LiDAR systems and working principles. Applications in atmospheric monitoring, surveillance, and metrology.

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Outline

1. What is the lidar?
2. Lidar system and how it works. Principle of lidar remote sensing for atmospheric application
3. Scattering mechanisms
4. Basic lidar returns equation for elastic lidar systems
5. Lidar applications

LiDAR Remote Sensing

Lidar areas of interest

- Astronomical (Telescopes, Very Large Array)
- Climate Change (Environmental monitoring, see the Dept. of Environmental Conservation, NOAA, Environmental Protection Agency, Dept of Energy, etc)
- Medical
- Military (surveillance, target detection, mapping, see Dept. of Defense, NASA)
- Communication systems (free space optical communications, wireless)
- Geoscience (natural hazards, earthquake and volcano monitoring)
- Transportation systems
- Archeology
- Mining

What can lidar measure:

- Planetary Boundary Layer detection
- Aerosol-cloud (particle) detection
- Water vapor distribution
- Meteorological visibility
- Ozone, SO_2 , CO, CO_2, N_2O, and other gases detection
- Wind velocity and direction
- Temperature profiles
- Metal atoms and ions detection
- Ranging and imaging
- Topography, bathymetry

http://grindgis.com/data/lidar-data-50-applications

1. What is the lidar?

- **LIDAR: Light Detection And Ranging,** or laser radar

An optical remote sensing technology that measures properties of scattered light to find range and/or other information of a distant target.

It uses the same principle as RADAR except that it uses a laser instead of radio waves.

- **Lidar VS. Radar** (different transmitting wavelength)

Radar: radio waves, wavelength: 0.3-10 cm, detect big particles and target (> 0.1 mm) such as rain and clouds droplet

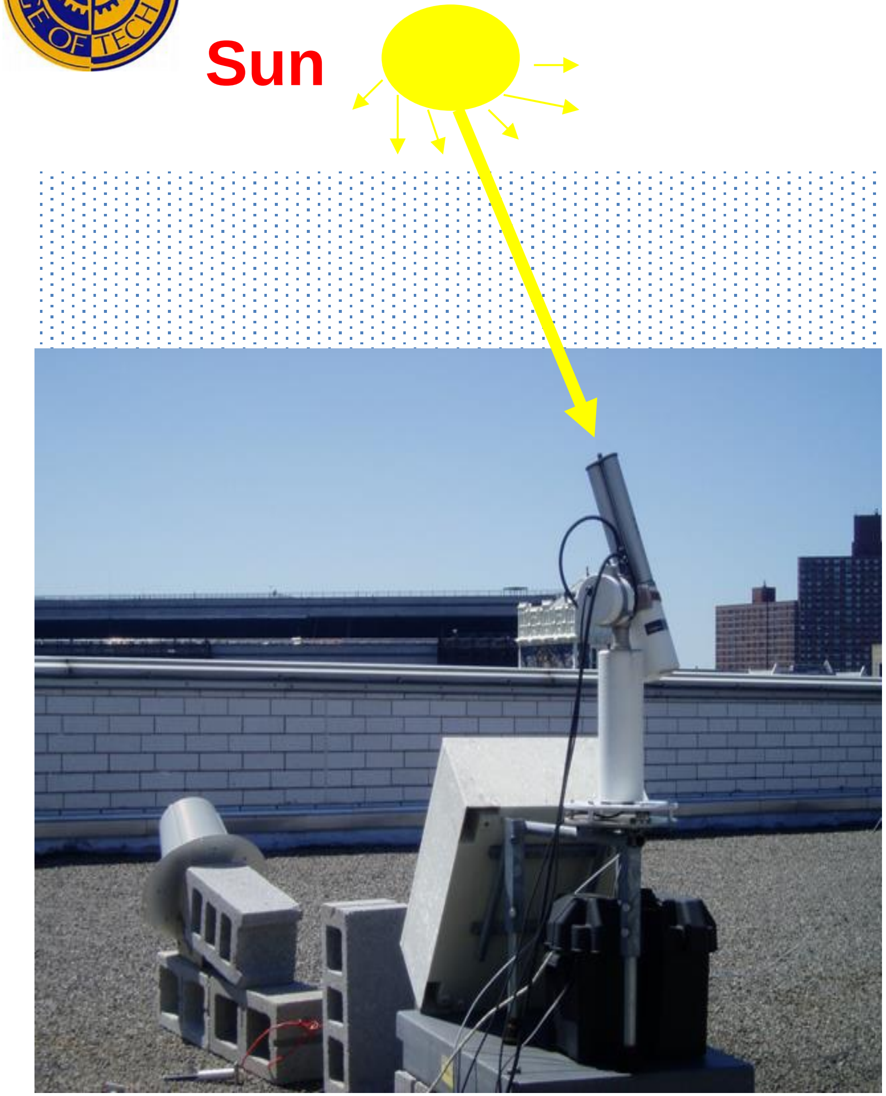
Lidar: shorter wavelength: 0.25-1µm, detect small particles such as aerosol and molecule

- **Active VS. Passive**

Active: instruments generate their own illumination/radiation source. such as RADAR, LiDAR, SODAR

Passive: The source of energy is the environment: naturally occurring radiation from the sun and the Earth, such as radiometer or sun-photometer

Passive remote sensing



Sun-photometer

Measures the whole column information of atmosphere (aerosol and water vapor)

Light source: Sun

No range-resolved information

No work in the night and overcast sky

How it works

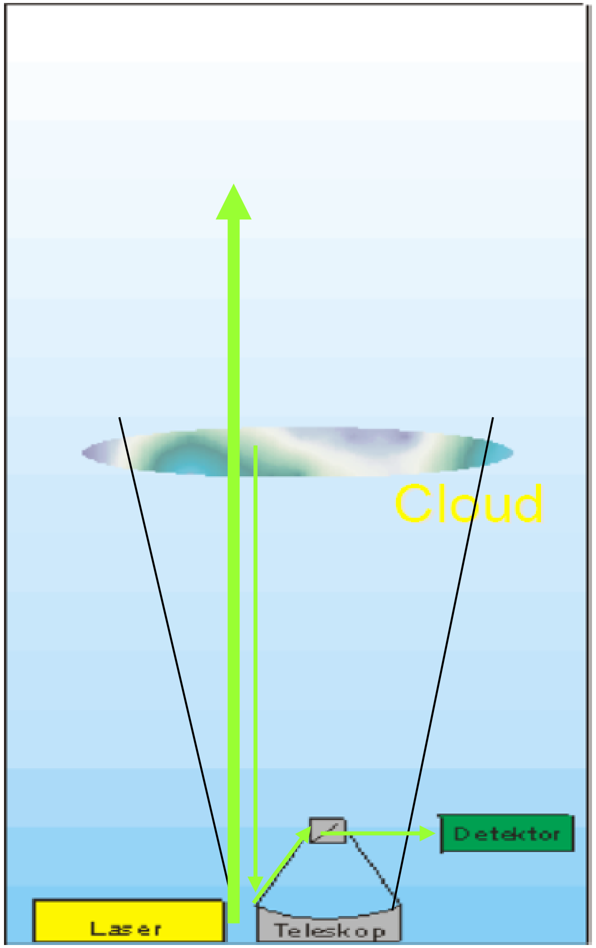
- Send light to the atmosphere
- Record light scattered by the atmosphere as a function of time.
- Convert the flight to distance

Time-range relationship: $R=C \bullet t/2$,

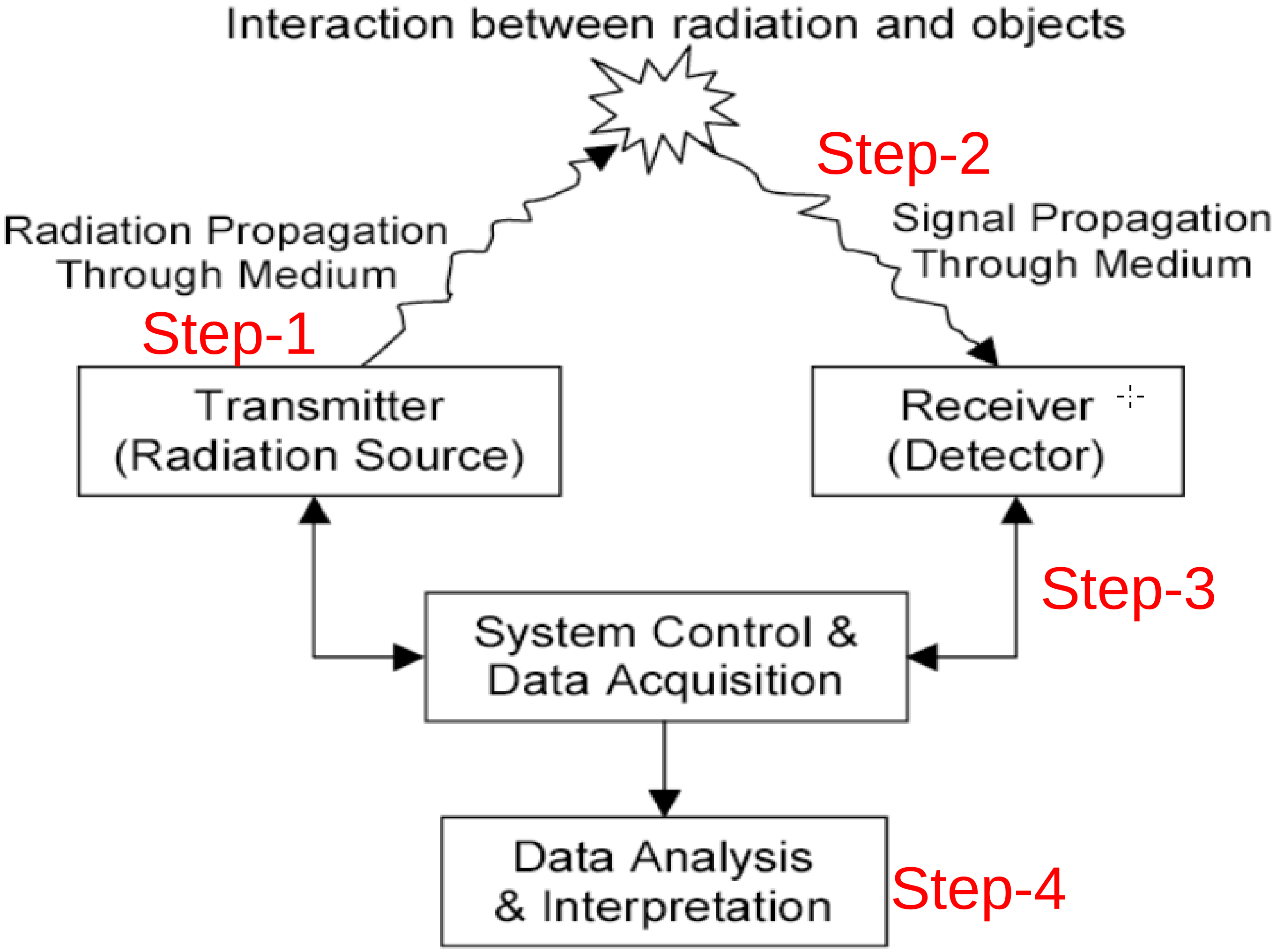
c is light speed, $3.0*10^8$ m/s
$t=1\ \mu s$, $R=150$ m; $t=1$ ms, $R=150$ km

Range resolution VS sampling rate:
$\Delta R=C\bullet \Delta t/2$,

10MHz---10^{-7} sec=0.1 μs =>15 meter,
40MHz---3.75 meter



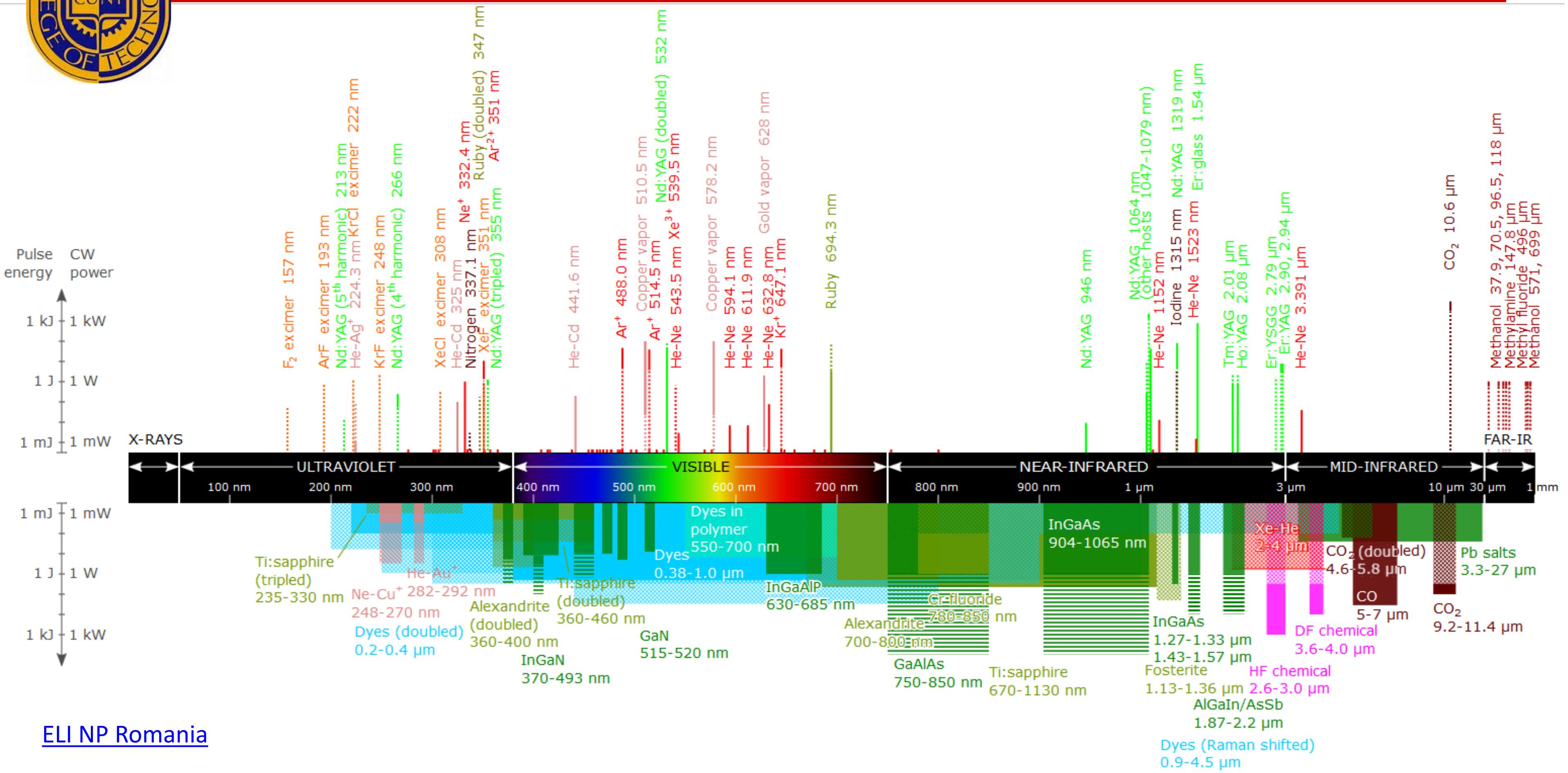
Active Remote Sensing



2. Lidar system and main components

- **Laser transmitter: laser and steering mirrors**
  (Wavelength, pulse energy, repetition rate, divergence angle, pulse- width etc)
- **Optical receiver: telescope and delay-optics**
  (Newtonian/Cassegrain, diameter, Field-of-View)
  (narrowband filter, beam-splitter, collimator lens)
- **Signal detection**
  Detector PMT or APD (Avalanche photodiode) and pre-amplifier
  (spectral sensitivity, quantum efficiency, gain, dark-current)
- **Data acquisition and control**
  A/DC: Analogue to digital converter (8~64-bits, sampling rate)
  Photon-counter (count rate, dead time)
  Control: scanner, synchronizer and computer

Wavelengths of commercially available lasers



ELI NP Romania

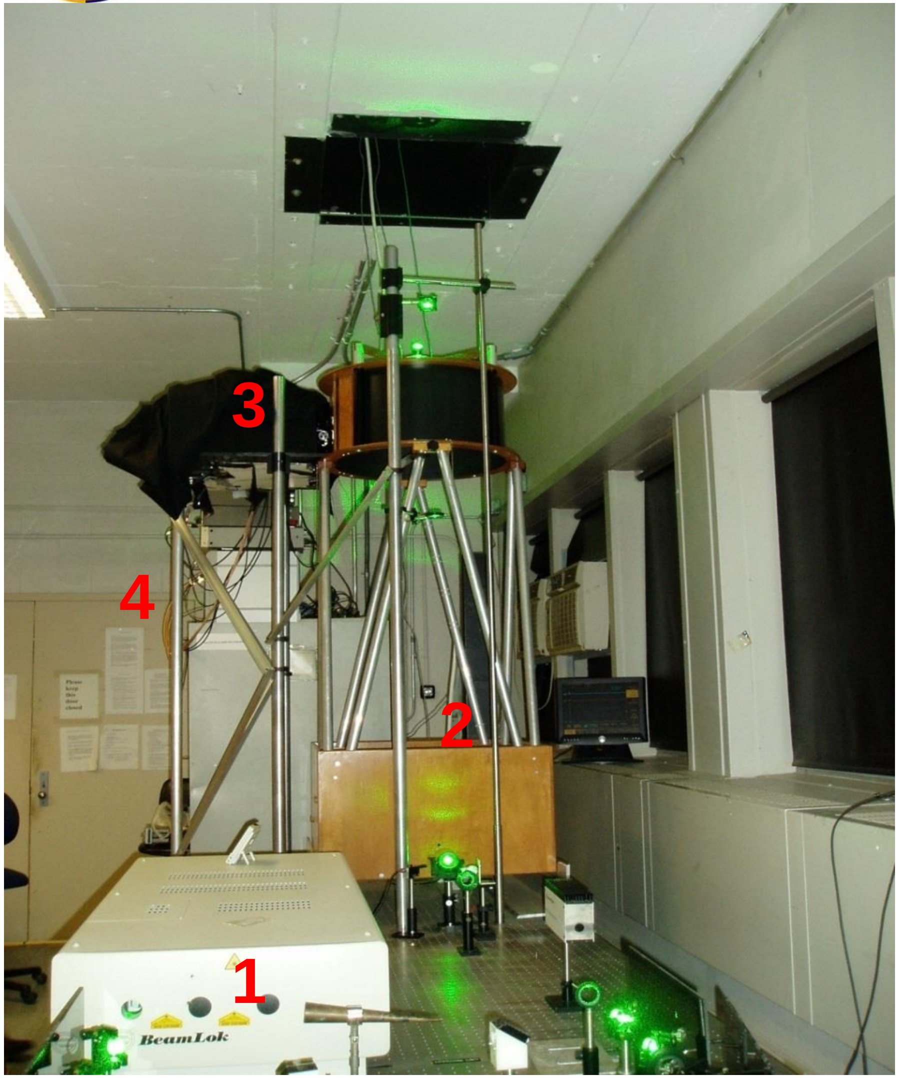
Gas lasers 🟧 Excimer laser 🟥 Noble gas laser ▨ Metal vapor laser 🟪 Chemical laser 🟫 Molecular gas laser 🟫 Far infrared laser

Solid state lasers 🟩 Lanthanides 🟩 Semiconductor laser 🟩 Transition metals 🟩 Organic dye in polymer host

Liquid lasers 🟦 Dyes ☐ CW emission ☐ pulsed emission ≡≡≡ laser diode bars or stacks

https://en.wikipedia.org/wiki/List_of_laser_types#/media/File:Commercial_laser_lines.svg

CCNY Multiwavelength Raman lidar



1. ND:YAG Laser (1064-532-355nm)

2. Telescope: diameter 500-mm

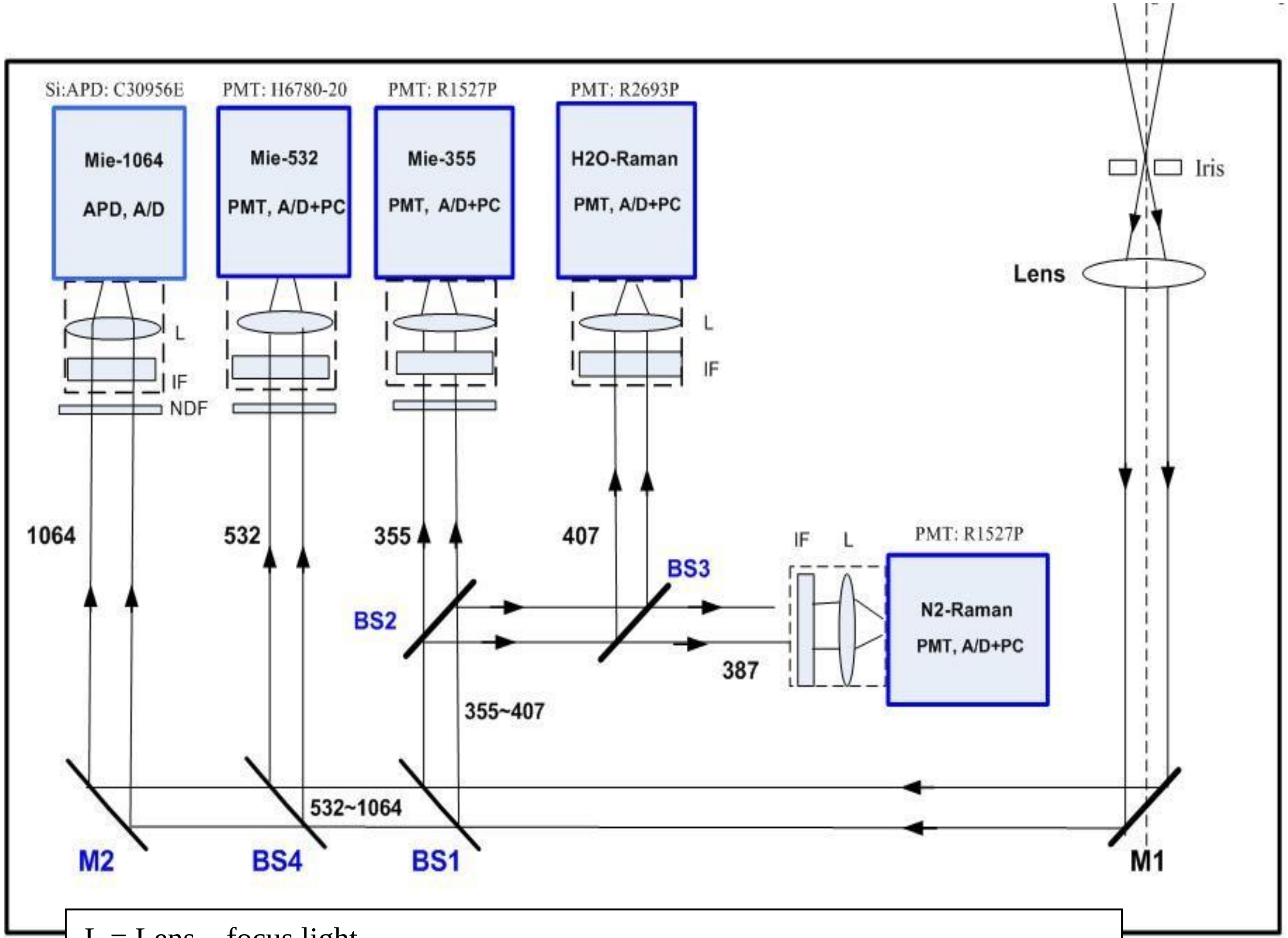
3. Detector: PMTs and Si-APD

4. Data acquisition:
   12-bit ADC and Photon-counting

Detection range and objective:
~10-12 km altitude
aerosol, cloud, water vapor, PBL

Working mode:
Only vertical pointing in the lab
Ancillary Radar for airplane
(not eye-safe)

A schematic of the CCNY Multiwavelength Raman lidar optical receiver



L = Lens – focus light
IF = Interference Filter – select the wavelength
NDF = Nurture Density Filter – attenuate the signal

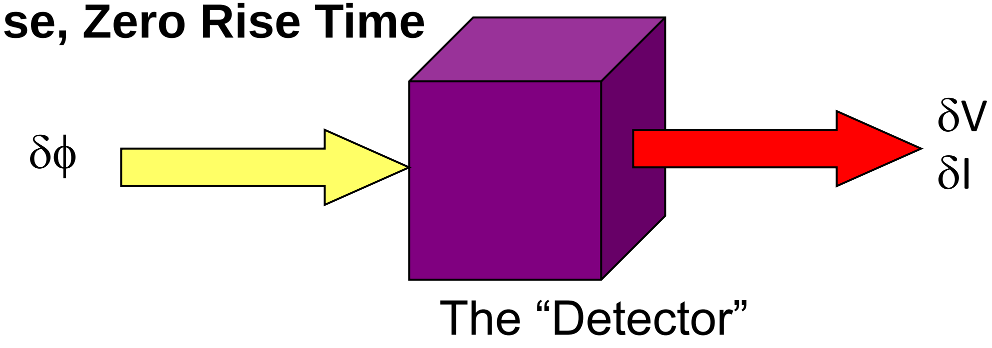
The Detector

What you Want

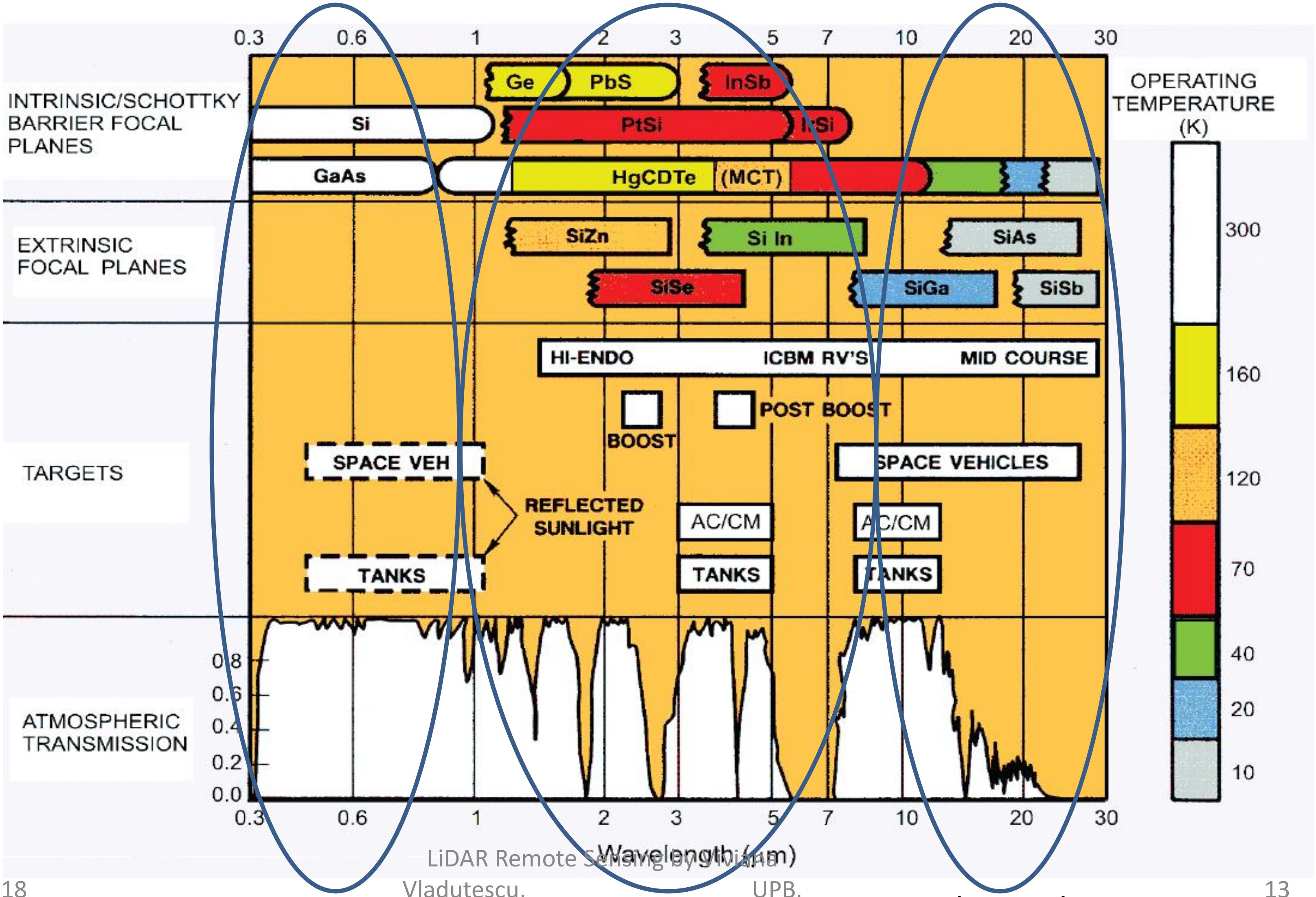
- **100% Quantum Efficiency**
- **Shot Noise Limited**
- **Tunable Cutoff Wavelength?**
- **Infinite Frequency Response, Zero Rise Time**
- **Same – Same**

What You Get

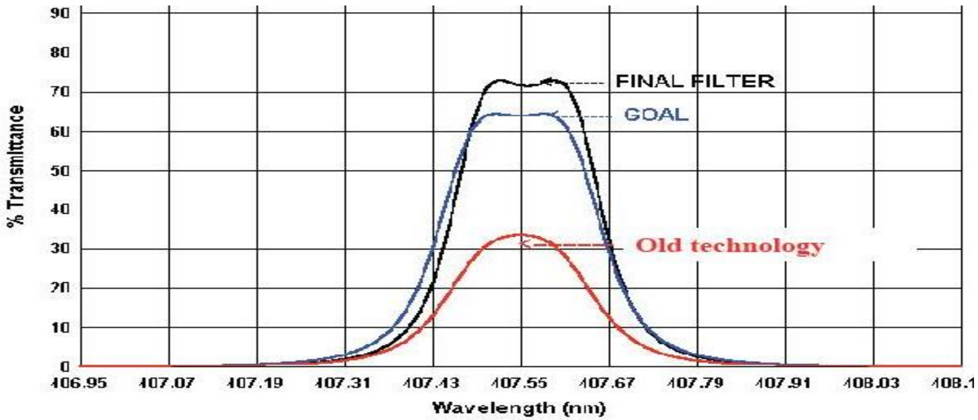
- **80% Quantum Efficiency**
- **Johnson Noise Limited**
- **Poor Cutoff Wavelength performance**
- **Real time constants**
- **Non-uniform**
- **Crosstalk**

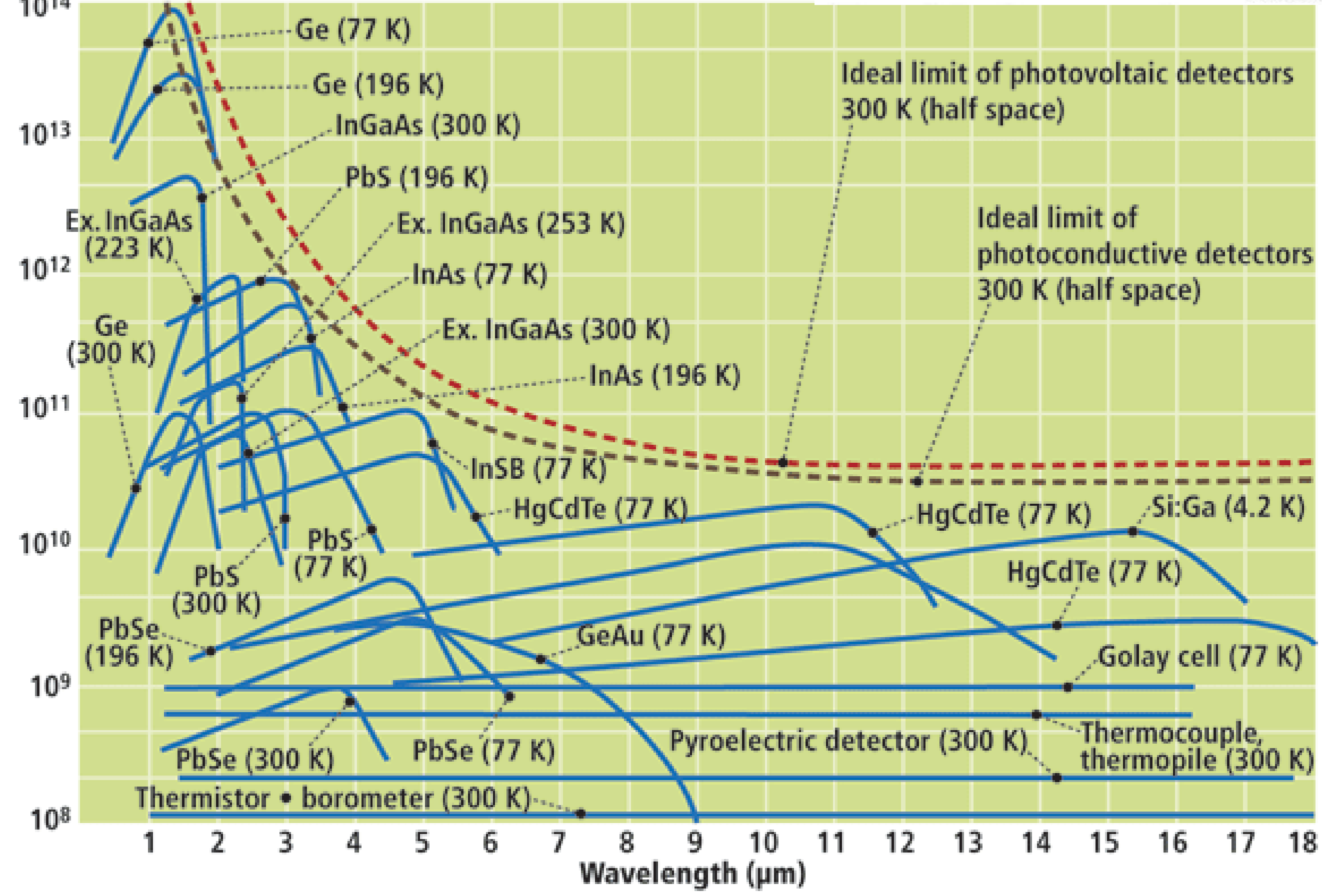


Spectral ranges of use for different focal plane materials



Receiver performance





Main specifications:

- Center wavelength:
- Bandwidth
  (1.0~0.2 nm)
- Peak transmittance %:
  >30%
- Block ratio: 1e-7

Source: http://www.vision-systems.com/articles/print/volume-16/issue-4/features/the-infrared-choice.html

Micropulse LiDAR

http://www.sigmaspace.com
/sigma/micropulseLidar.php

1. ND:YLF Laser (532-nm)   semiconductor laser,
   Output Energy 10 µj
   Pulse Repetition Frequency 2500 Hz

2. **Transceiver:** diameter 20 cm
   Beam Divergence 50 µrad
   Field-of-View 100 µrad

3. **Detector**: Si:APD

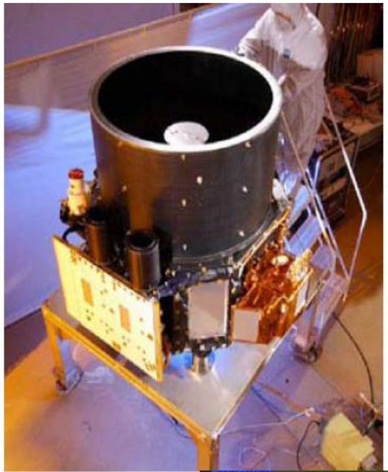
4. **Data acquisition**:
   photon-counter
   Vertical Resolution 5 m - 300 m

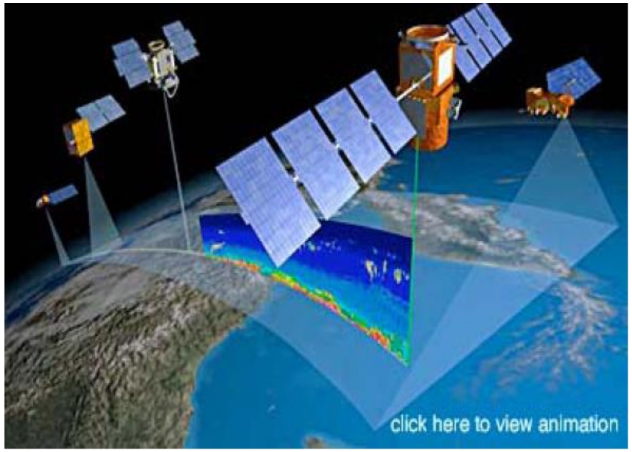
5. **Detection objective**:
   aerosol, cloud and PBL

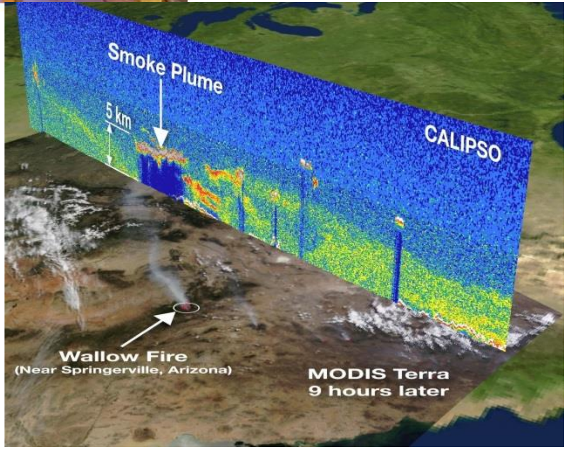
6. **Working mode**: 24-hr/7
   No operator

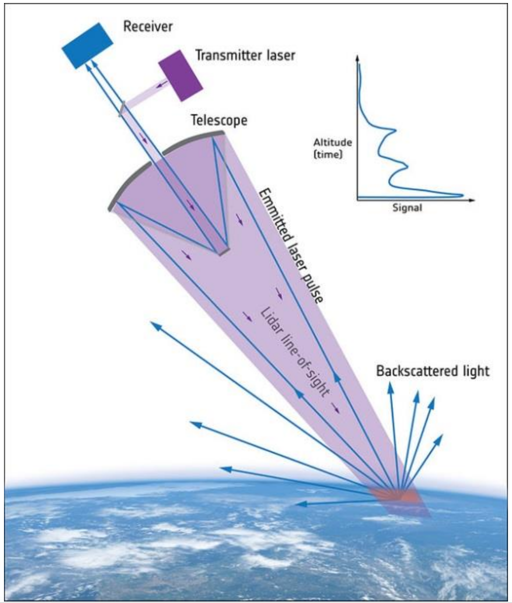
Satellite-borne lidars

https://www-calipso.larc.nasa.gov/

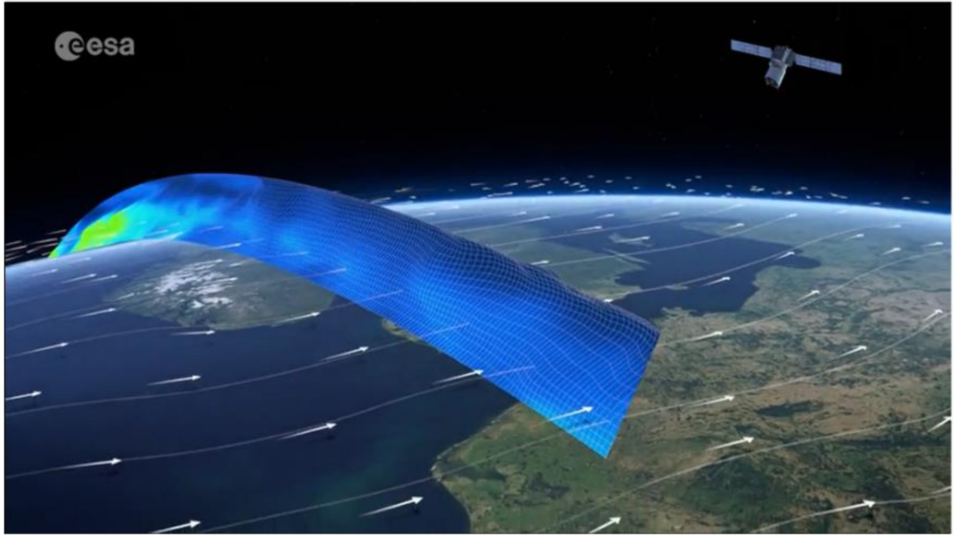








PROFILING THE WORLD'S WINDS



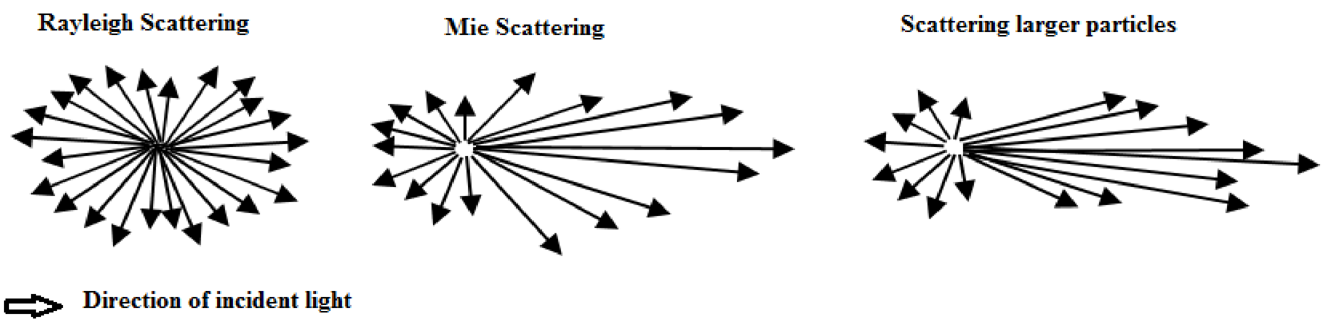
http://www.esa.int/spaceinvideos/Videos/2016/06/Profiling_the_world_s_winds

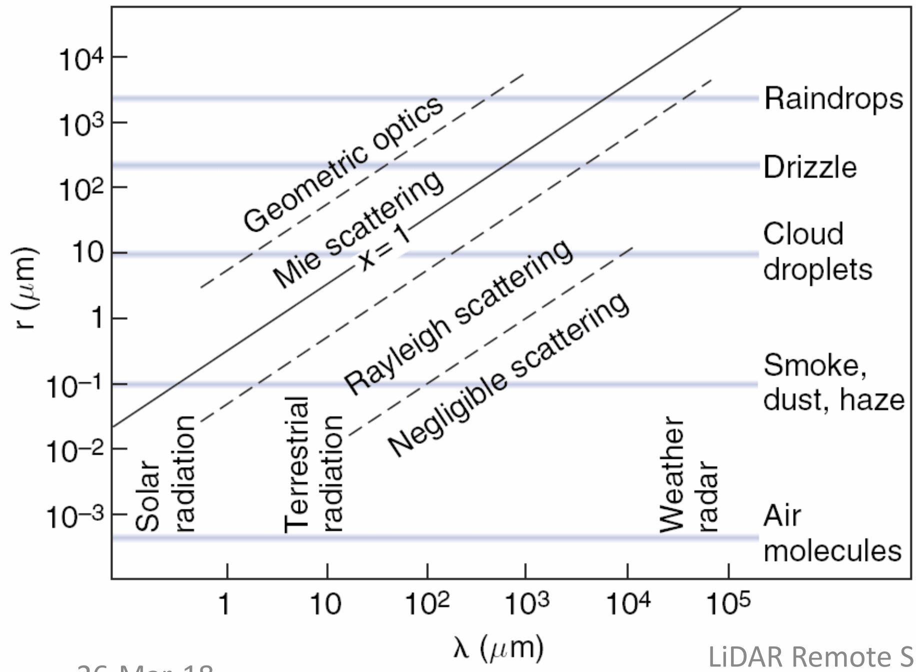
3. Principle of lidar remote sensing of atmosphere

Physical process of laser and atmosphere

- Elastic-scattering of molecule and particle (Rayleigh-Mie scattering)
- Raman-scattering (Water vapor, CH_4, N_2, O_2)
- Absorption of trace gas (Ozone, SO_2, NO_2 etc.)
- Fluorescent scattering (Na^+, Ca^+, K, Fe, etc)
- Doppler shift

Principle of lidar remote sensing of atmosphere based on light scattering by particles



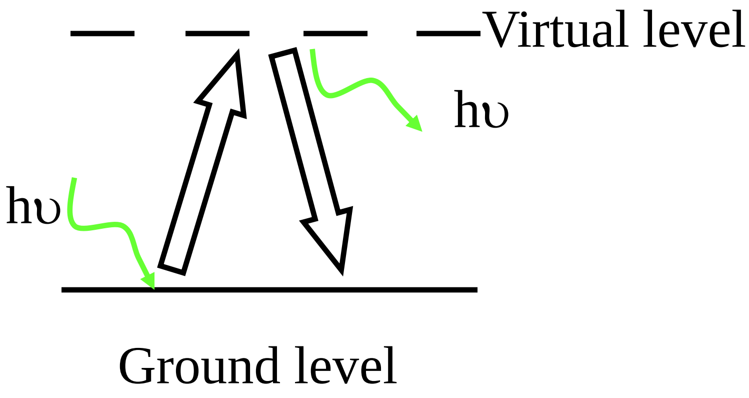


Size parameter ζ as a function of wavelength of the incident radiation and particle radius r

$\zeta = 2\pi r m / \lambda$ (where d is the geometric dimension of the diffuser), and the complex refractive index (m) with $m(\lambda) = n(\lambda) + i\,k(\lambda)$.

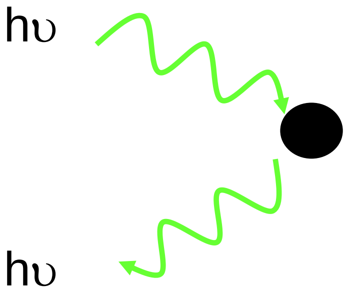
Lidar Interaction Elastic-scattering Mechanisms

- Rayleigh Scattering relevant for molecular gases including N_2,O_2 where d<<l
  - “Laser radiation elastically scattered from atoms or molecules is observed with no change of frequency”



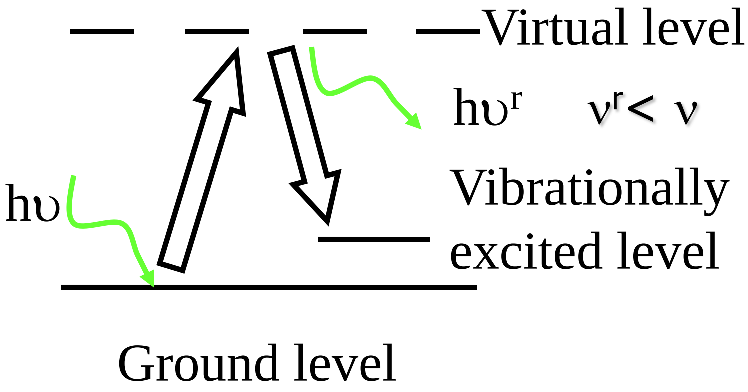
- Mie Scattering

  for particulates (spherical) where d~l
  - “Laser radiation elastically scattered from small particulates or aerosols (of size comparable to wavelength of radiation) is observed with no change in frequency”



No wavelength Change in either mechanism

Lidar Interaction Inelastic-scattering Mechanisms



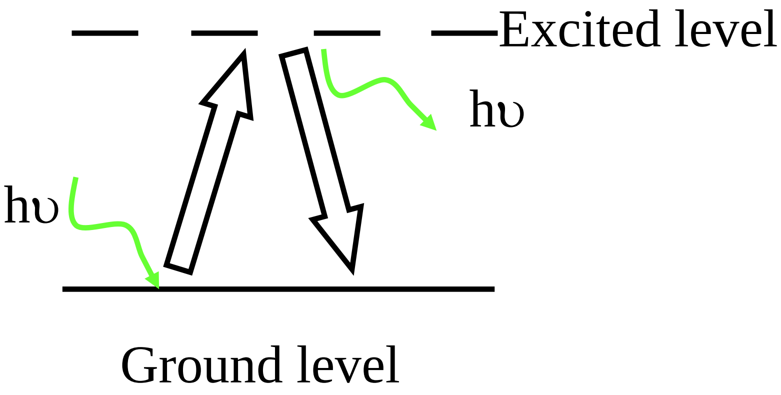
$\nu^r < \nu \longrightarrow \lambda^r > \lambda$

Raman Transition radiation generated at longer wavelength from excitation

- Raman Scattering
  - "Laser radiation inelastically scattered from molecules is observed with a frequency shift characteristic of the molecule ($h\nu - h\nu^r = E$)"

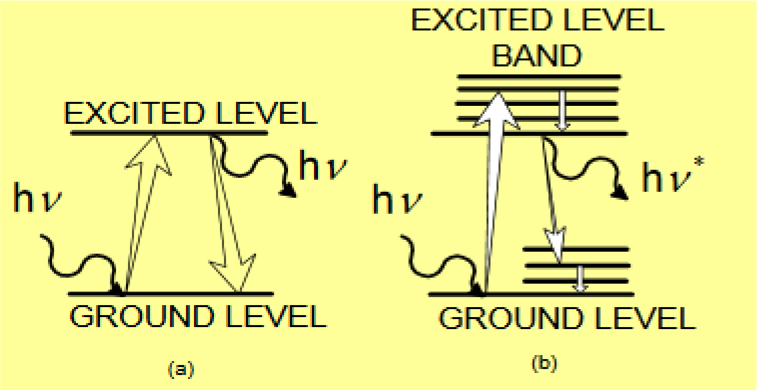
$$\lambda = 355 \text{ nm excitation} \begin{cases} \longrightarrow \lambda_R^{N_2} = 387 \text{ nm}, \\ \longrightarrow \lambda_R^{H_2O} = 407 \text{ nm}, \end{cases}$$

Lidar Interaction resonance-scattering Mechanisms



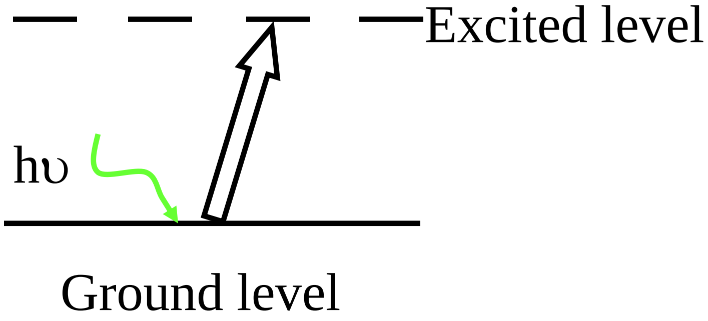
Laser radiation matched in frequency to that of a specific atomic transition is scattered by a large cross section and observed with no change in frequency.

Lidar Interaction Fluorescence Mechanisms



Laser radiation matched to a specific electronic transition of atom or molecule suffers absorption and subsequent emission at lower frequency: collision quenching can reduce effective cross section of this process: broadband emission is observed with molecules.

Lidar Interaction Absorption Mechanisms



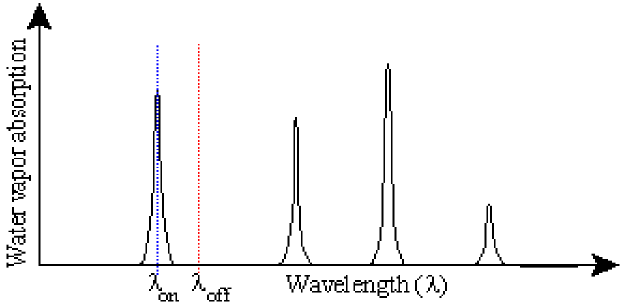
Excited level

hυ

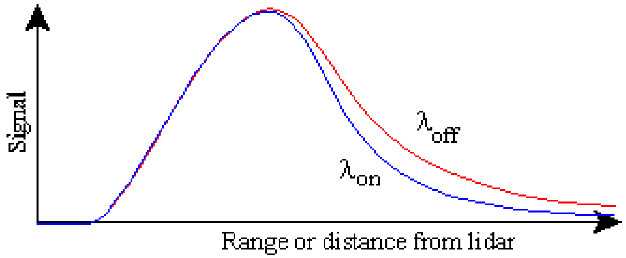
Ground level

Observe attenuation of laser beam when frequency matched to the absorption band of given molecule.

Lidar Interaction Differential Absorption and Scattering Mechanisms



(a) Water vapor absorption spectrum



(b) Typical DIAL signals as a function of range

The differential attenuation of two laser beams is evaluated from their backscattered signals when the frequency of one beam is closely matched to a given molecular transition while the other’s frequency is somewhat detuned from the transition

Physical process between laser-beam and atmospheric medium

(λ_t incident laser wavelength (WL)， λ_r receiving wavelength）

Physical-process	Medium	WL	Cross-section (cm^2)	Detection objective
Rayleigh-scat	molecule	$\lambda_t = \lambda_r$	10^{-27}	Air density， temperature
Mie-	aerosol	$\lambda_t = \lambda_r$	$10^{-8} \sim 10^{-27}$	Aerosol, cloud
Raman-	molecule	$\lambda_t \neq \lambda_r$	10^{-30}	Trace-gas (H_2O,SO_2,CH_4)
Resonance-	atom &mol	$\lambda_t = \lambda_r$	$10^{-14} \sim 10^{-23}$	Metal atom and iron Na^+, K^+, Ca^+, Li
Fluorescence	molecule	$\lambda_t \neq \lambda_r$	$10^{-16} \sim 10^{-25}$	
Absorption	atom & mol	$\lambda_t = \lambda_r$	$10^{-14} \sim 10^{-21}$	Trace-gas (O_3， SO_2, NO_2 etc)
Doppler-shift	atom & mol	$\lambda_t \neq \lambda_r$		Wind-speed, direction

4. Elastic-scattering lidar returns equation

The reflected power from the atmosphere, P_r , as a function of range, R and wavelength λ, C (Calibration Constant: includes Detector Area Efficiencies, the Field of View of Telescope etc.)

$$C(\lambda) = \eta_{trans.opt}(\lambda) \times A(\lambda) \times \eta_{rec.opt}(\lambda) \times \eta_{electron}(\lambda)$$

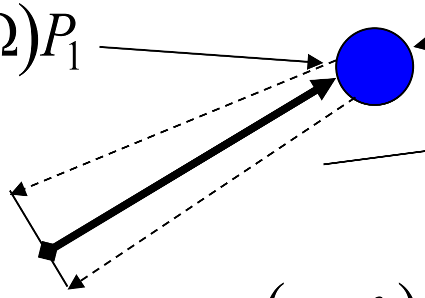
$\alpha_T = \alpha_M + \alpha_A$: total atmospheric (molecular + aerosol) extinction including Absorption + Scattering coefficient (m^{-1})

P_0= transmitted peak power (W).

$\beta_T = \beta_M + \beta_A$: Total Backscatter ($m^{-1}\ sr^{-1}$)

$$P_1(R) = P_0 e^{-\int_0^R [\alpha_T(r)]dr}$$

$$P_2 = (\beta_T(R)\, d\Omega) P_1$$



Atmospheric Extinction takes energy out of the beam in both directions

$$d\Omega = \frac{A}{R^2}$$

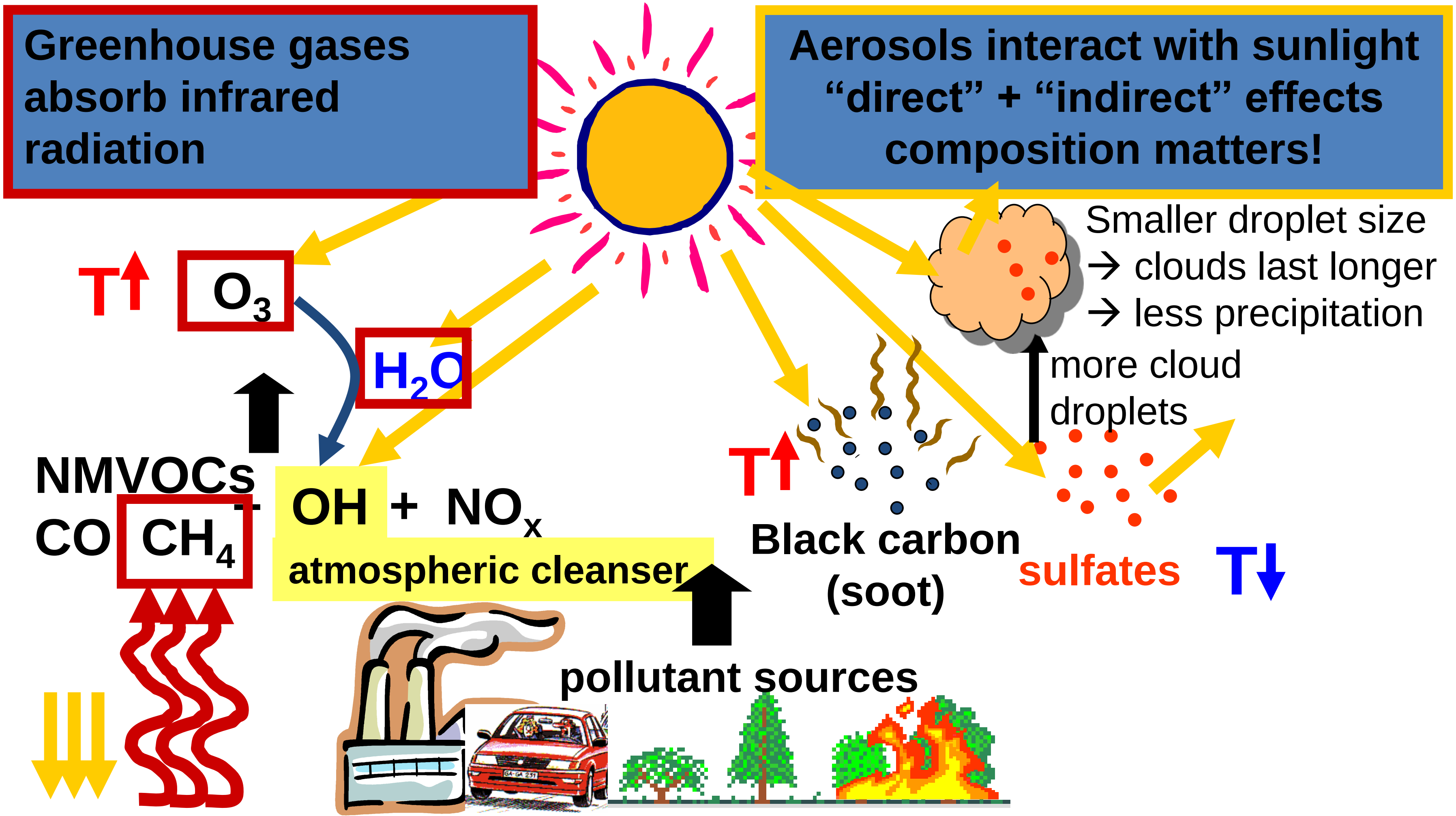
$$P_0$$

Standard Lidar Equation

$$P_r(R,\lambda) = \frac{CP_0(\lambda)\beta_T(R,\lambda)}{R^2} \underbrace{e^{-2\int_0^R [\alpha_T(r,\lambda)]dr}}_{T^2{}_{m,p}(\lambda,R)} + P_{noise}$$

$$P_{noise} = P_{sky} + P_{d\text{-}dark} + P_{d\text{-}thermo}$$

Air pollutants affect climate by absorbing or scattering radiation



Greenhouse gases absorb infrared radiation

Aerosols interact with sunlight
“direct” + “indirect” effects
composition matters!

T↑ O_3

H_2O

NMVOCs
CO CH_4 + **OH** + NO_x

atmospheric cleanser

pollutant sources

T↑

Black carbon (soot)

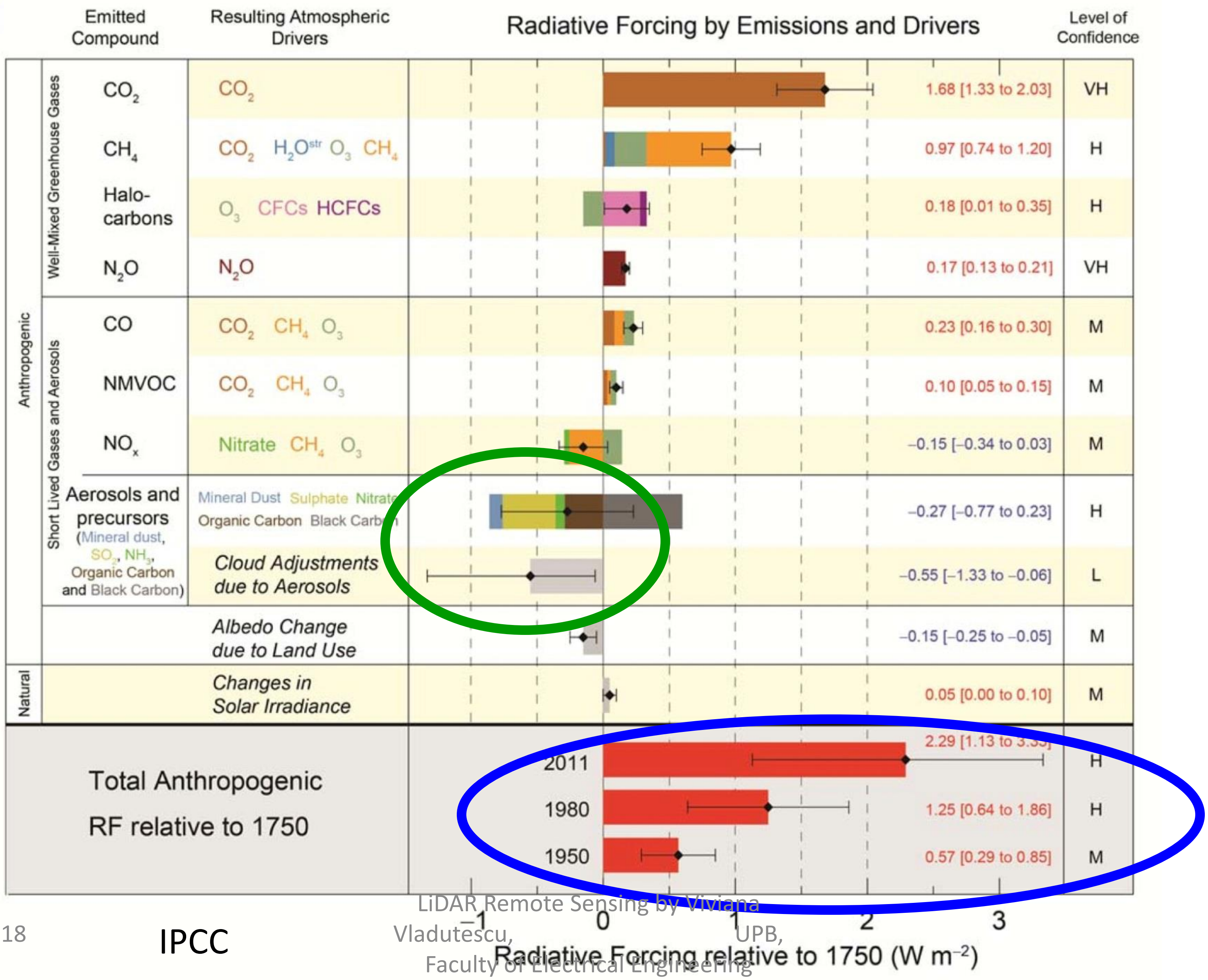
Smaller droplet size
→ clouds last longer
→ less precipitation

more cloud droplets

sulfates T↓

Surface of the Earth

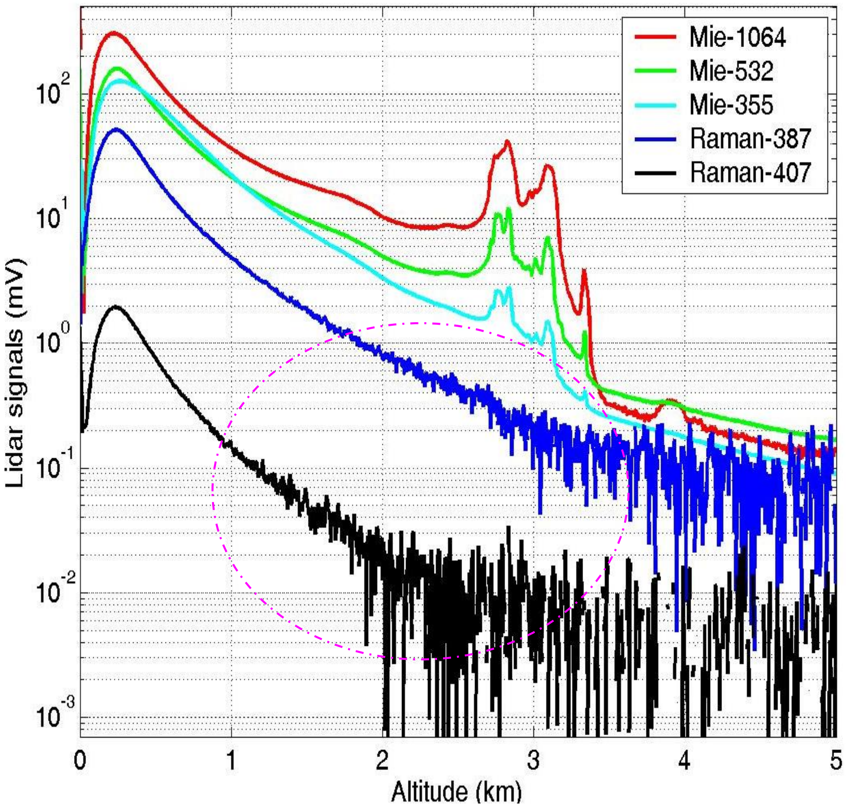
Radiative forcing of climate (1750 to present): Important contributions from air pollutants by IPCC

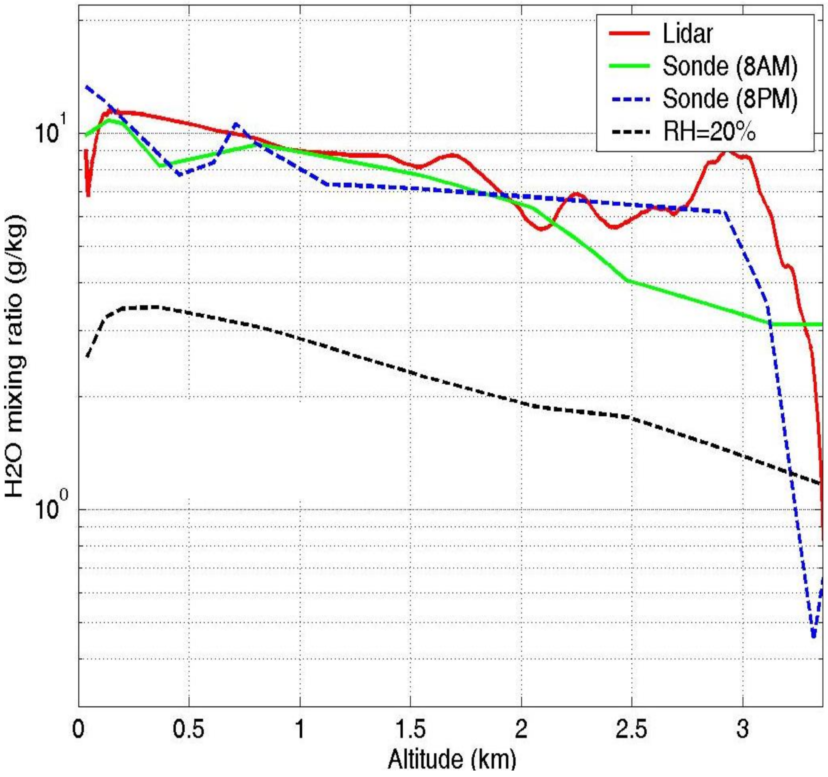


IPCC

Lidar Vertical Profiles

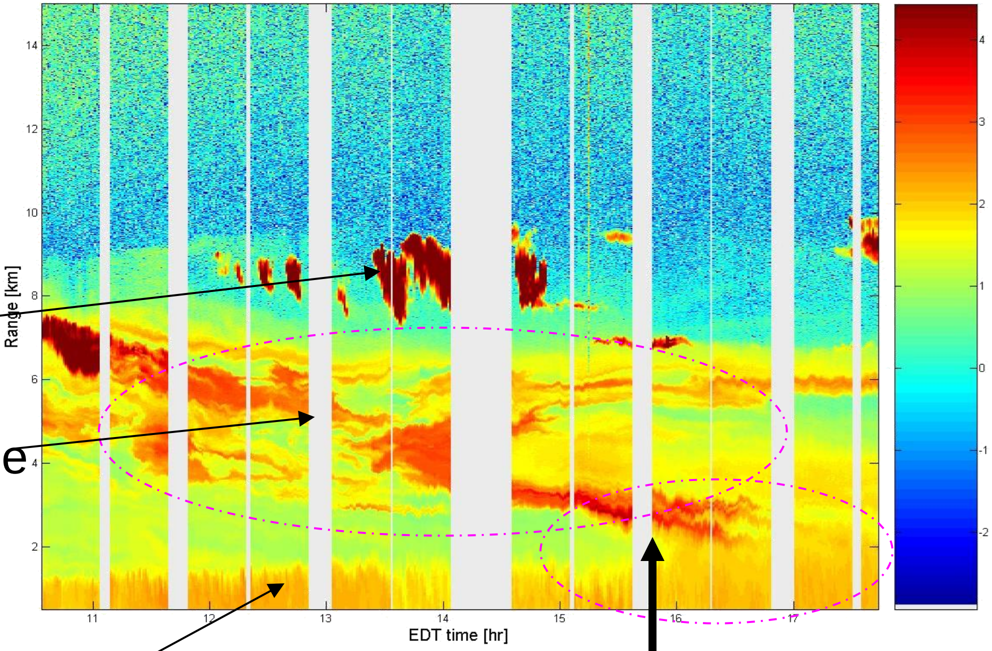
- Raman signals (black & blue) are much smaller than elastic signals
- No strong cloud returns in Raman-channel
- Consistent H_2O profile with radiosonde observation





Aerosol-plume

Asian dust or smoke-plume
Important to Air pollution & Climate Radiative Change

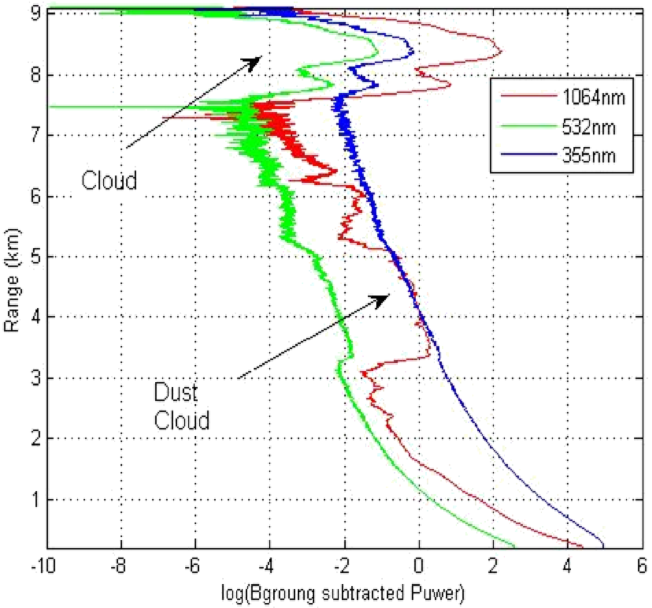


Cloud

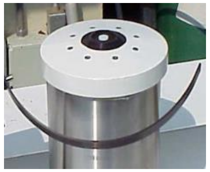
Dust plume

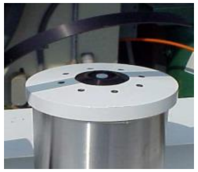
PBL

enter PBL



Synergy with other environmental instruments





MFRSR

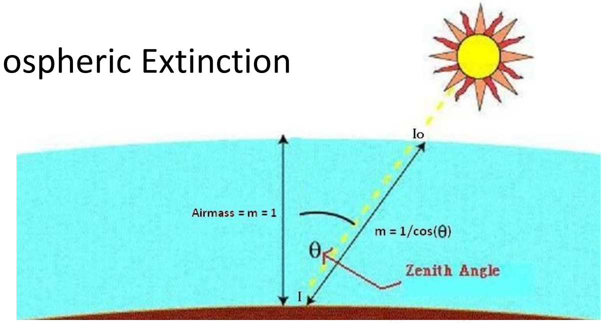
410, 500, 615, 675, 870, 936 nm.

Total Irradiance Diffuse Irradiance

Direct Irradiance = Total Irradiance – Diffuse Irradiance

Beer's Law $$I = I_o \cdot e^{(-\tau_T m)}$$

Atmospheric Extinction



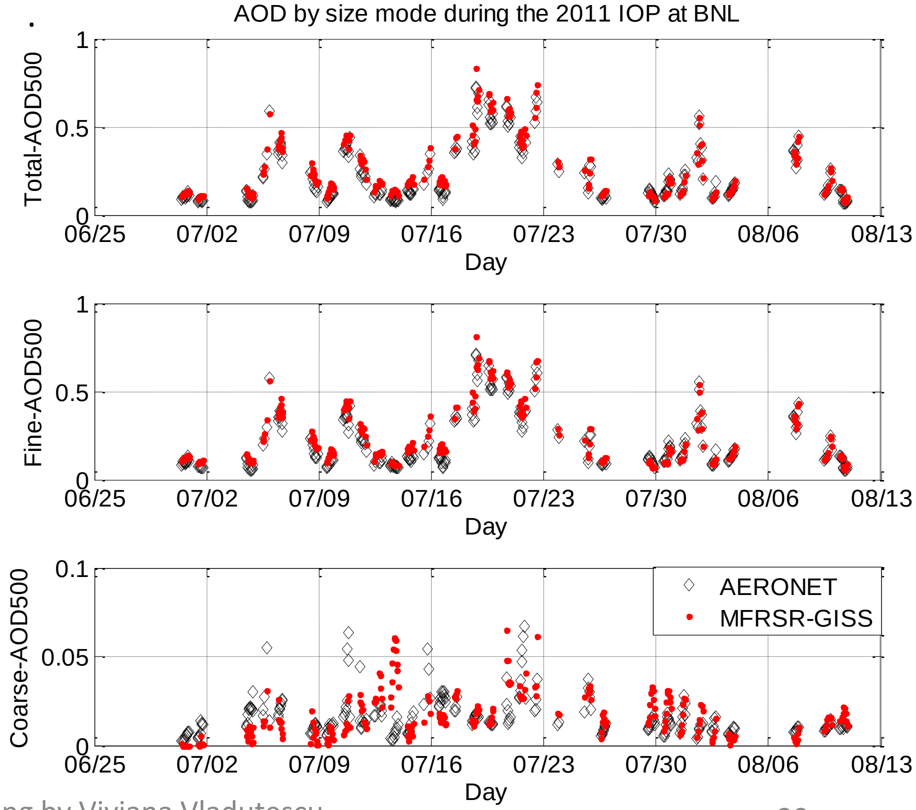
- **Total Optical Depth** (τ_T) is a measure of the extinction (absorption and scattering) of solar radiation through the atmosphere.

$$\tau_{aer} = \tau_T - \tau_{Ray} - \tau_{O_3} - \tau_{NO_2}$$

$$Å = -\ln\left[\frac{\left(\frac{\tau_1}{\tau_0}\right)}{\left(\frac{\lambda_1}{\lambda_0}\right)}\right]$$

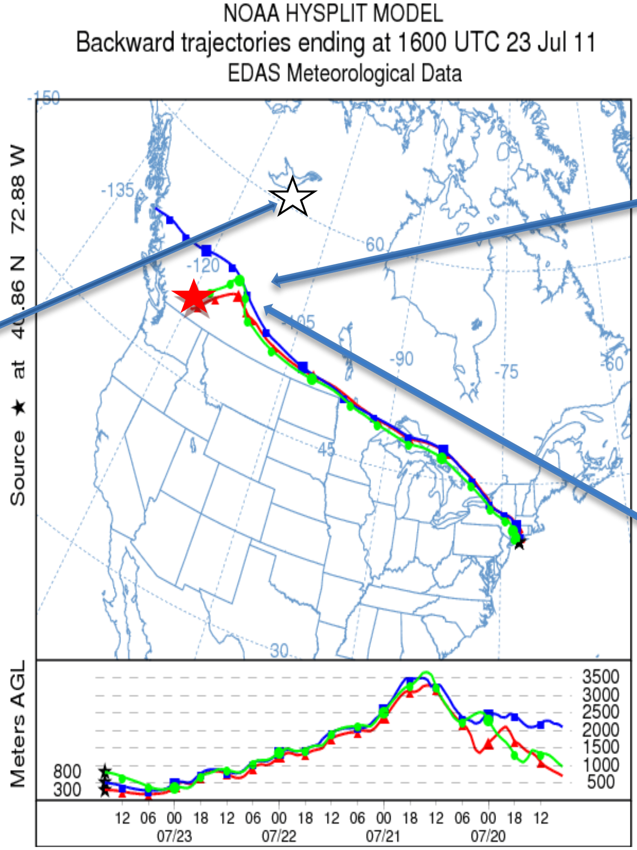
Removal of molecular extinction Ångström Coefficient

"Assessment of Langley and NASA GISS calibration techniques for MFRSR aerosol retrieval", **Daniela Viviana Vladutescu**, Bomidi Madhvan, Barry Gross, Antonio Aguirre, Fred Moshary, Samir Ahmed, Mohammad Razani and Reginald Blake, *IEEE Geoscience and Remote Sensing*, vol. 52, Issue 9, DOI: 10.1109/TGRS.2013.2293633, 2014.



Aerosol Transport and Source Attribution

Great Slave Lake, Northwest Territories, Canada, July 23rd, 2011



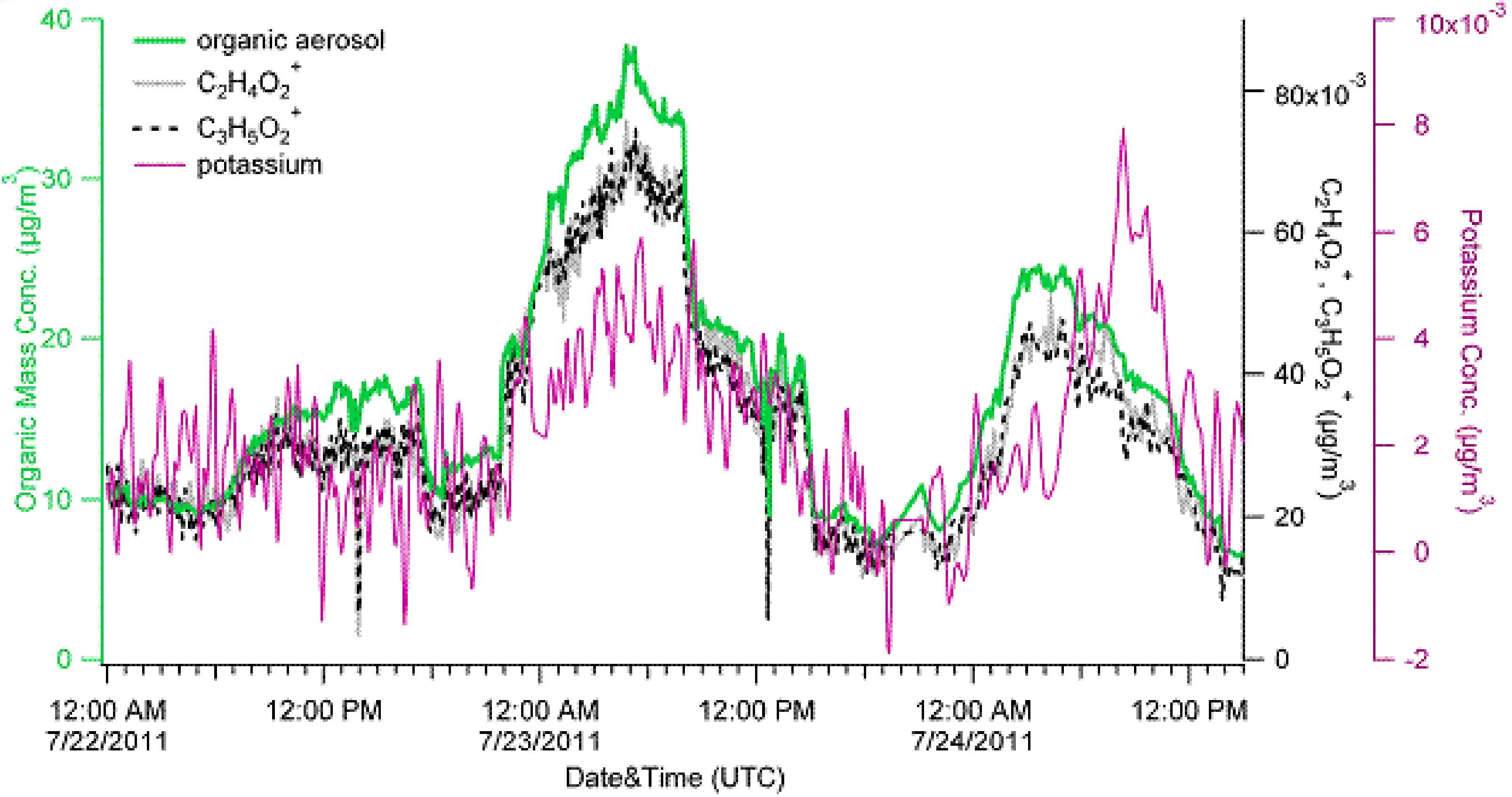
NOAA HYSPLIT MODEL
Backward trajectories ending at 1600 UTC 23 Jul 11
EDAS Meteorological Data

Kelowna, British Columbia, Canada, July 19th, 2011

"Aerosol transport and source apportionment using sunphotometers, models and in situ chemical composition measurements", **Daniela Viviana Vladutescu**, Bomidi L. Madhvan, Barry Gross, Qi Zhang, Shan Zhou, *IEEE Transactions on Geoscience and Remote Sensing*, vol. 51, No. 7, 2013]

The dramatic fine aerosol events occurring during the Summer 2011 BNL field campaign are due to Canadian fires. Fire danger in eastern Northwest Territories, Canada, was very high to extreme in late July 2011.

Analysis of aerosol chemical composition

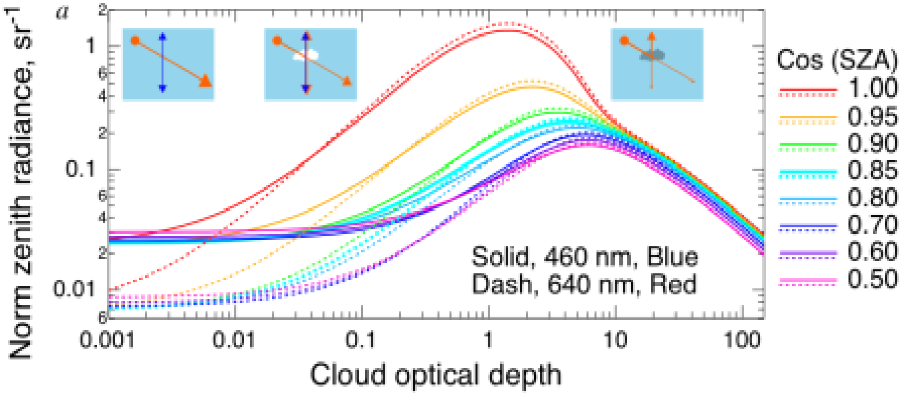


During this period, two high organic aerosol loading events occurred in association with elevated concentrations of three biomass burning tracer ions in the HR-ToF-AMS spectra: potassium, $C_2H_4O_2^+$ (*m/z* 60) and $C_3H_5O_2^+$ (*m/z* 73). Particle phase potassium is a well-known tracer for biomass burning emissions in the atmosphere while the signals of $C_2H_4O_2^+$ and $C_3H_5O_2^+$ in the AMS spectra were found to tightly correlate with levoglucosan – a major pyrolysis product of wood tissue during burning – in aerosols.

Thin Clouds
Radiative Effect

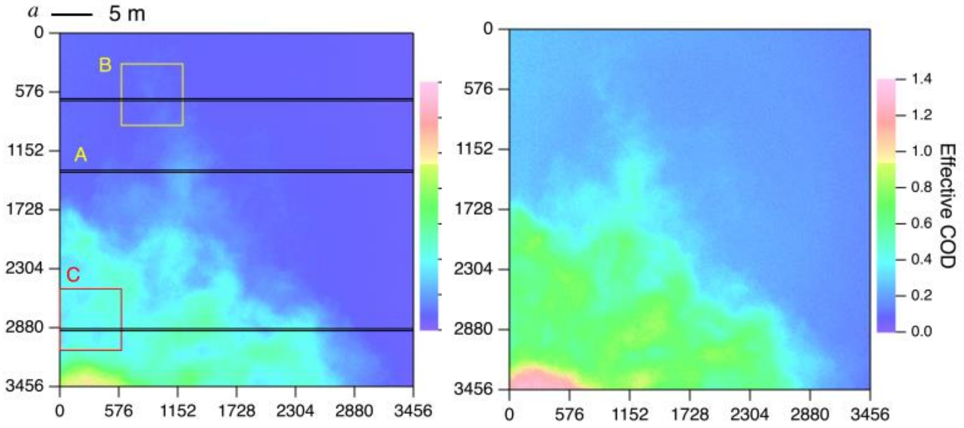
SGP/ Lamont
Oklahoma
36.6˚N, 97.5˚W
07/31/2015

$$R_s = R_{\min} + \frac{C - C_{\min}}{C_{\max} - C_{\min}}\left(R_{\max} - R_{\min}\right)$$



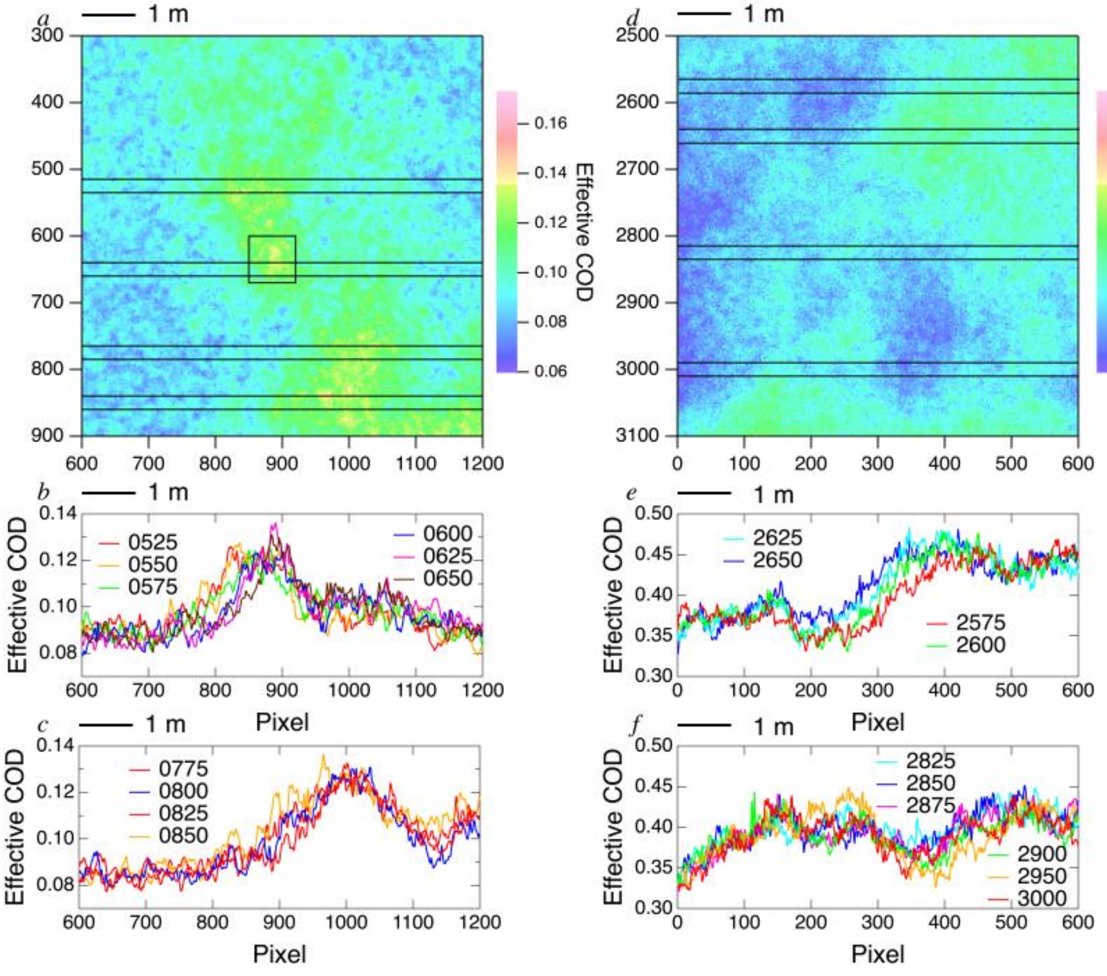
Defined at a given wavelength λ, as the ratio of downwelling zenith radiance (W m^{-2} nm^{-1} sr^{-1}) to incident downwelling irradiance at the top of the atmosphere (W m^{-2} nm^{-1}),

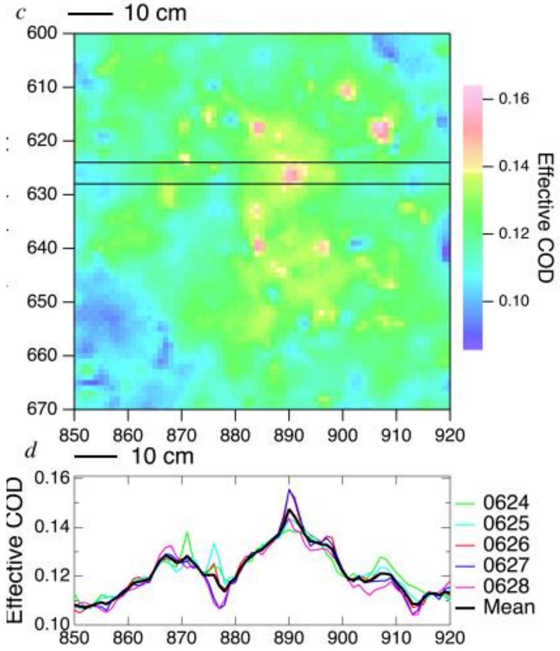
$$R_\lambda^{\mathrm{nz}}(\mu_0) = \frac{I_\lambda^{\mathrm{z}}(\mu_0)}{\mu_0 F_\lambda}$$

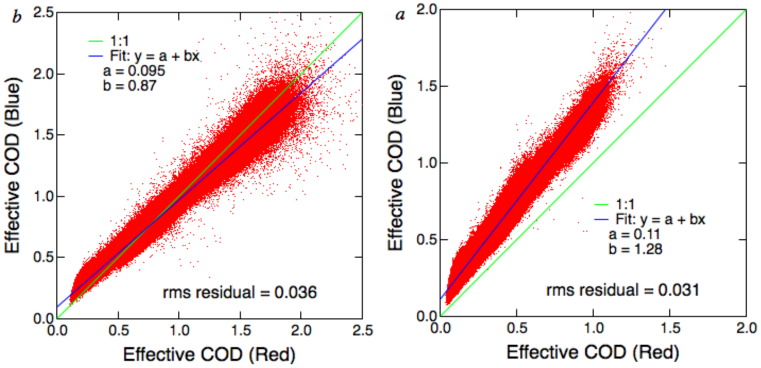


“High Resolution Photography of clouds from the surface: Retrieval of optical depth of thin clouds down to centimeter scale”, Schwartz, E.S., Huang, D., **Vladutescu, D.V.**, *JGR: Atmospheres* , DOI: 10.1002/ 2016.JD025384, 2017.

Pixel-by-pixel Effective Cloud Optical Depth





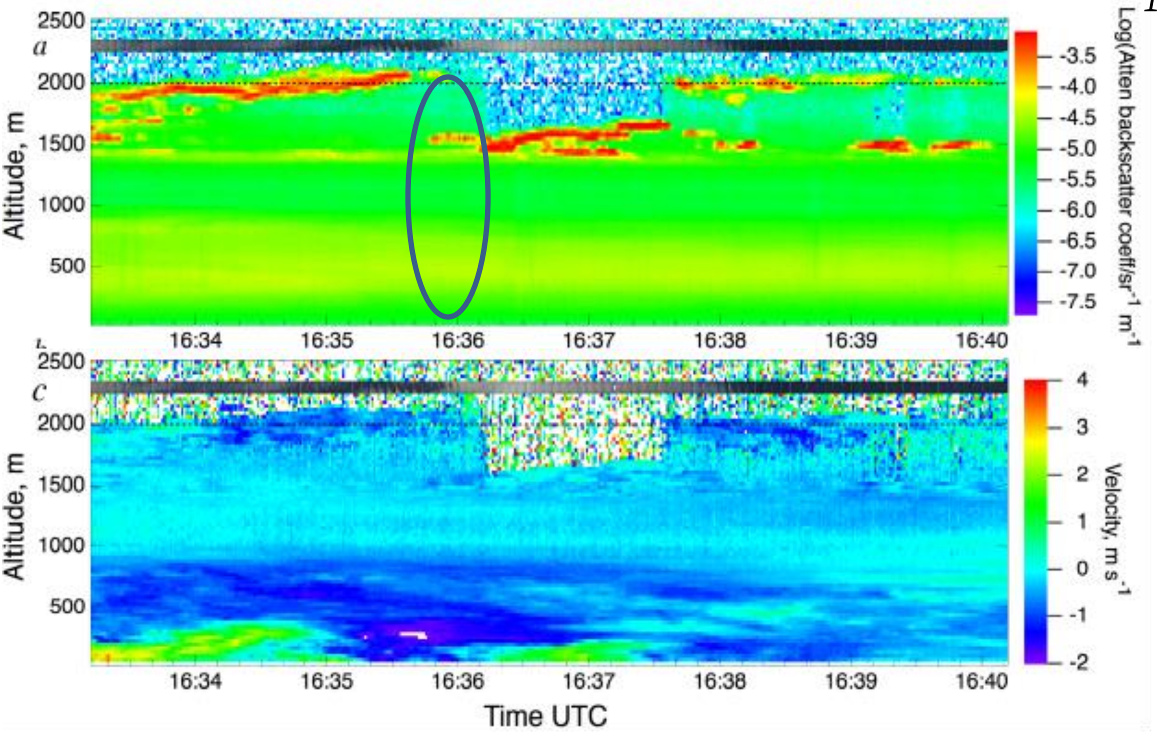


Lidar Vertical Profiles

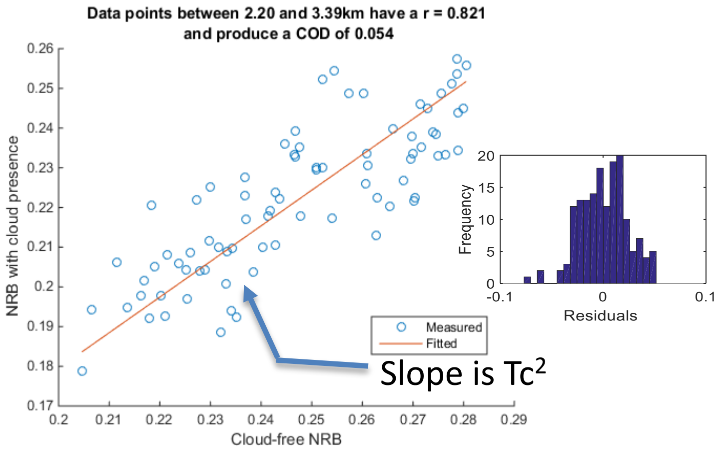
$$NRB^{ab\ cld}_{cld-free} = C[\beta_m + \beta_a]T_m^2 T_a^2$$

$$NRB^{ab\ cld}_{cldy} = C[\beta_m + \beta_a]T_m^2 T_a^2 T_c^2$$

Doppler Lidar



Best case scenario


Data points between 2.20 and 3.39km have a r = 0.821 and produce a COD of 0.054

Slope is T_c^2

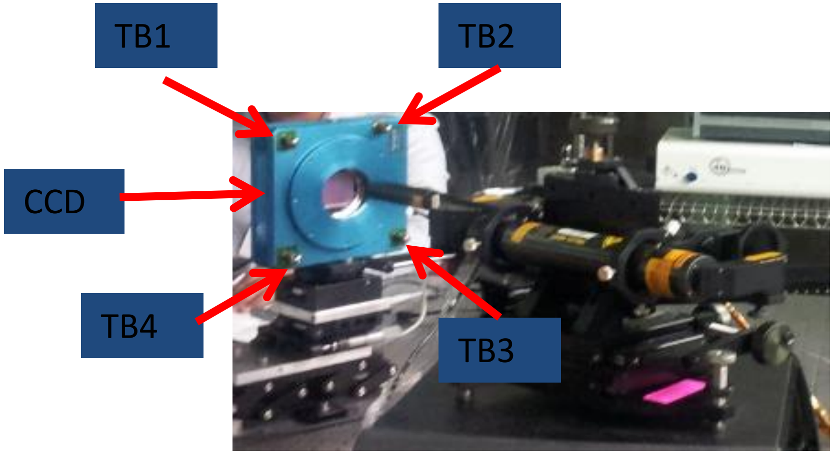
$$T_c^2 = e^{-2\tau} \Rightarrow \ln\left(T_c^2\right) = -2\tau$$

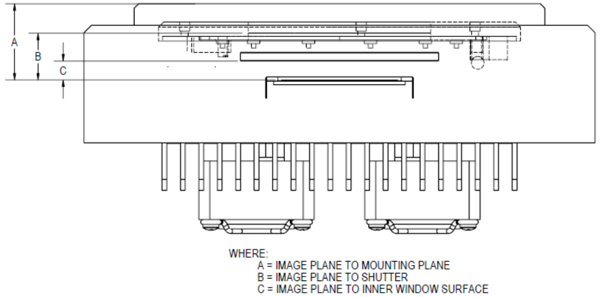
$$\Rightarrow \tau = \frac{-\ln\left(T_c^2\right)}{2} = -\ln\left(T_c\right)$$

For an angular translational velocity of 2 mrad s-^{1} and exposure time of 1/2000 s the angular translation is 1 μrad, well less than the resolution of 6.2 and 34 μrad for the NFOV and WFOV cameras, respectively, establishing that such blurring is negligible.

COD ranges between 0.3 and 0.5 in 1033. Least square analysis indicate error ranges on the order of 14%

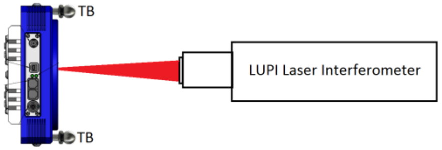
Optical Metrology of the JWST

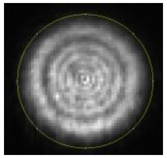


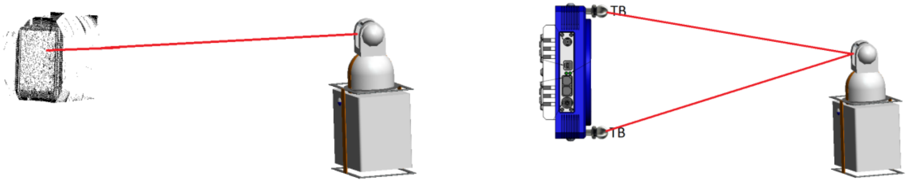


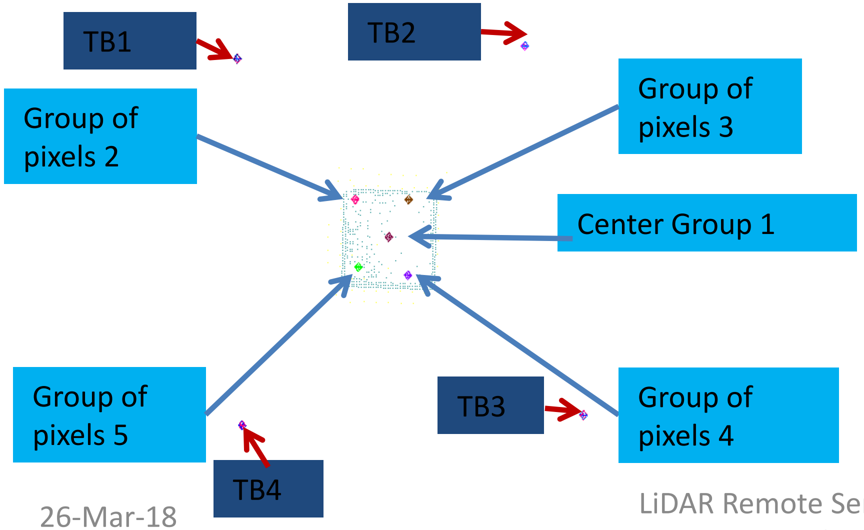
WHERE:
A = IMAGE PLANE TO MOUNTING PLANE
B = IMAGE PLANE TO SHUTTER
C = IMAGE PLANE TO INNER WINDOW SURFACE

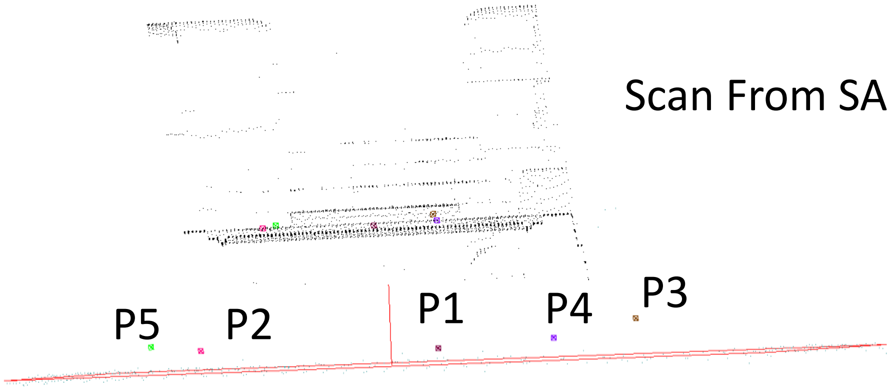
ENGLISH (IN)	CAMERA MODEL	CCD	MECHANICAL DIMENSION		
			A	B	C
STANDARD	U16M	KAF-16803	1.045	0.633	0.220





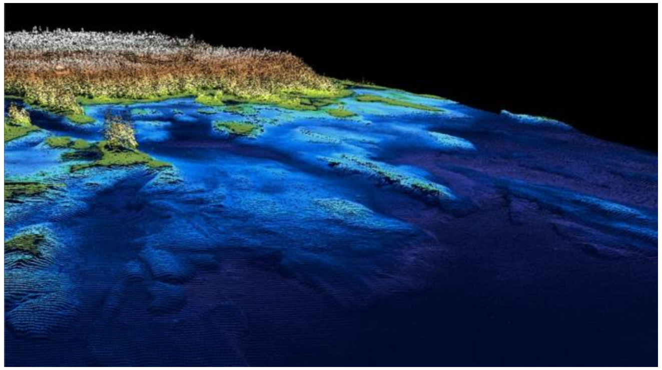






Bathymetry, mapping, and vegetation

Optech Titan



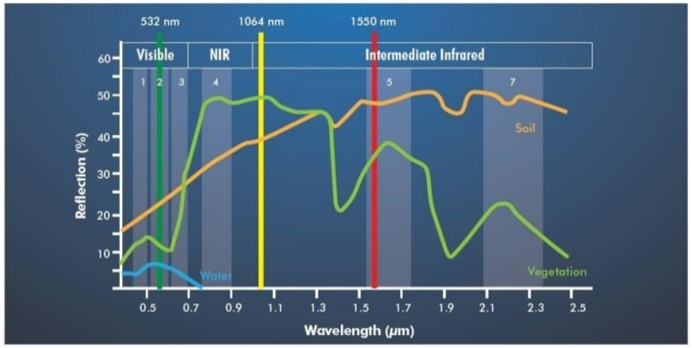
(http://www.teledyneoptech.com/index.php/product/titan/)

-<u>LIDAR</u>: independent wavelengths of 532 nm, 1064, nm and 1550 nm. Each beam has a 300 kHz effective sampling rate

-<u>Camera</u>: 29MP -80 MP fully-electronic; provides high-resolution RGB imagery at high frame rates.

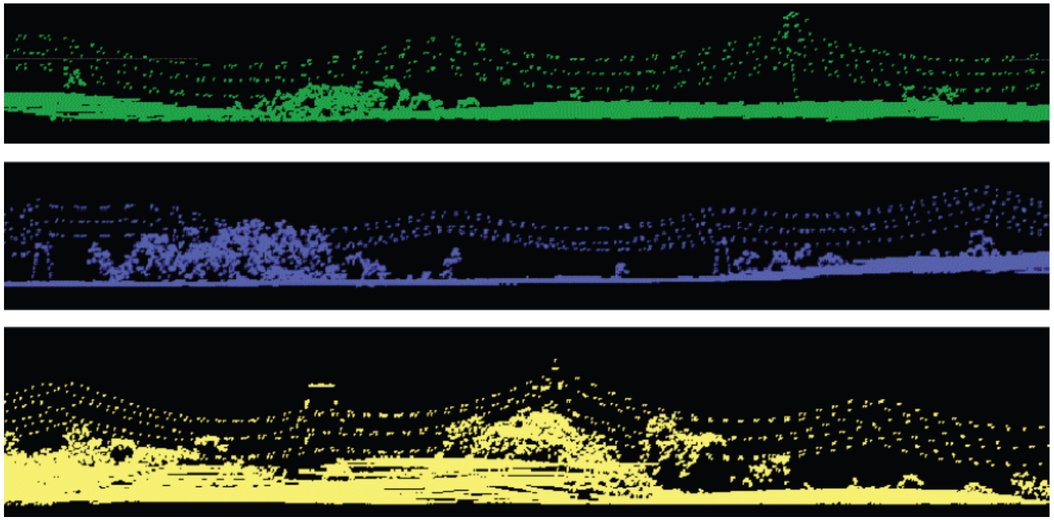
<u>Applications</u>:

- Topographic mapping
- Land cover classification
- Shallow water bathymetry
- Environmental modeling
- Forest inventory and vegetative classification
- Natural resource management
- Disaster response

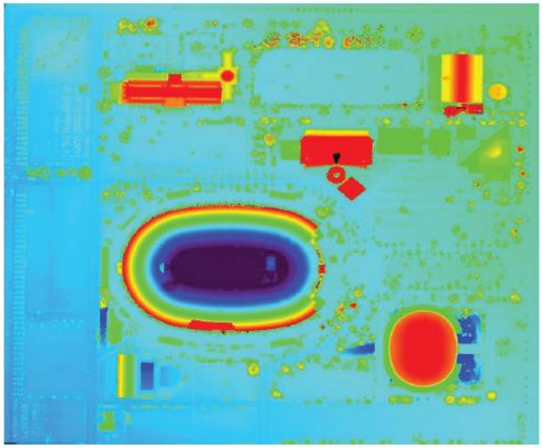


Airborne Laser - Terrain Mapper

Product: ALTM 3033 used for bathymetry

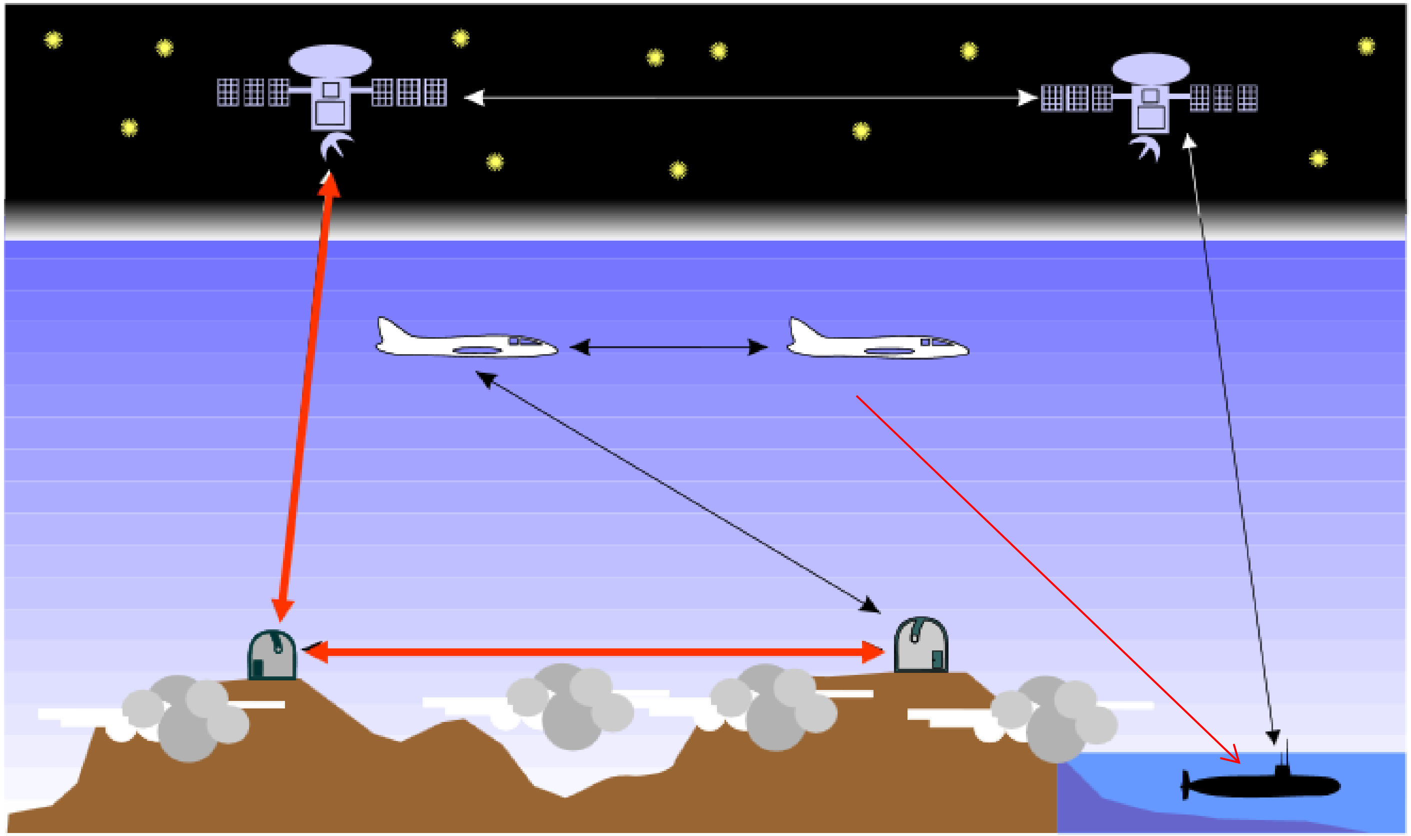


Product: ALTM 1020. Location Toronto, Canada.
Altitude 380 m AGL.
Laser Pulse Freq.: 5 kHz[9]



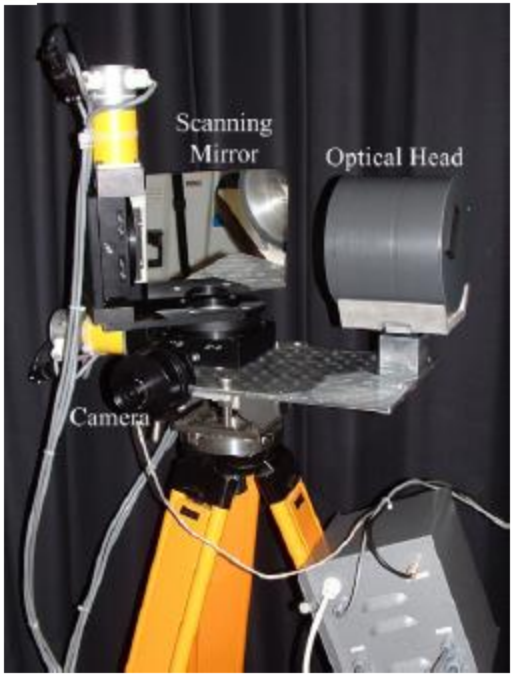
Los Angeles Coliseum.
Digital Elevation Model

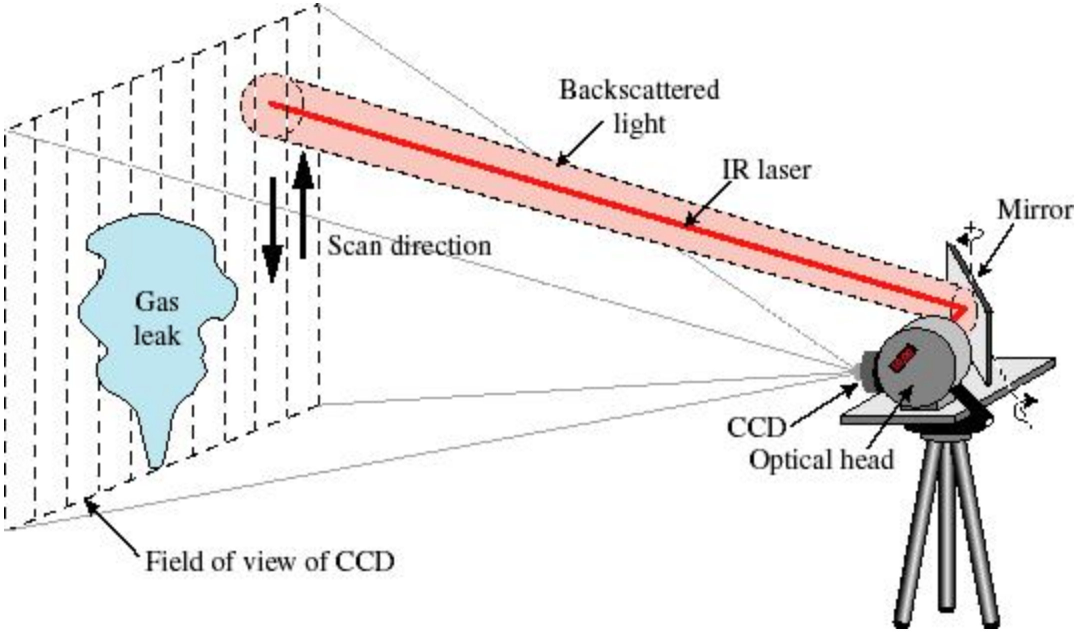
Free Space Optical Communications

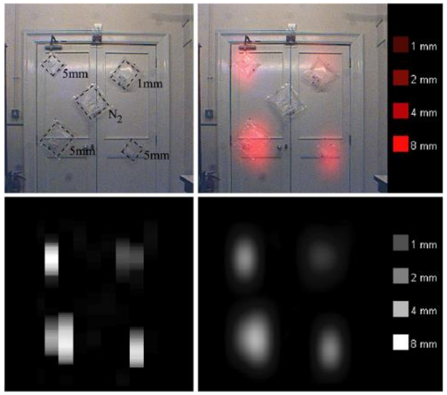


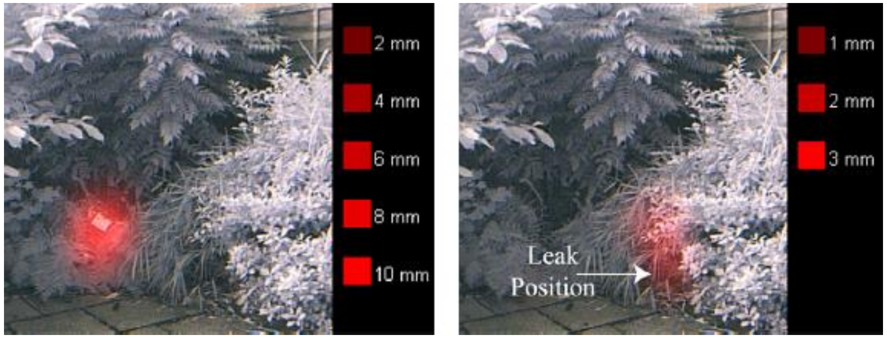
http://www.grss-ieee.org/wp-content/uploads/2010/06/IGARSS07.pdf
https://www.nrl.navy.mil/media/news-releases/2009/lasers-generate-underwater-sound

Scanning Open-Path LiDAR System





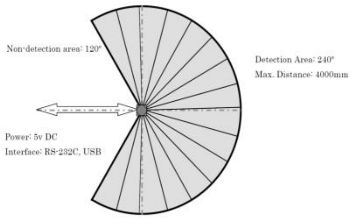




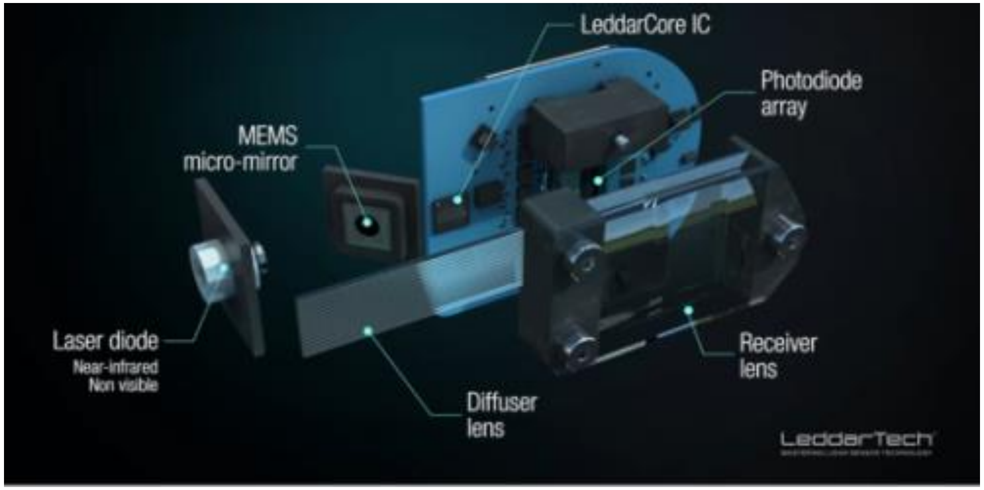
Imaging of methane gas using a scanning, open-path laser system 2006 New J. Phys. 8 26 (http://iopscience.iop.org/1367-2630/8/2/026)

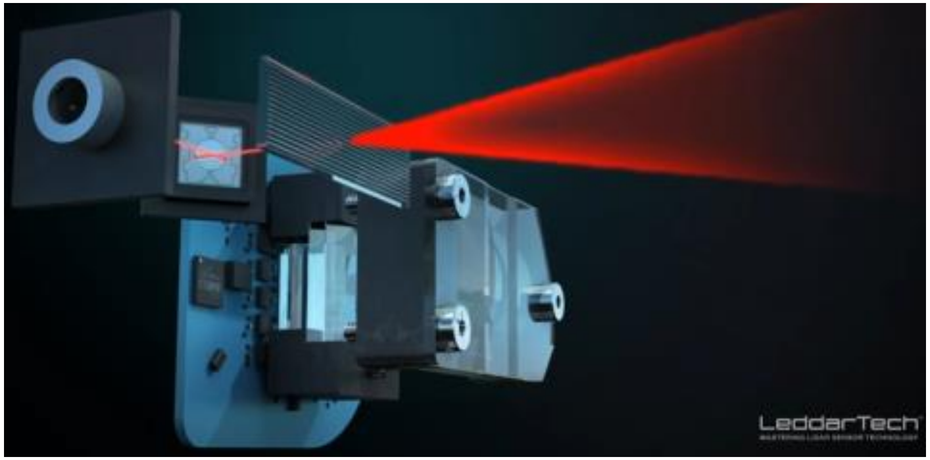
Scanning Range finders

$400-$6,150.00



http://www.hokuyo-aut.jp





http://leddartech.com/modules/leddarvu/

Conclusions

- Interaction of radiation with matter
- Lidar systems working principles
- Lidar system components
- Lidar applications
- How can NASA Glenn and CUNY collaborate to take these lidar applications to the next level?