29th Review of Atmospheric Transmission Models Meeting

13-14 June 2007
Museum of Our National Heritage
Lexington Massachusetts

Session 2: LIDAR

Invited Presentation ...

Chemical Species Measurements in the Atmosphere Using Lidar Techniques
Philbrick, C.R. (Slides & Paper)

White Light Lidar (WLL) Simulation and Measurements of Atmospheric Constituents
Brown, D.M., P.S. Edwards, Z. Liu and C.R. Philbrick (Slide Presentation)

Supercontinuum LIDAR Measurements of Atmospheric Constituents
Brown, D.M., P.S. Edwards, K. Shi, Z. Liu, and C.R. Philbrick (Paper)

Multistatic Lidar Measurements of Aerosol Multiple Scattering
Park, J.H., C.R. Philbrick and G. Roy
(Slides & Paper)

White Light LIDAR (WLL) Simulation and Measurement of Atmospheric Constituents

David Brown, P.S. Edwards,
Z. Liu, C.R. Philbrick

Penn State University
Department of Electrical Engineering

Outline

- Differential Absorption
- Existing Differential Absorption Approaches
  - 3λ DIAL Spectral Absorption
  - Wide Spectrum Absorption
    - Imaging
    - Incoherent Transmitter
    - Terawatt Coherent Transmitter
- Supercontinuum Absorption LIDAR at PSU
  - Low Power Coherent Transmitter
  - Measurement Configurations and Results

Solution Approach: Differential Absorption

- The Differential Absorption Method Basics
  - Start with lidar scattering equation for elastic scattering (Rayleigh)

$$P_{rec}(\lambda, R) = P_{out} \frac{A}{R^2} \frac{c\tau_L}{2} \xi(\lambda)\xi(R)\beta(\lambda, R) e^{-\int_0^R \kappa_T(R)dR}$$

  - Modify for long path absorption (switch to energy per pulse for on and off wavelength and ratio)

$$\Rightarrow \int_0^{R_T} N(R)dR = -\frac{1}{2\left[\sigma^A(\lambda_{on}) - \sigma^A(\lambda_{off})\right]} \ln\left[\frac{E_{rec,on}(\lambda_{on}, R_T)}{E_{rec,off}(\lambda_{off}, R_T)}\right]$$

Where the ***differential absorption cross section*** is.. (Measures 1984)

$$\sigma^A_{diff} = \sigma^A(\lambda_{on}) - \sigma^A(\lambda_{off})$$

So, for this simplified case, we require 3 parameters to determine the concentration path length…

1. Range to topographical scatterer (range finder or altimeter)
2. Differential cross section (known by spectra)
3. Received energy ratio (measured by detectors after collecting telescope)

Solution Approach: Differential Absorption of Multiple Spectrally Overlapping Species

- DOAS Approach

$$\chi_i^2 = \frac{\sum w\left(DOD_i^{FIT} - DOD_i^{OBS}\right)^2}{\sum w}$$

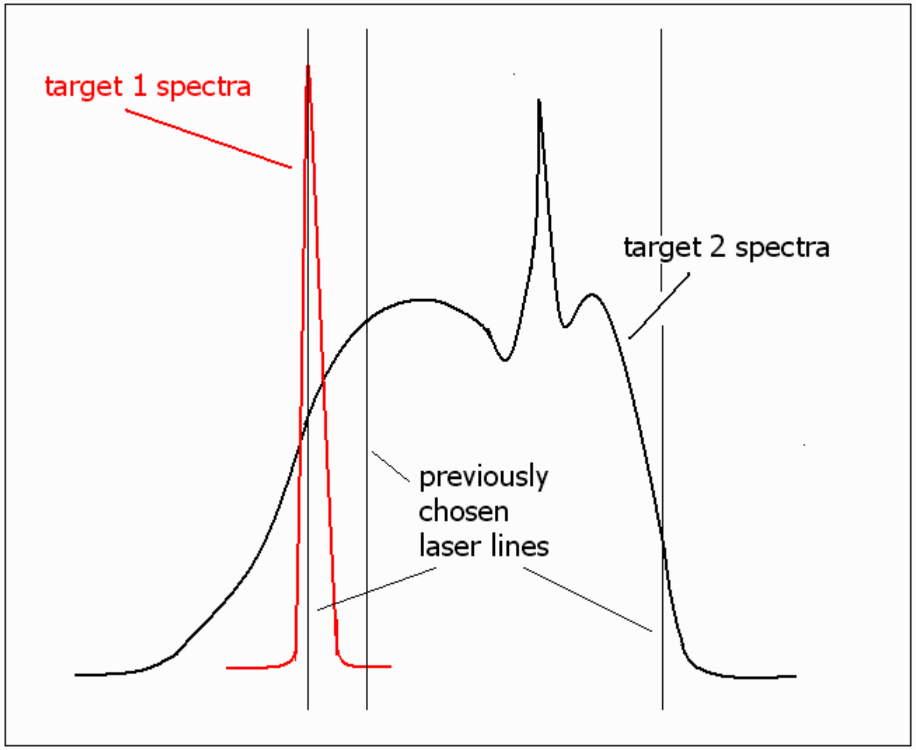
South, A.M., I.M. Povey, R.L. Jones "Broadband lidar Measurements of Troposphere Water Vapor Profiles" *Journal of Geophysical Research*, Vol 103, No. D23, pg 191 – 231, 1998

- Tassou Algorithm

$$F(a_1,\lambda) - F(a_2,\lambda) = \sum_{i=1}^{n} C_i\left(F_i(a_1,\lambda) - F_i(a_2,\lambda)\right)$$

Tassou M.1; Przygodzki C.2; Delbarre H.2; Boucher D.2 Atmospheric Gas Detection with Broadband Sources International Journal of Infrared and Millimeter Waves, Volume 23, Number 8, August 2002, pp. 1227-1239(13)

- Maximum likelihood estimators MLEs



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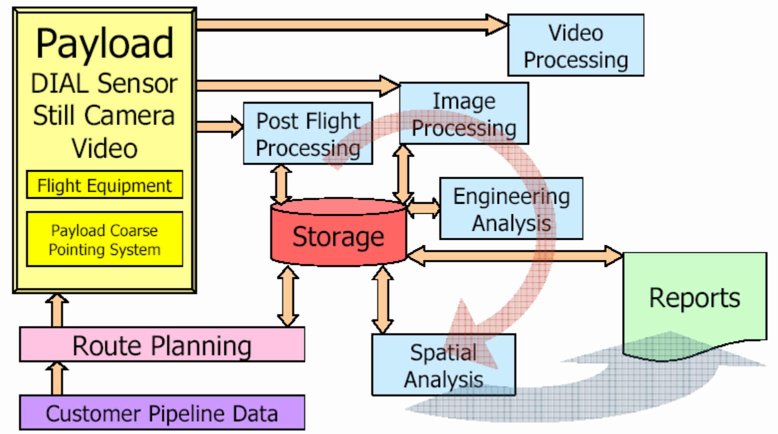
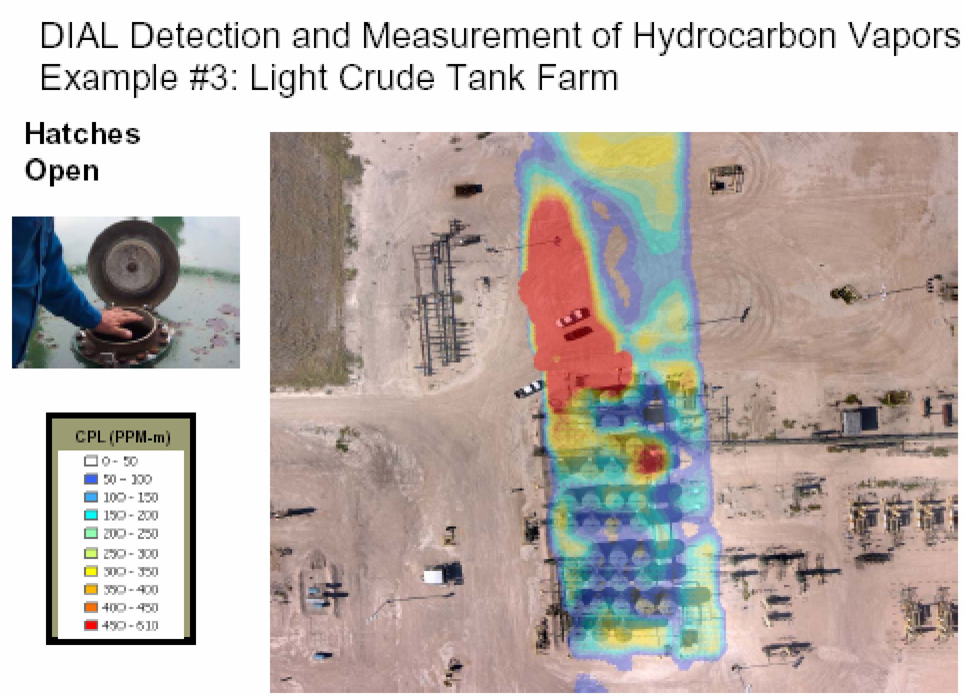
3λ Airborne DIAL Spectral Absorption

- Developed algorithms provide the foundation for the multi-component analysis of compounds other than methane that have absorption spectra in the midwave infrared.



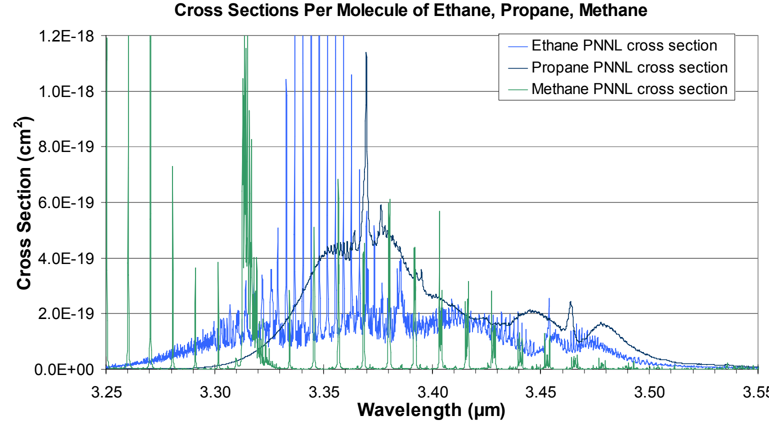


Stearns S.V., R. Lines, D. Murdock, M. Severski, D. Lenz, D. Brown, C.R. Philbrick. "Airborne Natural Gas Emission Lidar (ANGEL) System," *Proceedings of the International Symposium on Spectral Sensing Research (ISSSR), 2006.*

Wide Spectrum Absorption Imaging

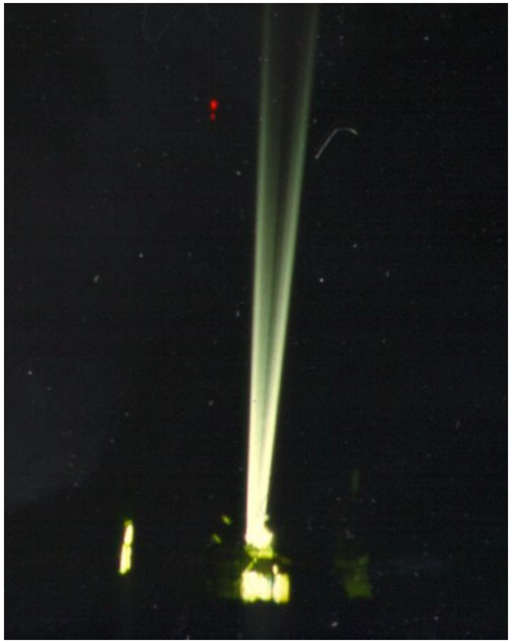
- **Passive** approach utilizes
  - Earths emission
  - Solar scatter
- Filter selection is paramount when using this approach

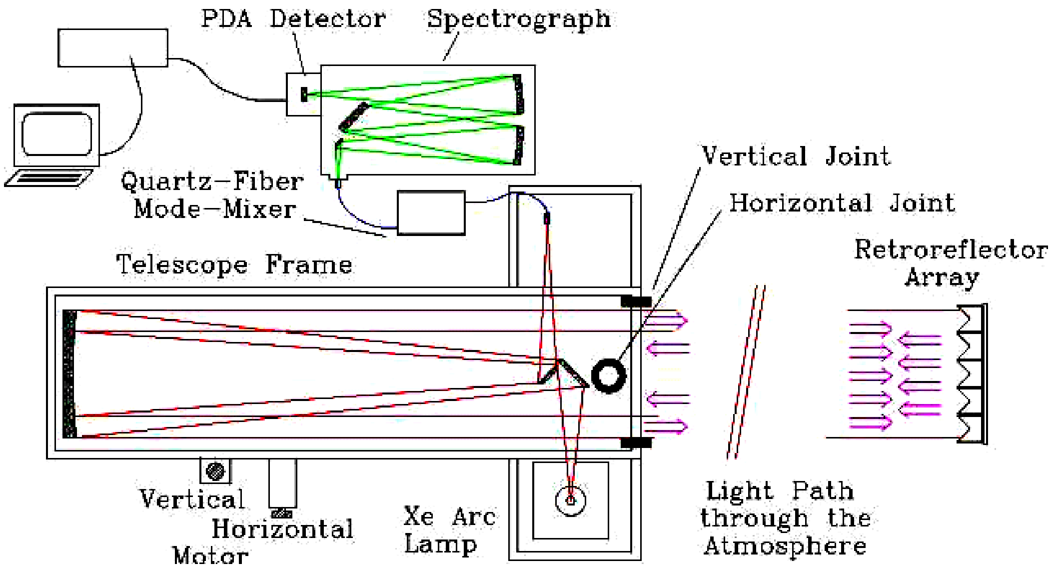
Approach was used for outfitting an imaging system for detection of propane at various ranges.



Wide Spectrum – Incoherent Transmitter

- **Active DOAS Approach (various groups)**
  - atmospheric turbulence and sunlight scatter can introduce significant noise
- **Disadvantages**
  - lamp powered DOAS cumbersome in urban environments
  - large amount of light pollution
  - limited range due to incoherent light source





http://www.atmos.ucla.edu/~jochen/research/doas/DOAS.html

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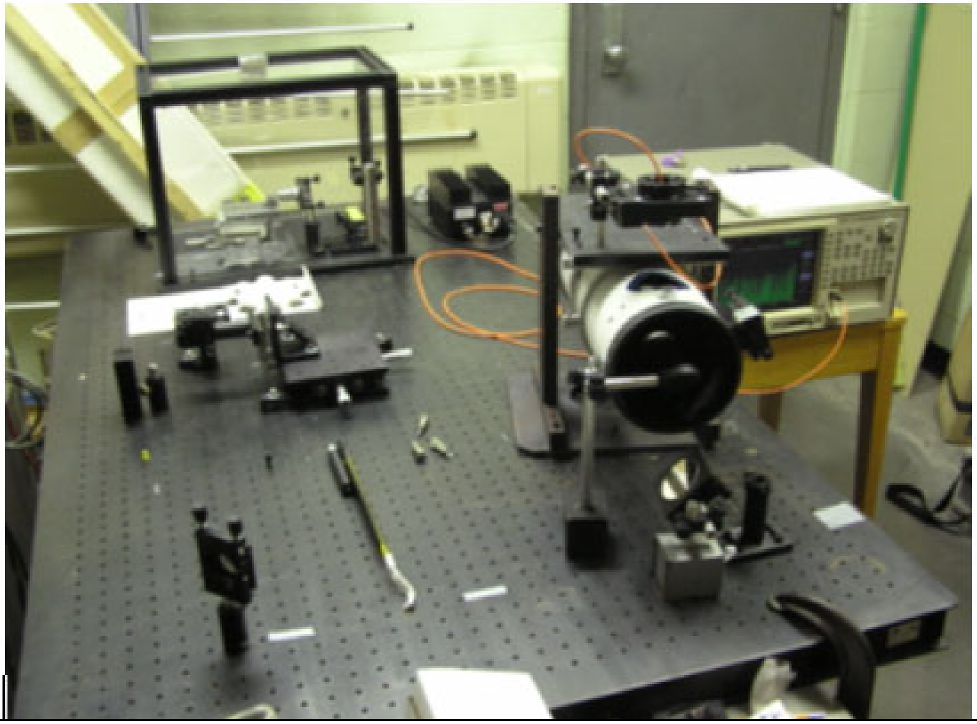
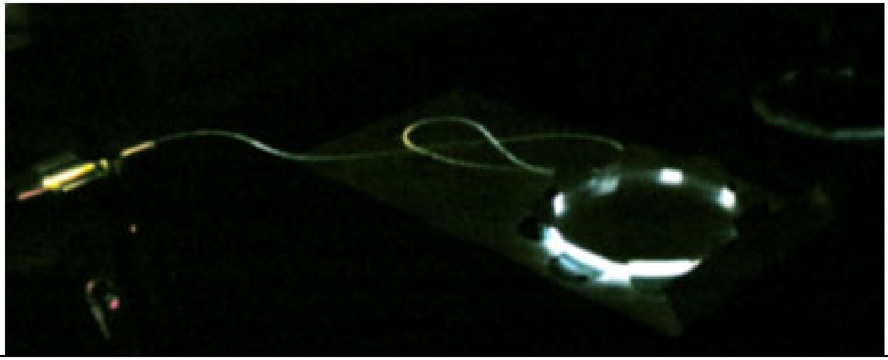
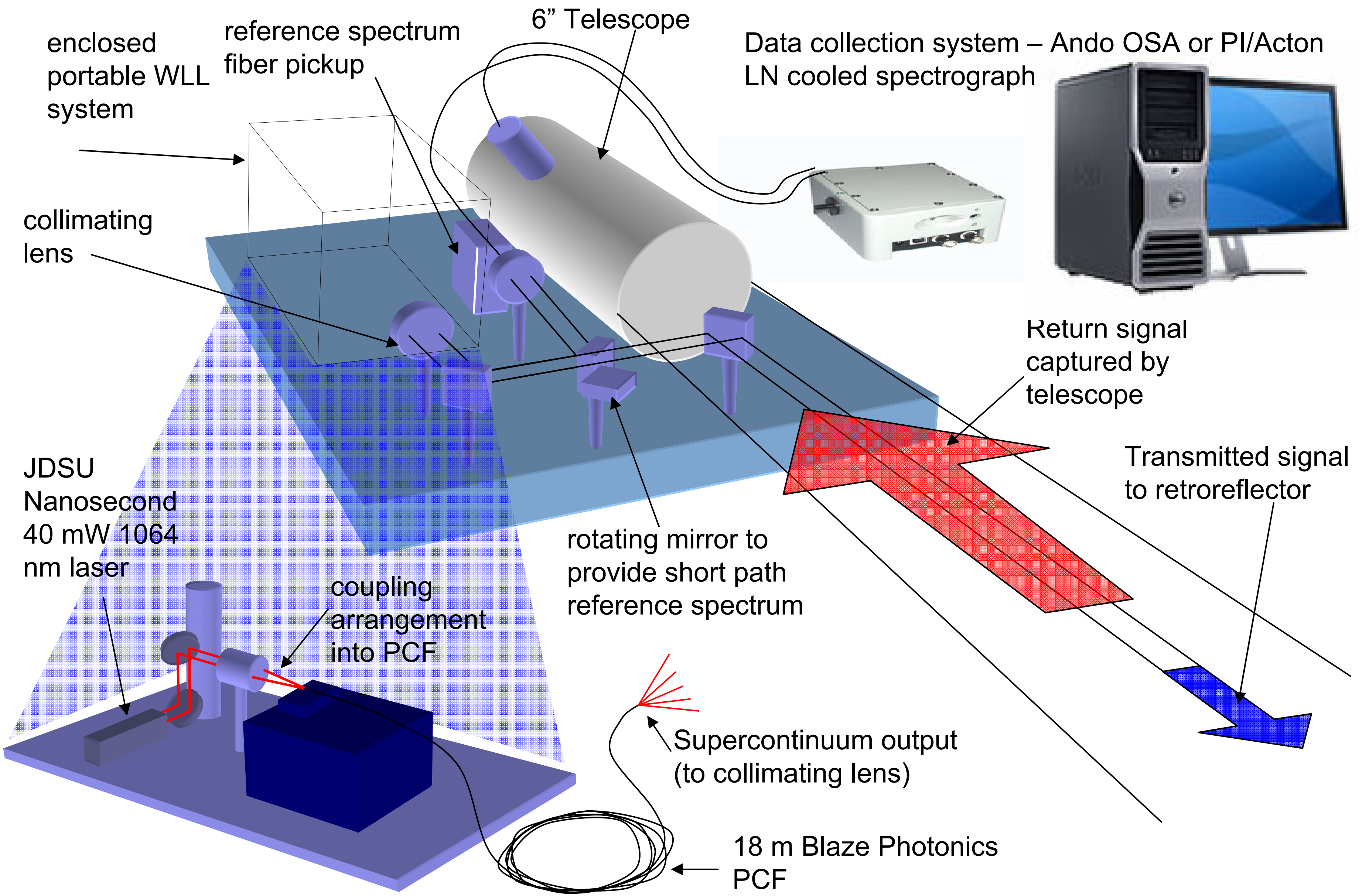
Supercontinuum Absorption LIDAR at PSU
Wide Spectrum – Coherent ~10 mW Transmitter





- ~mW pump power
- Increased sensitivity at reduced atmospheric range
- Promising for wide area assessment at high sensitivity
- Low relative cost

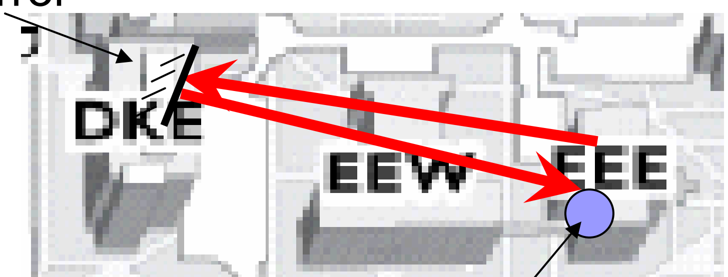
Supercontinuum Absorption LIDAR at PSU



Supercontinuum Absorption LIDAR testing at PSU

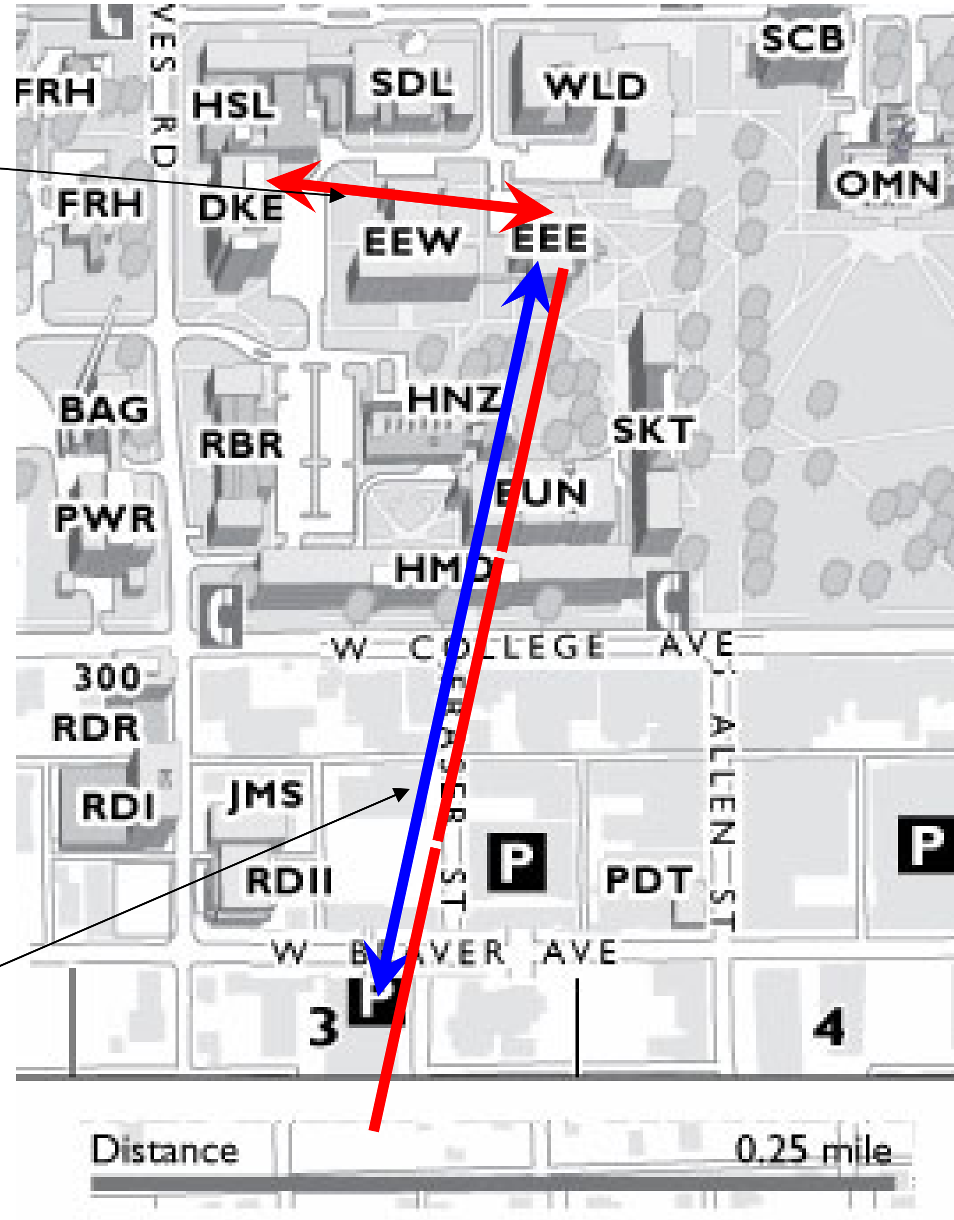
- Current – 4" telescope
  - 300 m path (two way to Dieke building)
  - 600 m path tested with mirror and retroreflector (for first successful oxygen meas.)

mirror

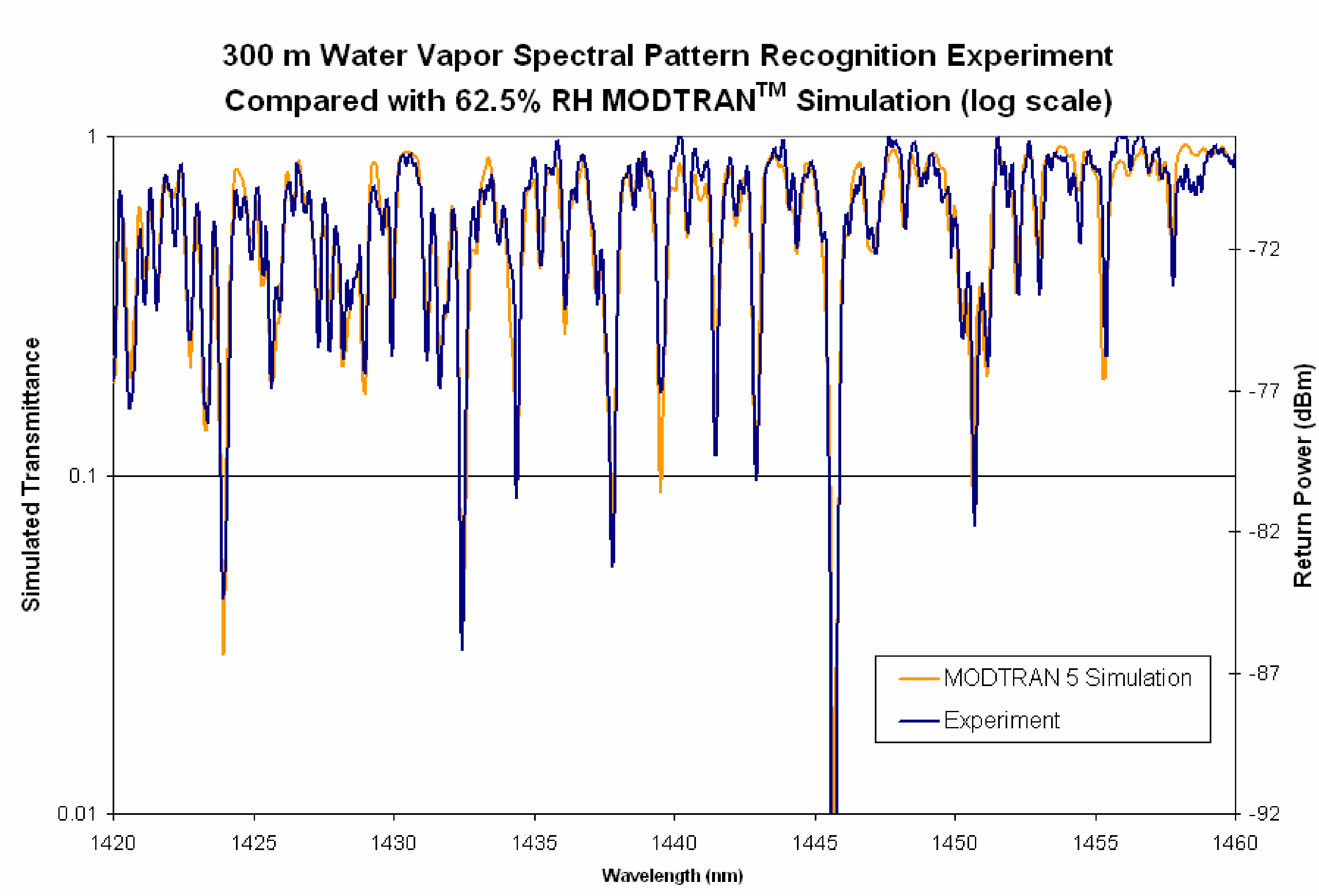


retroreflector

- Future – 10" telescope with turning mirror fixed to roof of EE East
  - >600 m path

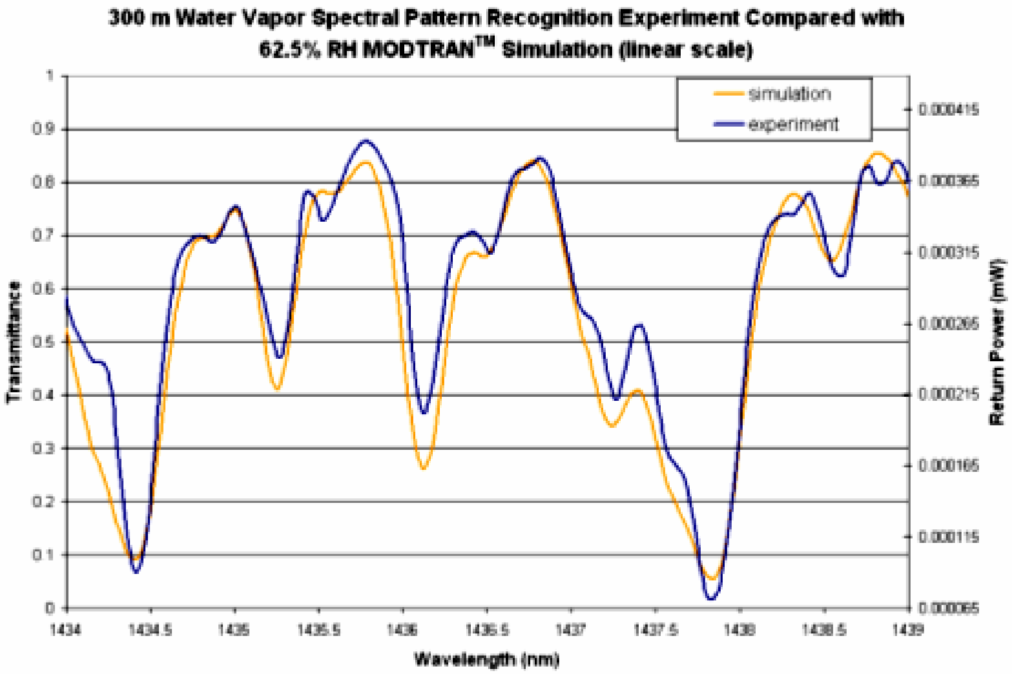


Water Vapor Results – 300 m path MODTRAN™ 5

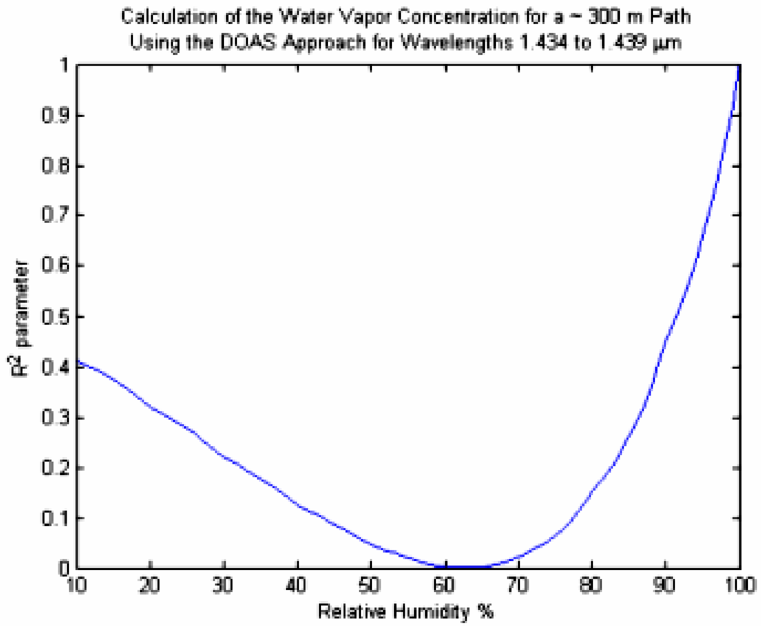


Spectral scan of the 1420 to 1460 nm band in the infrared.
Note the strong water vapor absorption bands.

Water Vapor Results – 300 m path



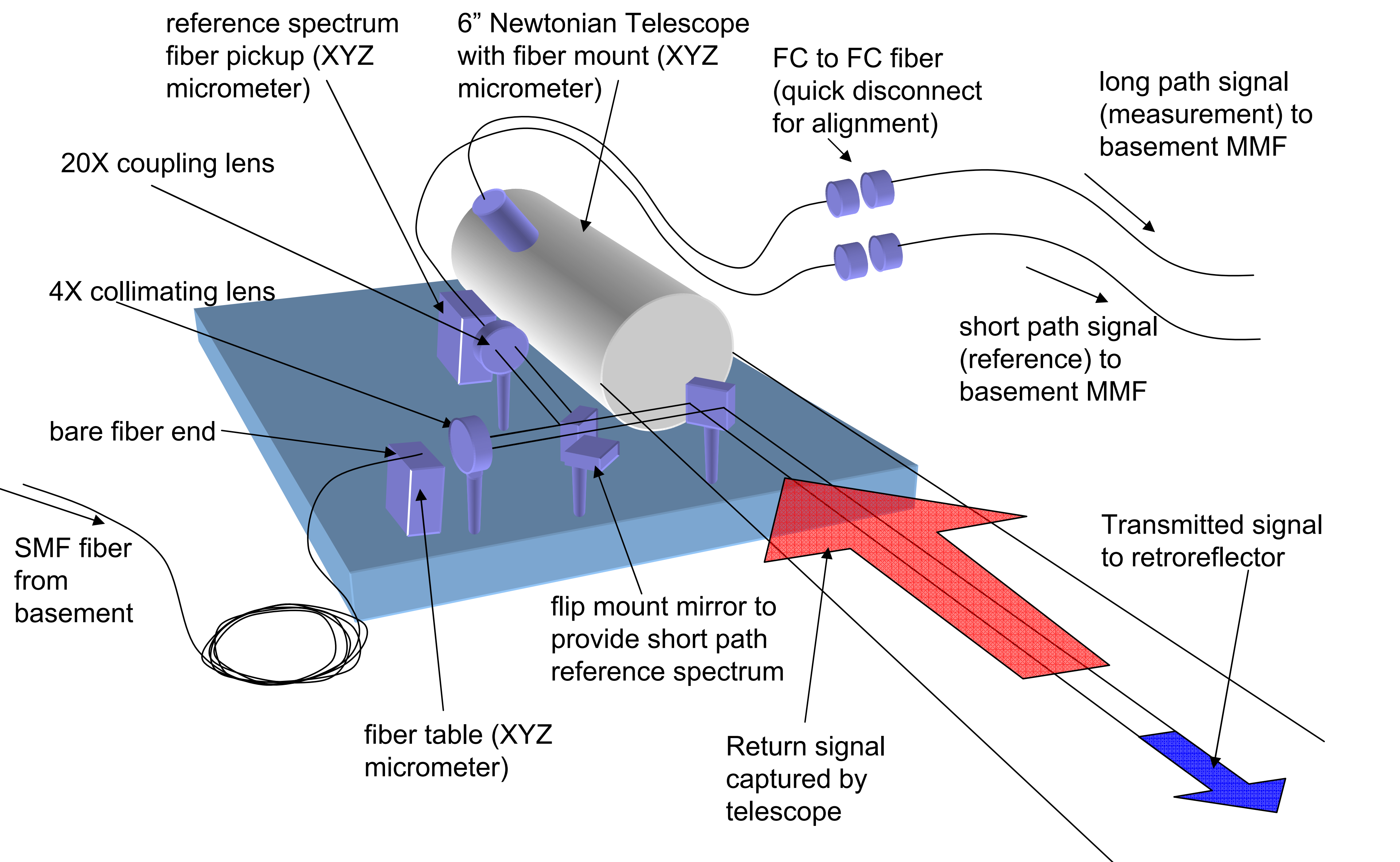
(a)



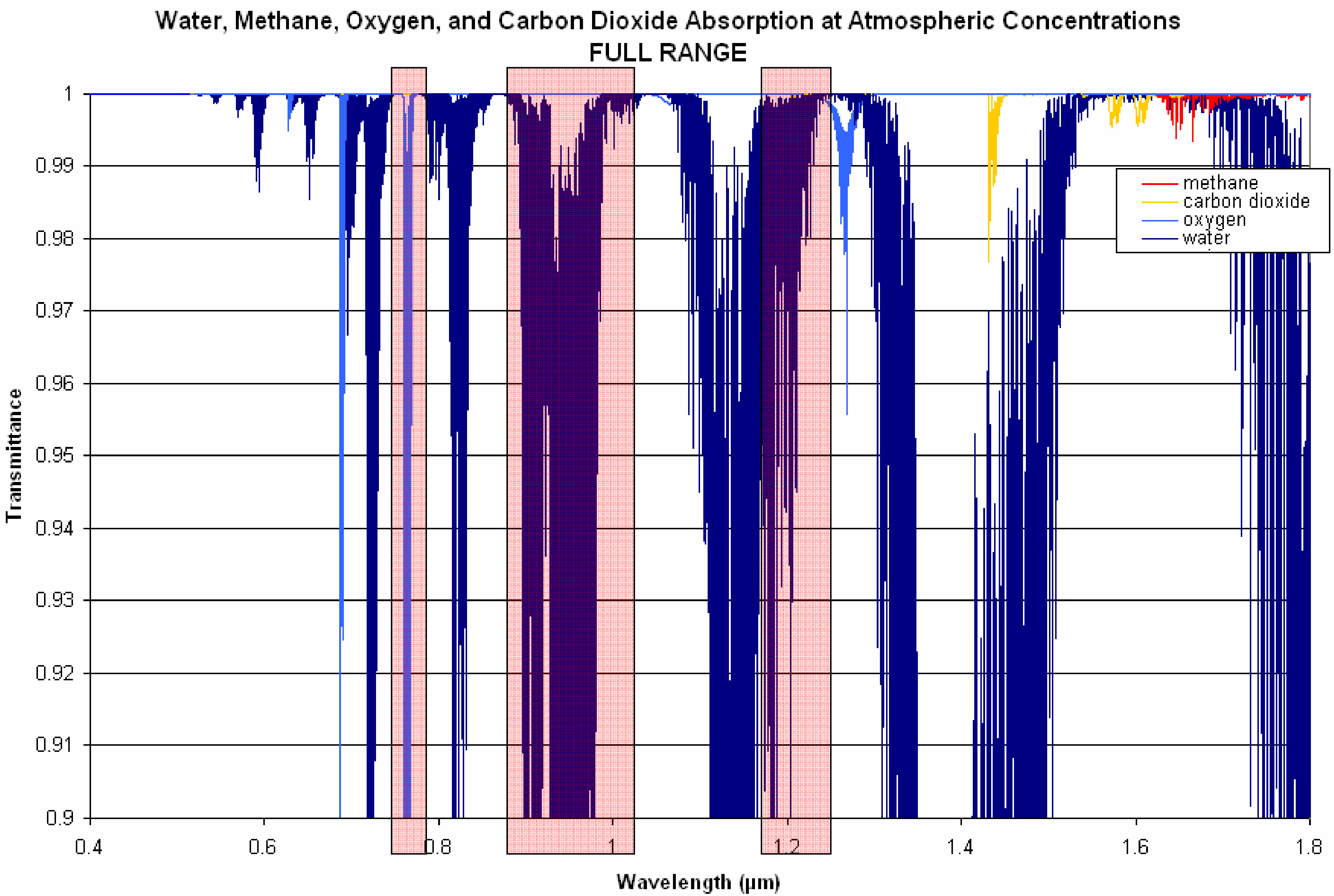
(b)

(a) A subset of the collected absorption spectra was used for a calculation of relative humidity percentage. (b) Using a least squares fit with the DOAS detection approach, an arrived water vapor relative humidity of 62.5 % is realized. This compares well with what was measured by a MET station deployed nearby.

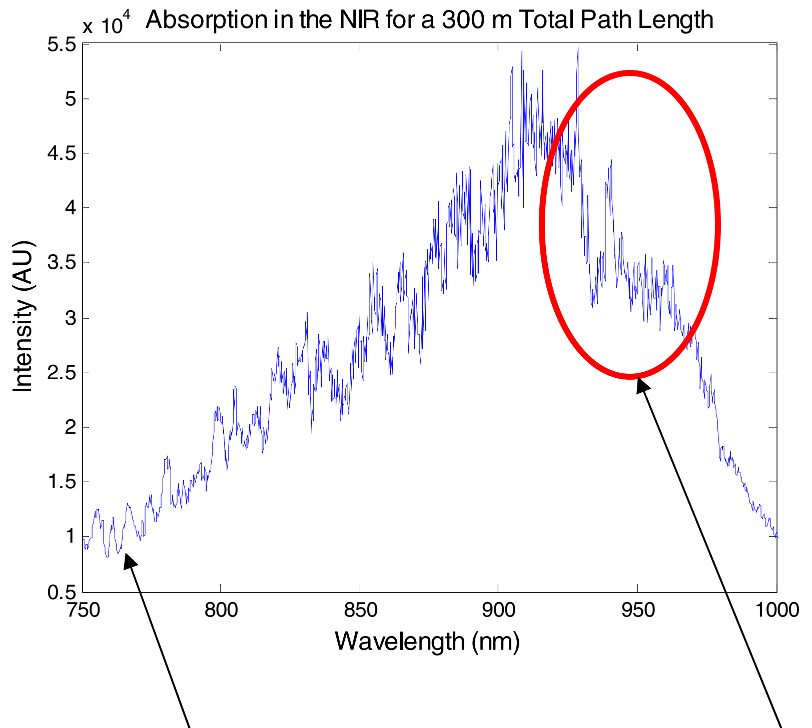
Supercontinuum Absorption LIDAR at PSU – Reconfiguration to increase sensitivity

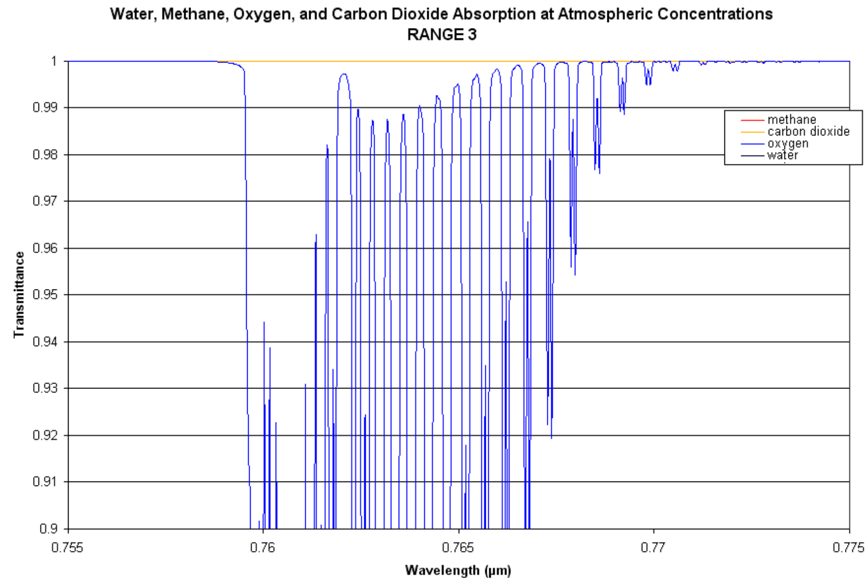


Spectral Ranges and Species Examined at PSU

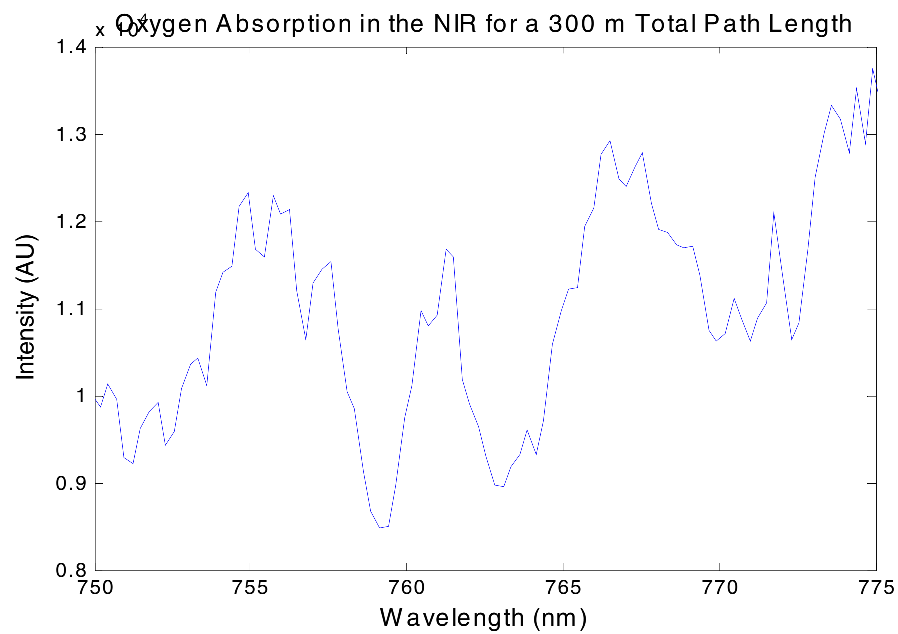


Raw Supercontinuum Spectrum – low resolution



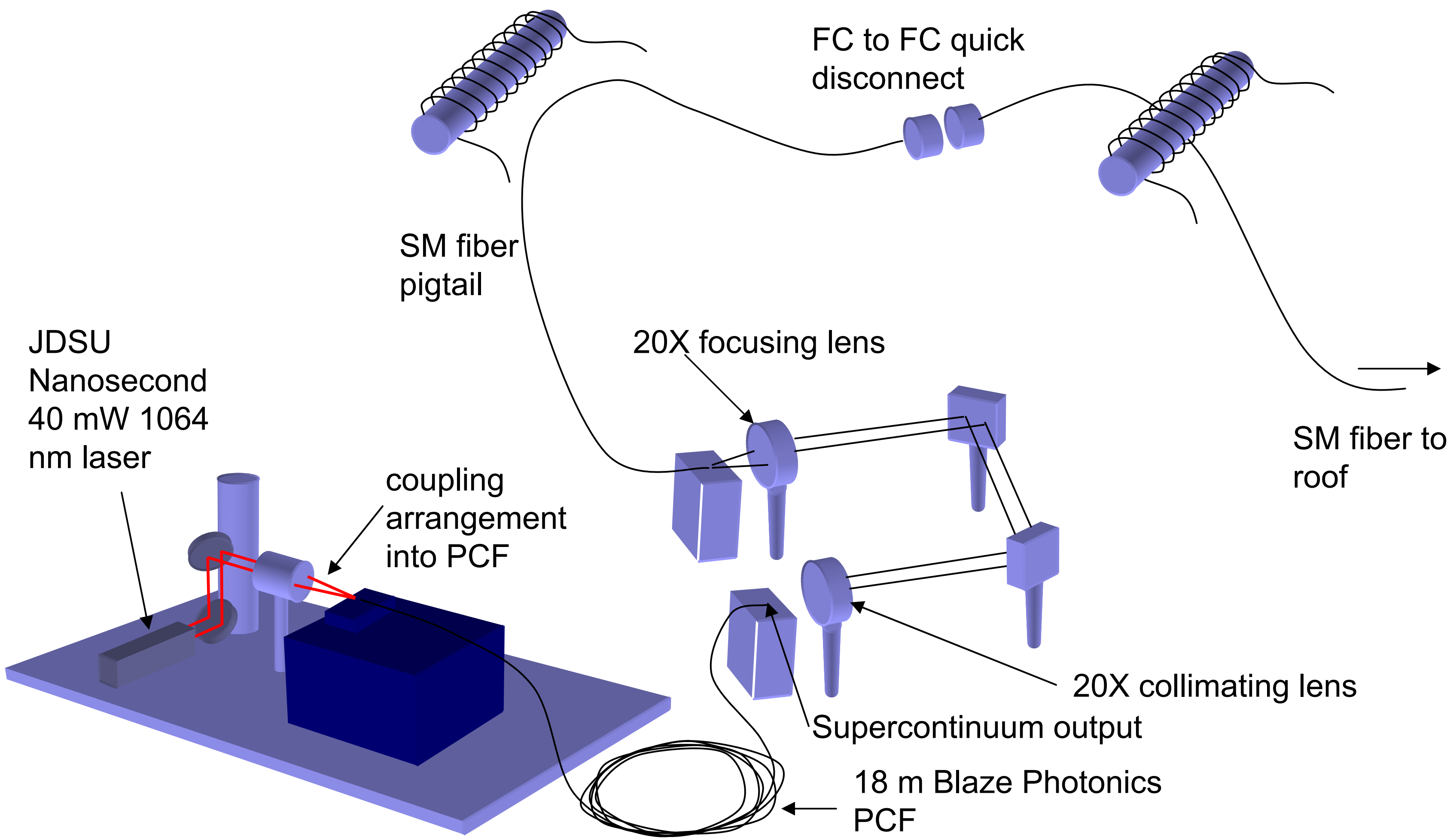


- oxygen is difficult to observe
- the water vapor absorption even at low resolution 150 gv/mm grating clearly observed



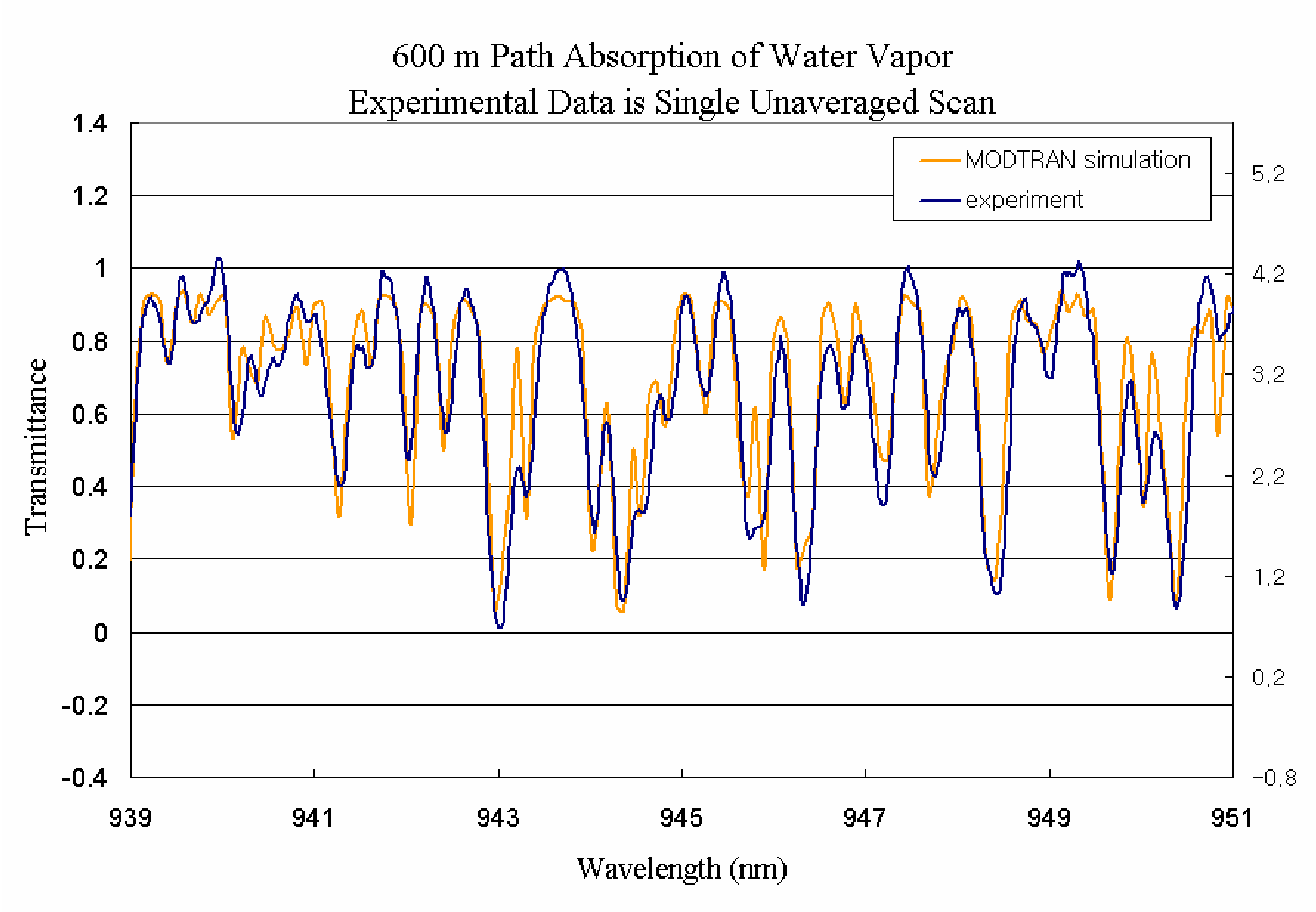
Mode Filtering the Supercontinuum Spectrum

Coil SM transmit side fiber around dowel to mode filter spectral signature.

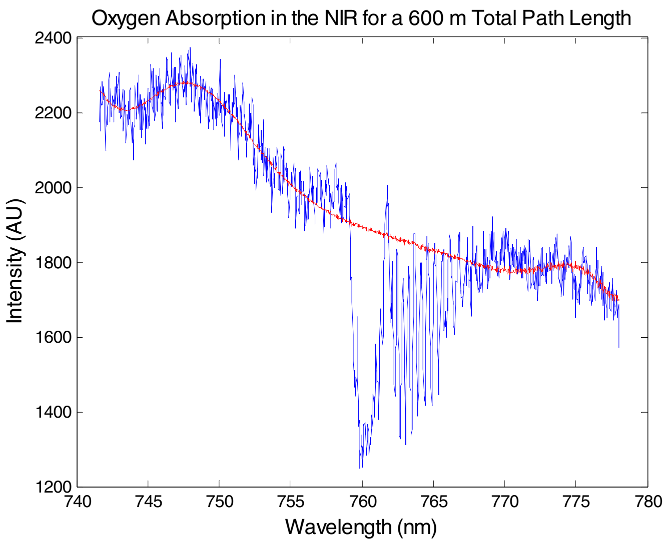


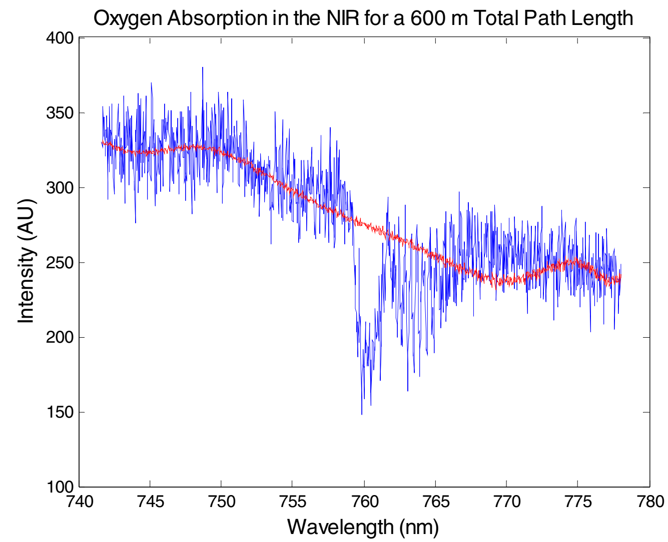
Filtered Supercontinuum – water vapor absorption

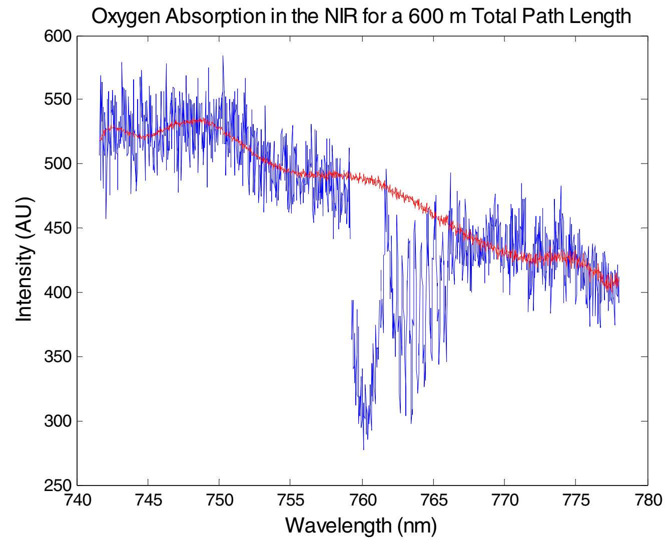
- Take a single mode filtered spectral scan and compare with MODTRAN™ 5 simulation

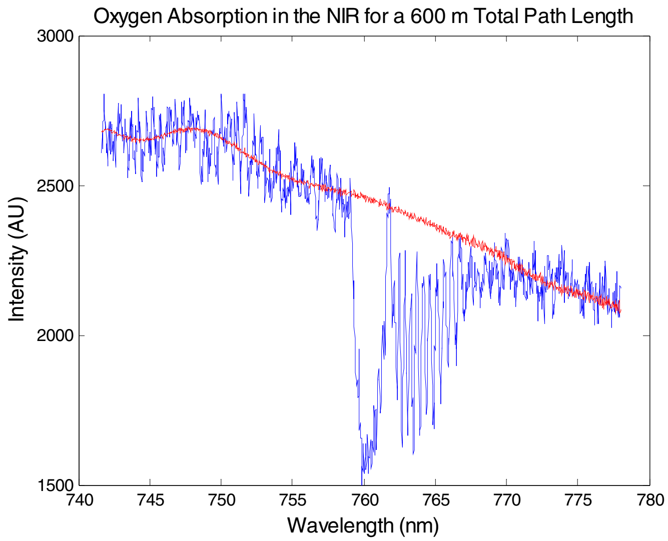


Filtered Supercontinuum – Oxygen absorption



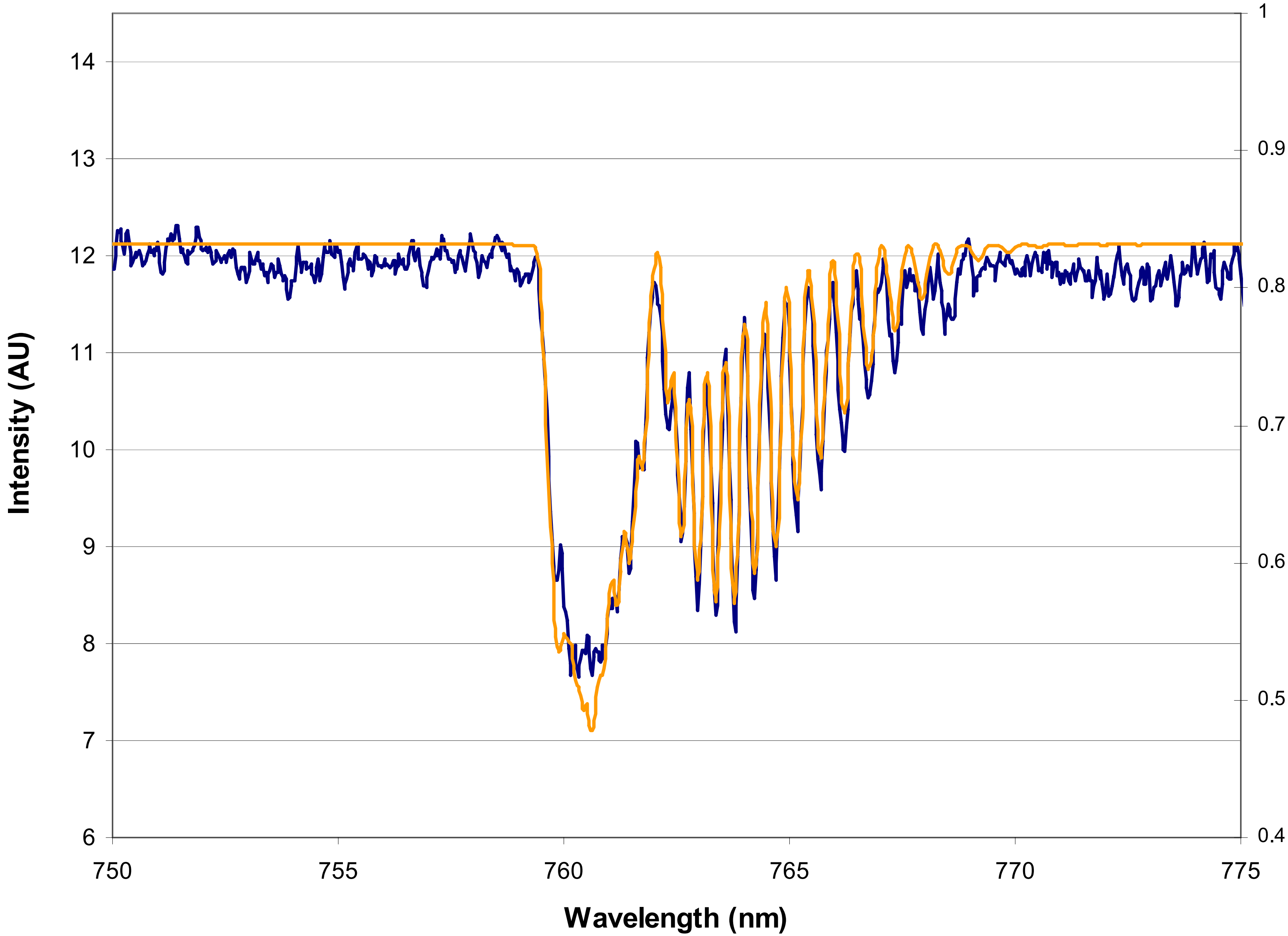




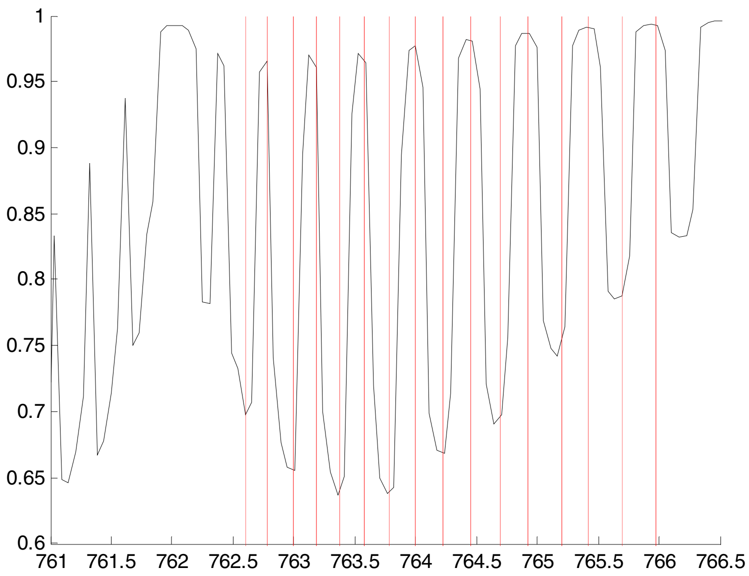


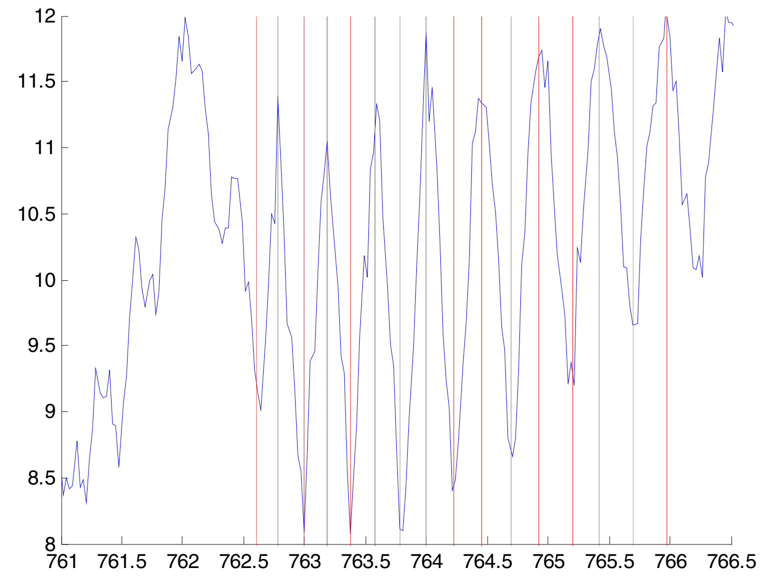
- Take the average of several normalized spectral captures in the region of interest
- Different spectra were collected by varying the number and magnitude of turns (transmit side)

Normalized Oxygen Absorption in the NIR for 600 m Total Path Length

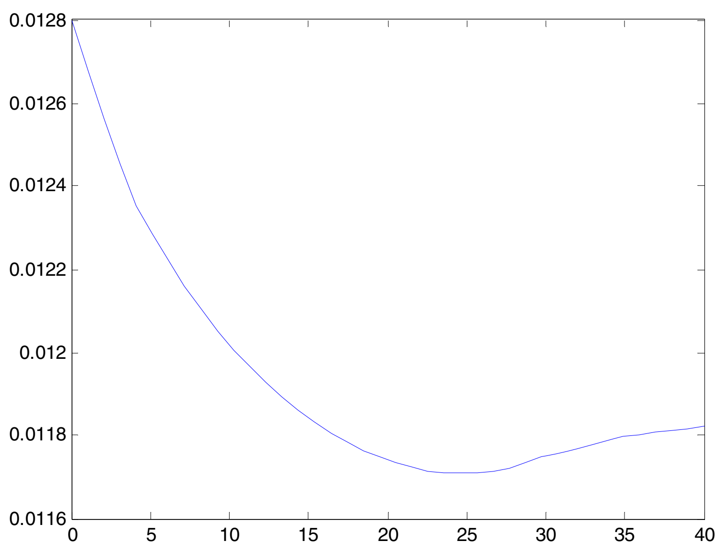


Approximation of Temperature using O_2 signature

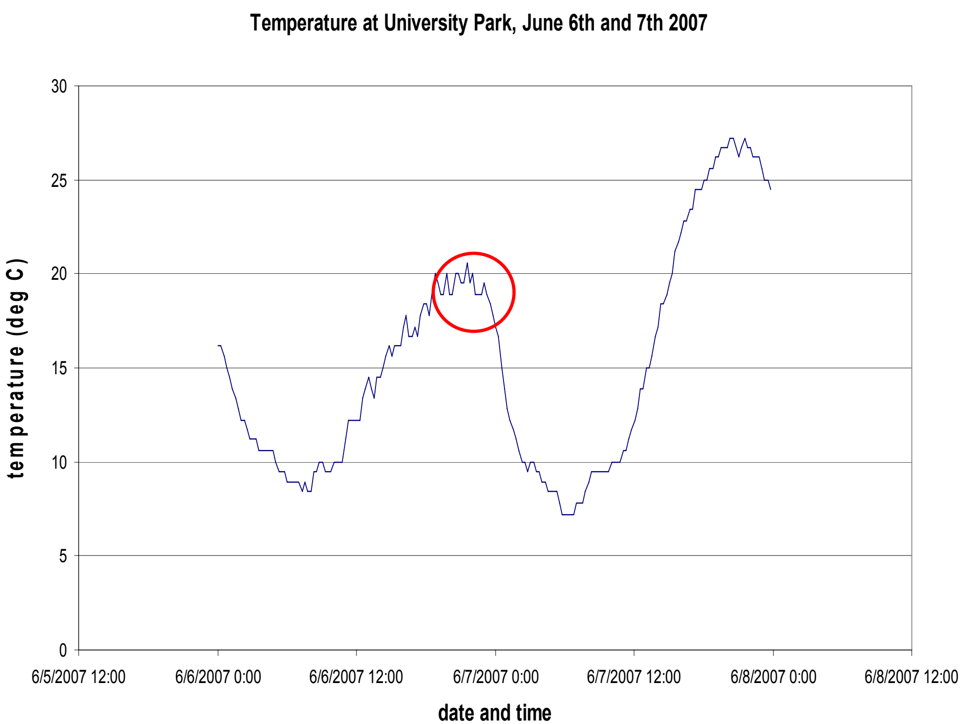


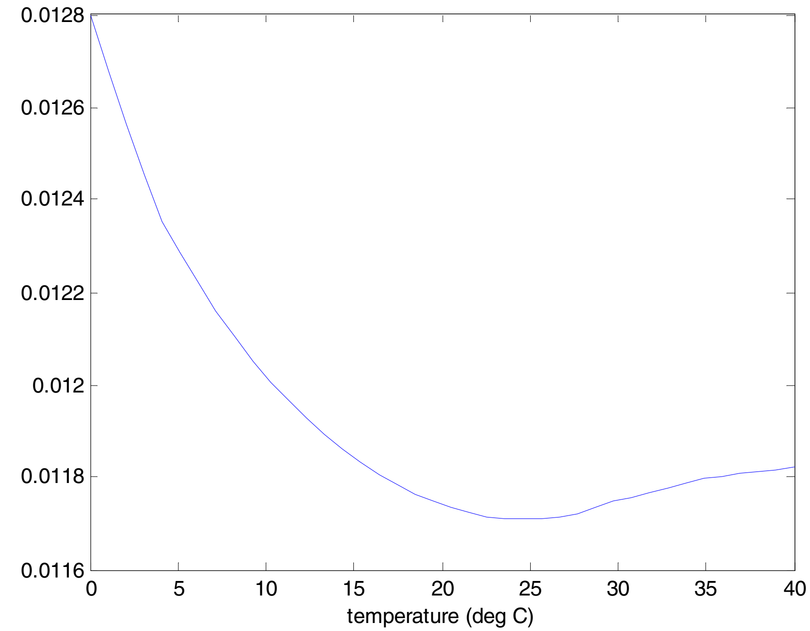


- Use many DIAL comparisons to calculate oxygen concentration
- Oxygen concentration is fixed in the atmosphere, so we can calculate the temperature of the atmosphere
- Vary the temperature in MODTRAN™ and calculate the least square error



- Compare calculated temperature [through change in oxygen absorption spectrum] with what was taken by the PSU weather station





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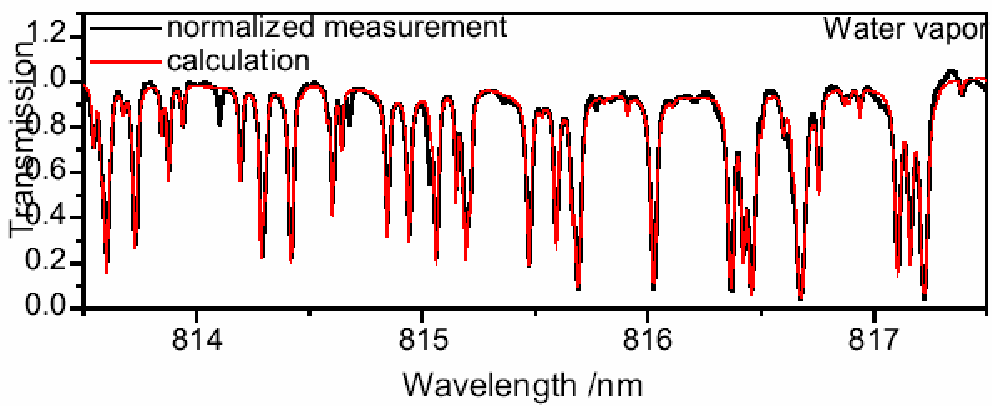
- questions

Backup

Wide Spectrum – Coherent Terawatt Transmitter

- **Supercontinuum or White Light LIDAR** (WLL)
  - The white light lidar was originally pioneered by Wöste et al. and later by Rairoux et al.
  - Teramobile White Light LIDAR
    - laser provides 5 TW (350 mJ in 70 fs pulses) at 800 nm, and 10 Hz repetition rate [Kasparian, 2002]
    - Atmospheric backscatter configuration
- Disadvantages
  - Massive power required for operation
  - Very expensive hardware
  - Large, non-portable system (uses a 2 m astronomical telescope)



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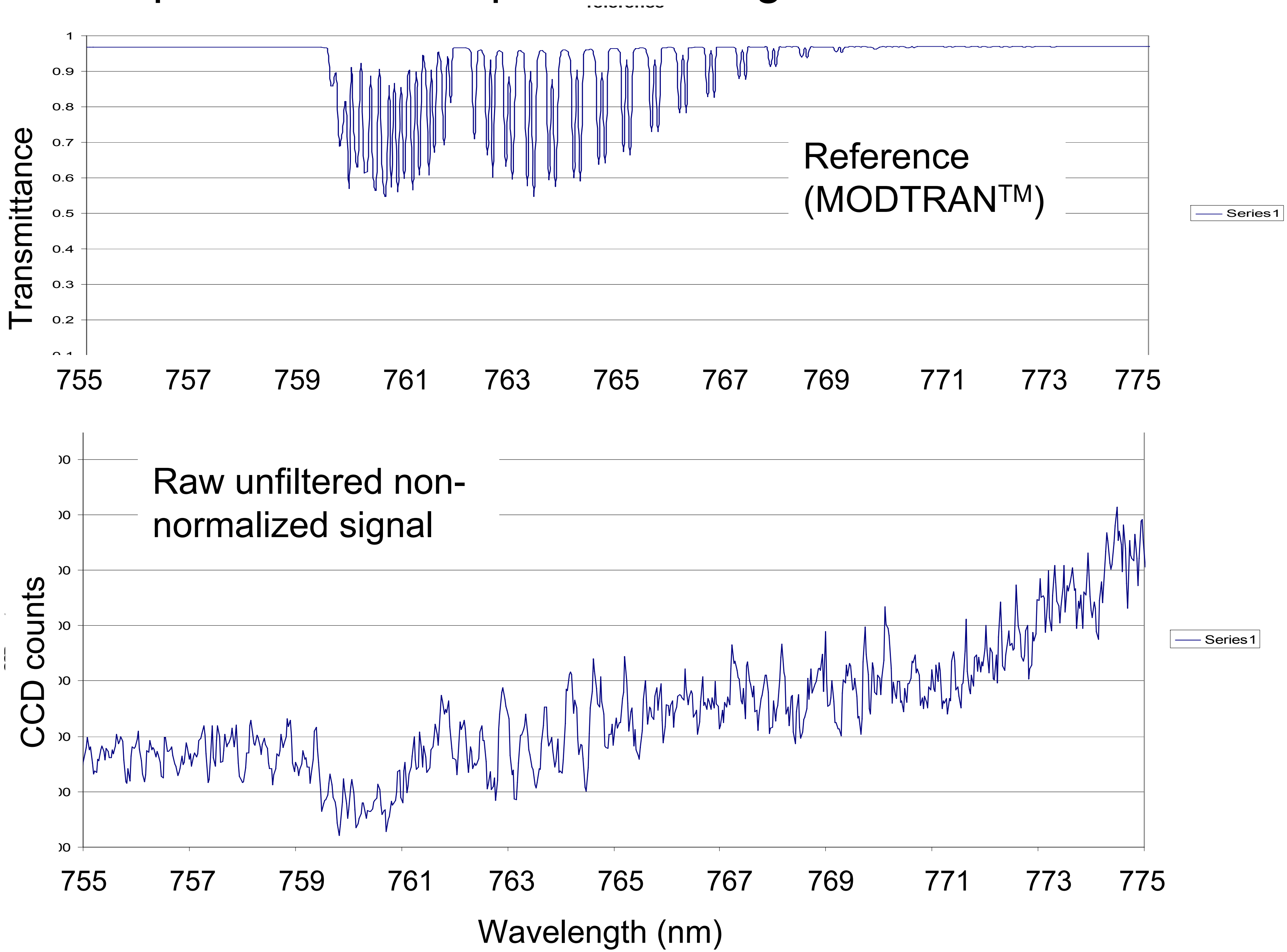
Kasparian, et. al. "Teramobile: a Mobile Femtosecond-Terawatt Laser and Detection System" *European Physical Journal - Applied Physics* , **20:**3, 183 (2002)

Raw Supercontinuum Spectrum – high resolution



Future Applications

- Multiple path
  - Tomography for 2D (maybe 3D) urban plume mapping
  - Wide area assessment of terrorist threat or natural disaster
- Ground to Space Nephelometer
  - Fingerprint region
  - Extremely long path absorption studies