Polarization Activity Monitoring of an Aerial Fiber Link in a Live Network

PEG CONFERENCE

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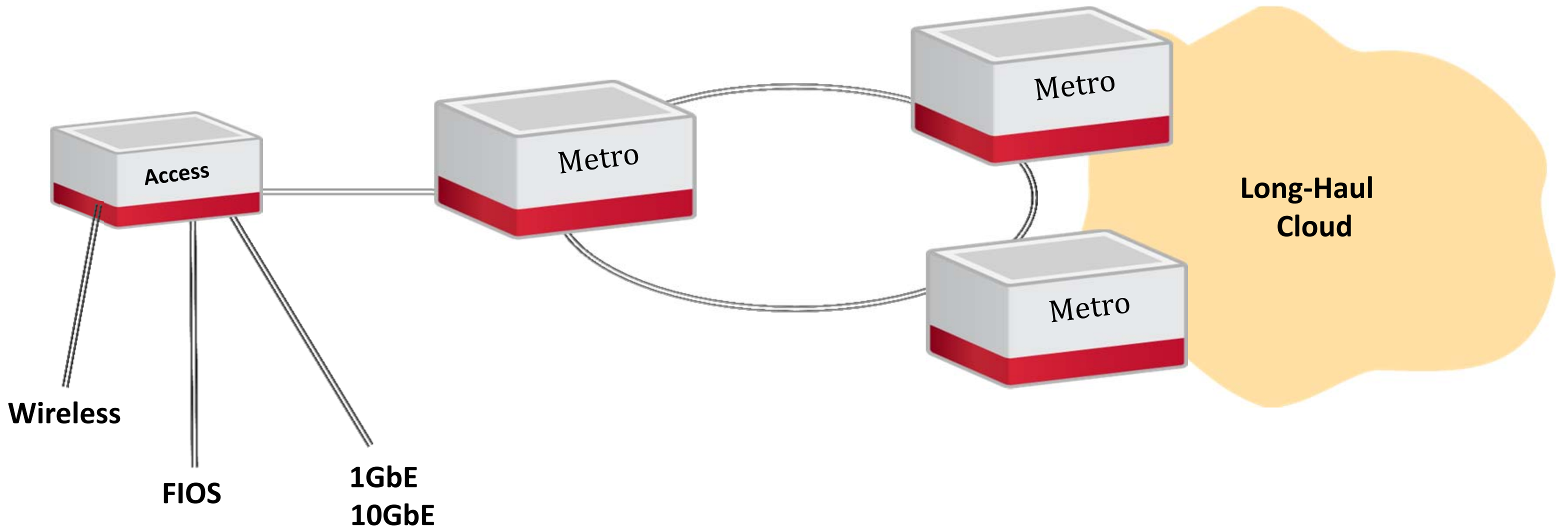
Agenda

- Introduction
- Optical Network/System Hierarchy
- Optical Fiber Basics
- Polarized Light Overview
- Field Measurement of Polarization Dynamics and Correlation to Environmental Conditions
- Next steps

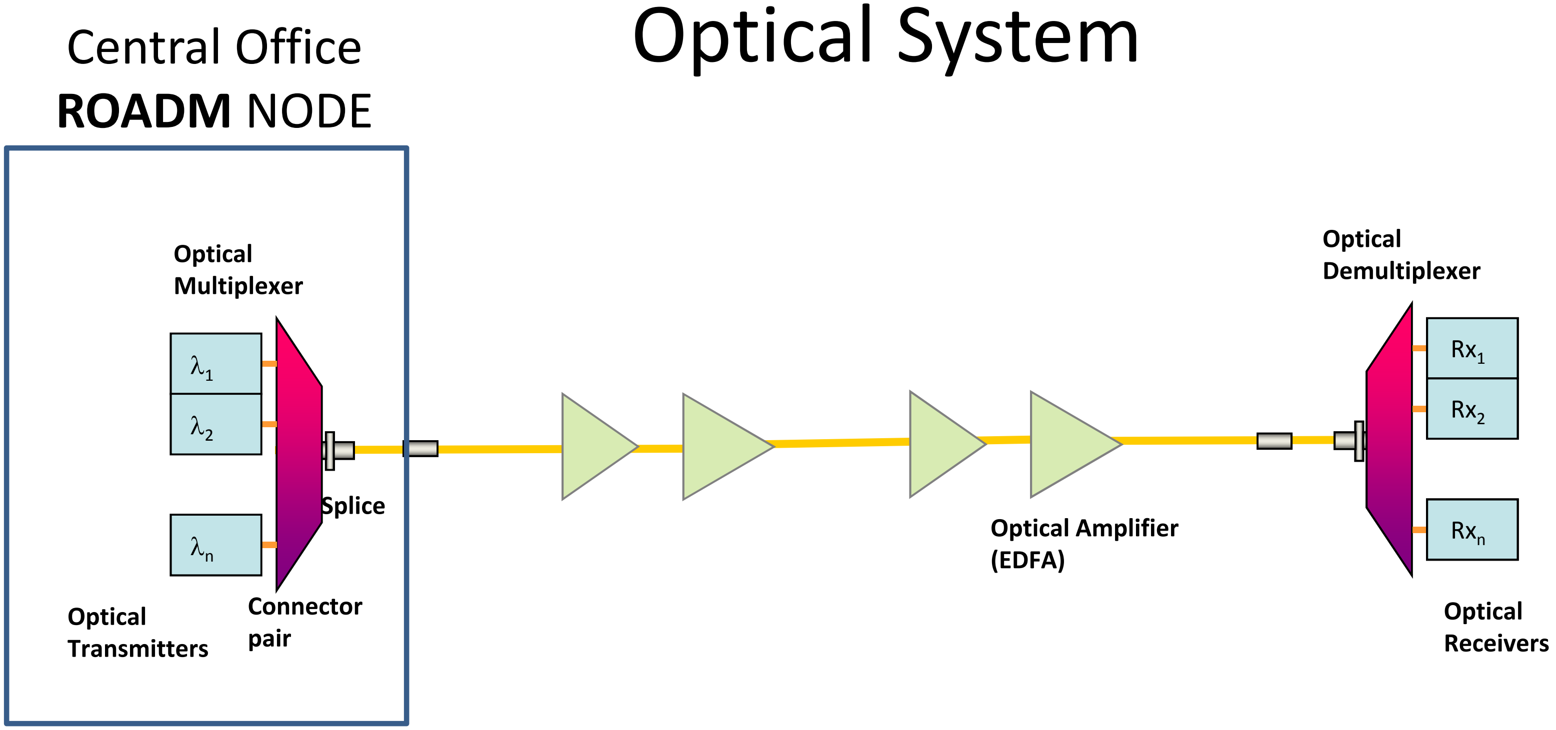
Optical Network and System Overviews

Optical Network



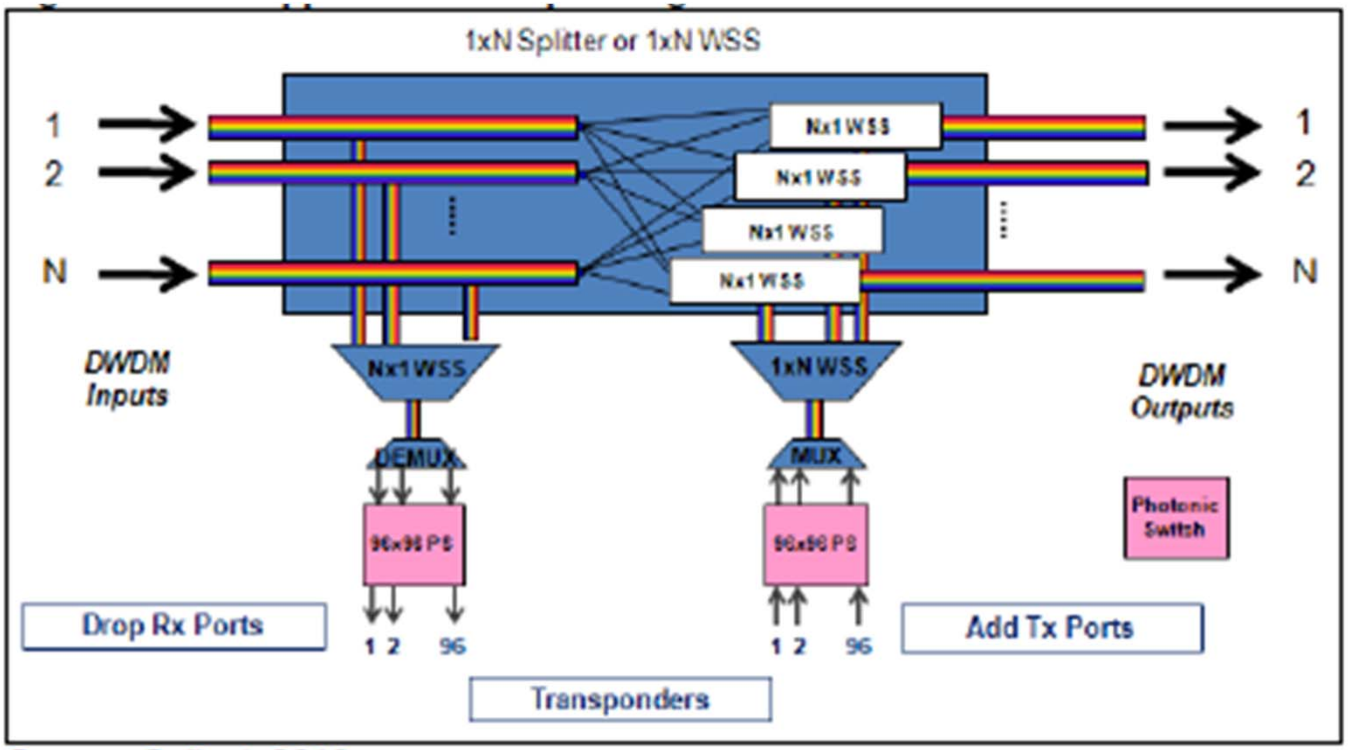
- All Optical to the Access Nodes
- Wavelength Reconfigurable Optical Add/Drop Multiplexer **(ROADM)**

Optical System



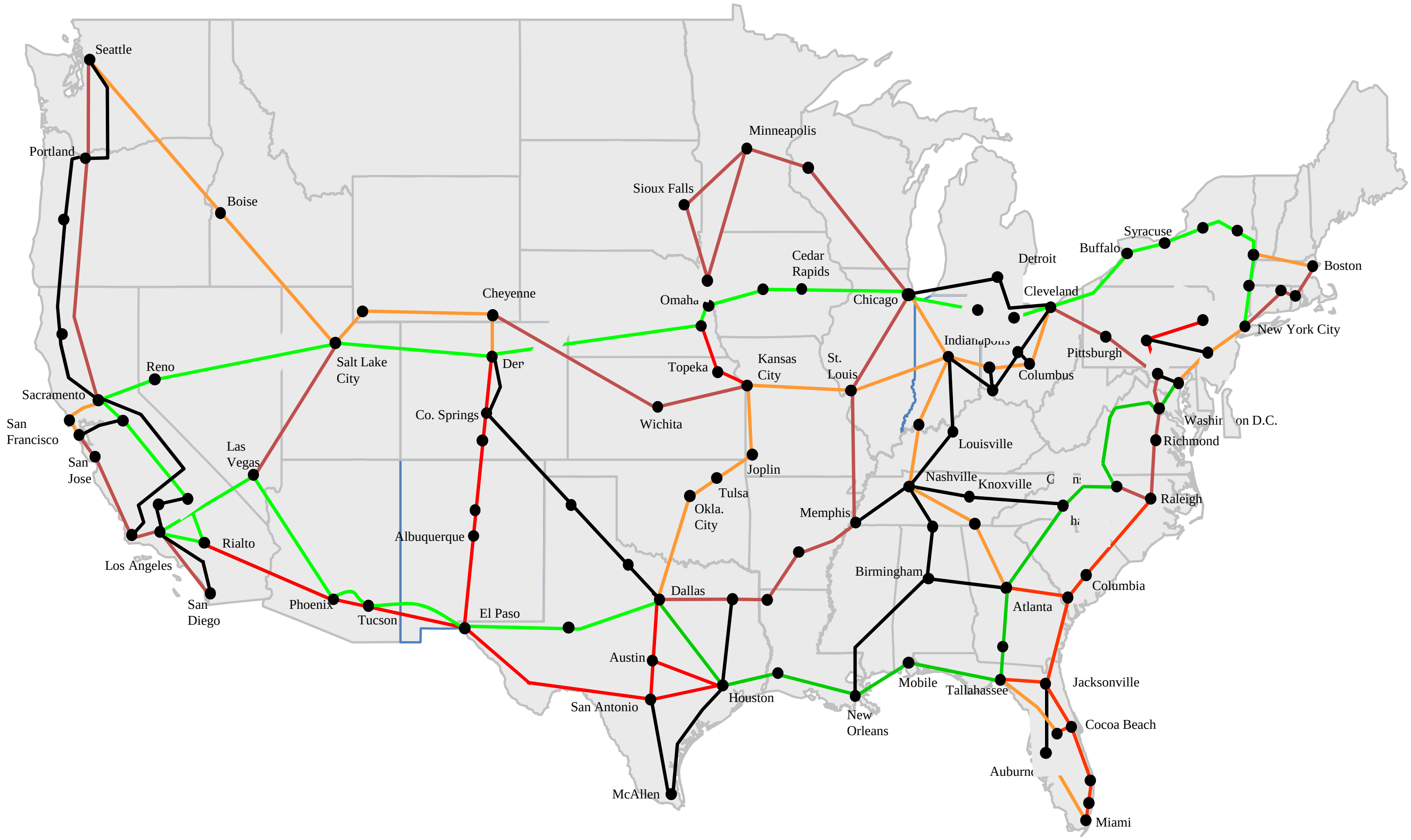
- All Long-haul and Metro nodes are ROADMs
- Wavelength transport - C-band ~1550nm
- Systems have multiple channels/wavelengths/colors separated by increments

ROADM Node



- Multi-degree node – any-to-any direction

Example Optical Long-Haul Network

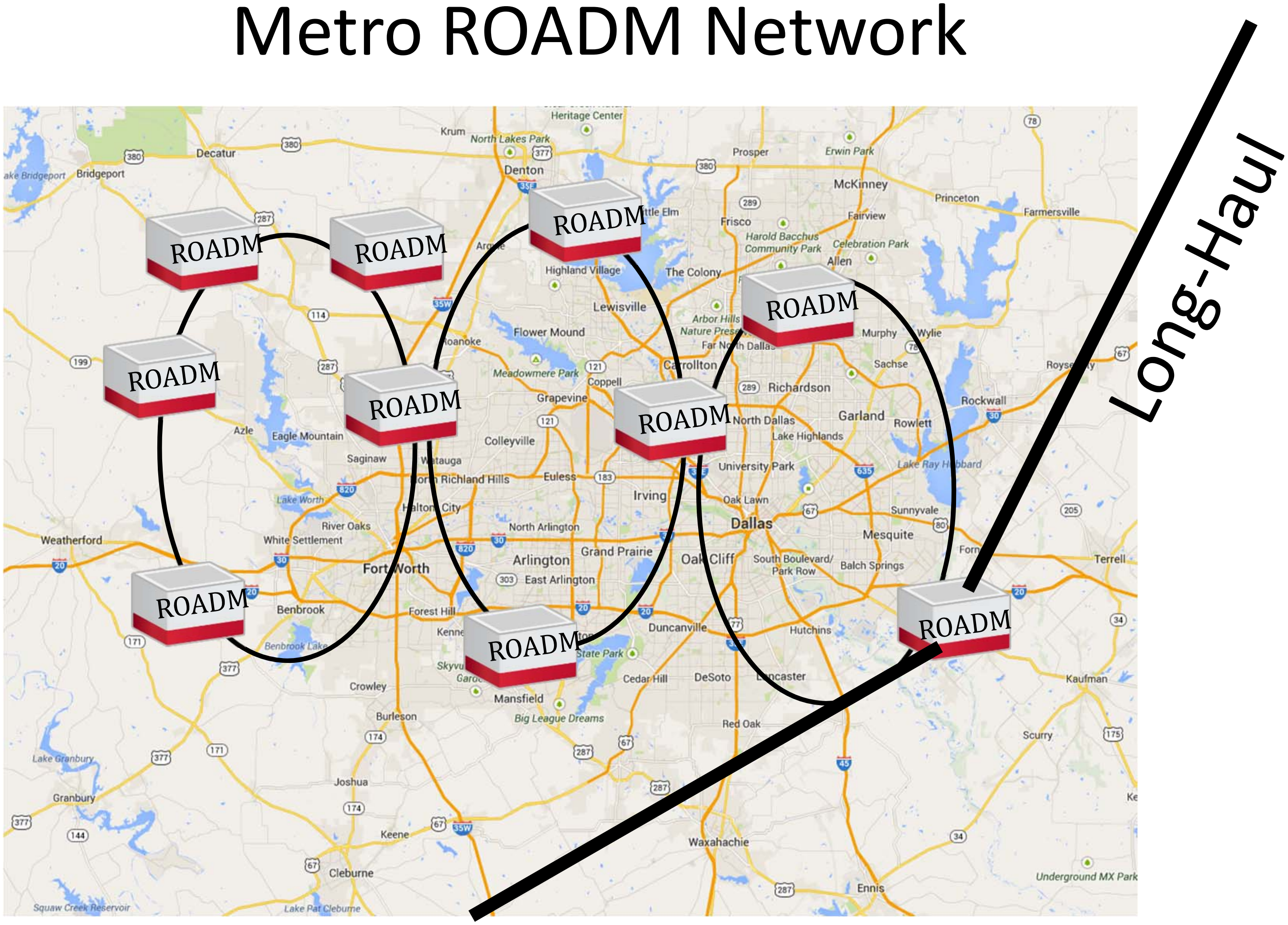


Long-Haul (long distance, LD) Network

- 90+ % rail-plowed – 1986-1994
- Hut-spacing 25km-45km
- Direct-Buried Cables – low fiber-count (24f – 48f)

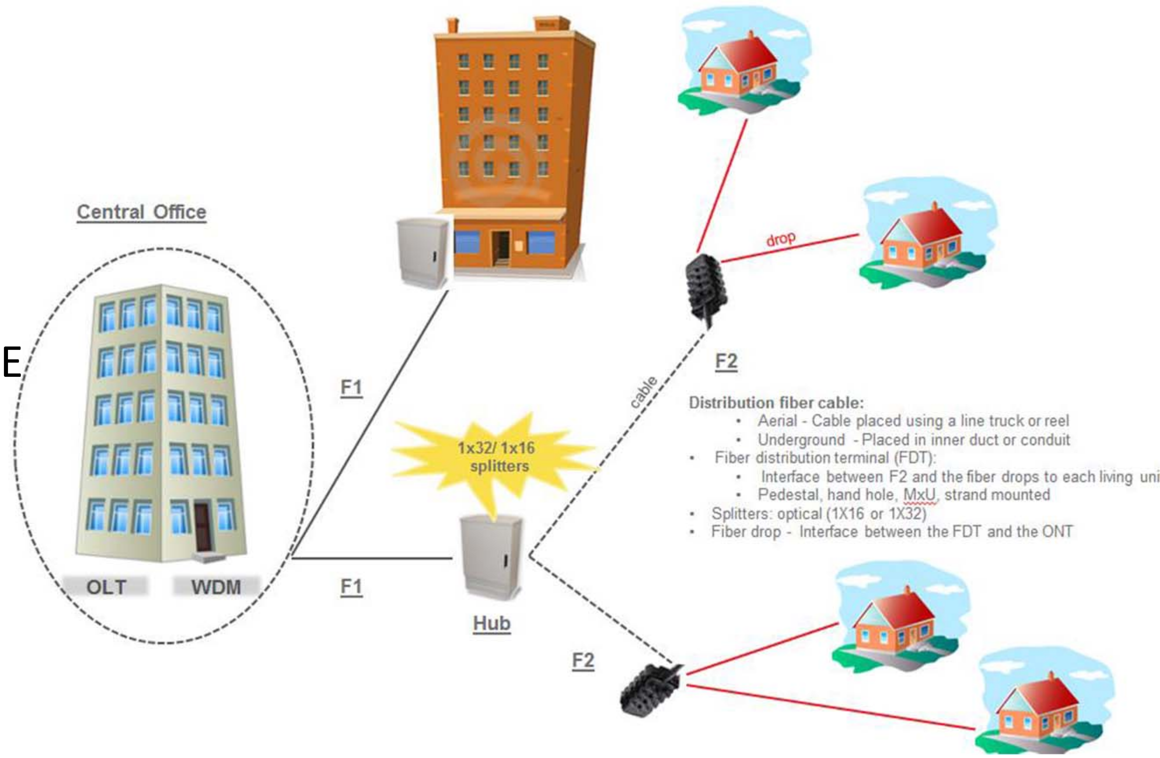
- High traffic – systems have Eighty Eight 100G channels (wavelengths)

Metro ROADM Network



Access Passive Optical Network (PON)

Metro ROADM NODE



Fiber Challenges

- Challenges are different, depending on which network (LD, metro, access)
  - line rates, modulation techniques, wavelength density, etc.
- Access Network (power meter)
  - Fiber loss
  - connector loss
- Metro Network (power meter, return loss, OTDR)
  - Fiber loss
  - Connector loss
  - Number /quality of splices – return loss

Fiber Challenges - LD network

- Long-Haul Network (power meter, return loss, OTDR, chromatic dispersion, PMD)
- Many challenges minimized by coherent modulation (phase-shift keyed)
  - Amplitude and phase known
- Mixed fiber types
  - Splice loss/mismatch – reflection
  - High power amplification (Raman) – nonlinearities
- Number/quality of connectors (reflected power/loss)
- Extra-Long distance spans (high attenuation)
- Polarization-related impairments

Optical Fiber Basics

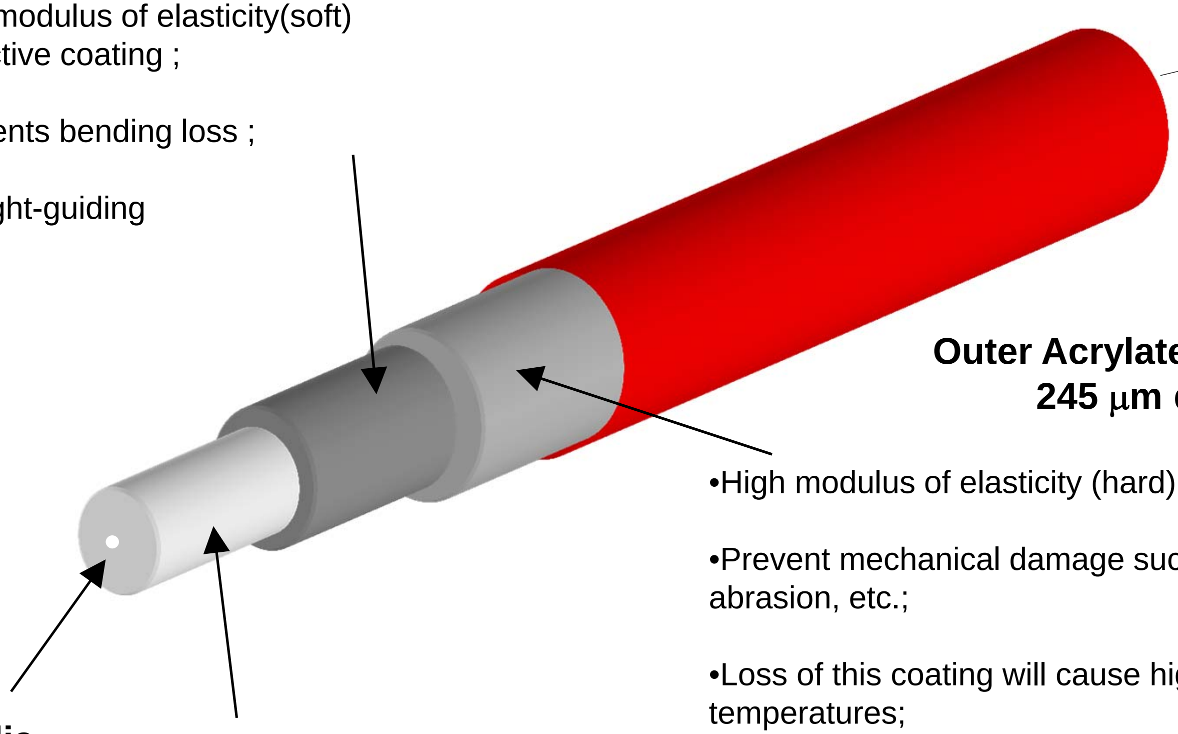
Fiber Strand Cross Section

Inner Acrylate coating
190 μm dia

- Low modulus of elasticity(soft) protective coating ;
- Prevents bending loss ;
- No light-guiding

Ink
250μm dia

- color only, no protection



Outer Acrylate coating
245 μm dia

- High modulus of elasticity (hard) protective coating ;
- Prevent mechanical damage such as scratches, chips, abrasion, etc.;
- Loss of this coating will cause high bending loss esp at low temperatures;
- Loss of this coating also allows stress concentrators (grit) in contact with the soft coating which erodes easily
- No light-guiding, only protection

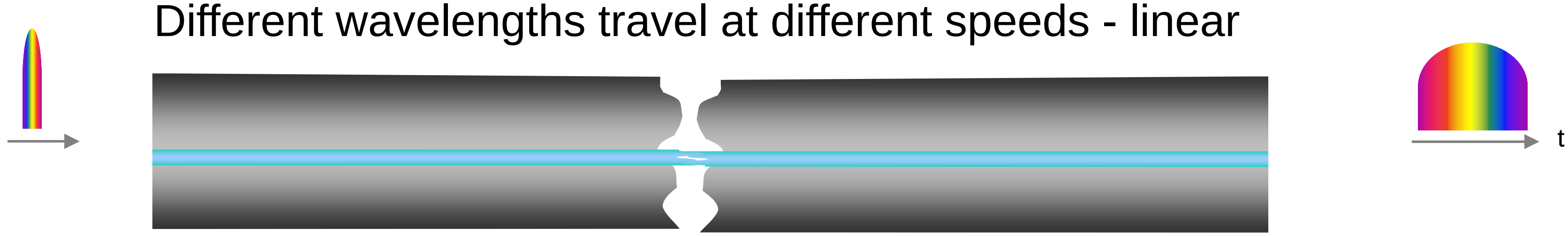
Core
~ 10 μm dia

Fiber strand
Core + Cladding
125 μm dia

Dispersion in Single-Mode Optical Fiber

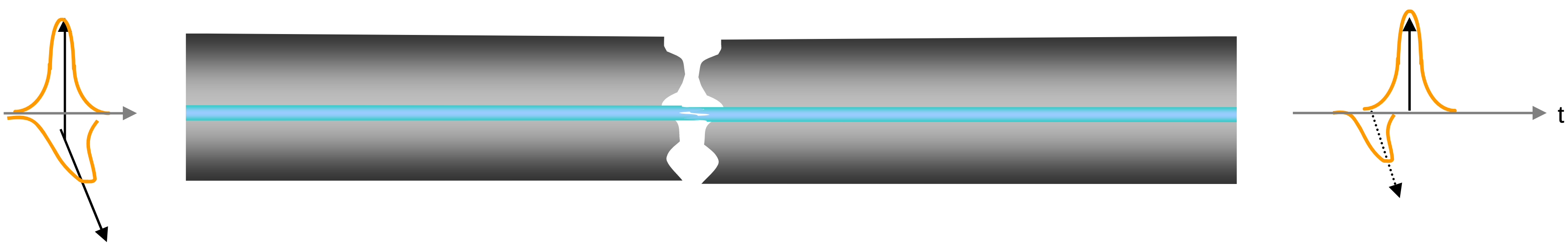
Intra-modal Dispersion, or Chromatic Dispersion (CD)

Different wavelengths travel at different speeds - linear



Polarization Mode Dispersion (PMD)

Different polarization modes travel at different speeds - nonlinear



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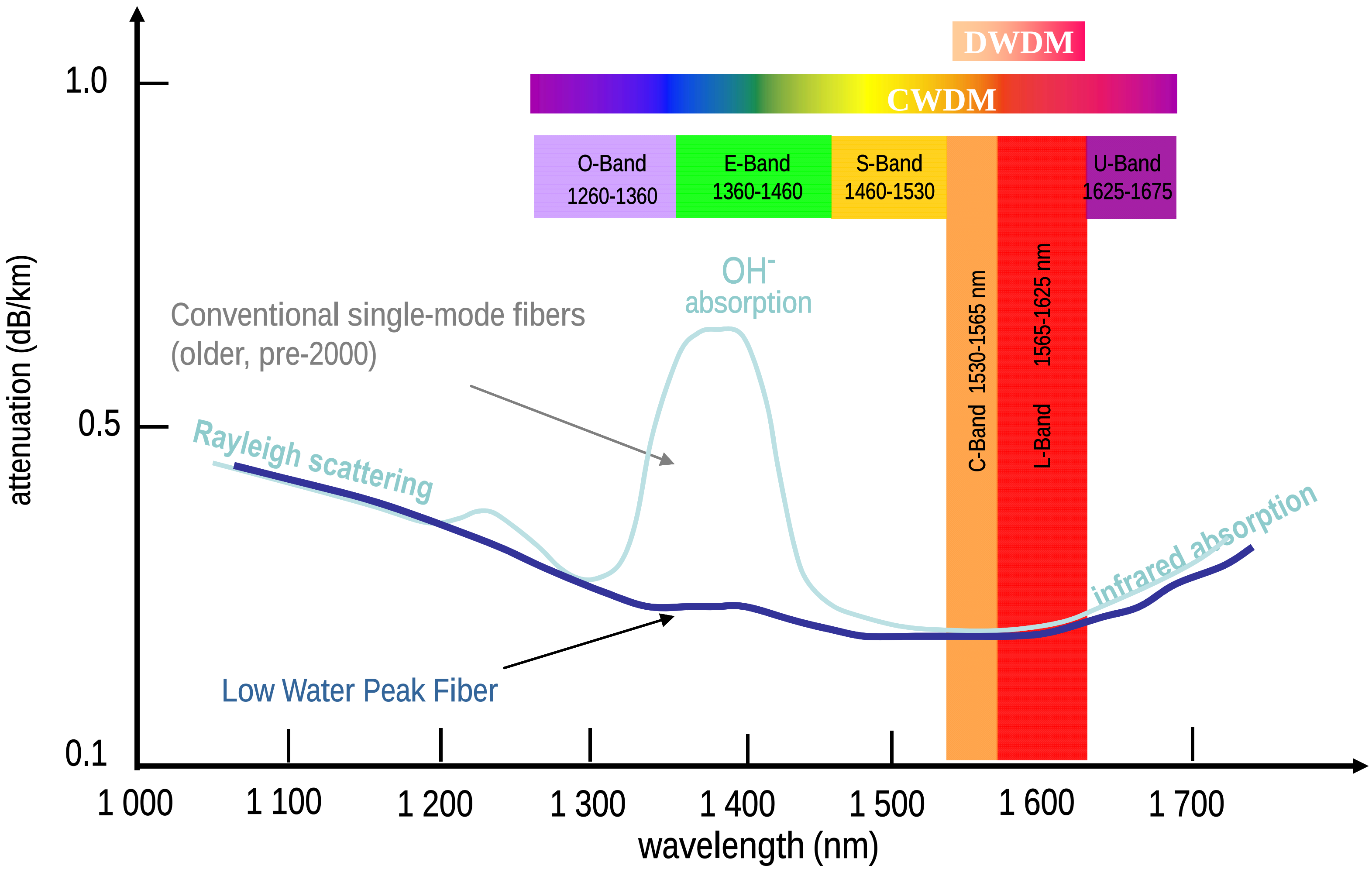
Optical Fiber Attenuation



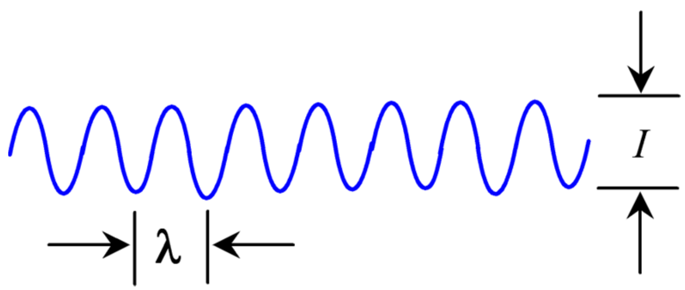
Polarization of Light
Overview

Polarization

- Description of polarized light
  (qualitative & quantitative)
- Generating and modifying polarization
- Polarization in optical fiber

Basic Description of Light

Three basic parameters describe light:

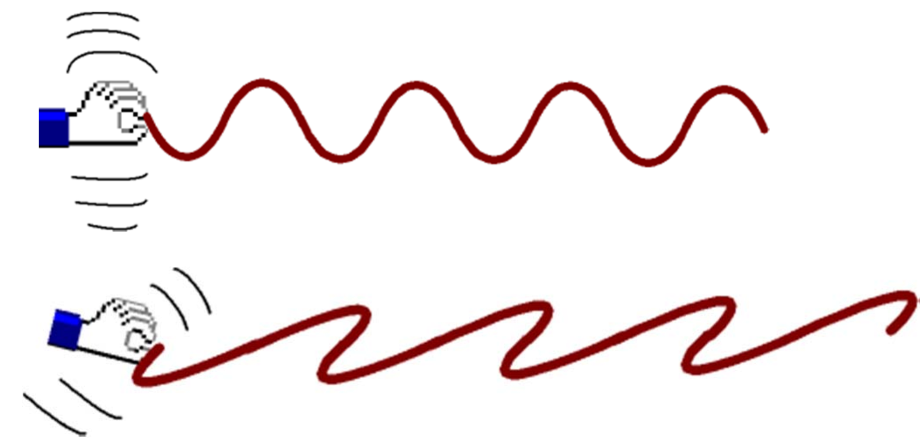


Wavelength: λ (color)

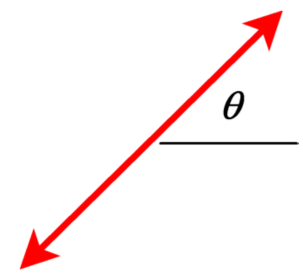
Intensity: I (brightness)

Polarization state: ***S*** (*subtle*)

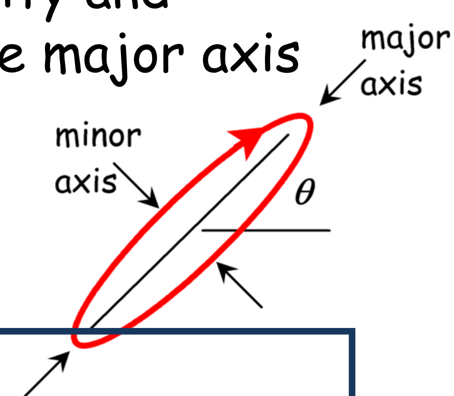
The polarization state is defined by path of the of E-field oscillation



Linear: Orientation of the plane of vibration



Elliptical: Ellipticity and orientation of the major axis



Abbreviations:

H (horizontal)	**+45** (+45 ° w/horizontal)	**RHC** (right-hand circular)
V (vertical)	**-45** (-45 ° w/horizontal)	**LHC** (left-hand circular)

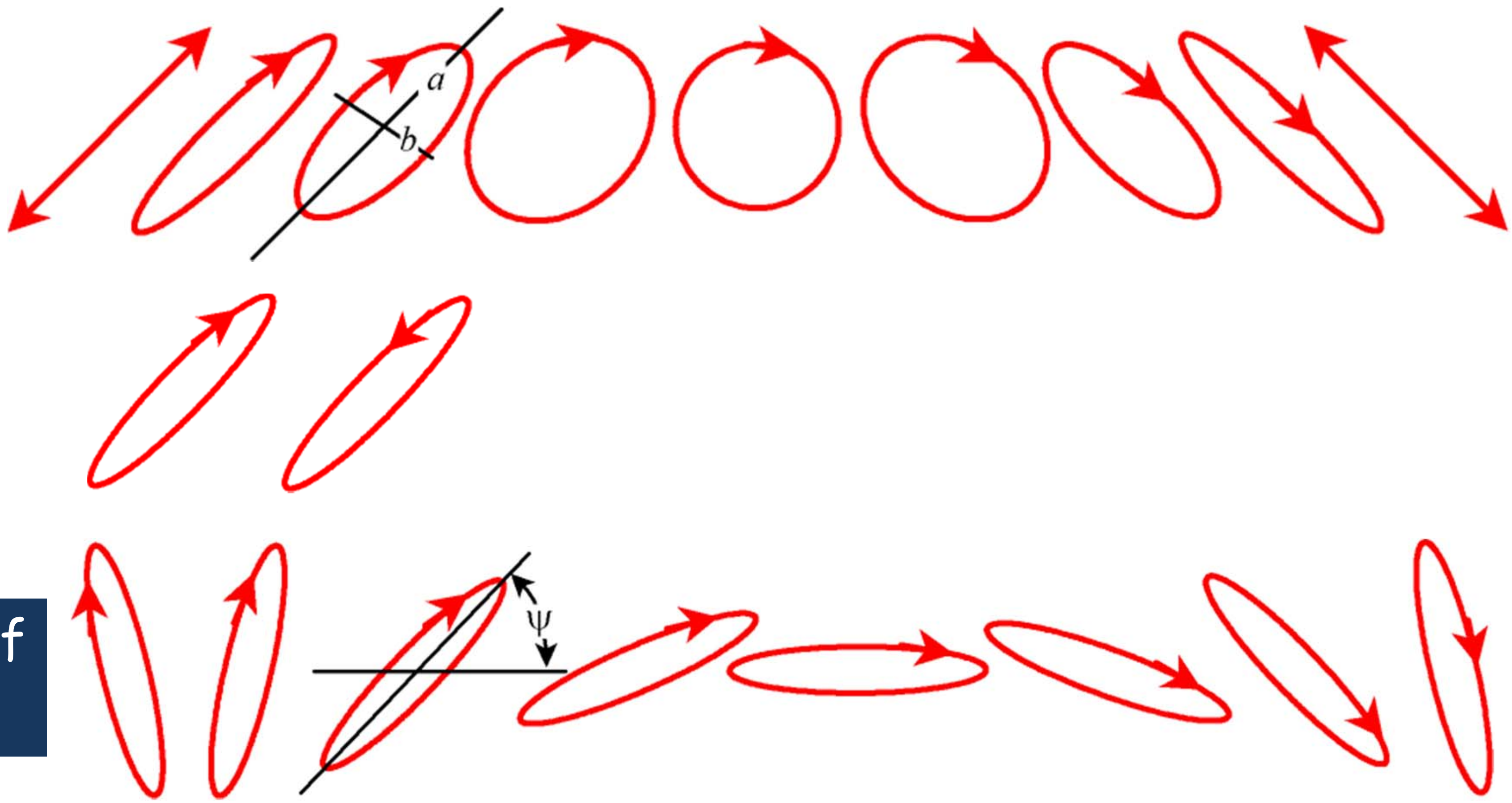
It only takes 2 numbers to describe the state of polarization of light.

Ellipticity χ

$$\tan \chi = \frac{\pm b}{a}$$

Handedness

Orientation of major axis ψ



State of polarization is commonly described in one of two ways: Stokes vectors/Mueller matrices and Jones vectors/matrices atis PROTECTION ENGINEERS GROUP

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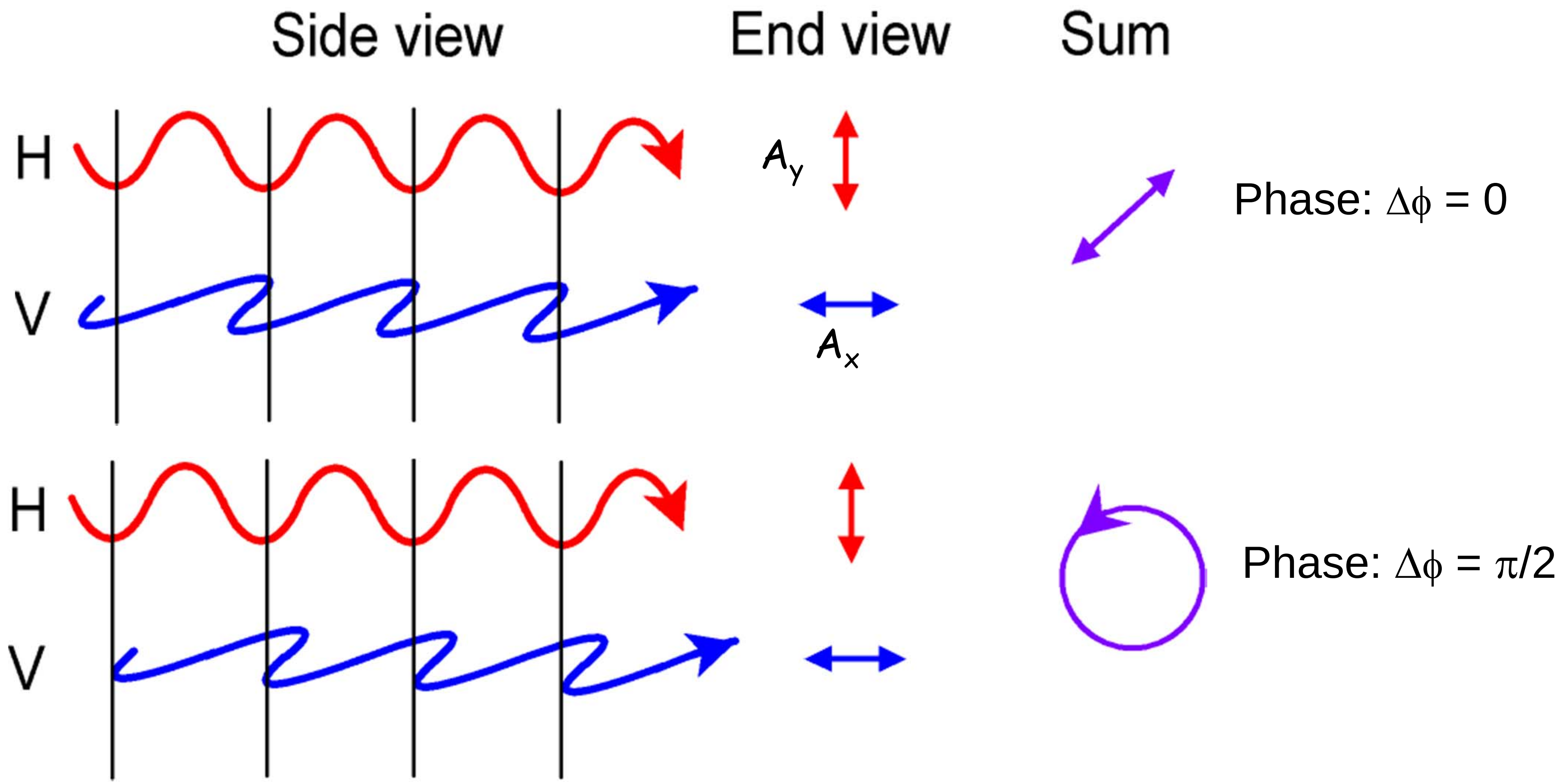
Elliptical Polarization



Relative amplitudes A_x and A_y determine axis orientation (ψ).

Phase (retardance) between H and V determines ellipticity (χ).

Measurement of Light: Stokes Vectors

$$\hat{\mathbf{S}} = \begin{pmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{pmatrix}$$

S_0 = Total intensity of light (typically "normalized" (S_0=1)

S_1 = Amount of light that is Horiz. or Vert. (linear)

S_2 = Amount of light that is ±45° (linear)

S_3 = Amount of light that is RHC or LHC

Stokes vectors describe the state of polarization using INTENSITY

- Easy to measure (based on observables)
- Includes "unpolarized" light
- Includes the total intensity of the light

Stokes Vectors Quiz

$$\hat{\mathbf{S}} = \begin{pmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{pmatrix}$$

- S_0: Normalized intensity
- S_1: Horiz. or Vert. (linear)
- S_2: ±45° (linear)
- S_3: RHC or LHC

General

$$\hat{\mathbf{S}} = \begin{pmatrix} 1 \\ \cos 2\chi \cos 2\psi \\ \cos 2\chi \sin 2\psi \\ \sin 2\chi \end{pmatrix}$$

QUIZ: What kind of polarization states do we have here?

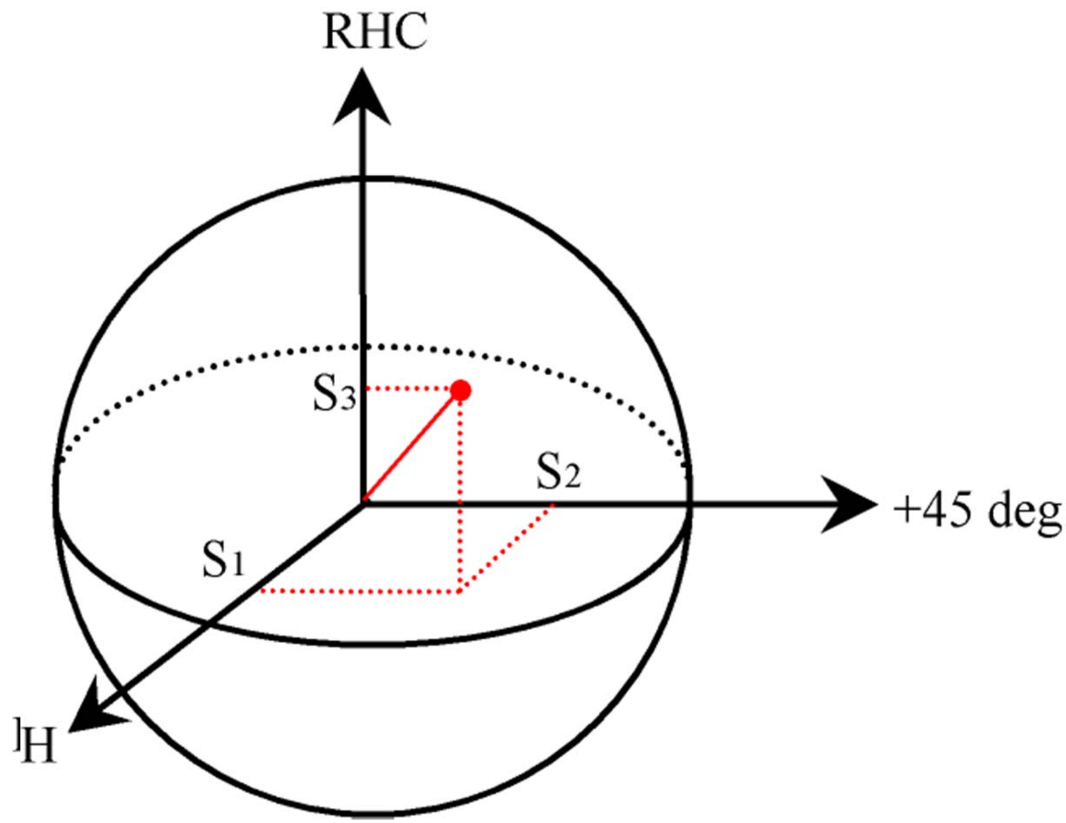
$$\hat{\mathbf{S}}_? = \begin{pmatrix} 1 \\ 0.5 \\ 0.866 \\ 0 \end{pmatrix} \qquad \hat{\mathbf{S}}_? = \begin{pmatrix} 1 \\ 0.482 \\ 0.835 \\ 0.286 \end{pmatrix} \qquad \hat{\mathbf{S}}_? = \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

Poincare Sphere – Polarization Mapping

$$\hat{S} = \begin{pmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{pmatrix} \begin{matrix} \text{Normalized intensity} \\ \text{Horiz. or Vert. (linear)} \\ \pm 45^\circ \text{ (linear)} \\ \text{RHC or LHC} \end{matrix}$$

The Poincaré sphere:

- Plots Stokes vectors
- Linear states on the equator
- Elliptical states off the equator
- The poles are RHC and LHC



Field Measurement of Polarization Dynamics and Correlation to Environmental Conditions

Ongoing

Measurement Drivers

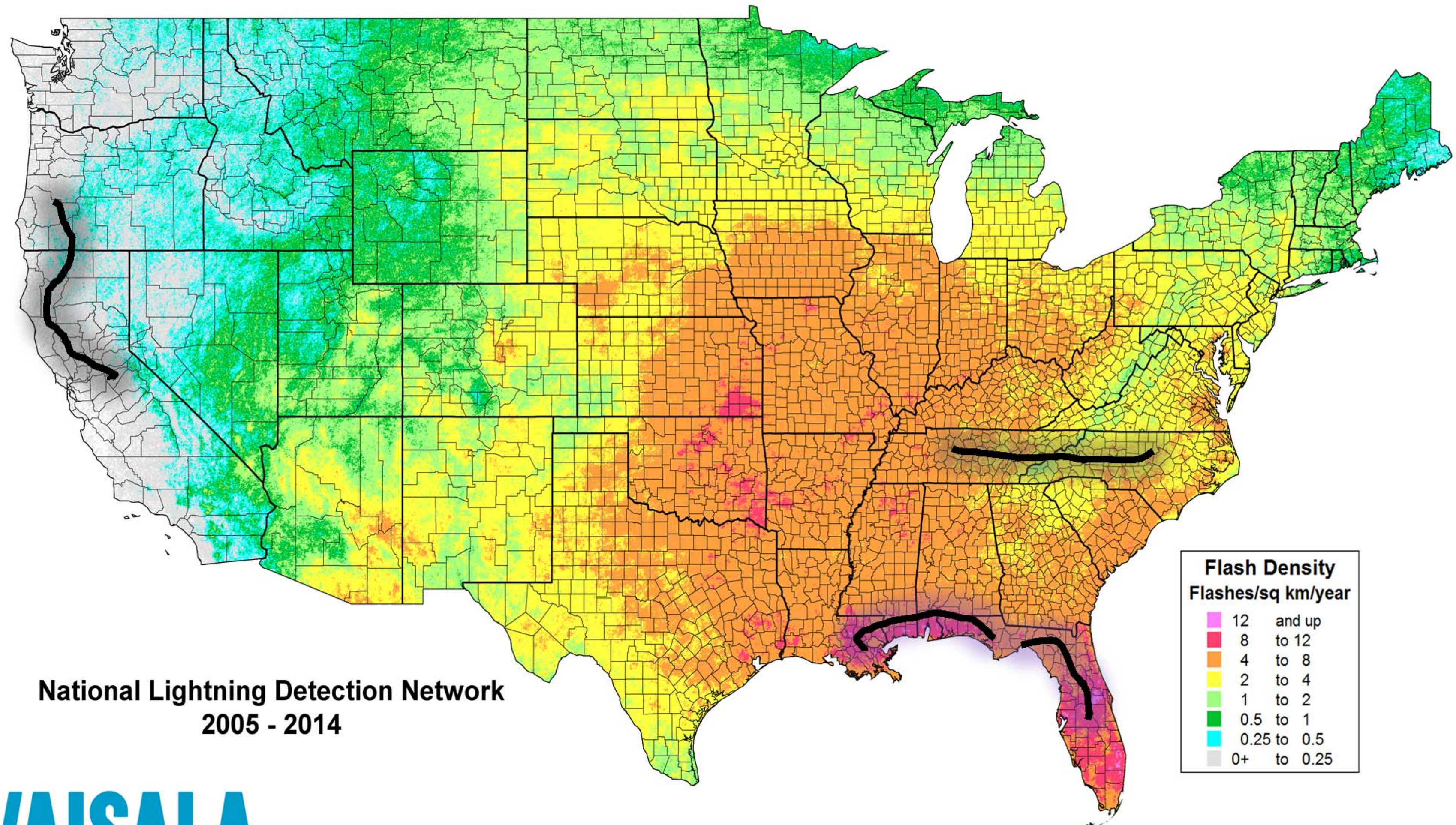
- Traffic interruptions measured on several Long-Haul routes
  - No outages, protection switches occurred
- Investigate polarization dynamics on different constructions
  - Buried, Aerial, Metro, Central Office (craft)
  - Large Temperature fluctuations (NE), Lightening (SE)
  - Train, subway, traffic, etc

- Started study with Lightening rich areas (SE)

Optical Ground Wire (OPGW)

- Unexplained protection switches witnessed on several Long-Haul routes containing OPGW in the SE
- Lightening can temporarily change the index of refraction (Kerr effect) as a result of the change of ε

Lightening Map



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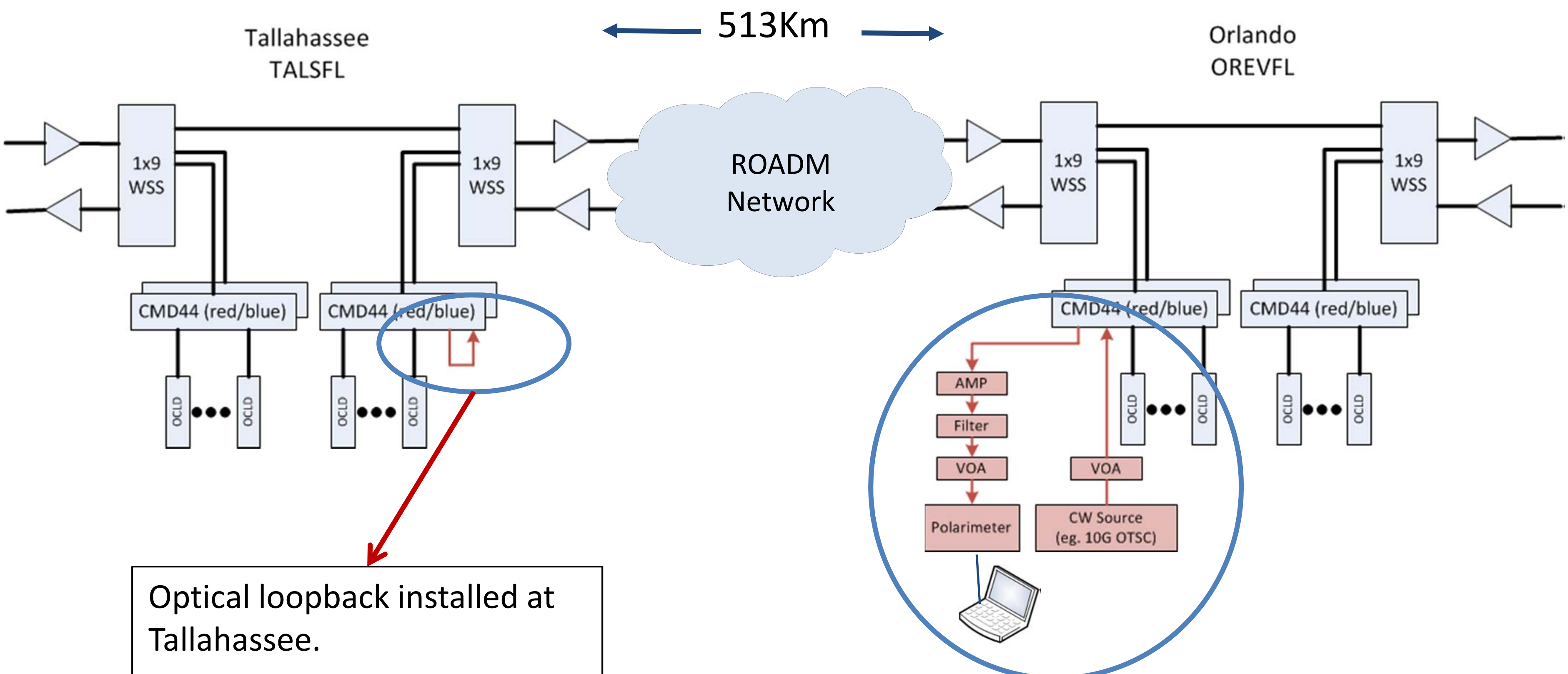
OPGW route candidates

Route	Length [km]	Reported [flashes/km²/yr]	Expected lightning strikes within 0.5km radius of link [flashes] Note: This is not expected fault on system
Orlando, FL to Tallahassee, FL	**513**	**8.1**	**4155**
Pensacola, FL to New Orleans, LA	**336 (130km OPGW)**	**9.8**	**3293**
Memphis, TN to Charlotte, NC	**992**	**4.8**	**4762**
West Orange, NJ to Harrisburg, PA	304	2.3	699
Indianapolis, IN to Louisville, KY to Nashville, TN	480	6.0	2880

The exact distance a strike can be from the link for the resulting change in SOP to be within our sensitivity is unknown. We use 0.5km as a coarse estimate and assume that whatever the actual distance, it will be constant across all links.

Measurement Setup



Optical loopback installed at Tallahassee.

Round-Trip Delay

Polarimeter installed at Orlando with a PC with LAN access

Measurement Setup

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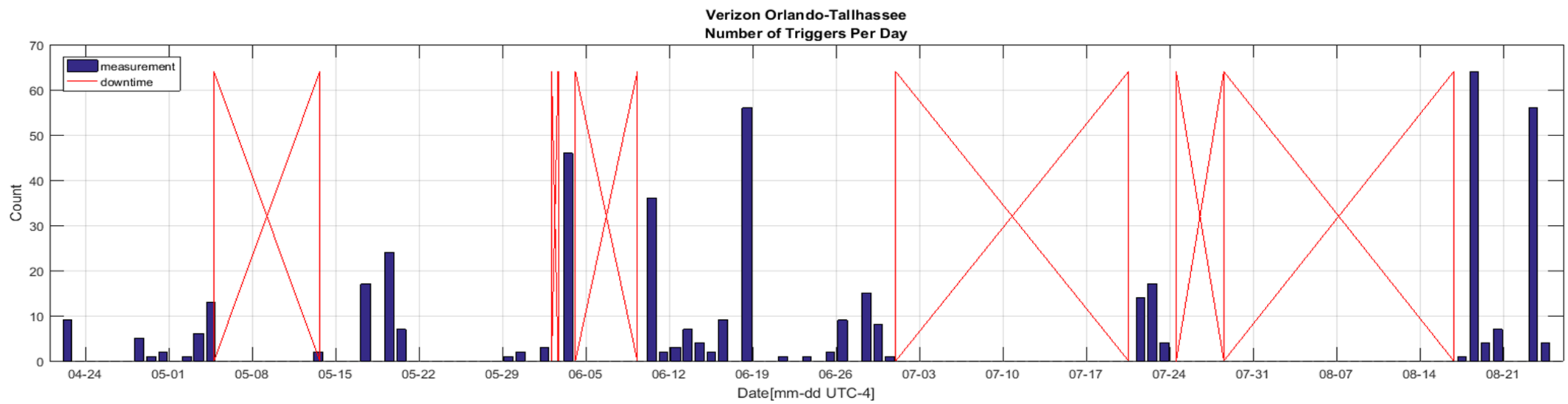
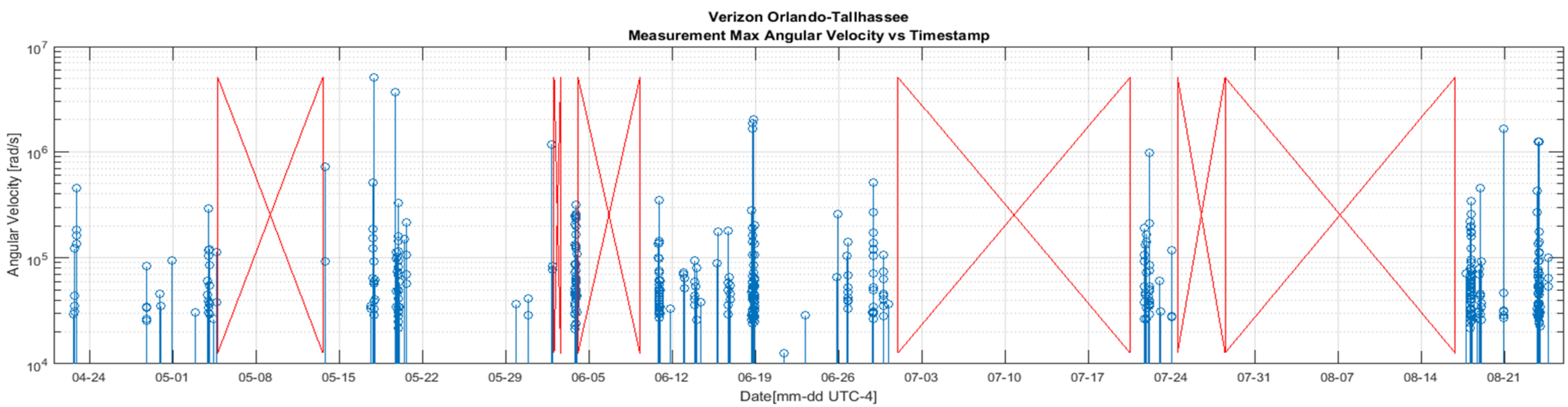
Orlando-Tallahassee SOP (4/16-8/16)



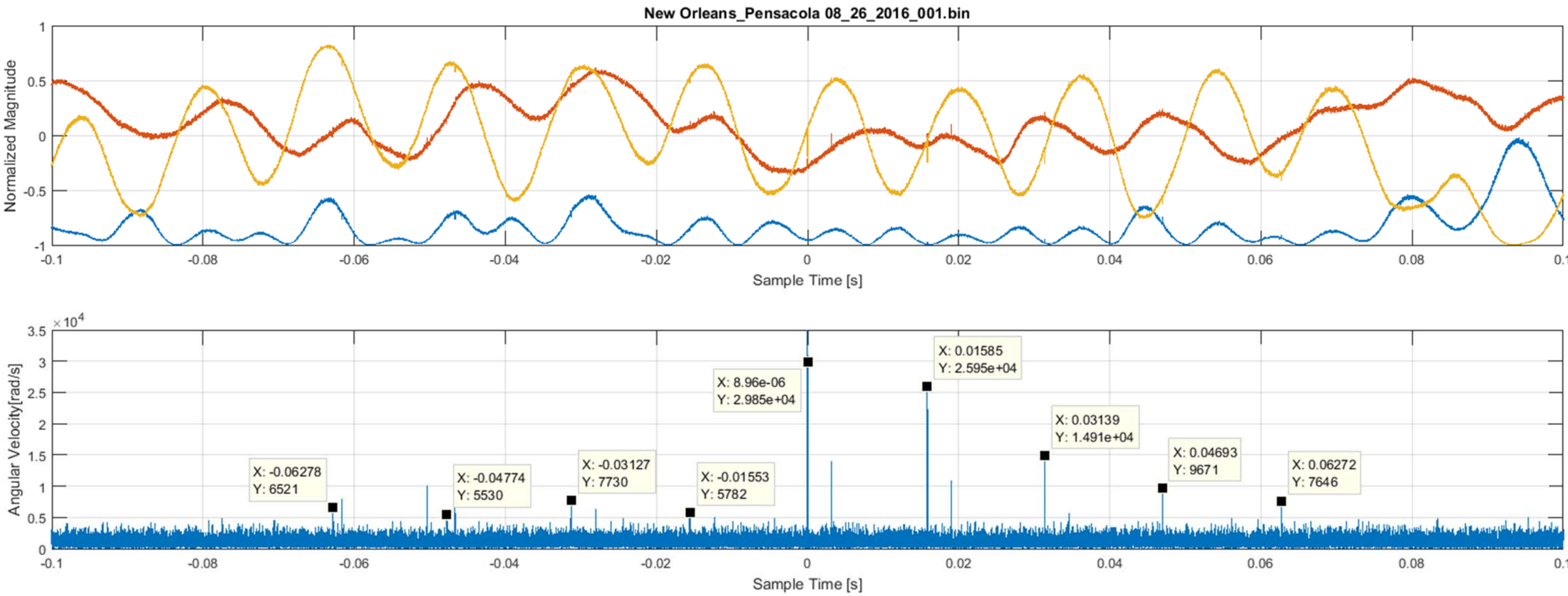


Orlando-Tallahassee SOP

- Set up turn on in April 2016
  - Collecting data ~ 55% of time

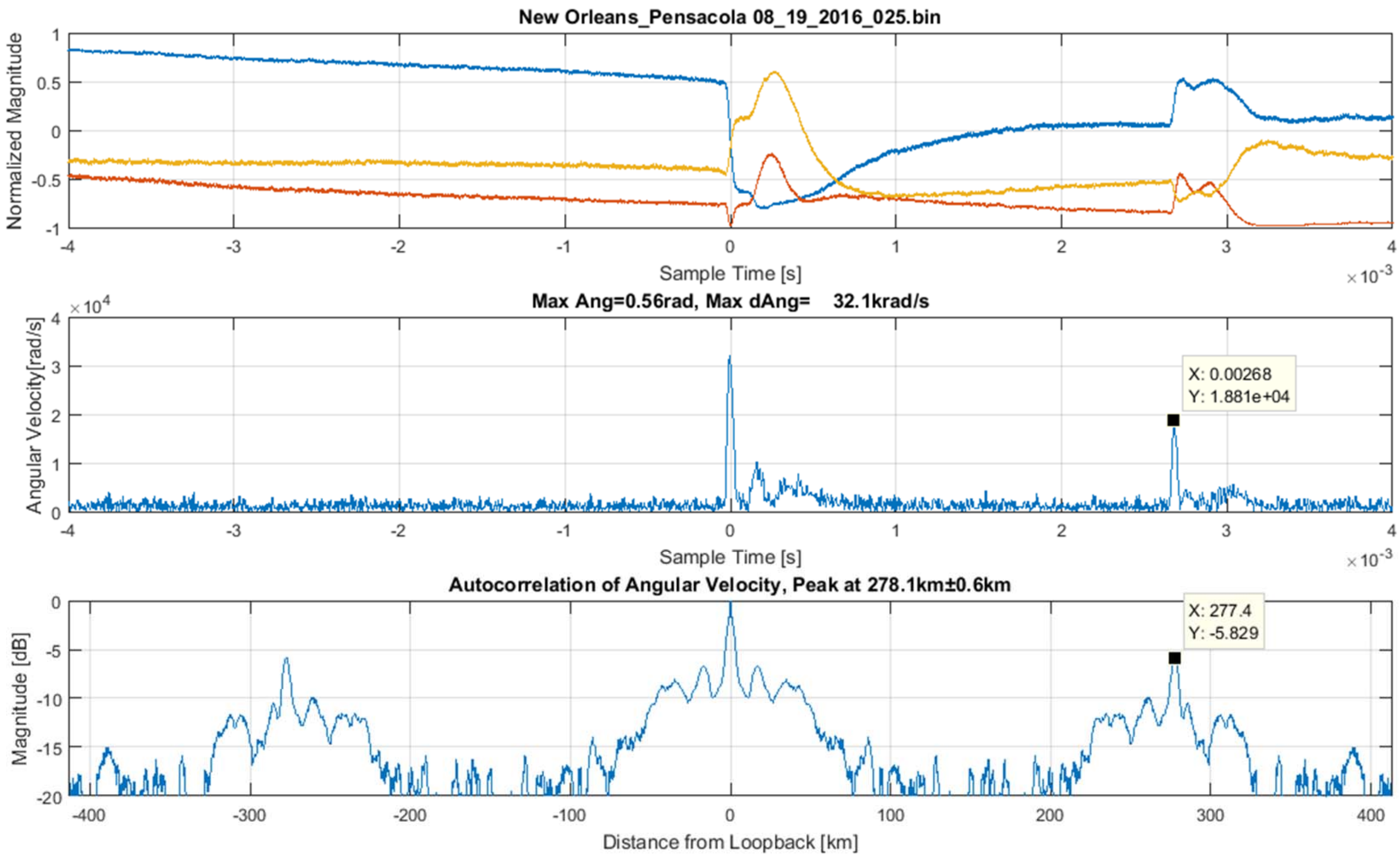
- Observation
  - Majority of transients within 500 krad/s
  - Some correlations made with lightening events
    - Lightening magnitudes vs SOP transients being analyzed
  - Measurements are ongoing
  - End Date TBD (end of lightning season in FL, Oct. – Nov.)

New Orleans – Pensacola SOP (8/16-2/17)

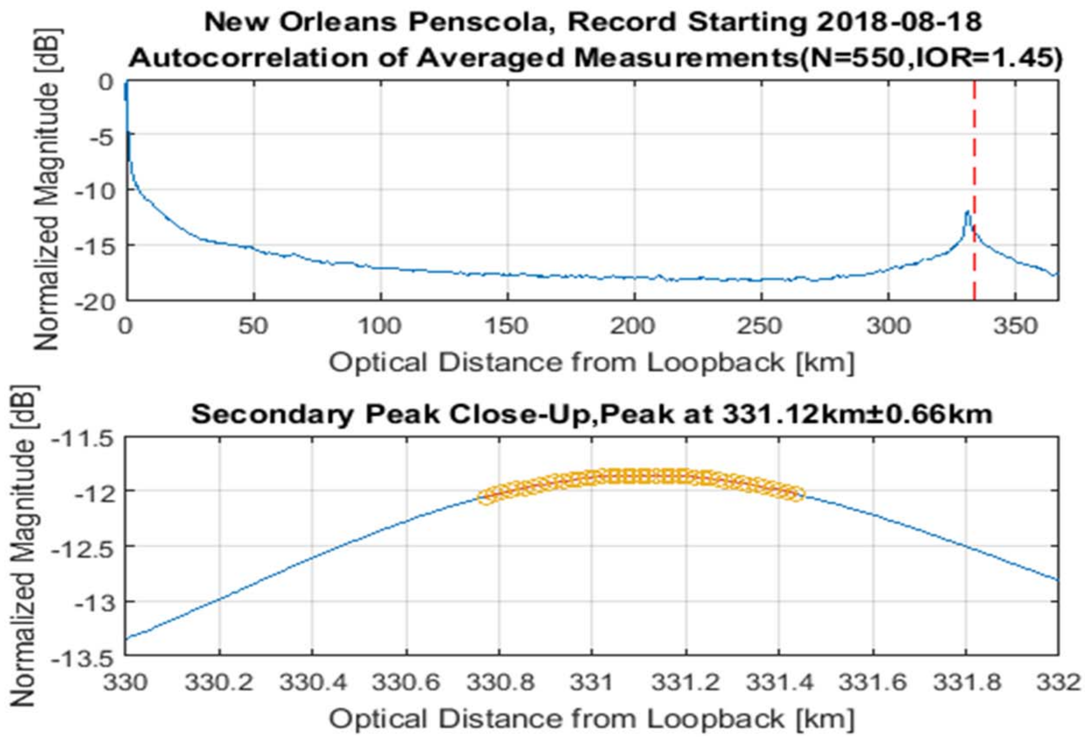


- Clusters of SOP transients measured
- Spacing between transients in cluster is roughly constant at ~16ms
- Pairs of each transient are ~3ms (RTD of events)

New Orleans – Pensacola SOP (8/16-2/17)



- RTD shows distance of events 278.1 km +/- 0.66km from N.O.



- Taking the 550 measurements starting Aug. 18 we average the autocorrelations of the set to observe a single peak at about 331.12km
- Error is due to index of refraction uncertainty

New Orleans – Pensacola SOP (8/16-2/17)

Observations

- Cause Unknown – mechanical?
- Hours exist where many triggers occur, followed by quiet hours.
  - We are investigated equipment PM data for patterns
- Observed angular velocities exceed 600krad/s
- Events originate near the test site in downtown New Orleans.
  - Optical distance from test site and map of fiber plant have us suspecting the North Rampart St. construction.
- Trigger settings adjusted to 10°@100krad/s
  - This should filter out the vast majority of the static transients so that we can proceed with monitoring for lightning induced transients.

Next Steps