Long-Term Monitoring of Local Temperature and Stress Changes in Buried Fiber-Optic Cable Using a BOTDA

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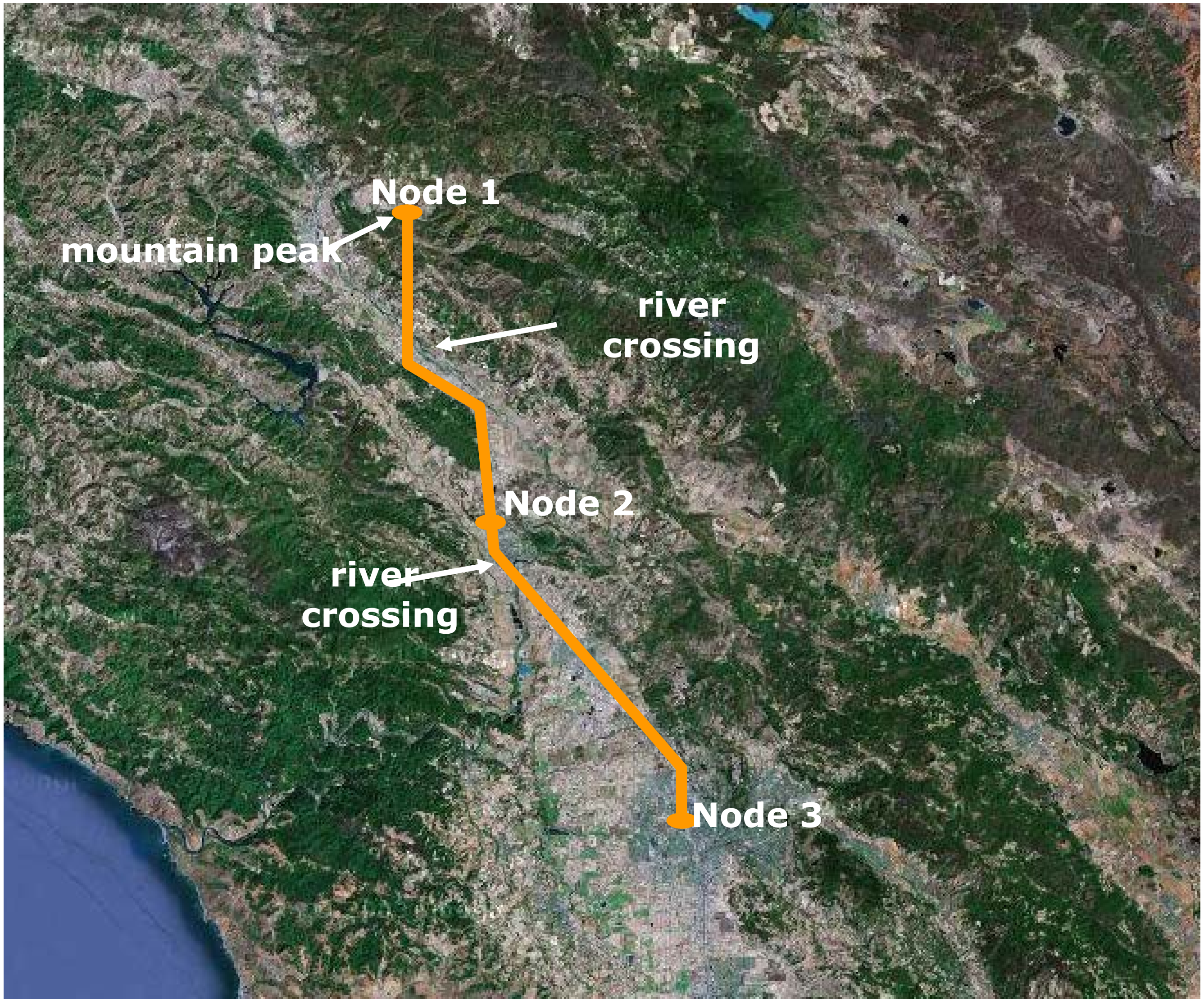
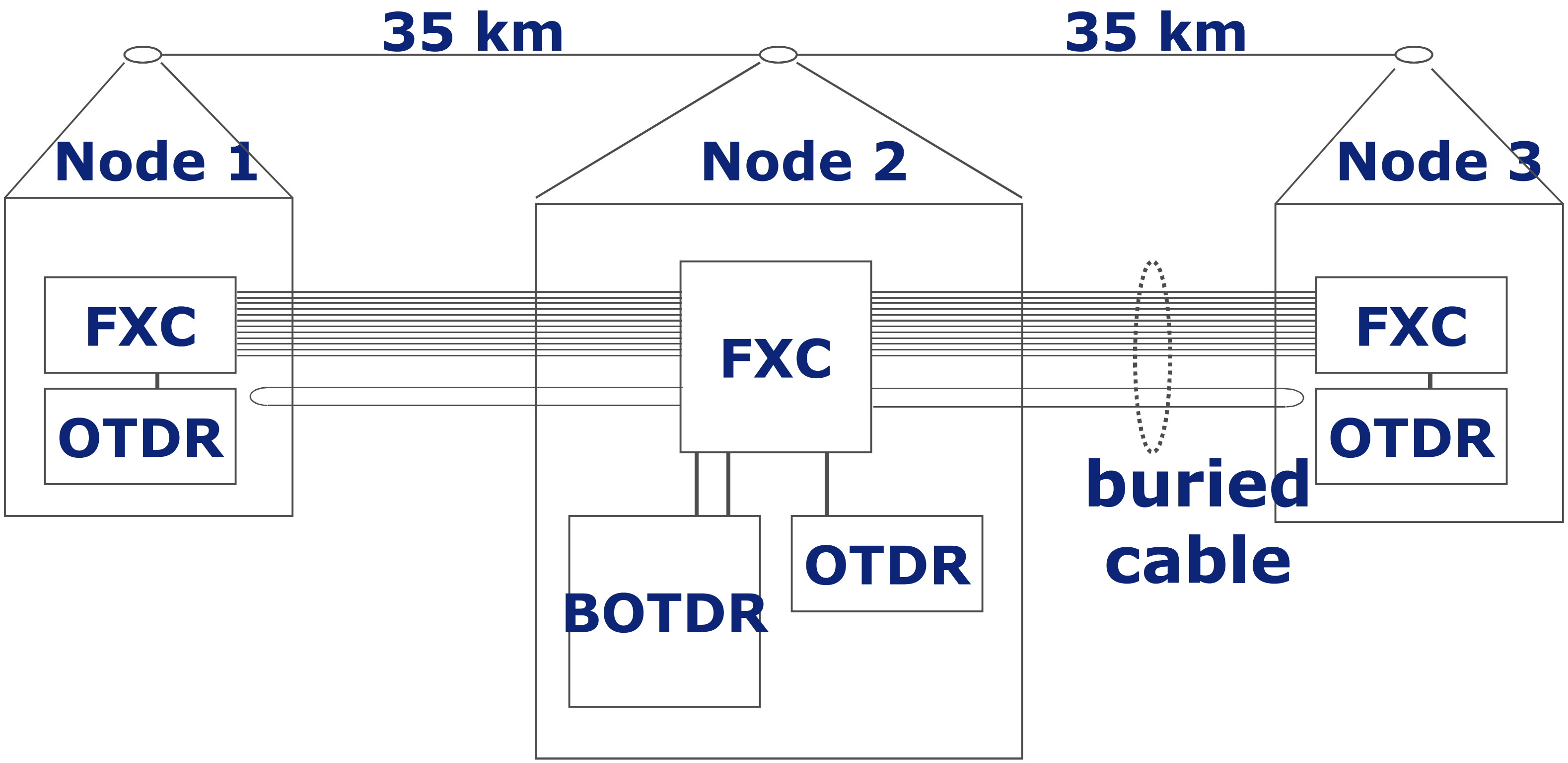
Installed fiber in Northern CA



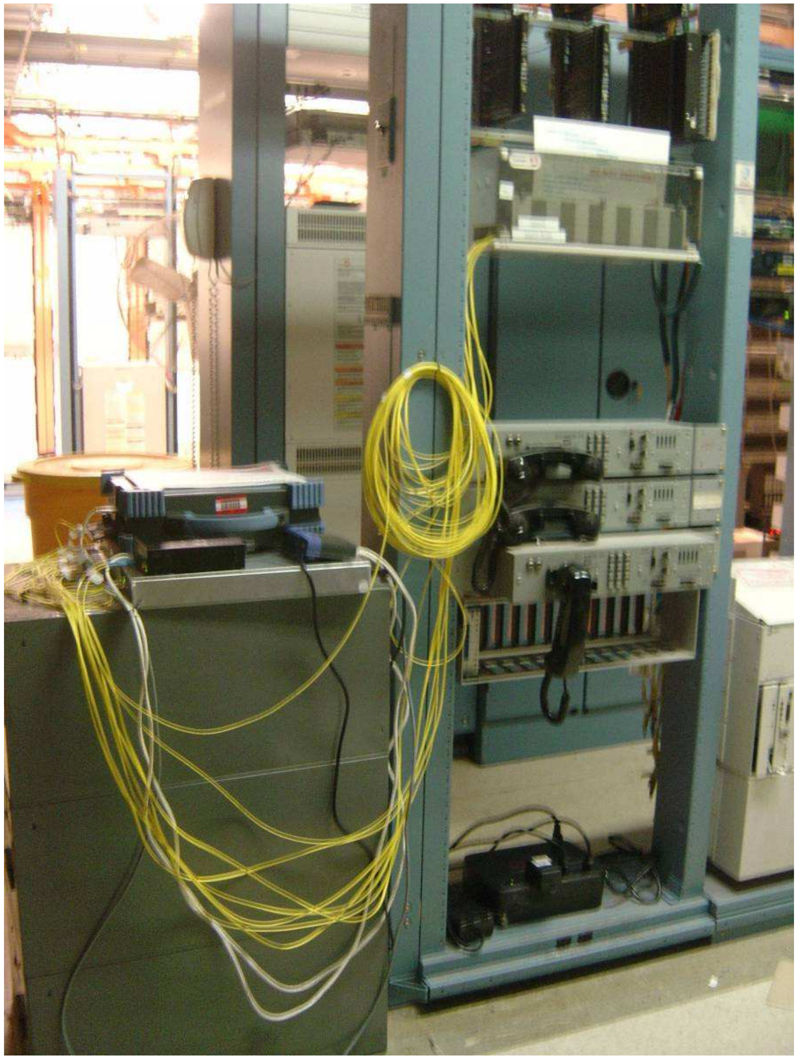
Experimental Setup

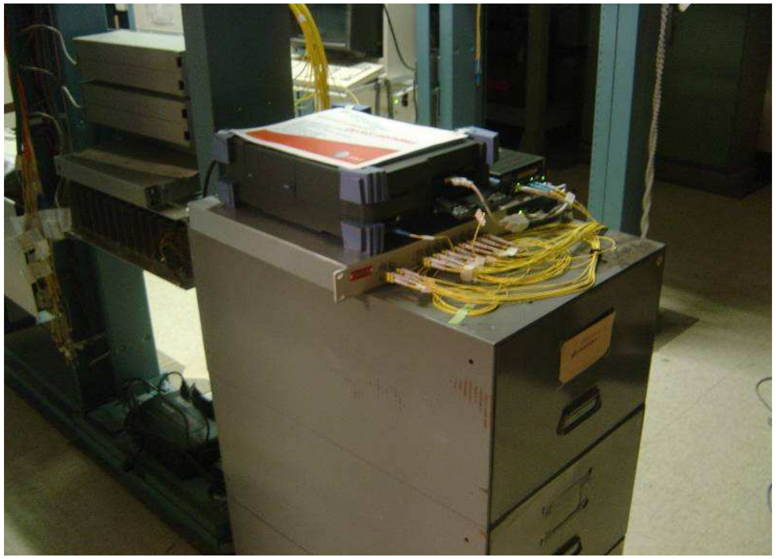


Fiber in in loose-tube cables
Direct-buried for first 8 km
In conduit thereafter
34.5 km Node 1 - Node 2
32.2 km Node 2 – Node 3

Computer Control at Node 2
Ethernet LAN through fibers

Node #1 :Interior

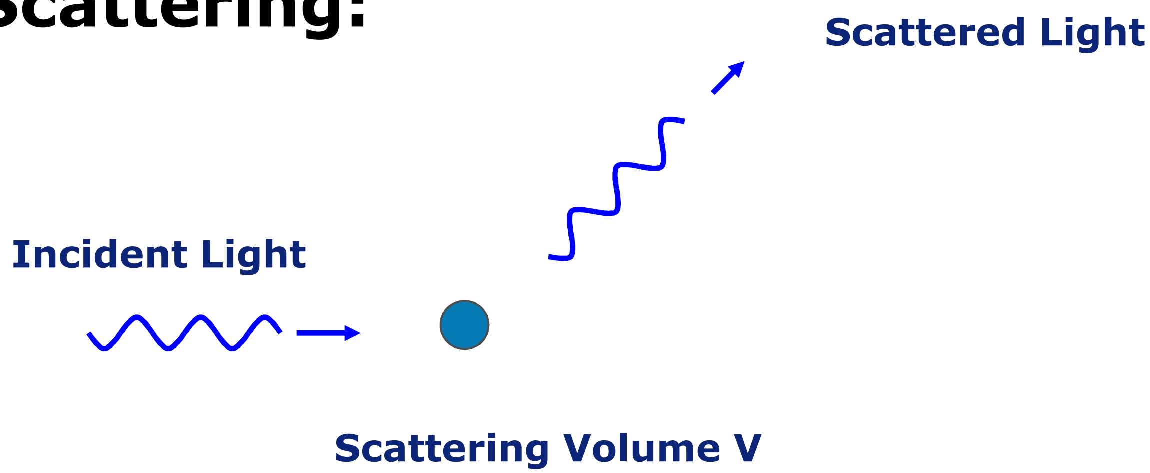




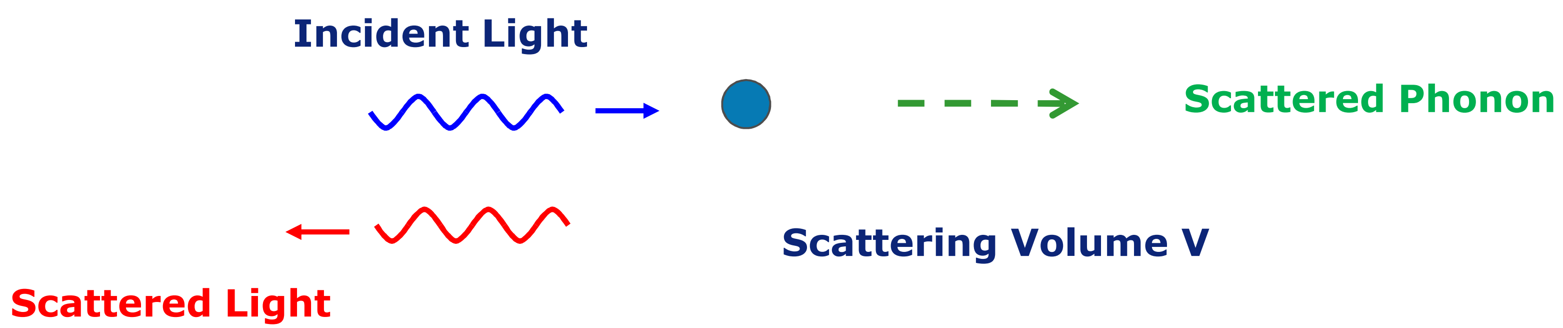
Node 1: Exterior

Node 2: Former Repeater Station

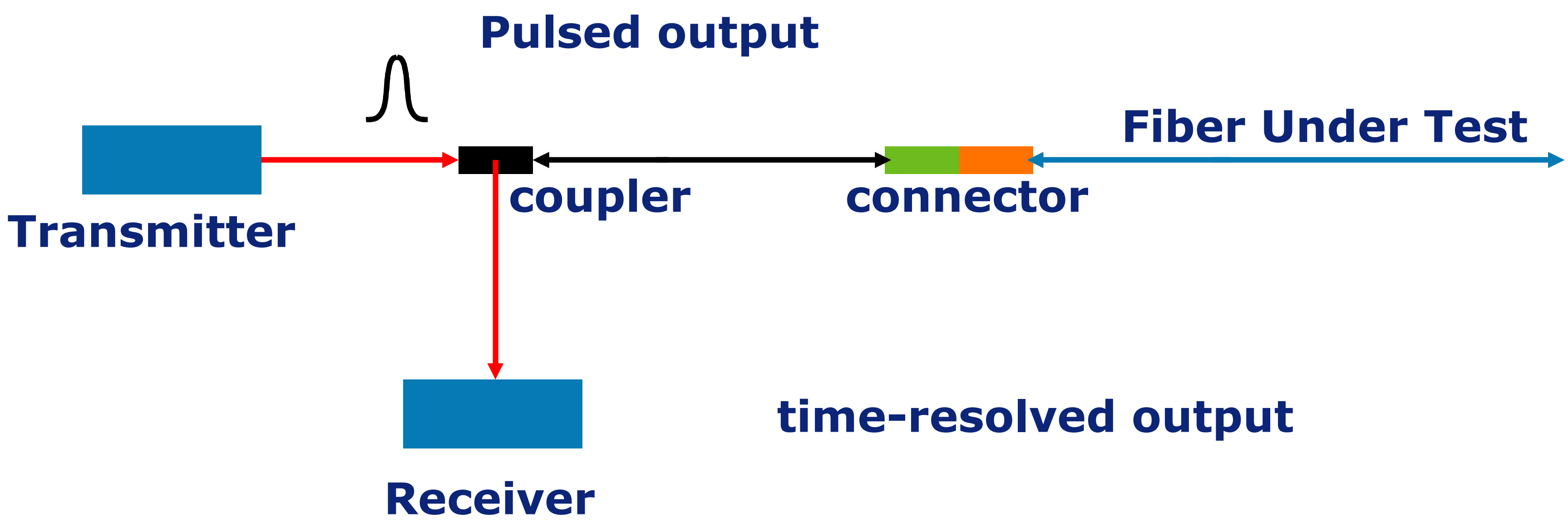
Rayleigh Scattering:



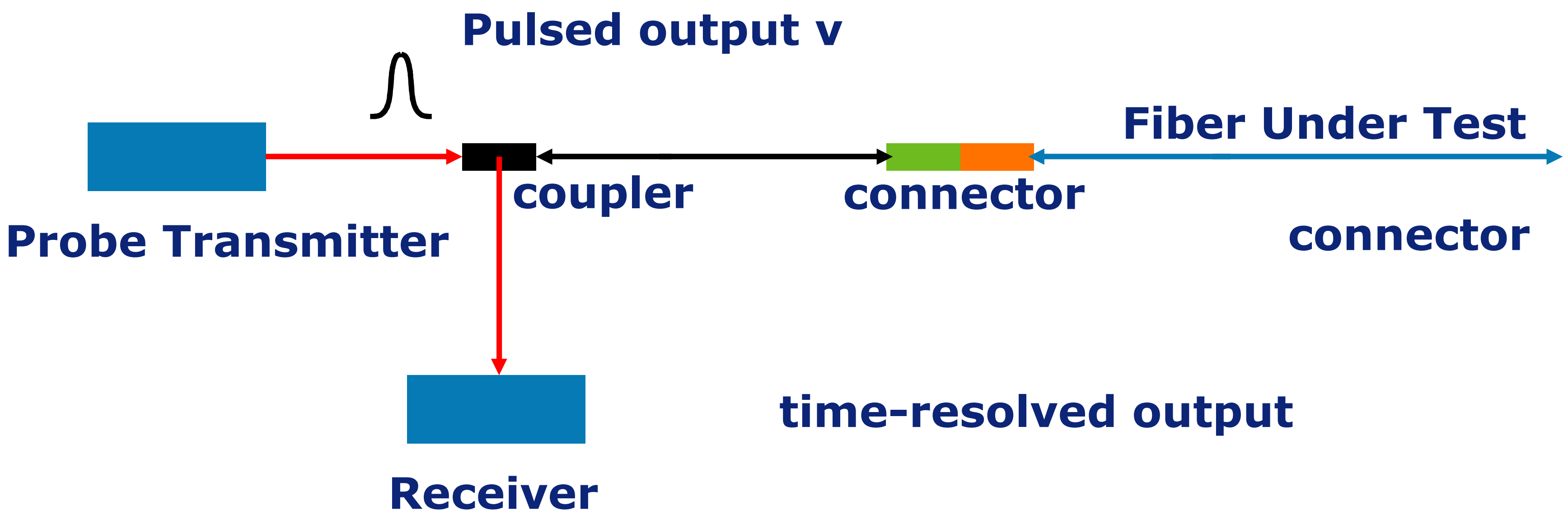
Brillouin Scattering:



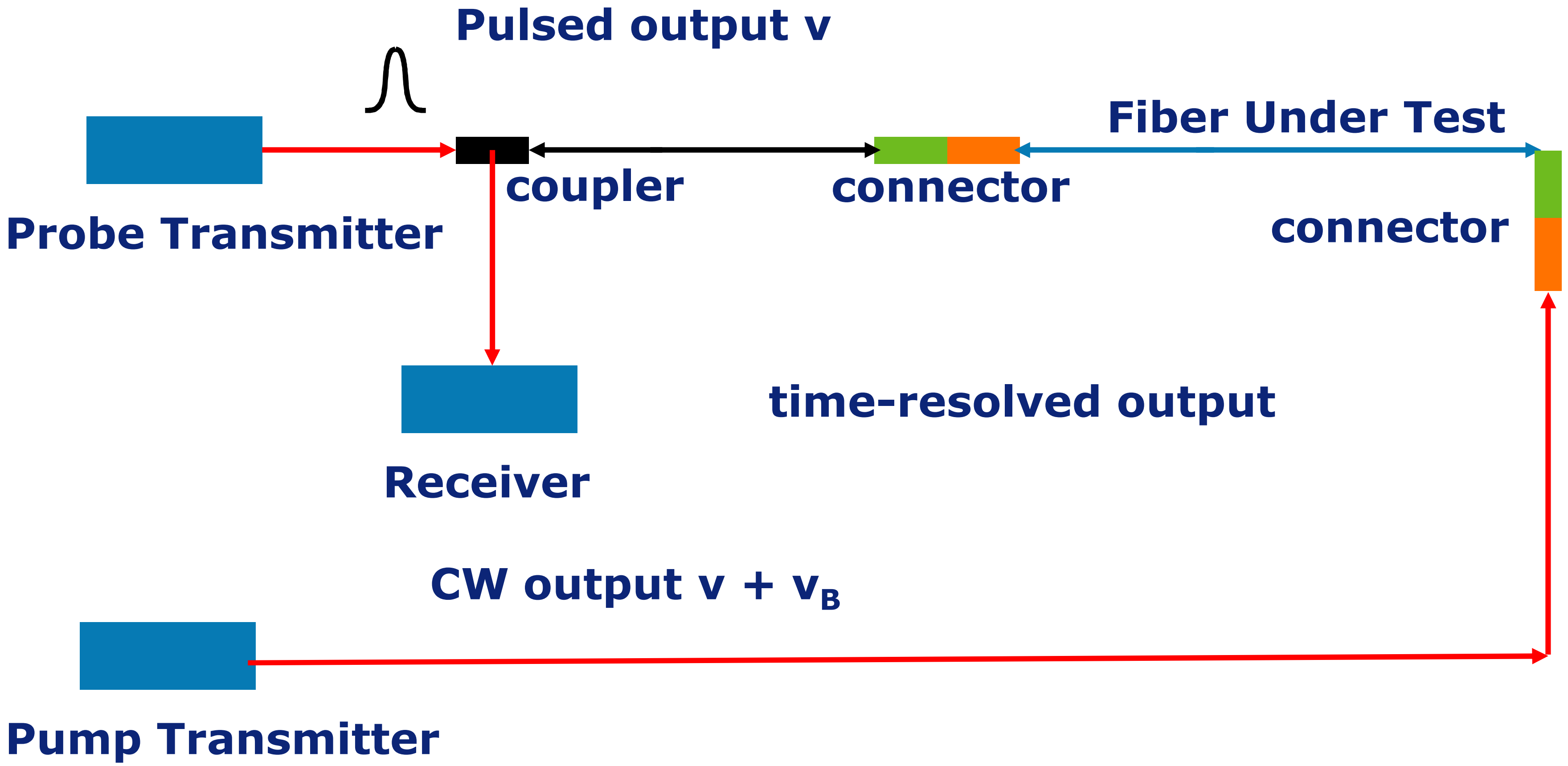
Optical Time-Domain Reflectometry



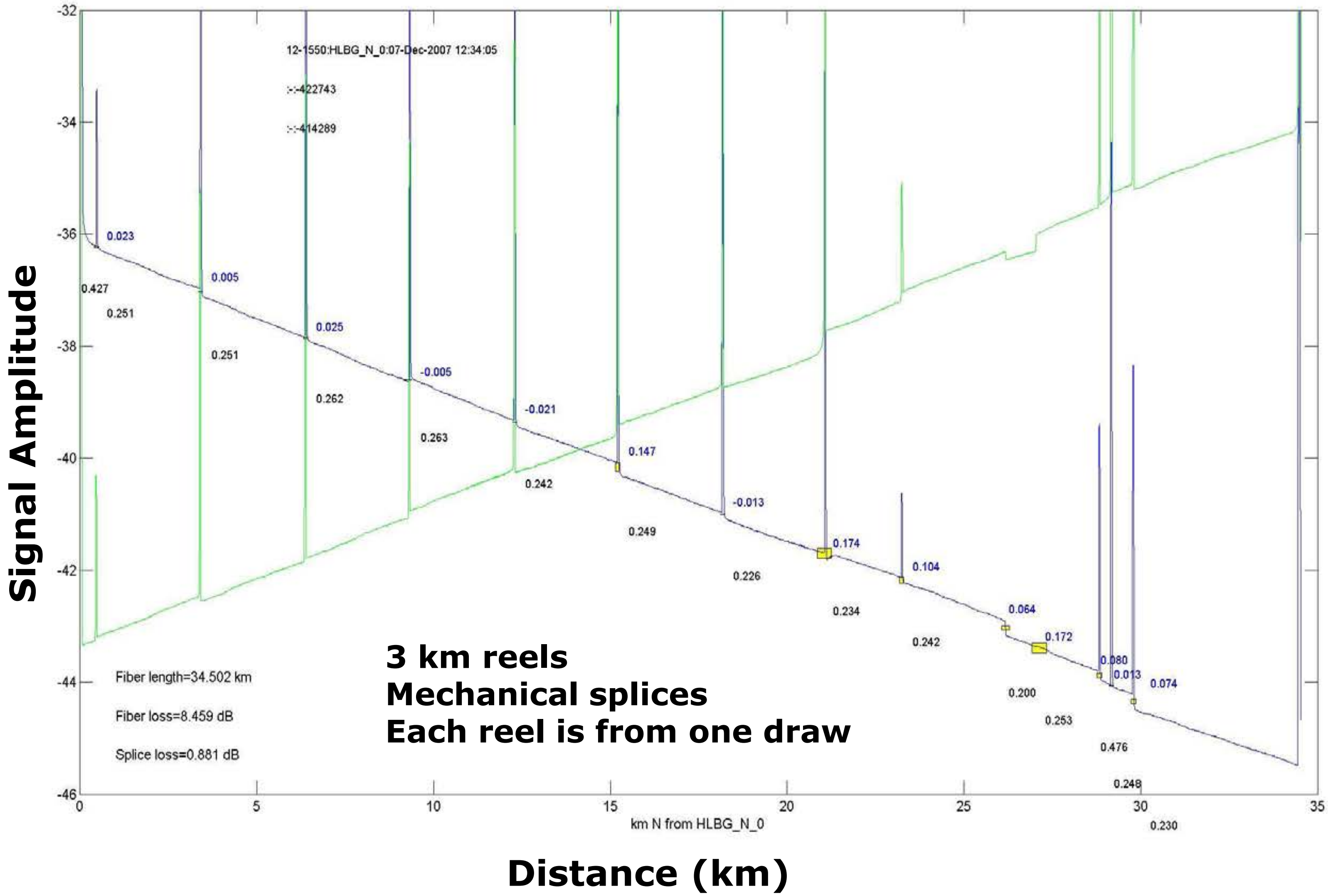
Brillouin Optical Time-Domain Reflectometer



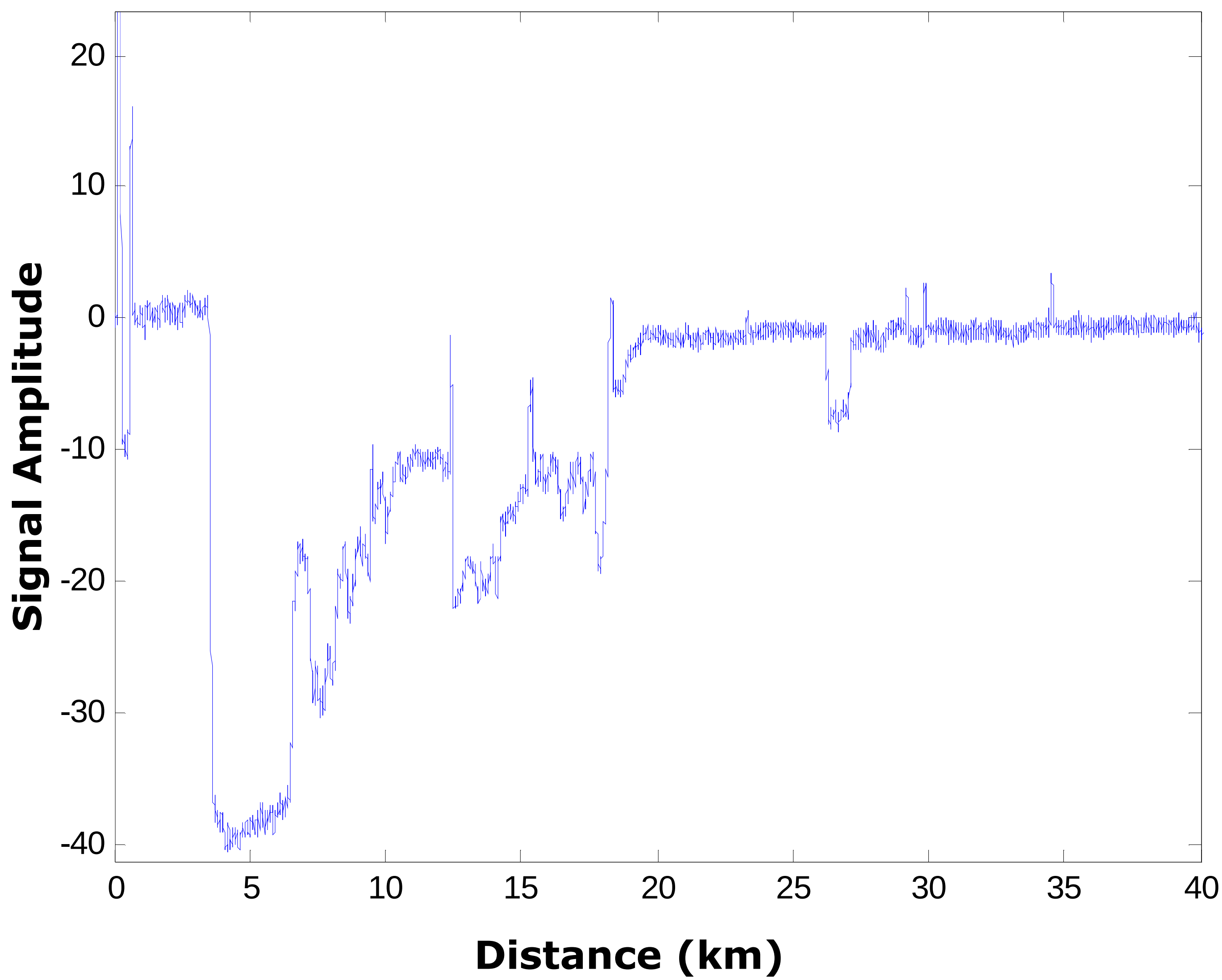
Brillouin Optical Time-Domain Analyzer



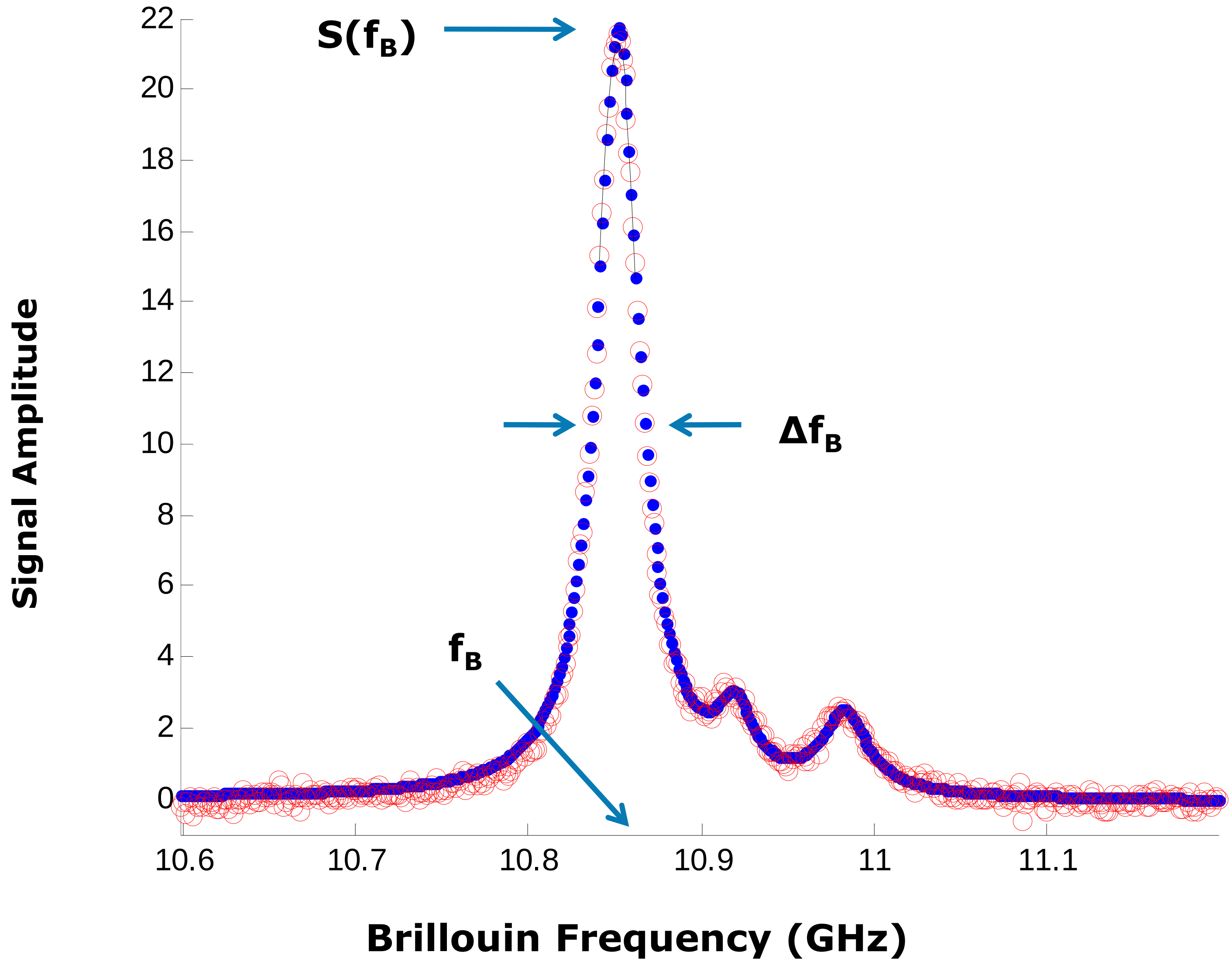
Bi-Directional OTDR Traces



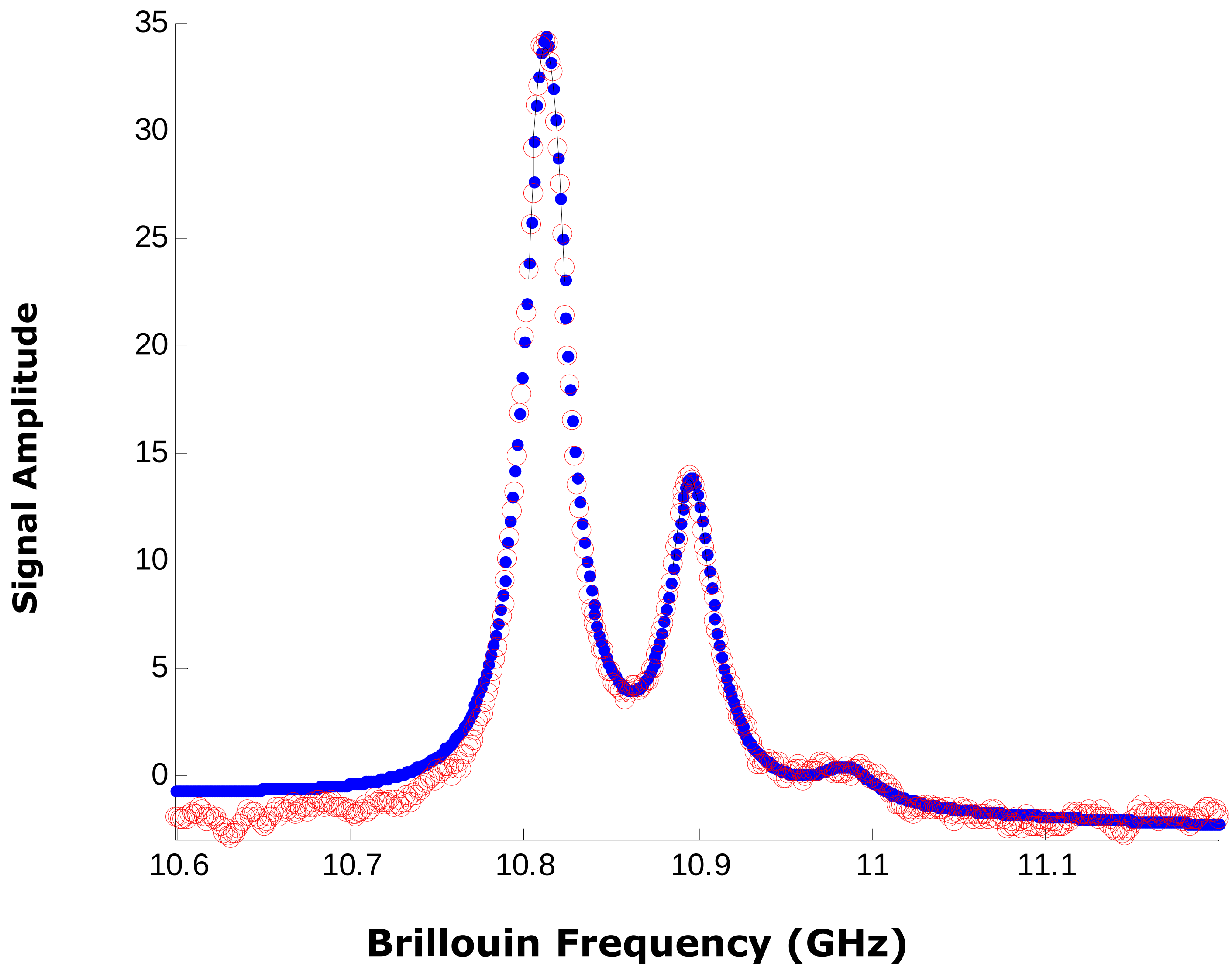
BOTDA scan at fixed frequency



Single-Peak Brillouin Spectrum



Double-Peak Brillouin Spectrum



Temperature and Strain Dependence of Brillouin Frequency Shift:

$$f_B = f_0 + C(T - T_0) + \varepsilon(S - S_0)$$

C=Brillouin shift parameter from temperature changes

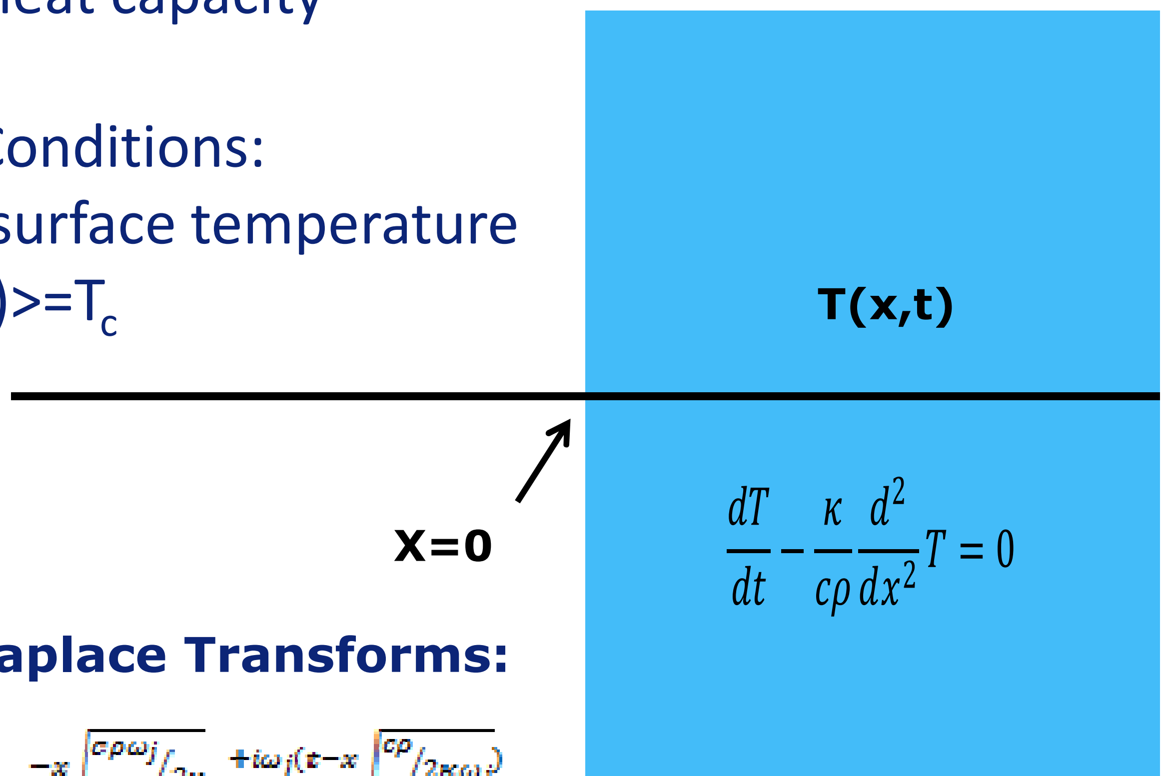
ε=Brillouin shift parameter from strain changes

How Can We Calibrate Buried Fiber?

- Fibers used as sensors can be calibrated in the lab for the Brillouin shift parameters.
- However most fibers used for Telecommunications were buried years ago, without characterizing the Brillouin shift parameters.
- Use Thermal Conductivity Model to Estimate ground Temperature:
  - Fiber is buried approximately 48” underground
  - 48” of dirt insulates and filters most variations of air temperature above
  - Seasonal variations remain
  - For each 100m section of buried fiber, use BOTDA to measure the Brillouin frequency shift vs. time for at least one season
  - Using thermal model, with known surface temperatures, to fit the Brillouin frequency shift vs time
  - Three parameter fit: α, f_0, and C
  - The three parameters are location-dependent

Thermal Conduction Model

K=thermal conductivity
C=specific heat capacity
ρ=density
Boundary Conditions:
T(0,t)=f(t)=surface temperature
T(∞,t)=<f(t)>=T_c



$$\frac{dT}{dt} - \frac{\kappa}{c\rho}\frac{d^2}{dx^2}T = 0$$

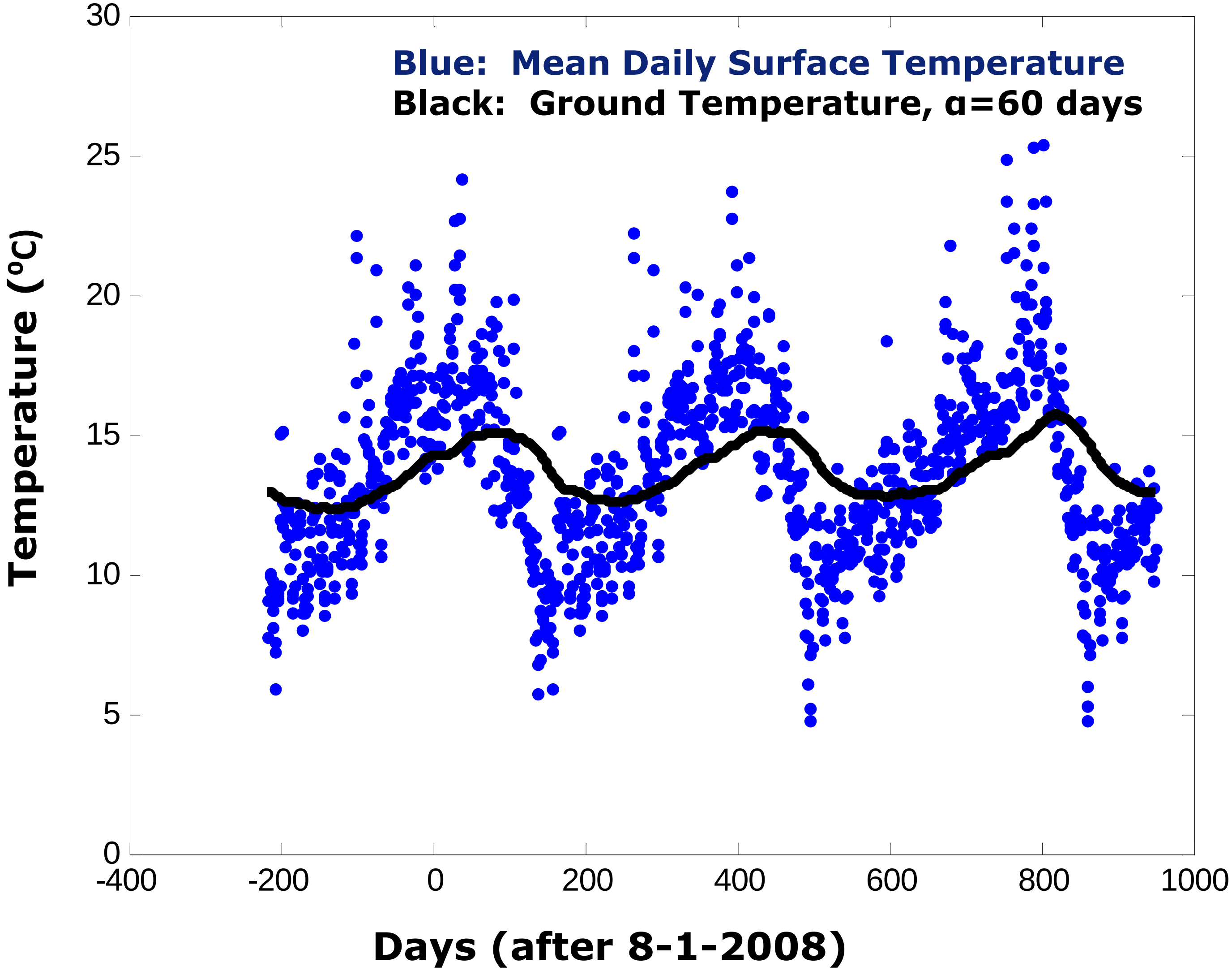
Solve using Laplace Transforms:

$$T(x,t) = T_c + \sum_{j=0}^{N} b_j e^{-x\sqrt{c\rho\omega_j/2\kappa}} e^{+i\omega_j\left(t - x\sqrt{c\rho/2\kappa\omega_j}\right)}$$

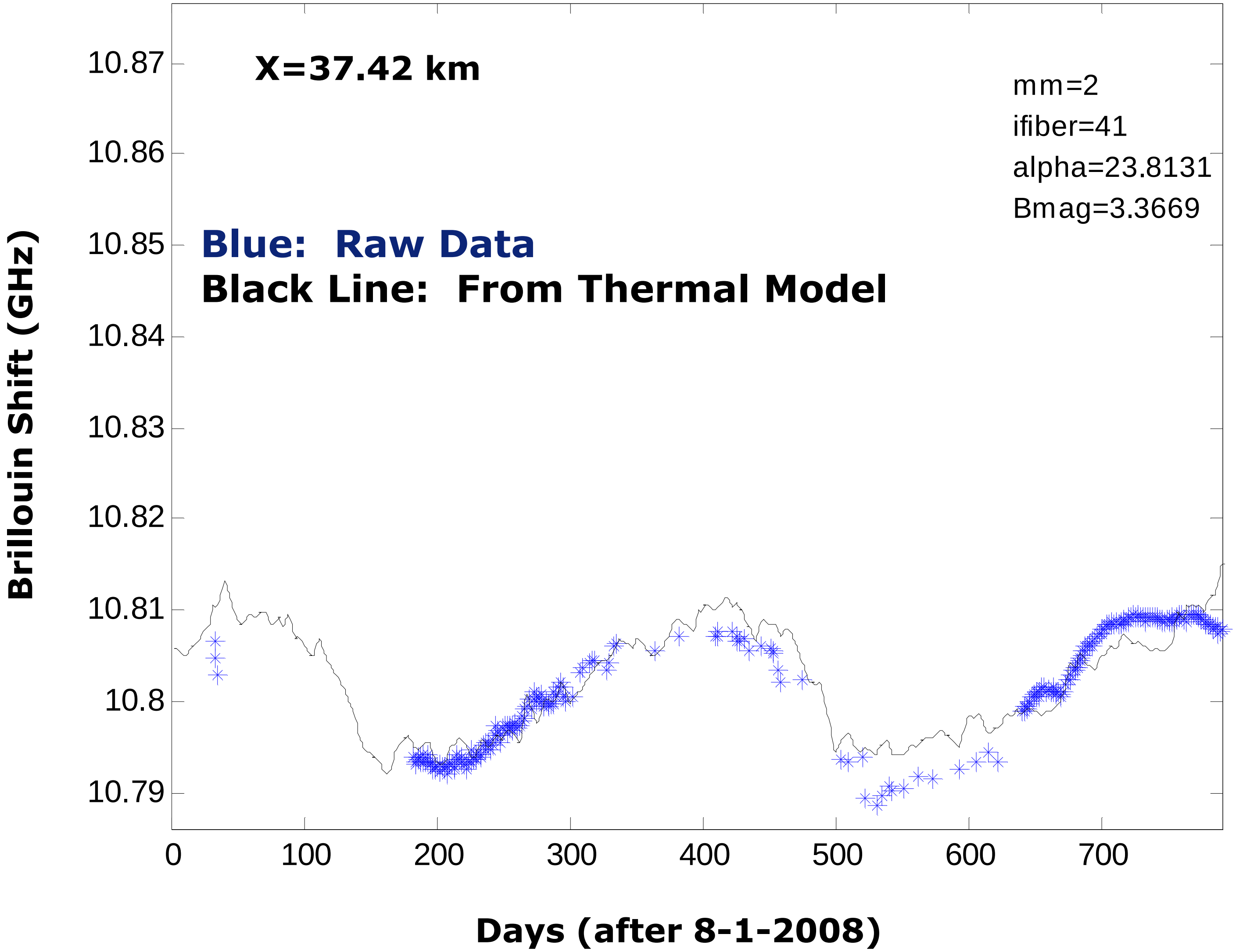
$$f(t) = \sum_{j=0}^{N} b_j e^{-i\omega_j t}$$

For x fixed, there is a single parameter: $\alpha = x\sqrt{\pi c\rho/\kappa T_{year}}$

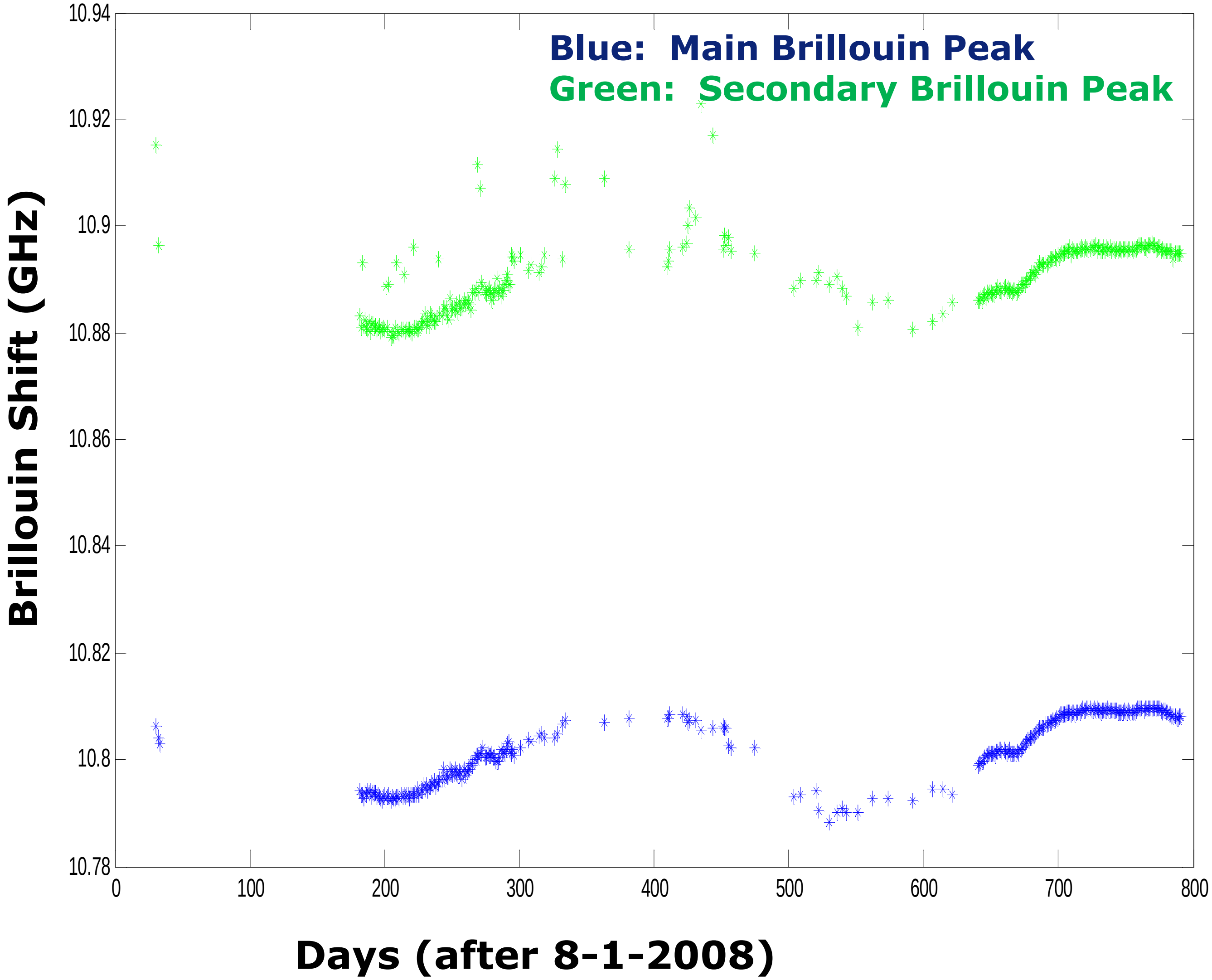
Surface and Ground Temperatures



BOTDR Temperature vs. Time: Example of 3-parameter thermal model fit



Second Brillouin Peak



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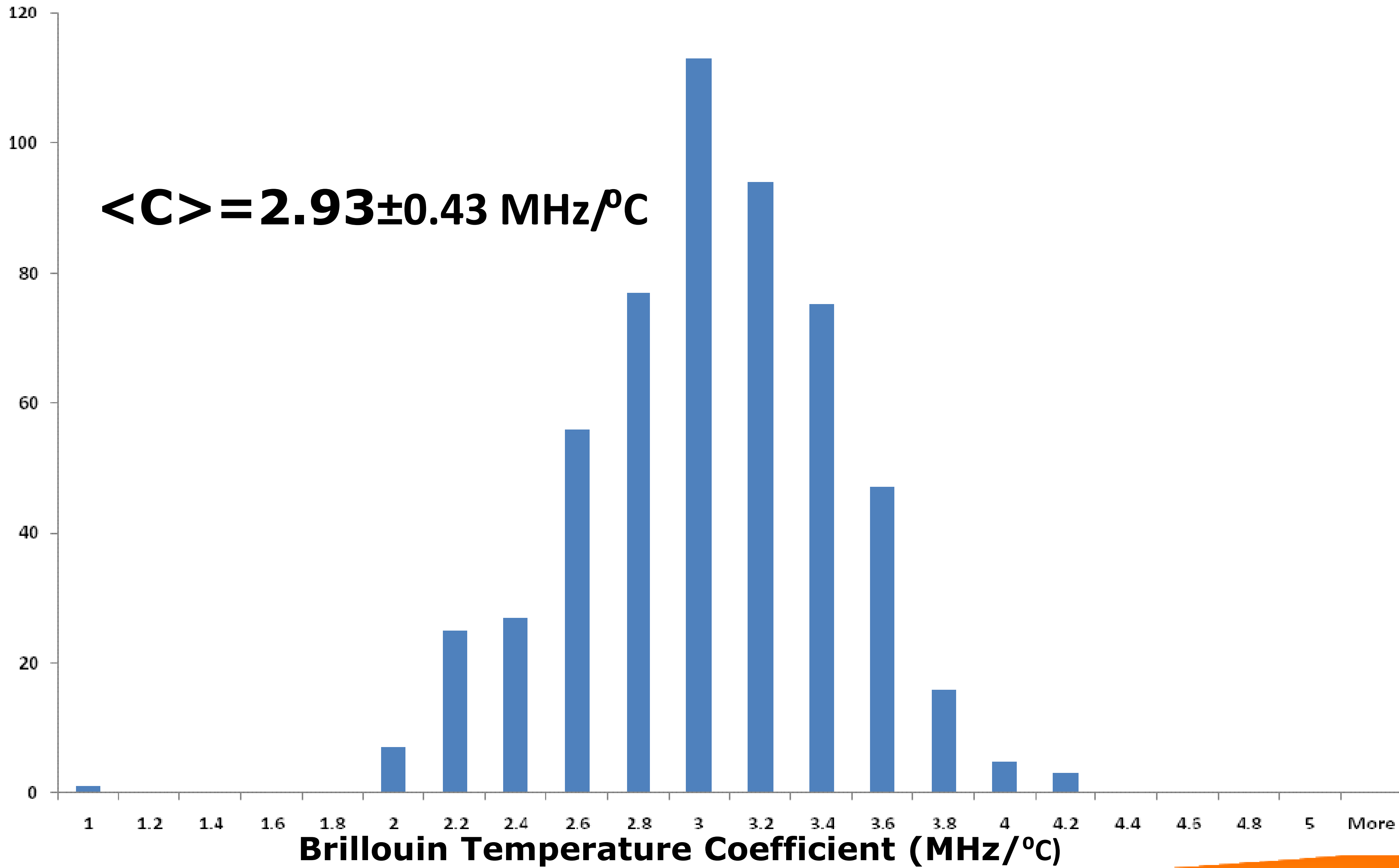
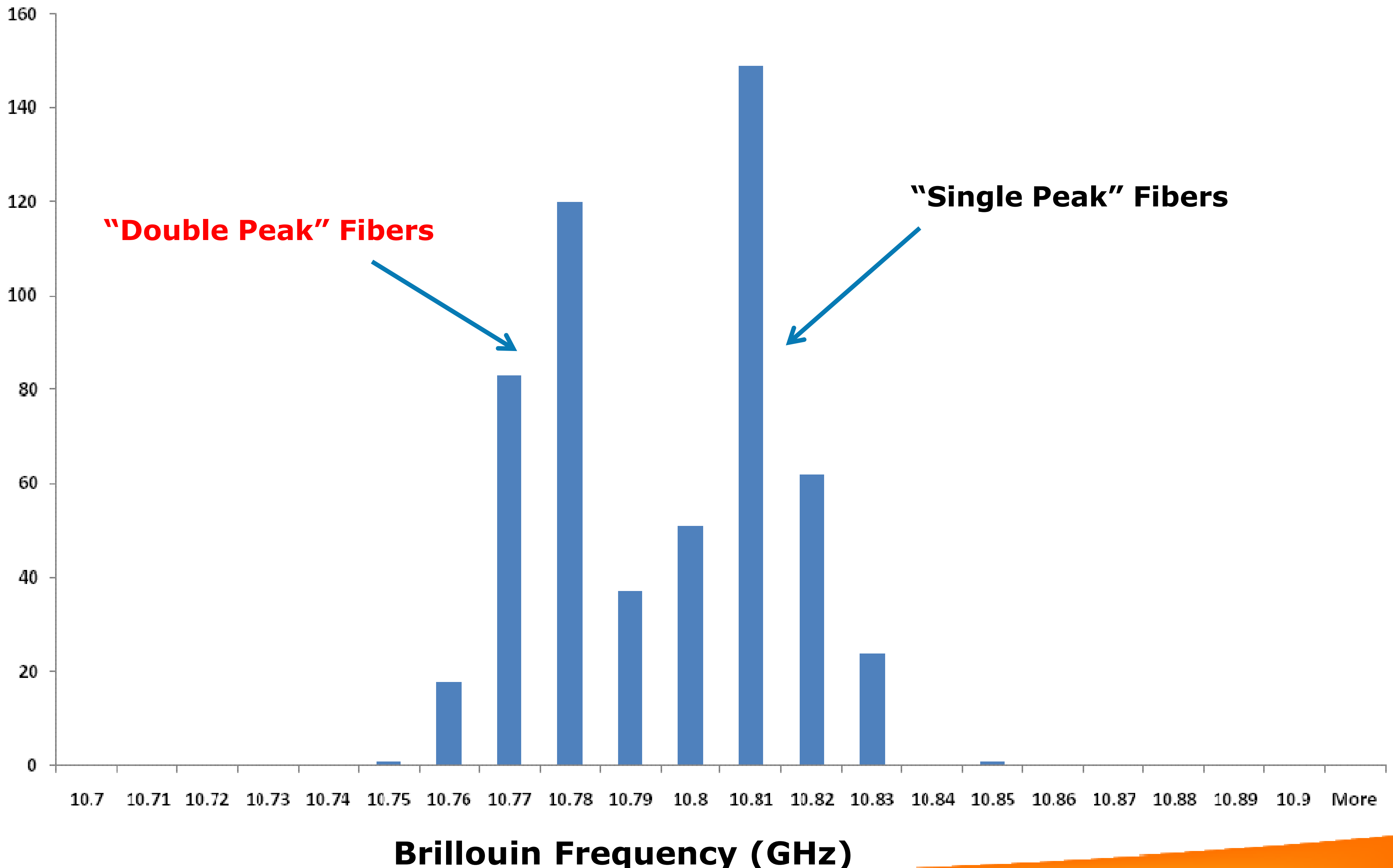
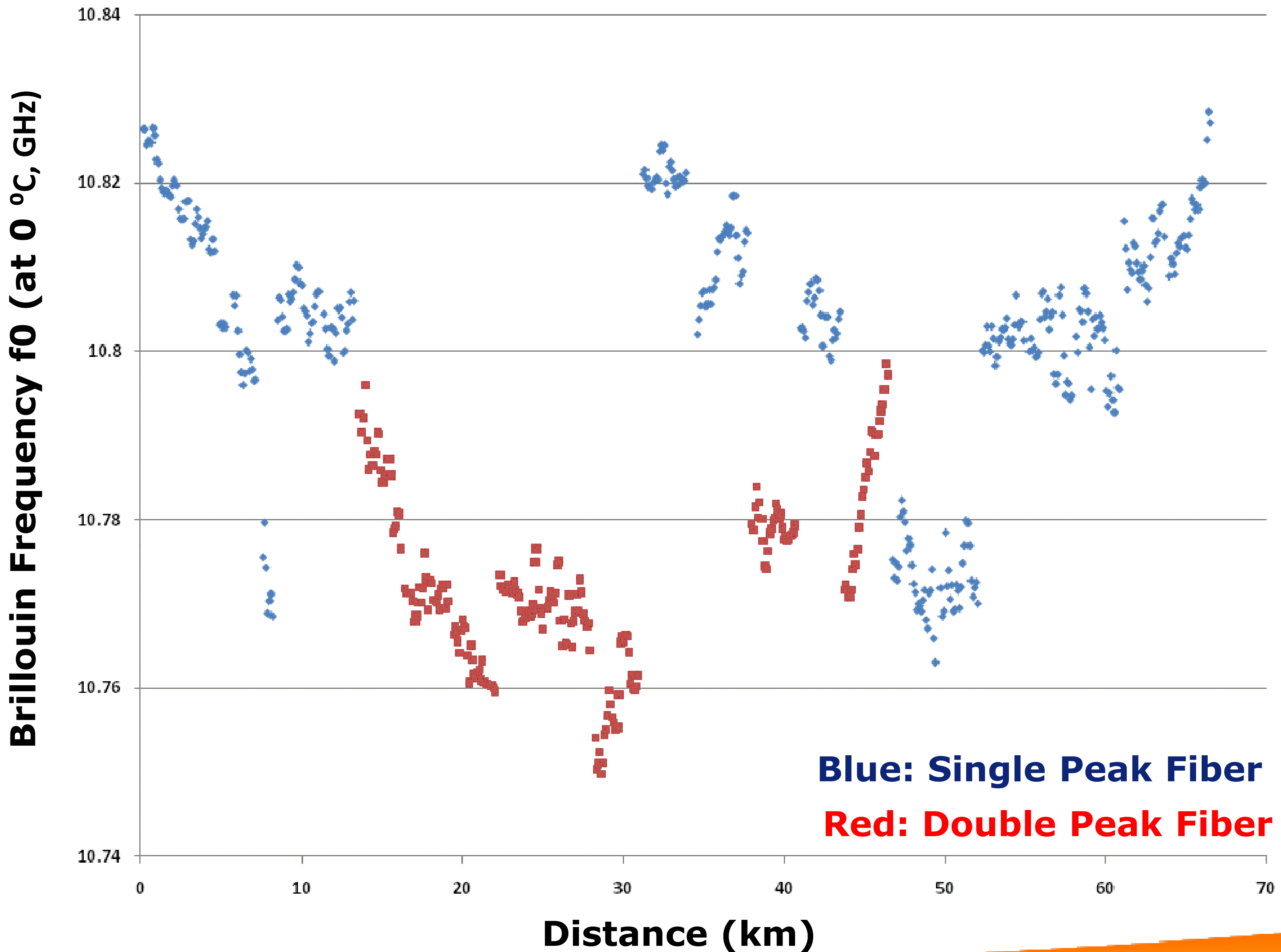
Distribution of Brillouin Temperature Coefficient



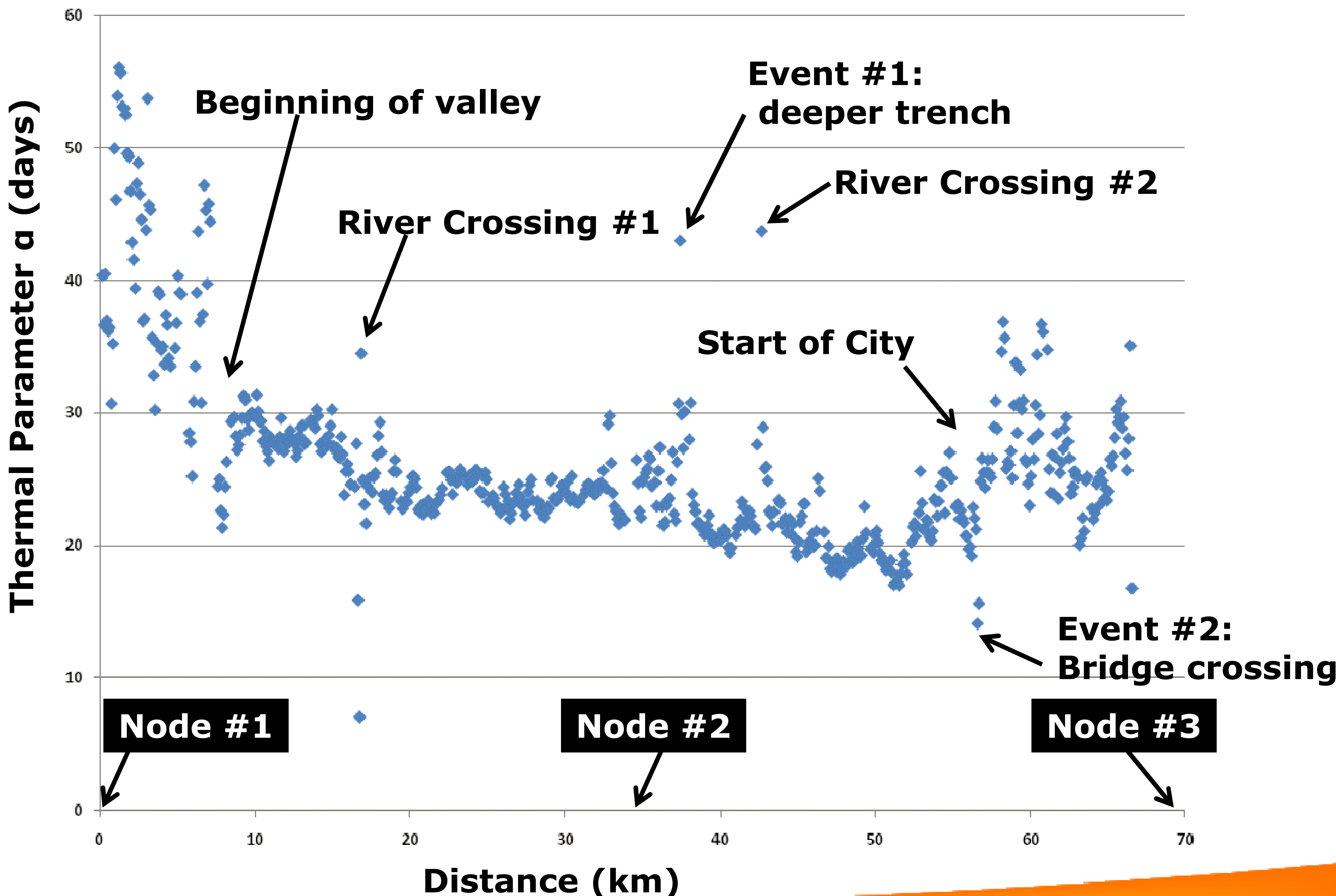
Distribution of Brillouin Frequencies ($0^{0}C$)



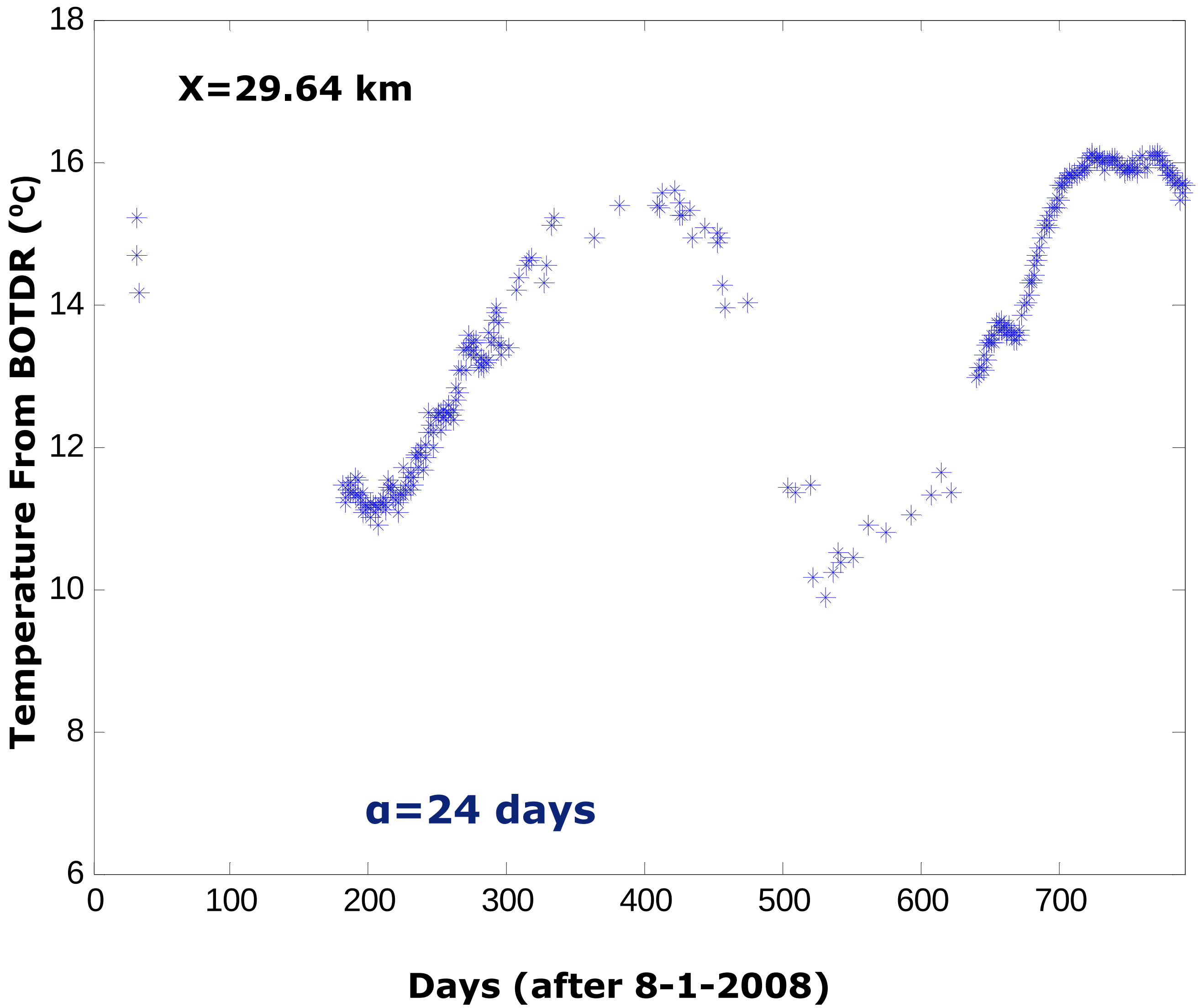
Brillouin Frequency f_0 vs. distance



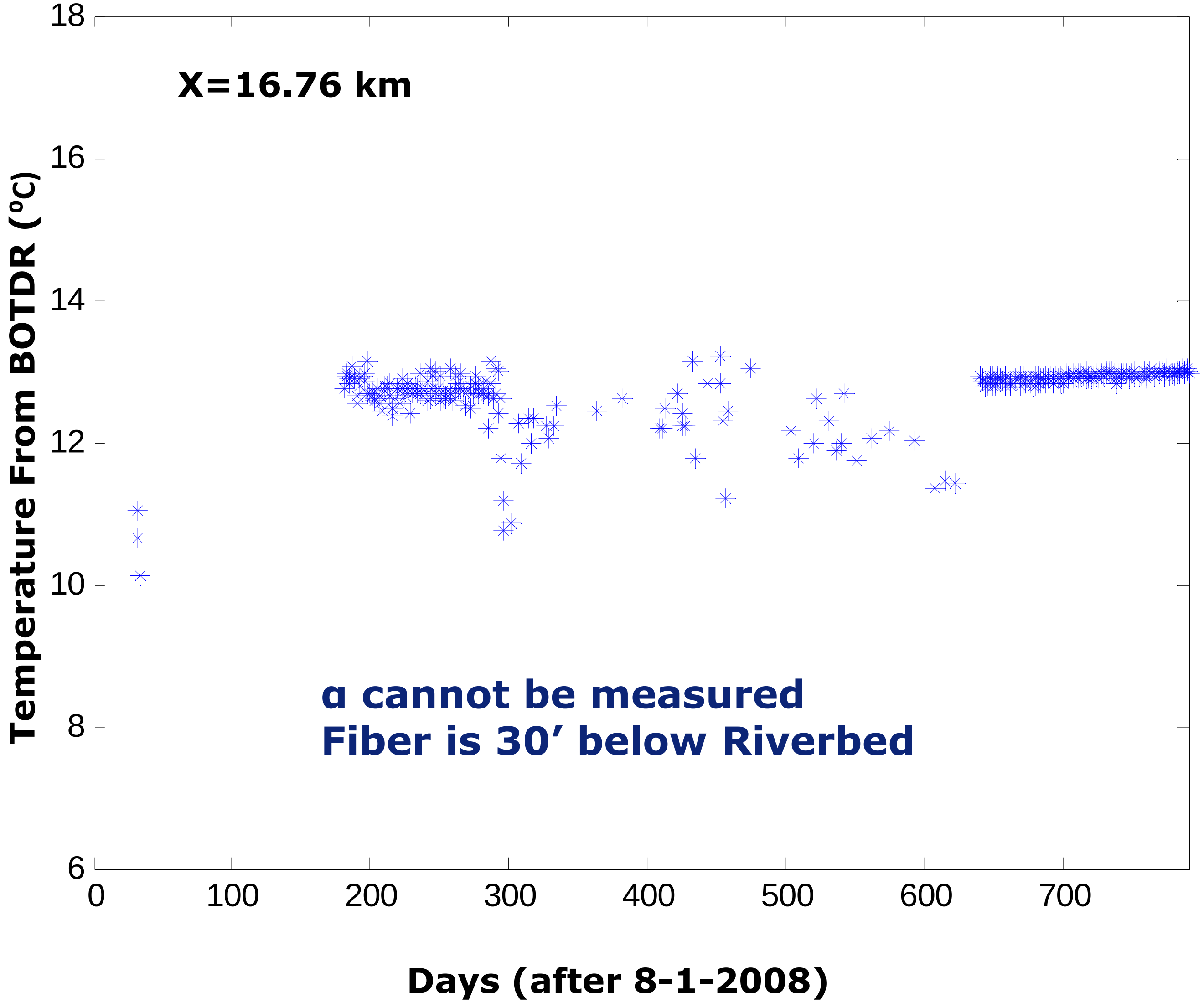
Thermal Parameter α vs. distance



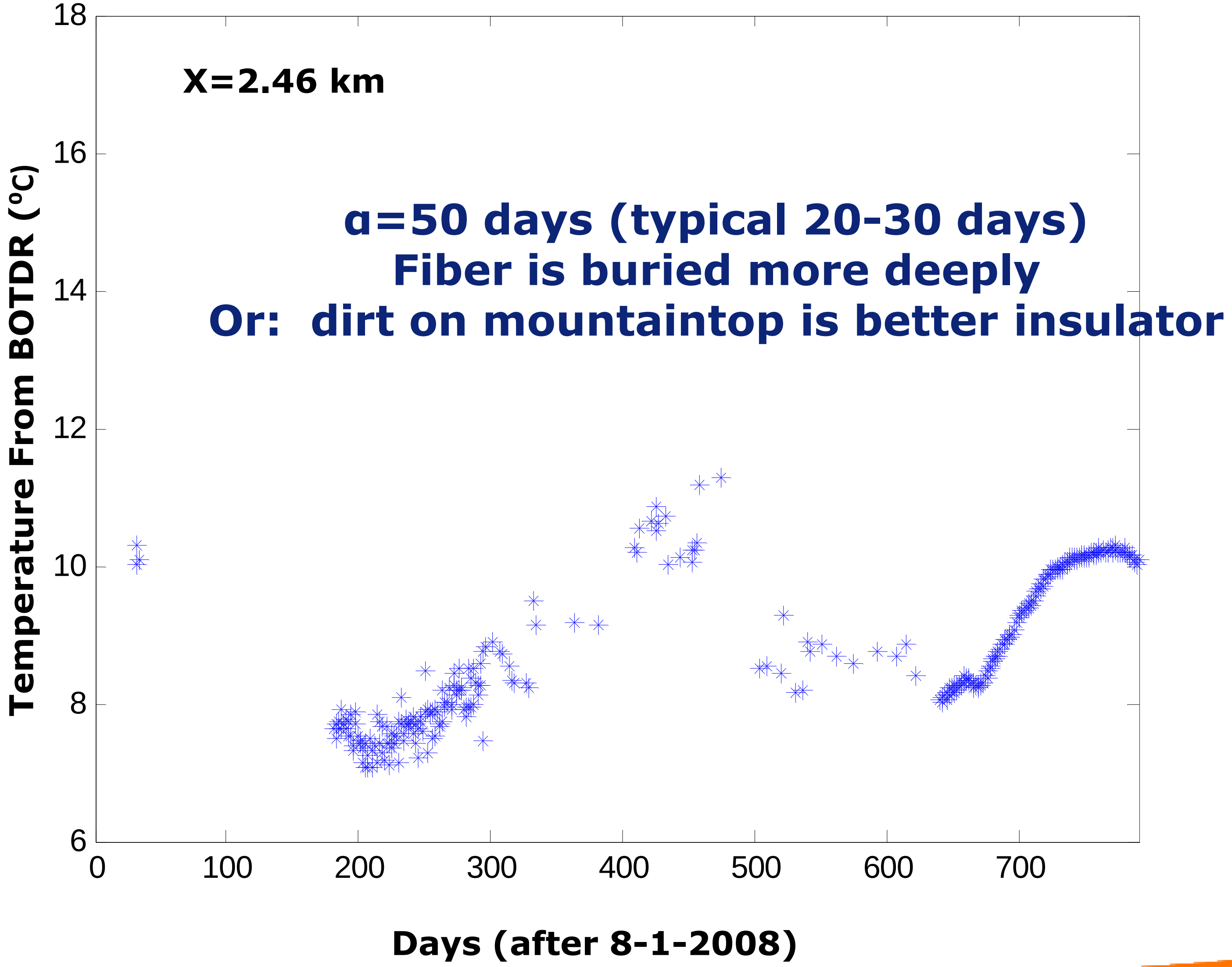
BOTDR Temperature vs. Time: typical location



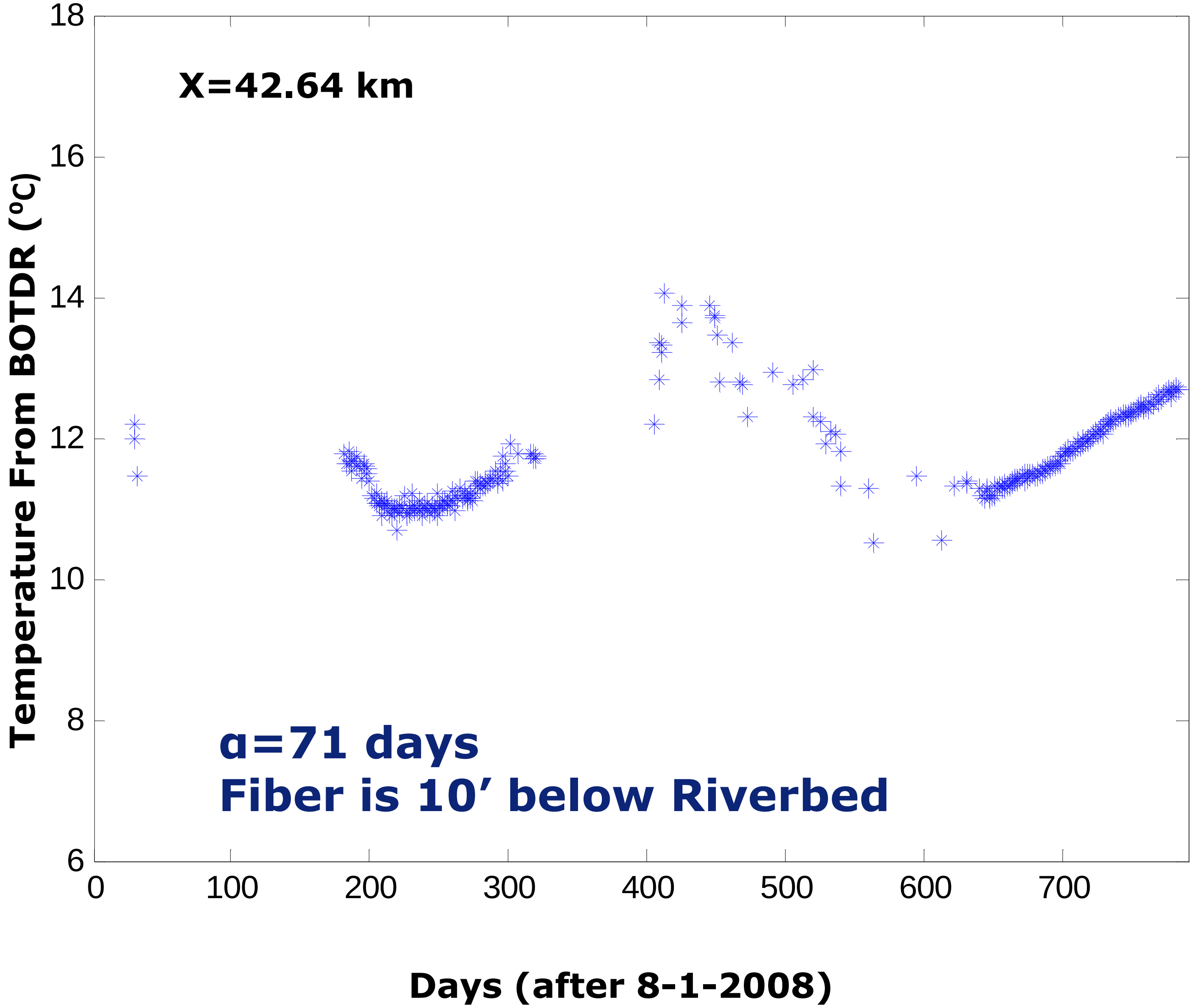
BOTDR Temperature vs. Time: River Crossing #1



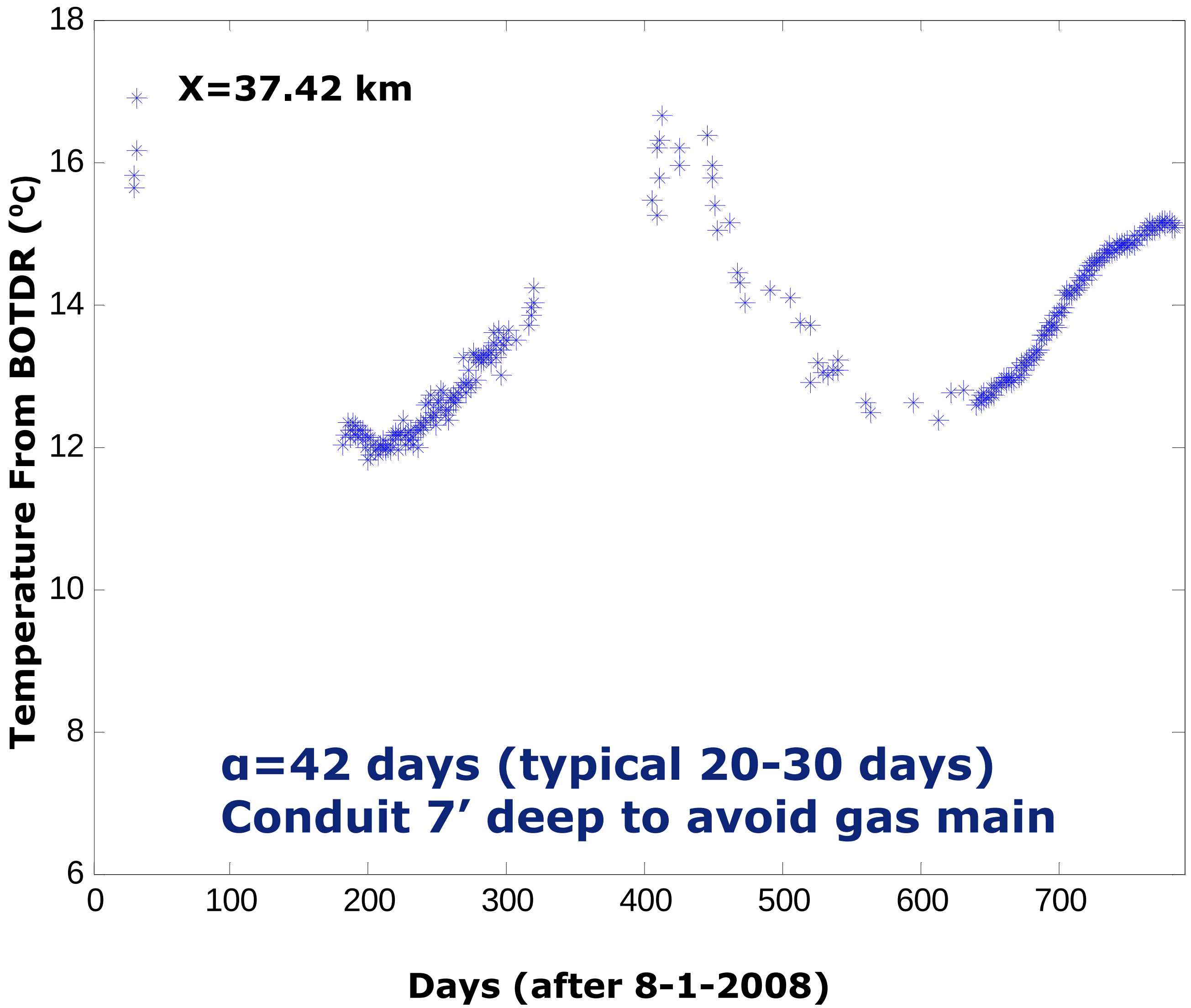
BOTDR Temperature vs. Time: mountaintop



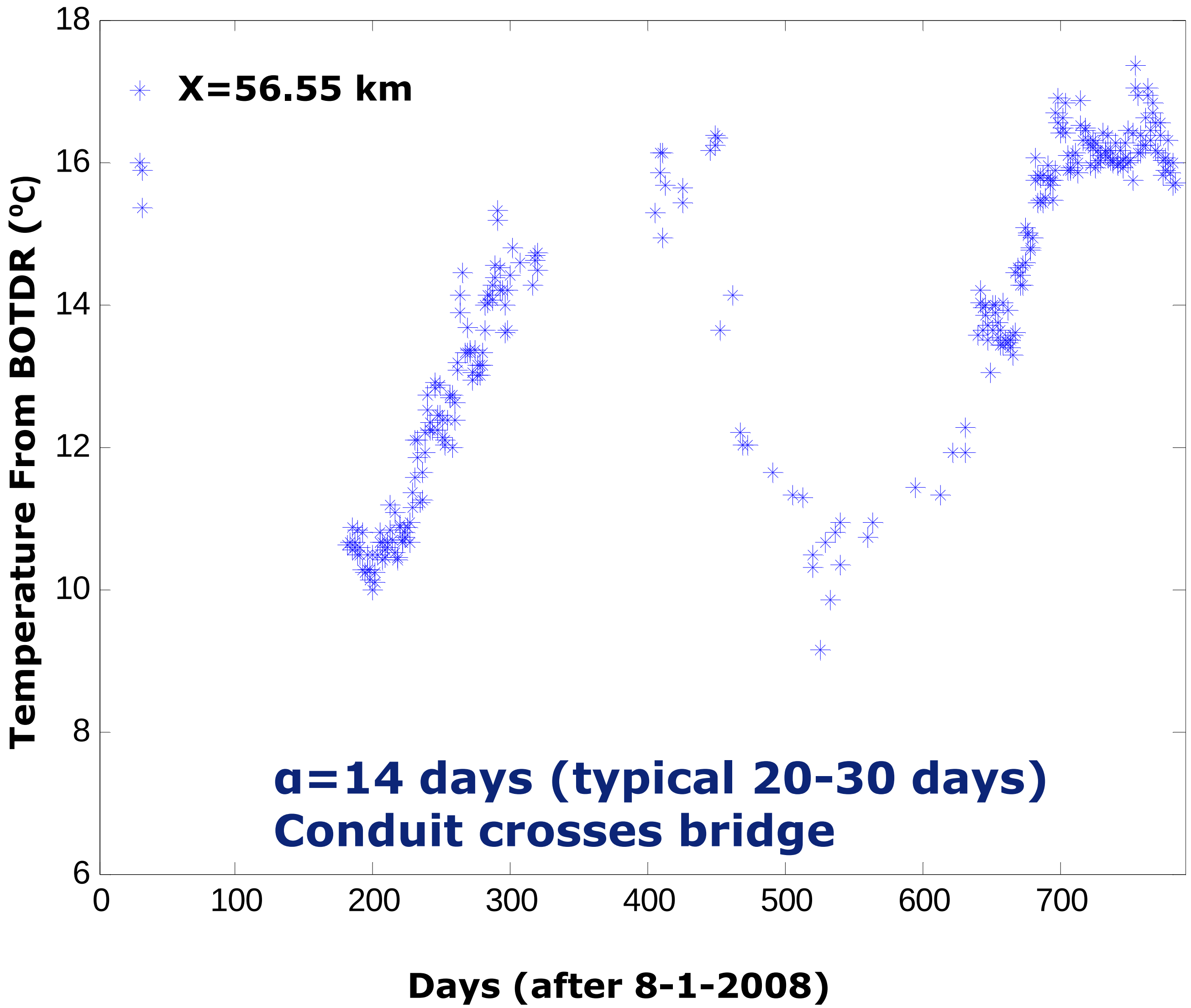
BOTDR Temperature vs. Time: River Crossing#2



BOTDR Temperature vs. Time: event#1



BOTDR Temperature vs. Time: event#2



What about Strain?

- All of the fiber is in loose-tube cable
- All of the cable except the first 8 km is in conduit
  - No strain expected
- Brillouin shifts from small strains are usually much larger than those from small temperature changes
- If there was time-dependent strain how would we know?
  - Departure from thermal model
  - No time-dependent strain seen
- If there was local, but constant strain, how would we know?
  - Changes in Brillouin frequency along fiber are usually continuous
  - Measurements of local Brillouin frequency shifts over many fibers are correlated if there are strains in the cable.
  - There is some evidence of strains in the direct-buried part of the cable.

What’s Next

- Improve Spectral Fits
- Local Brillouin gain factor and loss
- Effects of Mode-Field Diameter on Brillouin frequencies and linewidths
- Behavior of second and third Brillouin peaks