of aerial fibres. The reason being this instrument has SOP scrambling analysis (SSA) implemented in it to be able to measure an aerial optic fibre cable under aeolian perturbations.

Fig. 2 shows a histogram of the SO-PMD values measured also using the FTB-5700. The measurements were also carried out at random times during the winter month of June 2009. The average SO-PMD of the optical fibre was 0.10 ps/nm with a standard deviation of 0.04 ps/nm. The SO-PMD statistics we obtained are similar to those obtained by many researchers [6],[14]-[17].

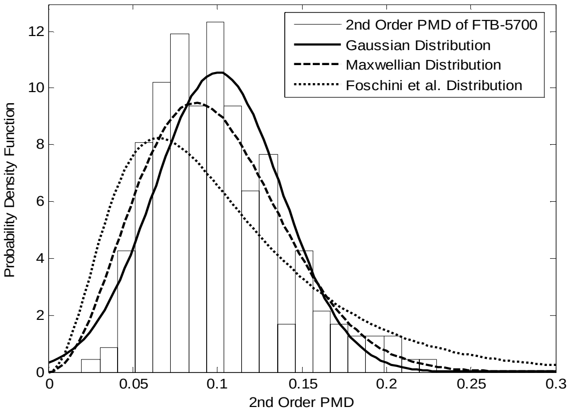


Fig. 2: The histogram of the SO-PMD values (ps/nm) obtained on measuring the aerial optic fibre (ITU-T G.652) from 8 to 23 June 2009 using the FTB-5700. The bin size is 20. Also shown are the Gaussian, Maxwellian and Foschini *et al.* distributions fittings.

The Gaussian, Maxwellian and Foschini *et al.* pdfs were fitted onto the histogram and to a good approximation it is seen that the Gaussian distribution is the best fit to the distribution followed by the Maxwellian and then the Foschini *et al.* distributions. This is in agreement to the findings made by [15], [17]-[21].

This was true notwithstanding the fact that we considered few SO-PMD values (in this case 224). We plan to carry out more extensive SO-PMD measurements for a longer period of time to confirm or disapprove our current findings.

## III. SOP MONITORING

The experimental setup used during the field measurements consisted of the looped fibre under test (FUT) which was 14.8 km long. This FUT was secured in a deployed loose-tube that contains 12 optical fibres. The Agilent 8164A narrow band tunable laser source (TLS) provided a continuous wave of a light beam that was launched into the FUT at a wavelength of $\lambda$=1550 nm. The propagating laser light in the FUT undergoes relative SOP changes and was measured using a polarimeter. All patchcords used at the transmission station where our equipment was stationed, were securely taped on the walls to ensure that the relative SOP changes were only due to the dynamic environmental changes of the FUT.

First, for 30 minutes, at intervals of 30ms, an SOP measurement run was carried out after joining together the taped patchcords excluding the FUT to ascertain the impact of the temperature and vibrations inside the Exchange station container. It was found that they had no major effects since the normalized Stokes parameters are approximately independent of each other as shown in Fig. 3(a). The mapping of the Stokes parameters illustrated in Fig. 3(b) on the Poincaré sphere was not as random like would be expected.

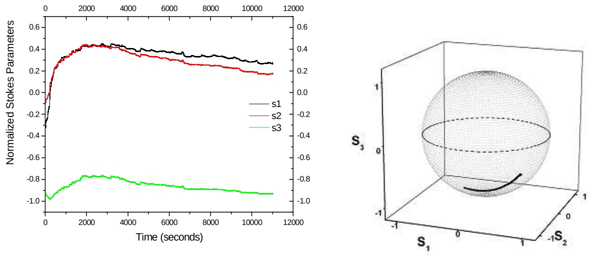

(a) (b)

Fig. 3: Time evolution of the normalized Stokes parameters of the taped patchcords excluding the 14.8 km long looped fibre under test (FUT) optical fibre monitored for 30 minutes, at 30ms intervals, during the winter month of June 2009.

Then, with the FUT included, SOP data collection was made lasting 30 minutes in steps of 30 ms for every measurement. The experimental directional time drift autocorrelation function (ACF) was used to determine the decorrelation of the laser light propagating in the aerial fibre [7].

$$R(\Delta t) = \frac{1}{N} \sum_{t=0}^{N-1} \vec{S}(t) \cdot \vec{S}(t+\Delta t) \qquad (2)$$

where $\vec{S}(t)$ and $\vec{S}(t+\Delta t)$ are the normalized Stokes vectors at times $t$ and $t+\Delta t$ respectively from the experimental SOP data and N is the total number of points used. The ACF describes how correlated the normalized Stokes vectors are in the time domain.

## IV. RESULTS AND DISCUSSIONS

The results shown in this section show the variations of SOPs and the calculated ACFs of the SOP measurements made during the month of June 2009(winter season). During this period, it was observed that the wind speed was fluctuating randomly with an average of 44.6 km/h. The temperature variations were not as random as those of wind speed with an average of 15.1 $^{o}$C, a highest of 27.4 $^{o}$C and a lowest of 14.3 $^{o}$C.

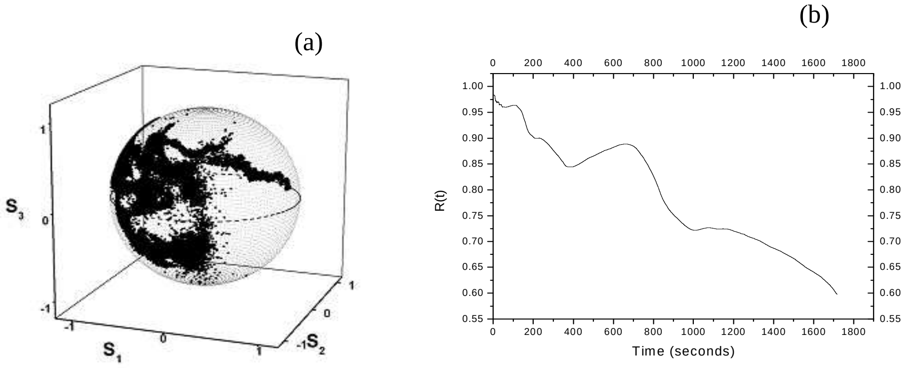
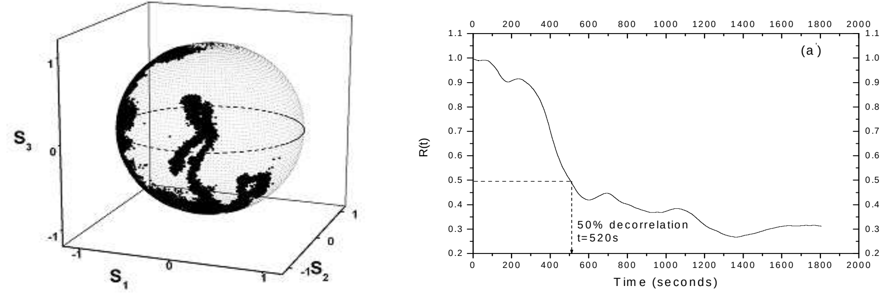

(a) (b)

Fig. 4: (a) Variation of SOPs, (b) the ACF for the aerial deployed optical fibre. The SOP measurements used for the mapping on the Poincaré sphere and also for calculation of the ACF, R(t), were collected on 17 June 2009 from 9:15 am - 9:45 am. Equation 2 was used to calculate the ACF.

(a)



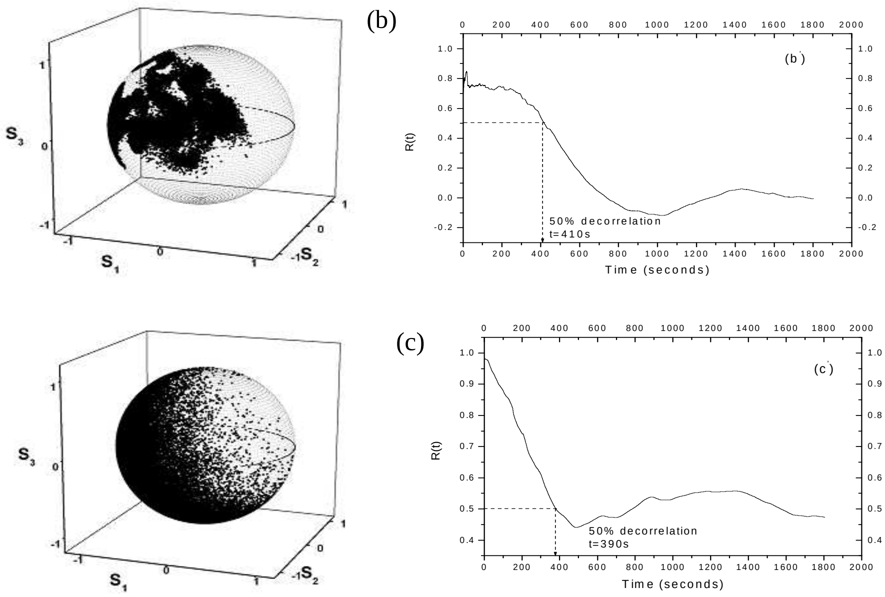


Fig. 5: ((a), (b) and (c)) Variation of SOPs on 17, 22 and 23 June 2009 at 12:50pm respectively. ((a$'$), (b$'$) and (c$'$)) The ACFs for the deployed aerial optical fibre. The SOP measurements used for calculation of the ACFs, R(t), were collected on 17, 22 and 23 June 2009 from 12:20 pm – 12:50 pm respectively. Equation 2 was used to calculate the ACF.

For SOP monitoring analyses, we used measurement data collected on 17, 22 and 23 June 2009. On 17 June, the wind speed fluctuations were relatively uniform (average wind speed was 9 km/h) and the temperature increased gradually from about 14$^{o}$C to 19$^{o}$C. The average temperature on this day was 12.8 $^{o}$C. Then on 22 June, the wind speed fluctuations gained compared to those on 17 June (average wind speed was 17.6 km/h with a highest of 37.4 km/h). The accompanying average temperature on this day was 16.9 $^{o}$C with a highest of 20.3 $^{o}$C and lowest of 13.5 $^{o}$C. On 23 June, the temperature also increased gradually with a minimum of 15$^{o}$C, a maximum of 20$^{o}$C and an average of 17.4 $^{o}$C while the random wind speed and wind gusts fluctuations were significant. The average wind speed was 27 km/h and a highest of 78.5 km/h.

Fig. 4(a) shows the population of the Poincaré sphere on 17 June 2009 from 9:15 am to 9:45 am for the normalized Stokes vectors collected for 30 minutes at 30 ms intervals. The SOP coverage on the Poincaré sphere is sparsely populated because on this particular day the environmental parameters were not fluctuating so fast. Fig. 4(b) shows the ACF of these SOP measurements. As can be seen, over a 1600 seconds time span, 50% decorrelation is not observed but after some more additional time it would be observed.

Figs. 5(a), (b) and (c) show variations of SOPs on 17, 22 and 23 June 2009 at 12:50 pm respectively. The random changes in birefringence and mode coupling along the aerial optical fibre length resulted in fast SOP fluctuations. The population of the Poincaré spheres increased on these days because of the changing environmental conditions experienced by the optical fibre cable. On 23 June 2009 the Poincaré sphere surface was almost completely populated because of the rapid fluctuations of the environmental parameters; wind speed, wind gusts and temperature (Fig. 5(c)). Population of the Poincaré sphere is close to and on its surface because the light source(tuneable laser) used was highly polarized with a degree of polarization (DOP) >0.9. Figs. 5(a$'$), (b$'$) and (c$'$) show the ACFs for the deployed aerial optical fibre. The SOP measurements used for calculation of the ACFs, R(Δt), were collected on 17, 22 and 23 June 2009 from 12:20pm – 12:50pm respectively for 30 minutes in steps of 30 ms. Equation 2 was used to calculate the ACF. It is observed that as the population of the Poincaré spheres increased, the 50% decorrelation times reduced. On 17 June in Fig. 5(a$'$) the decorrelation time was 520s, on 22 June in fig. 5(b$'$) it was 410s and on 23 June as shown in fig. 5(c$'$) it was 390s. This is in line with findings by Karlsson *et al.* [3].

In PMD compensation, the compensator has to track the changing PMD vector. This is the same as tracking the changing SOPs though the PMD vector fluctuations are normally slower [22]. Determination of the decorrelation time helps in knowing the time scale over which the polarization effects occur for PMD compensation to be made accurately. The time for PMD compensation should be slightly higher than the decorrelation time since SOP changes are always faster than PMD vector changes. From our measurements it would be slightly higher than 390s.

## V. CONCLUSION

We have shown that a Gaussian distribution fits both the FO-PMDs and the SO-PMDs for PMD values of an aerial fibre exposed to severe vortex-induced oscillations on the South African telecommunication network measured using an FTB-5700 Single-Ended Dispersion Analyzer. PMD values obtained confirmed its accuracy and robustness. Response times for accurate PMD compensation for the aerial fibre were also determined and the maximum would be slightly higher than 390s on a windy and hot day. This is due to the fact that the PMD vector changes slower than the SOPs.

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