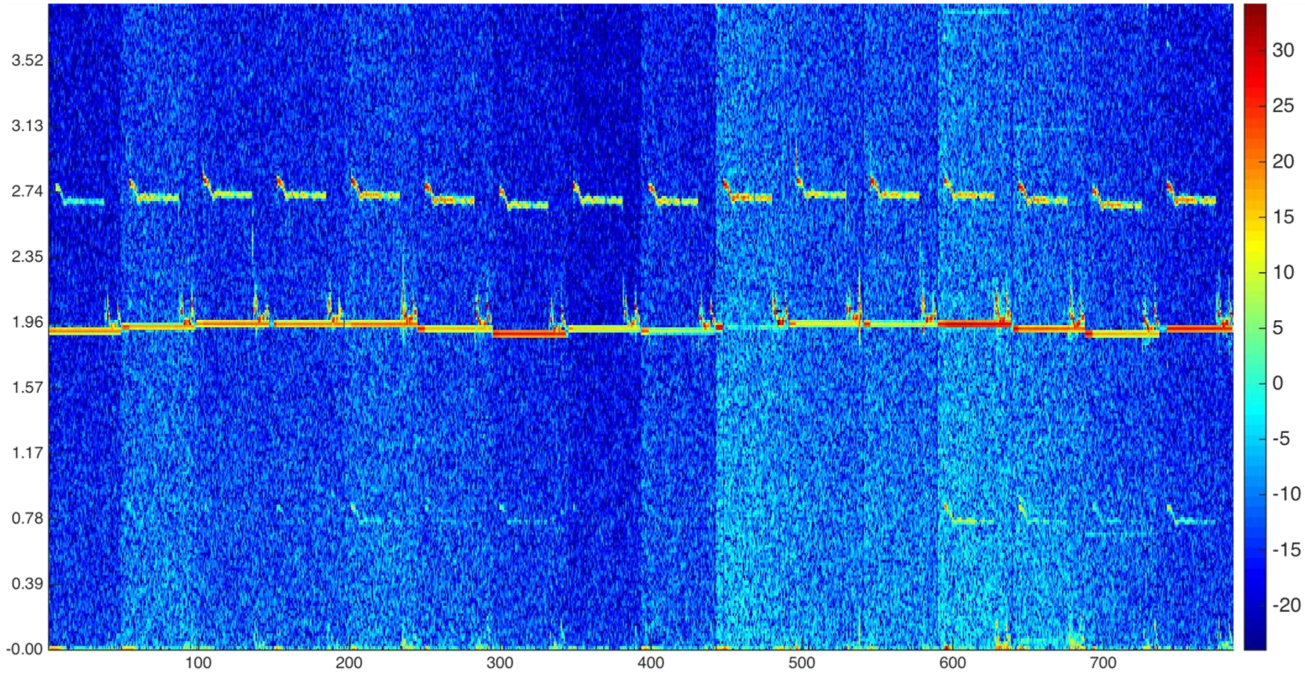
DOE/NV/25946--2857

Some Practical Issues in Deep-Time Multiplexing



Michael Peña
Defense Experimentation and Stockpile Stewardship
National Security Technologies, LLC

NEVADA NATIONAL NNSS SECURITY SITE

Managed and operated by
National Security Technologies, LLC

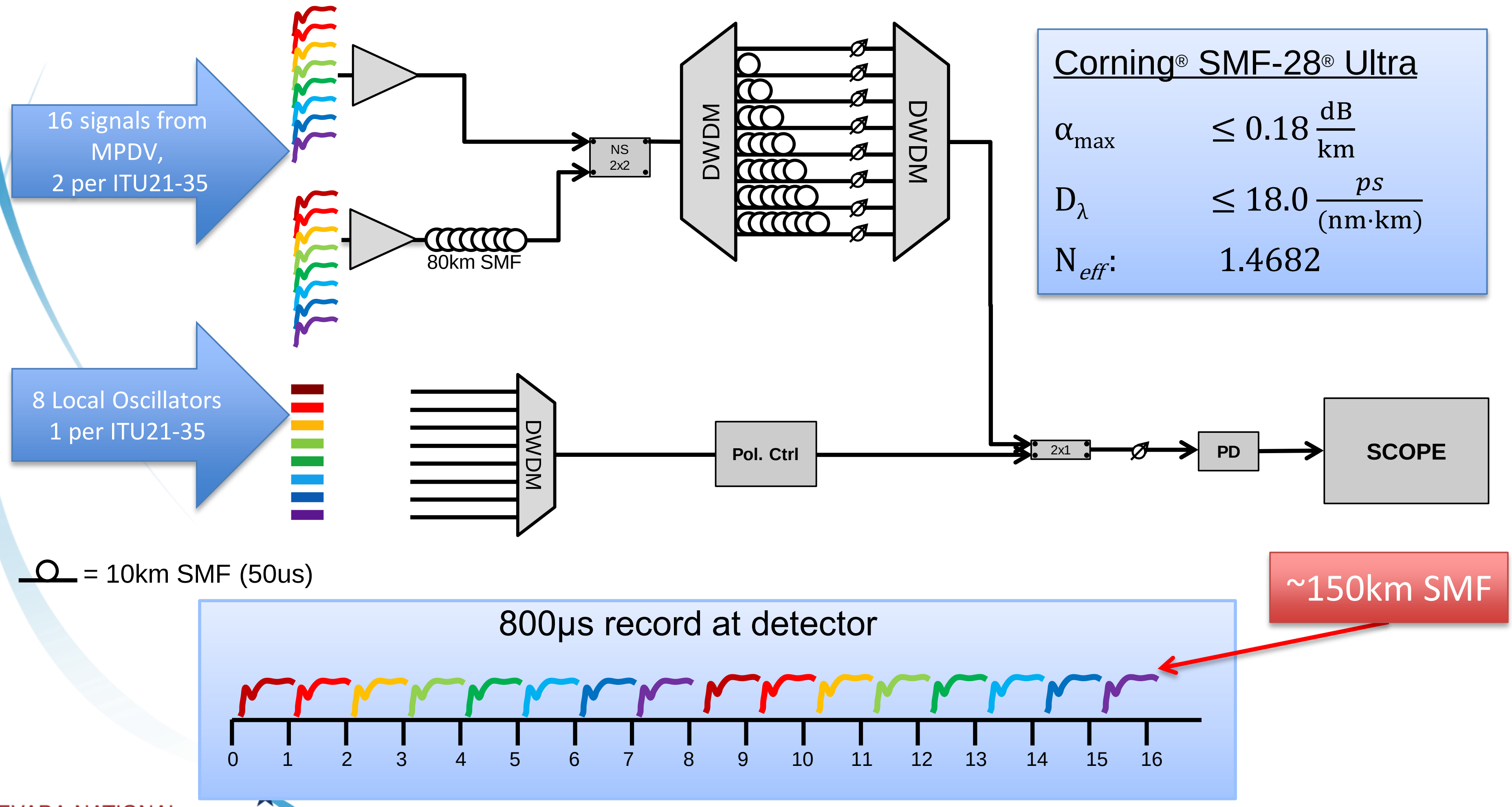
This work was done by National Security Technologies, LLC, under Contract No. DE-AC52-06NA25946 with the U.S. Department of Energy.

Outline

- Deep-time multiplexing
  - Conceptual design
- Index of refraction variations
  - Wavelength
  - Temperature
- State of Polarization
  - Stability
  - Control

Deep-Time Approach ROADDM

- Reconfigurable Optical Add Drop "Delay" Module



Corning® SMF-28® Ultra

α_{max} $\leq 0.18 \frac{dB}{km}$

D_λ $\leq 18.0 \frac{ps}{(nm \cdot km)}$

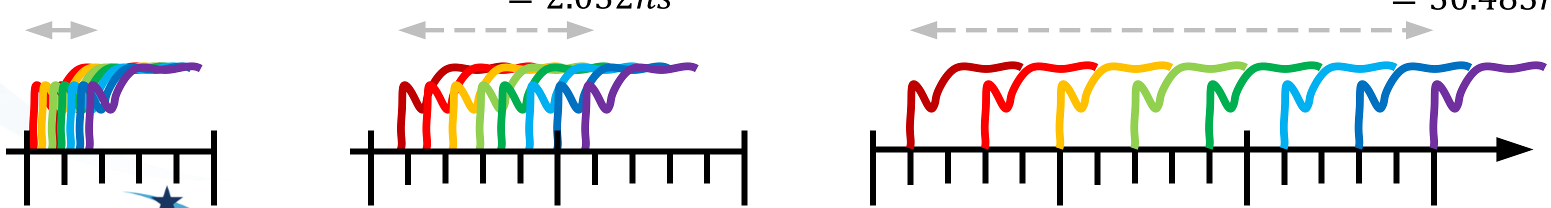
N_{eff}: 1.4682

Wavelength-Dependent Index of Refraction

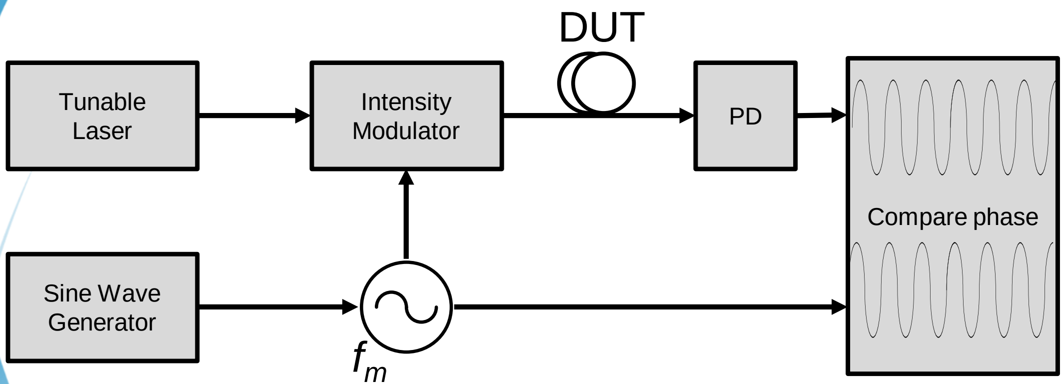
- *Index of Refraction,* $n(\lambda)$
- *Phase Velocity,* v_p: $\frac{\omega}{k}$ $\qquad \frac{c_o}{n(\lambda)}$
- *Group Velocity,* v_g: $\frac{d\omega}{dk};\ d\lambda = \frac{-\lambda^2}{2\pi c_o} d\omega$ $\qquad \frac{c_o}{n(\lambda)}\left(1 - \frac{\lambda}{n}\frac{dn}{d\lambda}\right)^{-1}$
- *Group Velocity Dispersion, GVD*: $\frac{d^2k}{d\omega^2}$ $\qquad \frac{\lambda^3}{2\pi c_o^2}\frac{d^2n}{d\lambda^2}$
- *Group Delay,* $\tau_g = \frac{L}{v_g} = \frac{d\varphi}{d\omega}$: $\frac{d\varphi}{d\omega} = \frac{d(kL)}{d\omega}$ $\qquad \frac{n}{c_o}\left(1 - \frac{\lambda}{n}\frac{dn}{d\lambda}\right) L$
- *Group Delay Dispersion, GDD*: $\frac{d\tau_g}{d\omega} = \frac{d^2(kL)}{d\omega^2}$ $\qquad \frac{\lambda^3}{2\pi c_o^2}\frac{d^2n}{d\lambda^2} L$

$$18\left[\frac{ps}{nm \cdot km}\right] \times 10[km] \times (1560.61 - 1549.32)[nm] = 2.032ns$$

$$18\left[\frac{ps}{nm \cdot km}\right] \times 150[km] \times (1560.61 - 1549.32)[nm] = 30.483ns$$



Modulation Phase Shift Dispersion Measurement



Measurement setup for fiber chromatic dispersion

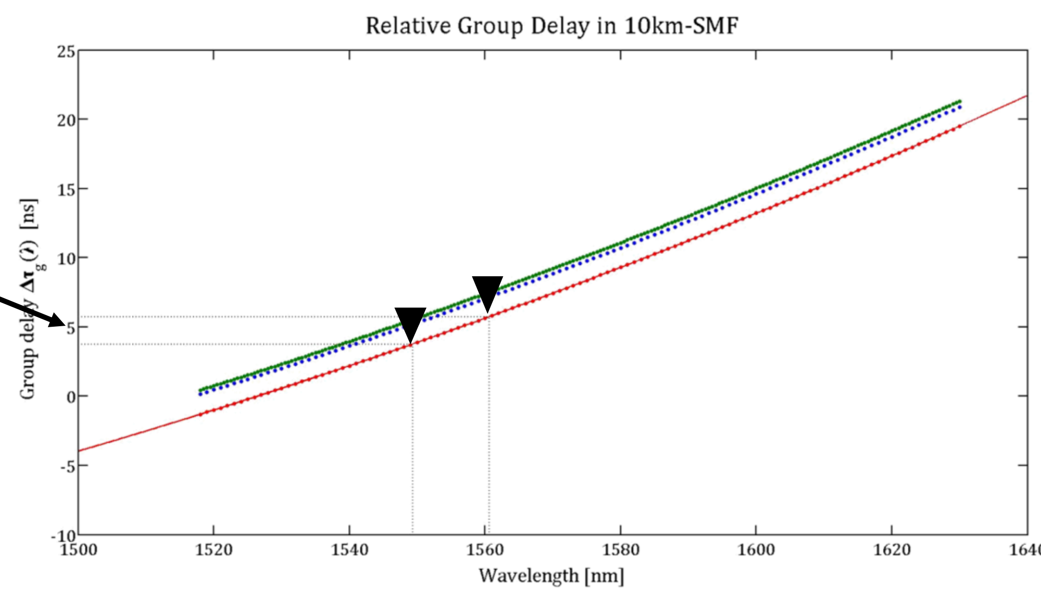
$$\Delta\tau_g(\lambda) = \frac{\varphi(\lambda) - \varphi(\lambda_r)}{360°}\frac{1}{f_m}$$

$$D(\lambda) = \frac{1}{L}\frac{d\left(\Delta\tau_g(\lambda)\right)}{d\lambda} = \frac{1}{360° L f_m}\frac{d\varphi(\lambda)}{d\lambda}$$

$$\Delta\tau(\lambda) = 0.00029598\lambda^2 - 0.7348\lambda + 440.16$$

$$\Delta\tau(1560.61\text{nm}) - \Delta\tau(1549.32\text{nm}) = 1.97305\text{ns}$$

$$D_\lambda = \frac{1973.05ps}{11.29nm \cdot 10km} = 17.476\left[\frac{ps}{nm \cdot km}\right]$$



Temperature-Dependent Index of Refraction

LUNA Technical Note EN_FY1406,

$$\frac{\Delta\tau}{\tau} = \frac{1}{L}\frac{\partial L}{\partial T}\Delta T + \frac{1}{n}\frac{\partial n}{\partial T}\Delta T = (\alpha_L + \alpha_n)\Delta T$$

α_L *: thermal expansion coeff*

0.55×10^{-6} °C^{-1}

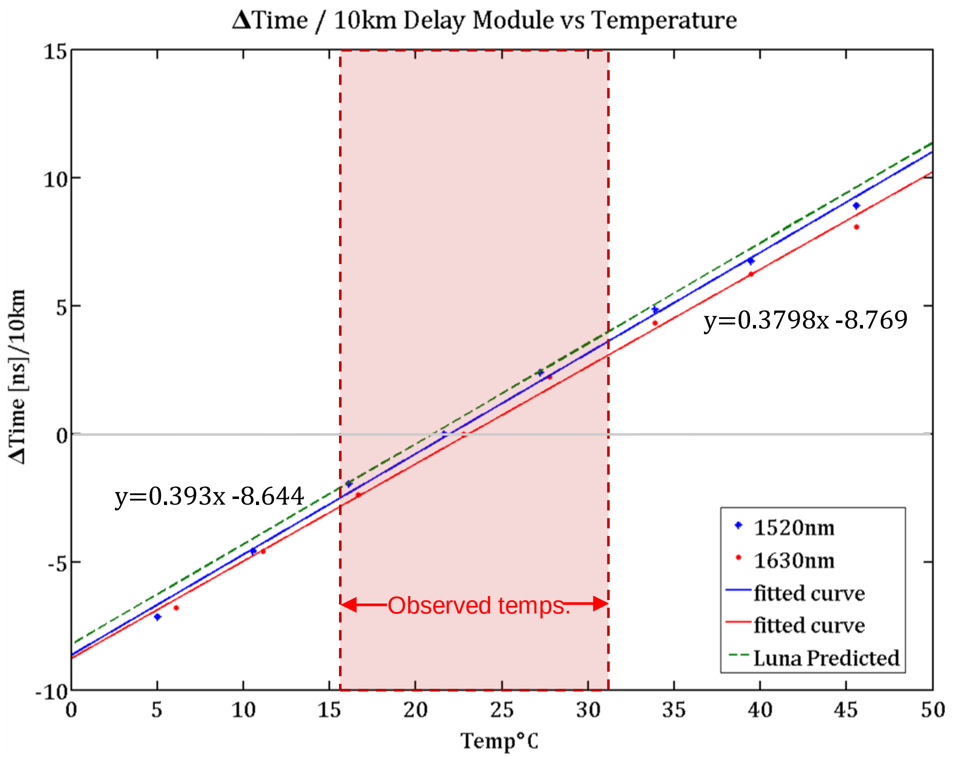
α_n *: thermo-optic coeff*

~7.0 to 9.0×10^{-6} °C^{-1}

(7.5×10^{-6} used below)

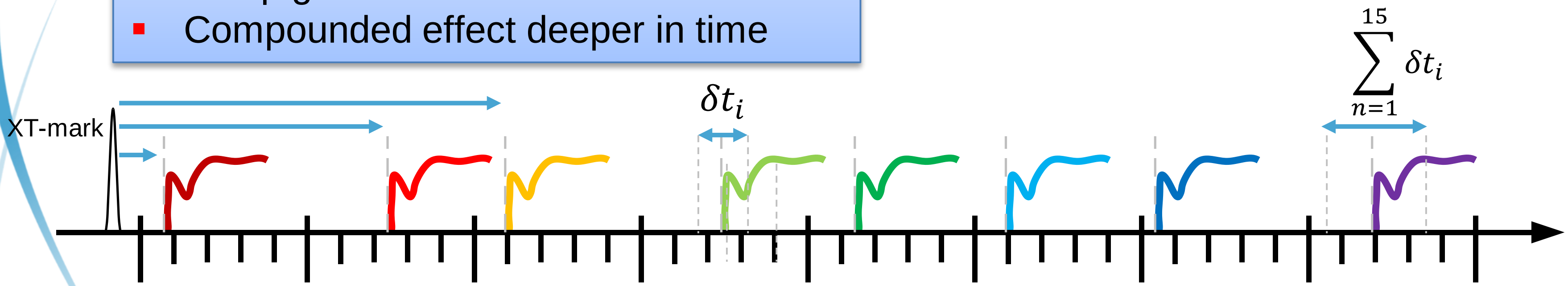
$$385\ \frac{ps}{°C \cdot 10km} \cdot 15\ delays = 5.78\frac{ns}{°C}$$

$$\left(210\ \frac{ps}{°F \cdot 10km} \cdot 15\ delays = 3.15\frac{ns}{°F}\right)$$

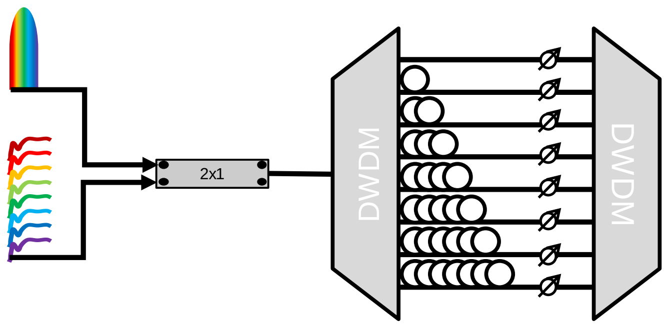


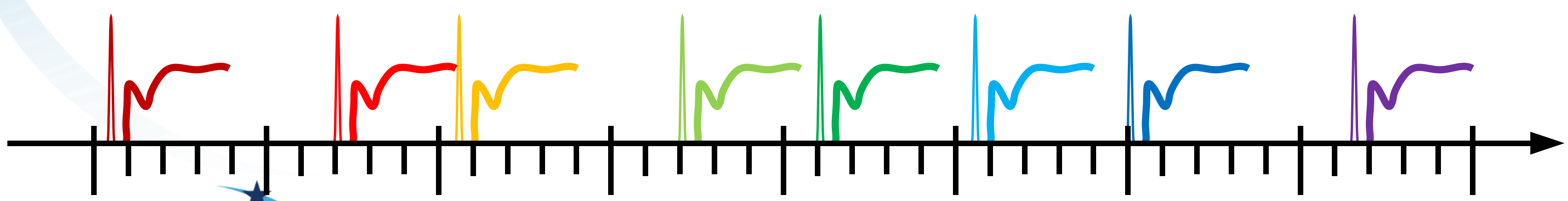
In situ Cross-Timing Mark

- Single XT-mark for 16 records (only 8 shown)
- Temperature fluctuations ~1–16 ns
- Temp gradients = inconsistent δt
- Compounded effect deeper in time

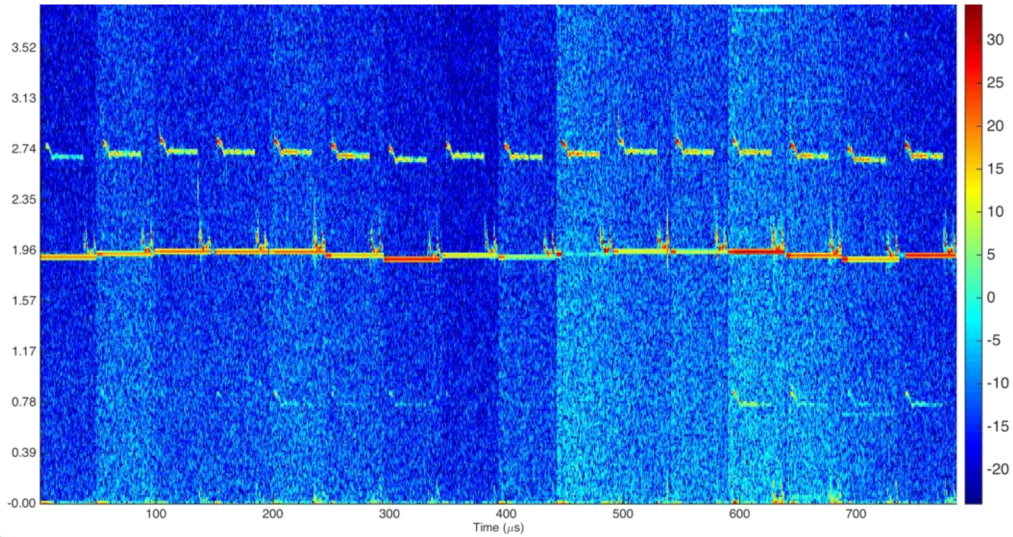


- ✓ XT-mark in each time window
  - ✓ Follow temp-time fluctuations
- ✓ XT-mark inherently same λ as velocity record

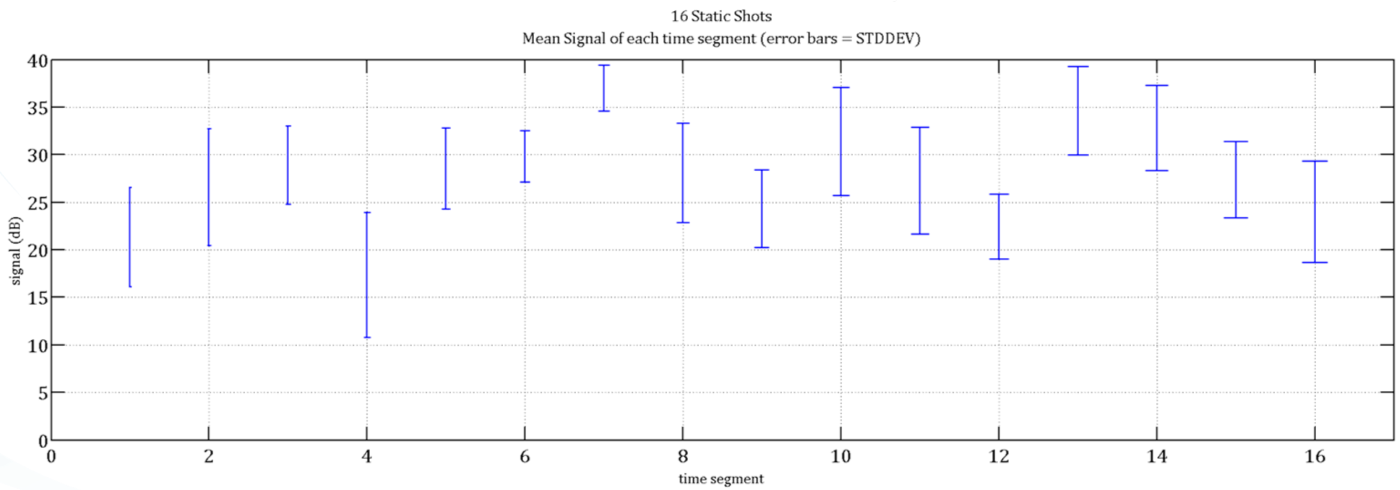




Static Signal Fluctuations

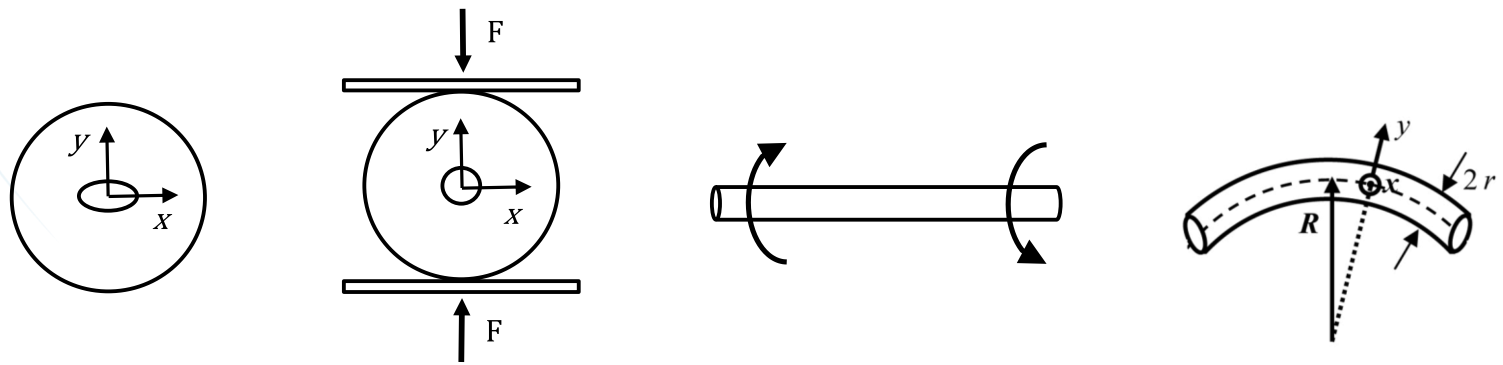


- All channels seeing same probe
- 30 m jumpers to firing chamber
- Shot-to-shot variability ~10 dB



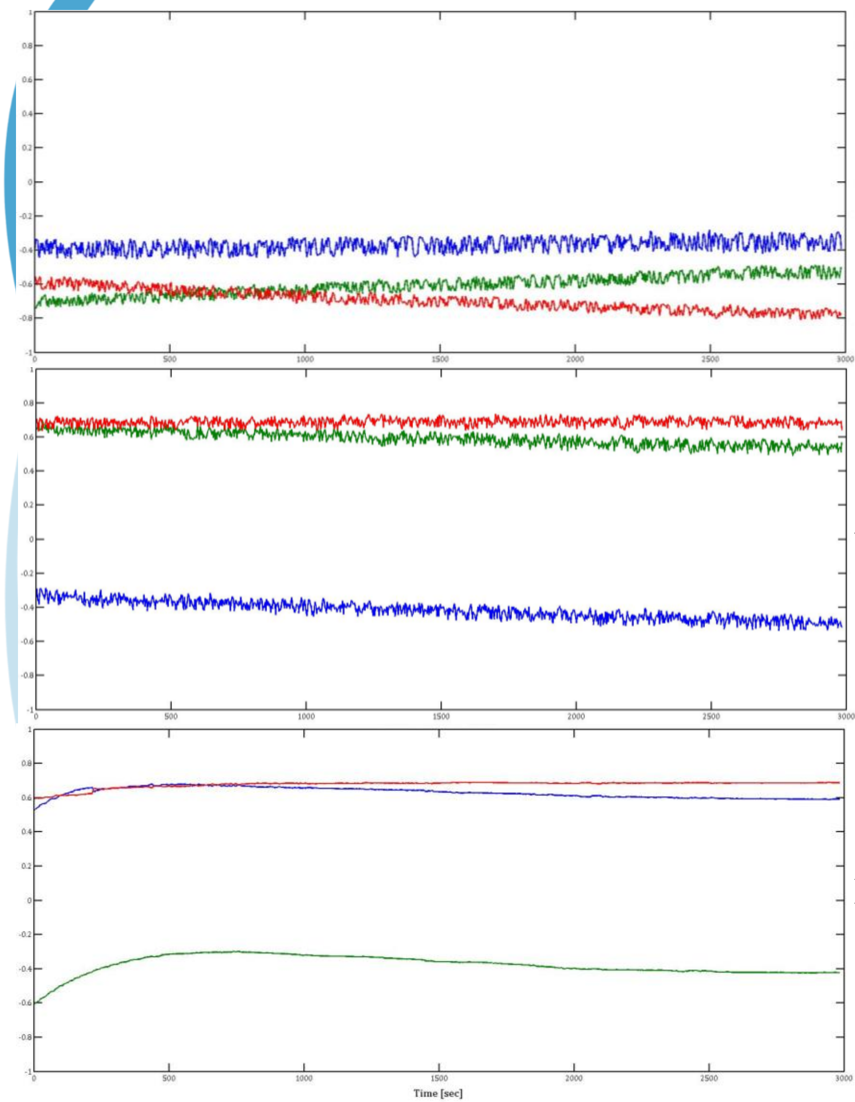
Polarization/Induced Birefringence

- Real single-mode fibers exhibit elliptical birefringence due to
  - Deviations of core shape from circularity
  - Lateral compression
  - Residual twist
  - Bending



Core ellipticity Compression Twist Bending

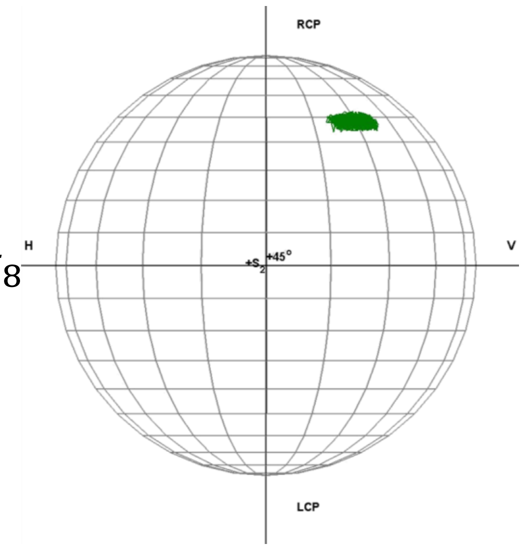
Stokes Parameters vs. 50 min

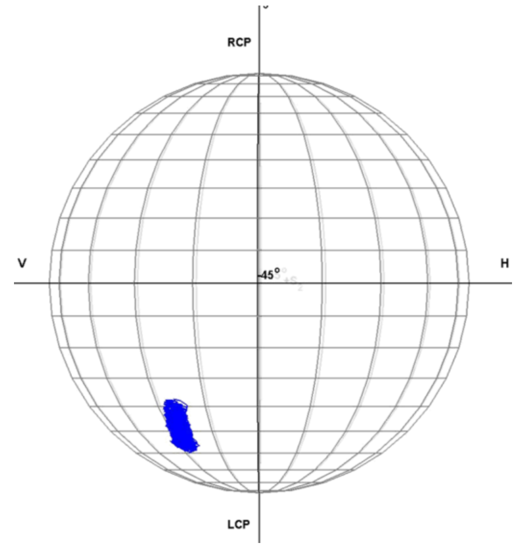


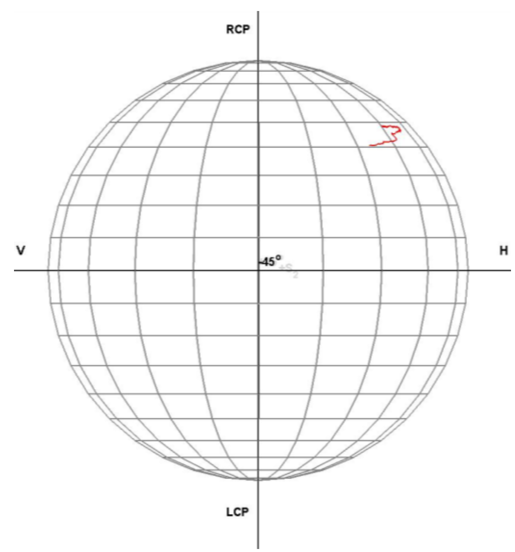
τ_1

τ_8

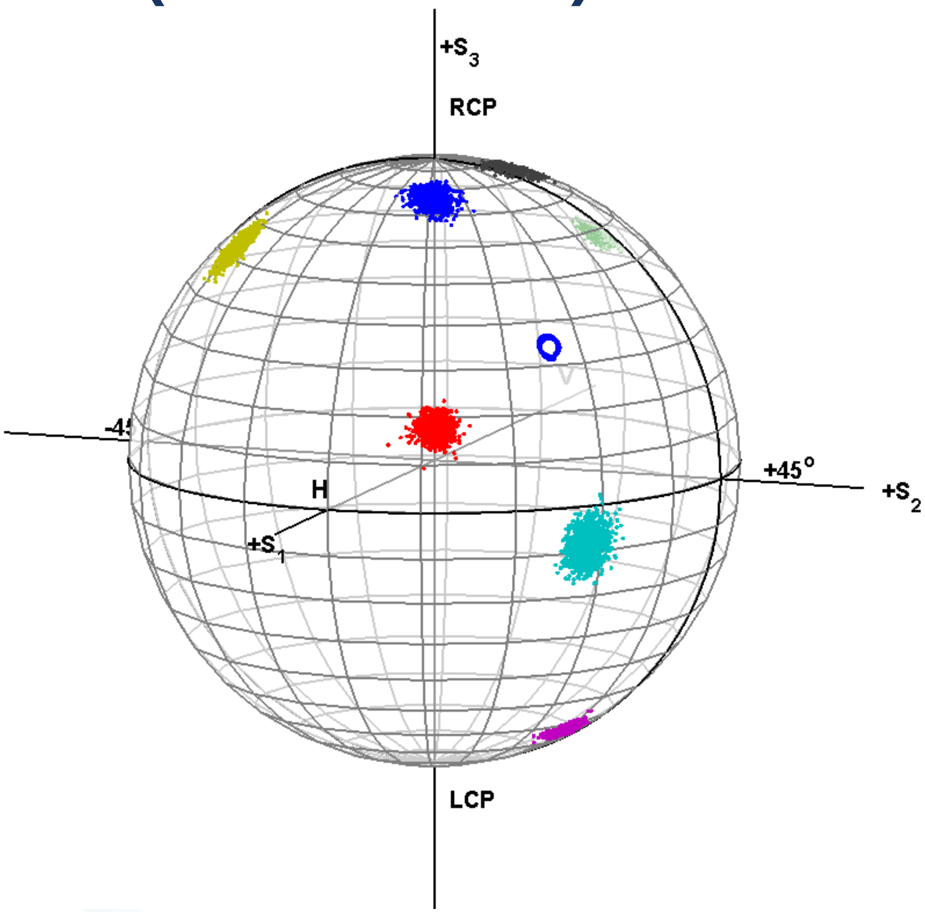
LO21

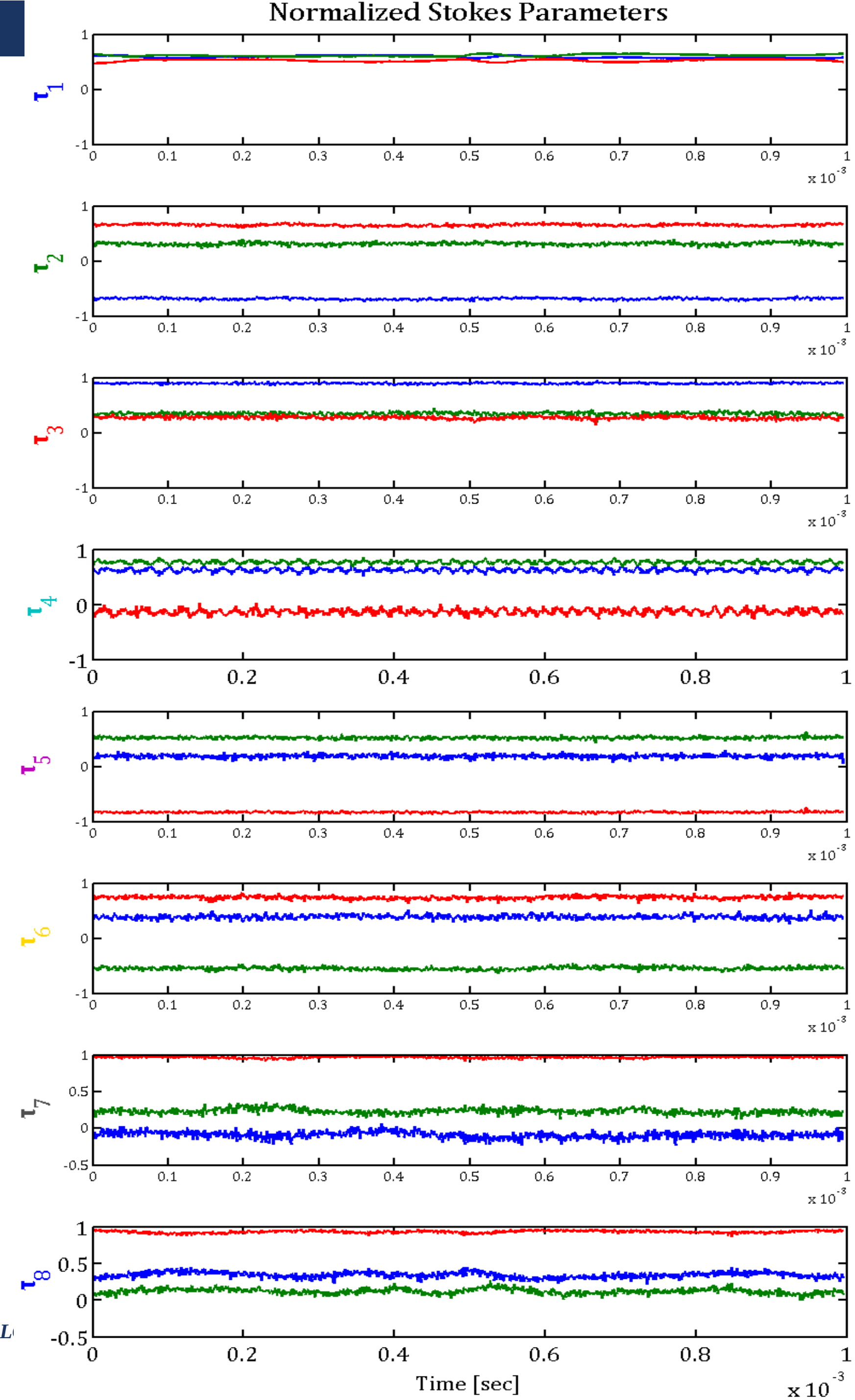






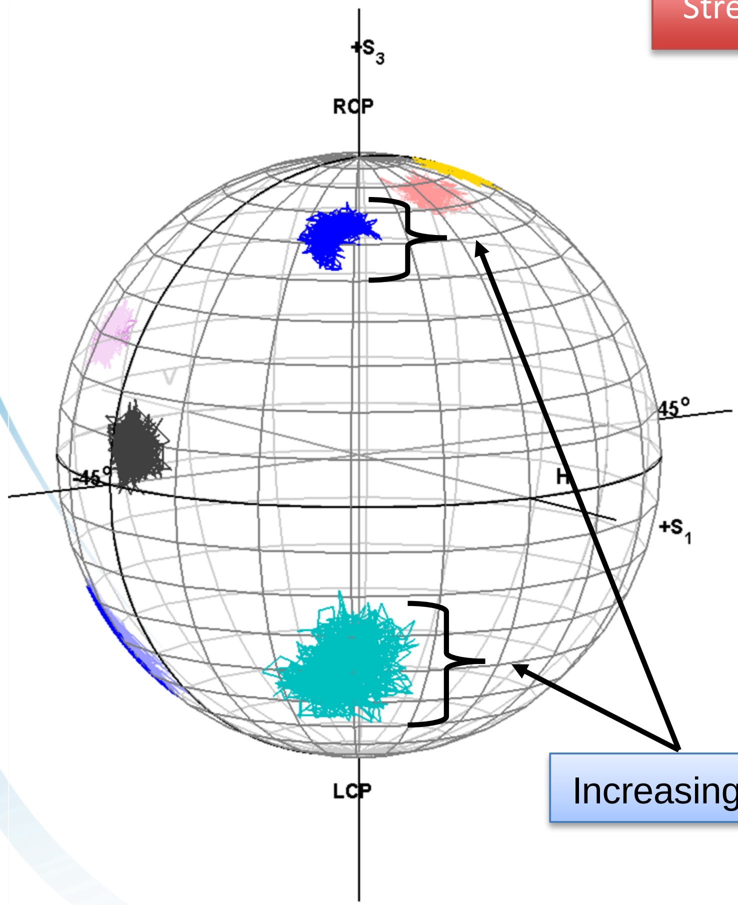
Tau Windows 1 through 8 (1 millisecond)



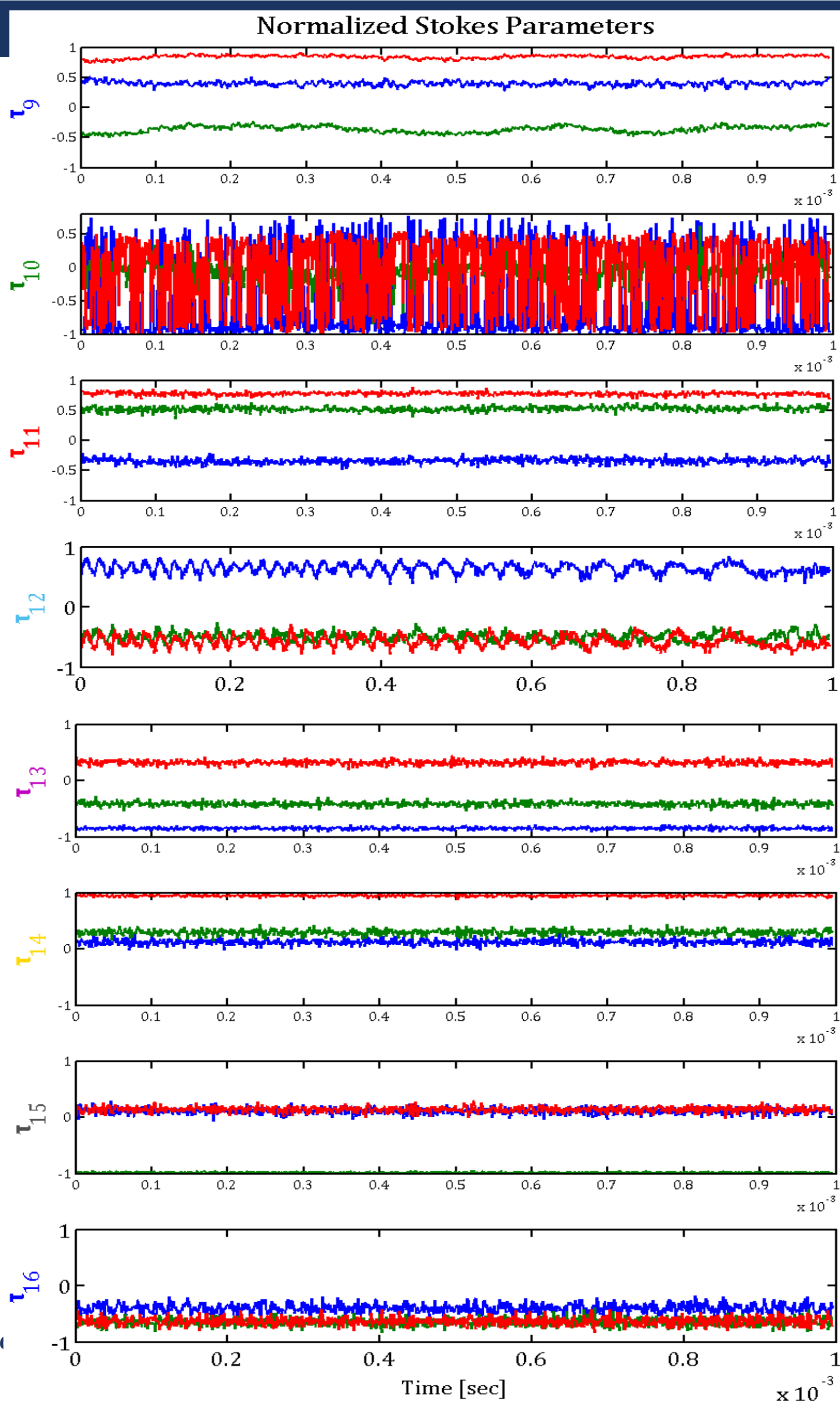


Tau Windows 9 through 16 (1 millisecond)

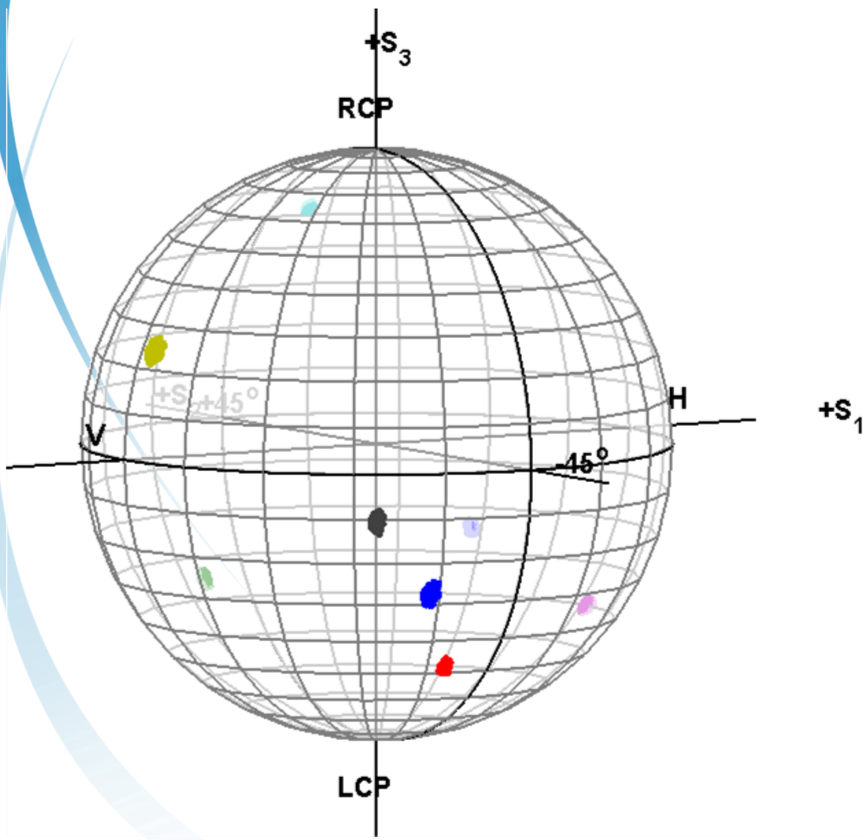
Stressed Fiber?

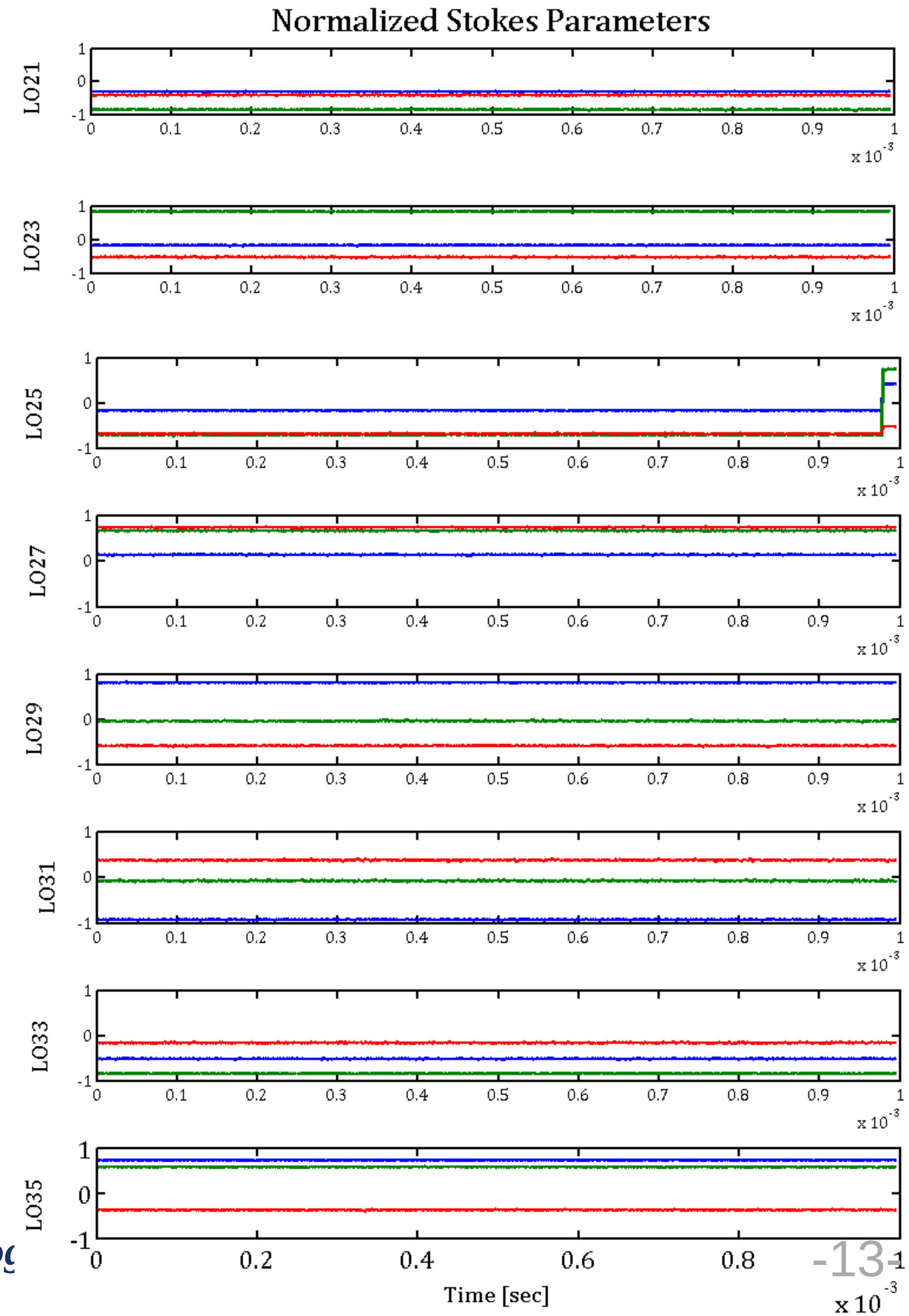


Increasing variations

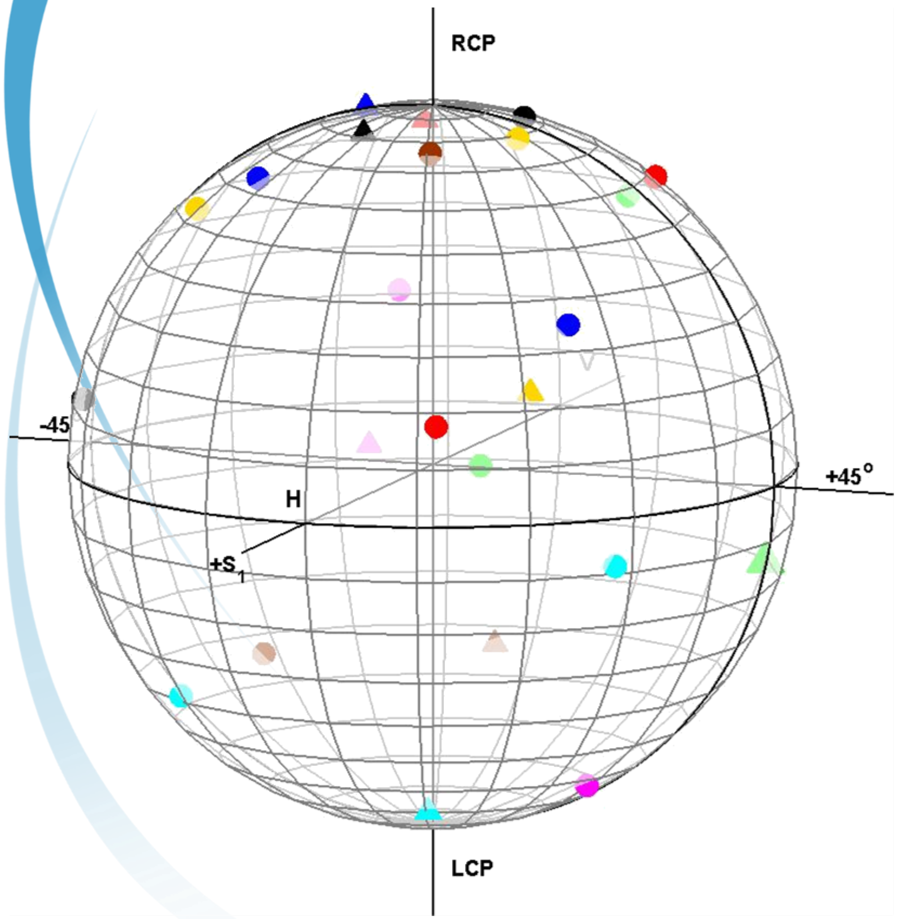


Local Oscillator SOP (1 millisecond)





Aligning Local Oscillators with Signals



$QW_1 = \frac{\pi}{2}$ $QW_2 = \frac{5\pi}{3}$ $QW_3 = \frac{\pi}{3}$ $QW_4 = \frac{\pi}{3}$

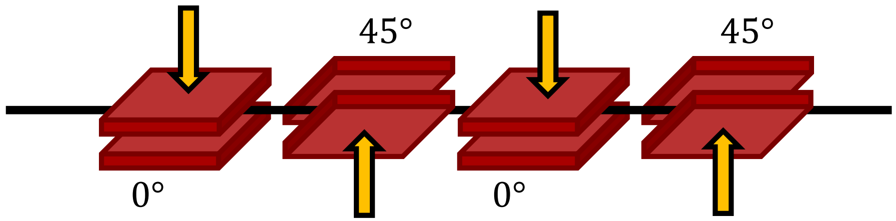
Dot Products (Signal,LO)

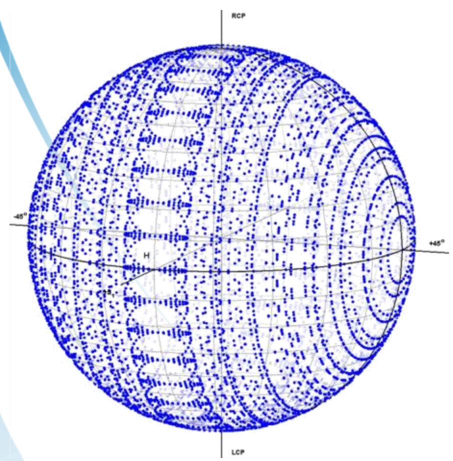
$\tau_1 = 0.3546$	$\tau_9 = 0.8797$	ITU21
$\tau_2 = 0.4207$	$\tau_{10} = 0.3000$	ITU23
$\tau_3 = -0.1510$	$\tau_{11} = 0.7326$	ITU25
$\tau_4 = 0.5092$	$\tau_{12} = 0.7100$	ITU27
$\tau_5 = -0.3259$	$\tau_{13} = 0.8980$	ITU29
$\tau_6 = 0.2449$	$\tau_{14} = 0.5950$	ITU31
$\tau_7 = 0.8789$	$\tau_{15} = 0.2652$	ITU33
$\tau_8 = -0.8642$	$\tau_{16} = 0.7807$	ITU35

$$-1 \leq [Signal \cdot LO] \leq 1$$

Polarization Controllers – Fiber Squeezers (EPC-300)

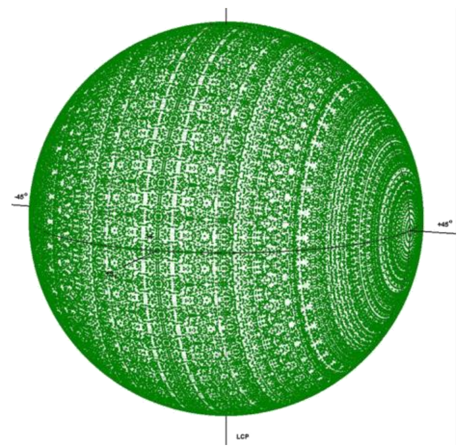
- Not all inputs are affected equally!





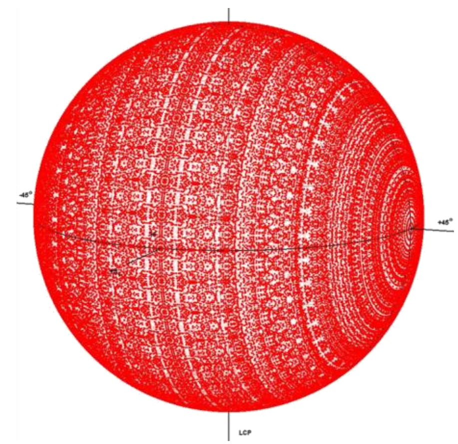
$$S_{out} = M_{0°45°0°45°} \begin{bmatrix}1\\0\\0\end{bmatrix}$$

Linear Horizontal



$$S_{out} = M_{0°45°0°45°} \begin{bmatrix}0\\1\\0\end{bmatrix}$$

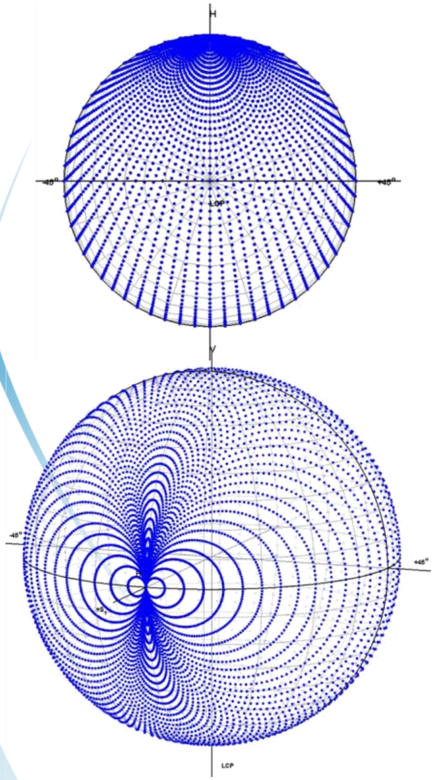
Linear +45



$$S_{out} = M_{0°45°0°45°} \begin{bmatrix}0\\0\\1\end{bmatrix}$$

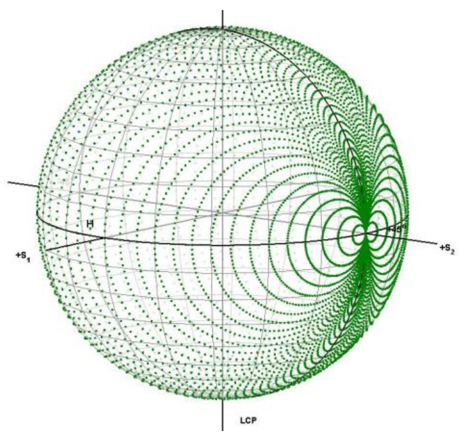
Right Circular

Polarization Controllers – PolarRITE (VarRotQWP)



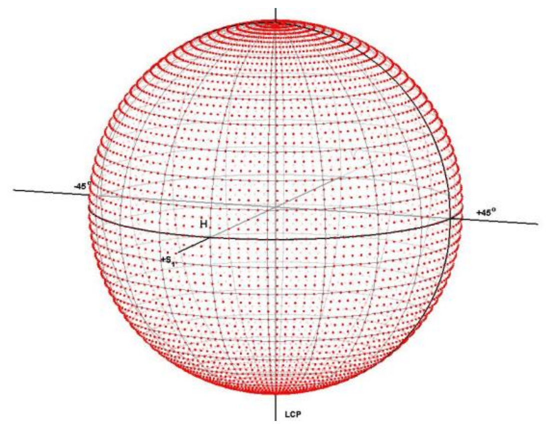
$$S_{out} = M_{\theta,\varphi} \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}$$

Linear Horizontal



$$S_{out} = M_{\theta,\varphi} \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}$$

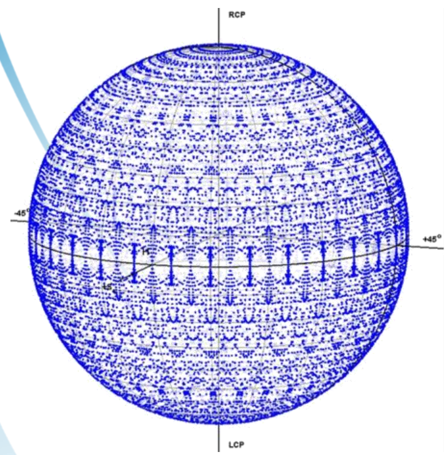
Linear +45



$$S_{out} = M_{\theta,\varphi^{\circ}} \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$$

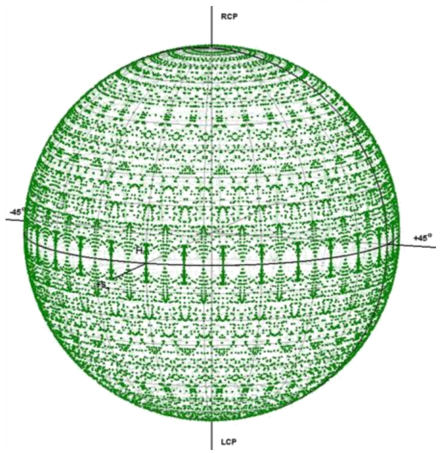
Right Circular

Polarization Controllers 3-Paddle (RQW-RHW-RQW)



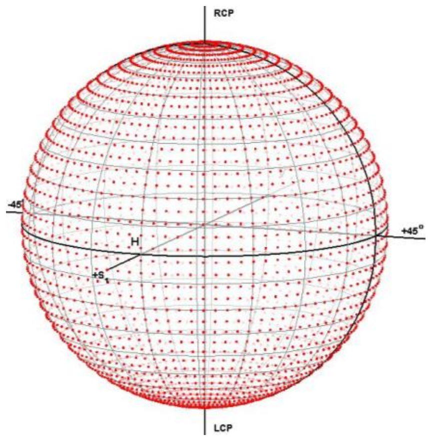
$$S_{out} = M_{\theta_1,\theta_2,\theta_3}\begin{bmatrix}1\\0\\0\end{bmatrix}$$

Linear Horizontal



$$S_{out} = M_{\theta_1,\theta_2,\theta_3}\begin{bmatrix}0\\1\\0\end{bmatrix}$$

Linear +45



$$S_{out} = M_{\theta_1,\theta_2,\theta_3}\begin{bmatrix}0\\0\\1\end{bmatrix}$$

Right Circular

Still a work in progress

- Solution to current systems will need to be:
  - Single- or few-point solution
  - Endless tracking (i.e., no reset or operation discontinuity)
  - Feedback loop, detection and compensation
    - System time constants ~seconds
    - Dynamic excursions from experiment
  - Practical
    - Ease of use
    - Cost
    - Physical footprint

- Looking at all-optical solutions
  - Based on nonlinear interactions
    - Raman, four-wave mixing, SBS

Conclusion

- Timing issues
  - Wavelength- and temperature-dependent Index of Refraction
    - $\sim 21 \frac{ps}{°F \cdot km}$ / $\sim 38 \frac{ps}{°C \cdot km}$
  - In situ timing marks follow time variations
- State of Polarization
  - Each time window will have unique state
  - SOP distribution increases with time
  - SOP relatively stable over ~1 hr and ~100s μs
  - Polarization controllers effect SOPs differently

Questions?