Atmospheric Optical Propagation Determined Using Rayleigh, Raman and Bistatic Lidars

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Goal of this presentation –

Overview of PSU lidar investigations of atmospheric optical properties …

Motivation for this work –

Many systems and applications require better knowledge of the optical propagation along various paths and under a wide range of atmospheric conditions.

The challenge today is to extend our capability <u>from point sensor measurements</u> of the properties of aerosols and airborne particulate matter <u>to path measurements using remote sensing techniques</u> which profile optical properties along any path through the lower atmosphere.

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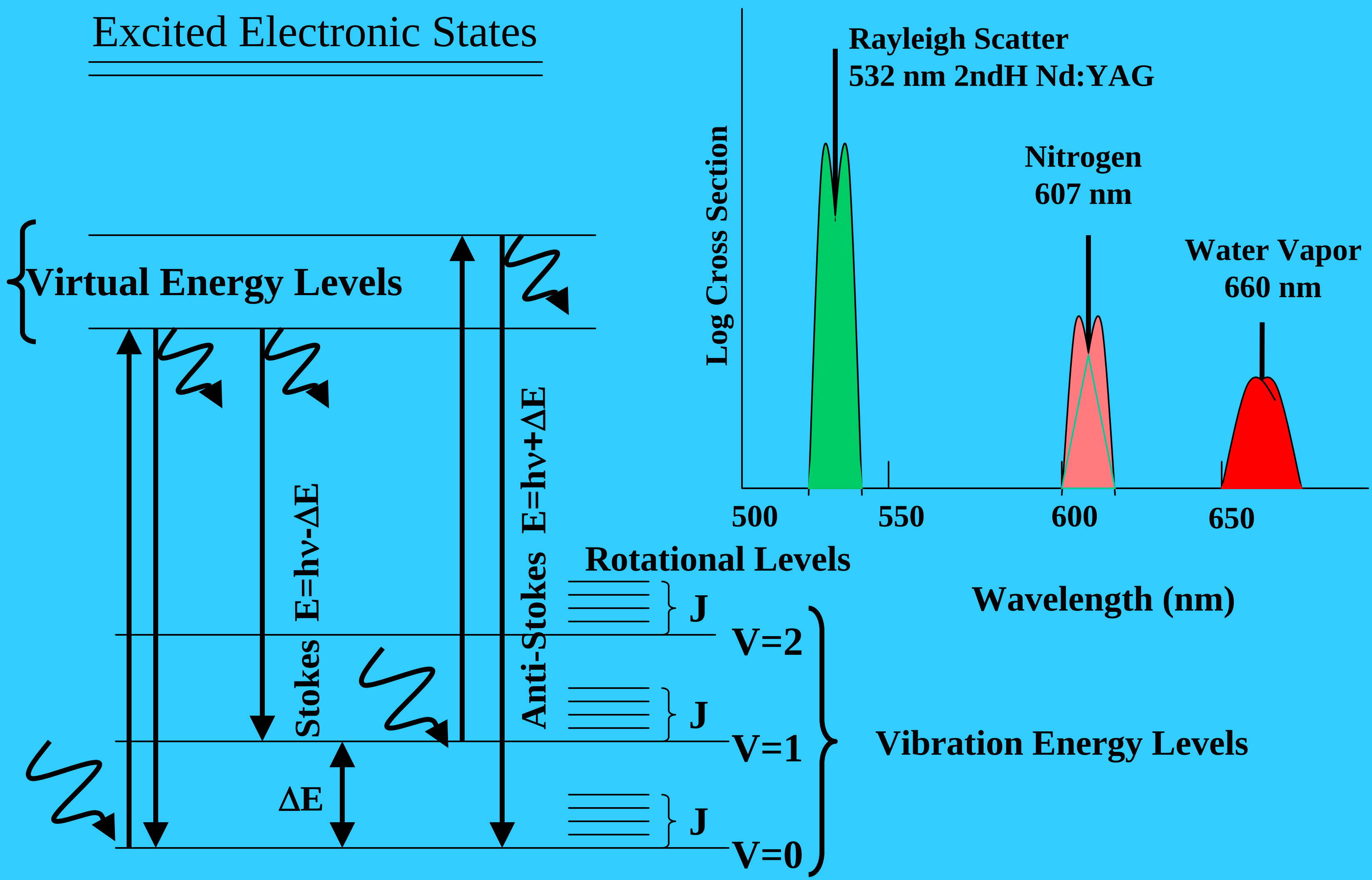
Outline

- Introduction to Raman Scattering
- LAMP and LAPS LIDARS
- Raman Lidar Optical Extinction
- Bistatic and Multistatic LIDAR
- Summary

Raman Scatter



LIDAR Equation *[Measures, 1984]*

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

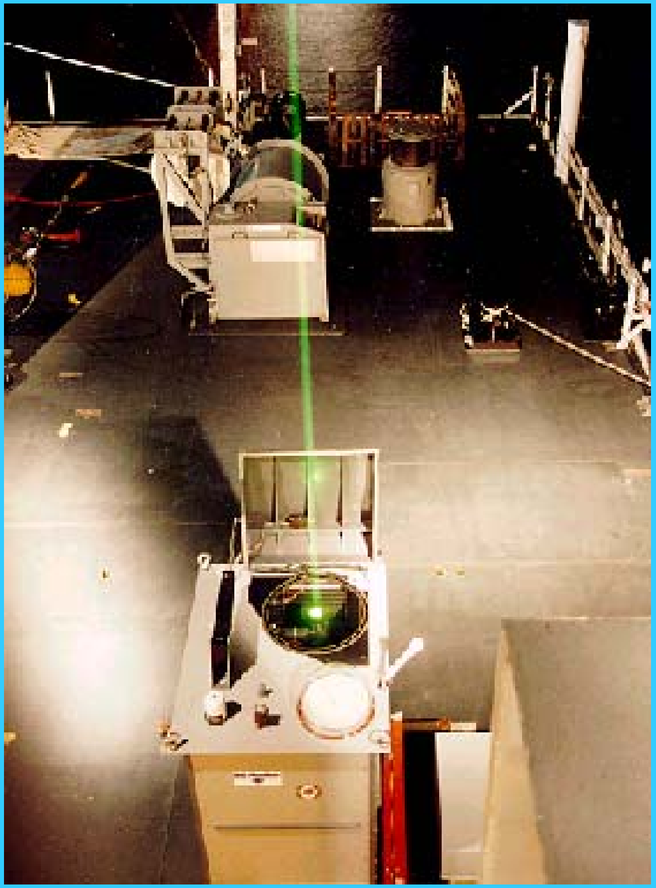
where,

z	is the altitude of the volume element from which the return signal is scattered [m]
λ_T	is the wavelength of the laser light transmitted [m]
λ_R	is the wavelength of the laser light received [m]
$P_T(\lambda_T)$	is the power transmitted at wavelength λ_T [W]
$\xi_T(\lambda_T)$	is the net optical efficiency at wavelength λ_T of all transmitting devices [unit less]
$\xi_R(\lambda_R)$	is the net optical efficiency at wavelength λ_R of all receiving devices [unit less]
c	is the speed of light [m/s]
τ	is the bin width [s]
A	is the area of the receiving telescope [m^2]
$\beta(\lambda_T,\lambda_R)$	is the back scattering cross section of the volume scattering element for the laser wavelength λ_T at Raman shifted wavelength λ_R [m^{-1}]
$\alpha(\lambda,z')$	is the extinction coefficient at wavelength λ at range z‘ [m^{-1}]

Raman Lidar Development

LAMP Lidar

LAPS Lidar



Five generations of Raman Lidar

1st GLEAM (1978)
2nd GLINT (1984)
3rd LAMP (1990)
4th LARS (1994)
5th LAPS (1996)

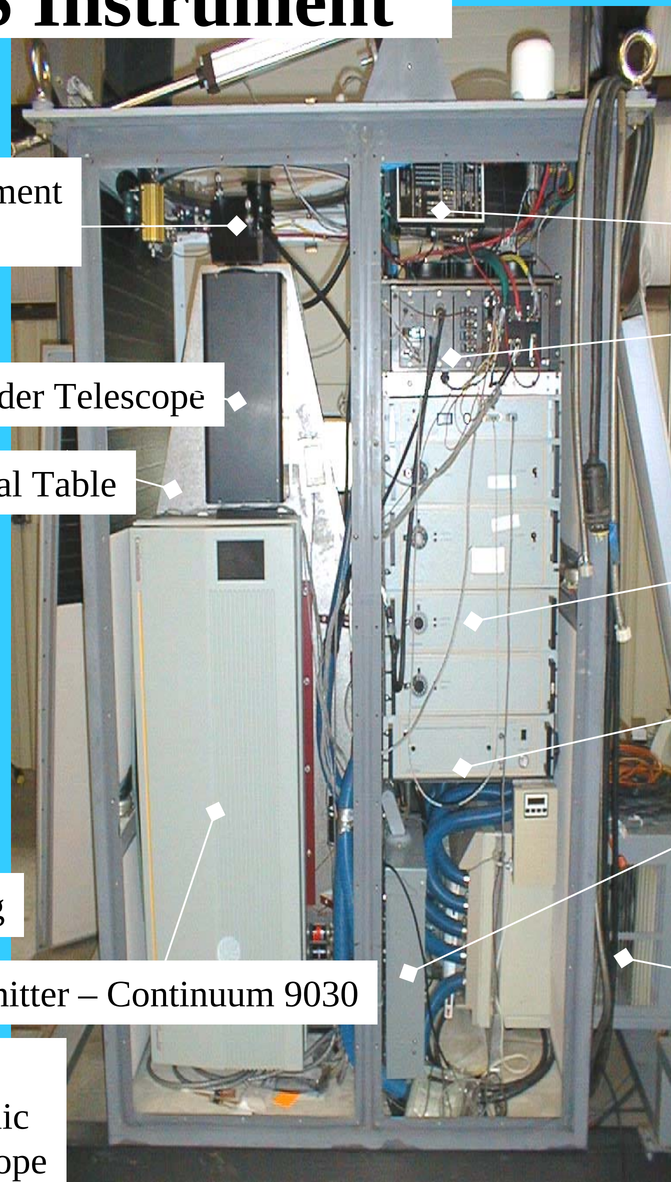
Breadboard Research
Instrument ………….. to ..… Operational Prototype (ADM)

Arctic to Antarctic — **Testing on USNS Sumner**
Testing at Point Mugu — **Advanced Development Model**

LAPS Instrument

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

Backside of LAPS Instrument



LAPS Instrument Characteristics and Measurements

Transmitter	Continuum 9030 (30 Hz) 5X Beam Expander	600 mj @ 532 nm 120 mj @ 266 nm
Receiver	61 cm Dia. Prime Focus Telescope	Fiber optic pickup
Detector	8 PMT Channels Photon Counting	528 + 530 nm – Temperature 660 + 607 nm – Water vapor 294 + 285 nm – Daytime Water Vapor 276 + 285 nm – Raman/DIAL
Data System	DSP 100 MHz	75 m bins (upgrade to 15 meter)
Safety System	Marine R-70 – X-Band	Protect near field and aircraft observers

Property	**Measurement**	**Altitude**	**Time - Resolution**
Water Vapor	660/607 (H_2O/N_2) 294/285 (H_2O/N_2)	Surface to 5 km Surface to 3 km	Night -1 min Day & Night -1 min
Temperature	528/530 Rotational Raman	Surface to 5 km	Night 10 to 30 min
Extinction 530 nm	530 nm Rotational Raman	Surface to 5 km	Night 10 to 30 min
Extinction 607 nm	607 nm N_2 1st Stokes	Surface to 5 km	Night 10 to 30 min
Extinction 285 nm	285 nm $N_2$1st Stokes	Surface to 3 km	Day & Night 10 to 30 min
Ozone	O_2/N_2 (276/285)Raman/DIAL	Surface to 2-3 km	Day & Night - 30 min

Optical Extinction Measurements
Raman Lidar Profiles

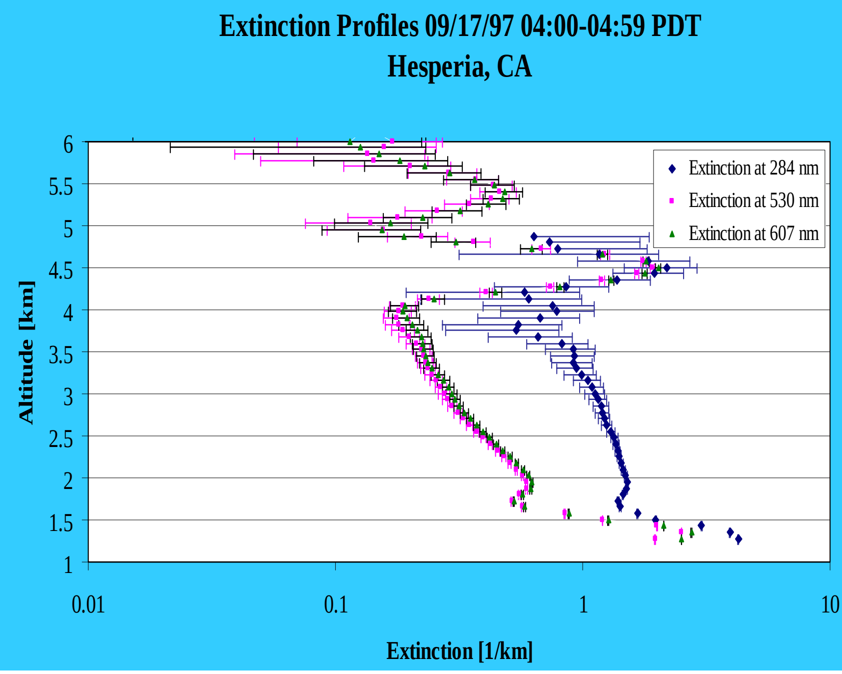
$$\alpha_R^{aer} = \frac{d}{dz}\left[\ln \frac{N_R(z)}{P_R(z)\cdot z^2}\right] - \alpha_0^{mol}(z) - \alpha_R^{mol}(z) - \alpha_0^{aer}(z)$$

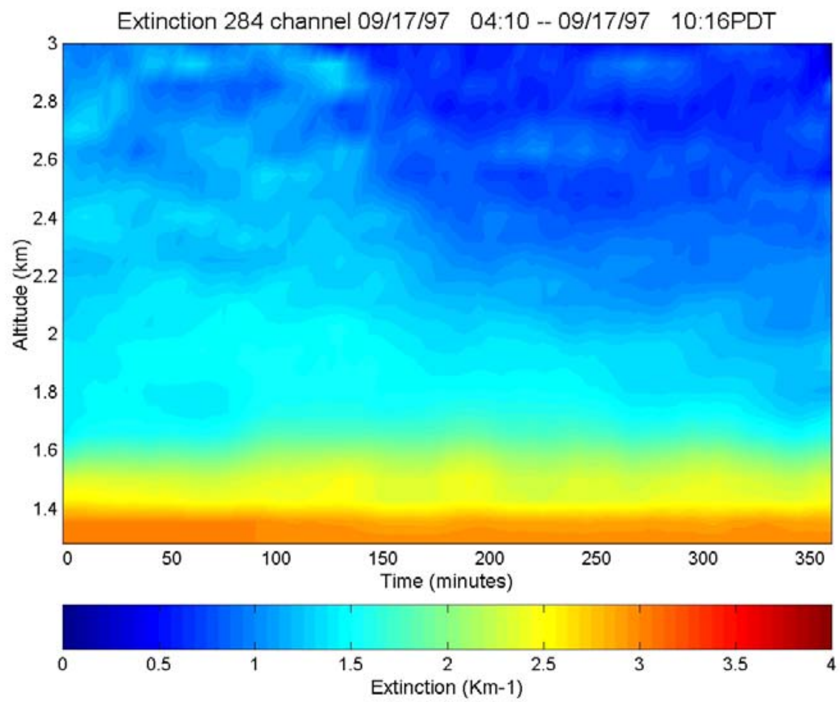
$$\alpha_{532}^{aer} = \frac{d}{dz}\left[\frac{1}{2}\ln \frac{N(z)}{P_{530}(z)\cdot z^2}\right] - \alpha_{532}^{mol}(z) \quad .$$

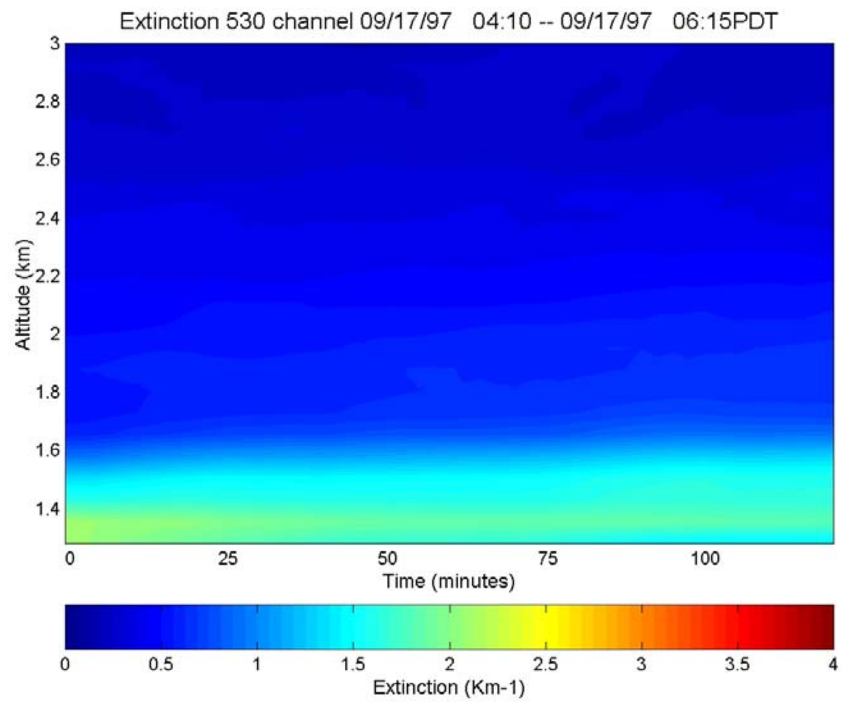
O - outgoing - 532 or 266 nm

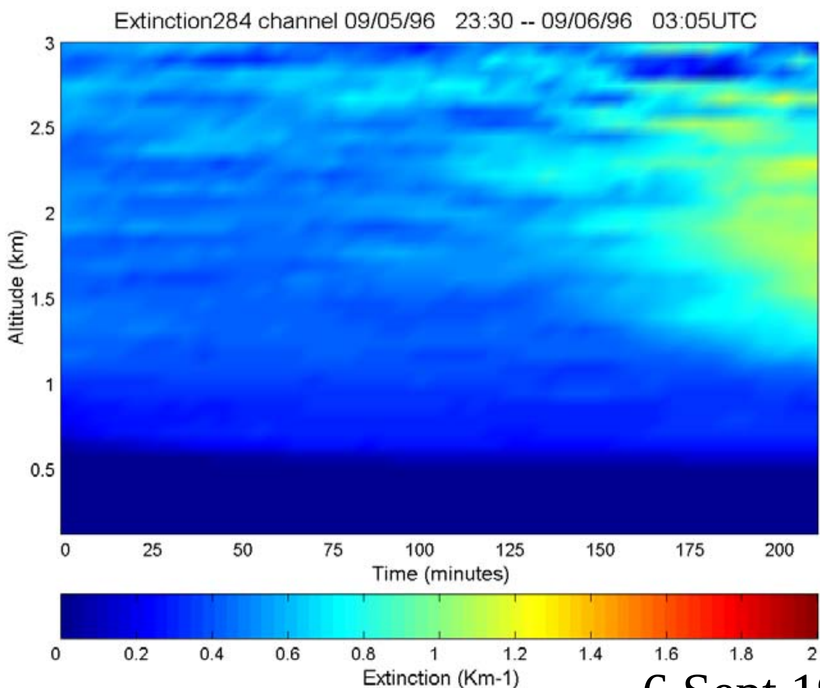
R - return - 530 (rot), 607 (N_2), 285 (N_2) or 276 (O_2) nm

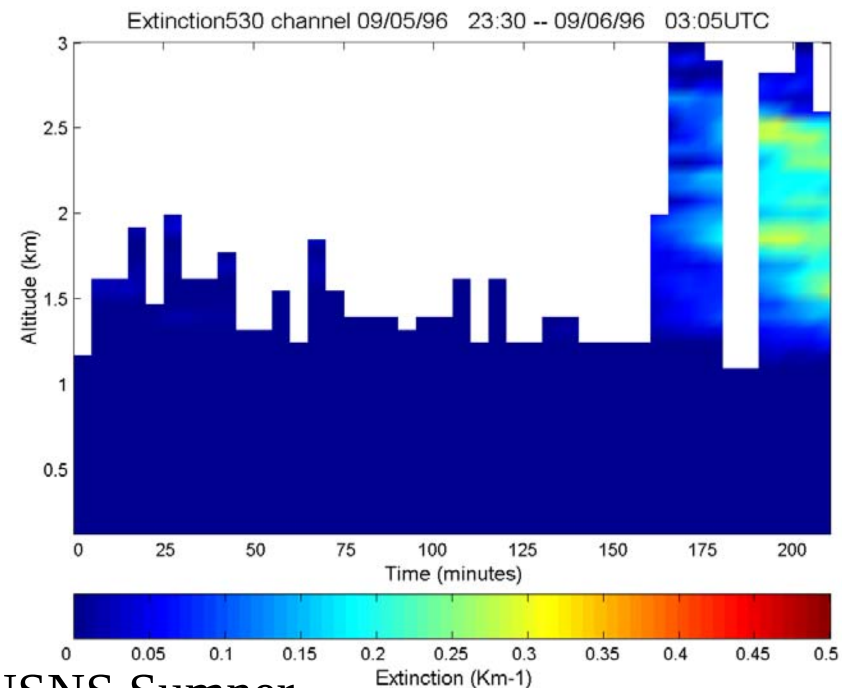
Time sequence and integrated profiles of optical extinction



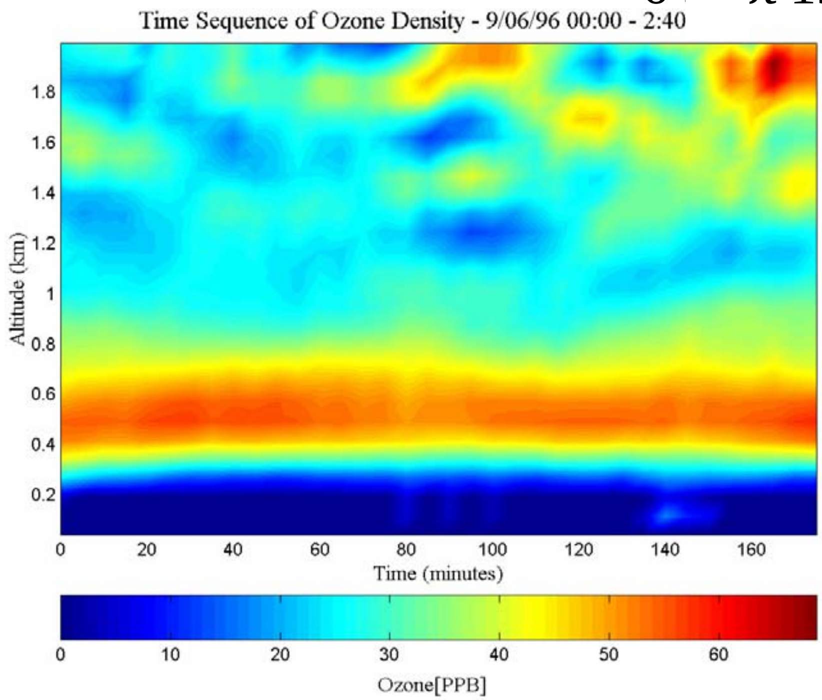


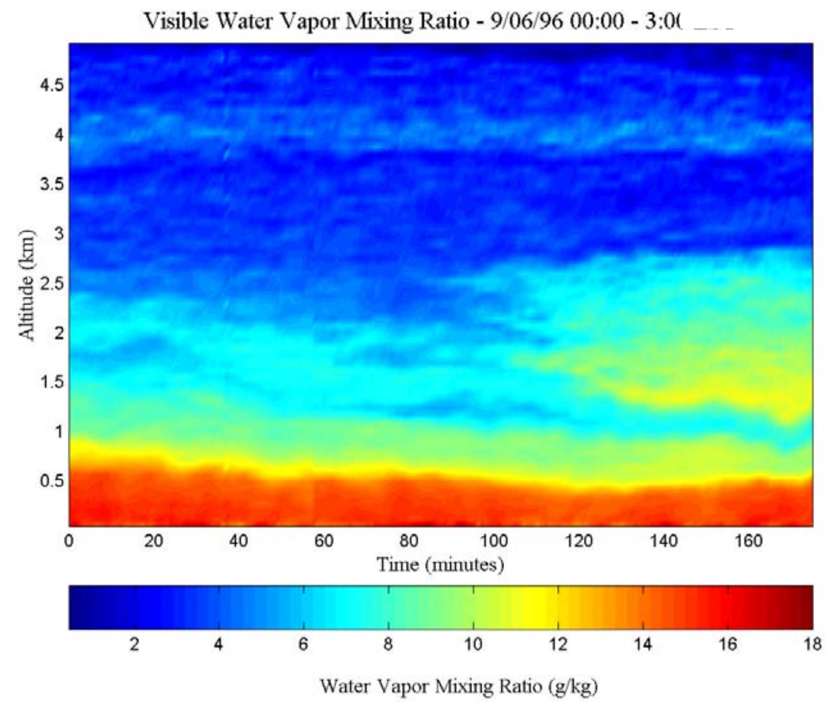




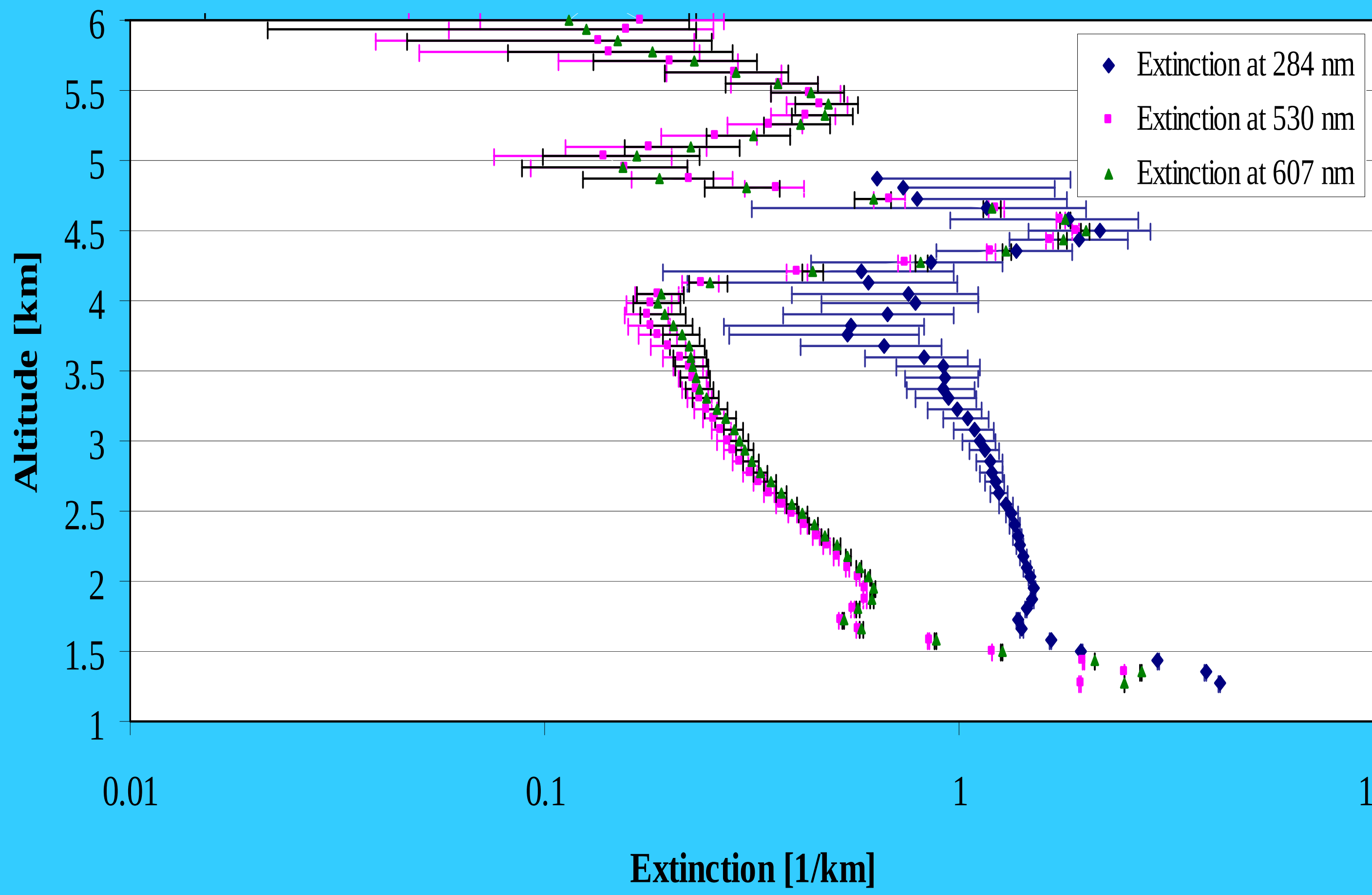


6 Sept 1996 USNS Sumner



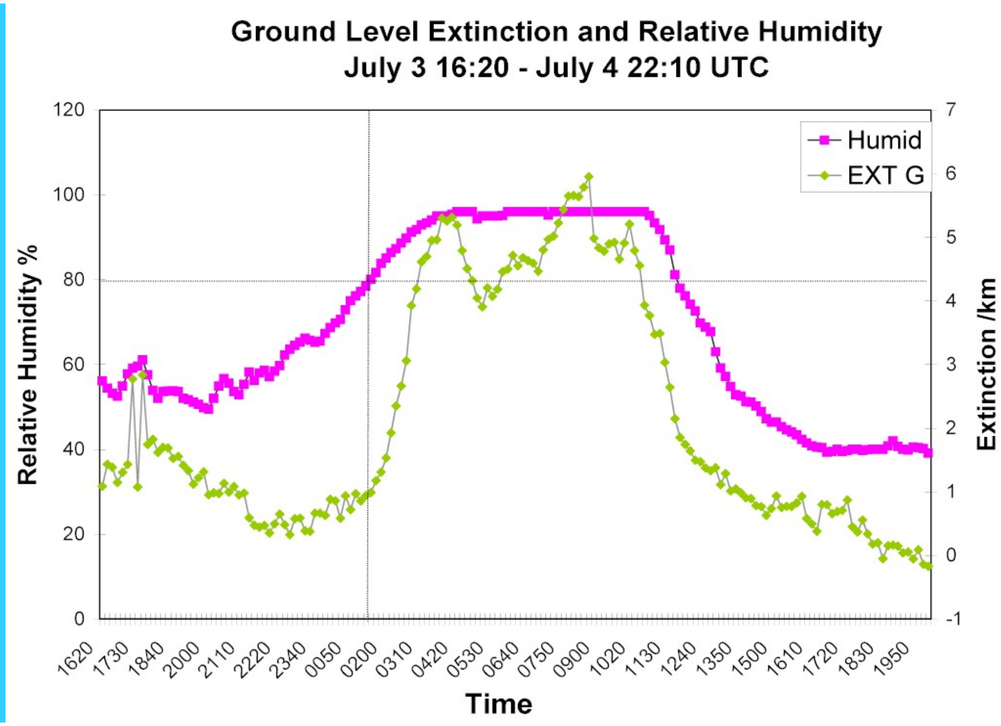


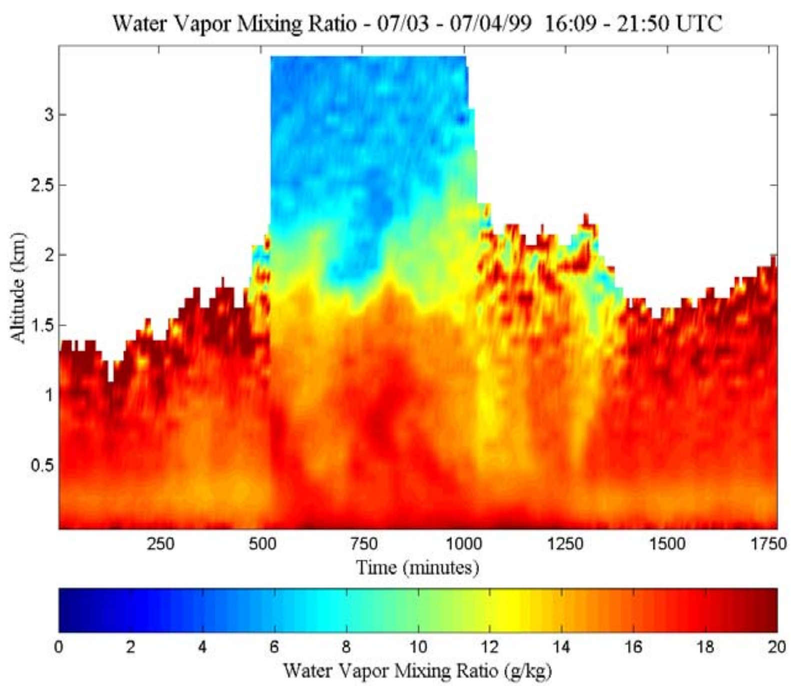
Extinction Profiles 09/17/97 04:00-04:59 PDT
Hesperia, CA

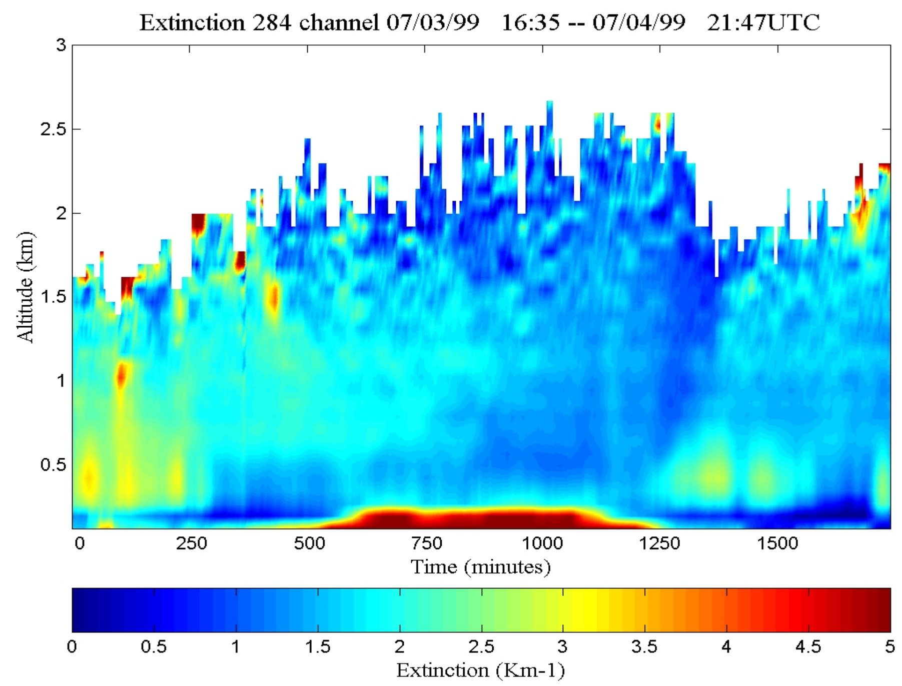


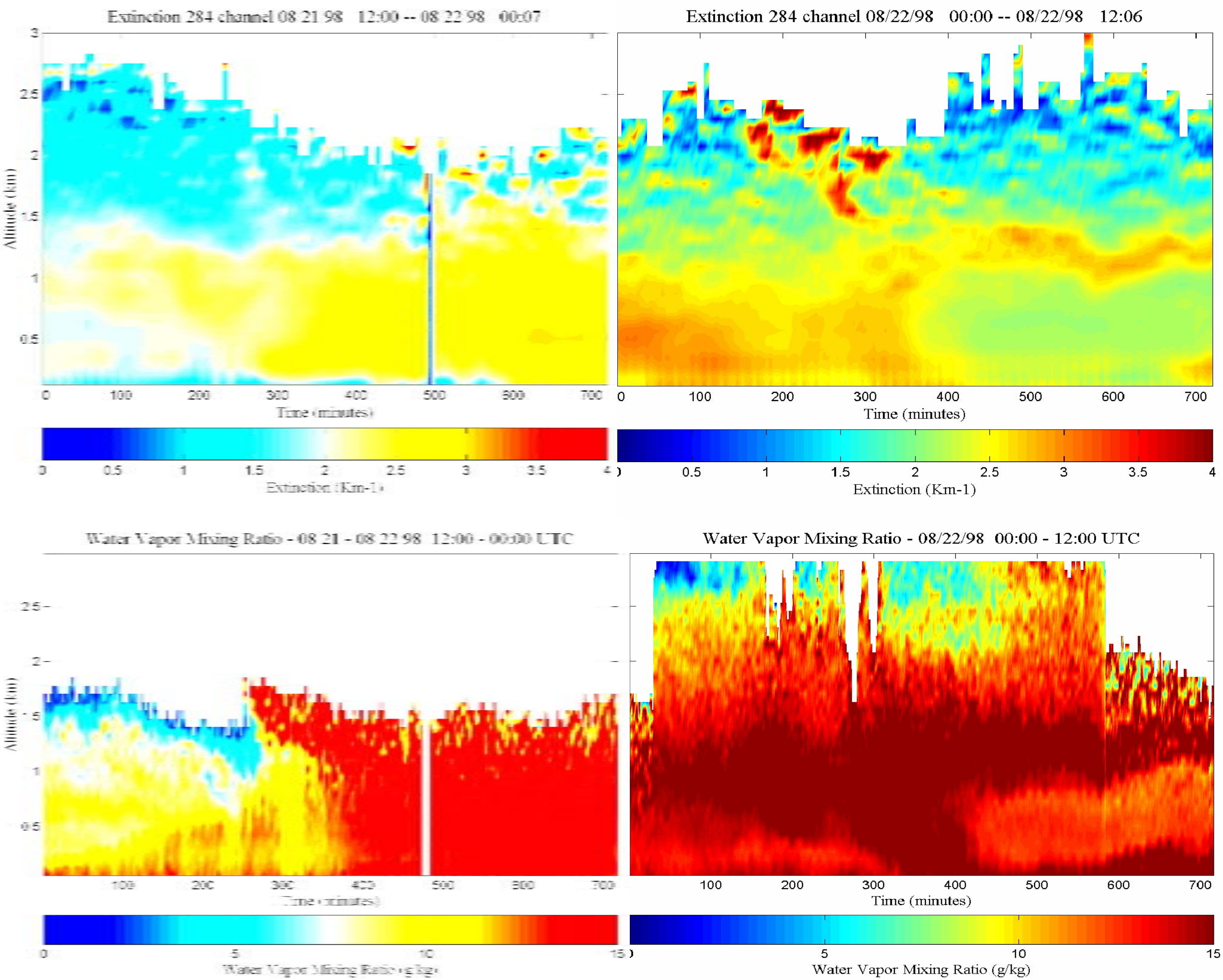
Humidity control of extinction

>80% relative humidity causes striking increase in extinction



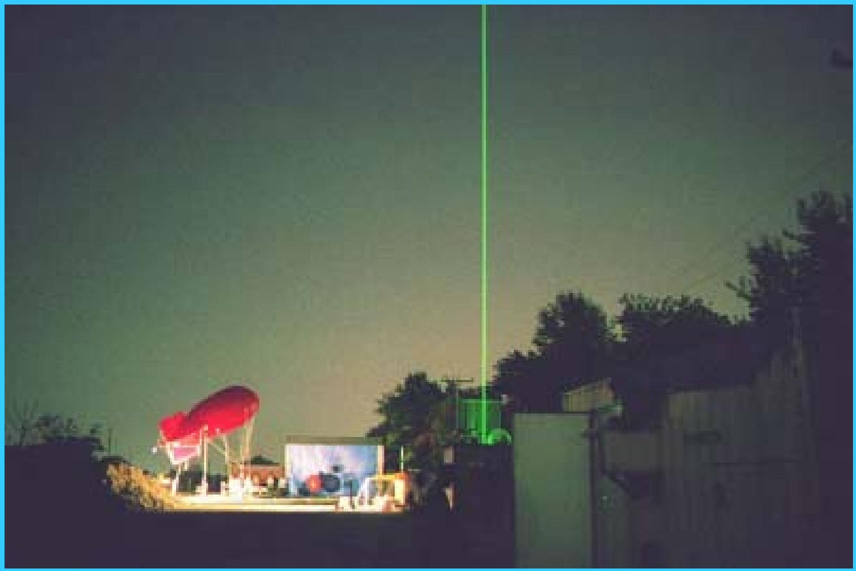






Extinction 284 channel 08/21/98 12:00 -- 08/22/98 00:07
Altitude (km)
Time (minutes)
Extinction (Km-1)
Extinction 284 channel 08/22/98 00:00 -- 08/22/98 12:06
Time (minutes)
Extinction (Km-1)
Water Vapor Mixing Ratio - 08/21 - 08/22/98 12:00 - 00:00 UTC
Altitude (km)
Time (minutes)
Water Vapor Mixing Ratio (g/kg)
Water Vapor Mixing Ratio - 08/22/98 00:00 - 12:00 UTC
Time (minutes)
Water Vapor Mixing Ratio (g/kg)

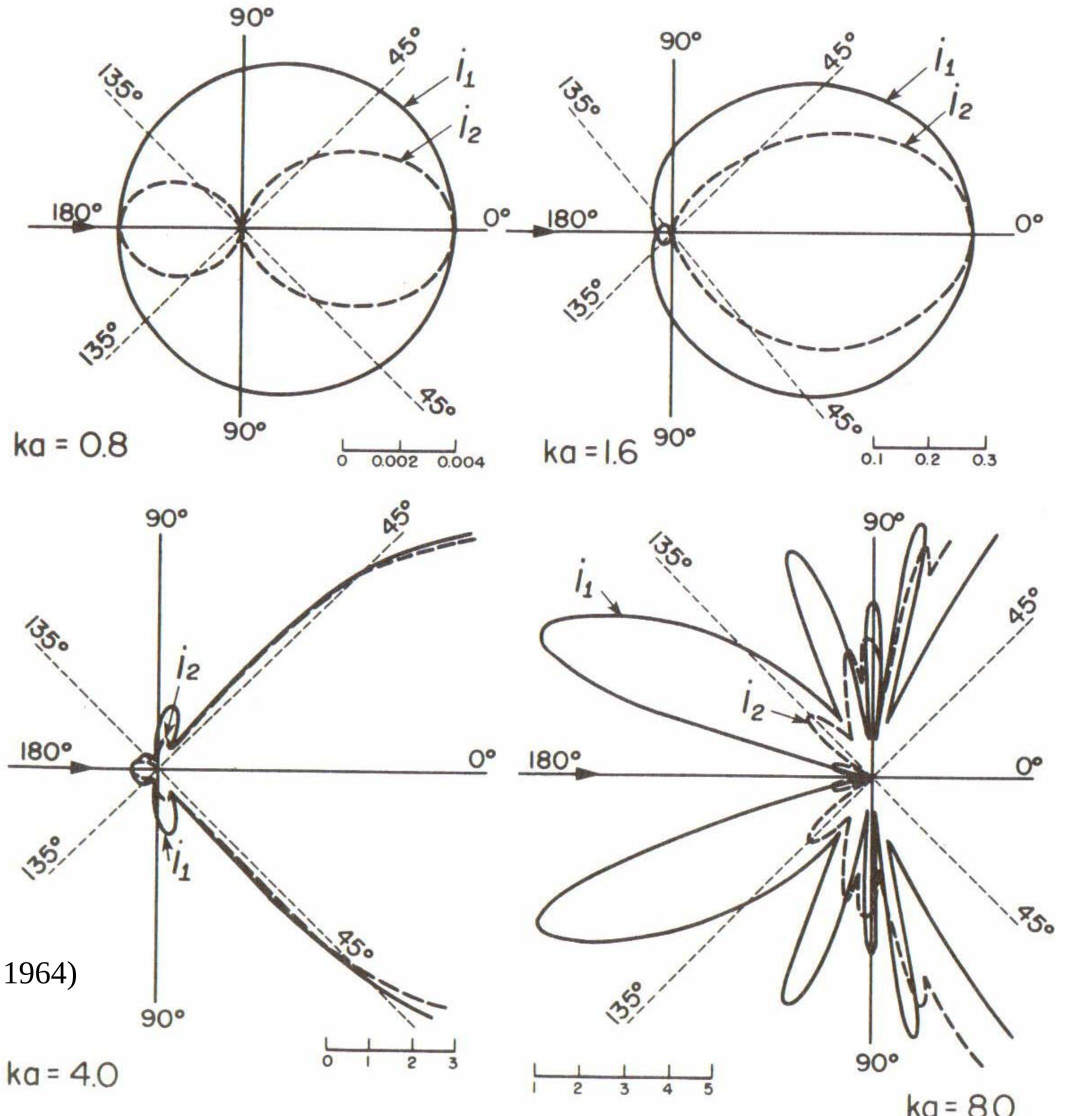
RAMAN LIDAR



- Raman lidar uses signal ratios
  and provides robust technique
- Several important properties
  can be routinely measured -
  - water vapor
  - temperature
  - ozone
  - optical extinction - 530 nm, 607 nm, 285 nm
  - optical backscatter - 532 nm, 266 nm
- Time sequences provide description of the dynamics (1 min time step and 5 min smooth for water vapor and extinction, 10 min time step and 30 min smooth for ozone and temperature)
- Lidar measurements are now capable of providing the data needed to test and validate models and replace balloon sondes

Bistatic and Multistatic Lidar

Scattering Phase Function



(Born and Wolf, 1964)

Pictures of Scattering in Horizontal Path

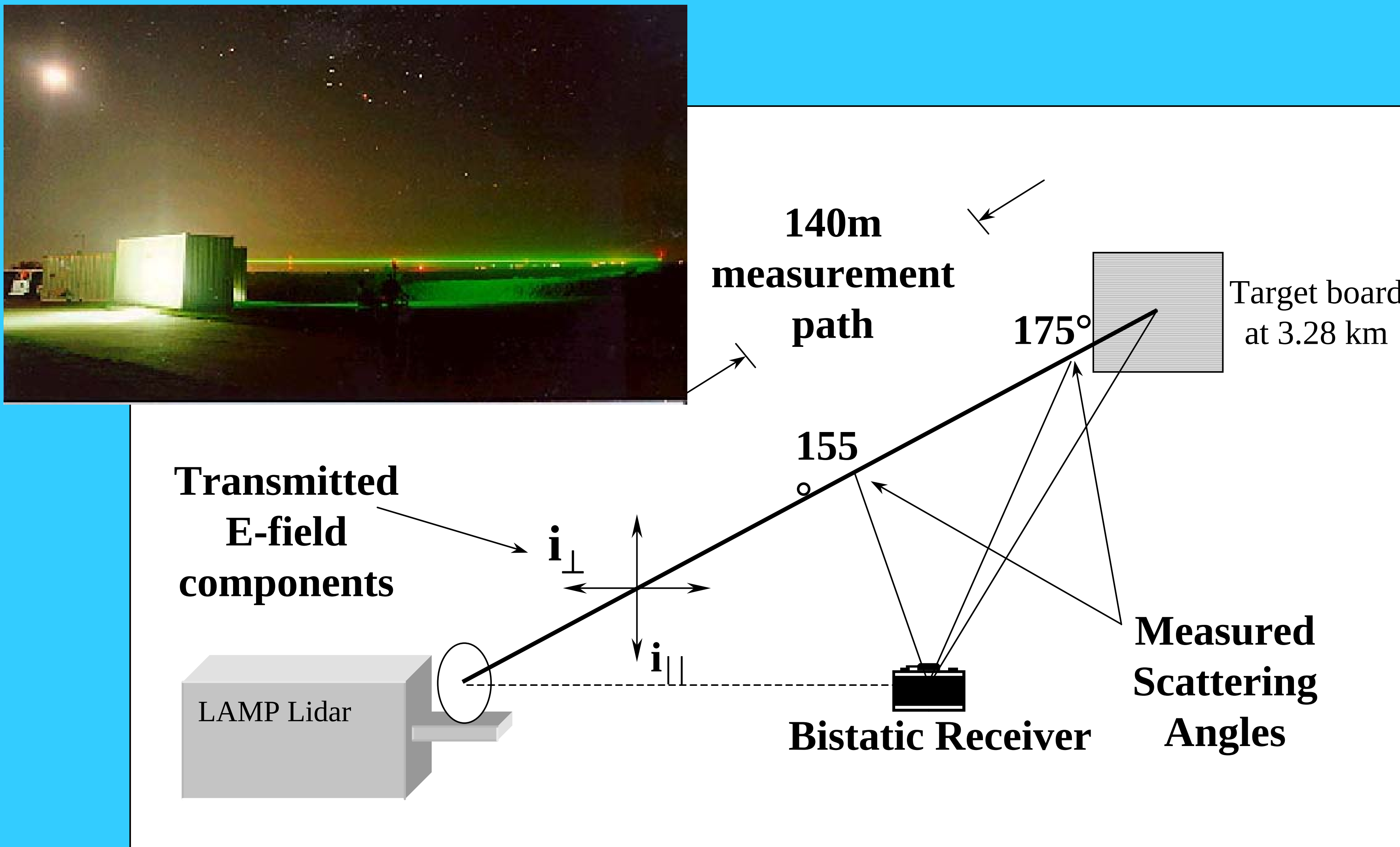
From Laser Looking at Target

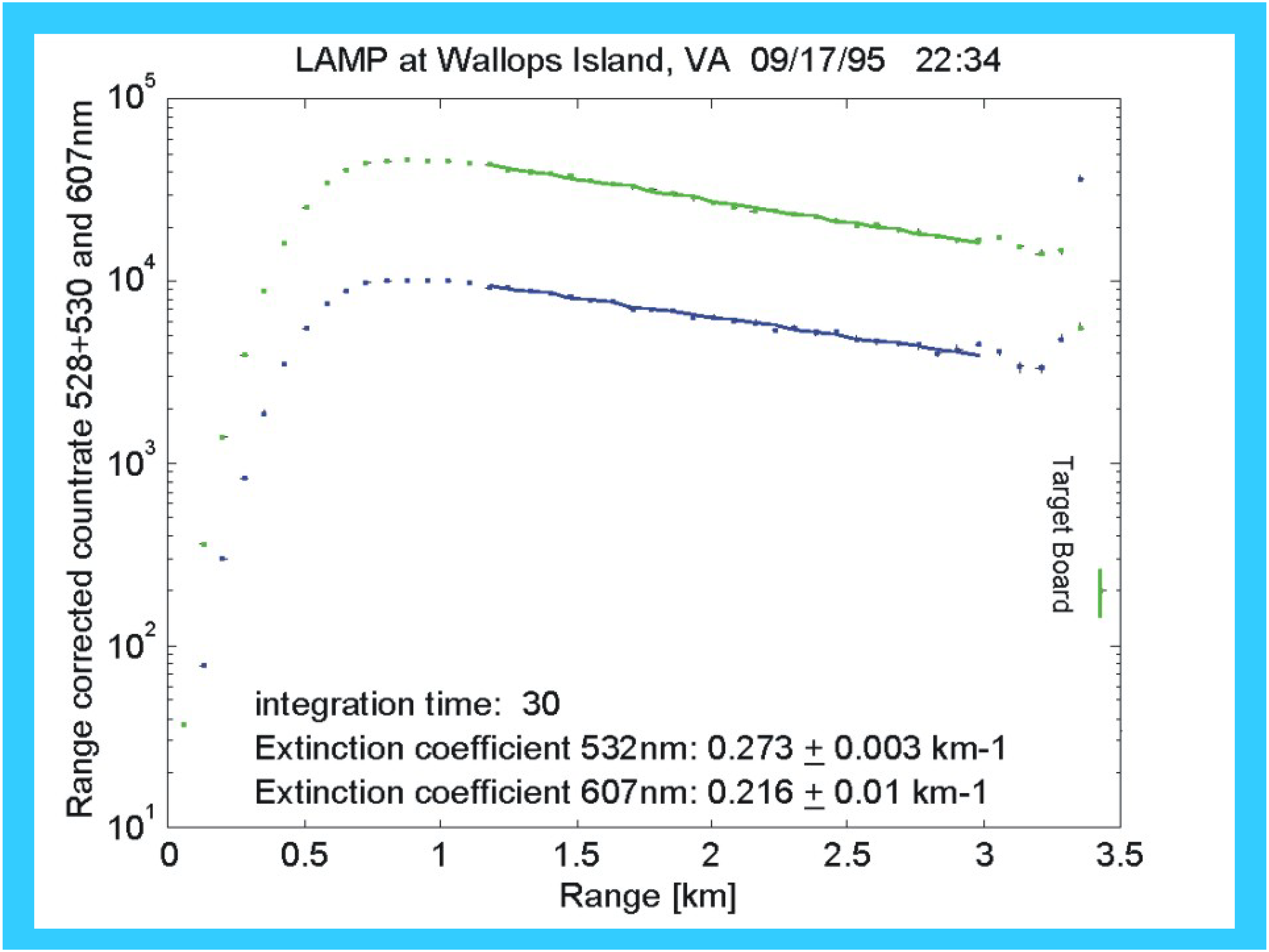
From Target looking at Laser

Looking from Side

Laser scattering from light haze in horizontal 3 km path through stable layer

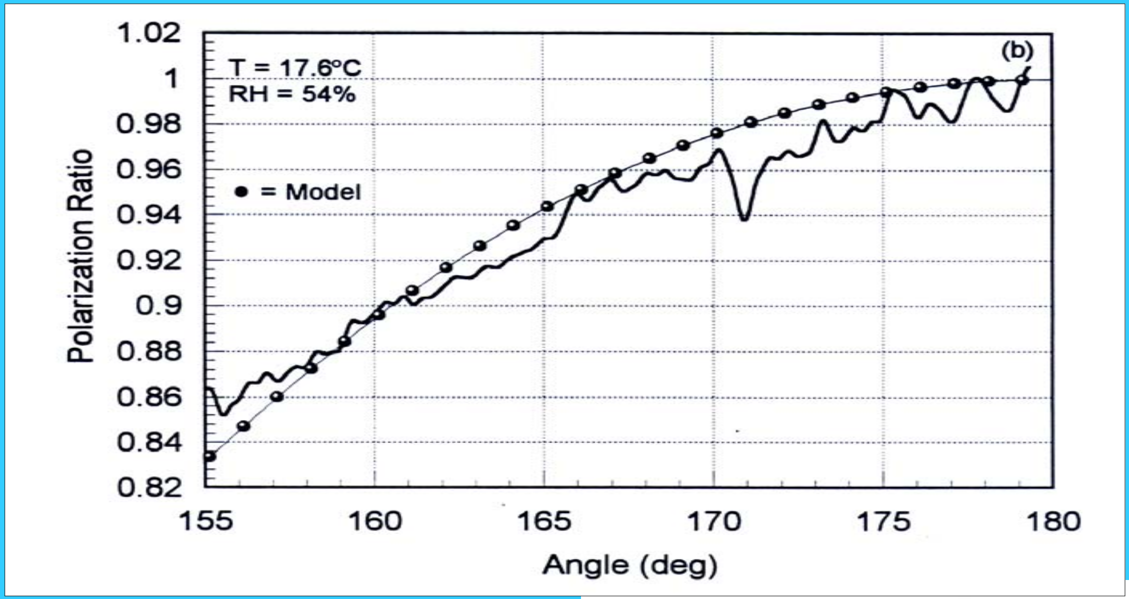
Bistatic Methodology and Equipment





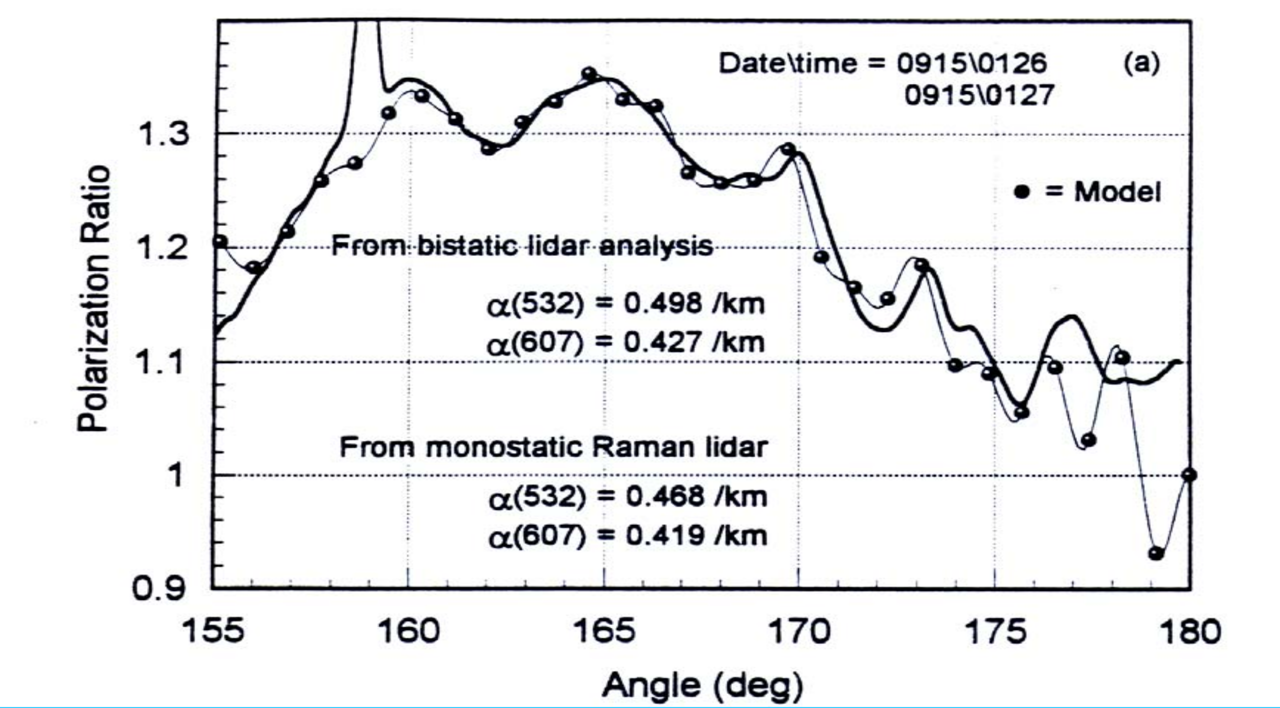
LAMP at Wallops Island, VA 09/17/95 22:34
Range corrected countrate 528+530 and 607nm
Range [km]
Target Board
integration time: 30
Extinction coefficient 532nm: 0.273 ± 0.003 km-1
Extinction coefficient 607nm: 0.216 ± 0.01 km-1

Polarization Ratio from Bistatic LIDAR



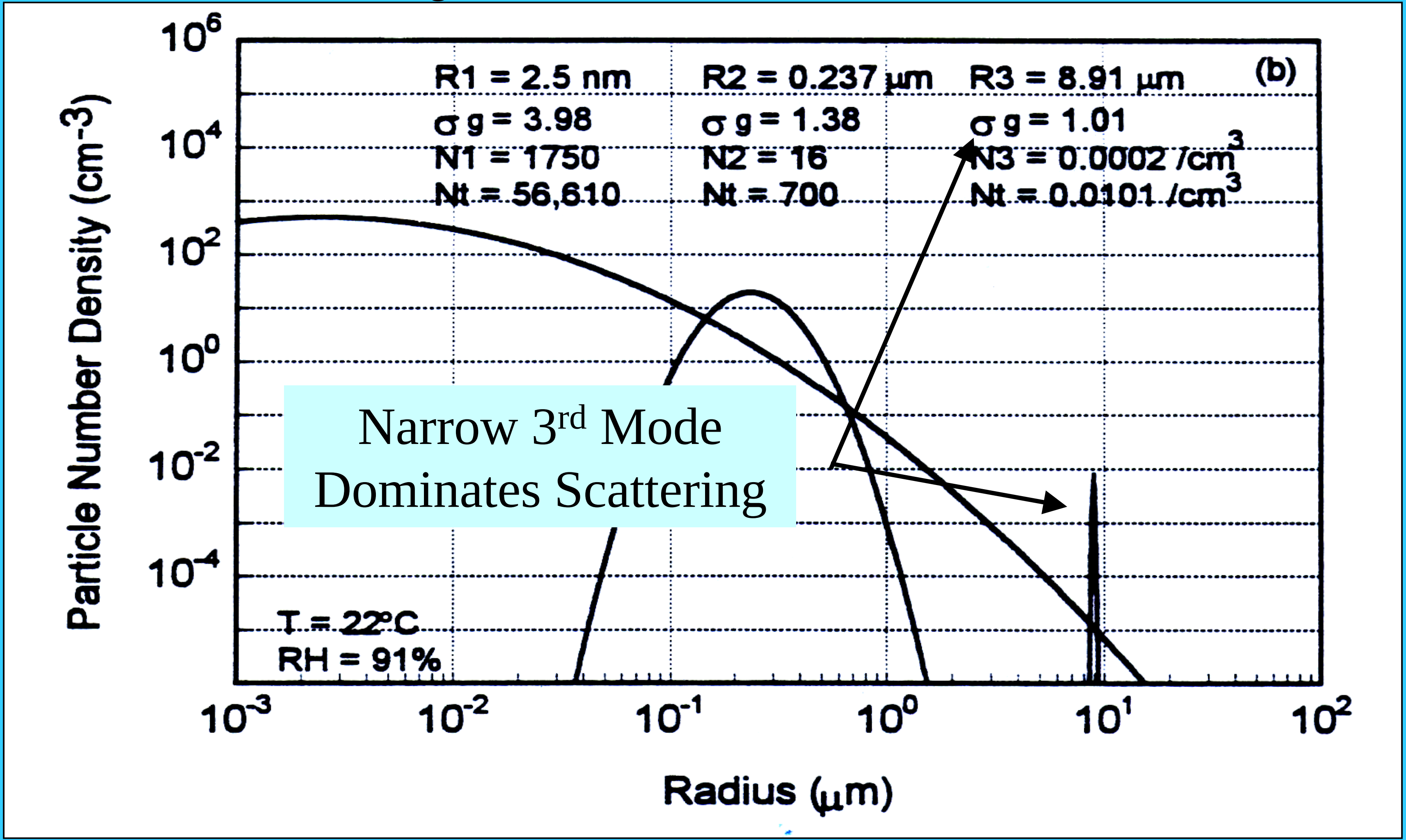
Mostly clear path

Aerosol - Fog



Polarization Ratio Best Fit

- Stevens' Best Fit Lognormal Distribution



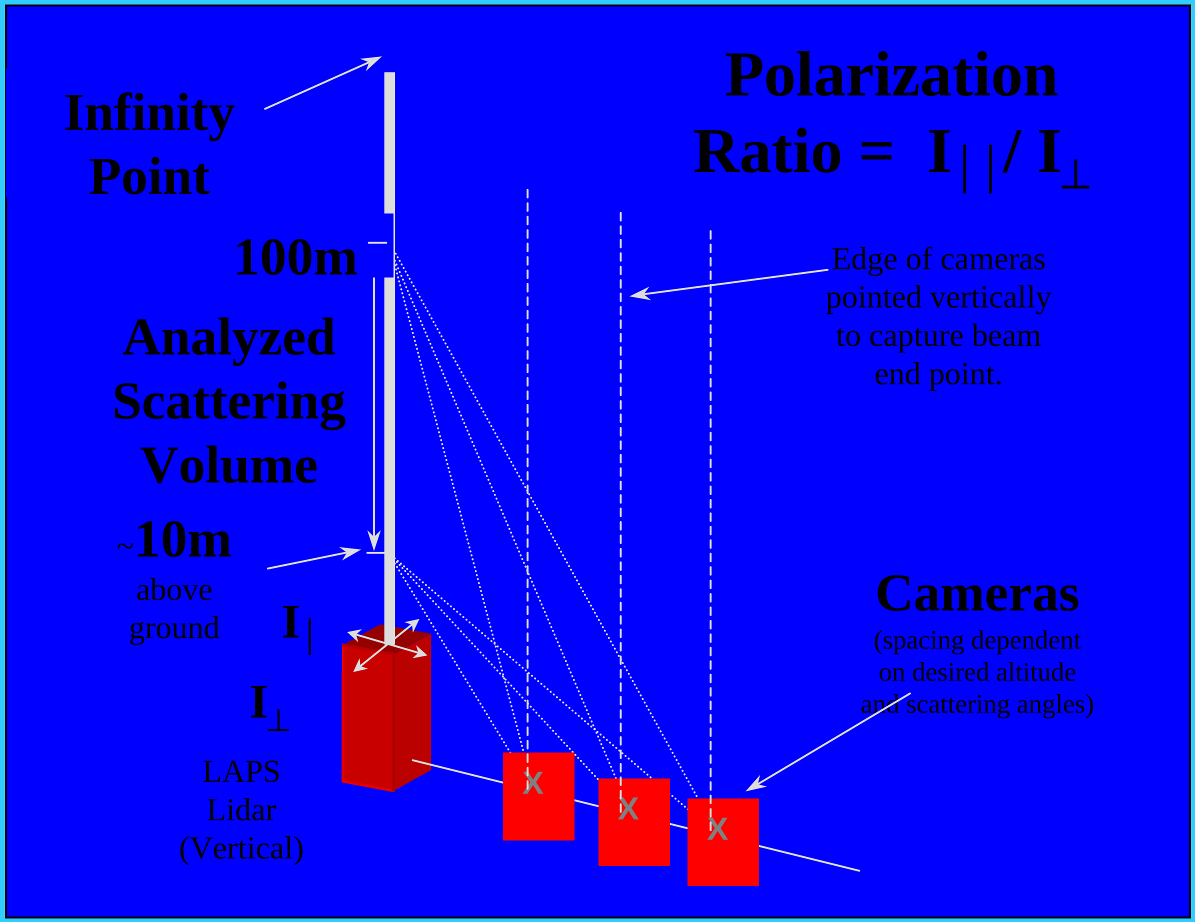
Bistatic Results

- Difficult to find (close) fit with 9 lognormal parameters.
- Good fit in situation with radiation fog.
- Overall, showed reasonable agreement between experiment and theory yet results unverified (no direct particle sizing information).
- Limited to horizontal stratified stable layer

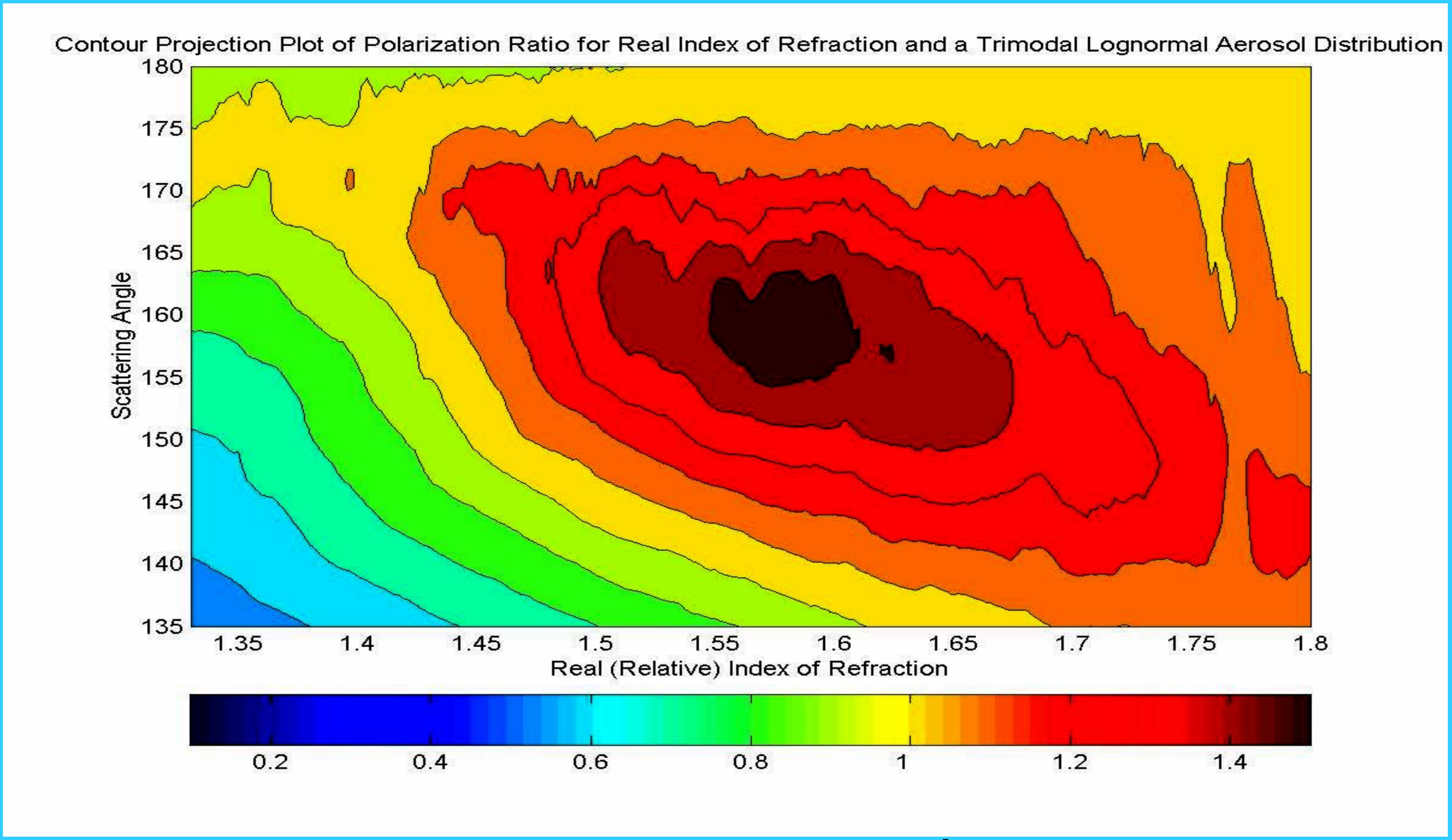
Multi-static Approach

- Several imaging devices (CCD cameras)
  - Vertical path expected uniform, yet stratified.
- Vertical atmospheric path (profile).
  - Beam end point at infinity.
- Mie scattering theory & lognormal distributions primary modeling tools.
- Index of refraction variable.
  - Must investigate effect in scattering theory

Multi-static Pictorial Representation & Test Arrangement (July 2001)

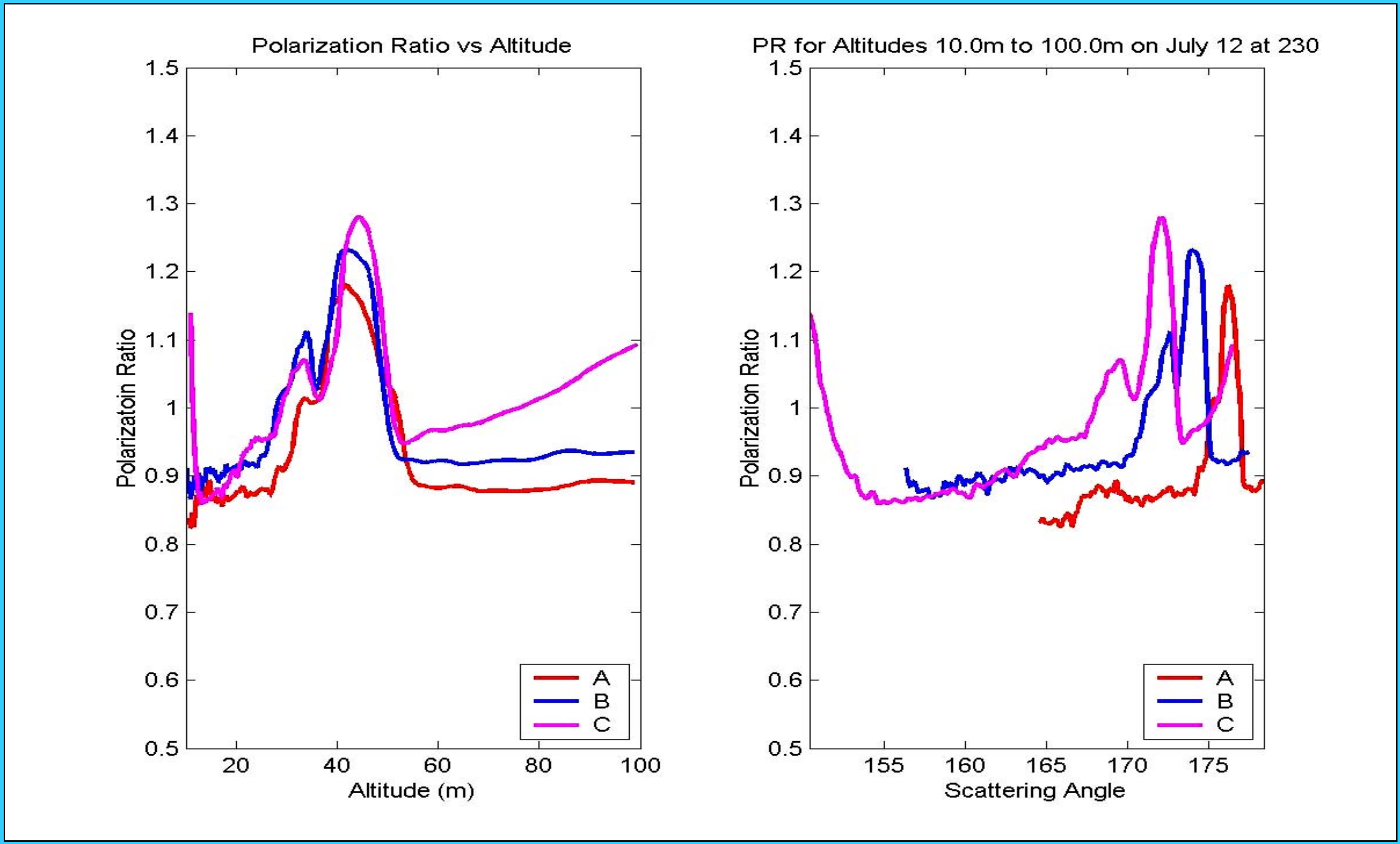


Index of Refraction Projection

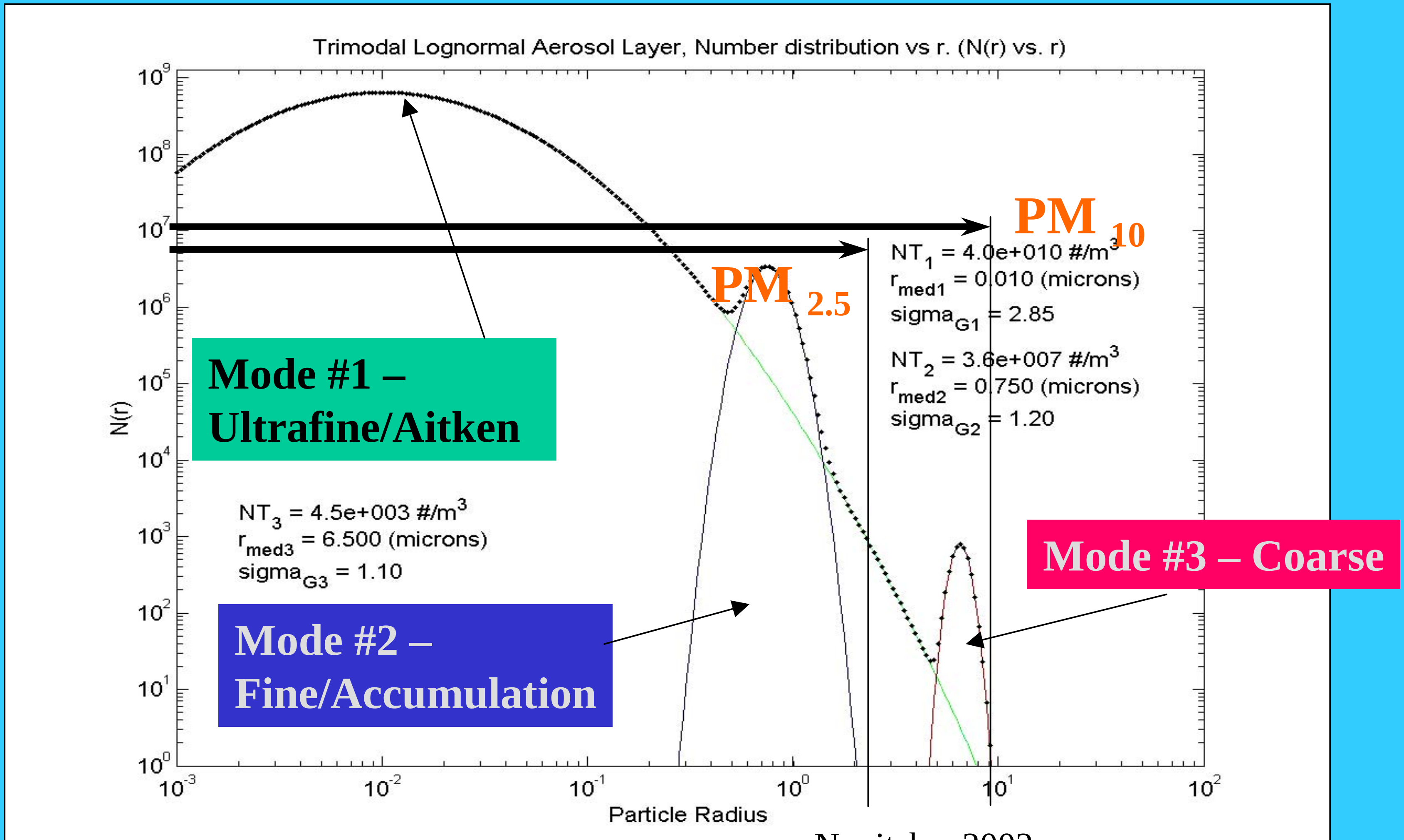


Novitsky, 2002

Results – July 12, 2001 - 2:30am

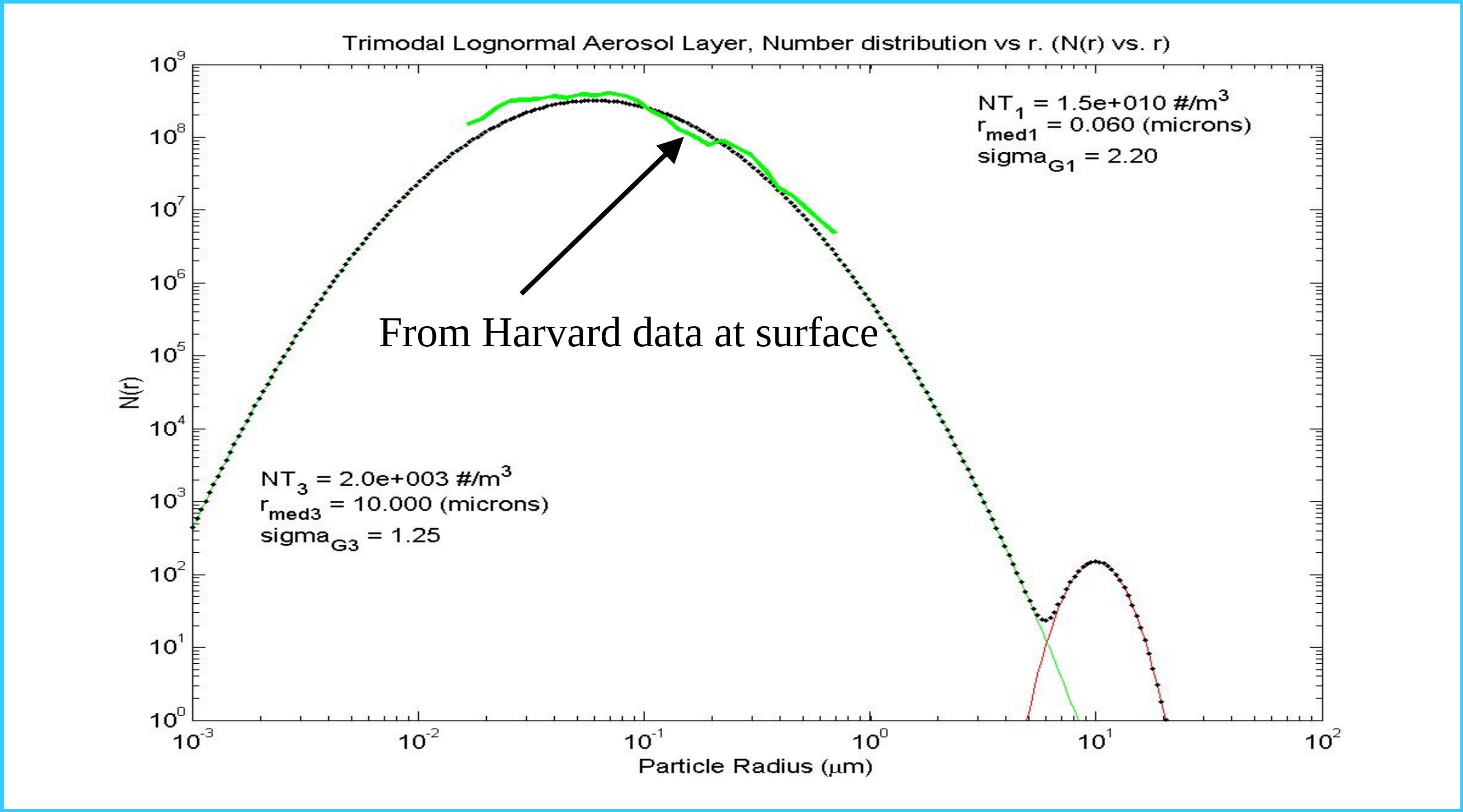


Trimodal Lognormal Distribution



Novitsky, 2002

Particle Sizing Information



Summary of Altitude Dependence & Inversion Using Multistatic Lidar

- Produced a plausible model with features similar to observations.
- Exact nature of altitude dependence on aerosol distributions unknown (may vary by number, size, distribution width, index or combination).
- Can still obtain aerosol parameters if uniform mixing of atmosphere.
- Process for obtaining particle size information (lognormal parameters) from light scattering data has been tested.
- No automated algorithm available (yet).
- Must rely on supporting information to make reasonable assumptions until additional measurements and evaluation are completed.
- Altitude structure complicates inversion.

Summary

Raman Lidar has been demonstrated to provide important 3-D characteristics of the meteorological and air quality properties: Ozone, Water Vapor, Optical Extinction, Temperature

Combining the Raman Lidar data with other measurements, such as Doppler radar, provides a complete set of results for testing model predictions, evaluating dynamical processes (vertical and horizontal), investigating turbidity, obtaining optical extinction profiles and describing the meteorology of the lower atmosphere.

Raman Lidar is expected to provide the replacement for balloon sondes with improved temporal and spatial resolution in the near future.

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Acknowledgments

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