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)

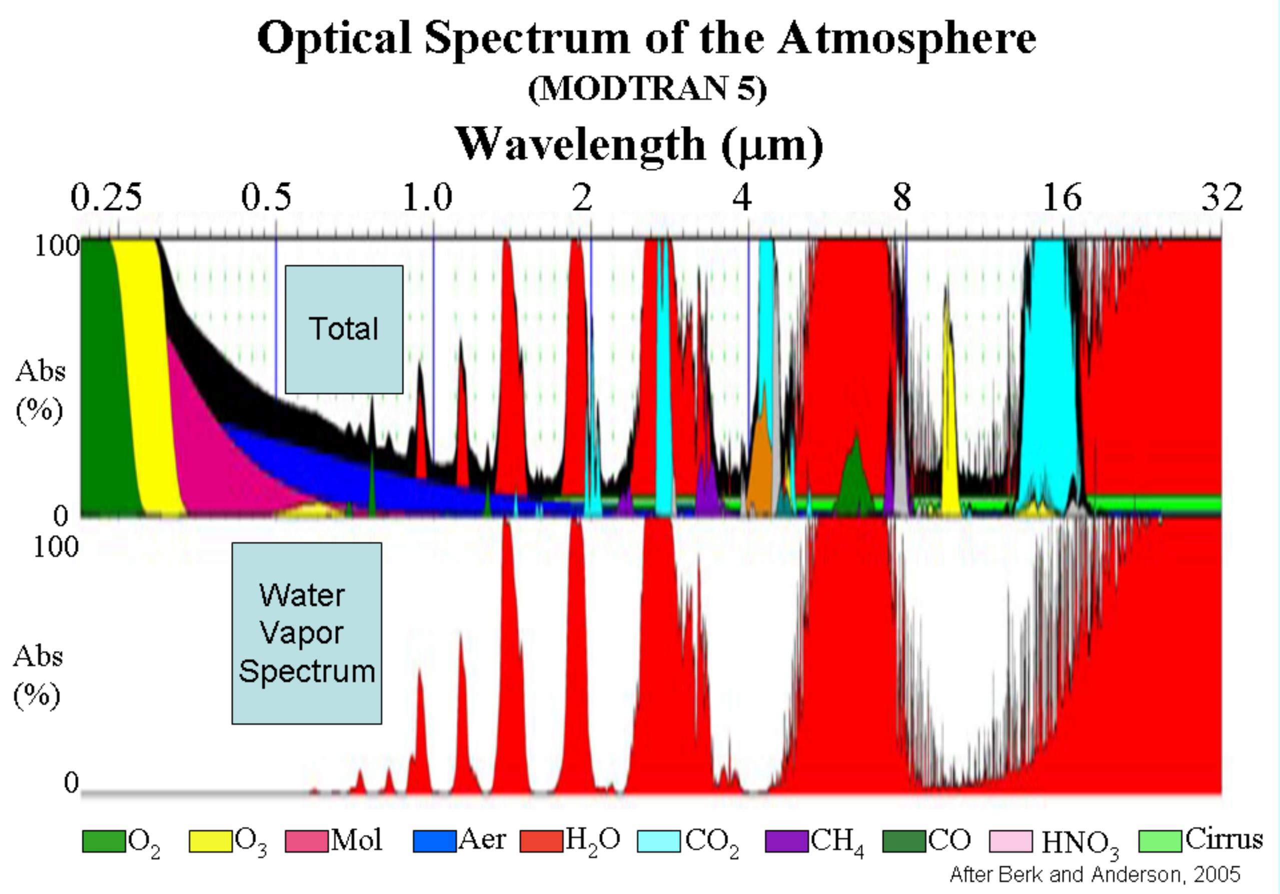
PENNSTATE

1 8 5 5

CHEMICAL SPECIES MEASUREMENTS IN THE ATMOSPHERE USING LIDAR TECHNIQUES

C. Russell Philbrick

Prof. of Electrical Engineering
Penn State University



AFRL 29th Review of Atmospheric Transmission Models
13-14 June 2007
Lexington, MA

Topical Outline

GOAL: Improved detection at lower concentrations.

Optical Absorption and Scattering Processes

- IR Absorption
- Rayleigh Scattering (Cabanas + Rotational Raman Lines)
- Raman Scattering (Vibrational Stretch and Bend, Rotation)
- Resonance Raman
- Fluorescence
- Cross Sections for Processes

LIDAR Techniques

- Rayleigh
- Aerosol and Cloud (Mie scatter)
- Doppler (Coherent and Direct)
- DIAL (Multi-wavelength)
- Raman (Raman-DIAL)
- Bistatic and Multistatic

Current and Future Topics

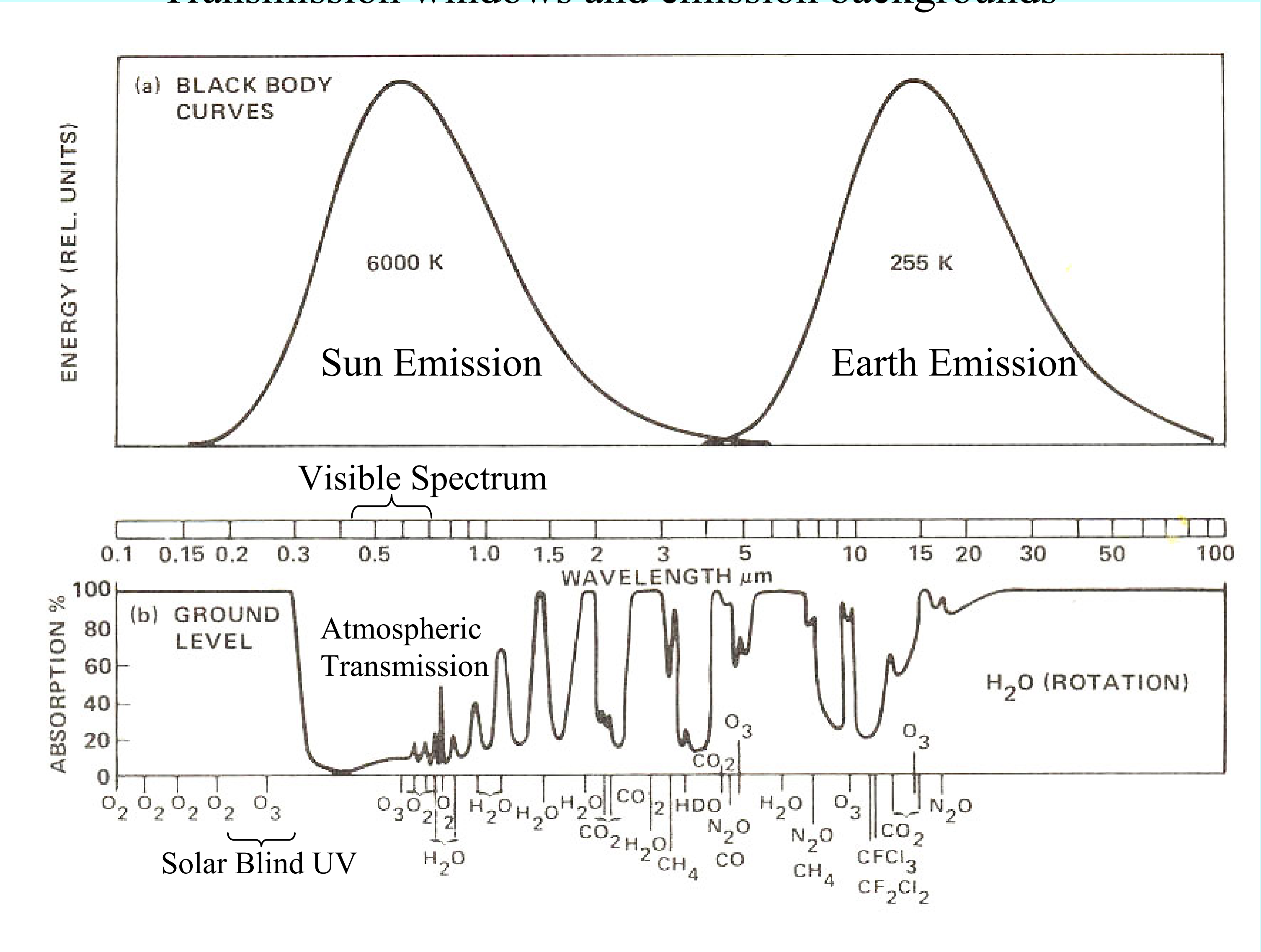
- Resonance Raman and Fluorescence LIDAR
- White Light Laser Long Path Absorption (DAS)
- Single Particle Scatter Properties (White-light Laser)
- Polarization Ratio of Scattering Phase Function (Forward and Backscatter)
- RF Refraction

Detection Processes

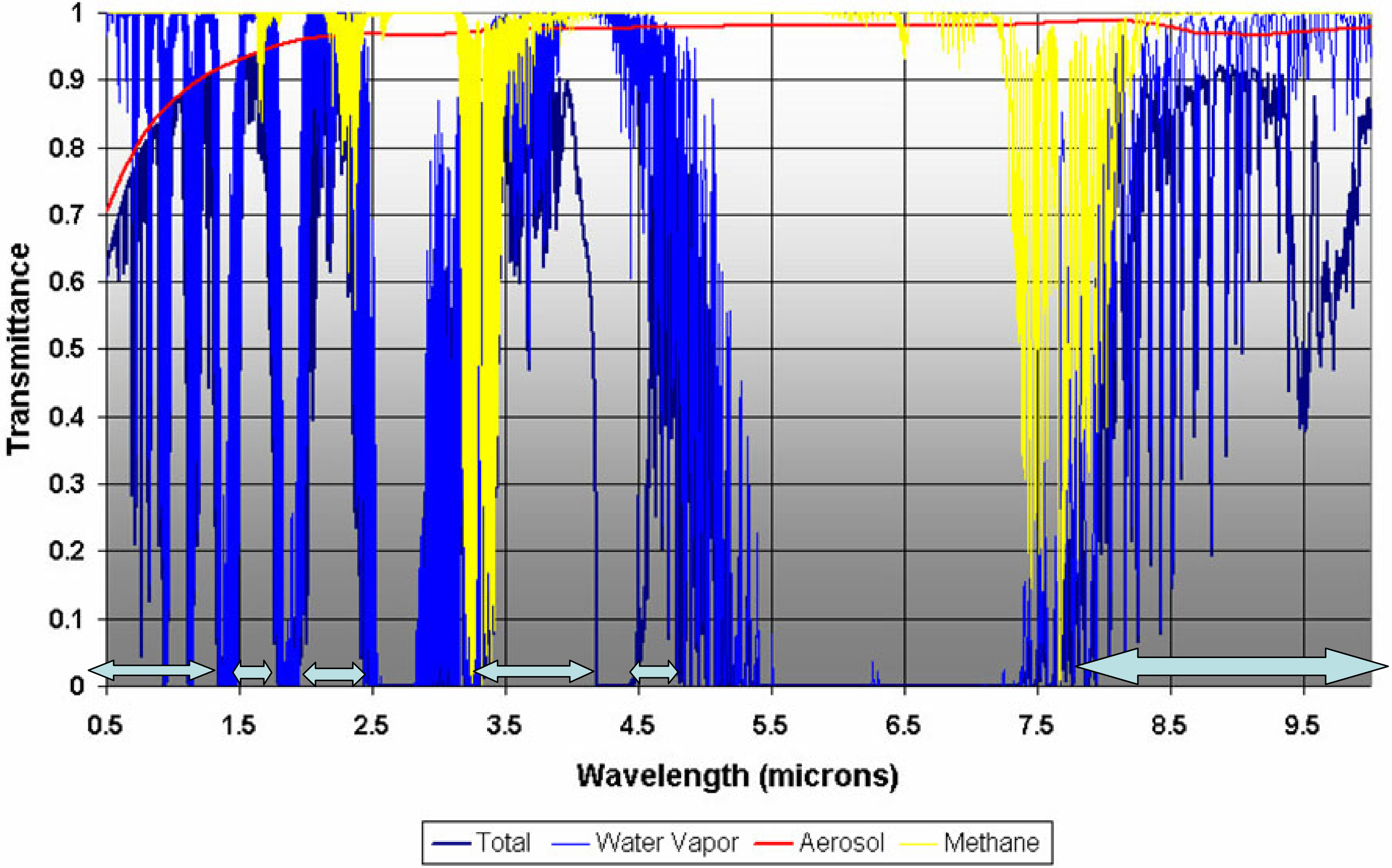
Process	Type	Cross section (cm^2/sr)	Use
Scattering	Rayleigh	$\sim 10^{-26}$	Molecules, atoms T, ρ
	Mie	10^{-26}-10^{-8}	Aerosols, particles α, n, r
	Raman		
	Non-resonance	10^{-30}-10^{-28}	Molecules T, $[N_i]$, α
	Resonance	10^{-28}-10^{-20}	$[N_i]$
Absorption	DIAL	10^{-24}-10^{-20}	$[N_i]$
	DAS	~(DIAL) x 10^4	N_i (path integrated)
Emission	Fluorescence	10^{-26}-10^{-20}	Species detection $\sim N_i$ (quenching)

Where can LIDAR measurements be carried out?

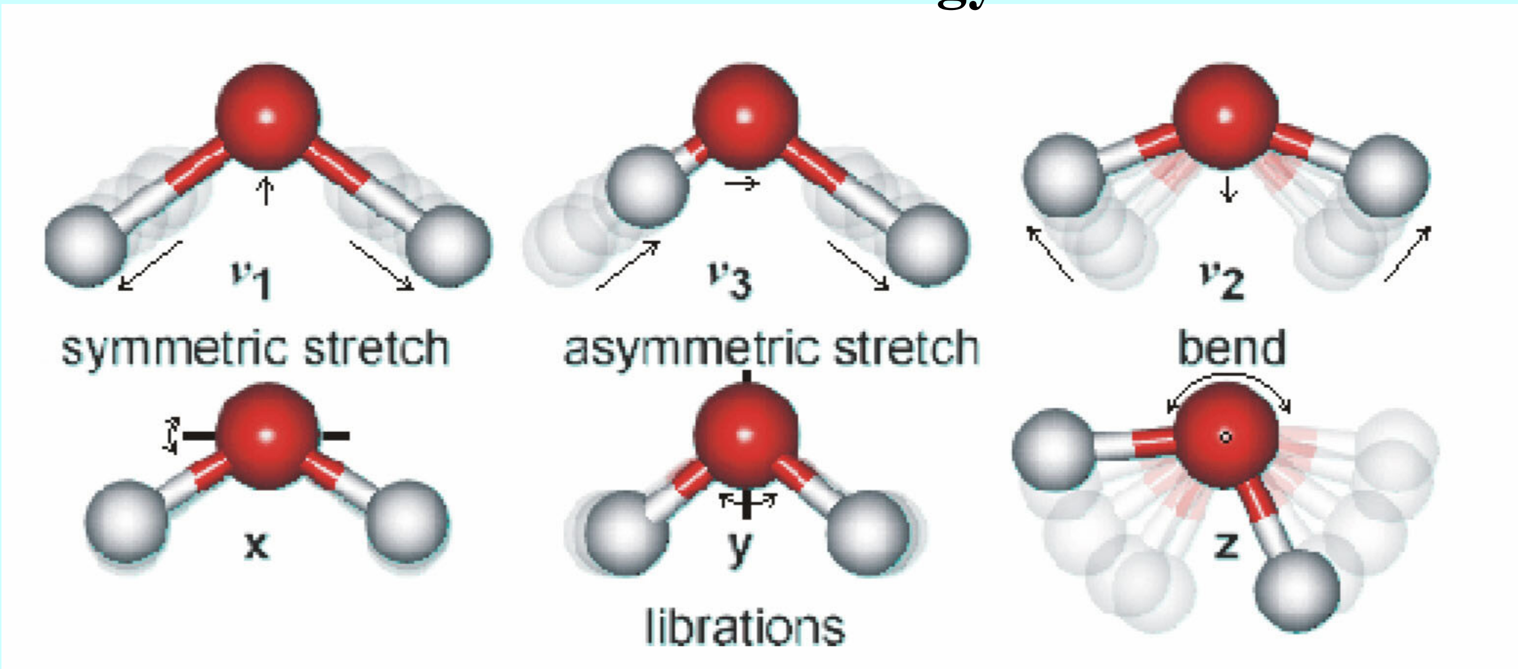
- Laser transmitters available
- Transmission windows and emission backgrounds

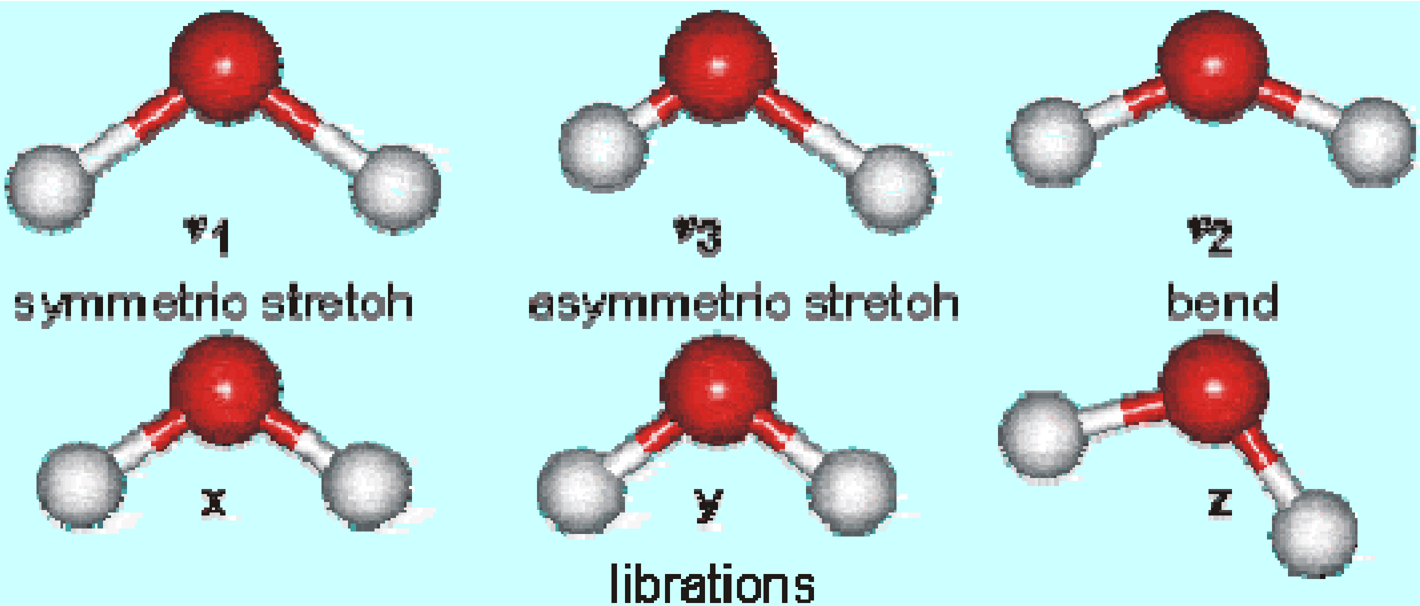


Atmospheric Transmission Windows

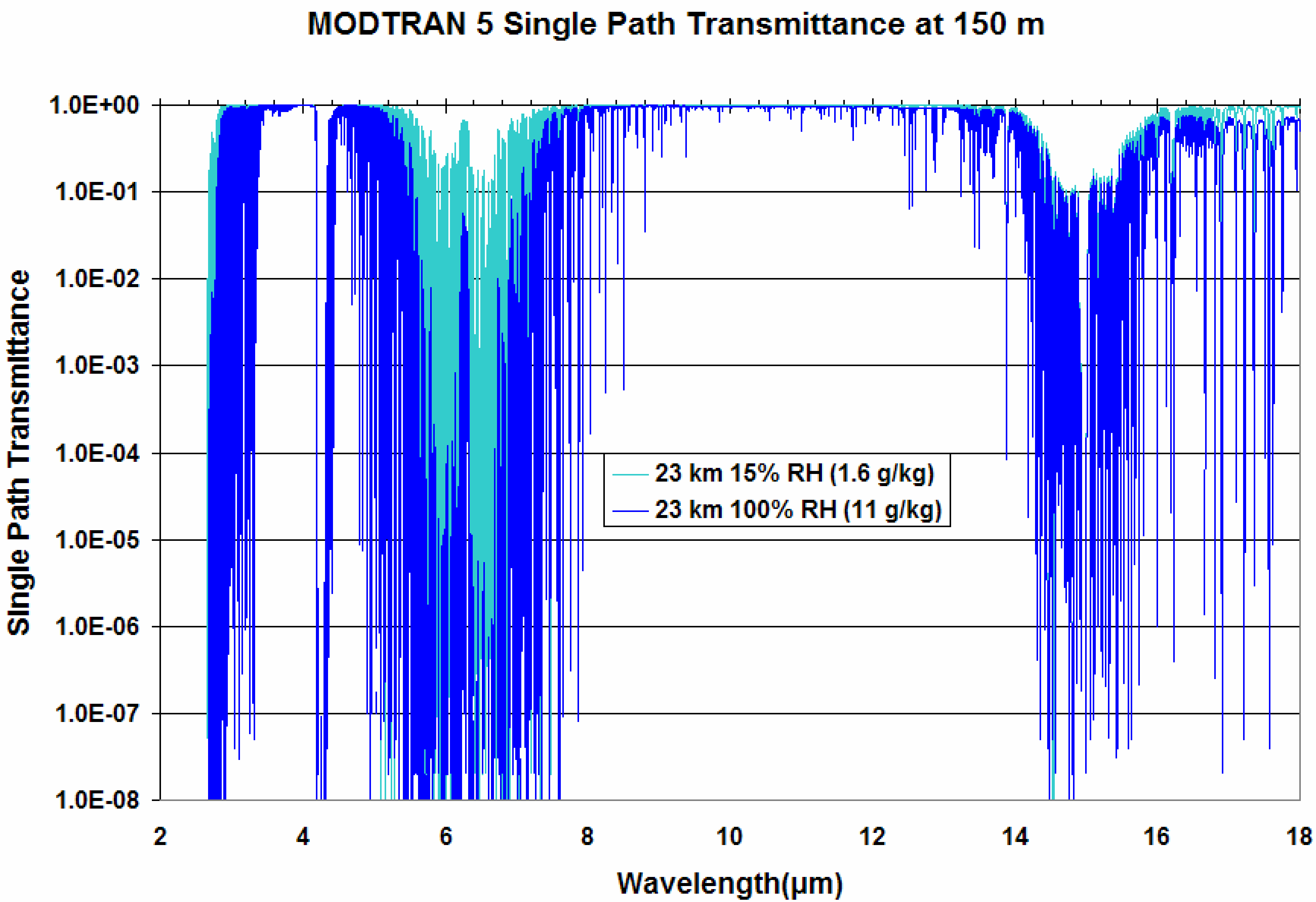


Water Molecule - Energy States





http://www.lsbu.ac.uk/water/images/v1.gif


MODTRAN 5 Single Path Transmittance at 150 m
Single Path Transmittance
1.0E+00
1.0E-01
1.0E-02
1.0E-03
1.0E-04
1.0E-05
1.0E-06
1.0E-07
1.0E-08
2
4
6
8
10
12
14
16
18
Wavelength(µm)
23 km 15% RH (1.6 g/kg)
23 km 100% RH (11 g/kg)

IR Absorption and Raman Scattering Provide Complementary Pictures of a Molecule

IR Absorption

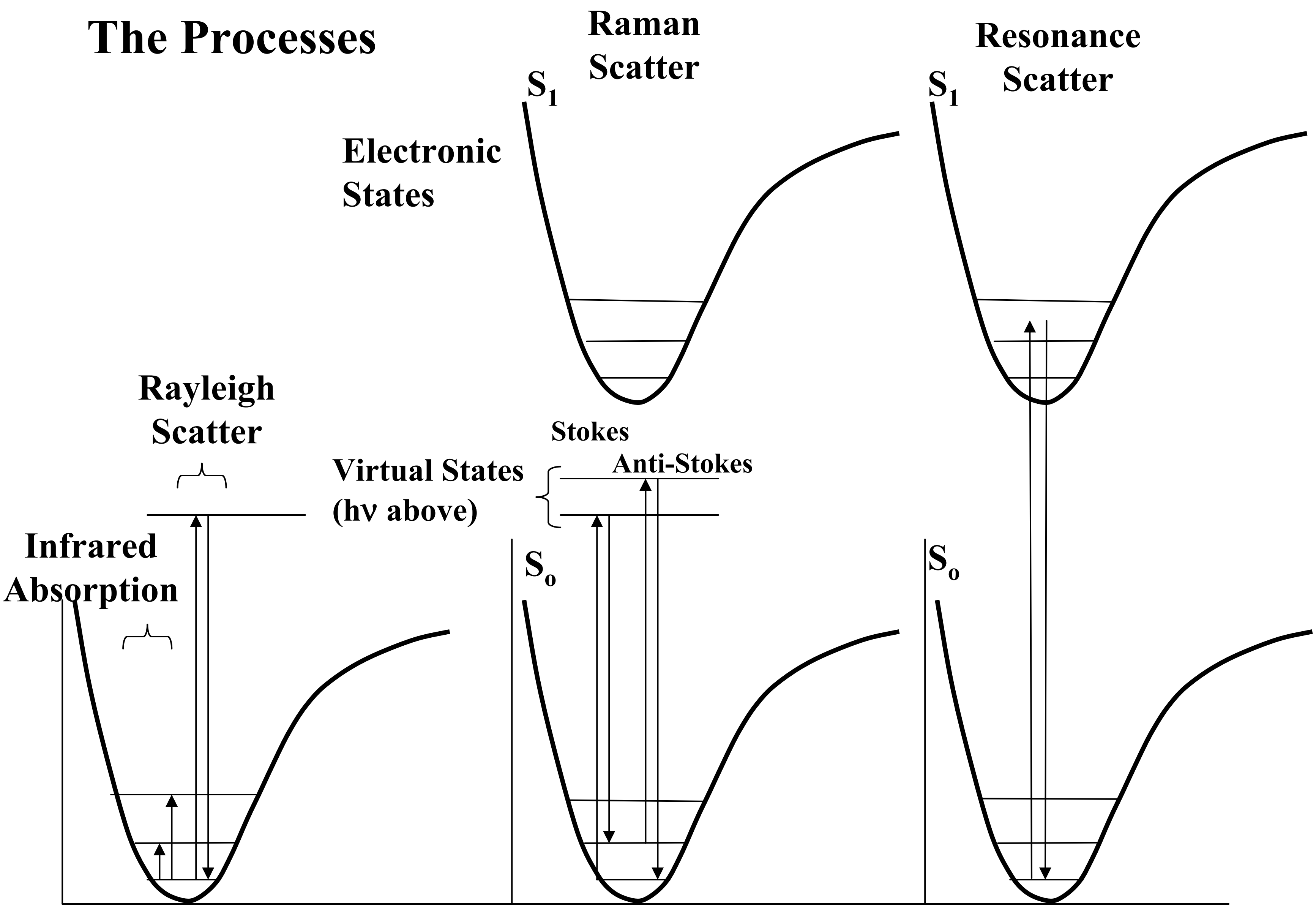
Vibration is **infrared active** if the molecules normal dipole moment is modulated. Radiation field must be near the same frequency as the oscillation of the electric dipole moment.

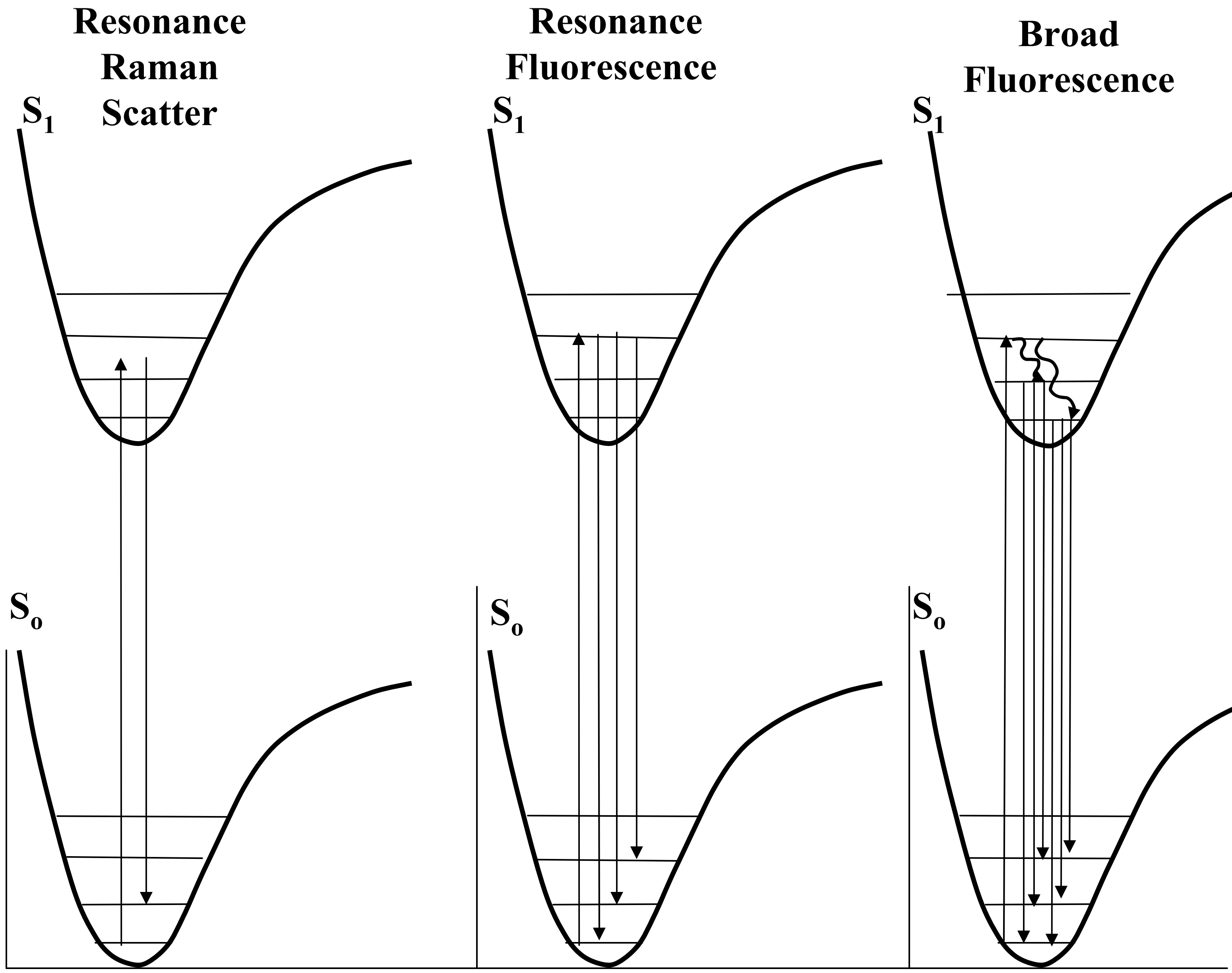
Raman Scattering

A molecule is **Raman active** if a dipole is induced by the action of a radiation electric field in forcing a relative motion between the electrons and the nuclei. The induced dipole moment is proportional to the radiation electric field strength and the polarizability of the molecule.

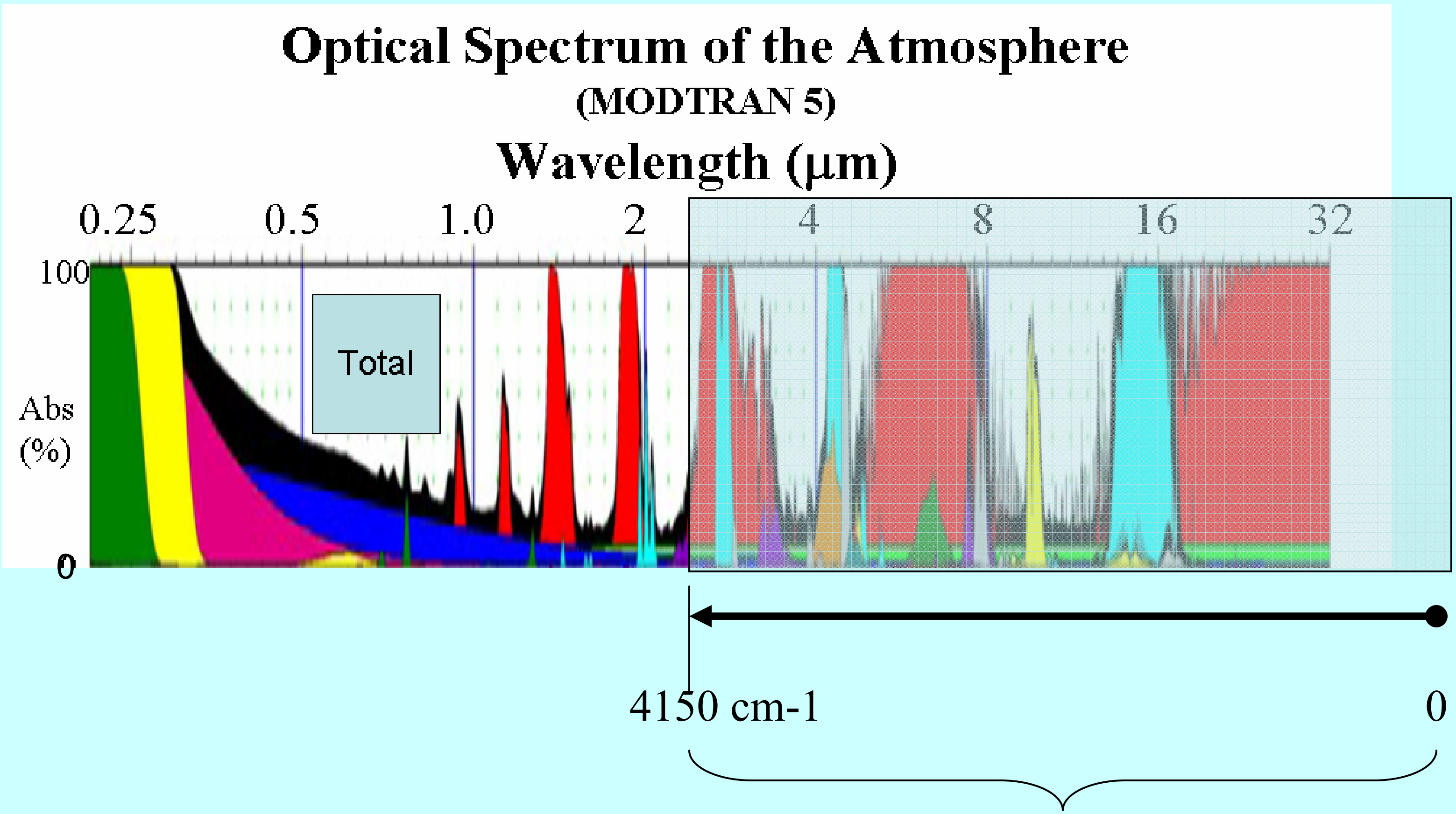
Both **IR spectra** and **Raman scatter intensity** provide "fingerprints" of molecules.

The Processes



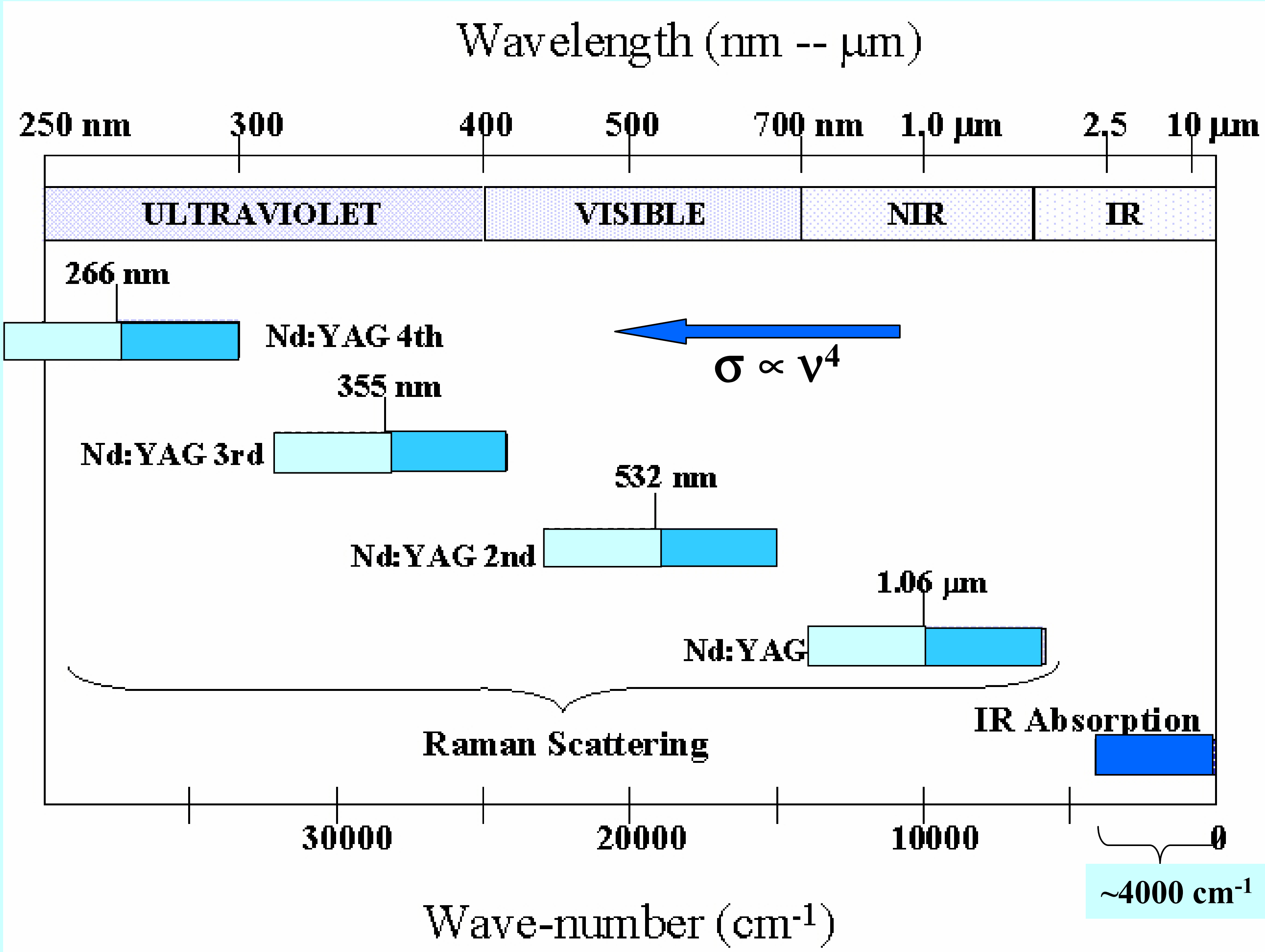

Resonance
Raman
Scatter
Resonance
Fluorescence
Broad
Fluorescence
S_1
S_1
S_1
S_o
S_o
S_o

Infrared active region corresponds to the Raman active region

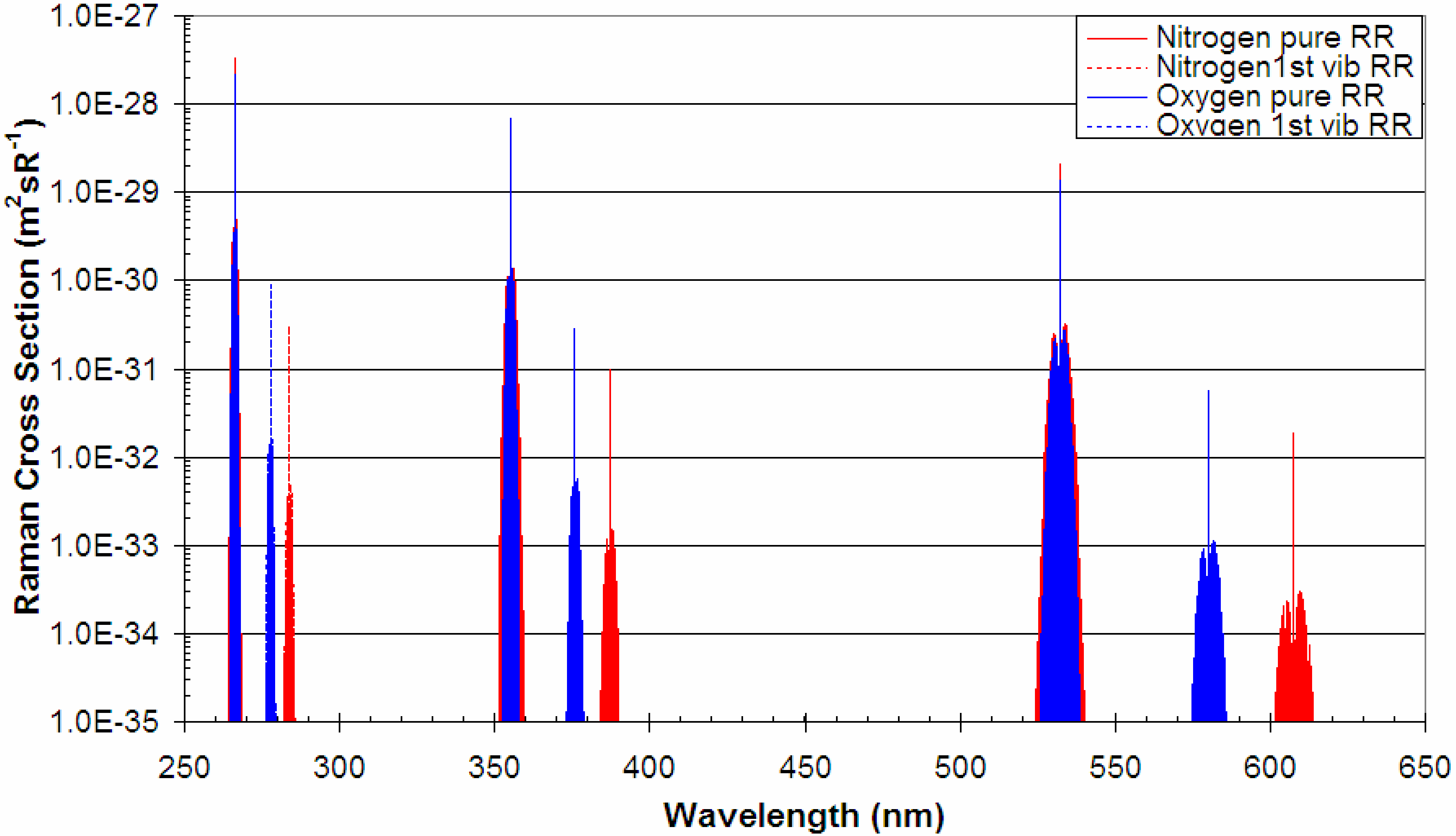


Range of energies for vibration, rotation, Stretching, and bending of molecules.

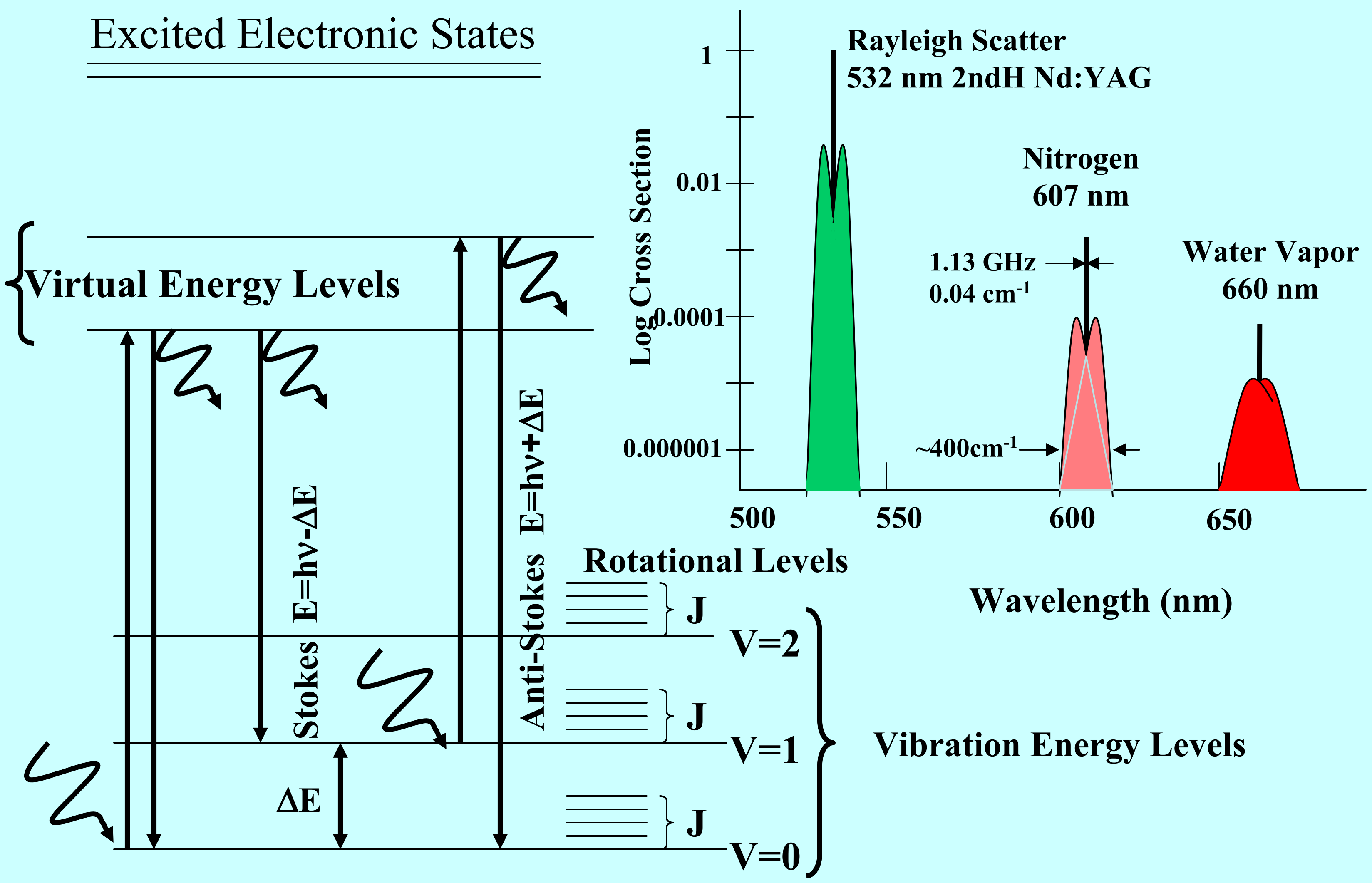
IR Absorption Spectrum Correspondence to Raman Scattering



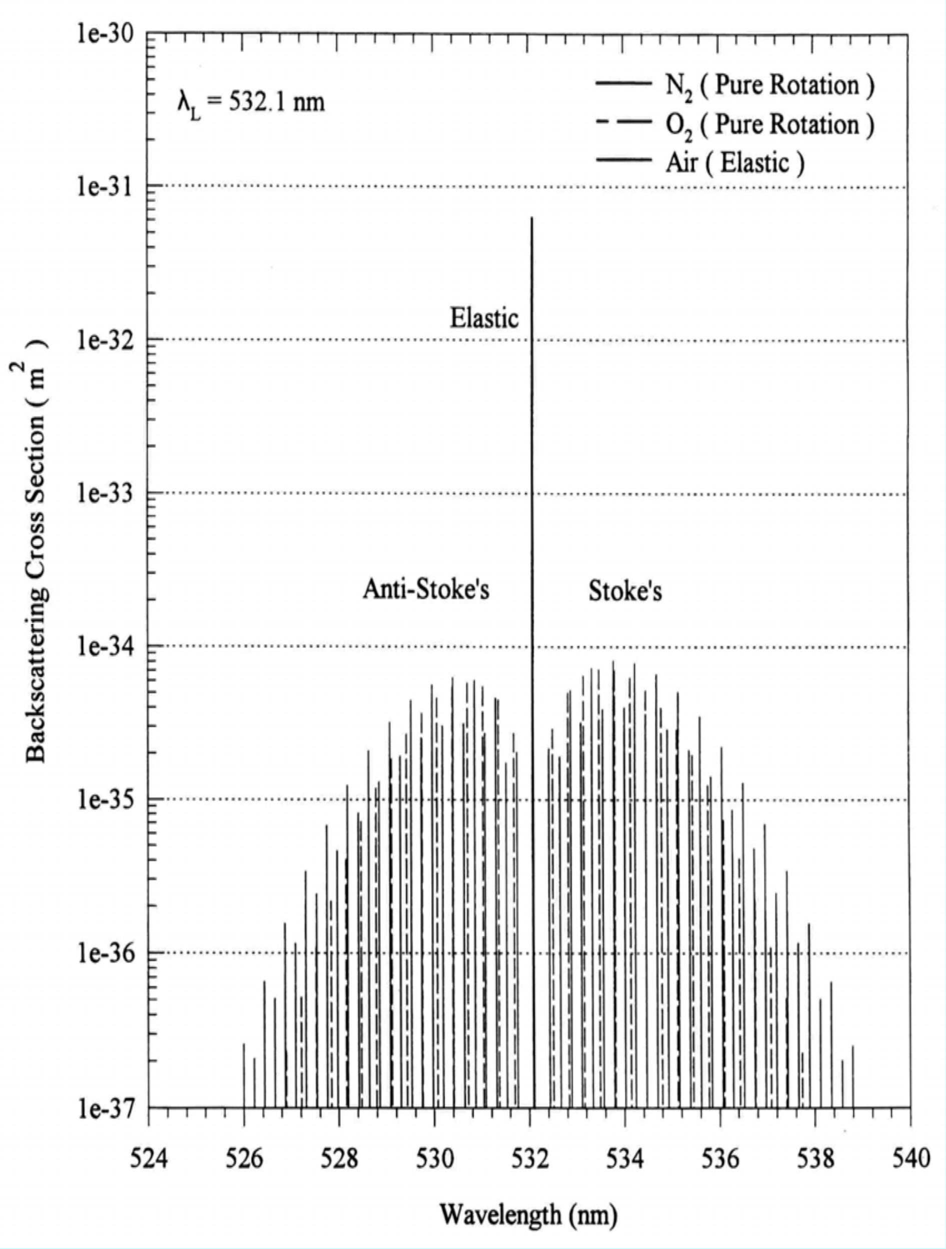
Pure Rotational Raman and 1st Vibrational Rotational Raman for N_2 and O_2 with Excitation at Nd:YAG Harmonics

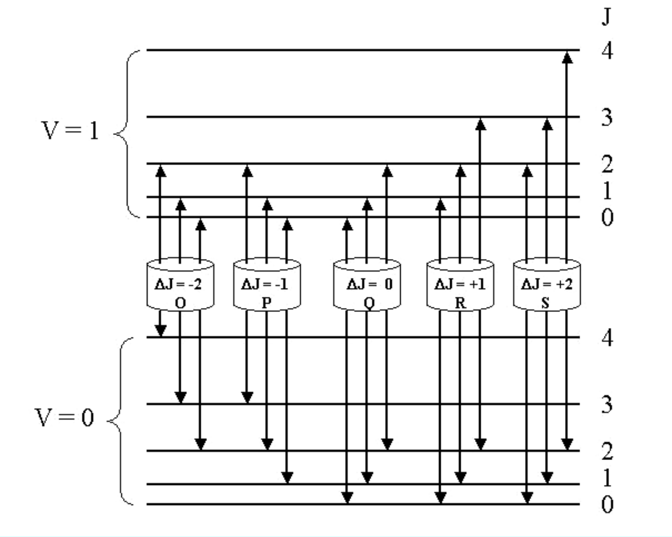


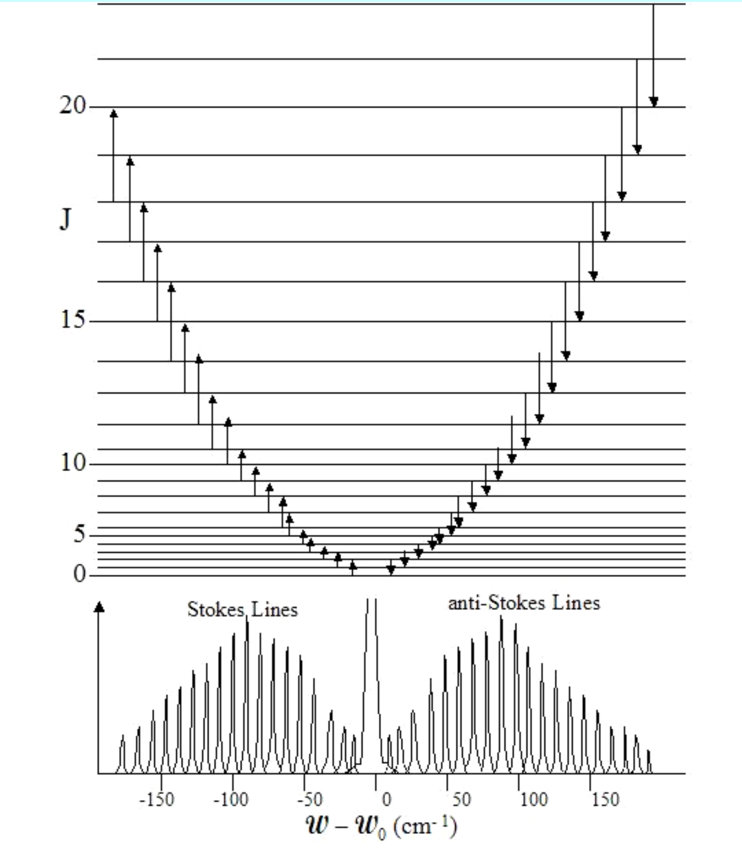
Raman Scatter



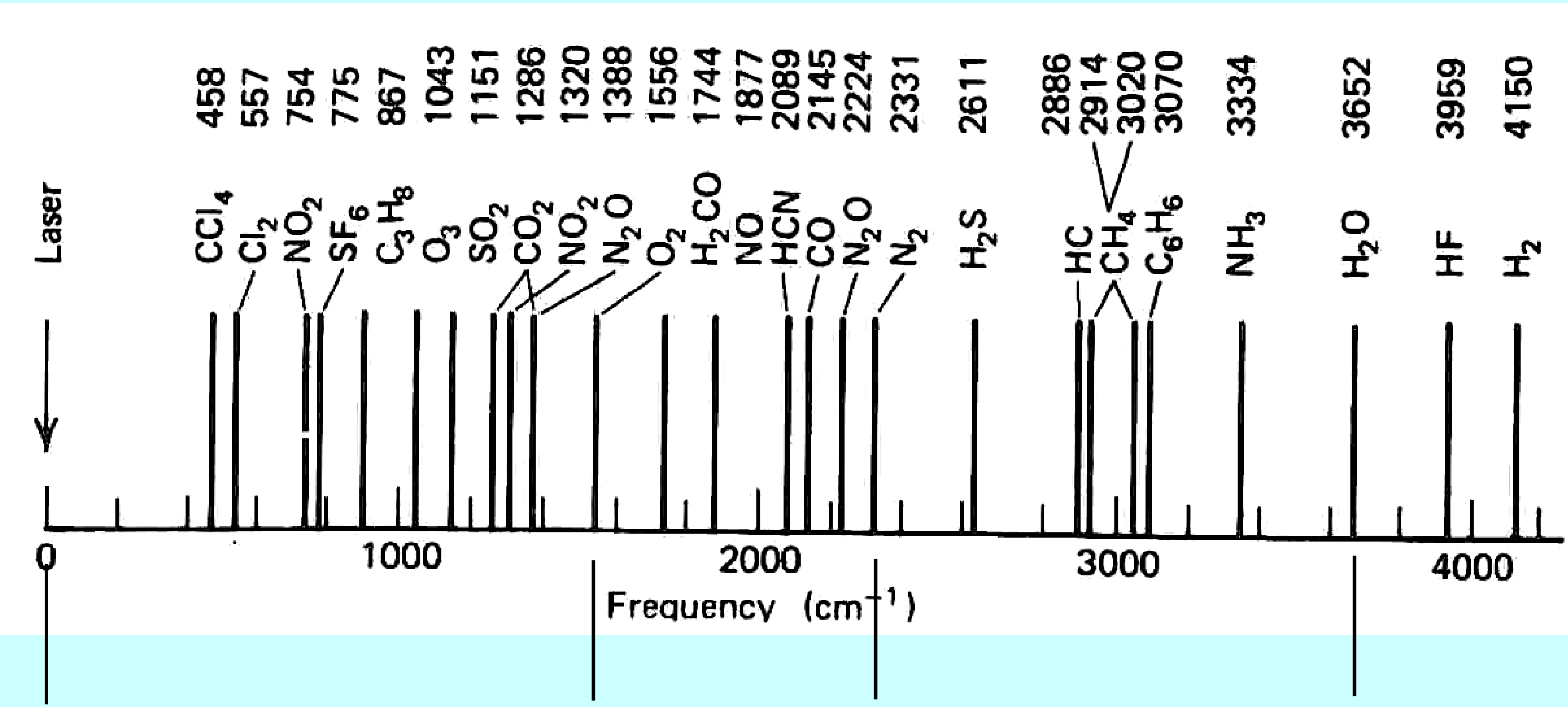
Rotational Raman







Q-branch Shifts of Vibrational-rotational Raman Spectra for Several Molecular Species

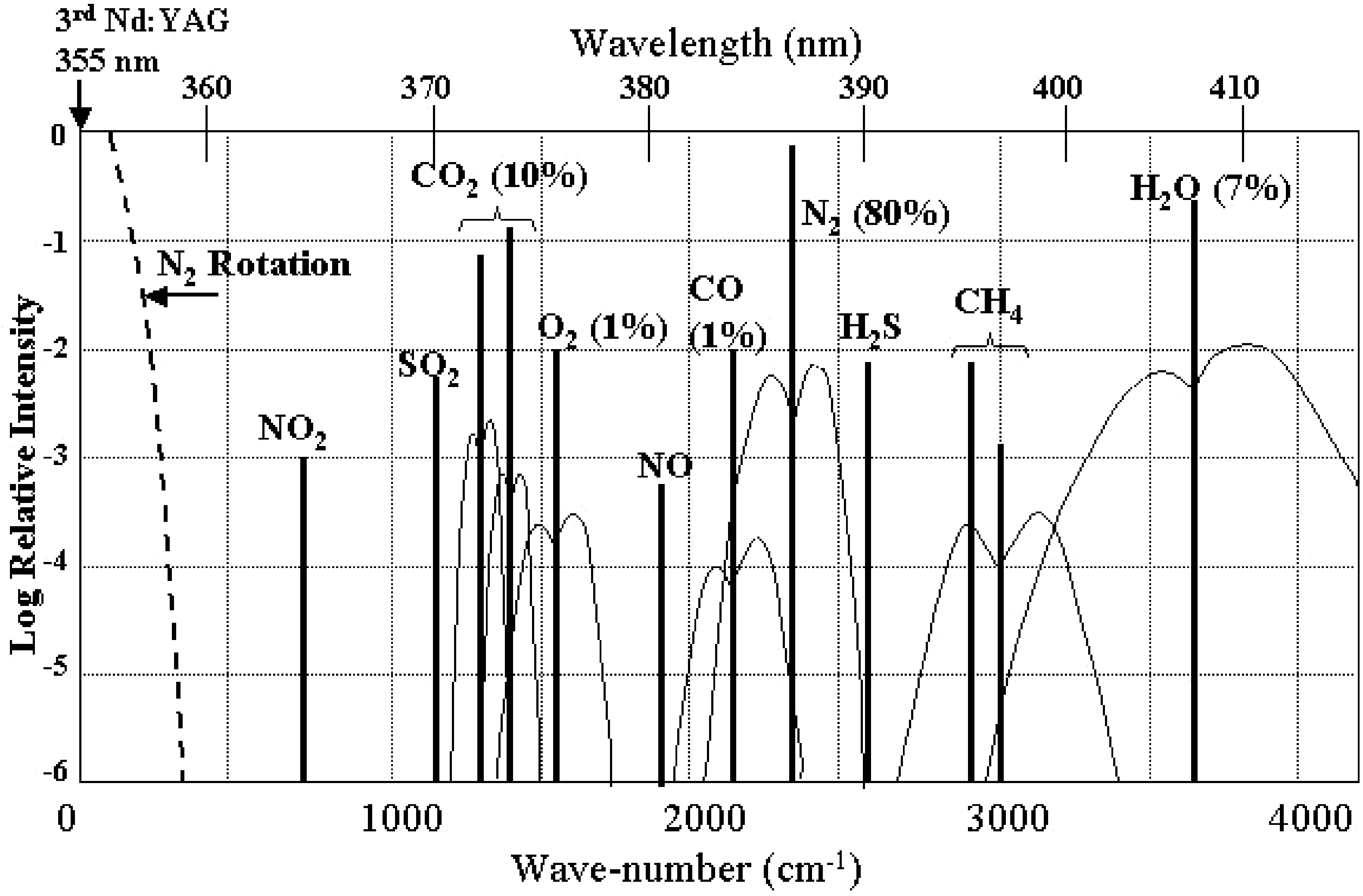


532 nm	580 nm	607 nm	660 nm
355 nm	376 nm	388 nm	407 nm
266 nm	277 nm	284 nm	294 nm

[after Inaba and Kobayasi, 1972]

Calculated Raman Signatures for a Smoke Plume

Probed by 3rd Harmonic ND:YAG Laser (after Inaba and Kobayasi)



Optical Absorption and Scattering Processes

- IR Absorption
- Rayleigh Scattering (Cabanas + Rotational Raman Lines)
- Raman Scattering (Vibrational Stretch and Bend, Rotation)
- Resonance Raman
- Fluorescence
- Cross Sections for Processes

LIDAR Techniques

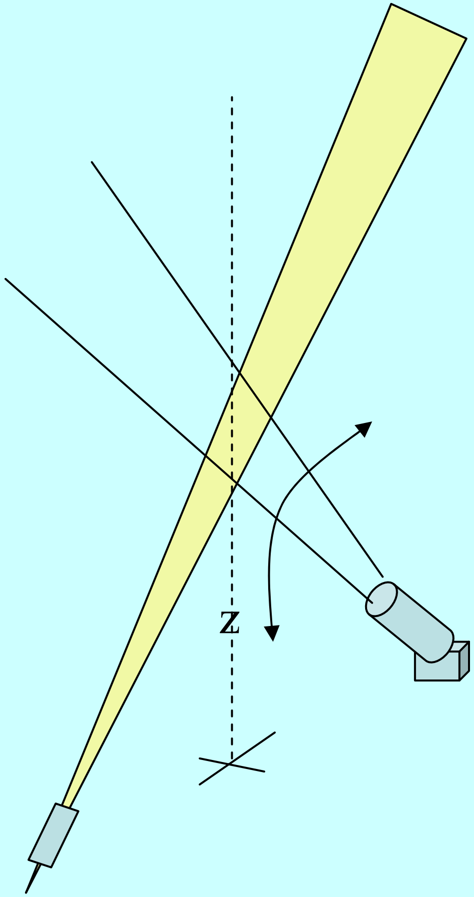
- Rayleigh
- Aerosol and Cloud (Mie scatter)
- Doppler (Coherent and Direct)
- DIAL
- Raman (Raman-DIAL)
- Bistatic and Multistatic

Current and Future Topics

- Resonance Raman and Fluorescence LIDAR
- White Light Laser Long Path Absorption (DAS)
- Single Particle Scatter Properties (White-light Laser)
- Polarization Ratio of Scattering Phase Function (Forward and Backscatter)
- RF Refraction

LIDAR (LIght Detection And Ranging)

First ‘LIDAR’ used a search light



Elterman, JGR **59** 351-358, 1954

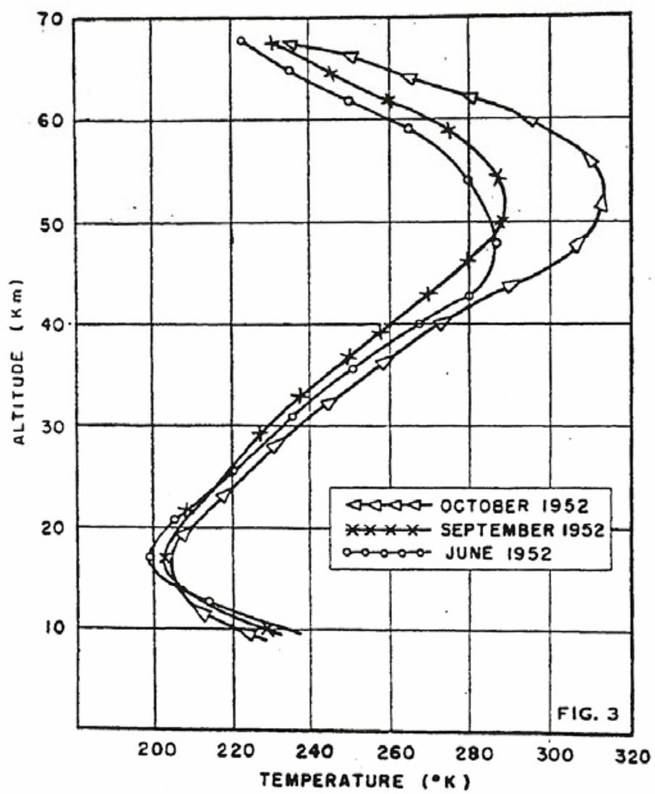


Fig. 3—Comparison of monthly profiles, New Mexico

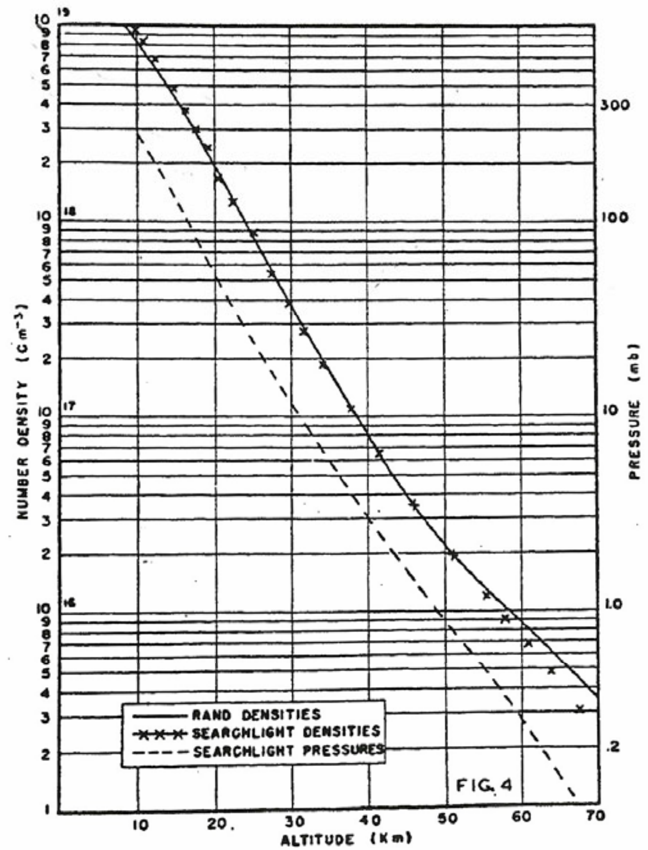


Fig. 4—Average density and pressure distributions, 29 May - 23 October 1952, New Mexico

Lidar Scattering Equation [Measures, 1984]

$$P(\lambda_R, z) = E_T(\lambda_T)\xi_T(\lambda_T)\xi_R(\lambda_R)\frac{c\tau}{2}\frac{A}{z^2}\beta(\lambda_T, \lambda_R)\exp\left[-\int_0^z [\alpha(\lambda_T, z') + \alpha(\lambda_R, z')]dz'\right]$$

z is the altitude of the volume element where the return signal is scattered,

λ_T is the wavelength of the laser light transmitted,

λ_R is the wavelength of the laser light received,

$E_T(\lambda_T)$ is the light energy per laser pulse transmitted at wavelength λ_T,

$\xi_T(\lambda_T)$ is the net optical efficiency at wavelength λ_T of all transmitting devices,

$\xi_R(\lambda_R)$ is the net optical efficiency at wavelength λ_R of all receiving devices,

c is the speed of light,

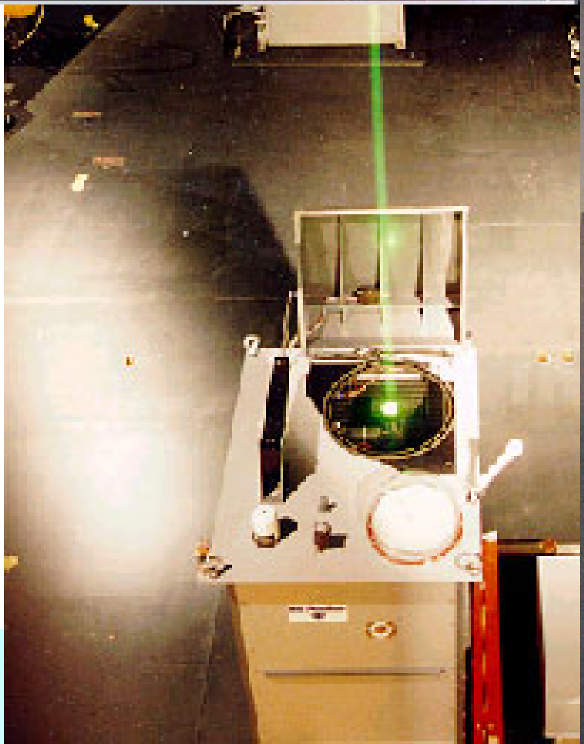
τ is the time duration of the laser pulse,

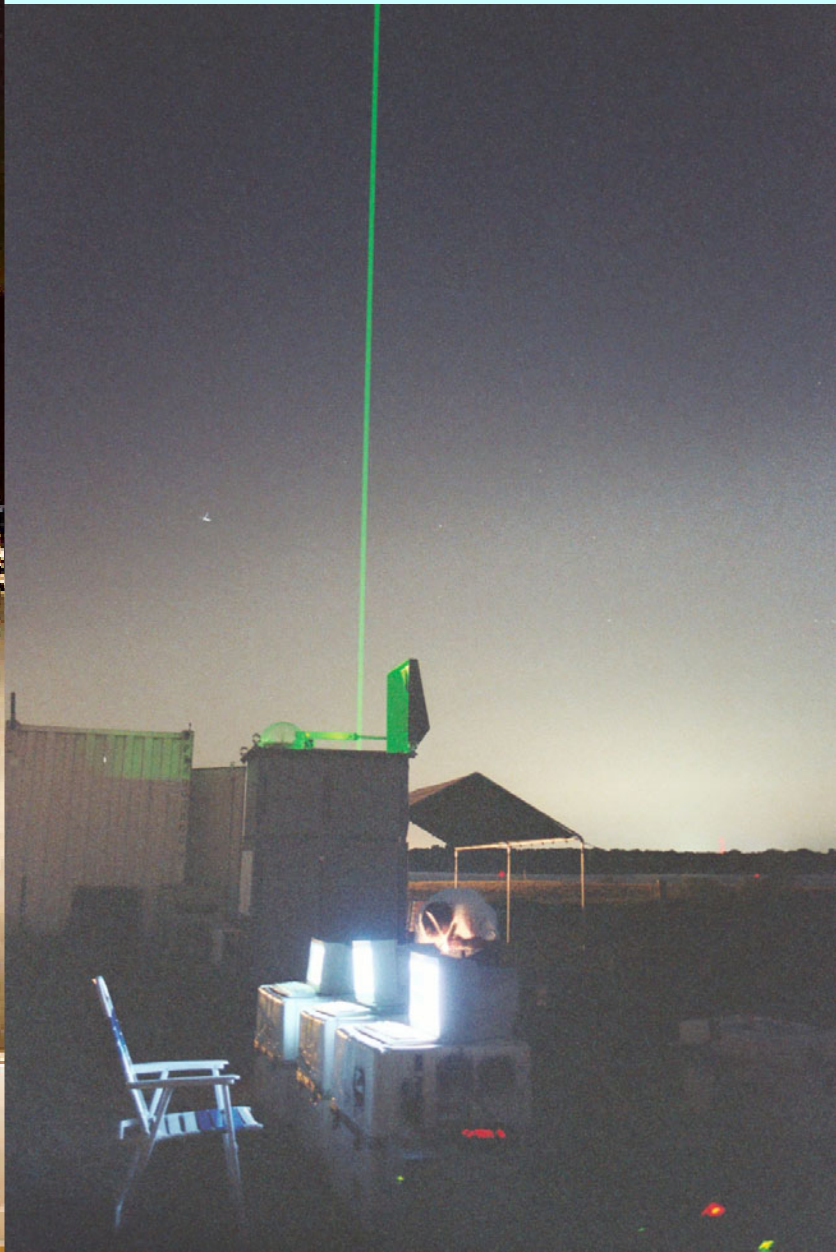
A is the area of the receiving telescope,

$\beta(\lambda_T, \lambda_R)$ is the back scattering cross section of the volume scattering element for the laser wavelength λ_T at Raman shifted wavelength λ_R,

$\alpha(\lambda, z')$ is the extinction coefficient at wavelength λ at range z'.

Lidar Configurations





Monostatic
Bistatic
Multistatic

LIDAR Types

Scattering cross section of dielectric sphere:

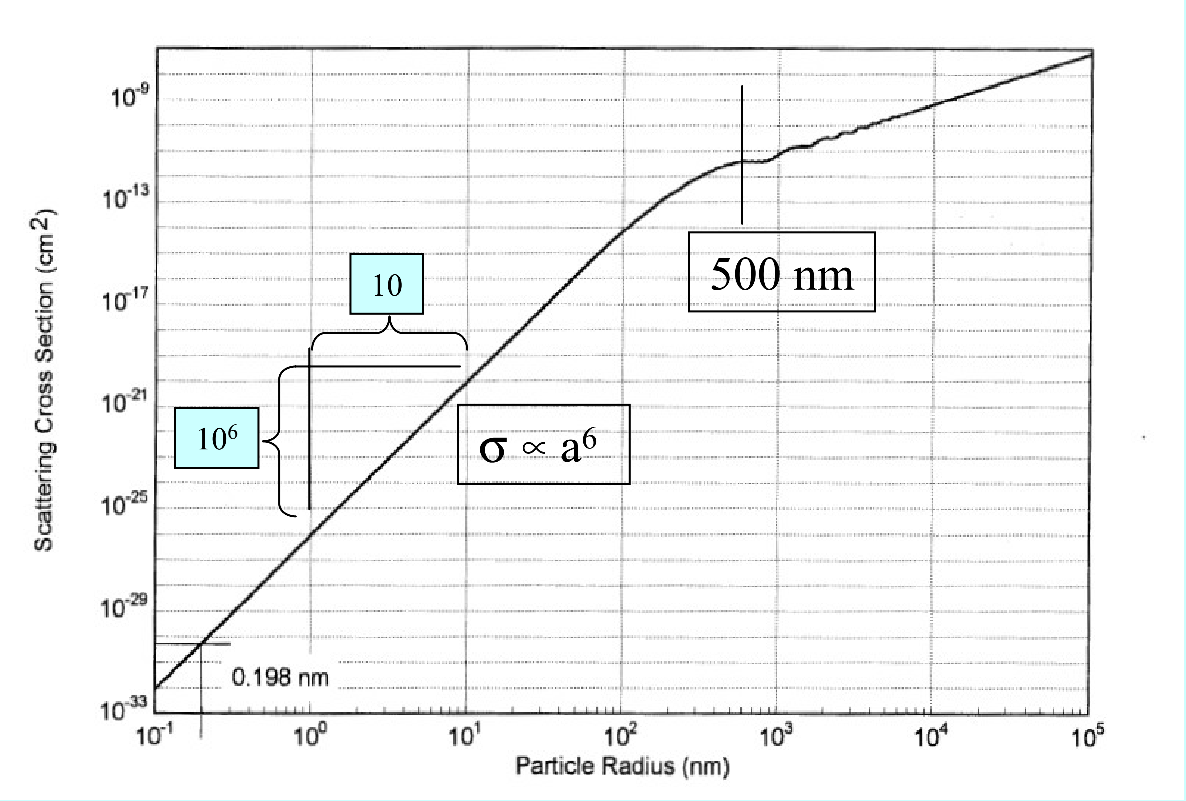
$\sigma = 4\pi[(\varepsilon - \varepsilon_o)/\varepsilon + 2\varepsilon_o)]^2 k^4 a^6 \sin^2\theta$

Backscatter cross section:

$\sigma_{back} \propto a^6$

Rayleigh Scatter

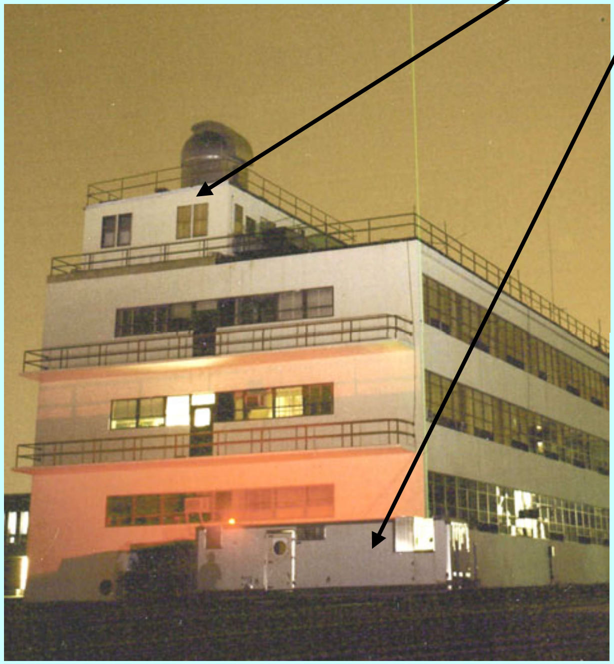
Aerosol and Cloud (Mie scatter)

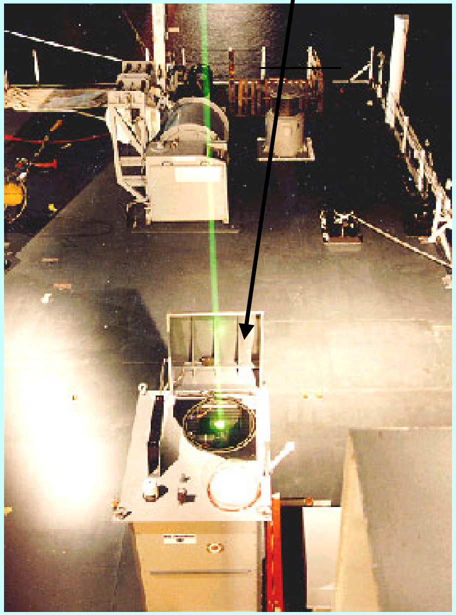


Raman Lidar Development

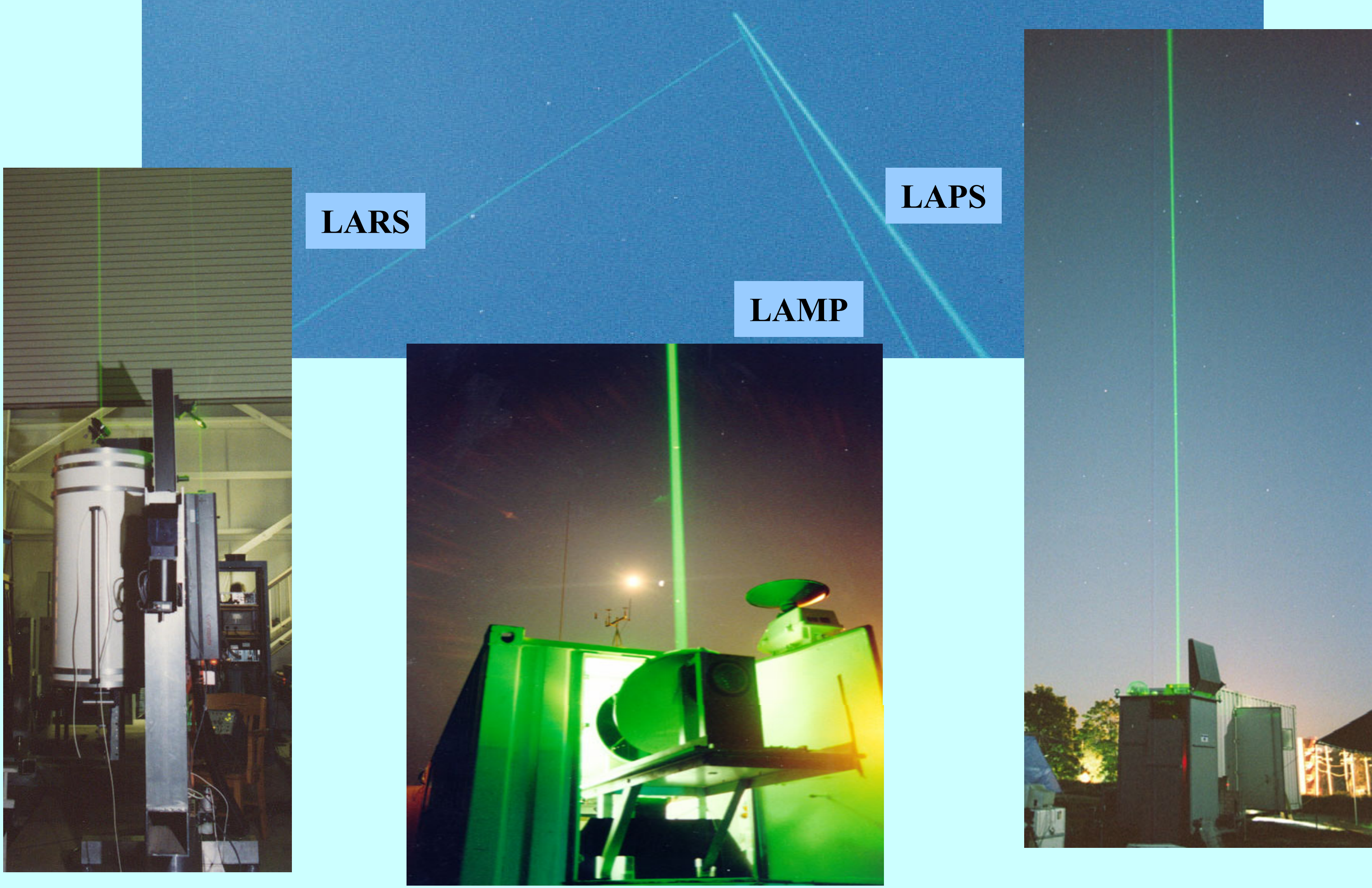
Five generations of Raman Lidars

GLEAM (1978)
GLINT (1983)
LAMP (1990)
LARS (1994)
LAPS (1996)





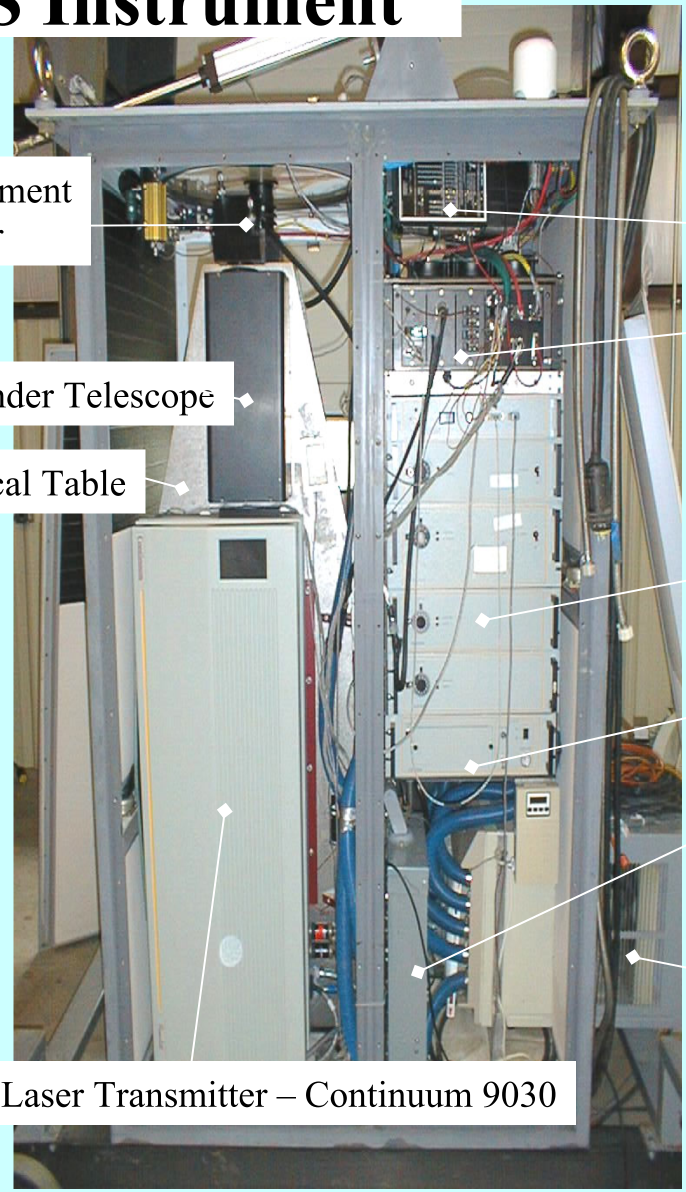
Three Raman Lidar Operating Simultaneously at PSU



Lidars were designed by staff and students, and fabricated in the PSU shops.

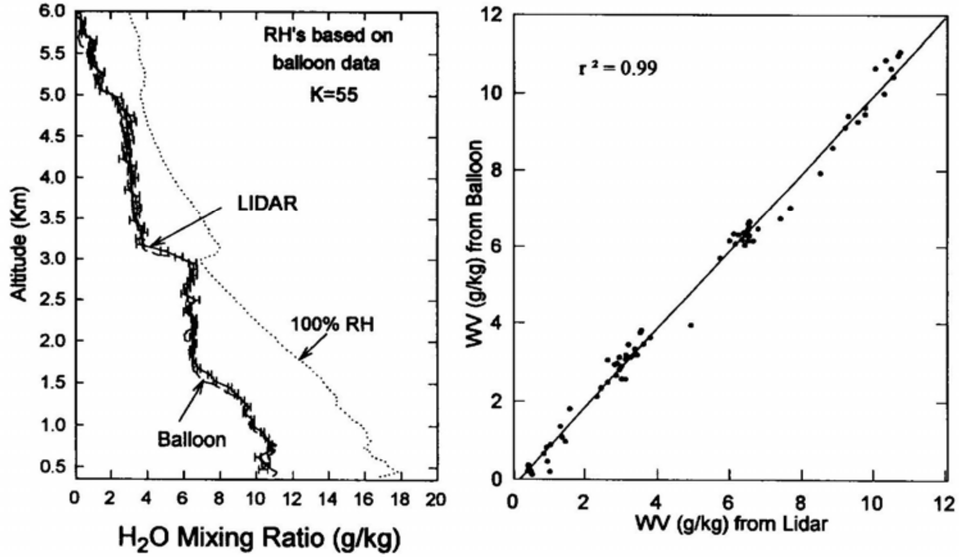
LAPS Instrument

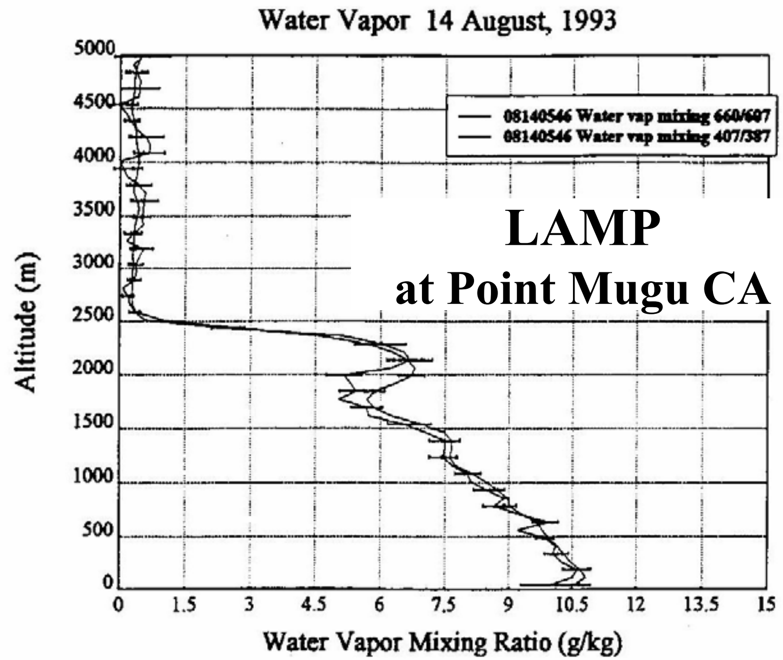
The LAPS instrument is first prototype for an operational system – Rugged, weather-sealed, compact, semi-automated



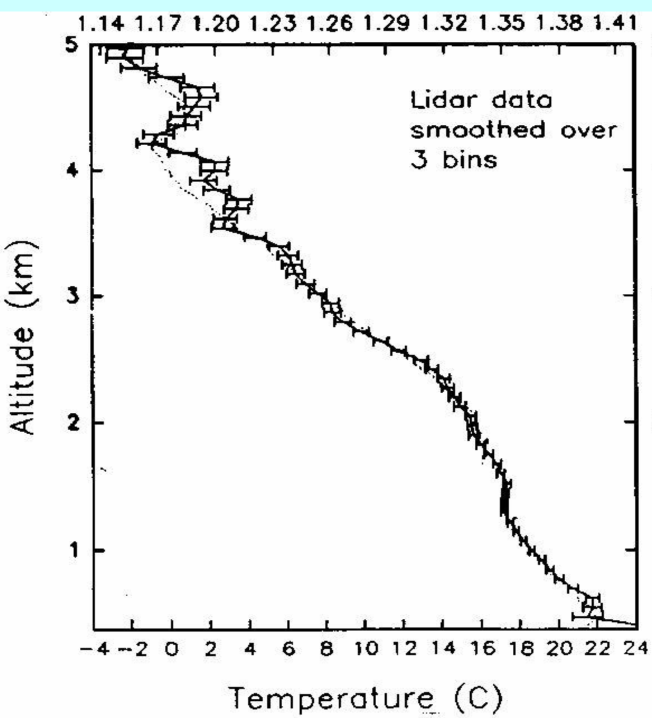
Backside of LAPS Instrument

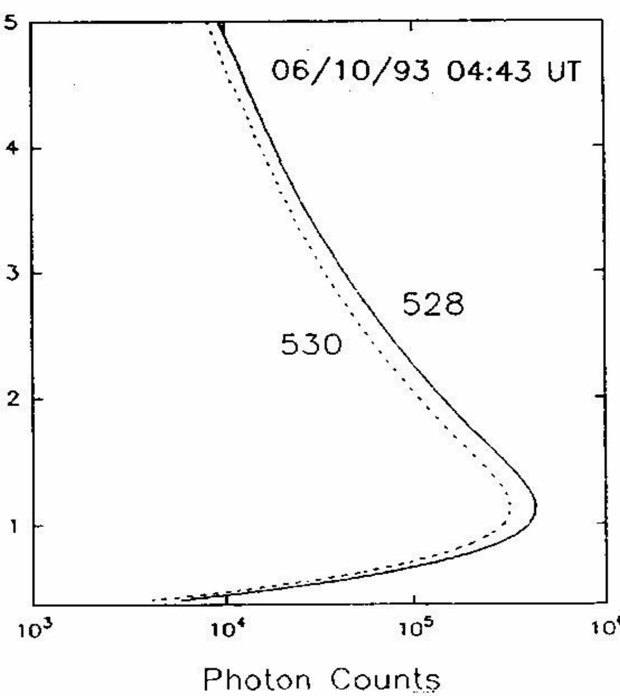
Mixing Ratio For Water from
30 Min. LIDAR Run Starting @ 05-10-93 03:26 UT
Balloon Launch @ 05-10-93 03:55 UT
75 meter resolution

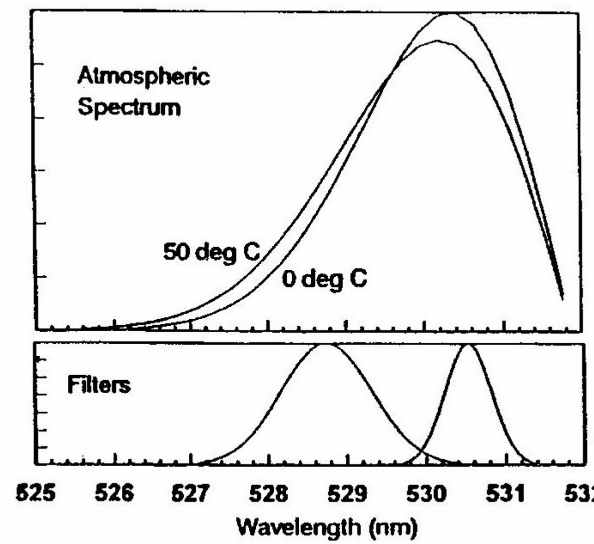




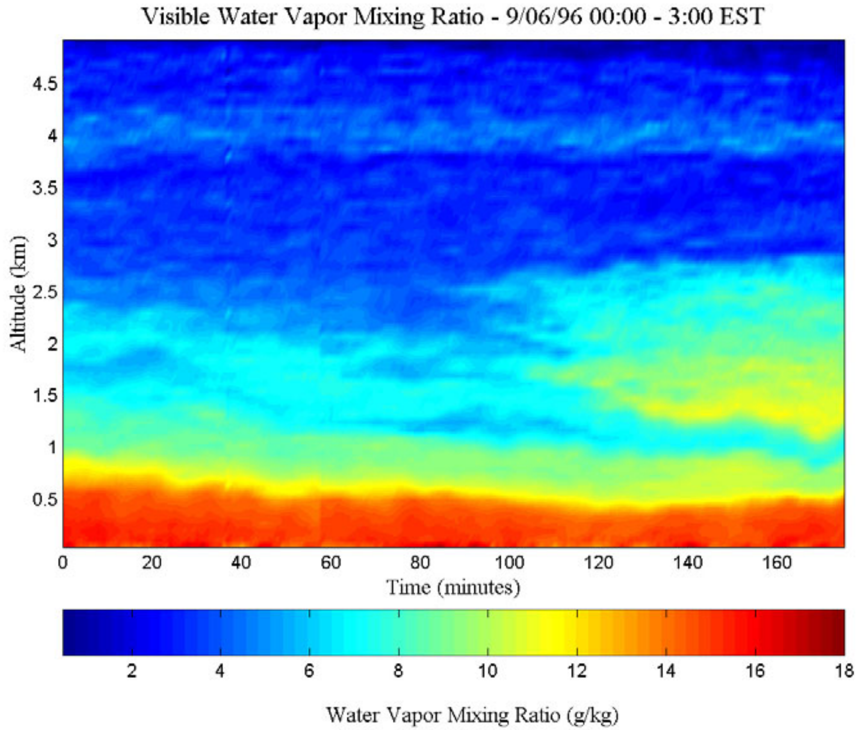
LAMP
at Point Mugu CA







Raman Lidar
Water Vapor & Temperature



Water Vapor –

Ratio of 660 to 607 nm

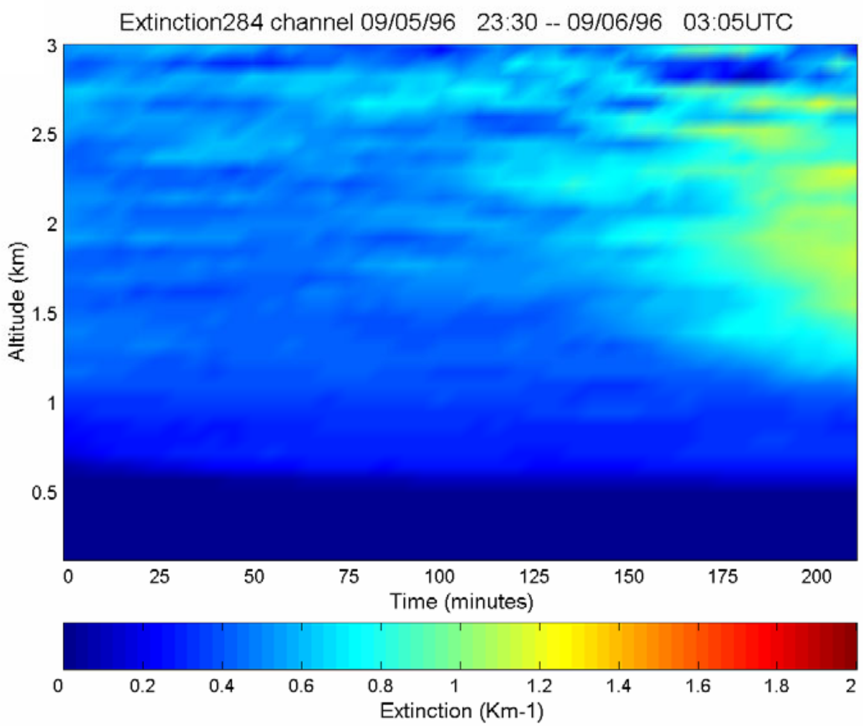
Ratio of 294 to 287 nm

Optical Extinction –

Incremental change in return signal at each range bin

6 Sept 1996 USNS Sumner

Water Vapor
Extinction
Cloud



RF Refractivity Variation

$N = (n - 1) \times 10^6 = 77.6\ P/T + 3.73 \times 10^5\ e/T^2$

$e\,(\text{mb}) = (r\,P)/(r + 621.97)$

P - surface pressure   r - specific humidity   T - temperature

T(K) ~ 295 K   P(mb) ~ 1000 mb   r ~ 7 g/kg   N ~ 310

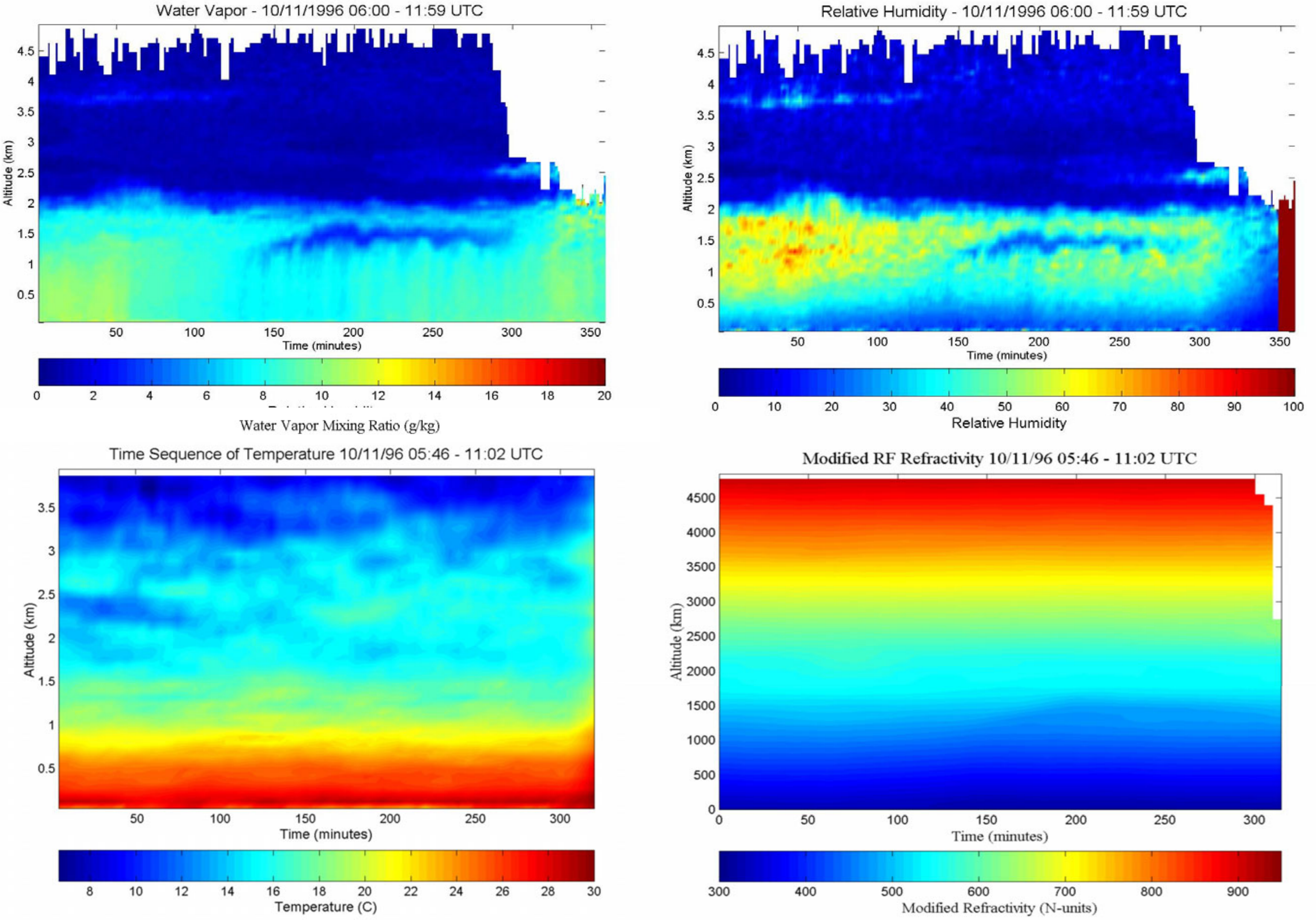
$\Delta N = (\delta N/\delta r)\,\Delta r + (\delta N/\delta T)\,\Delta T + (\delta N/\delta P)\,\Delta P$

$\delta N/\delta r \sim 6.7$ $\delta N/\delta T \sim -1.35$ $\delta N/\delta P \sim 0.35$

$dN/dz = 6.7\ dr/dz - 1.35\ dT/dz + 0.35\ dP/dz$

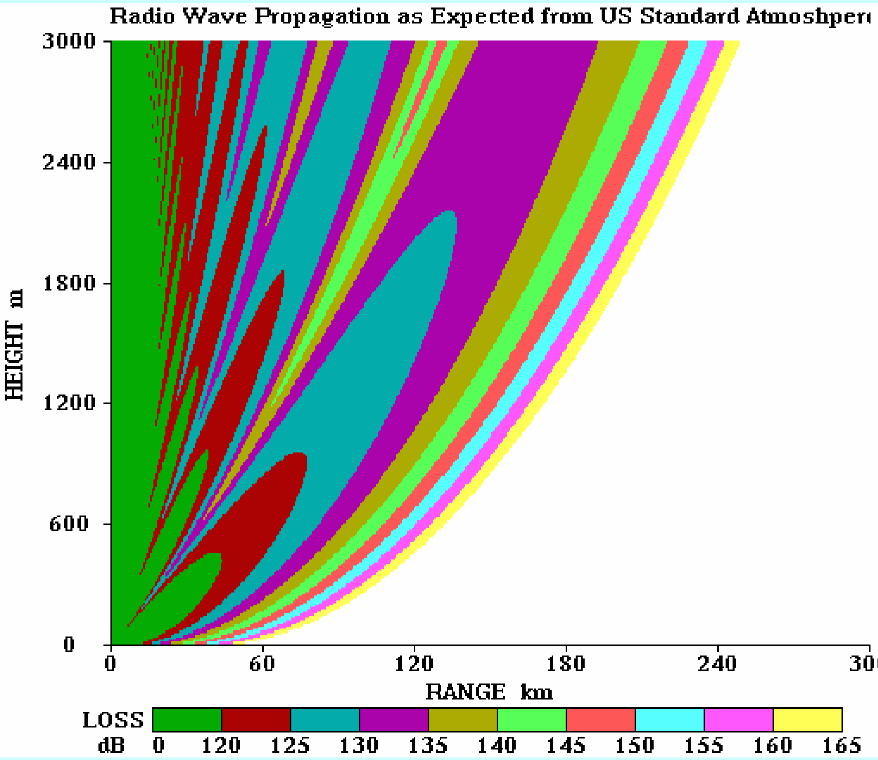
Gradients in water vapor are most important in determining RF ducting conditions.

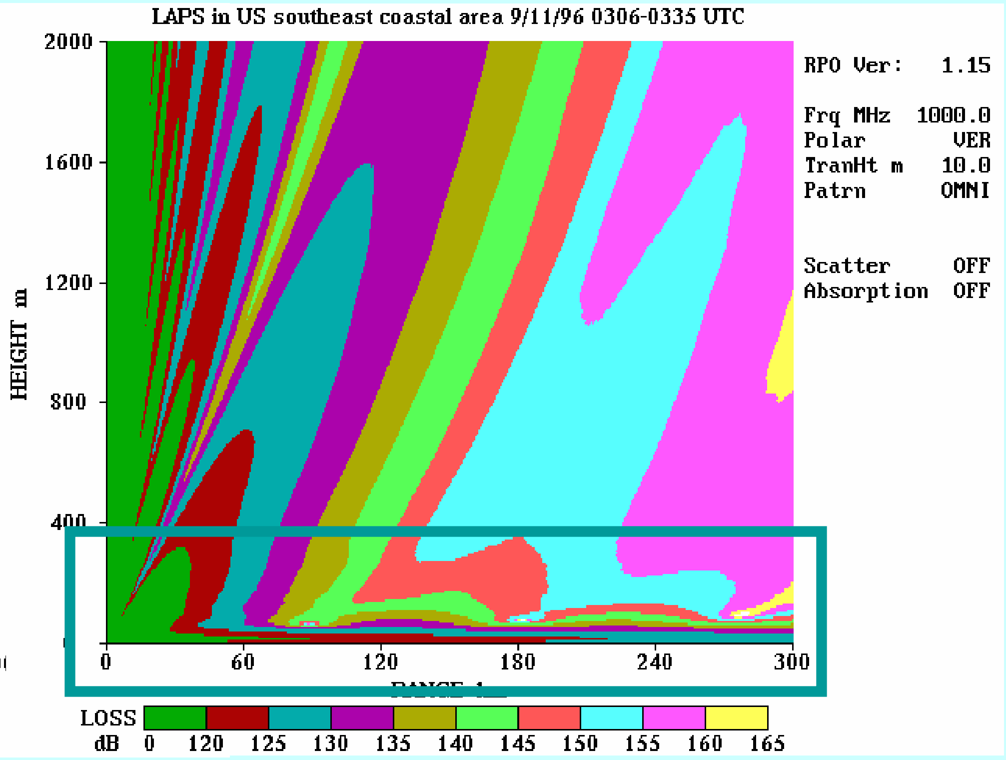
Water Vapor and Temperature



Radar Effects

- U.S. Standard Atmosphere
- Surface/Evaporative Duct

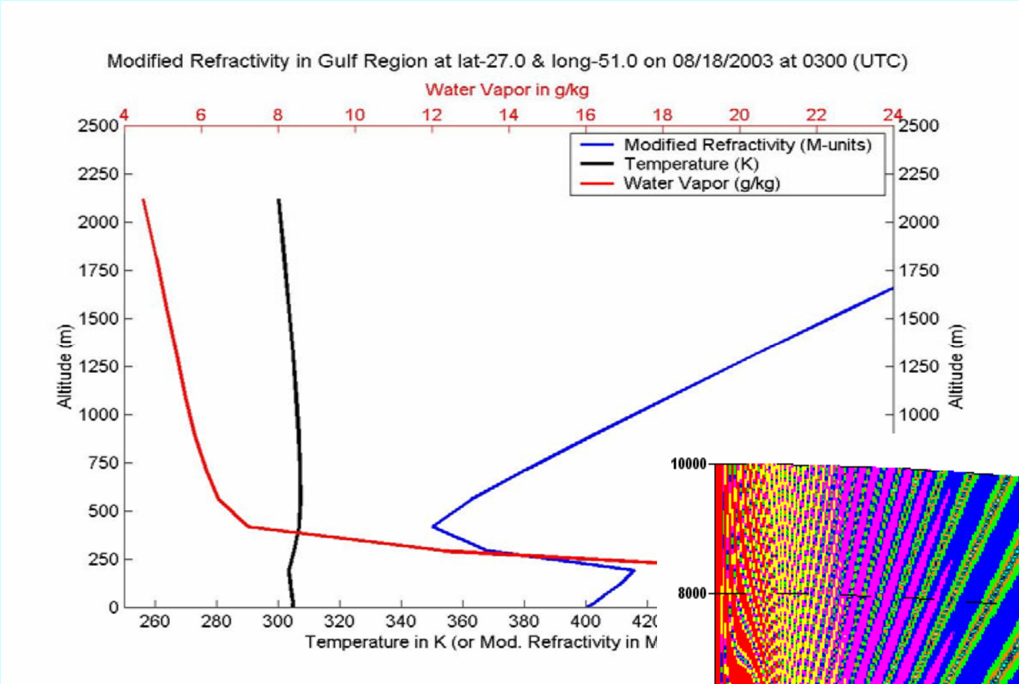


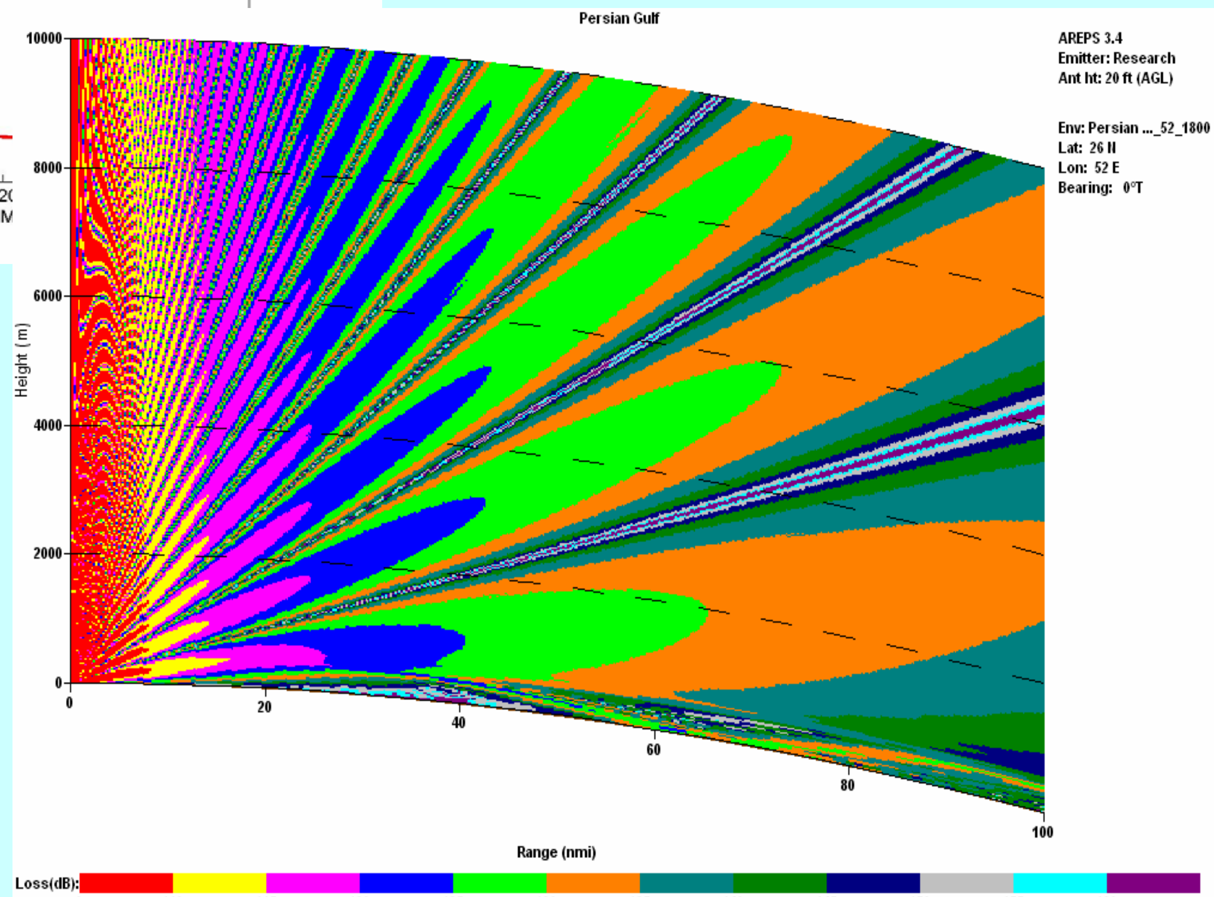


Collier, PSU MS Thesis 2004

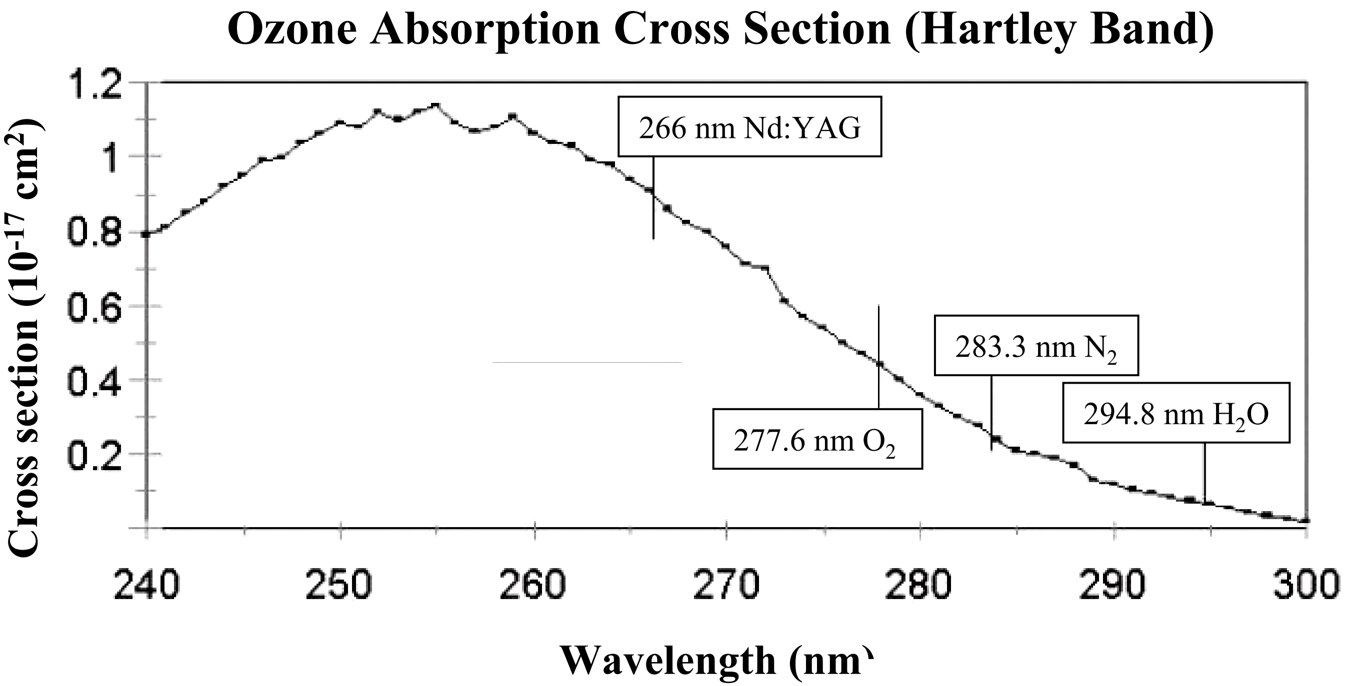
Radar Propagation Results – Vertical Profiles –

Persian Gulf



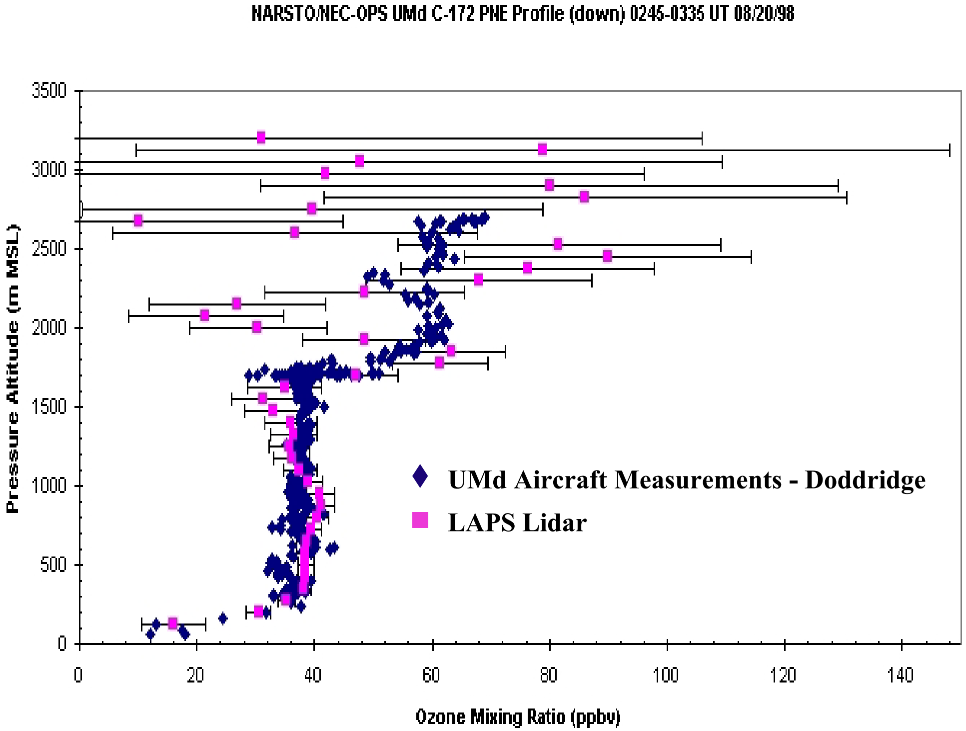


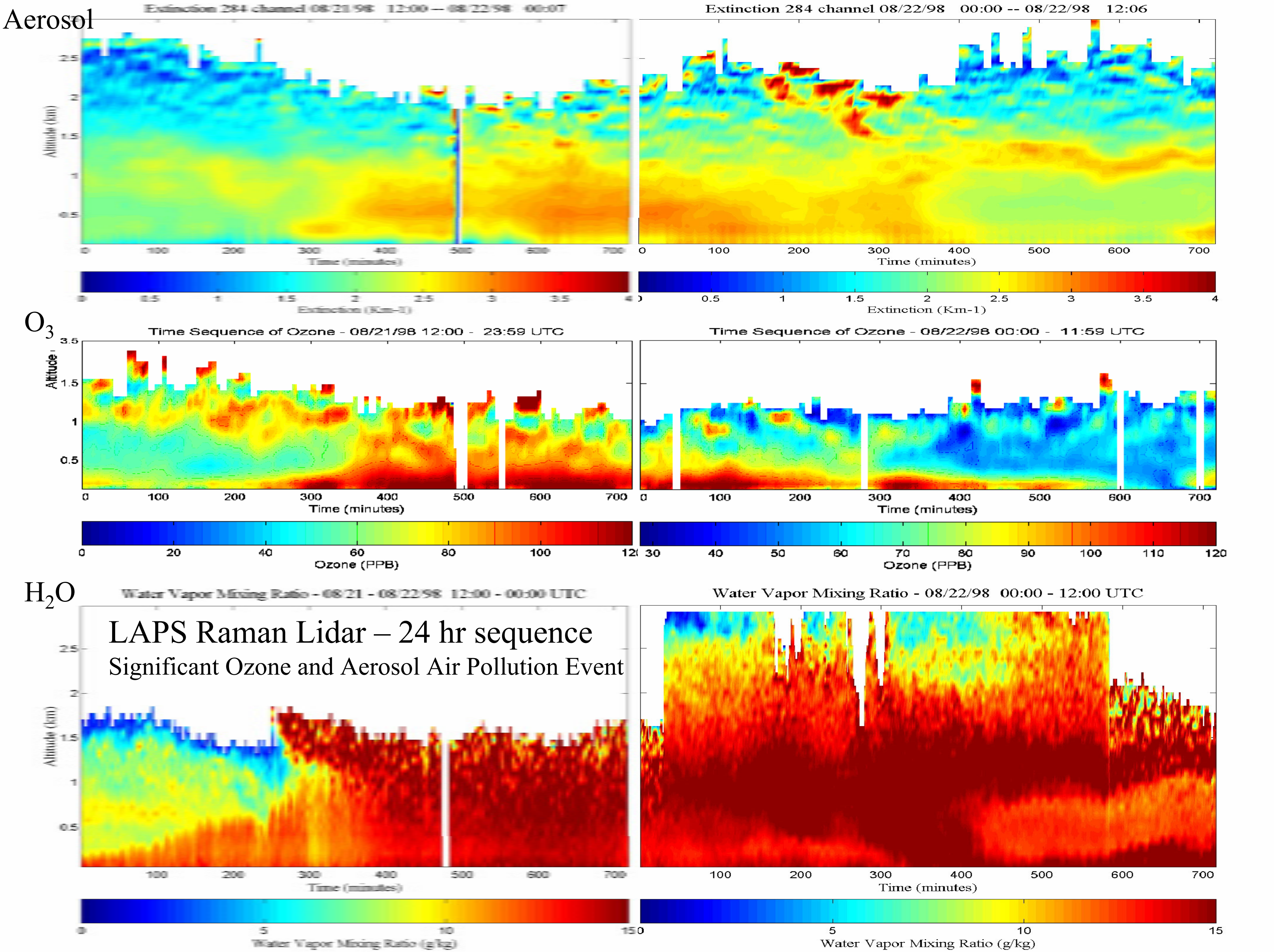
Collier, PSU MS Thesis 2004



Ozone

Ratio of Raman signals of O_2 to N_2 are used to determine O_3 absorption based on departure from known constant ratio.

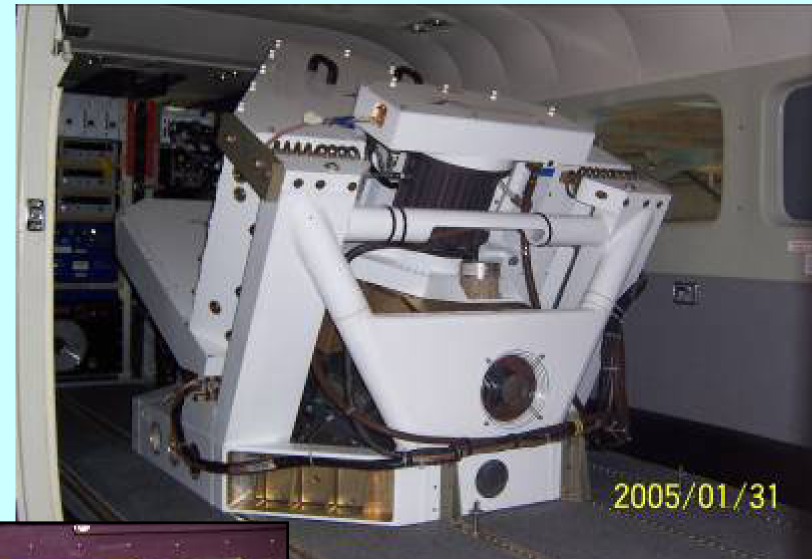




Aerosol
Extinction 284 channel 08/21/98 12:00 -- 08/22/98 00:07
Extinction 284 channel 08/22/98 00:00 -- 08/22/98 12:06
Altitude (km)
Time (minutes)
Extinction (Km-1)
O_3
Time Sequence of Ozone - 08/21/98 12:00 - 23:59 UTC
Time Sequence of Ozone - 08/22/98 00:00 - 11:59 UTC
Altitude
Time (minutes)
Ozone (PPB)
H_2O
Water Vapor Mixing Ratio - 08/21 - 08/22/98 12:00 - 00:00 UTC
Water Vapor Mixing Ratio - 08/22/98 00:00 - 12:00 UTC
LAPS Raman Lidar – 24 hr sequence
Significant Ozone and Aerosol Air Pollution Event
Altitude (km)
Time (minutes)
Water Vapor Mixing Ratio (g/kg)

DIAL Sensor System and Supporting Hardware

ITT's Airborne Natural Gas Emission Lidar (ANGEL)



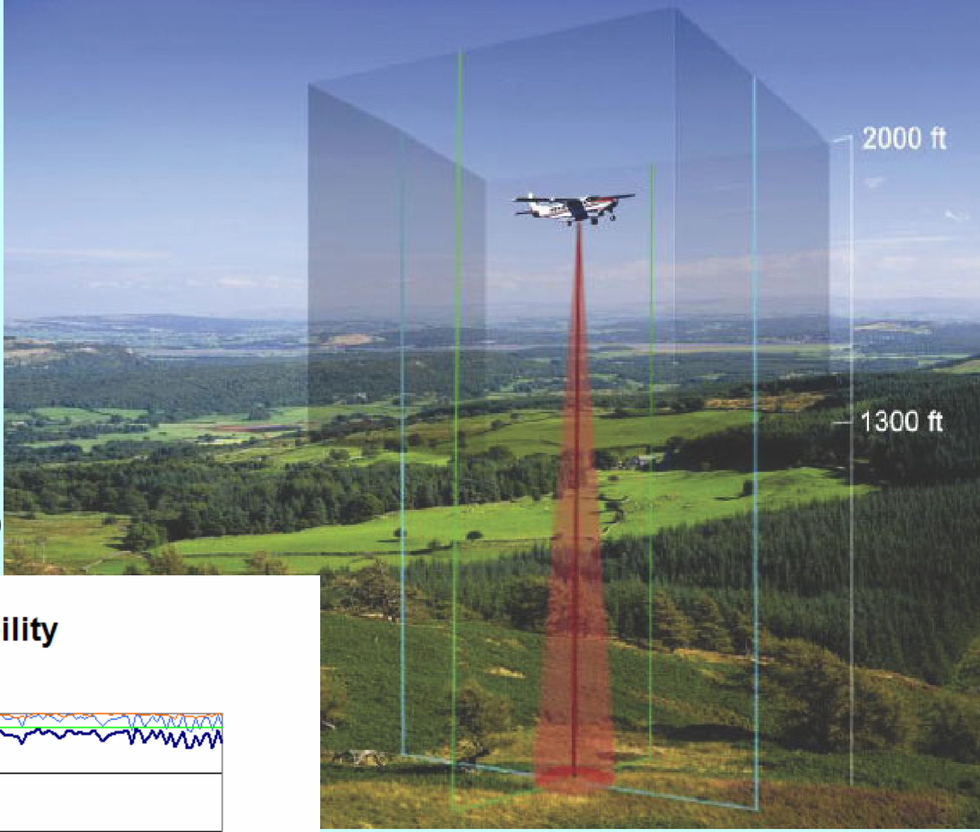
DIAL Sensor

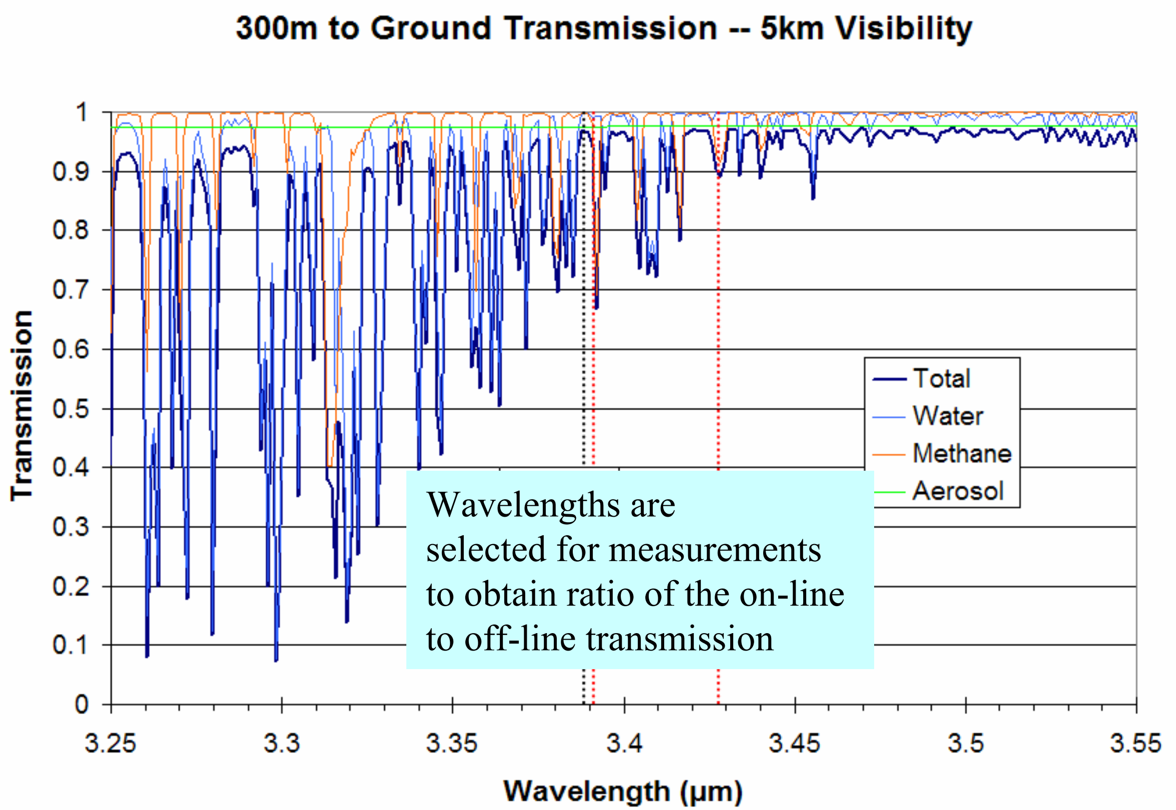
High Resolution Mapping Camera

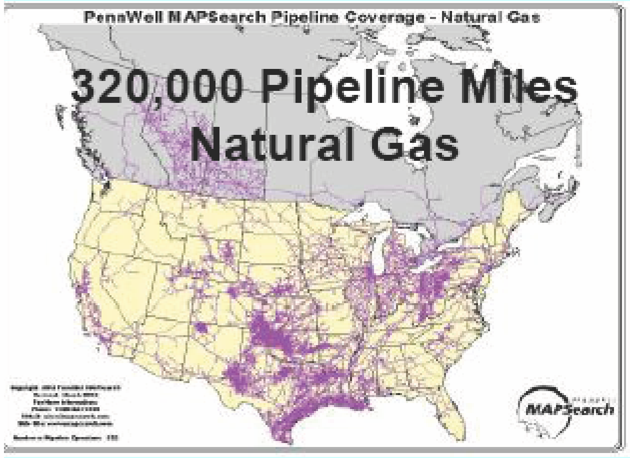
Digital Video Camera

DIAL Lidar uses the ratio of on-line to off-line transmission to determine the species concentration

(First commercial Application of DIAL Lidar)

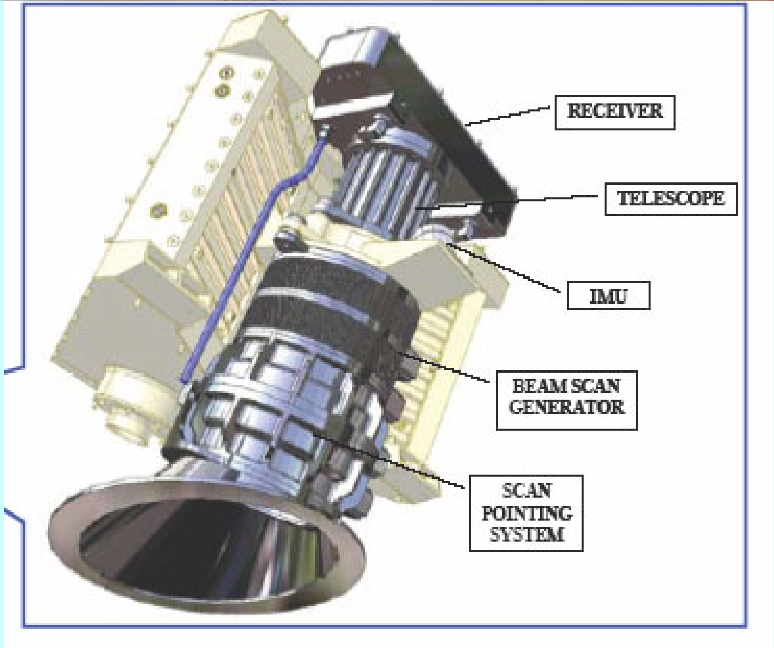




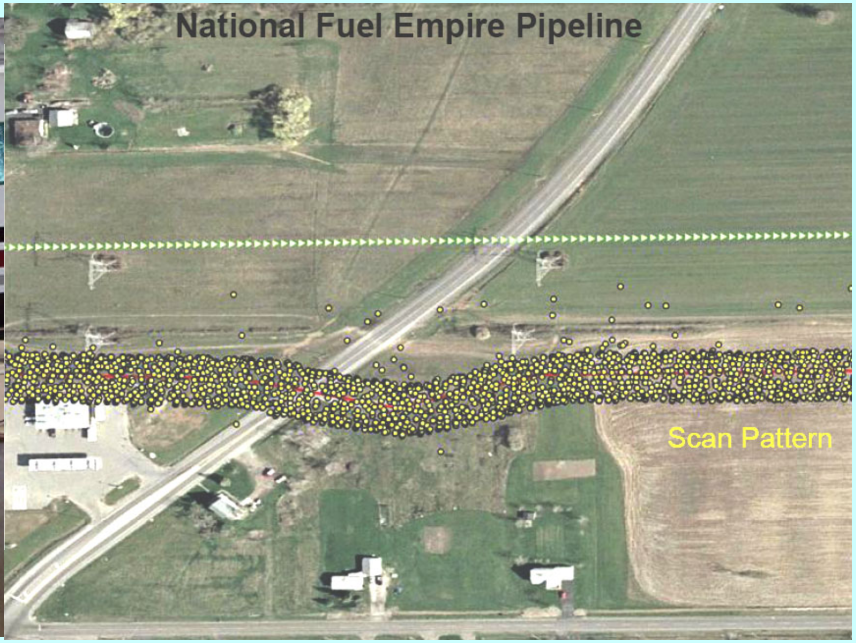


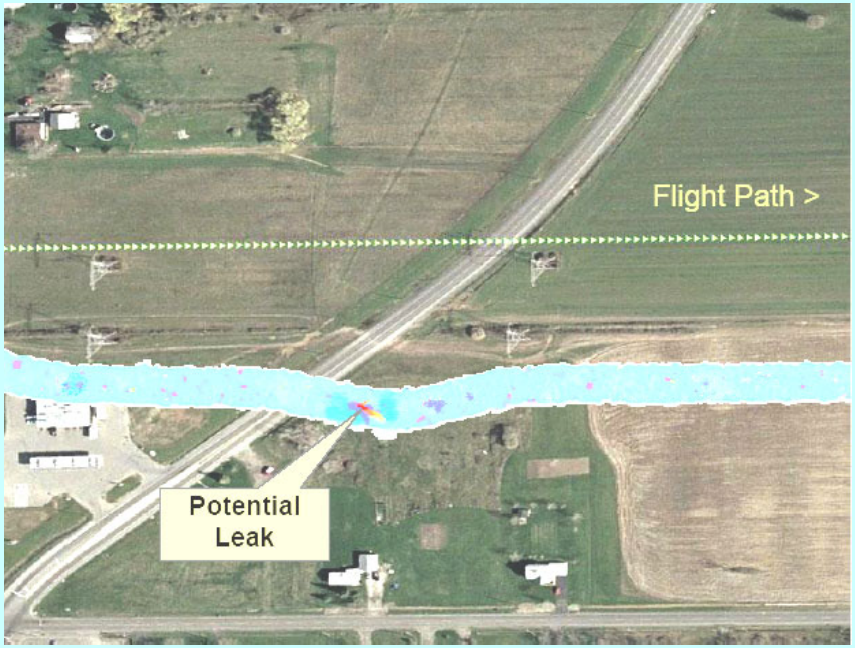
Murdock and Stearns, NYS Remote Sensing Sym, May 2005

ITT - ANGEL System



C. Grund, S. Shald and S. Stearns, SPIE Proc **5412**, Defefence & Security, 2004.



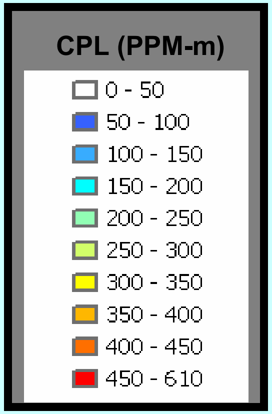


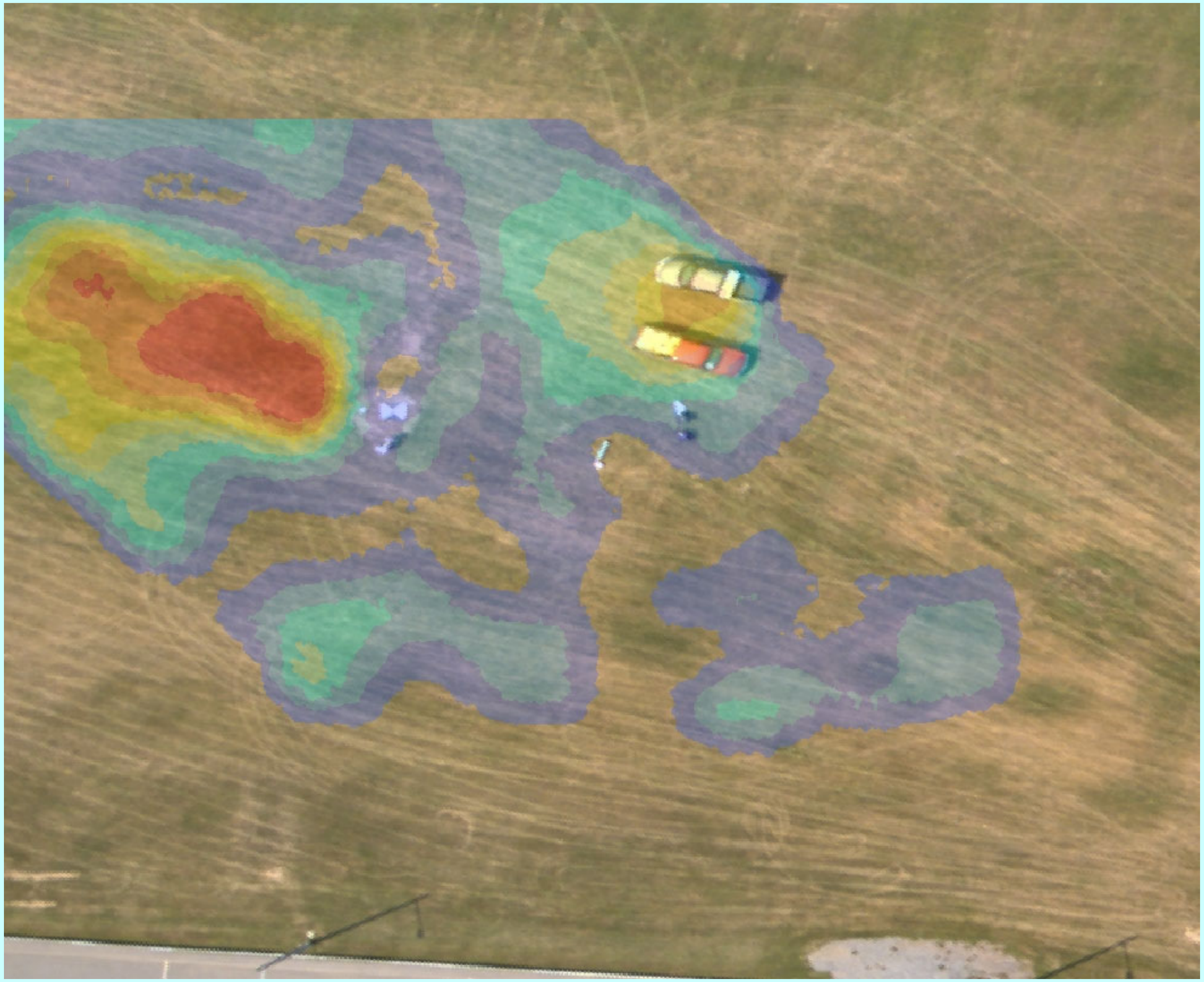
Murdock and Stearns, NYS Remote Sensing Sym, May 2005

DIAL Detection and Measurement of Propane Gas

Detection over grass – open field

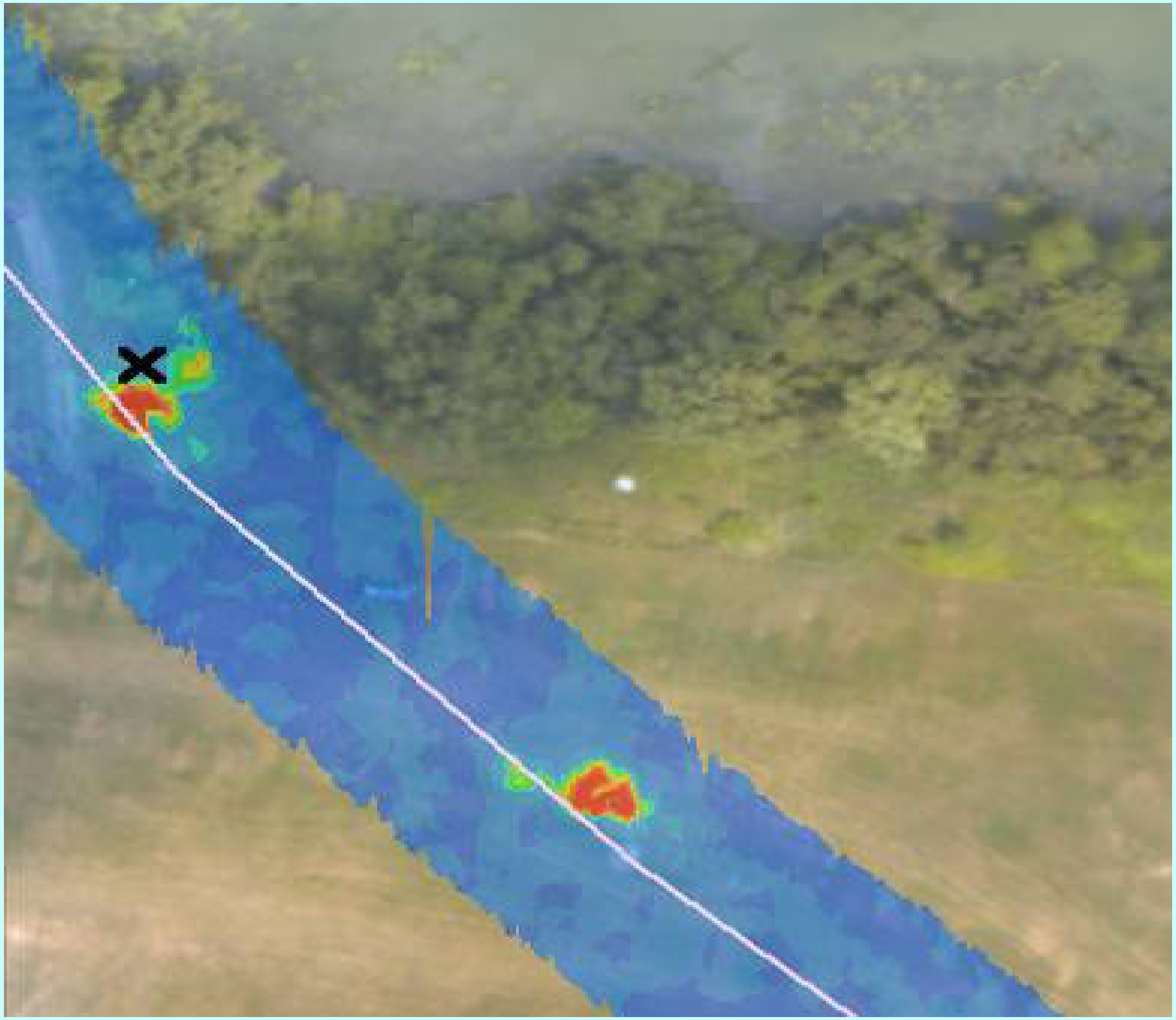
Less than 3 seconds of collection from 1,000’ altitude





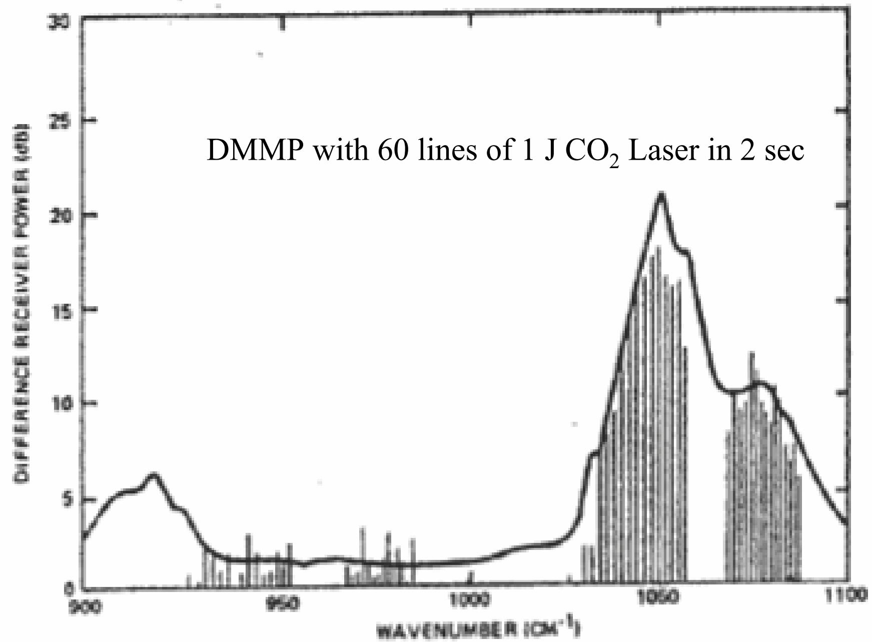
ITT's ANGEL Service Aircraft:

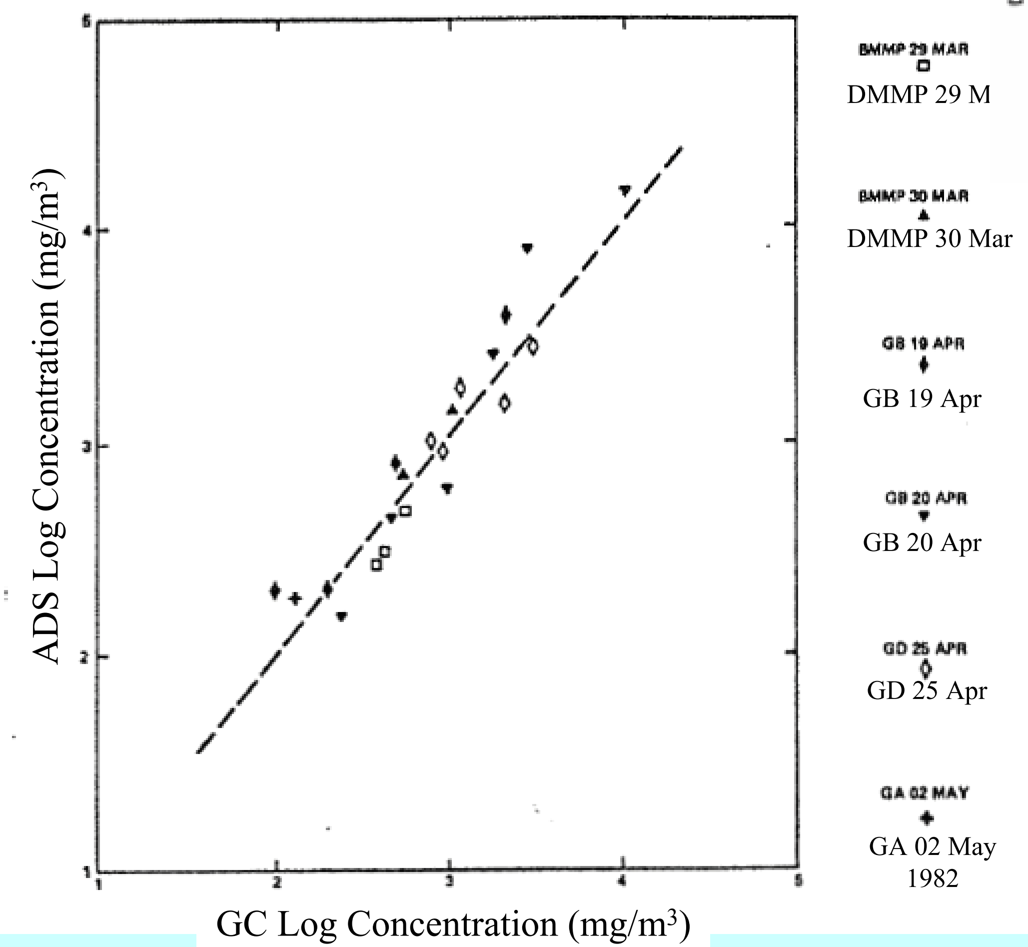
Computer controlled pointing, scanning and tracking system

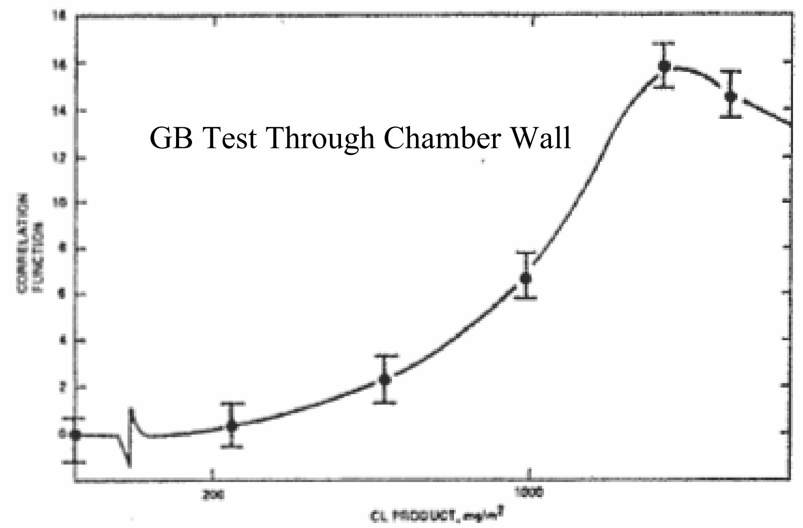


ADS (Area Detection System)

1978-1984 AF-WPAFB – GTE Sylvania

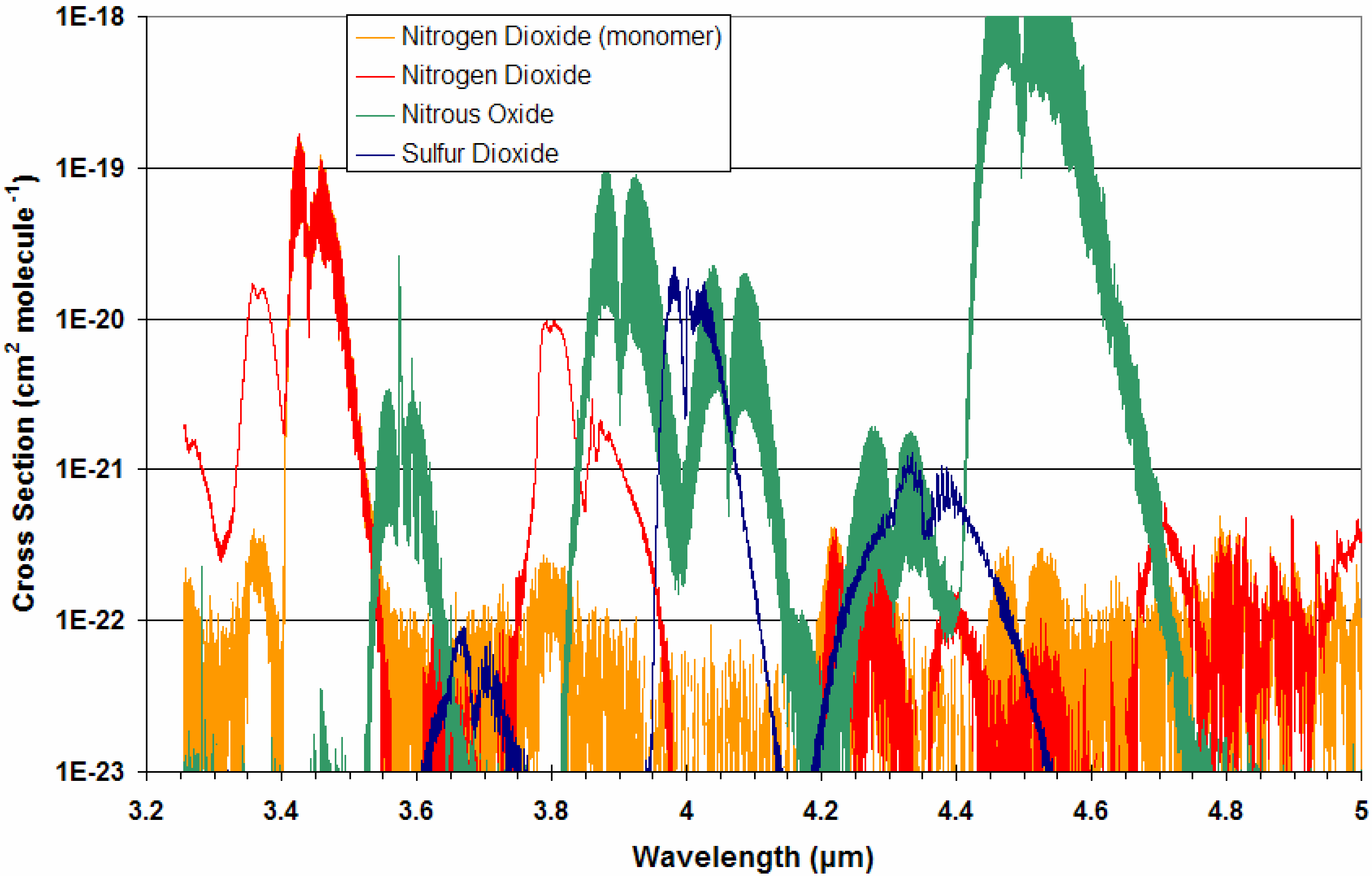






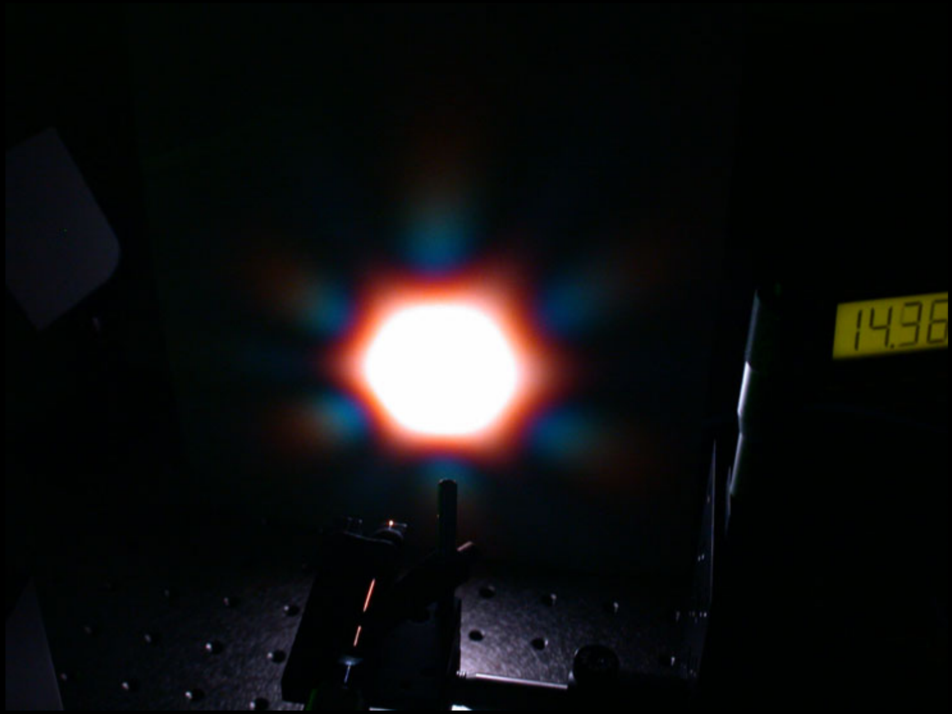
Leonard, et al. SPIE 2831, 20-31, 1996.

Trace Constituents

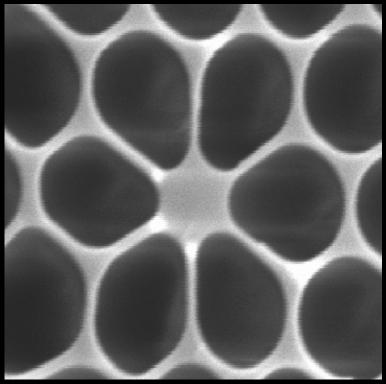


PNNL Infrared Spectral Data Base

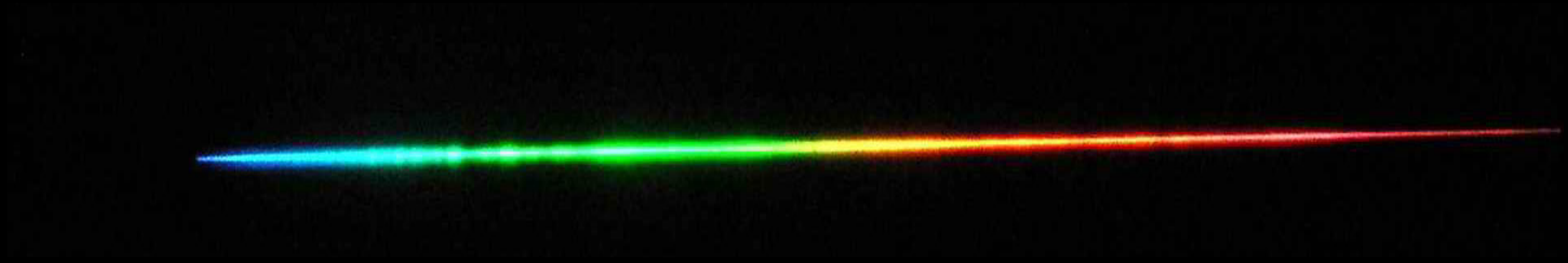
White light laser (supercontinuum)
Application for DAS

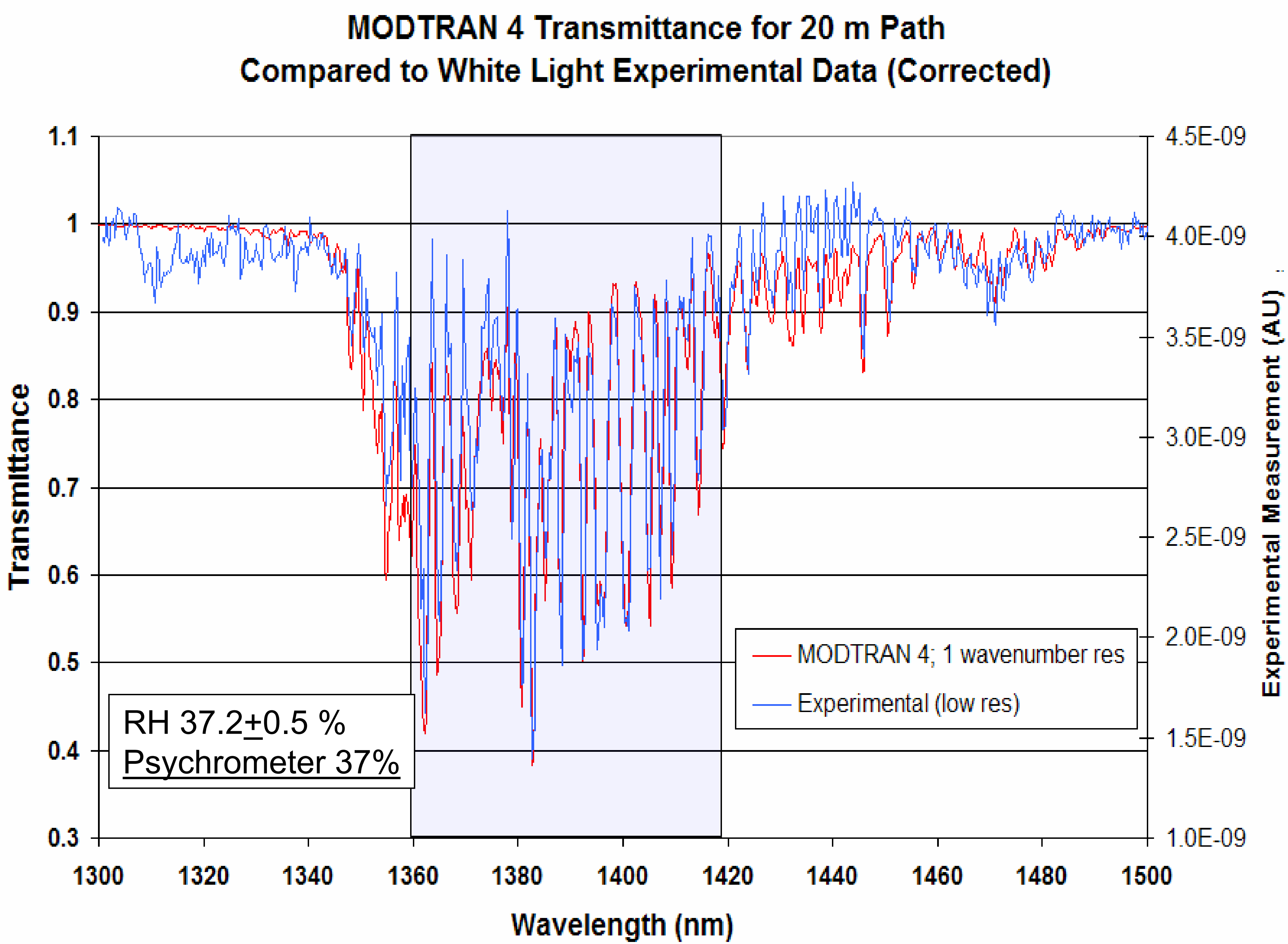


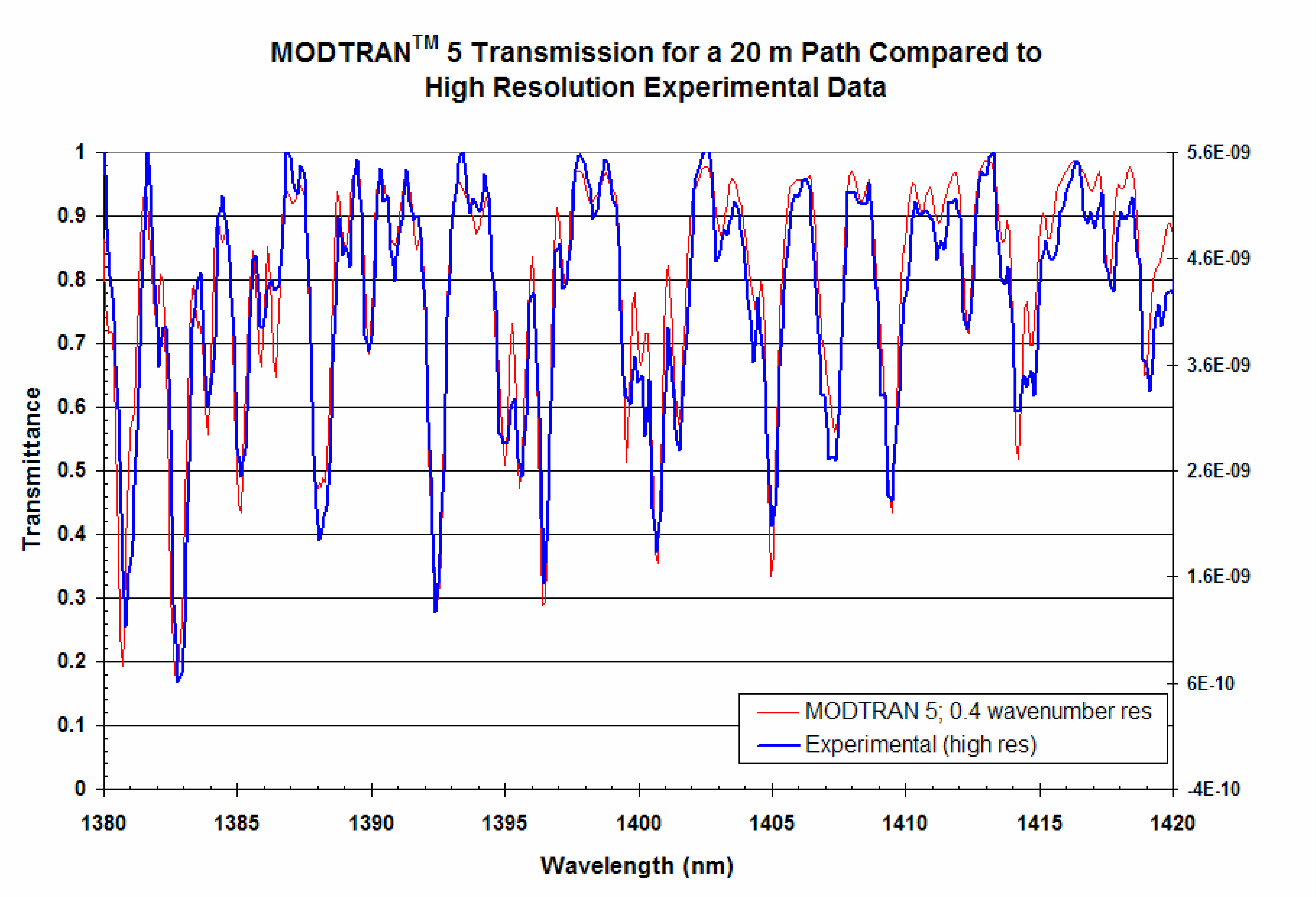
Photonic crystal fiber



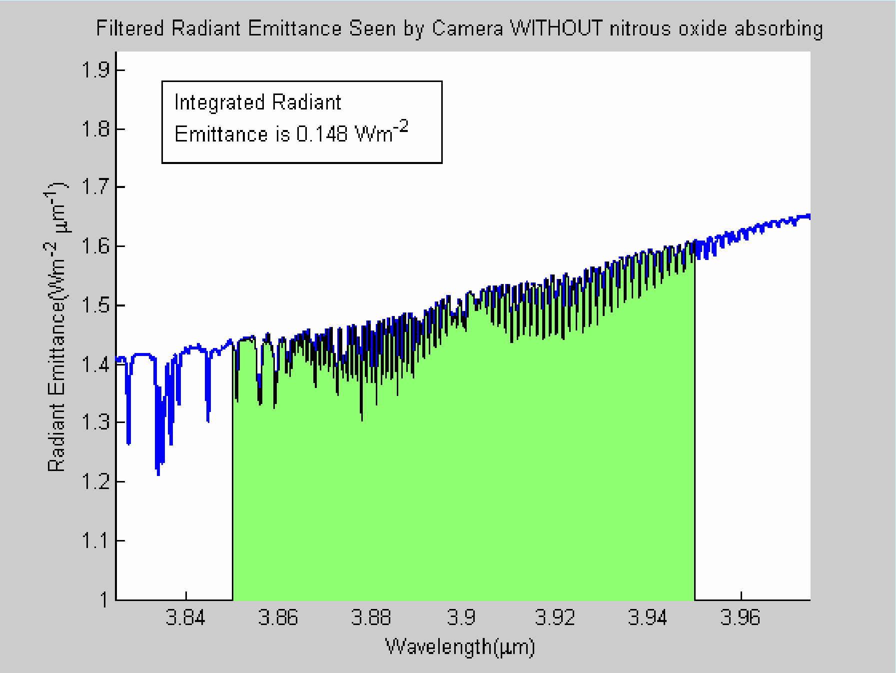
(From http://www.crystal-fibre.com)

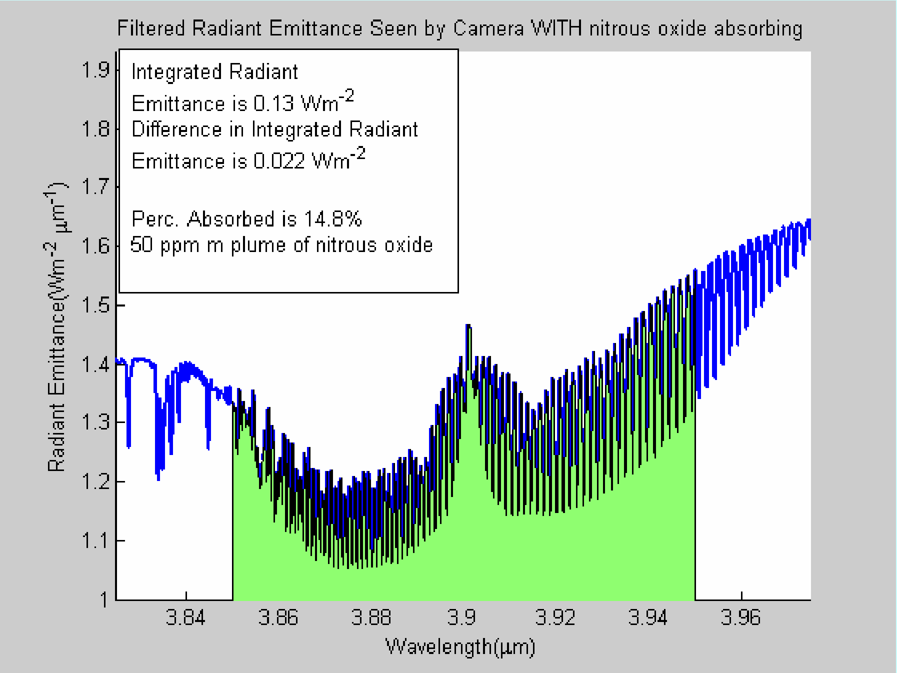



MODTRAN 4 Transmittance for 20 m Path
Compared to White Light Experimental Data (Corrected)
Transmittance
Experimental Measurement (AU)
Wavelength (nm)
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
4.5E-09
4.0E-09
3.5E-09
3.0E-09
2.5E-09
2.0E-09
1.5E-09
1.0E-09
1300
1320
1340
1360
1380
1400
1420
1440
1460
1480
1500
MODTRAN 4; 1 wavenumber res
Experimental (low res)
RH 37.2±0.5 %
Psychrometer 37%


MODTRAN™ 5 Transmission for a 20 m Path Compared to
High Resolution Experimental Data
Transmittance
Wavelength (nm)
1380
1385
1390
1395
1400
1405
1410
1415
1420
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
-4E-10
6E-10
1.6E-09
2.6E-09
3.6E-09
4.6E-09
5.6E-09
MODTRAN 5; 0.4 wavenumber res
Experimental (high res)

N_2O Detection



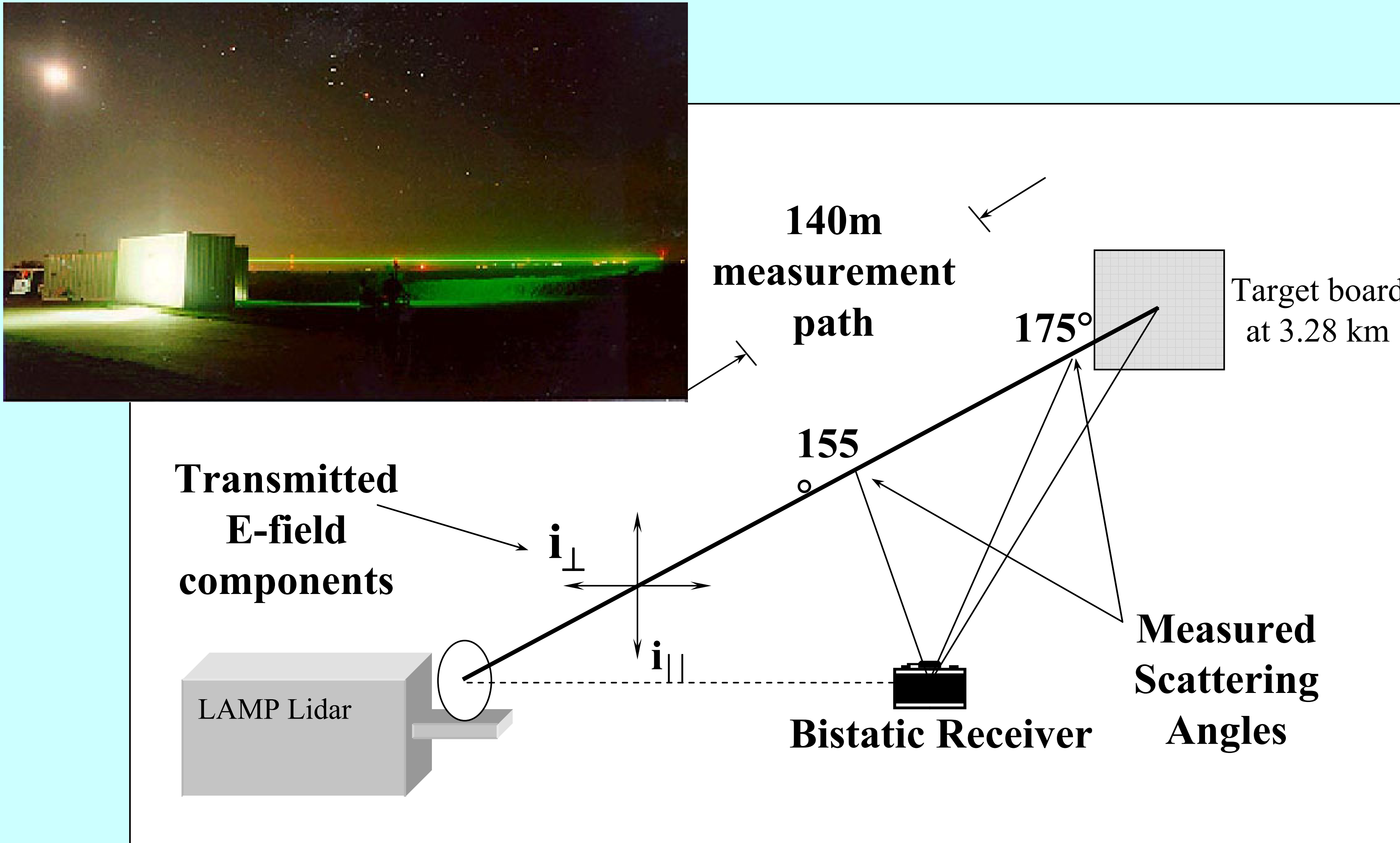


Nitrous oxide in atm 320 ppb

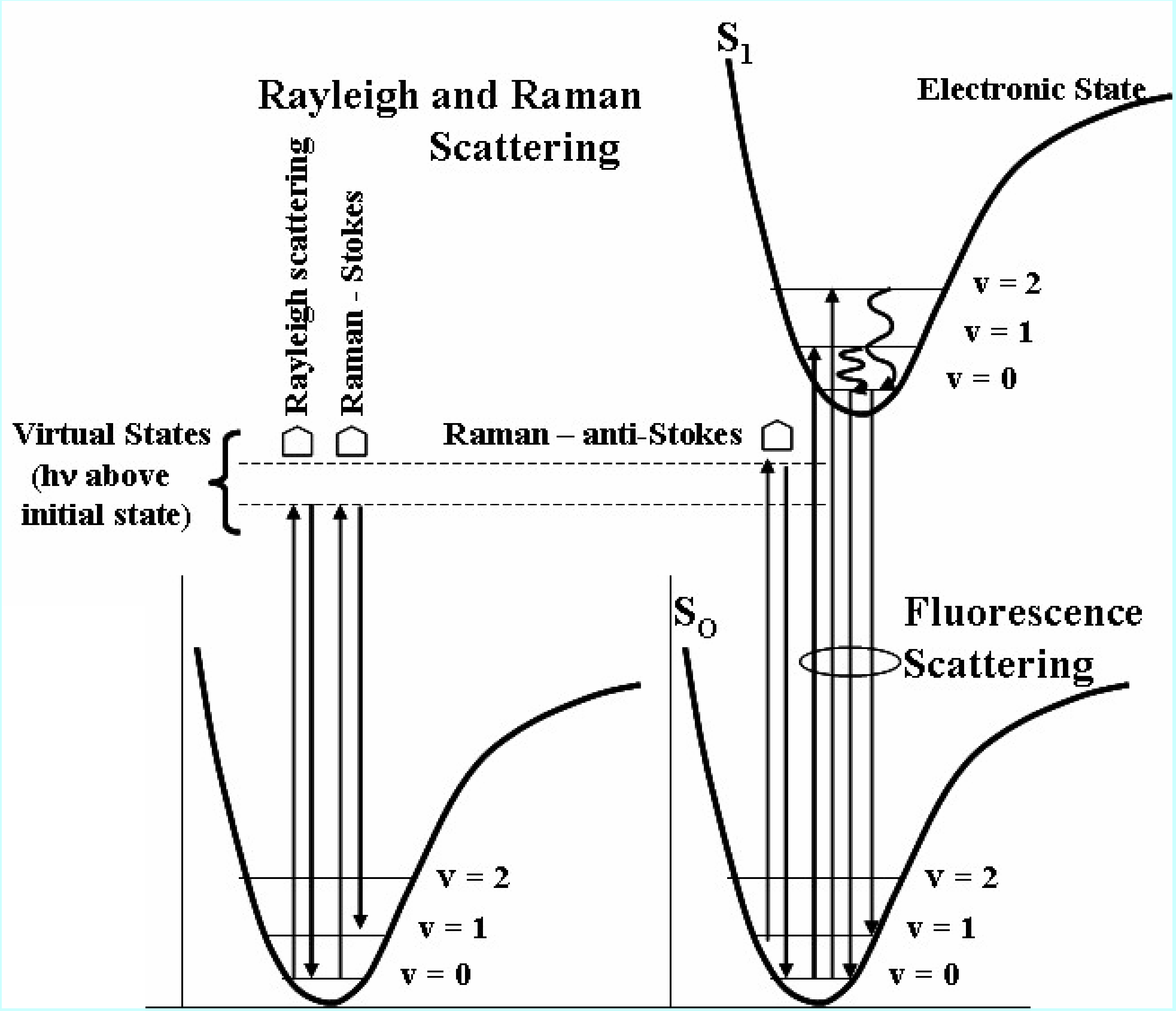
Automobile exhaust average 4-8 ppm

high as 23 ppm

Bistatic Methodology and Equipment

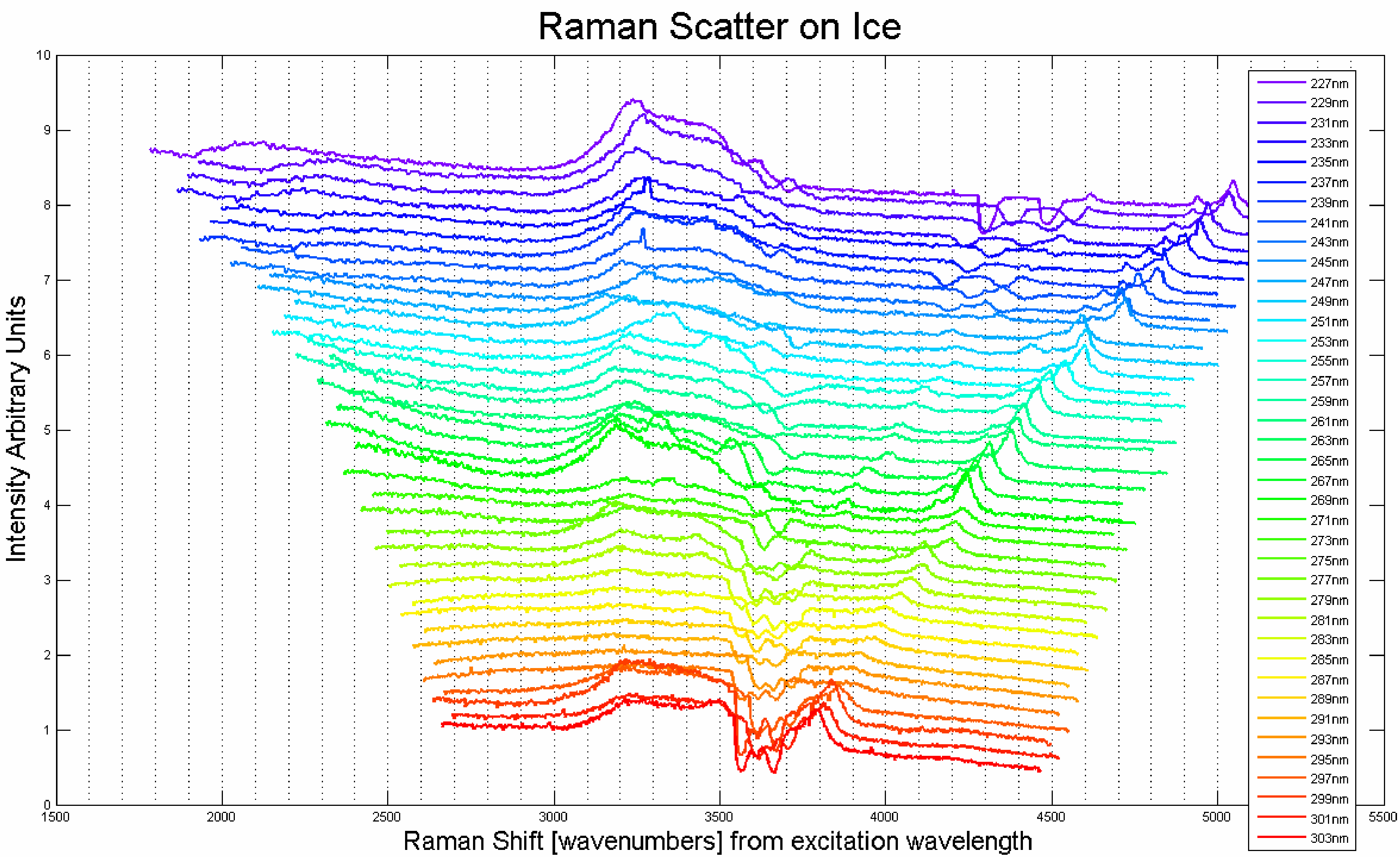


Resonance Raman



Raman Spectra of Ice

Function of Excitation Wavelength



Measurements of Species Concentration

Model Simulations and measurements in the lower atmosphere (1-3 km range)

DIAL ~ ppm

100 ppm – 10 ppb

DAS ~ 10's ppb

10 ppm – 100 ppt

Raman ~ 100's ppm

1000 ppm – 10 ppm

Raman/DIAL ~ 10 ppb (Hartley band of ozone)

Resonance Raman ~ ppm

100 ppm – 10 ppb - - - - 100 ppt (?)

Fluorescence ~ 10's ppm

1 ppm – 10 ppt (?)

Many Factors: Laser Power, Collector Size, Range, Range Resolution, Integration Time, Optical Signatures Available ….

Current and Future Topics

Focus on extending capability to trace concentrations

Resonance Raman and Fluorescence LIDAR

Use the solar blind UV-region with transmitter 210 to 250 nm to gain several orders of magnitude in sensitivity for minor species

White Light Laser Long Path Absorption (DAS)

Make use of the developments in hyper-spectral remote sensing extended to using a WLL source

Single Particle Scatter Properties (White-light Laser)

Angle, polarization, and wavelength dependent scatter information simultaneously from individual particles

Polarization Ratio of Scattering Phase Function

Forward scatter nose less dependent on shape

Backscatter extend to non-spherical particles (T-matrix and Monte-Carlo techniques)

RF Refraction (Emphasis on evaporation duct)

Horizontal Path for definition of the evaporation duct for real time measurements of radar beam propagation characteristics

Acknowledgments

The PSU lidar development, testing, and field investigations have been supported by the following organizations: US Navy through SPAWAR PMW-185, NAVOCEANO, NAWC Point Mugu, ONR, DOE, EPA, Pennsylvania DEP, California ARB, NASA and NSF. The hardware and software development has been possible because of the excellent efforts of several engineers, technicians, and graduate students at PSU in the Applied Research Laboratory and the Department of Electrical Engineering. Special appreciation goes to D. Sipler, B. Dix, Gil Davidson, D.B. Lysak, T.M. Petach, F. Balsiger, T.D. Stevens, P.A.T. Haris, M. O'Brien, S.T. Esposito, K. Mulik, A. Achey, E. Novitsky, G. Li, Sachin Verghese, David Brown, and many graduate students who have made contributed to these efforts. The NE-OPS research investigations have been supported by the USEPA STAR Grants Program #**R826373,** Investigations of Factors Determining the Occurrence of Ozone and Fine Particles in Northeastern USA, and by the Pennsylvania DEP. The cooperation and collaborations with many university and government laboratory researchers are gratefully acknowledged, in particular the contributions of Rich Clark, S.T. Rao, George Allen, Bill Ryan, Bruce Doddridge, Hans Hallen, Zhiwen Liu, Steve McDow, Delbert Eatough, Susan Weirman and Fred Hauptman are particularly acknowledged because of their very significant contributions.