LIDAR DETECTION OF PARTICULATE MATTER:

OVERVIEW AND APPLICATION TO AUTOMOTIVE EMISSIONS

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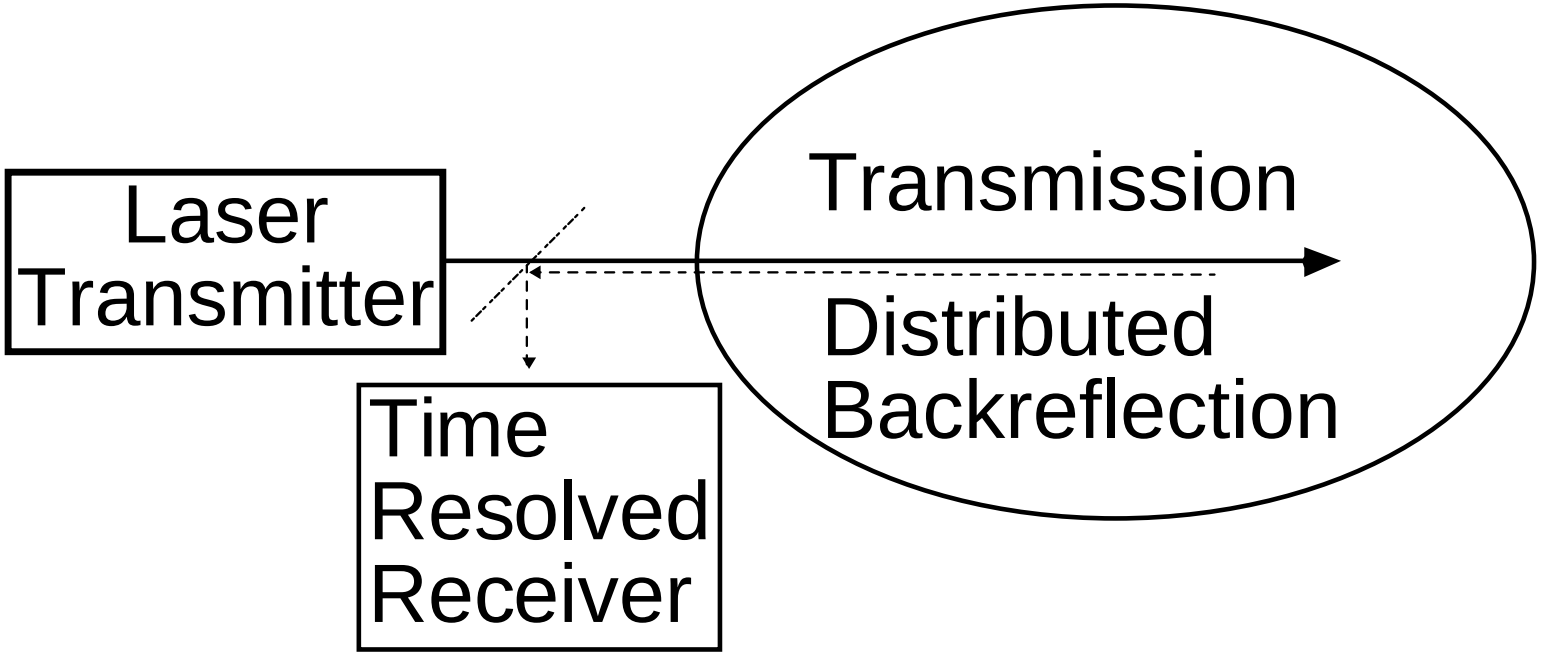
LIDAR Principle



Spatially Resolved Measurement Along Line (1-D)

r = c/2 t

Scanning => 2-D or 3-D Measurements

$$S(r) = C\,T(r)\,\beta(r)$$

LIDAR Equation

$$S(r) = C\,T(r)\,\beta(r)$$

- For each distance r, there are two unknowns T(r) and β(r), but only one measurement S(r)
- If extinction and backscatter can be related, and C is known, equation may be solved (Klett Inversion)
- If either T(r) or β(r) are well known, the other quantity can be determined

Distributed Backreflection

- **Particle Scattering**
  Particle Concentration, Shape , Size(?), Wind Velocity
- **Rayleigh Scattering**
  Atmospheric Density, Temperature, Wind Velocity
- **Raman Scattering**
  Gas Density, Temperature
- **Fluorescence (Quenching!)**
  Atoms, Molecules, Biological Material?

Distributed Return

- **Terra-Watt Femtosecond Laser**
  10^{12}W, 10 - 100 fs = 10^{-13}- 10^{-15} s
- **Nonlinear Effects in Atmosphere**
  1 - 20 km distance
- **Plasma Channel (several 100 m)**
  Self-Focusing, Filamenting
- **White Light Source**
  DOAS in the Sky

Transmission

- **Atmospheric Extinction**
  Visibility, Radiative Transfer,
  Aerosol Size Distribution, Concentration
- **Differential Absorption Lidar**
  Gas Concentrations: e.g., O_3, NO_2, SO_2, Hg, H_2O
  Temperature
  Pressure

Automotive Emissions

- **Dynamometer Testing**
  Few vehicles under a large range of operating conditions
  Applications: I&M, Emission Factors for Inventories and Modeling (e.g., MOBILE, EMFAC)
  Missing: Real Time PM Measurements
- **Remote Sensing**
  Large (10,000/day) number of vehicles under a limited number of operating conditions
  Applications: I&M (Clean Screening & Gross Emitter Identification), Emission Factors for Inventories and Modeling (e.g., MOBILE, EMFAC)
  Missing: PM Measurements

Gaseous Remote Sensing

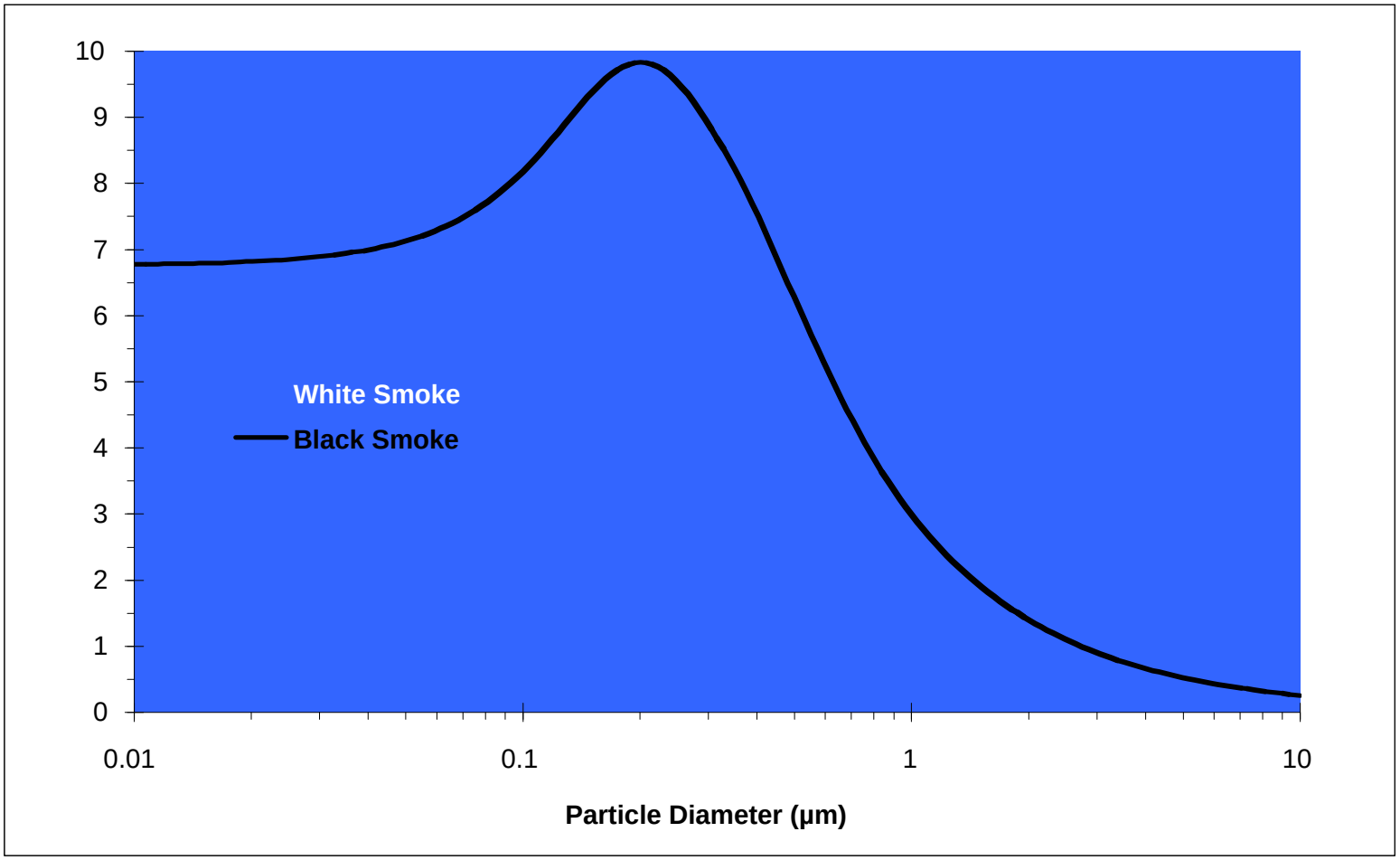
- Pioneered by Stedman & Bishop (DU)
- Commercially Available
- Measures Gaseous Column Content across Road behind Vehicle
- CO_2, CO, NO, HC by IR, UV Absorption
- Ratio to CO2 (& CO, HC) to Obtain Fuel-Based Emission Factor (i.e., g/kg fuel)
- Ancillary Measurements: Speed, Acceleration, License Plate

PM Emissions

- PM Mass Nearly Exclusively Elemental (EC) & Organic (OC) Carbon
- EC: Strongly Light Absorbing (i.e., Black Smoke)
- OC: No Light Absorption (i.e., White Smoke)
- Mass Mean Diameter 0.1-0.2μm
- Not Covered by I&M Programs
  (Exceptions: no visible emissions, Diesel opacity)

  Why is there no PM I&M?

Visible PM Emissions?



Remote Sensing of PM

- IR Extinction: Insensitive Measure of EC
- UV Backscatter: Sensitive to both EC & OC
  Assume Transmission = 1
- UV Extinction: Insensitive Measure of both EC & OC
- Lidar System helps to discriminate against Road Dust and Beam Terminus Signal

LORAX

Lidar **O**n-**R**oad **A**erosol e**X**periment

Bob Keislar (Operation)

Claudio Mazzoleni (Grad. Student)

Peter Barber (Theory)

Hampden Kuhns (CEO)

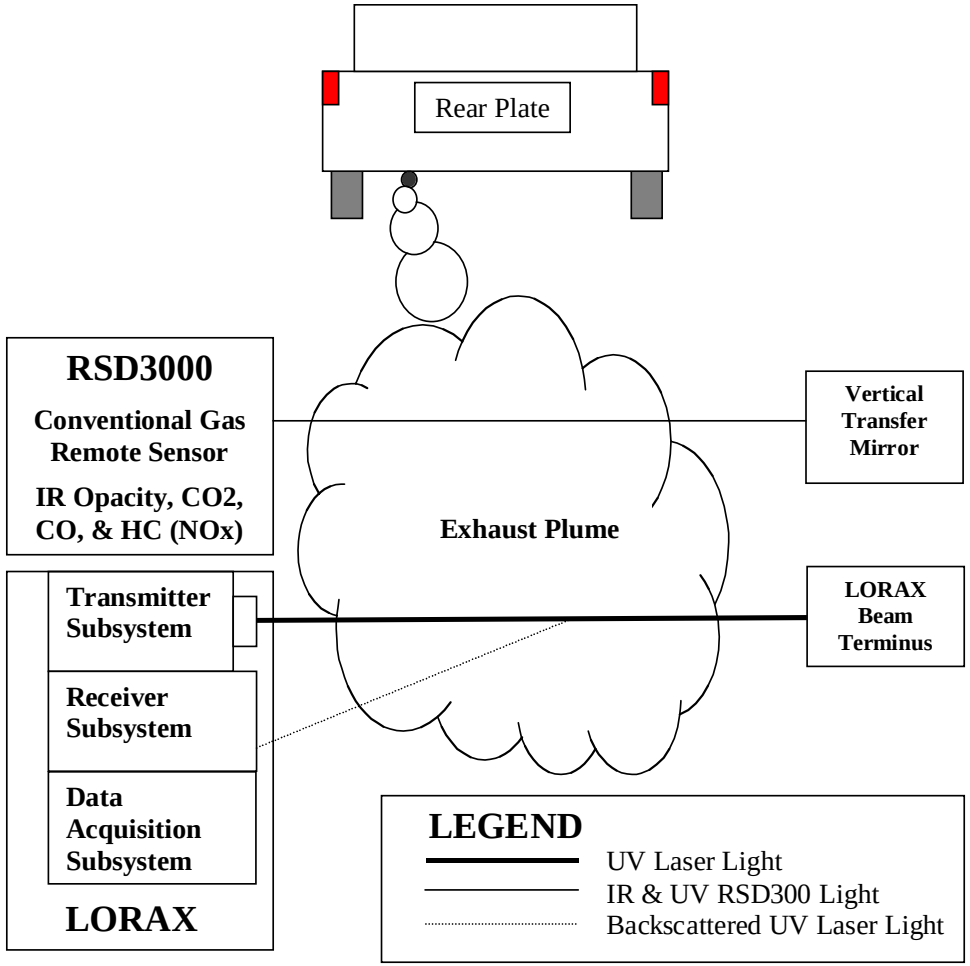
John Watson (PI)

LORAX

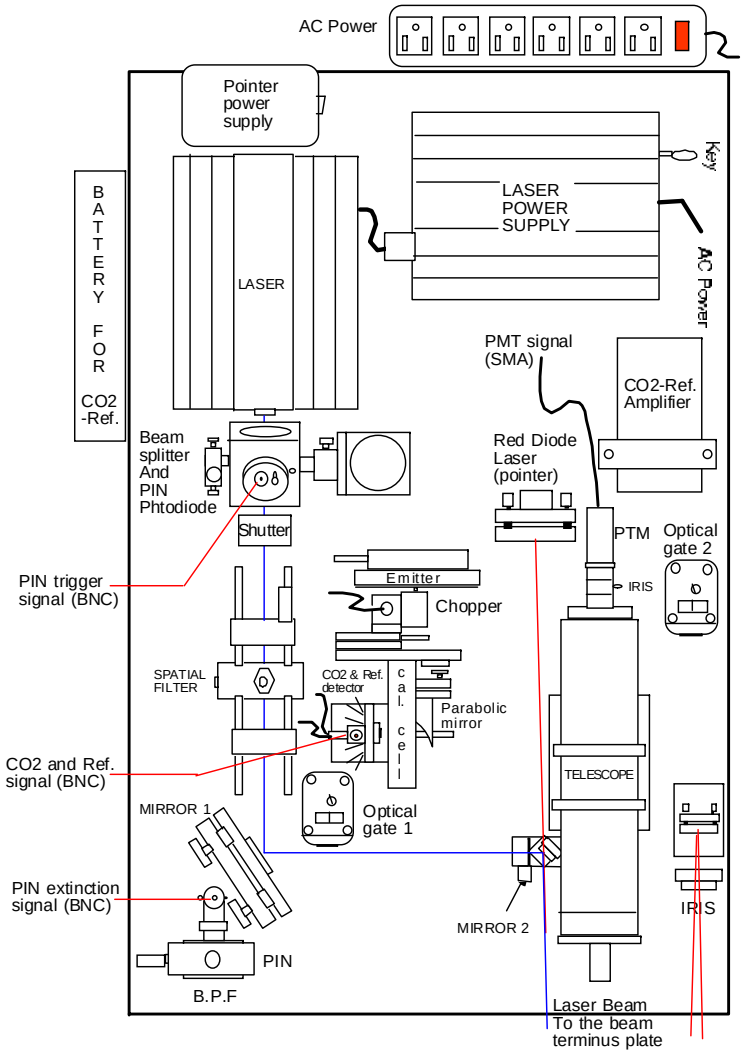
Lidar **O**n-**R**oad **A**erosol e**X**periment

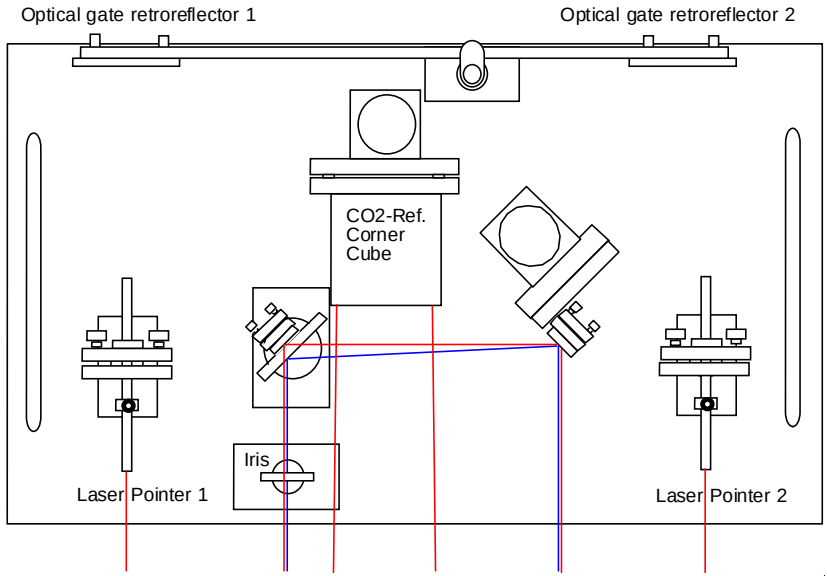
- Transmitter: 266-nm Passively Q-Switched, All Solid-State Nd:YAG Laser (6 kHz PRF)
- Receiver: 2” Telescope with Compact PMT
- Data Acquisition: 8 GS/s, 1.5 GHz Oscilloscope, IEEE 488 Interface to PC Running LabView
- Spatial Resolution: 20 cm

SCHEMATIC

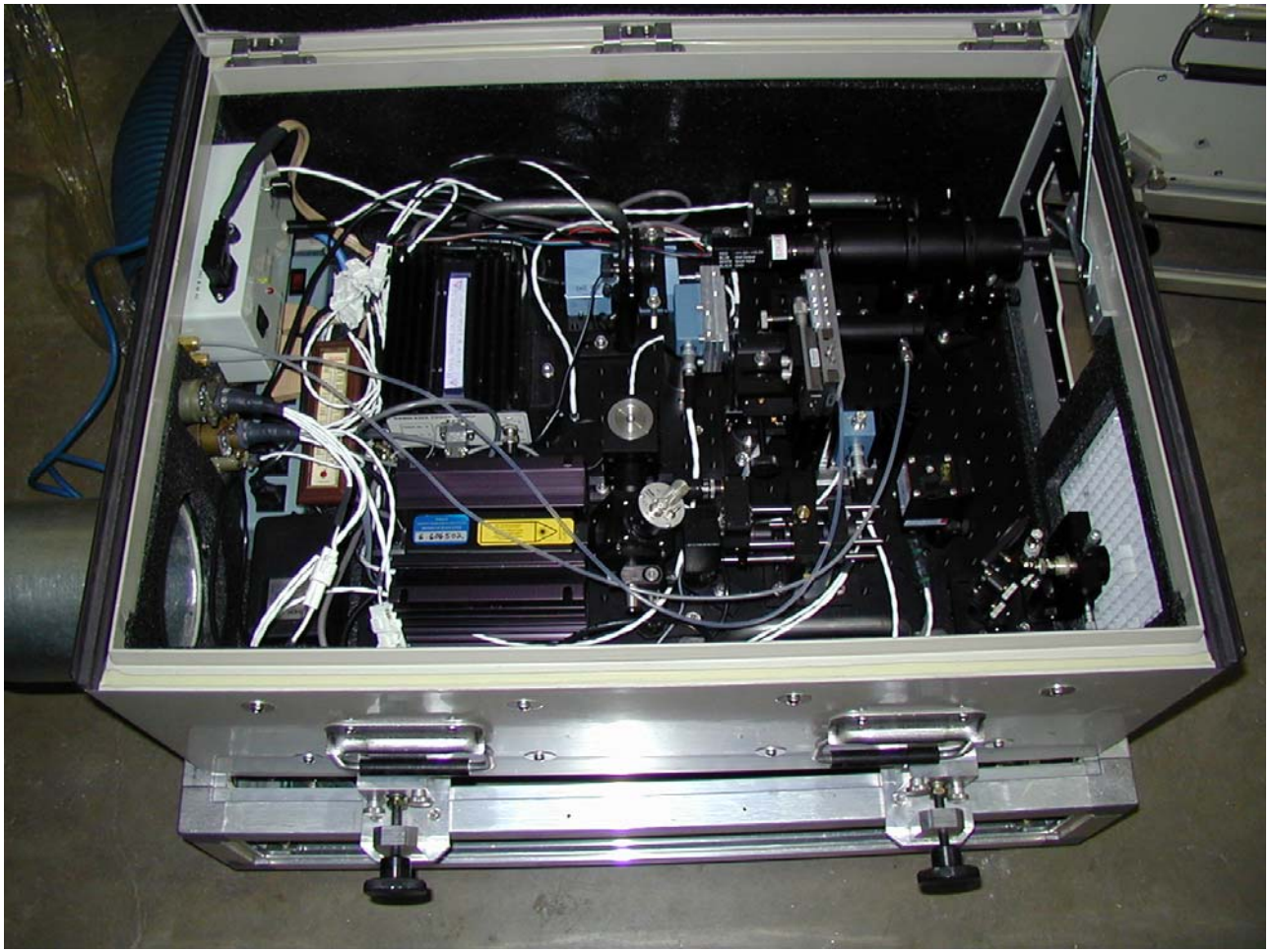

Rear Plate
RSD3000
Conventional Gas Remote Sensor
IR Opacity, CO2, CO, & HC (NOx)
Vertical Transfer Mirror
Exhaust Plume
Transmitter Subsystem
Receiver Subsystem
Data Acquisition Subsystem
LORAX
LORAX Beam Terminus
LEGEND
UV Laser Light
IR & UV RSD300 Light
Backscattered UV Laser Light

Main System & Beam Terminus





Main System



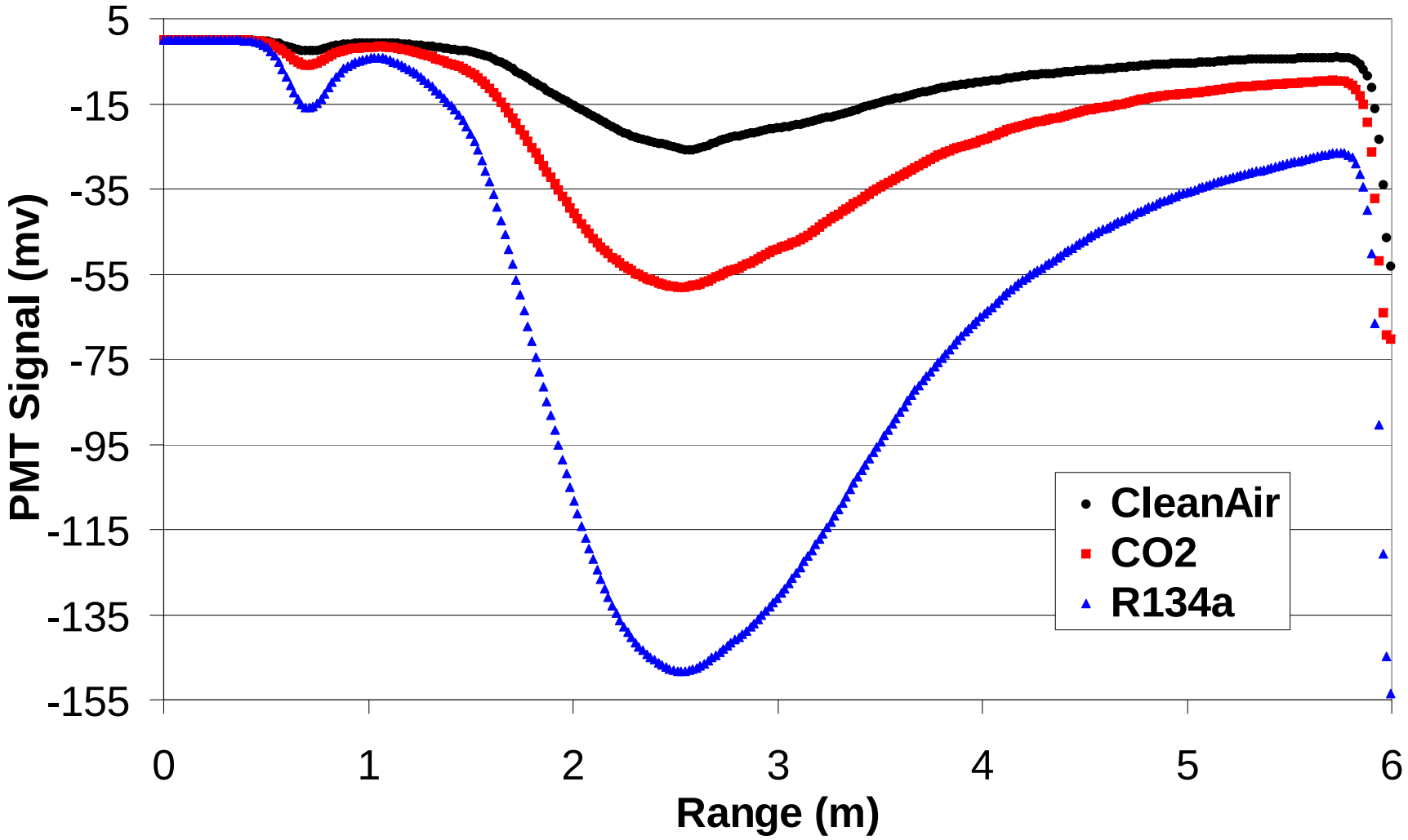
Beam Terminus

On-Road Operation

Lidar Calibration (1)

- 6-m Calibration Tube Filled with Filtered Air (25.5 Mm^{-1}/sr) or CO2 (75.5 Mm^{-1}/sr)
- Calibration Similar to Nephelometer Calibration for each Range Gate
- Results in Absolute Calibration Including Lidar Overlap Correction
- Calibrates LORAX for Measuring PM Backscatter in Units of Rayleigh (1 Rayleigh = 25.5 Mm^{-1}/sr)

Example Gas Calibration



Lidar Calibration (2)

- Convert from PM Backscatter (Rayleigh) to PM Mass Density (g/m^3)
- Define Calibration PM

  LogNormal Size Distribution, Density = 1250 kg/m^3,
  (Mass Mean Diameter = 0.1μm, Geometric Standard Deviation = 1.5 μm)
  Refractive Index: $n_{OC} = 1.5$, $n_{EC} = 1.5 + i\ 0.5$
  PM_{SI}: OC Sphere,
  PM_{Diesel}: Sphere with EC Core & OC Shell of Equal Volume
- Calibration Coefficients

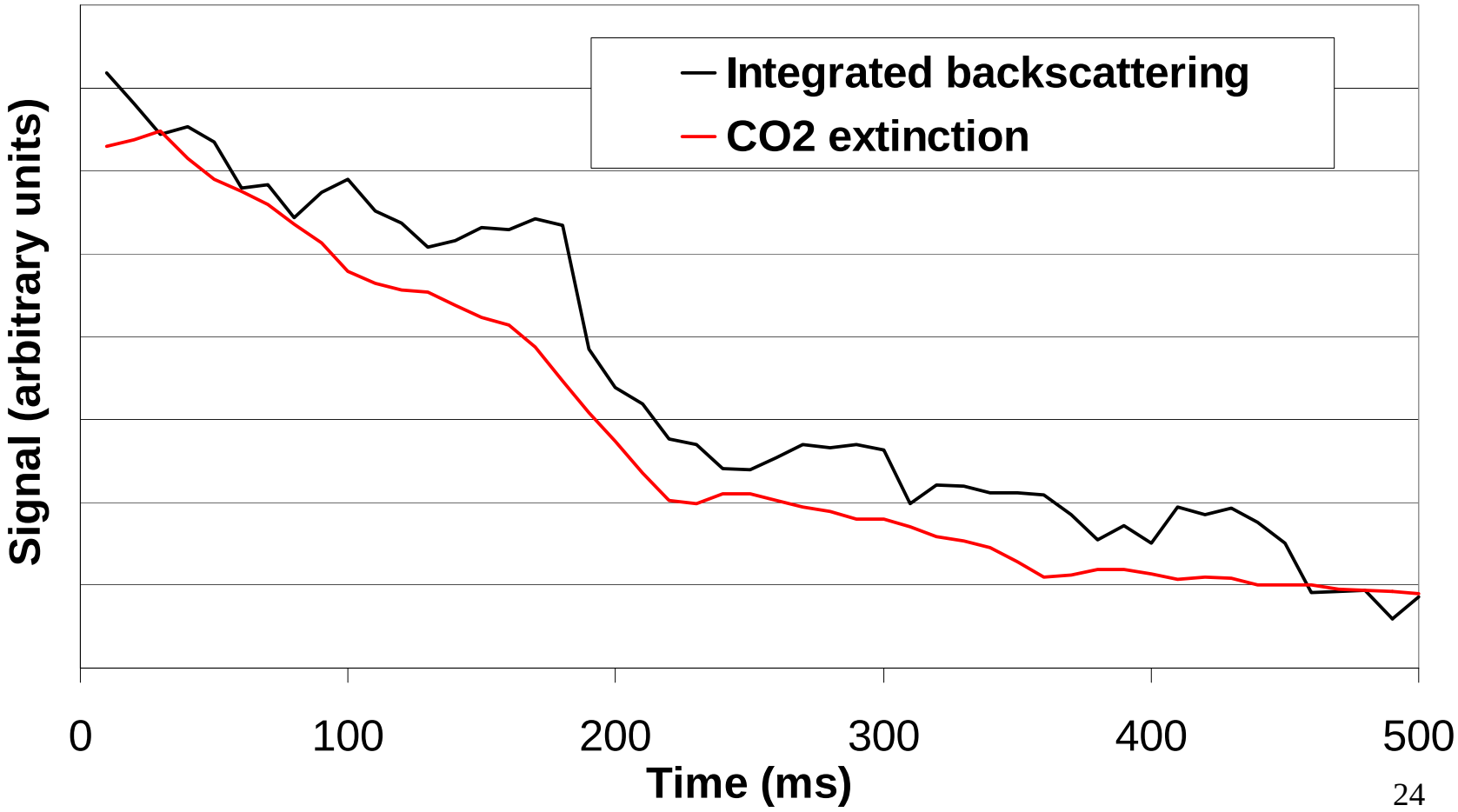
  $C_{SI} = 0.16\ mg/(m^3\ Rayleigh)$
  $C_{Diesel} = 0.18\ mg/(m^3\ Rayleigh)$

LORAX Use

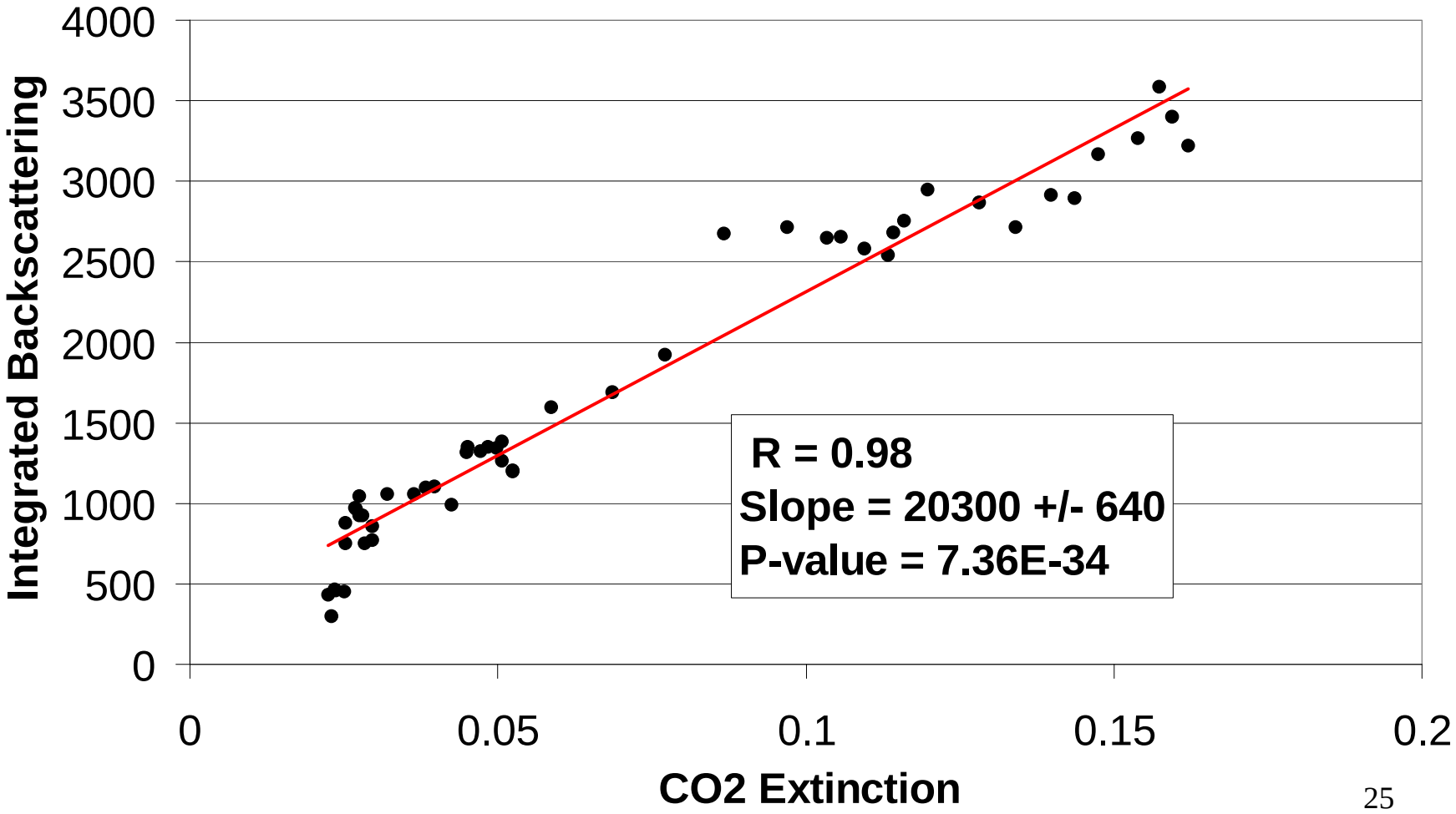
- Initial Small Scale Use for Instrument Testing and Debugging
- First Large Scale Use During Summer 2002 in Las Vegas
- Measurement of 150,000 Vehicles
- Southern Nevada Air Quality Study (SNAQS)
  (Sponsored by Federal Transit Administration)
- Clark County Remote Sensing Study
  (Sponsored by Clark County Division of Air Quality Management and Department of Comprehensive Planning)

Some High PM Emitters (>500 mg/mi) Las Vegas, May 2002

Example: CO_2 and Backscatter Signals



Example Correlation: CO_2 and Backscatter



Future Work

- Full Analysis of Las Vegas Study
- Dissemination of Results (Papers & Conferences)
- Use for Off-Road Military Diesel Vehicles
- Build Next Generation Instrument:
  Higher Sensitivity
  Integrated PM & Gas Measurements
  Easier Use
- Commercialization

Conclusions

- Lidar used to add PM channel to on-road remote sensing system
- Measure PM emissions for large number (10^4-10^6) of vehicles under a limited number of operating conditions
- Get PM emission statistics for SIPs in PM non-attainment areas
- Use for PM I&M (Clean Screening & Gross Emitter Identification)
- Lots of interest from ARB, BAR, and CRC