CHARACTERIZATION OF POLARIZATION-MODE DISPERSION ON BURIED STANDARD SINGLE-MODE FIBERS

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OVERVIEW

- Introduction
- PMD concepts
- PMD measurement methods: JME method
- Measurement setup
- Measurement results and data analysis
- Conclusions and Future work

INTRODUCTION

- Fiber-optic communication technology is barely three decades old but it has made tremendous progress
- Currently fourth-generation fiber-optic systems are in use.
- Problems in the past included huge fiber loss, inter-modal dispersion, chromatic dispersion, electronic repeaters, etc.
- As the bit rate approaches >10 Gb/s per channel, current fiber-optic systems face a different dispersion impairment called ‘polarization-mode dispersion’ (PMD)
- PMD is random in nature and so statistical characterization is necessary for better understanding

PMD CONCEPTS

- **PMD in fibers**
  - Fundamental property of single-mode fibers
  - Signal energy at a given λ is resolved into two orthogonal polarization modes with different refractive indices
  - Difference in propagation time between both modes is differential group delay (DGD)
  - PMD is a vector quantity in Stokes space
  - Specified using PMD coefficient (ps/(km) or ps/$(km)^{1/2}$)
- **Causes of PMD**
  - Birefringence
  - Mode coupling

BIREFRINGENCE AND MODE COUPLING

- **Birefringence**
  - Despite their name, ‘single-mode’ fibers support two orthogonal modes of propagation
  - Loss of degeneracy of the two modes is called birefringence
  - Intrinsic and extrinsic factors
  - PMD is typically larger in older fibers
- **Mode coupling**
  - Energy of light pulse launched in one mode will couple into the other and vice versa as it propagates along the fiber until both the modes are equally populated
  - The length of the fiber at which the average power in one mode is within $1/e^2$ of that of other is coupling length, L_c
  - Short fibers ($L \ll L_c$) and long fibers ($L \gg L_c$)

PRINCIPAL STATES MODEL

- Developed by Poole and Wagner in 1986
- Assumes coherence time of source is high and PDL (polarization-dependent loss) in the link is negligible
- It states that for a length of fiber, there exists for every frequency a special pair of orthogonal polarization states, called the Principal states of polarization (PSPs)
- PSP– input polarization for which output state of polarization is independent of frequency to first order
- In time-domain, a light pulse launched in any PSP results in an output pulse that is undistorted to first order
- Difference in time delays of the two PSPs is DGD

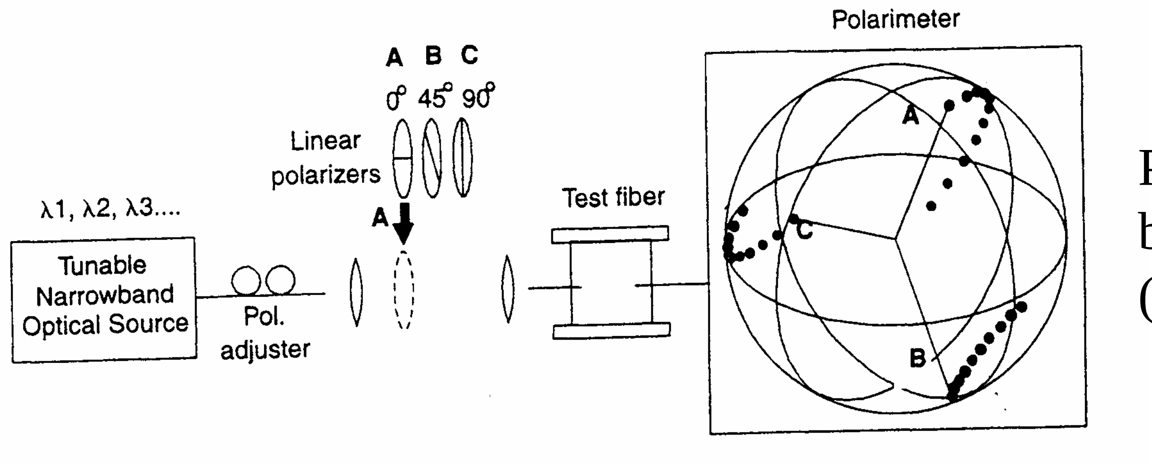
SYSTEM IMPAIRMENTS DUE TO PMD

- PMD causes pulse spreading and distortion and thus can lead to system penalties
- In digital systems, DGD results in intersymbol interference (ISI) and hence power penalty
- Second-order PMD results in polarization-dependent chromatic dispersion (PCD) and PSP depolarization
- PMD induces coherent cross-talk between channels in polarization-multiplexed transmission systems

PMD MEASUREMENT METHODS

- **Time-domain methods**
  - Operate by sensing pulse delays
  - Slow because of the need to determine PSPs experimentally
  - Generally not suitable for field measurements
- **Frequency-domain methods**
  - Operate by detecting changes of polarization with frequency
  - Suitable for field measurements
- Some methods measure scalar instantaneous DGD, few measure mean DGD and some others measure instantaneous PMD vectors

JONES MATRIX EIGENANALYSIS (JME) METHOD



PMD measurement by JME method (Frequency-domain method)

- Measures instantaneous DGD vectors
- Any polarized signal can be expressed as a Jones vector
- Jones matrix describes the polarization-transforming characteristic of a two-port device
- Measurement of Jones matrix requires application of 3 known states of linearly polarized light to the DUT

JONES MATRIX EIGENANALYSIS (JME) METHOD (cont'd ..)

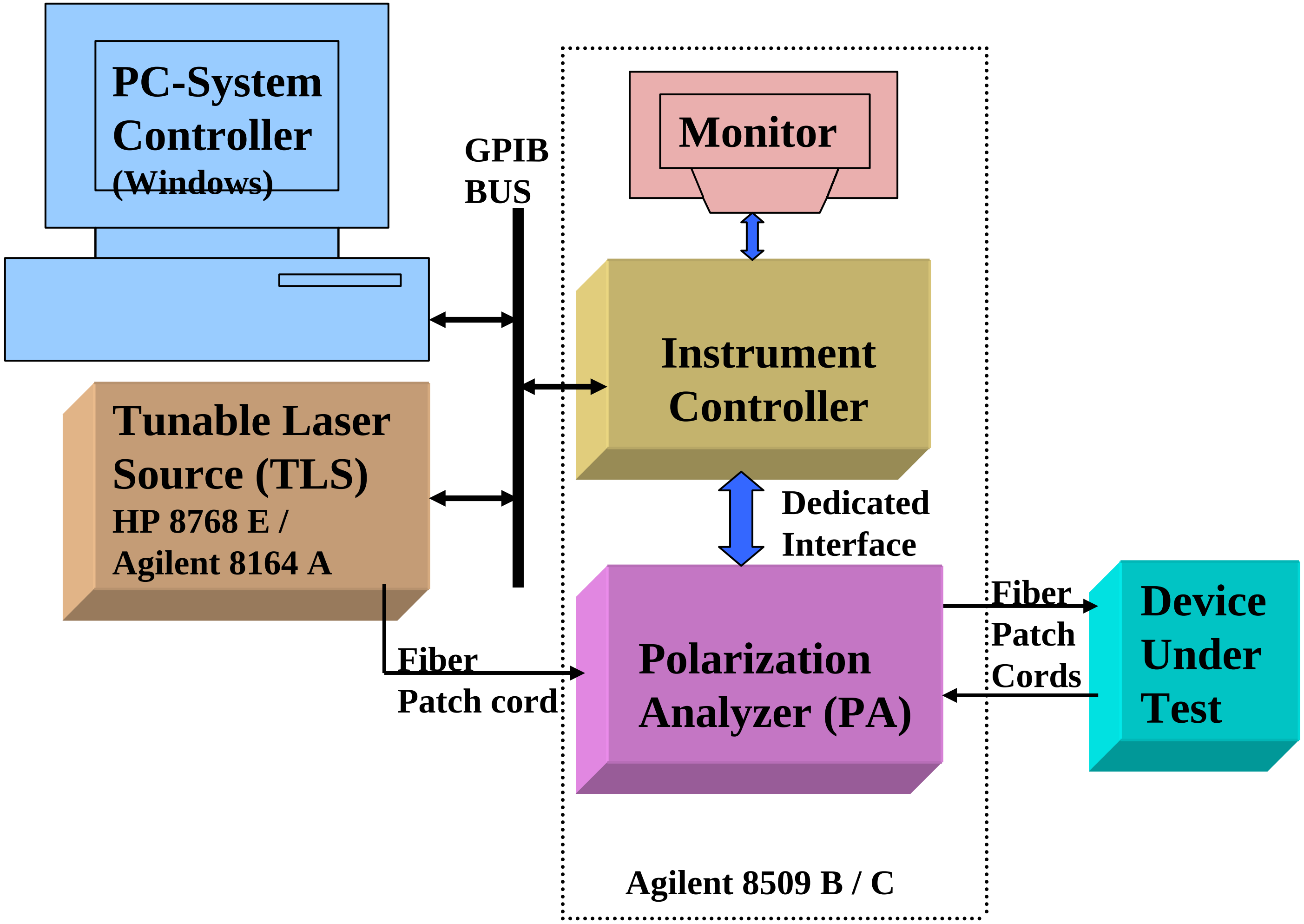
- Jones matrix is determined from the relationship of the measured output states to the known input states
- To determine DGD at a particular λ, Jones matrices at two different λs equally spaced about λ are measured
- DGD, Δτ, is then determined using

$$\Delta \tau = \left| \frac{Arg\left(\frac{\rho_1}{\rho_2}\right)}{\Delta \omega} \right|$$

ρ_1 and ρ_2 are the Eigen values of $T(\omega+\Delta\omega)T^{-1}(\omega)$; T is Jones matrix
Eigen vectors of $T(\omega+\Delta\omega)T^{-1}(\omega)$ locate the output PSP as a function of ω

- This method can be readily automated
- Not always practical in field tests

MEASUREMENT SETUP



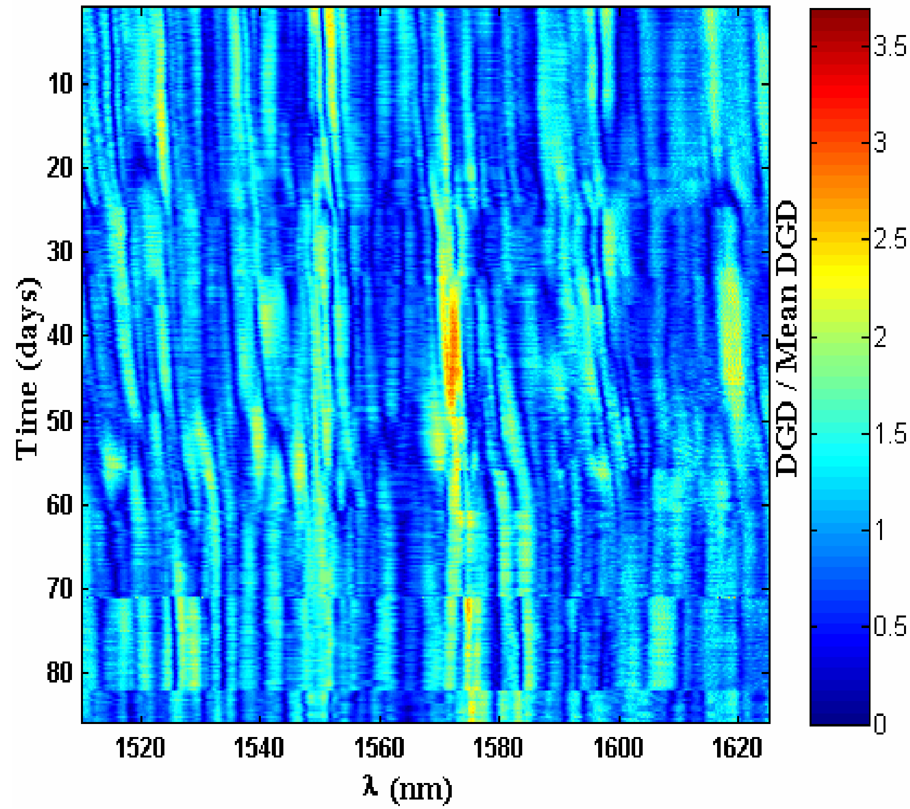
Measurement setup for making automated DGD measurements.

MEASUREMENT SETUP (cont'd..)

- Visual basic software running on the system controller controls the system
- One measurement at a specific λ and time takes ~ 4 sec.
- Max. measurable DGD with 0.1 nm step is ~ 40 ps
- Measurement uncertainty is ~ ± 310 fs for 0.1 nm step
- Data automatically saved into text files (8 kB - 30 kB)
- Measurement system is usually very reliable, but occasionally (once in a month or so) any of the instruments might become frozen

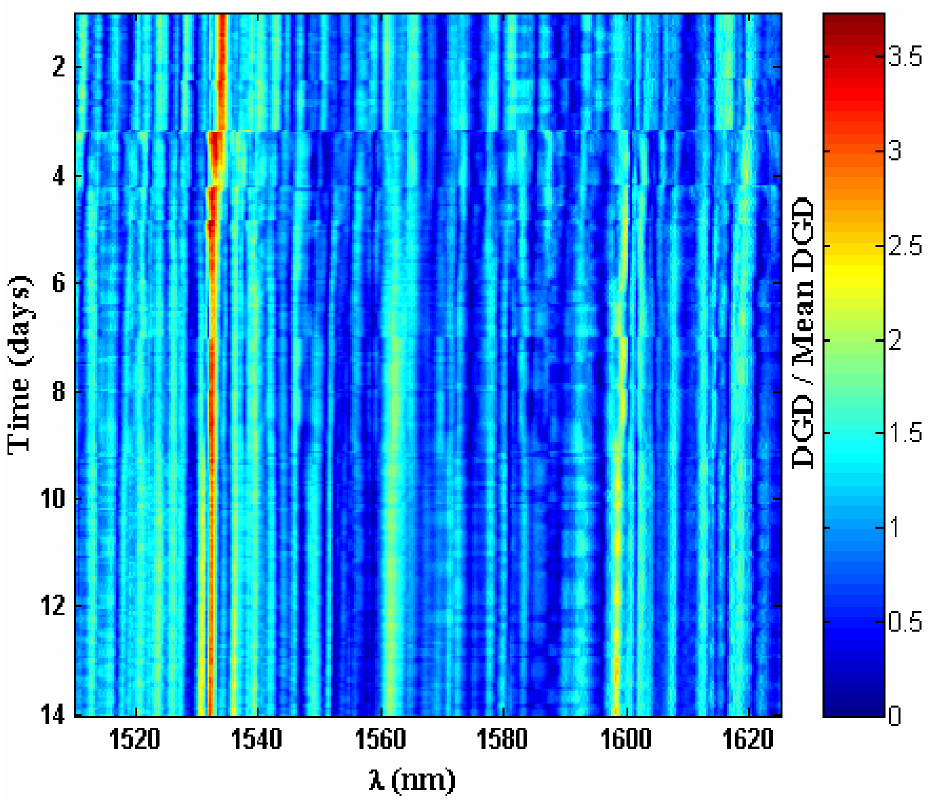
MEASUREMENT RESULTS AND DATA ANALYSIS: INDIVIDUAL FIBER SPANS

- 3 different 95-km fibers (1, 2, and 3) within a slotted-core, direct buried, standard single-mode fiber-optic cable
- Wavelength band:
  1510 – 1625 nm
- Spectral resolution: 0.1 nm
- Measurement repetition:
  on span 1, once every 3 hrs
  on spans 2 and 3, once every 1 ½ hours

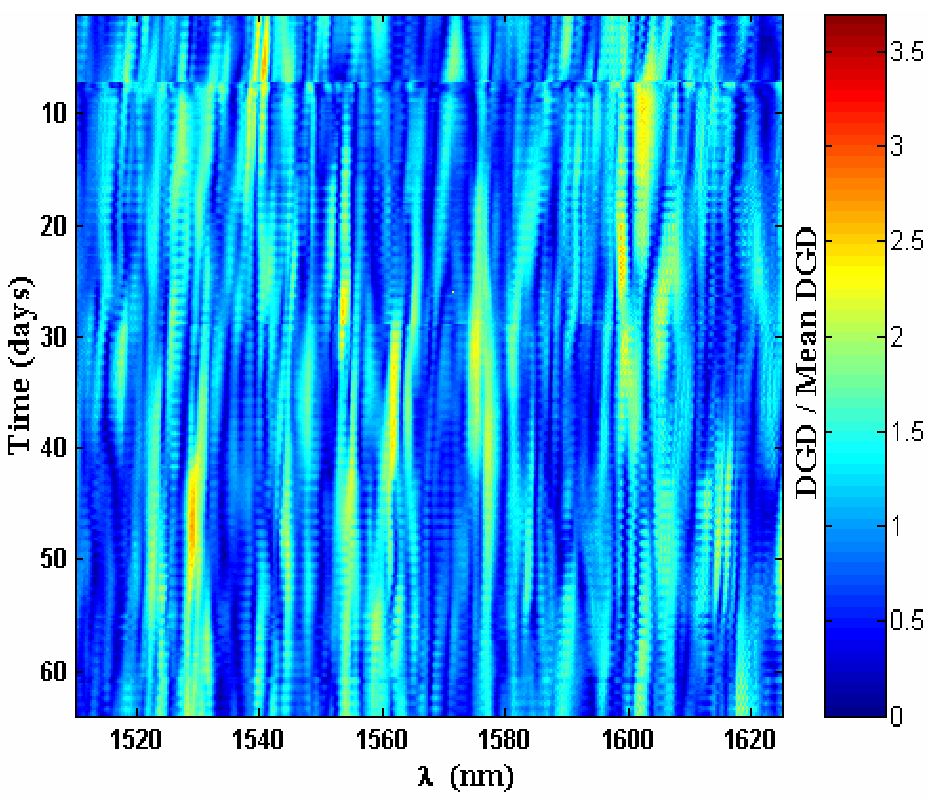


Measured, normalized DGD vs. wavelength and time for fiber span 1 (86 days, Nov. 9, 2001 – Feb. 2, 2002)

COLOR MAPS (cont'd)

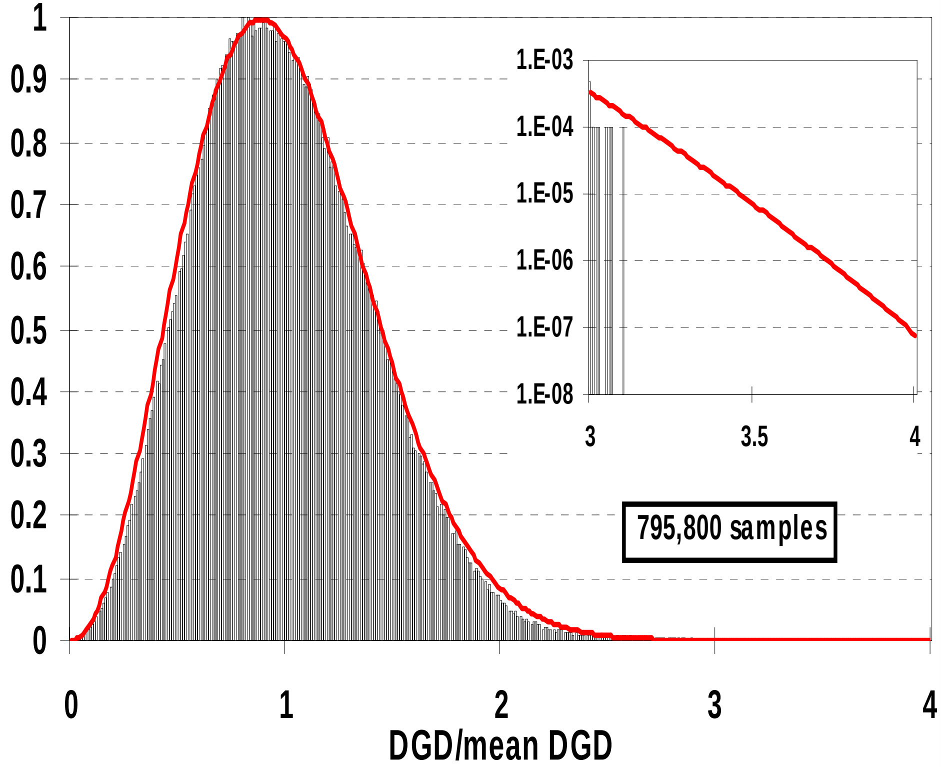


Measured, normalized DGD vs. wavelength and time for fiber span 2 (14 days, May 4, 2002 – May 18, 2002)

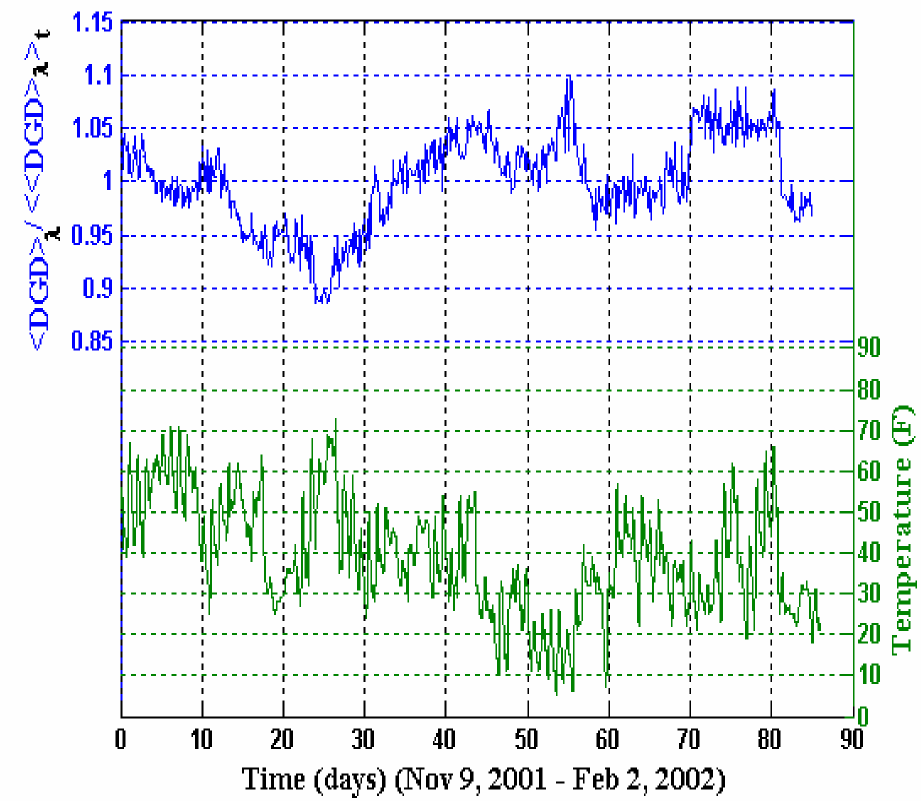


Measured, normalized DGD vs. wavelength and time for fiber span 3 (64 days, May 29, 2002 – Aug. 1, 2002)

DGD HISTOGRAM AND MEAN DGD VARIATION (SPAN 1)

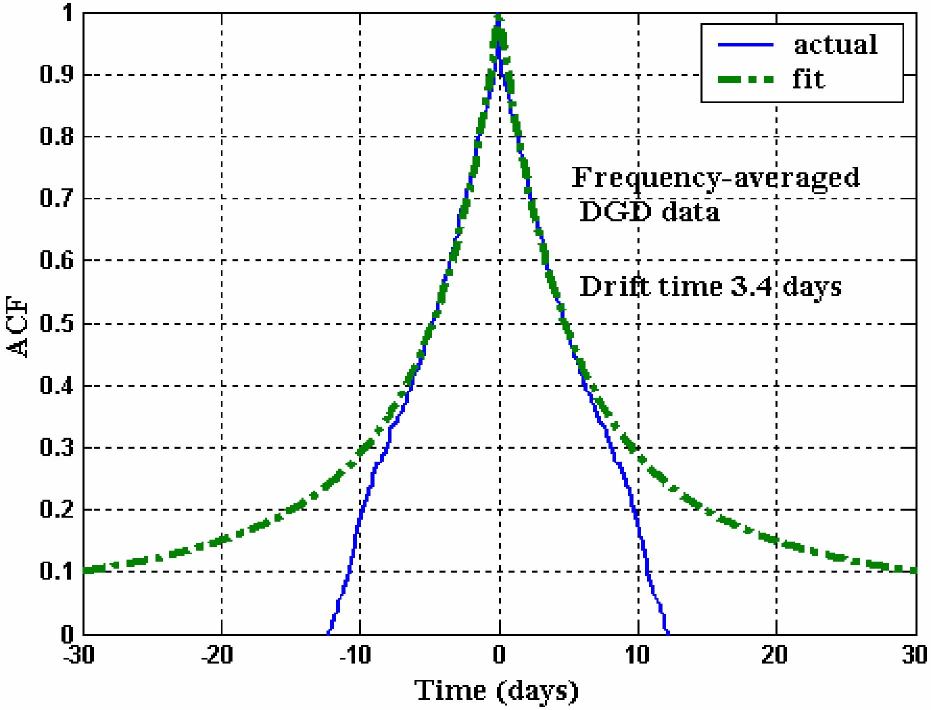


Histogram of measured, normalized DGD data on fiber span 1

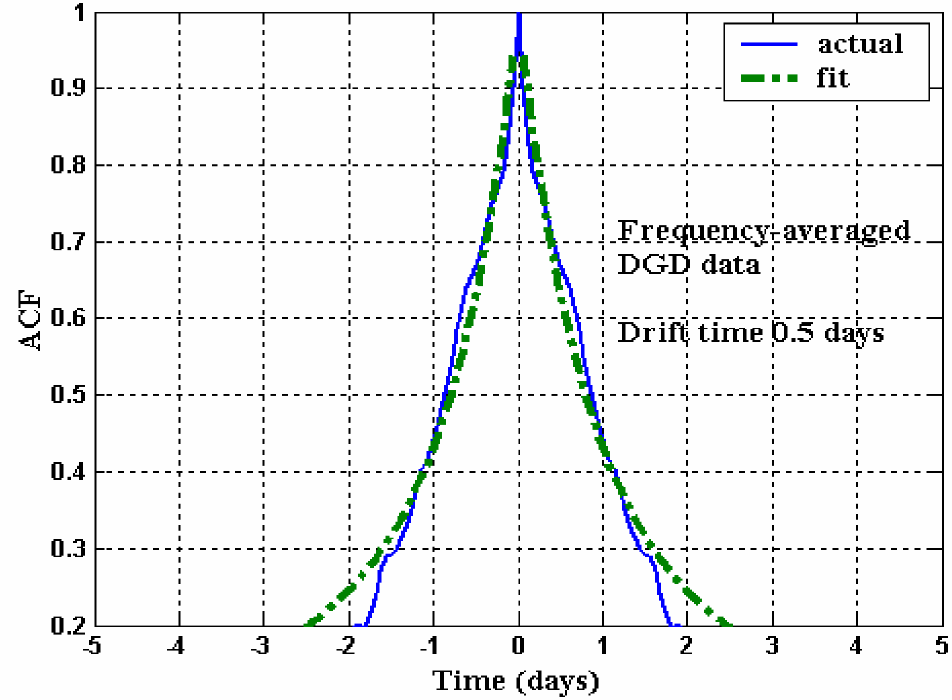


Frequency-averaged DGD and temperature vs. time for fiber span 1

TEMPORAL AUTOCORRELATION FUNCTIONS (ACFs) (SPANS 1 AND 2)



Normalized temporal ACF of frequency-averaged DGD data on fiber span 1 and its theoretical curve-fit

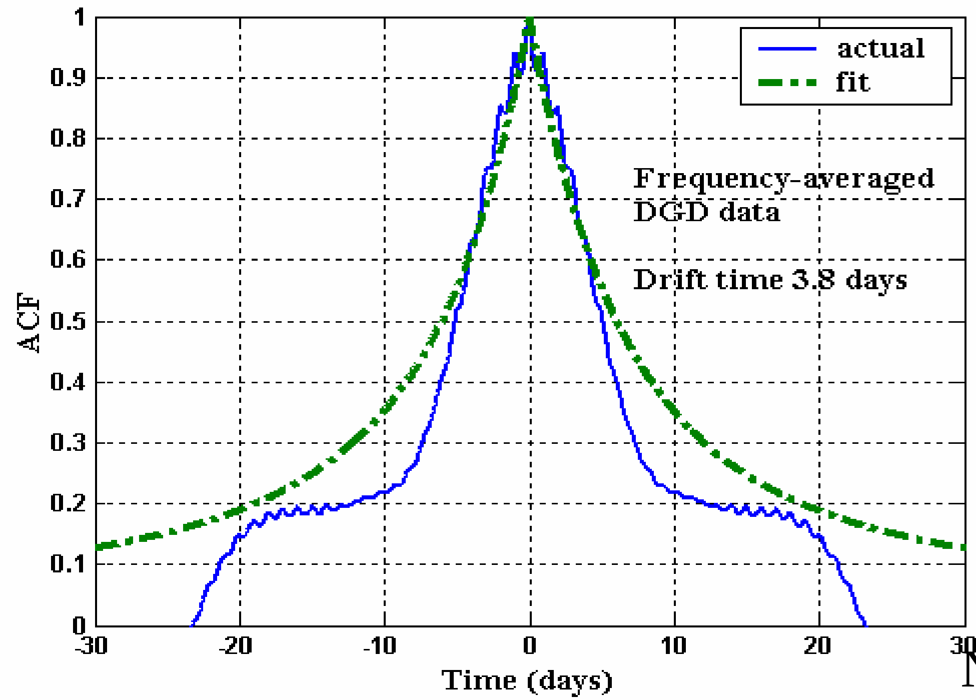


Normalized temporal ACF of frequency-averaged DGD data on fiber span 2 and its theoretical curve-fit

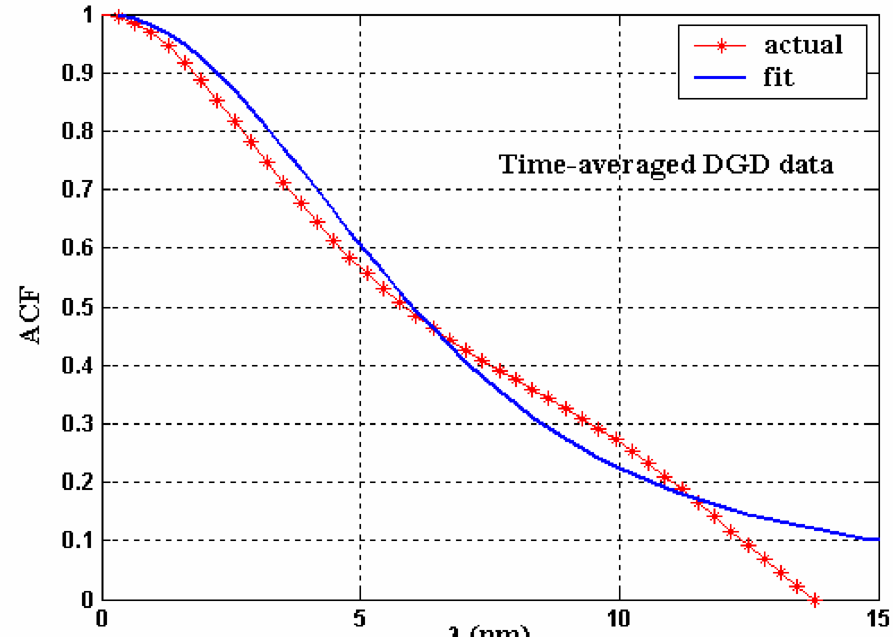
Theoretical fit: $ACF(\Delta t) = \dfrac{1-\exp\left(-|\Delta t|/t_d\right)}{|\Delta t|/t_d}$

(Source: Paper by Karlsson et.al, JLT, Vol 18, July 2000)

TEMPORAL ACF (SPAN 3) AND SPECTRAL ACF (SPAN1)



Normalized temporal ACF of frequency-averaged DGD data on fiber span 3 and its theoretical curve-fit



Normalized spectral ACF of time-averaged DGD data from fiber span 1 and its adjusted theoretical curve-fit

$$\omega_c = 4\sqrt{2}/\langle \Delta\tau \rangle$$

Theoretical fit: $$ACF(\Delta\omega) = 3\frac{1-\exp\left(-\langle \Delta\tau^2 \rangle \Delta\omega^2/3\right)}{\Delta\omega^2}$$

(Source: Paper by Karlsson et.al, Optics Letters, Vol 24, July 1999)

SYSTEM OUTAGE ANALYSIS

- Goal is to determine outage probability, mean outage rate and mean outage duration as a function of threshold/<Δτ>
- From "WDM design issues with highly correlated PMD spectra of buried optical cables" by Caponi et.al, OFC '02
  - Outage probability: $P_{out} = P(\Delta\tau \geq \Delta\tau_{th}) = 1 - \int_0^{\Delta\tau_{th}} f_{\Delta\tau}(\Delta\tau)\, d\Delta\tau$

    P_{out} usually expressed in [minutes/year]

  $\Delta\tau_{th}$ is threshold; $f_{\Delta\tau}(\Delta\tau)$ is the pdf of DGD (Maxwellian)
  - Mean outage rate: R_{out} = mean number of outage events per unit time [1/year]
  - Mean outage duration: $T_{out} = P_{out}/R_{out}$ = mean duration of an outage event [minutes]

SYSTEM OUTAGE ANALYSIS (cont'd)

$$R_{out} = \frac{1}{2} f_{\Delta\tau}(\Delta\tau_{th}) \int_{-\infty}^{\infty} |\Delta\tau'| f_{\Delta\tau'|\Delta\tau}(\Delta\tau' | \Delta\tau) \cdot d\Delta\tau'$$

$\Delta\tau'$ is the first derivative of $\Delta\tau$ w.r.t time

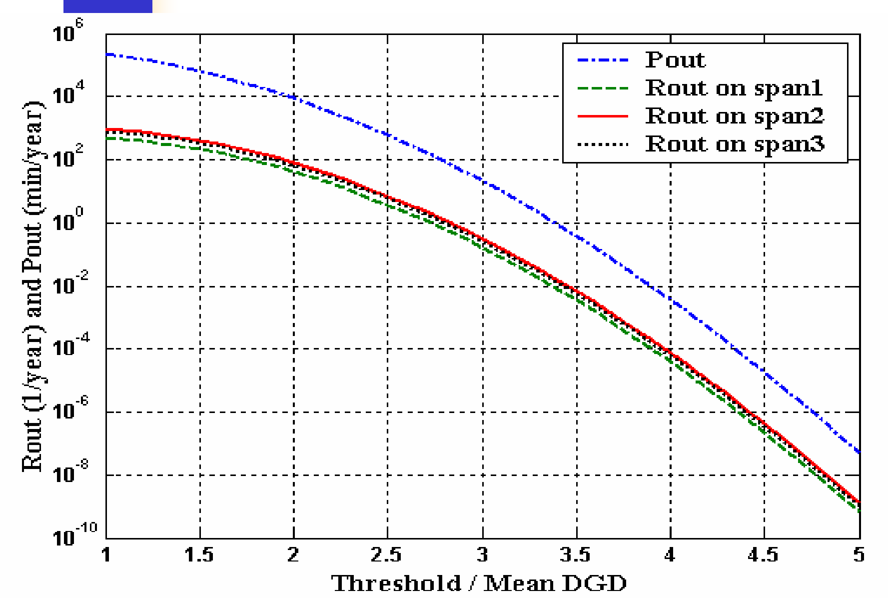
$f_{\Delta\tau'|\Delta\tau}$ is the Conditional probability distribution

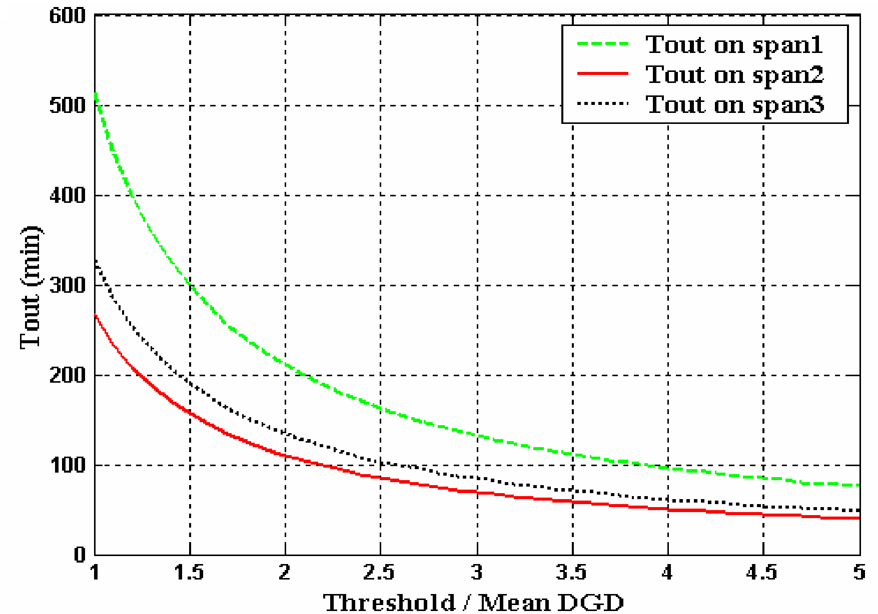
Caponi has showed that $\Delta\tau'$ is independent of $\Delta\tau$

$$R_{out} = \frac{1}{2} f_{\Delta\tau}(\Delta\tau_{th}) \int_{-\infty}^{\infty} f_{\Delta\tau'}(\Delta\tau') |\Delta\tau'| d\Delta\tau'$$

$f_{\Delta\tau}(\Delta\tau)$, and $f_{\Delta\tau'}(\Delta\tau')$ are the pdfs of DGD and first derivative of DGD

P_{out}, R_{out} and T_{out} values (Individual spans)





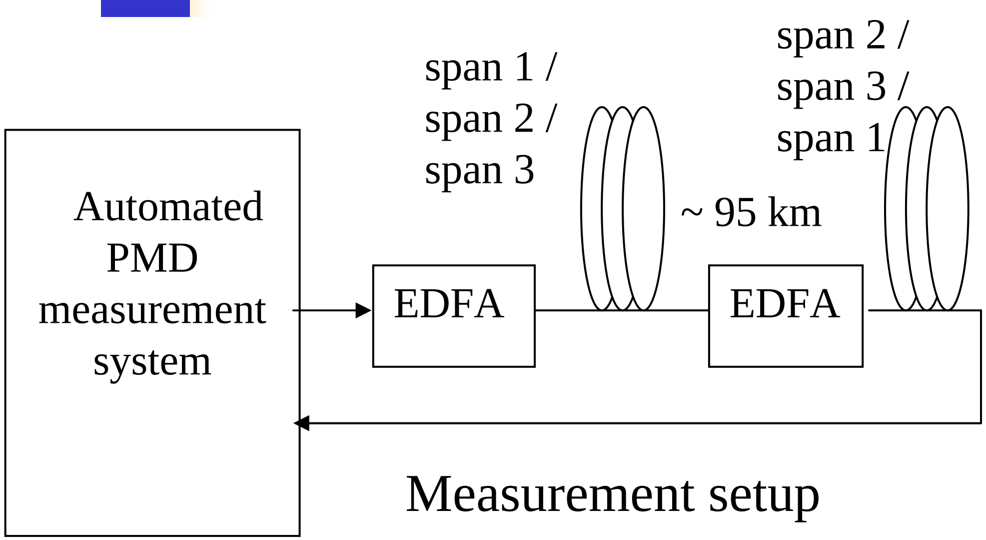
Calculated P_{out}, R_{out}, and T_{out} versus threshold/mean DGD for the three fiber spans

	3*<DGD>	3.7*<DGD>
Span 1:MTBO Outage duration	6.39 years 136 min	1648 years 108 min
Span 2:MTBO Outage duration	3.25 years 69 min	833 years 55 min
Span 3:MTBO Outage duration	3.96 years 84 min	1021 years 67 min

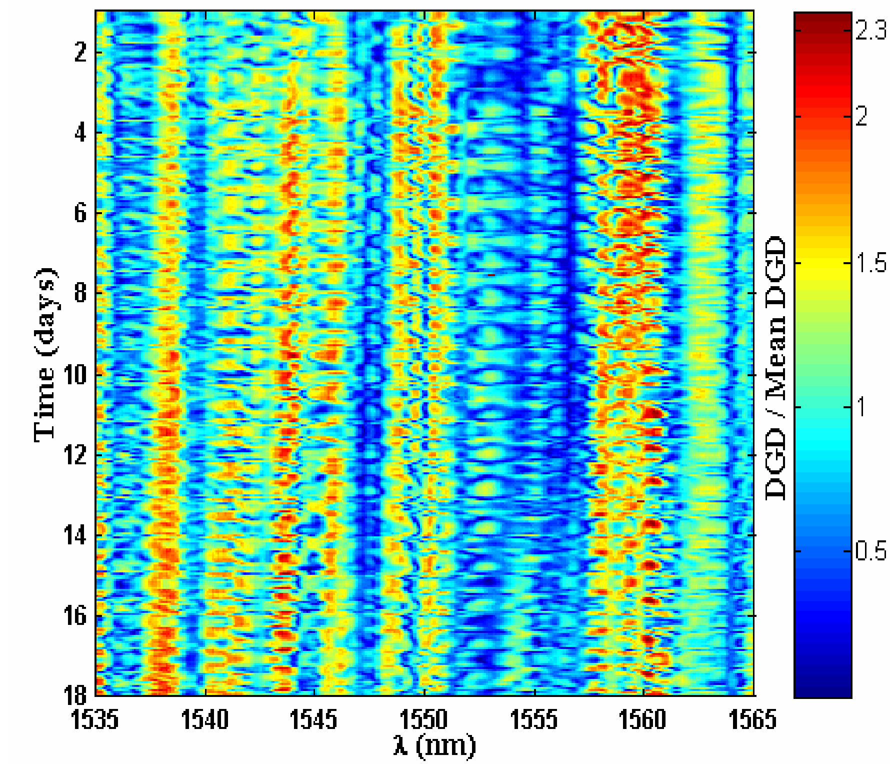
MTBO = mean time between outages

$= 1 / R_{out}$

TWO-FIBER CONFIGURATION: COLOR MAPS



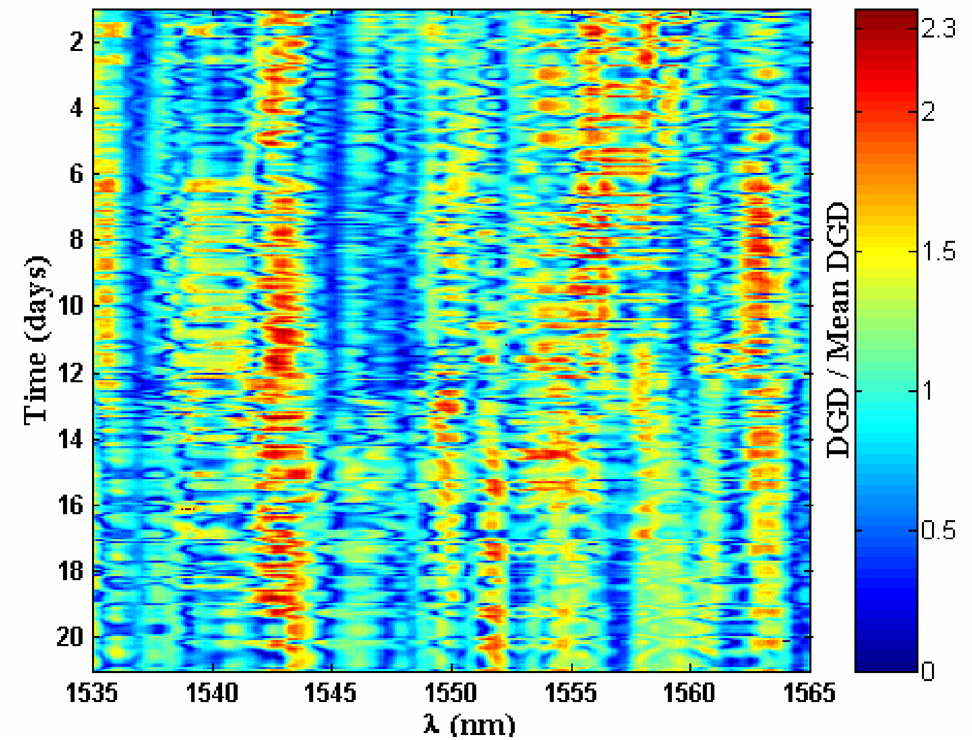
Measurement setup



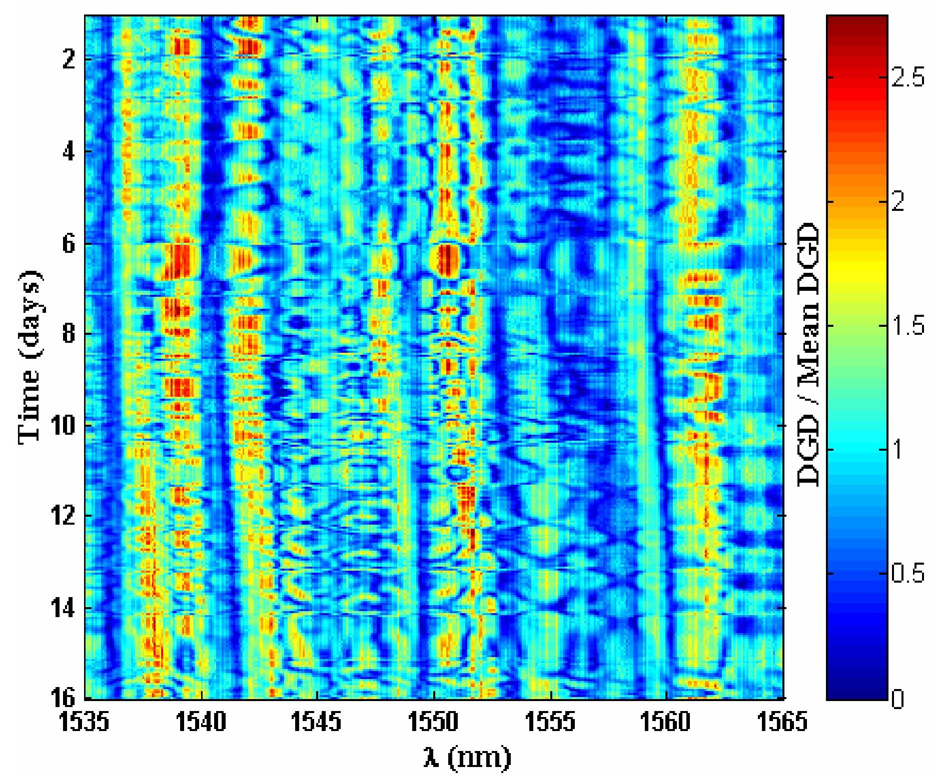
Measured, normalized DGD vs. wavelength and time for fiber spans 1 and 2 concatenated (18 days, Aug. 22, 2002 – Sept. 9, 2002)

- Wavelength band: 1535-1565 nm
- Spectral resolution: 0.1 nm
- Measurement repetition: once every 23 minutes

COLOR MAPS (cont'd)



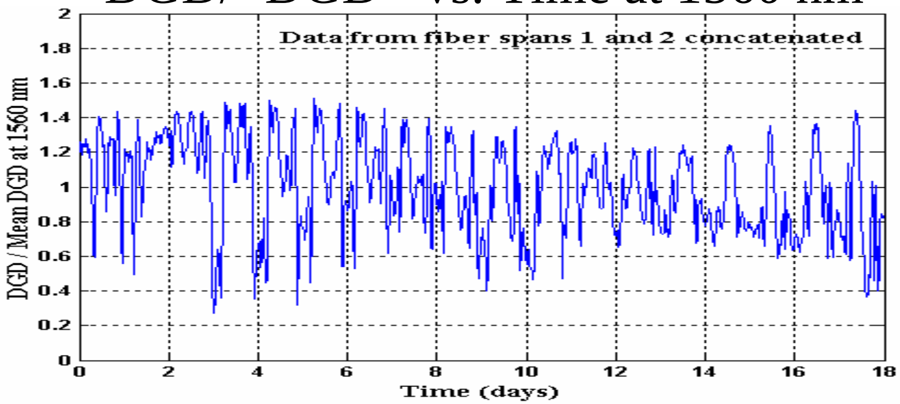
Measured, normalized DGD vs. wavelength and time for fiber spans 2 and 3 concatenated (21 days, Aug. 1, 2002 – Aug. 22, 2002)



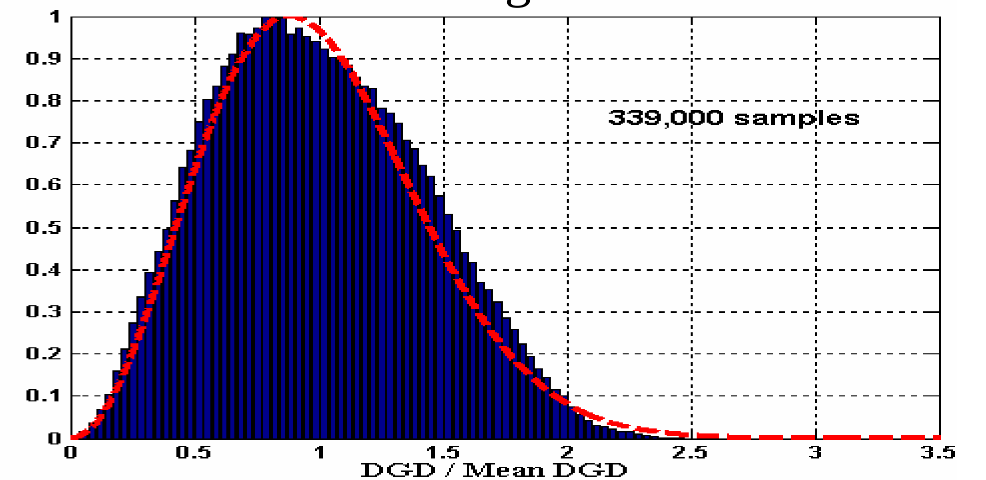
Measured, normalized DGD vs. wavelength and time for fiber spans 1 and 3 concatenated (16 days, Sept. 27, 2002 – Oct. 13, 2002)

DFT PLOT, HISTOGRAM AND MEAN DGD VARIATION FOR SPANS 1&2 CON.

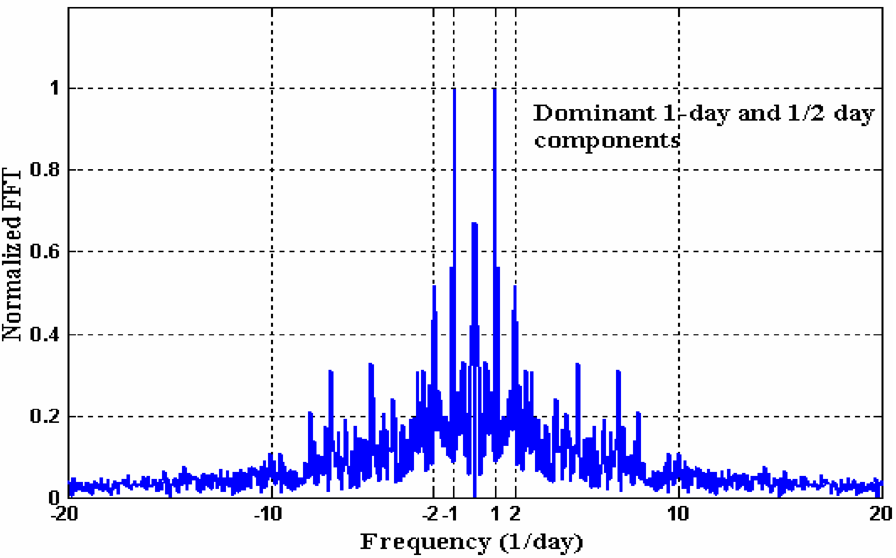
DGD/<DGD> vs. Time at 1560 nm



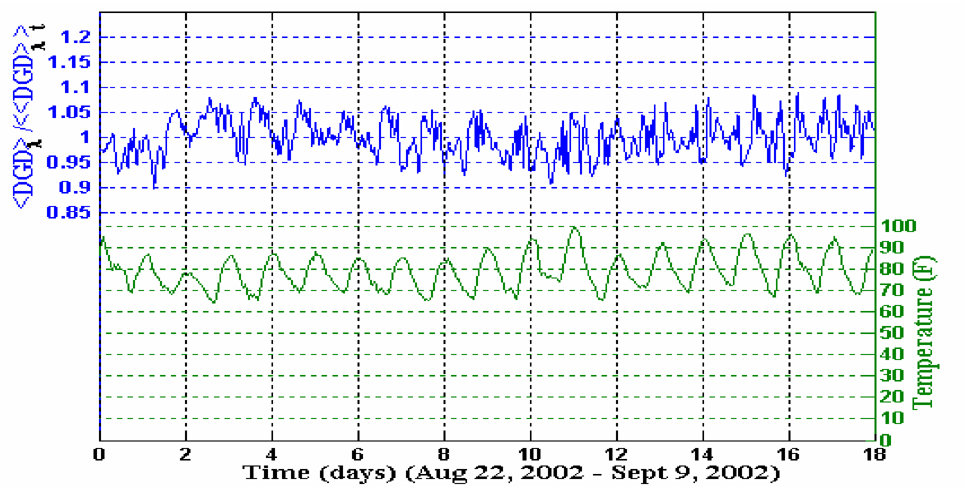
DGD histogram



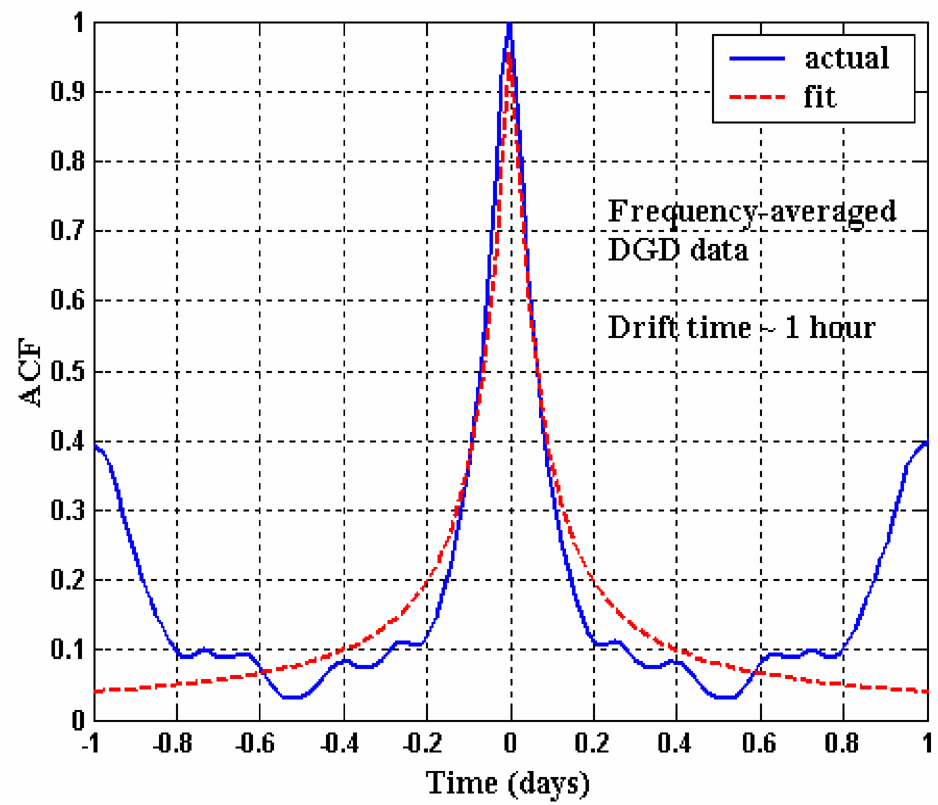
DFT of DGD at 1560 nm



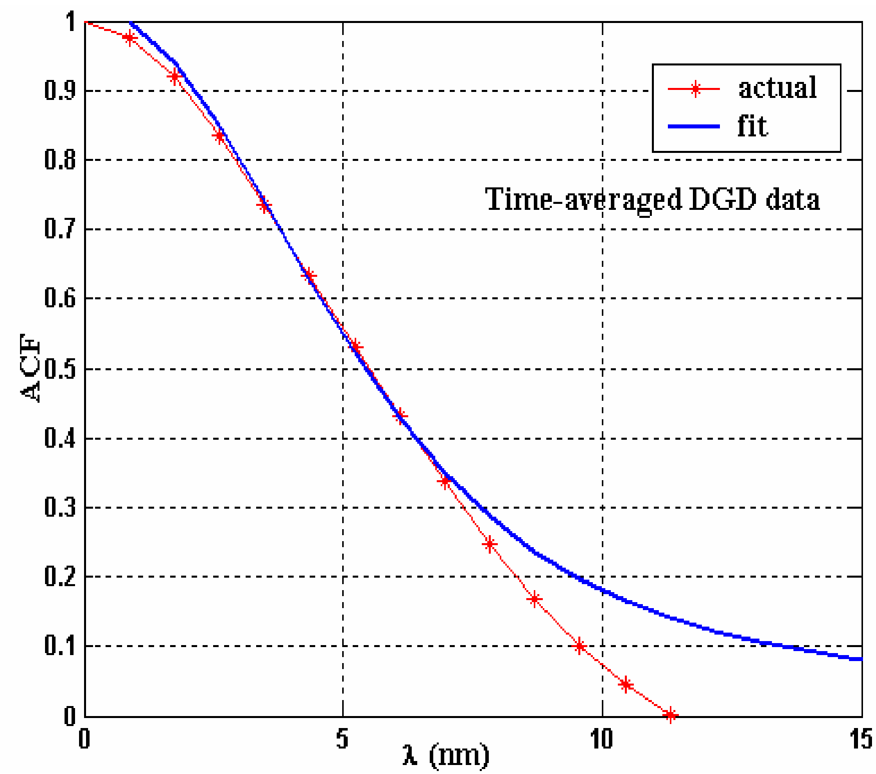
Mean DGD, temperature variation with time



TEMPORAL AND SPECTRAL ACFs FOR SPANS 1 & 2 CON.

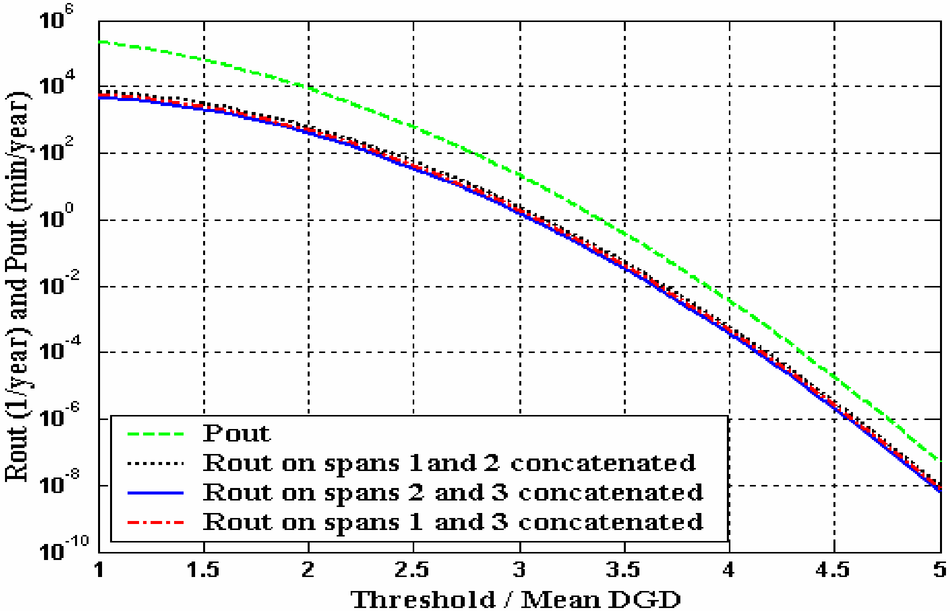


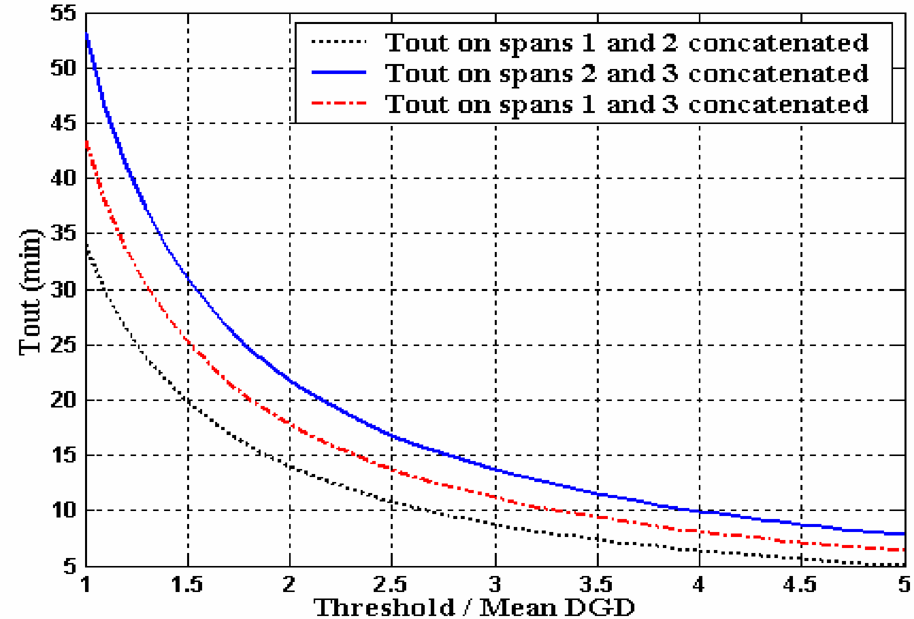
Normalized temporal ACF of frequency-averaged DGD data on fiber spans 1 and 2 concatenated and its theoretical curve-fit



Normalized spectral ACF of time-averaged DGD data on fiber spans 1 and 2 and it's adjusted theoretical curve-fit

SYSTEM OUTAGE ANALYSIS





Calculated P_{out}, R_{out}, and T_{out} versus threshold/mean DGD for two-fiber configurations

	3*<DGD>	**3.7*<DGD>**
Spans 1&2: MTBO Outage duration	0.413 years 9 min	106 years 7 min
Spans 2&3: MTBO Outage duration	0.644 years 14 min	167 years 11 min
Spans 1&3: MTBO Outage duration	0.525 years 11 min	135 years 9 min

MTBO = mean time between outages

$= 1 / R_{out}$

DESIGN RULES BASED ON DGD MARGIN

- DGD margin $M_\tau = \Delta\tau_{Rx} / \langle\Delta\tau\rangle$; $\Delta\tau_{RX}$ is receiver's DGD tolerance and $\langle\Delta\tau\rangle$ is the mean DGD
- For cases where $M_\tau > 3$, the frequency of PMD-induced outages will be low, and their duration may be brief
  - Use of reserved protection channels in WDM systems is a viable solution
- For cases where $M_\tau < 3$, the frequency of PMD-induced outages will be high with reasonably long duration
  - Use of PMD compensators, alternate modulation formats, or even replacing particular fiber segments may be appropriate

CONCLUSIONS

- An automated PMD measurement system was used to make long-term measurements on buried fibers
- Results showed DGD to vary slowly with time and high-DGD episodes to be spectrally localized
- DGD histograms had shapes consistent with Maxwellian
- <DGD> varied by 10 % or less during the measurements
- Drift times of DGD, measured for a long period, agreed with those reported by others, but needs further study
- DGD bandwidths estimated agreed well with those found using the theoretical spectral autocorrelation fits
- Outage analysis showed DGD excursions of > 3 times the <DGD> to be infrequent and relatively short lived

FUTURE WORK

- Variation of DGD with controlled fiber temperatures could be studied using a temperature chamber
- A detailed study of second-order PMD on buried fibers would be extremely useful
- Discrepancy in temporal autocorrelation analysis should be studied
- It would be interesting to see if the behavior observed on two-fiber configurations is repeatable with buried EDFAs

QUESTIONS?