CEDAR Mini Lidar School on 24 June 2010

LIDAR Exploration of Atmosphere and Space

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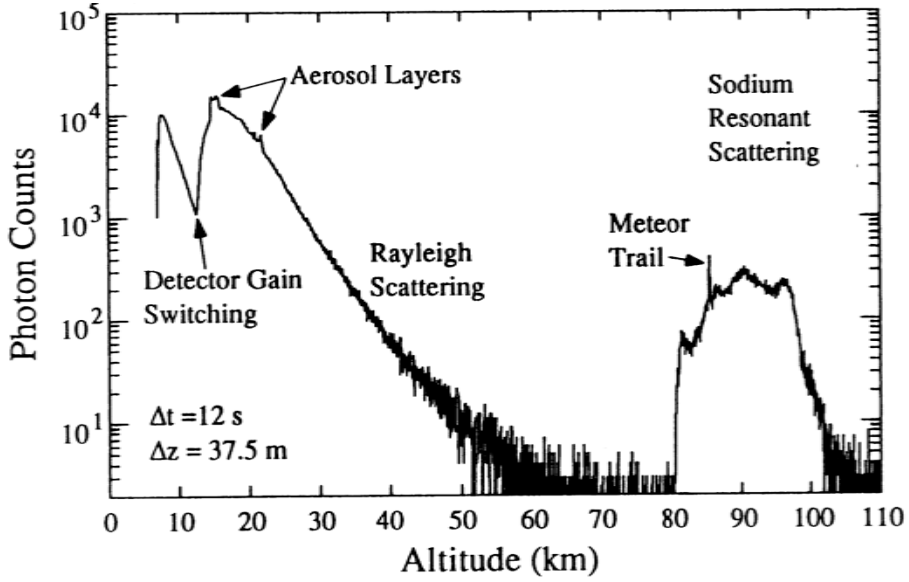
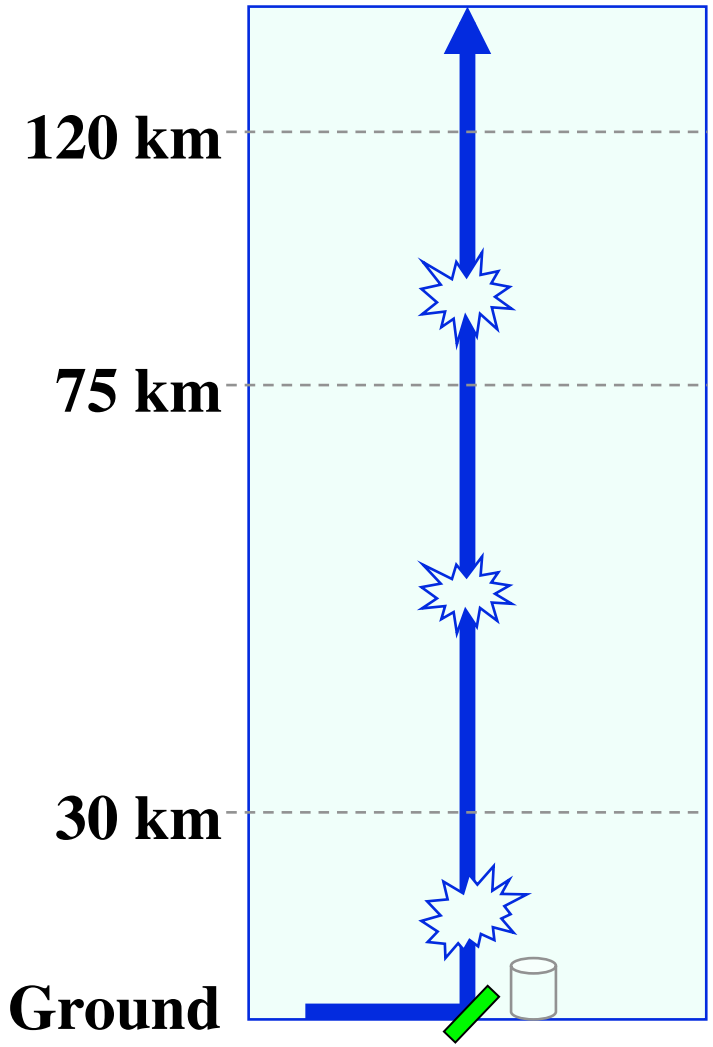
Light Detection And Ranging

- LIDAR Fundamentals
- Physical Interactions in Lidar
- Lidar Data Retrieval
- Lidar Science Highlight
- Conclusions





Time of Flight ⇨ Range / Altitude R = C Δt / 2

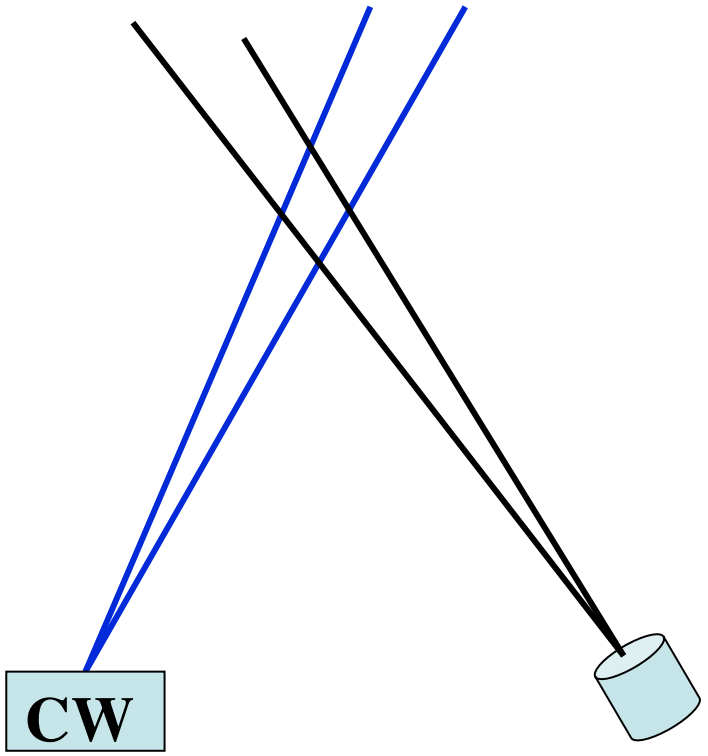
From Searchlight to Modern Lidar

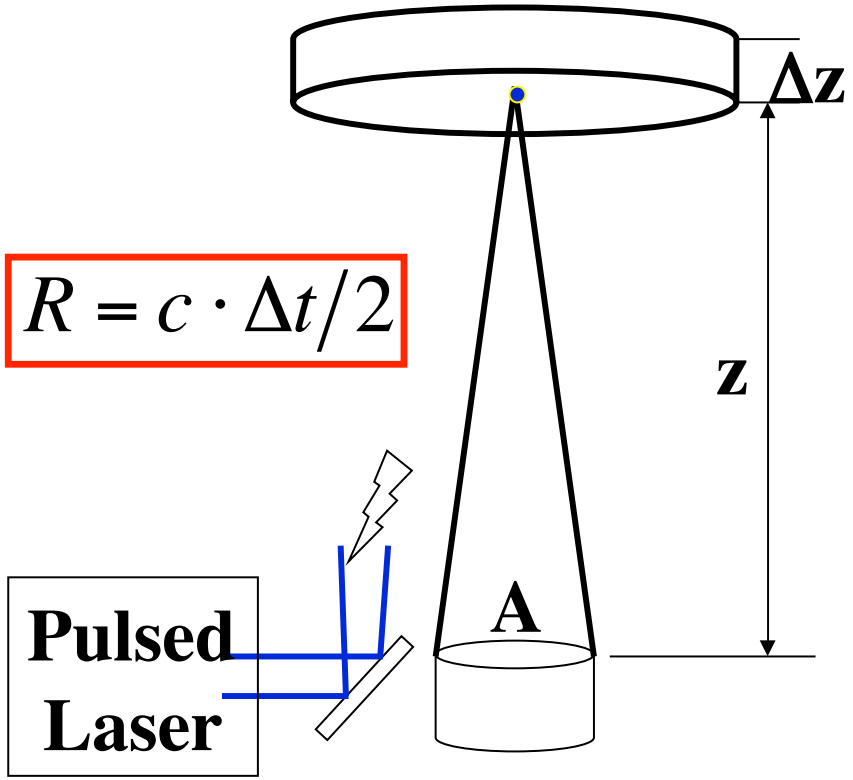
- Light detection and ranging (LIDAR) started with using CW searchlights to measure stratospheric aerosols and molecular density in 1930s.
- Hulburt [1937] pioneered the searchlight technique. Elterman [1951, 1954, 1966] pushed the searchlight lidar to a high level and made practical devices.
- The first laser - a ruby laser was invented in 1960 by Schawlow and Townes [1958] (fundamental work) and Maiman [1960] (construction). The first giant-pulse technique (Q-Switch) was invented by McClung and Hellwarth [1962].
- The first laser studies of the atmosphere were undertaken by Fiocco and Smullin [1963] for upper region and by Ligda [1963] for troposphere.

From Aerosol Detection to Spectral Analysis

- The first application of lidar was the detection of atmospheric aerosols and density: detecting only the scattering intensity but no spectral information.
- An important advance in lidar was the recognition that the spectra of the detected radiation contained highly specific information related to the species, which could be used to determine the composition of the object region. Laser-based spectral analysis added a new dimension to lidar and made possible an extraordinary variety of applications, ranging from groundbased probing of the trace-constituent distribution in the tenuous outer reaches of the atmosphere, to lower atmosphere constituents, to airborne chlorophyll mapping of the oceans to establish rich fishing areas.

Lidar Configuration

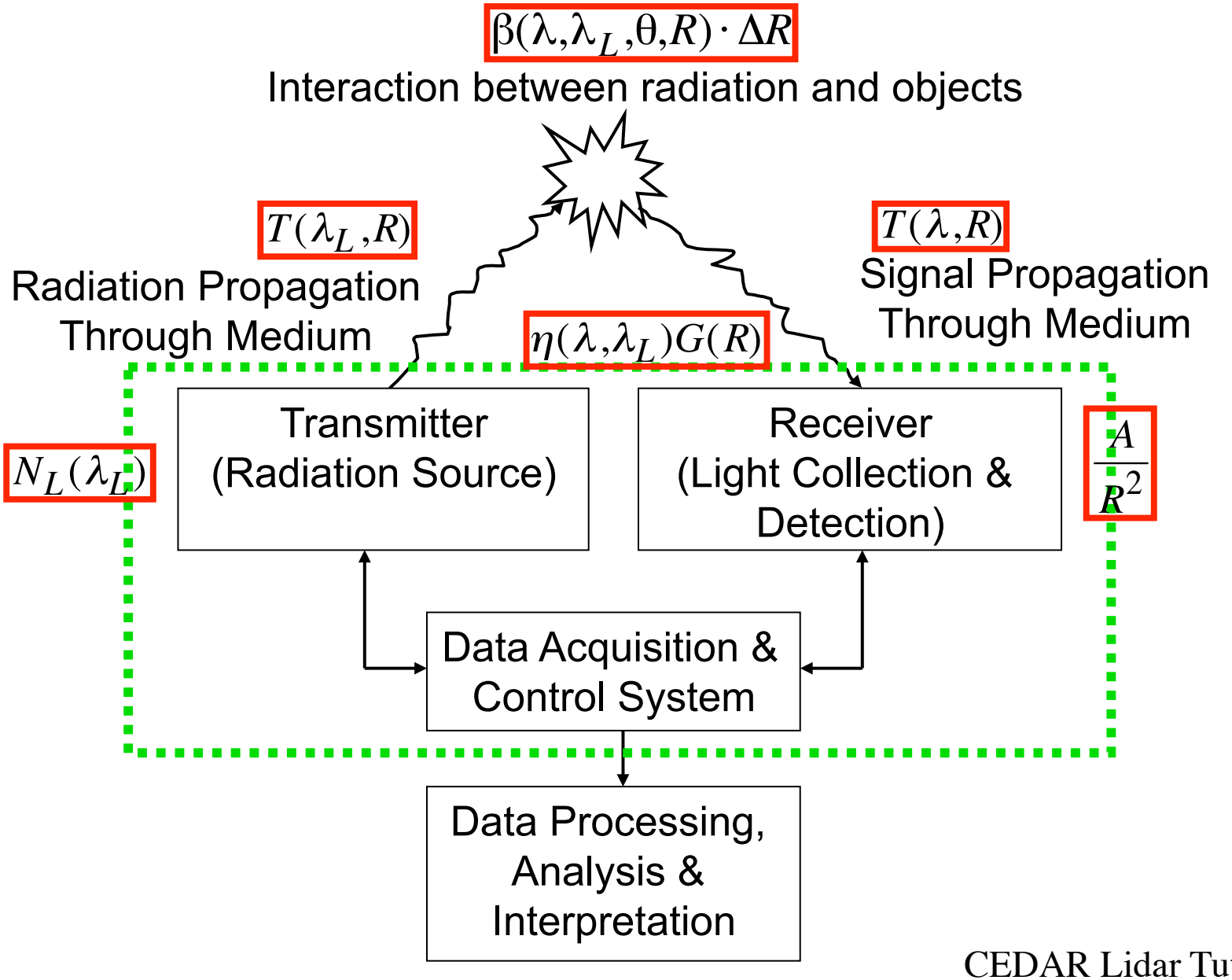




Bistatic Configuration **Monostatic Configuration**

CW searchlight → ns laser pulse

Picture of Lidar Remote Sensing



Lidar Equation

- General lidar equation with angular scattering coefficient

$$N_S(\lambda,R) = N_L(\lambda_L)\cdot\left[\beta(\lambda,\lambda_L,\theta,R)\Delta R\right]\cdot\frac{A}{R^2}\cdot\left[T(\lambda_L,R)T(\lambda,R)\right]\cdot\left[\eta(\lambda,\lambda_L)G(R)\right]+N_B$$

Photons received

Photons transmitted

Scattering Probability

Receiving Probability

Transmission through medium

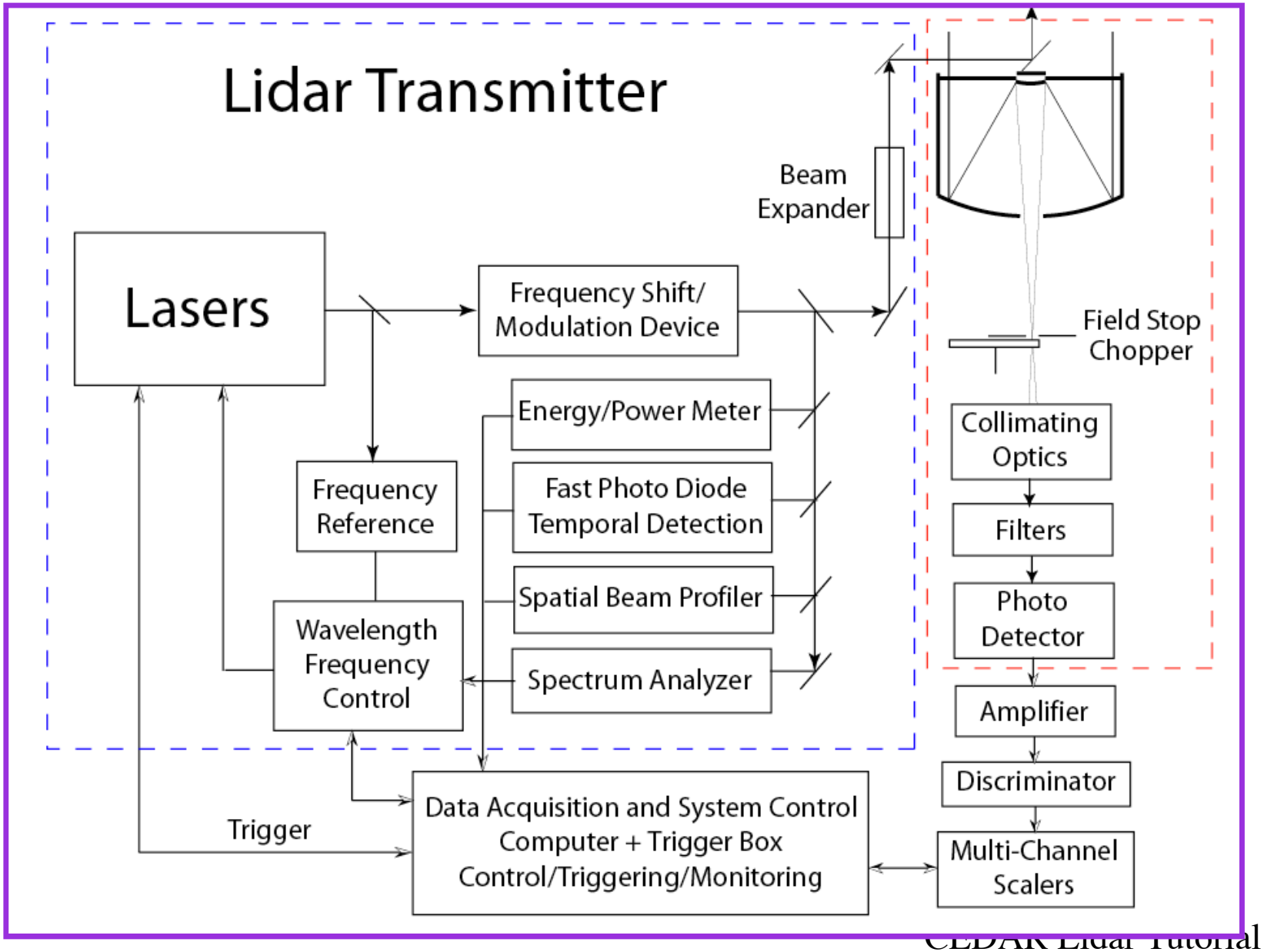
Lidar system efficiency

Background counts

- General lidar equation in angular scattering coefficient β and extinction coefficient α form

$$N_S(\lambda,R) = \left[\frac{P_L(\lambda_L)\Delta t}{hc/\lambda_L}\right]\left[\beta(\lambda,\lambda_L,\theta,R)\Delta R\right]\left(\frac{A}{R^2}\right)$$
$$\cdot\exp\left[-\int_0^R\alpha(\lambda_L,r')dr'\right]\exp\left[-\int_0^R\alpha(\lambda,r')dr'\right]\left[\eta(\lambda,\lambda_L)G(R)\right]+N_B$$

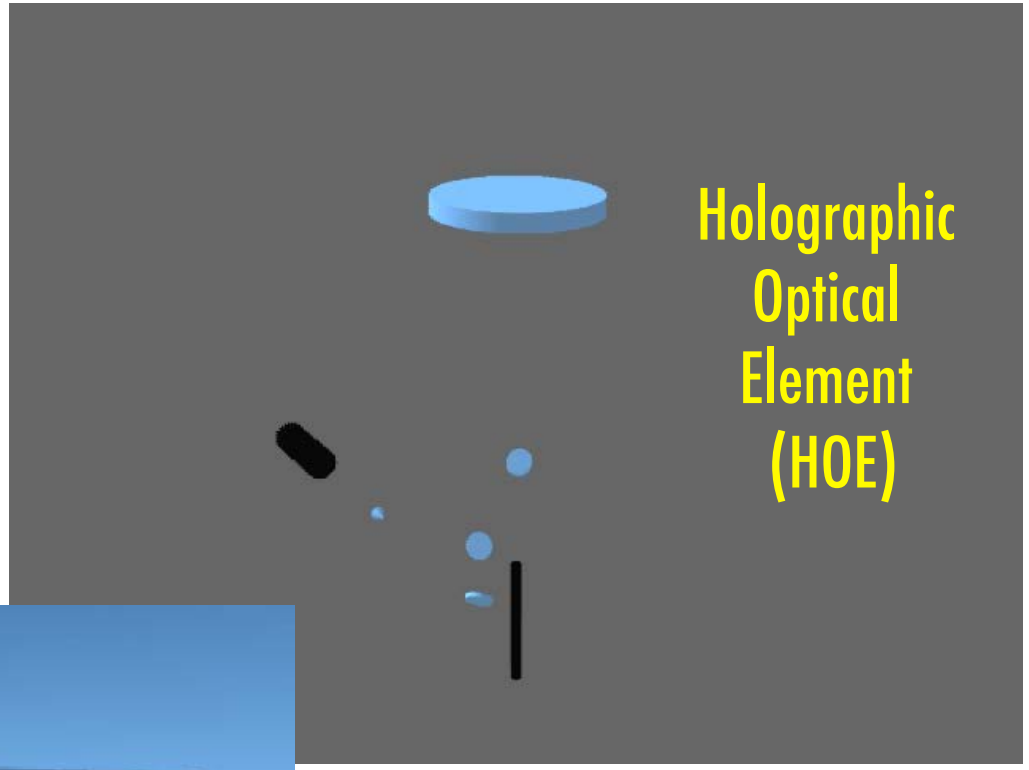
Biaxial vs. Coaxial Arrangements

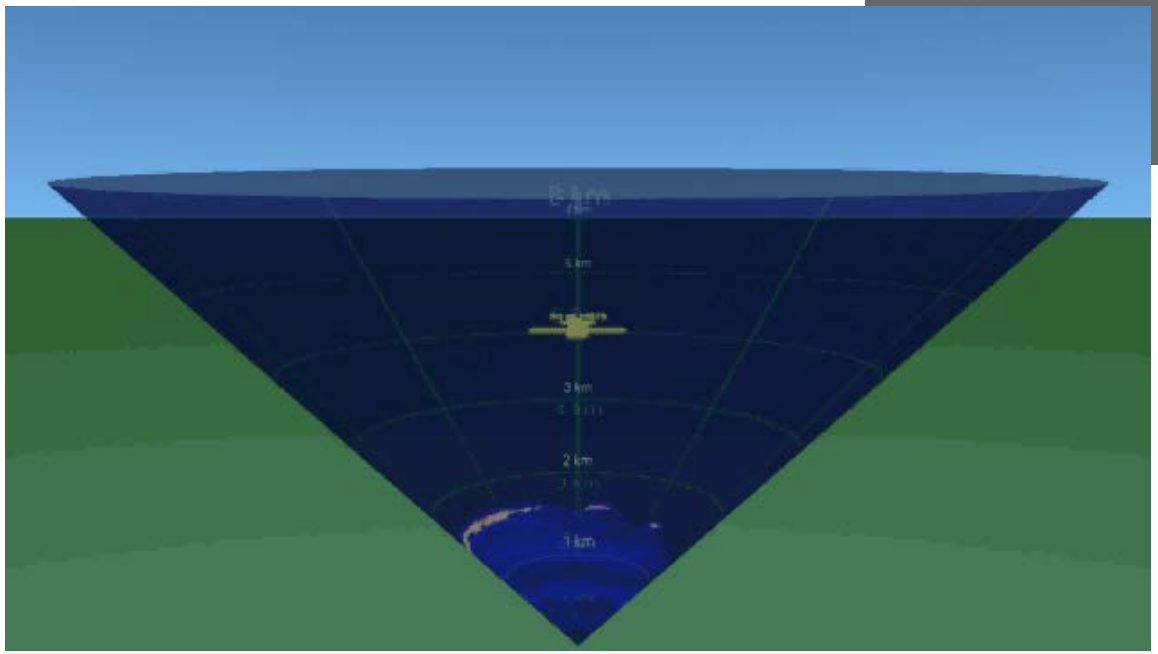


"Fancy" Lidar Architecture

Transceiver
(Light Source, Light Collection, Lidar Detection)

Data Acquisition & Control System

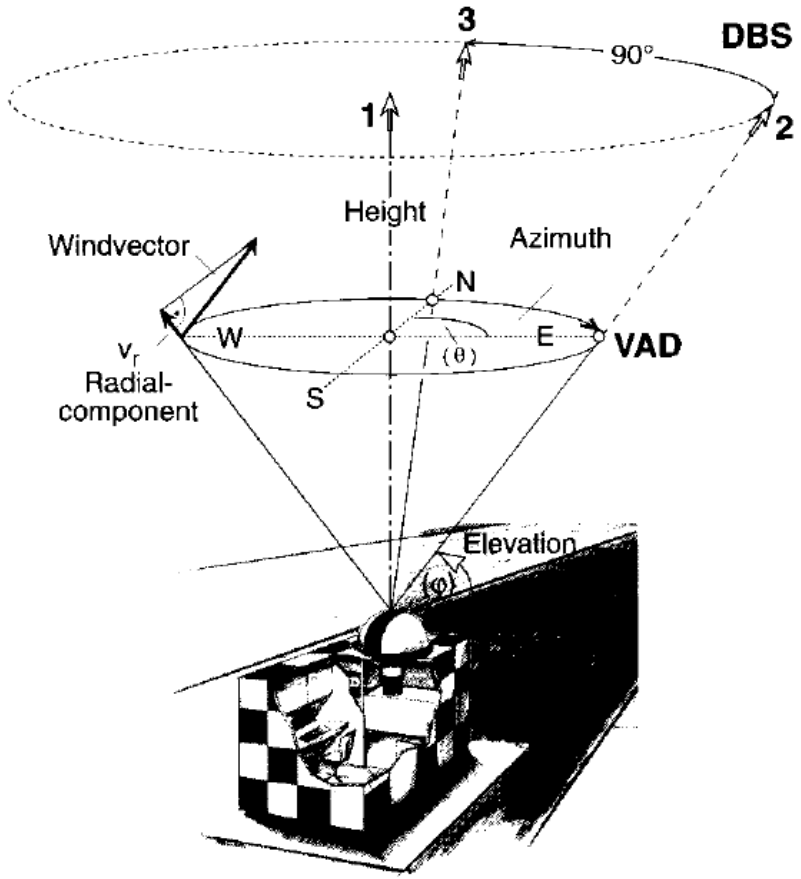


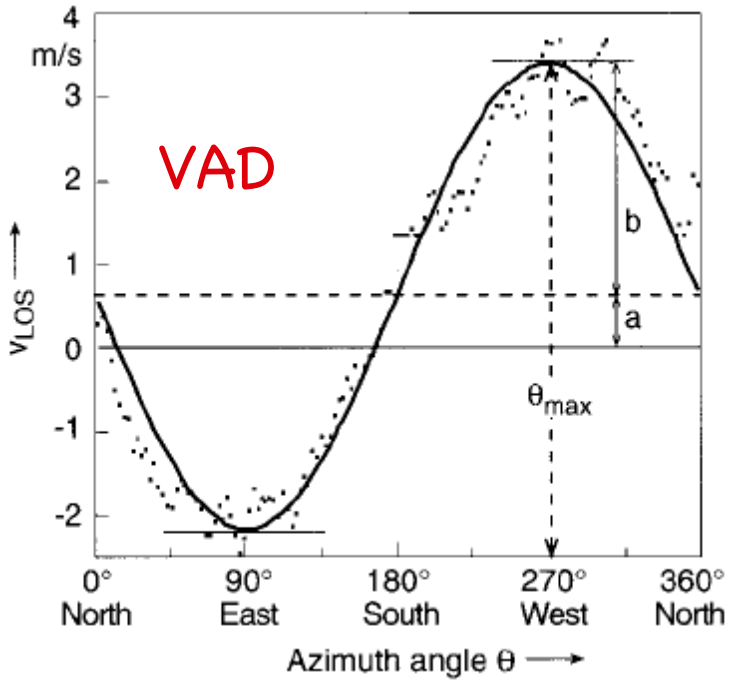


Courtesy to Geary Schwemmer

VAD Technique for Vector Wind

- Velocity-Azimuth-Display (VAD) technique: swing lidar beam through 360° azimuth at a fixed elevation angle - lower atm lidar.



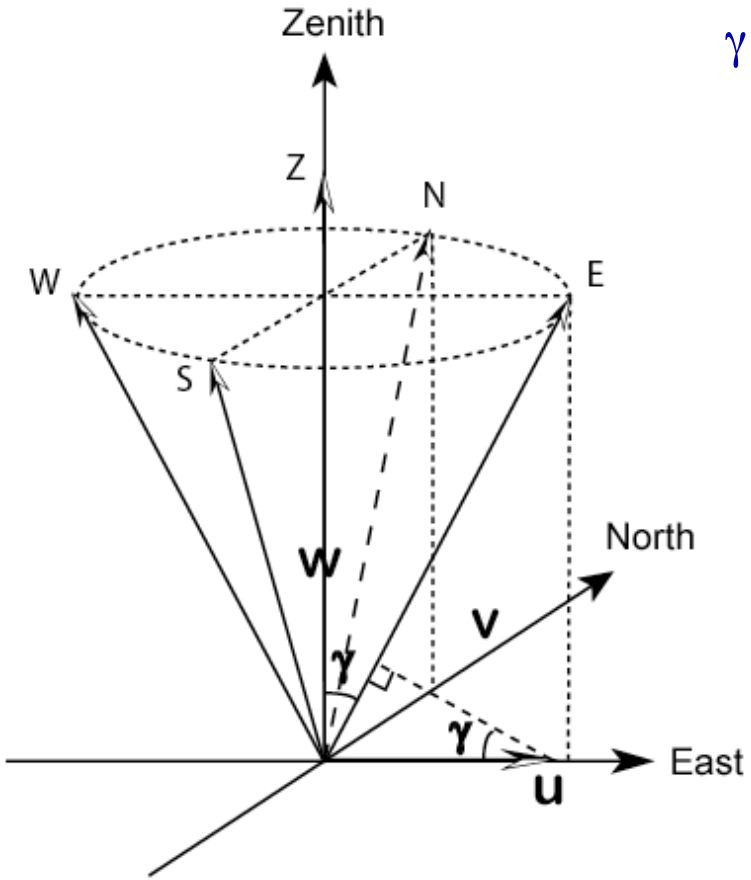


$$V_R = u\sin\theta\cos\varphi + v\cos\theta\cos\varphi + w\sin\varphi$$

$$VectorWind = (u,v,w) = (b\sin\theta_{\max}/\cos\varphi, b\cos\theta_{\max}/\cos\varphi, a/\sin\varphi)$$

DBS Technique for Vector Wind

- Doppler-Beam-Swinging (DBS) technique: pointing lidar beam to vertical, north, and east, or plus south and west (ZNEZSW).



γ is the off-zenith angle

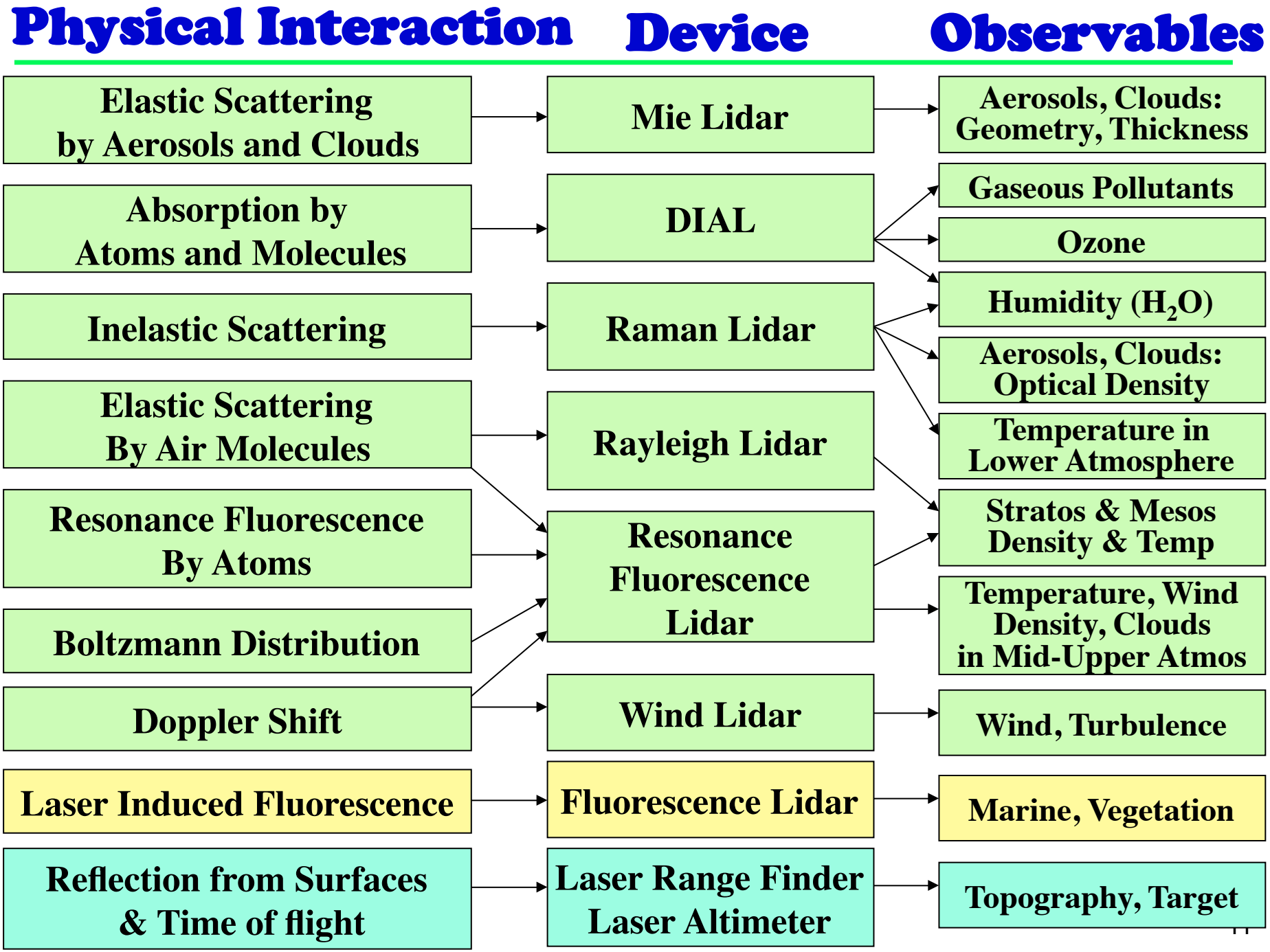
$$V_{RE} = u\sin\gamma + w\cos\gamma$$
$$V_{RN} = v\sin\gamma + w\cos\gamma$$
$$V_{RZ} = w$$

$$u = (V_{RE} - V_{RZ}\cos\gamma)/\sin\gamma$$
$$v = (V_{RN} - V_{RZ}\cos\gamma)/\sin\gamma$$
$$w = V_{RZ}$$

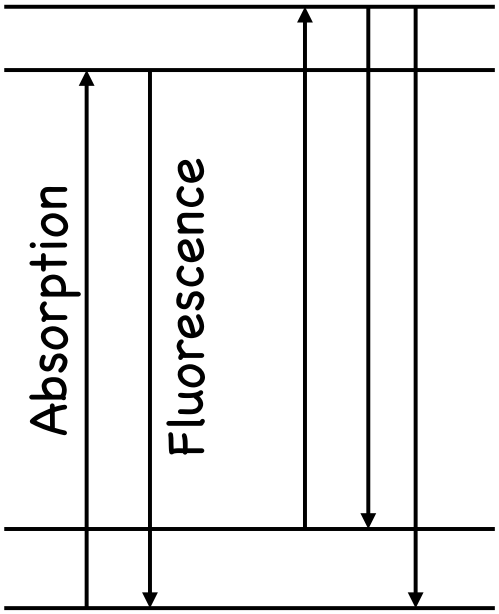
$$V_{RE} = u\sin\gamma + w\cos\gamma$$
$$V_{RW} = -u\sin\gamma + w\cos\gamma$$
$$V_{RN} = v\sin\gamma + w\cos\gamma$$
$$V_{RS} = -v\sin\gamma + w\cos\gamma$$
$$V_{RZ} = w$$

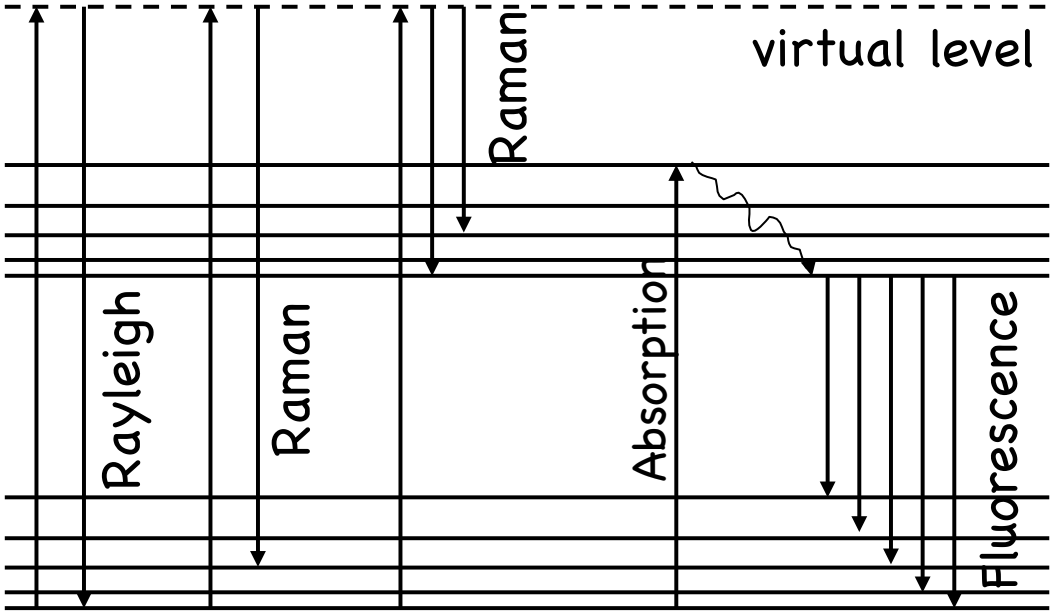
$$u = (V_{RE} - V_{RW})/\sin\gamma/2$$
$$v = (V_{RN} - V_{RS})/\sin\gamma/2$$
$$w = V_{RZ}$$

V_R > 0, w > 0, u > 0, v > 0 for wind towards away, upward, east, and north


Physical Interaction
Device
Observables
Elastic Scattering by Aerosols and Clouds
Absorption by Atoms and Molecules
Inelastic Scattering
Elastic Scattering By Air Molecules
Resonance Fluorescence By Atoms
Boltzmann Distribution
Doppler Shift
Laser Induced Fluorescence
Reflection from Surfaces & Time of flight
Mie Lidar
DIAL
Raman Lidar
Rayleigh Lidar
Resonance Fluorescence Lidar
Wind Lidar
Fluorescence Lidar
Laser Range Finder Laser Altimeter
Aerosols, Clouds: Geometry, Thickness
Gaseous Pollutants
Ozone
Humidity (H_2O)
Aerosols, Clouds: Optical Density
Temperature in Lower Atmosphere
Stratos & Mesos Density & Temp
Temperature, Wind Density, Clouds in Mid-Upper Atmos
Wind, Turbulence
Marine, Vegetation
Topography, Target

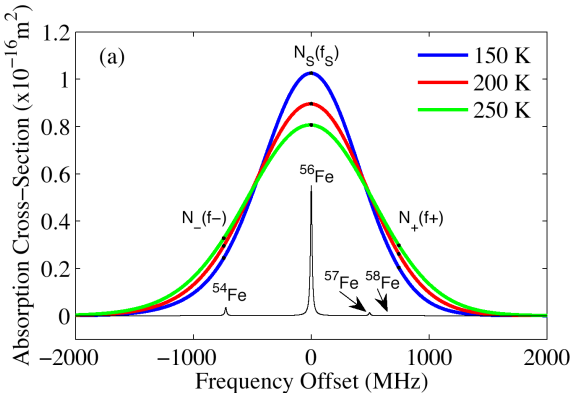
Elastic and Inelastic Scattering

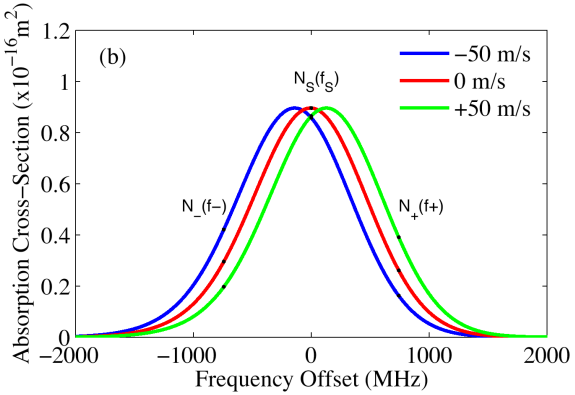


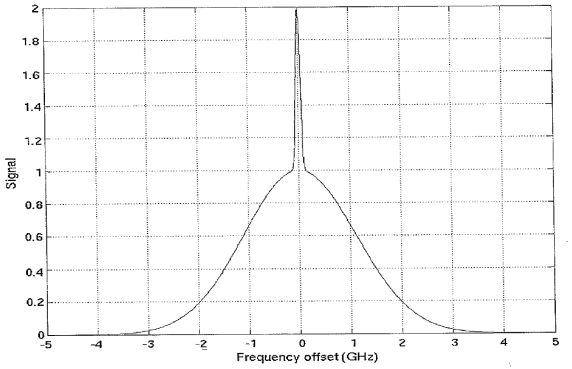


Atomic absorption & (resonance) fluorescence

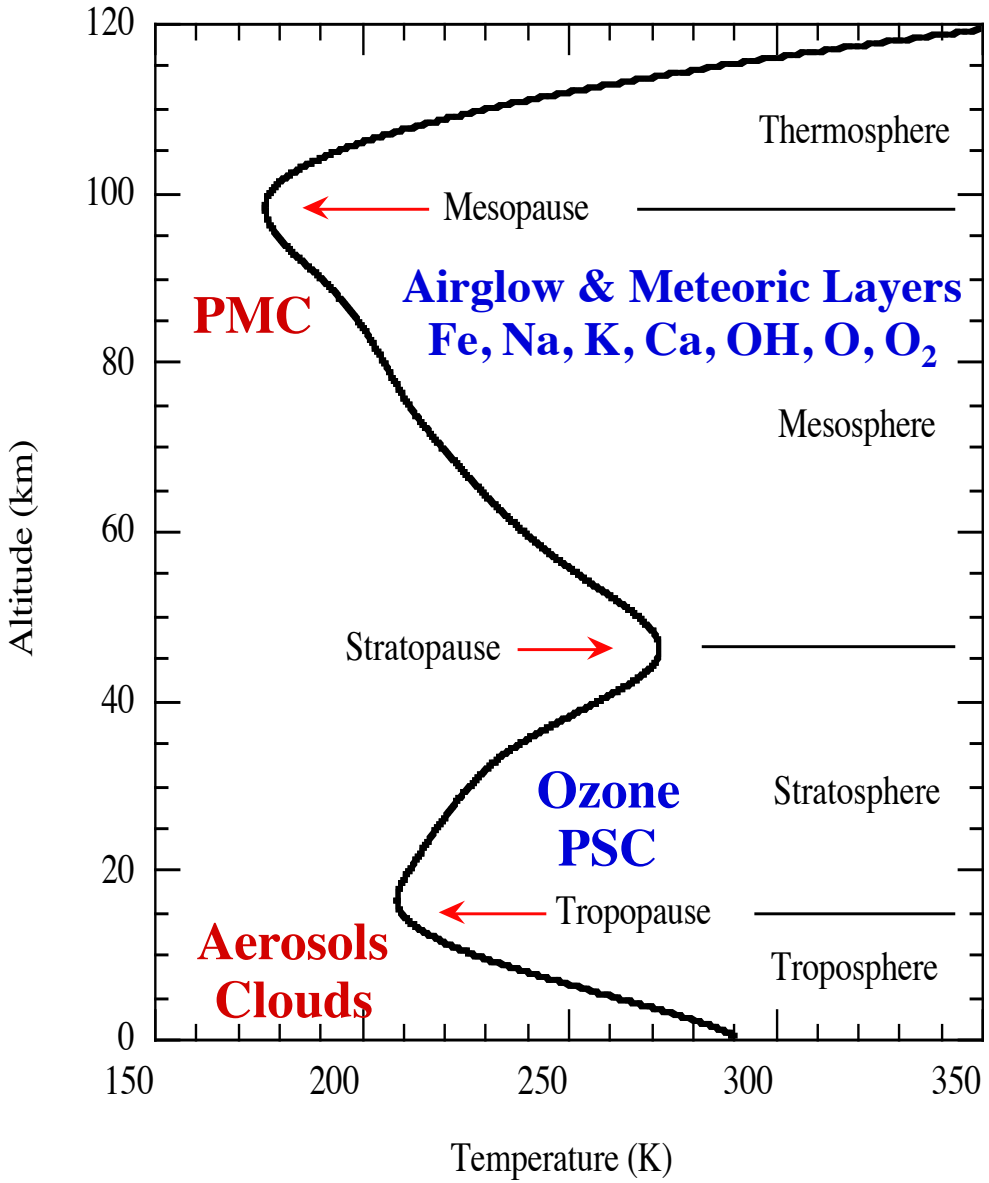
Molecular elastic and inelastic scattering, absorption and fluorescence





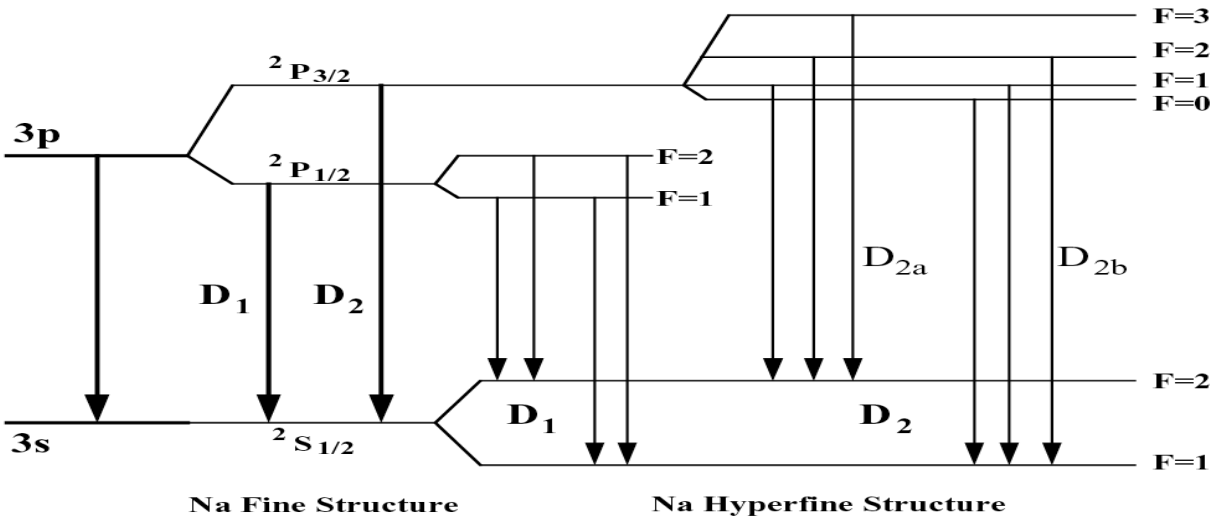


Physical Interactions in Lidar



- 70-120 km and above 120 km: resonance fluorescence (Fe, Na, K, He, O, N_2^+) Doppler, Boltzmann, differential absorption lidar
- Airglow, FP Interferometer
- Molecule & aerosol scattering, Rayleigh and Raman integration , direct detection Doppler lidar
- Molecular species, differential absorption and Raman lidar
- Molecule & aerosol scattering High-spectral resolution lidar, Coherent detection Doppler lidar, Direct detection Doppler lidar, Direct motion detection tech (tracking aerosols, LDV, LTV)

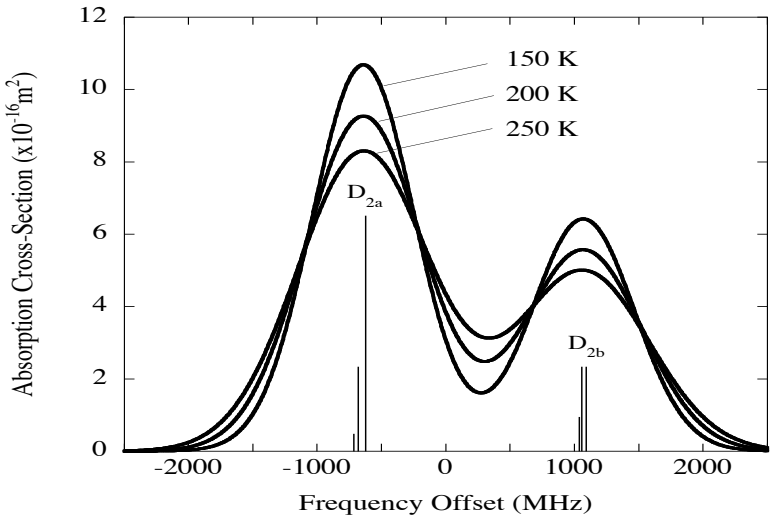
Na Doppler (Wind & Temp) Lidar

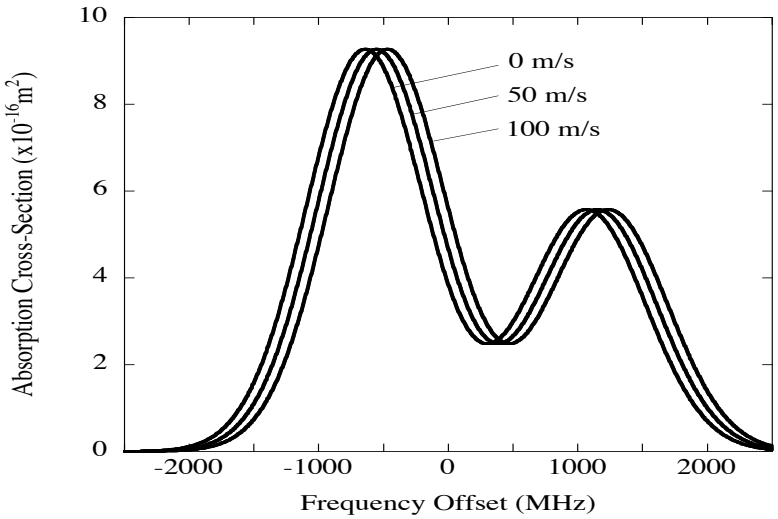


Energy Level Diagram of Atomic Na

$$\sigma_D = \sqrt{\frac{k_B T}{M\lambda_0^2}}$$

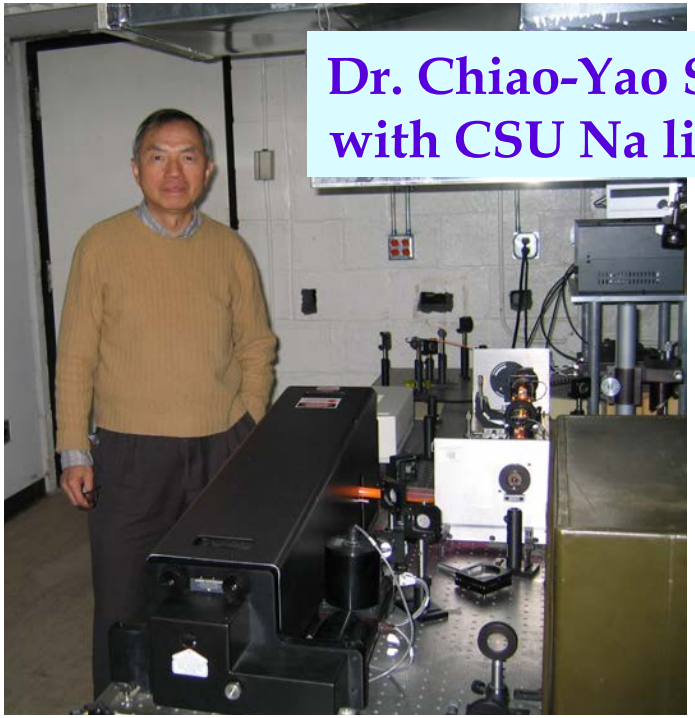
$$\nu' = \nu\left(1 - \frac{V_R}{c}\right)$$



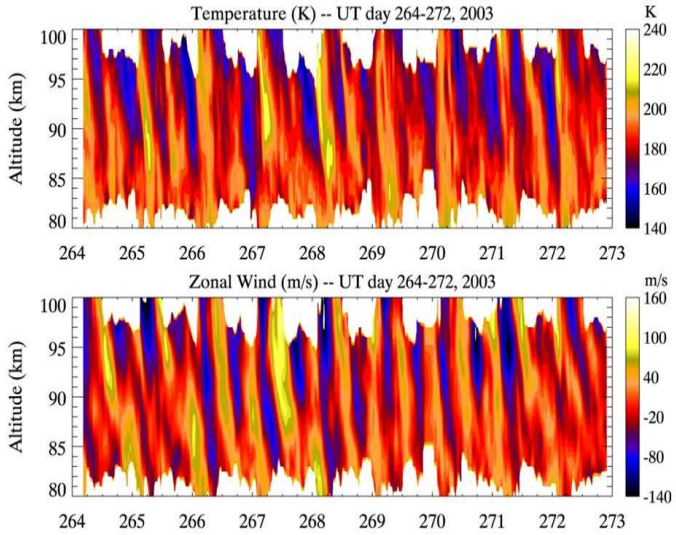


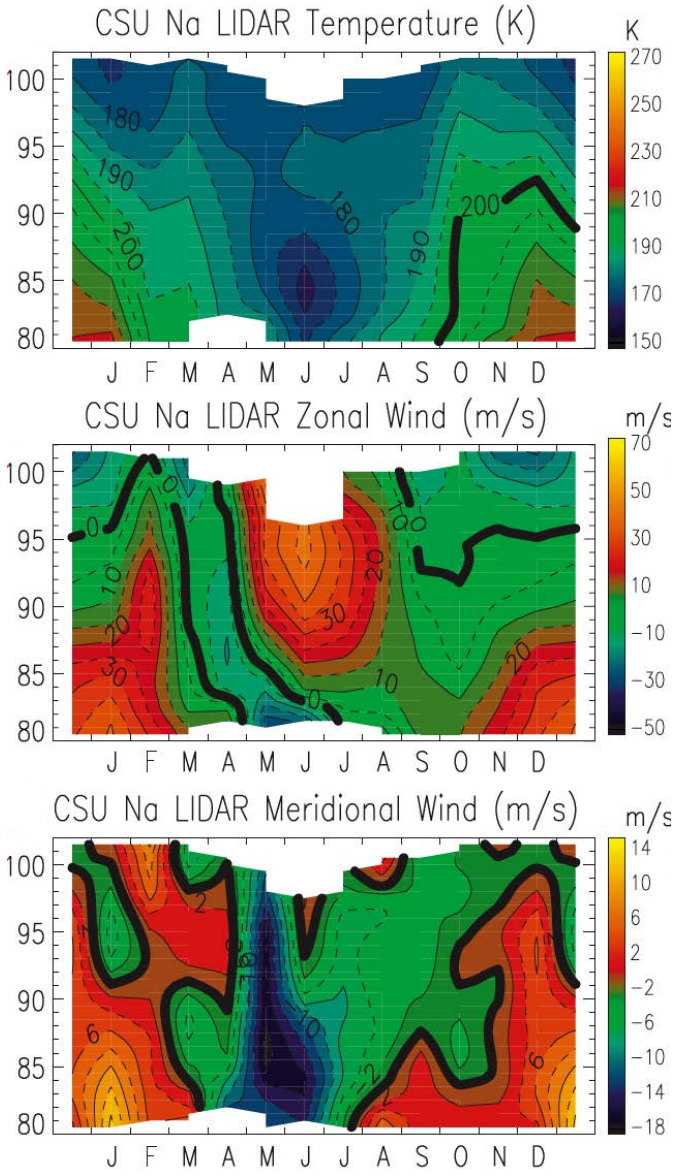
Resonance Fluorescence, Frequency Analyzer in Atmosphere

Full-Diurnal Multiple-Beam Obs.



Dr. Chiao-Yao She with CSU Na lidar

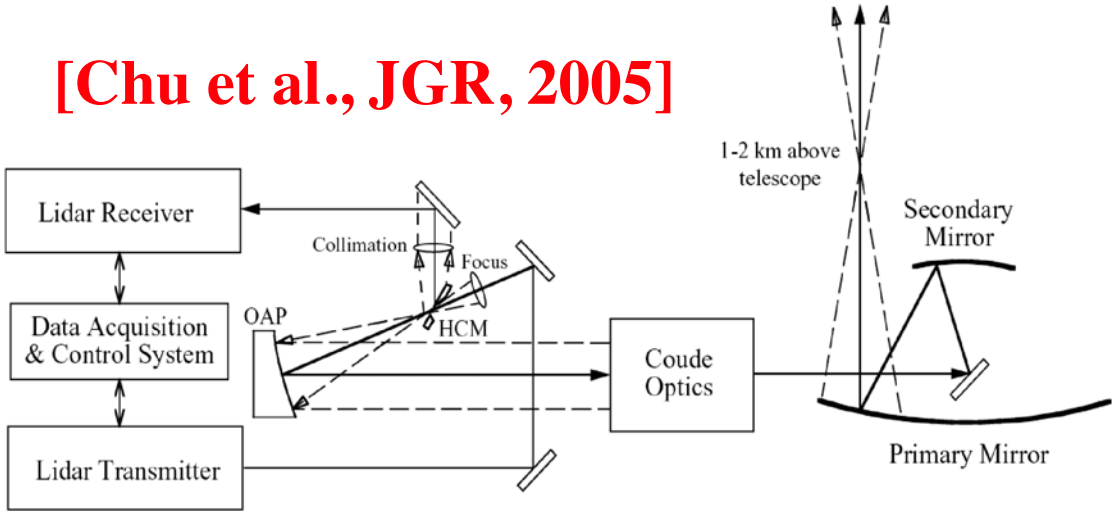




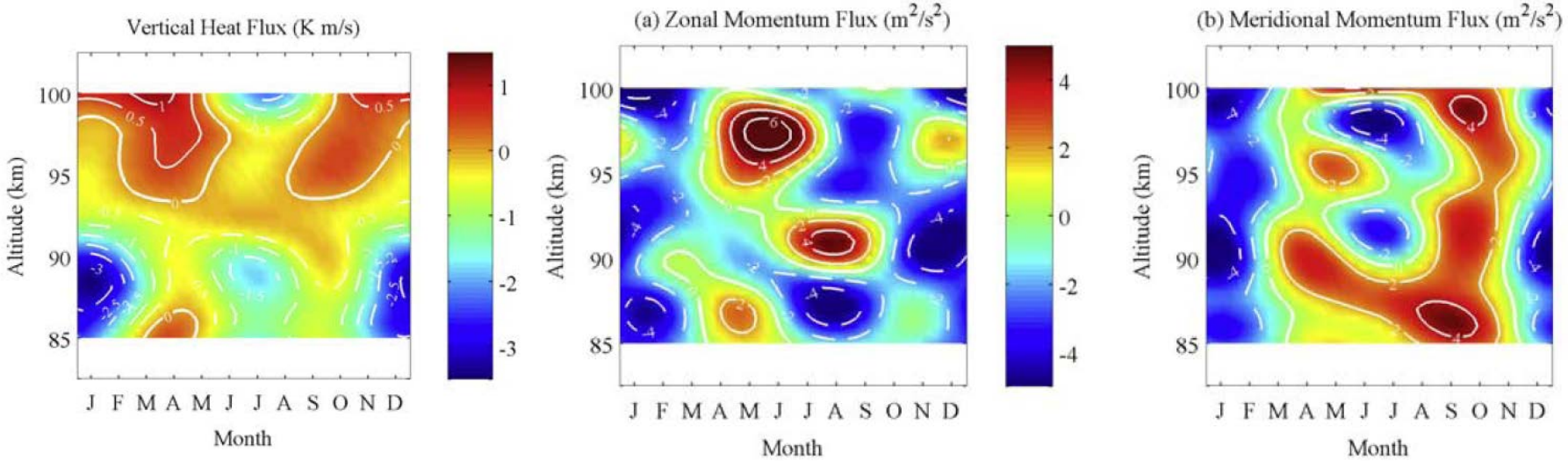
[Yuan et al., JGR, 2008]

Large Aperture for High Precision

[Chu et al., JGR, 2005]

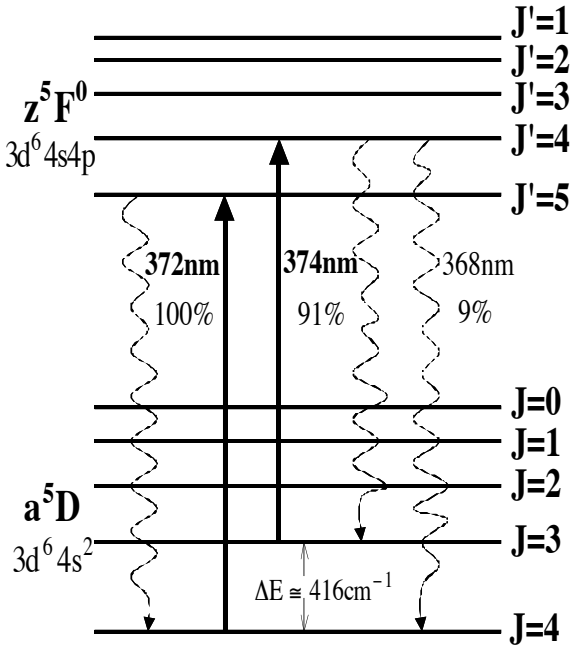


UIUC Na Wind & Temperature Lidar Coupled with Large Telescope



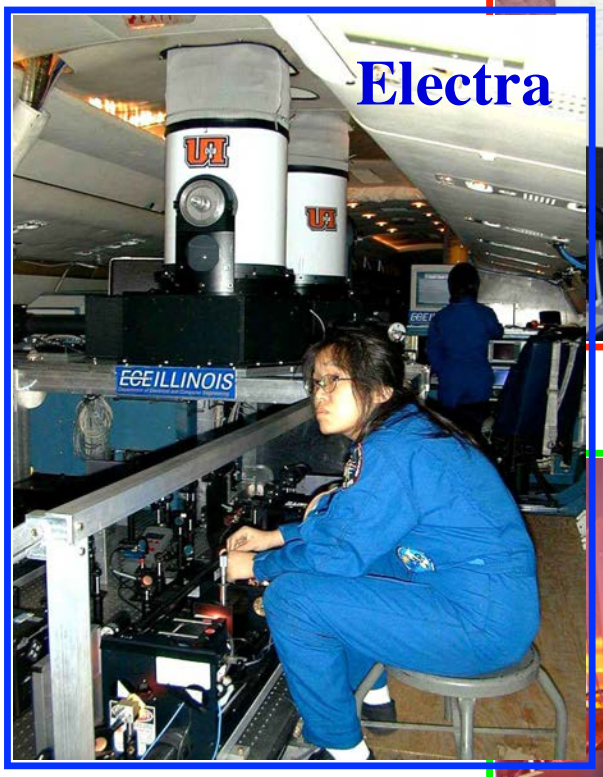
[Gardner and Liu, JGR, 2007]

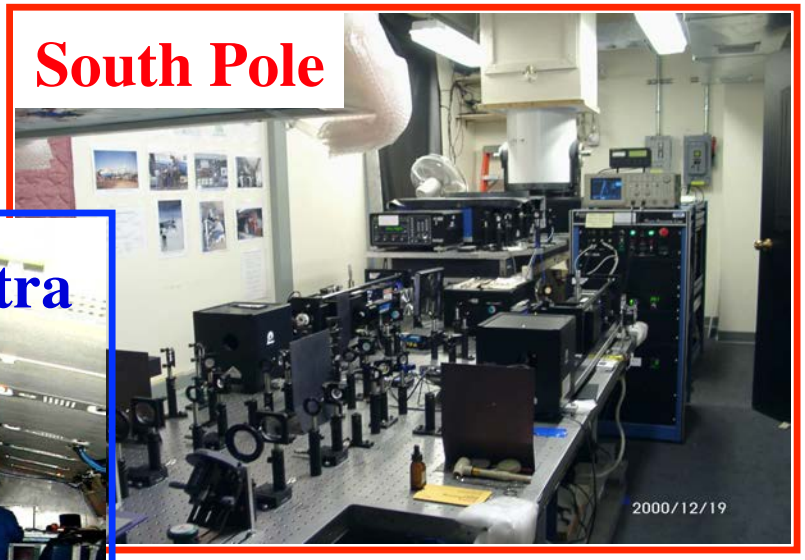
Fe Boltzmann Temperature LIDAR

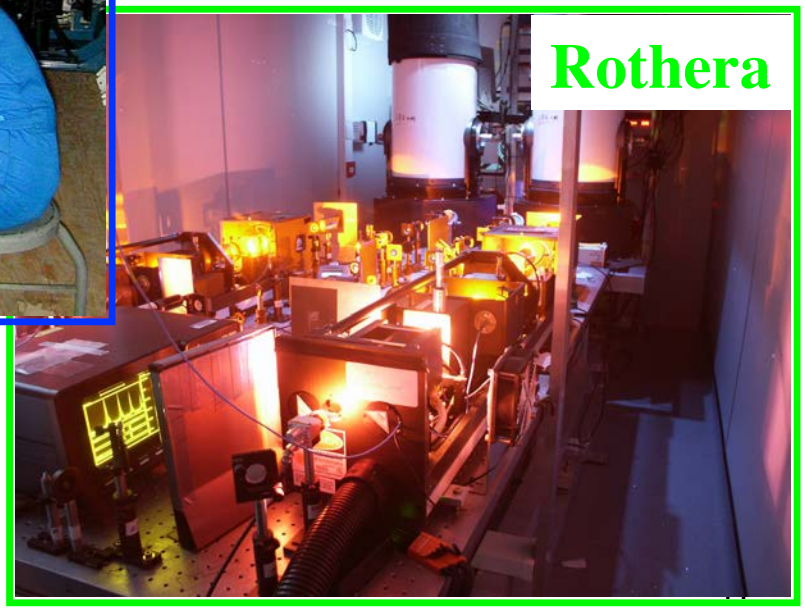


$$\frac{P_2(J=3)}{P_1(J=4)} = \frac{g_2}{g_1}\exp(-\Delta E/k_B T)$$

$$T = \frac{\Delta E / k_B}{ln\left(\frac{g_2}{g_1}\cdot\frac{P_1}{P_2}\right)}$$

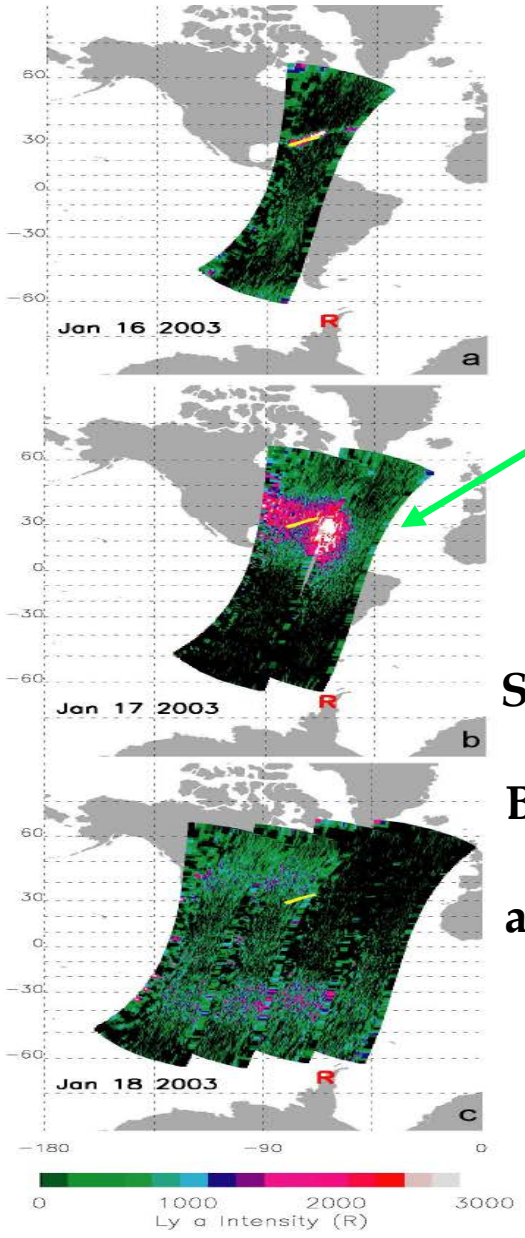






[Gelbwachs, 1994; Chu et al., 2002]

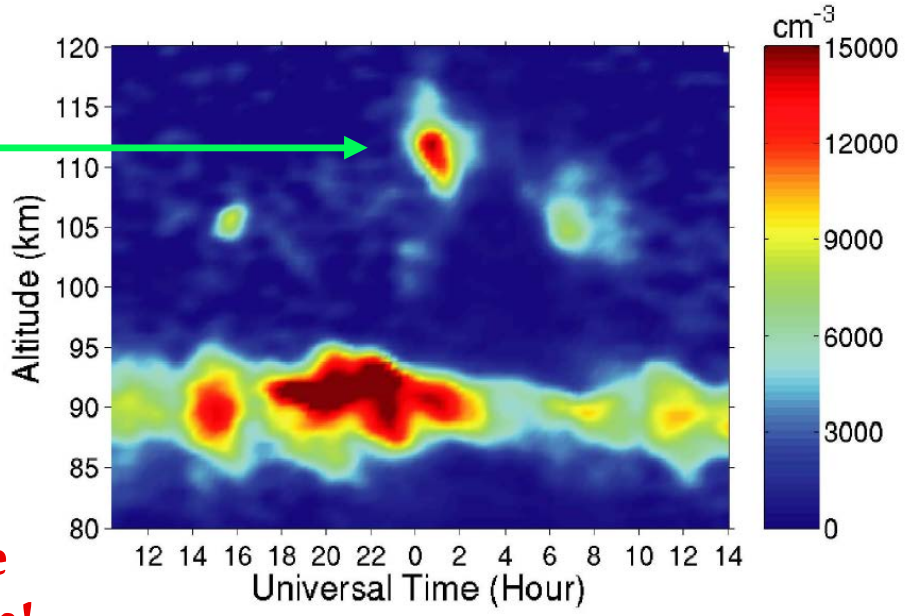
Shuttle Formed High-Z Sporadic Fe



Columbia Space Shuttle launched on Jan 16, 2003

Lyman α Images from GUVI/ TIMED

High-Altitude Sporadic Fe layer detected by Fe Boltzmann Lidar on Jan 19, 2003 at Rothera (67.5S)

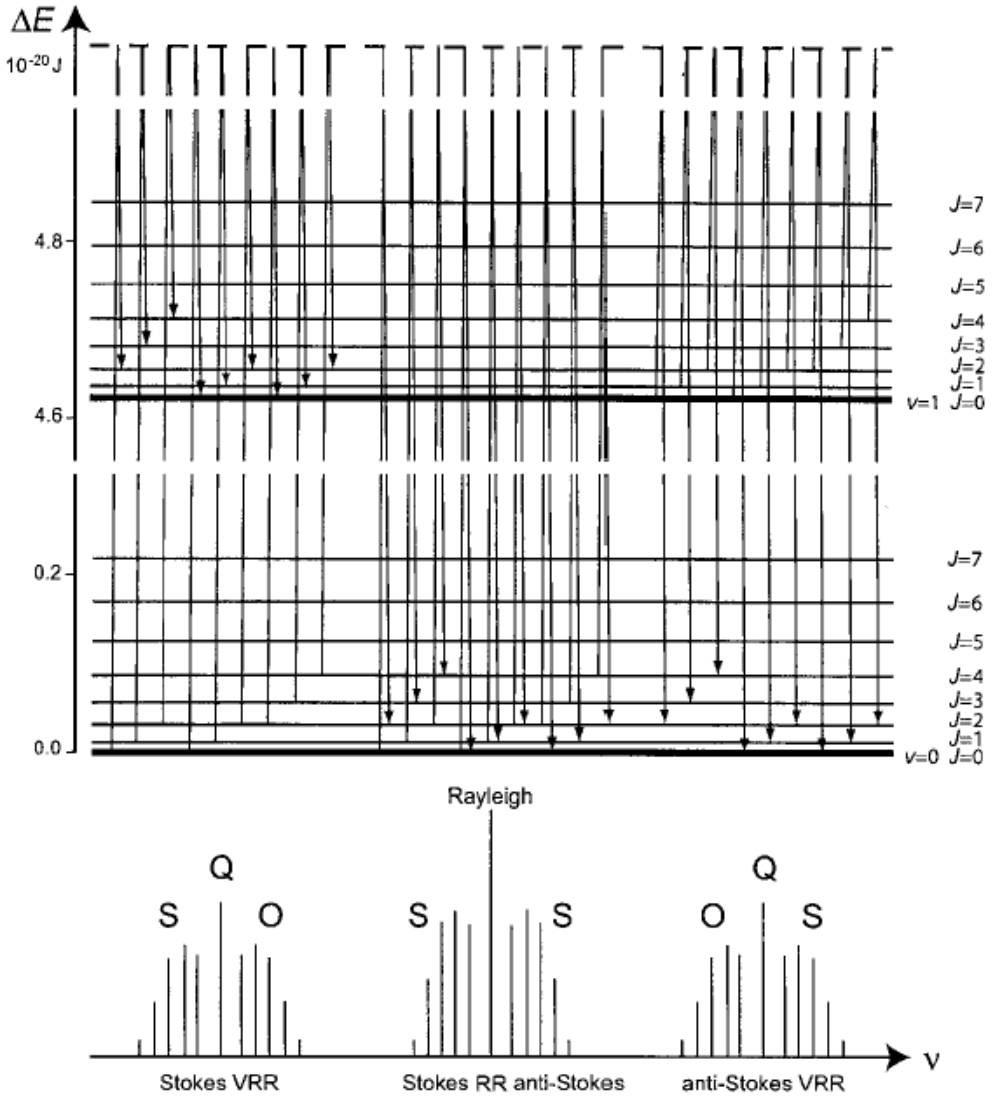


Causes: Shuttle Engine Ablation!

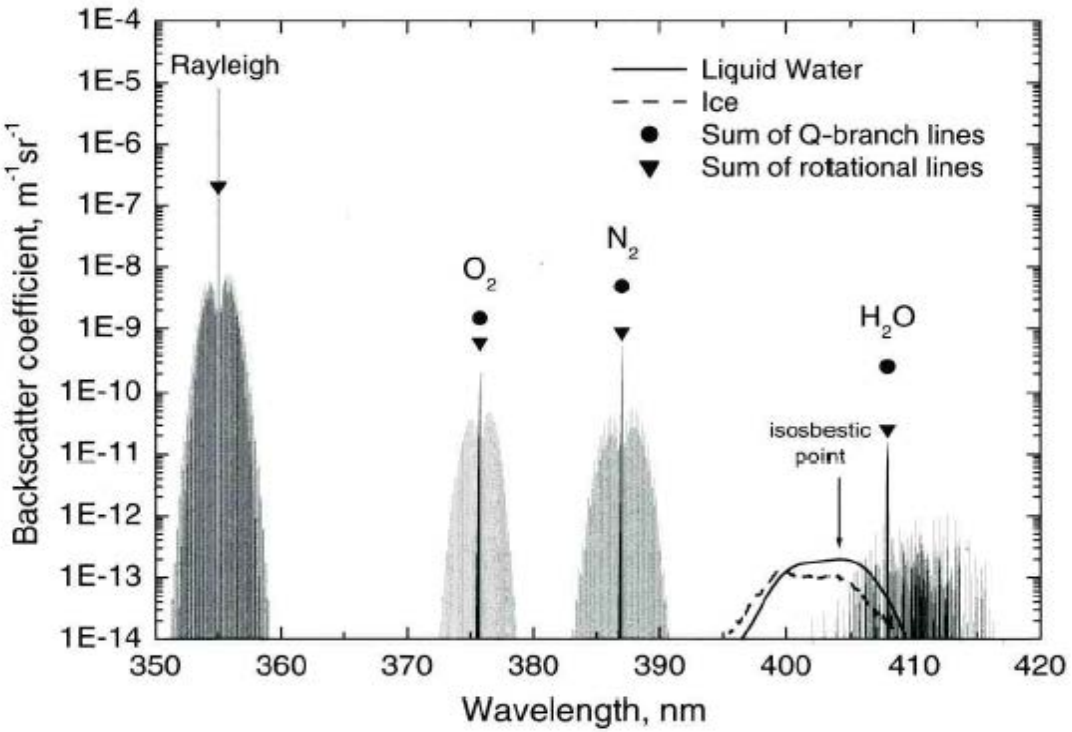
[Stevens et al., GRL, 2005]

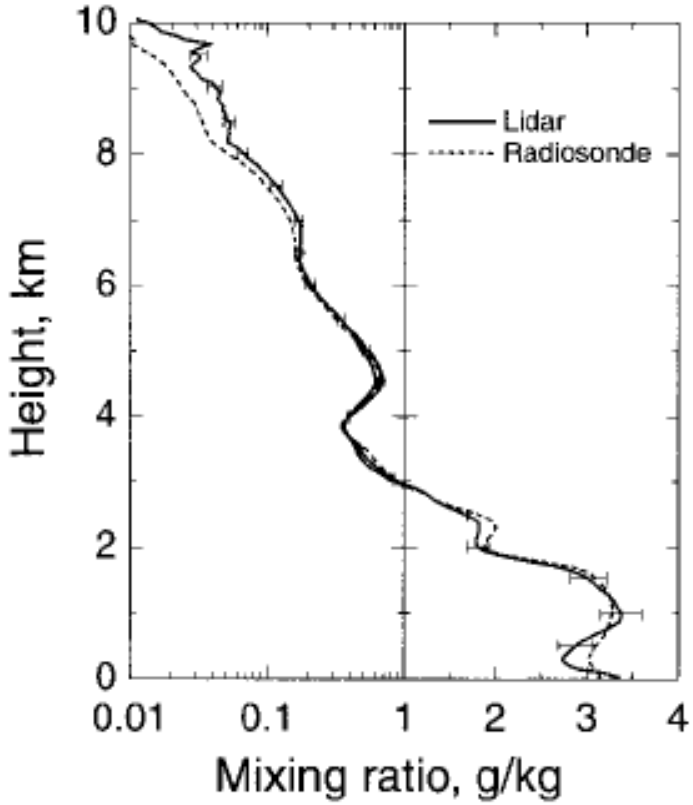
DIAL & Raman Lidar for Trace Gases

- The atmosphere has many trace gases from natural or anthropogenic sources, like H_2O, O_3, CO_2, NOx, CFC, SO_2, CH_4, NH_3, VOC, etc.
- Can we use resonance fluorescence to detect them?
- Quenching effects due to collisions make fluorescence impossible in lower atmosphere for molecules.
- We still need spectroscopy detection - differential absorption and Raman lidars!



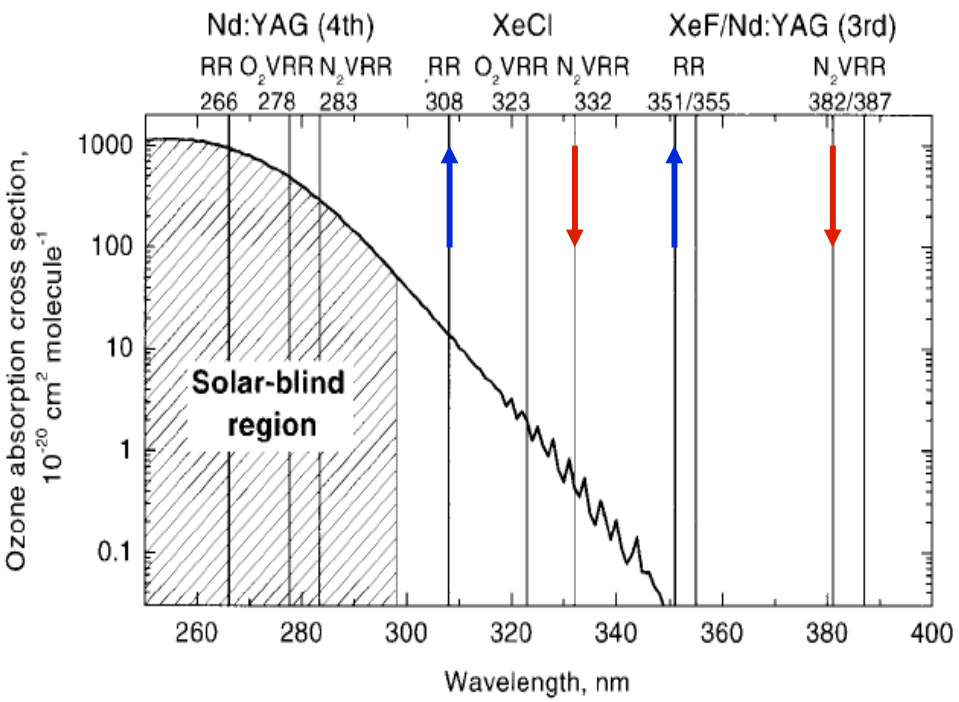
Raman Lidar for Water Vapor





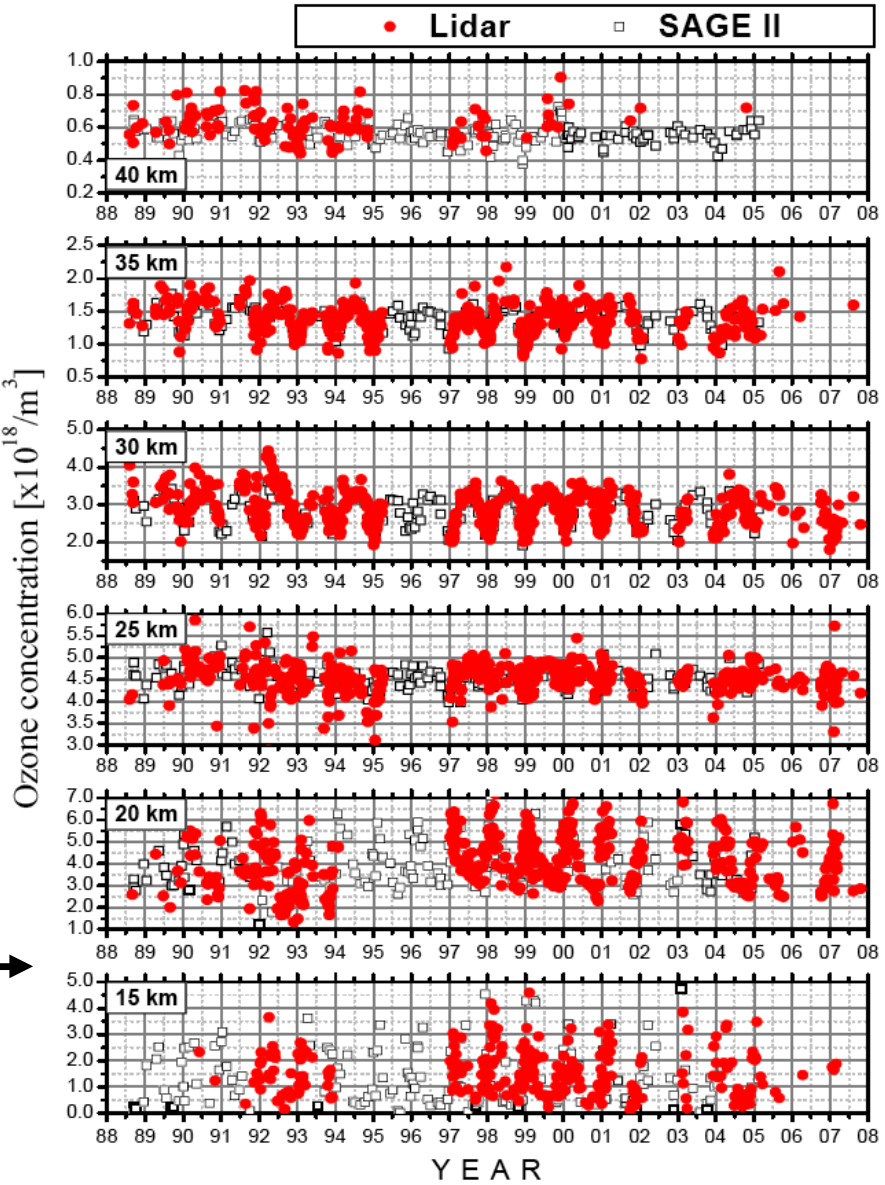
- H_2O molecules exhibit specific spectra - fingerprints!
- Raman lidar catches this 'fingerprints' and avoid the aerosol scattering in the Raman-shifted channel. Thus, only aerosol extinction will be dealt with in deriving H_2O mixing ratio.

DIAL for Ozone in Two Decades



$$\Delta\sigma_{abs} = \sigma_{abs}(\lambda_{ON}) - \sigma_{abs}(\lambda_{OFF})$$

Tsukuba (36N, 140E), Japan
[Tatarov et al., ILRC, 2008]



Rayleigh + Raman Integration Lidar

Hydrostatic Equation

$$dP = -\rho g dz$$

+

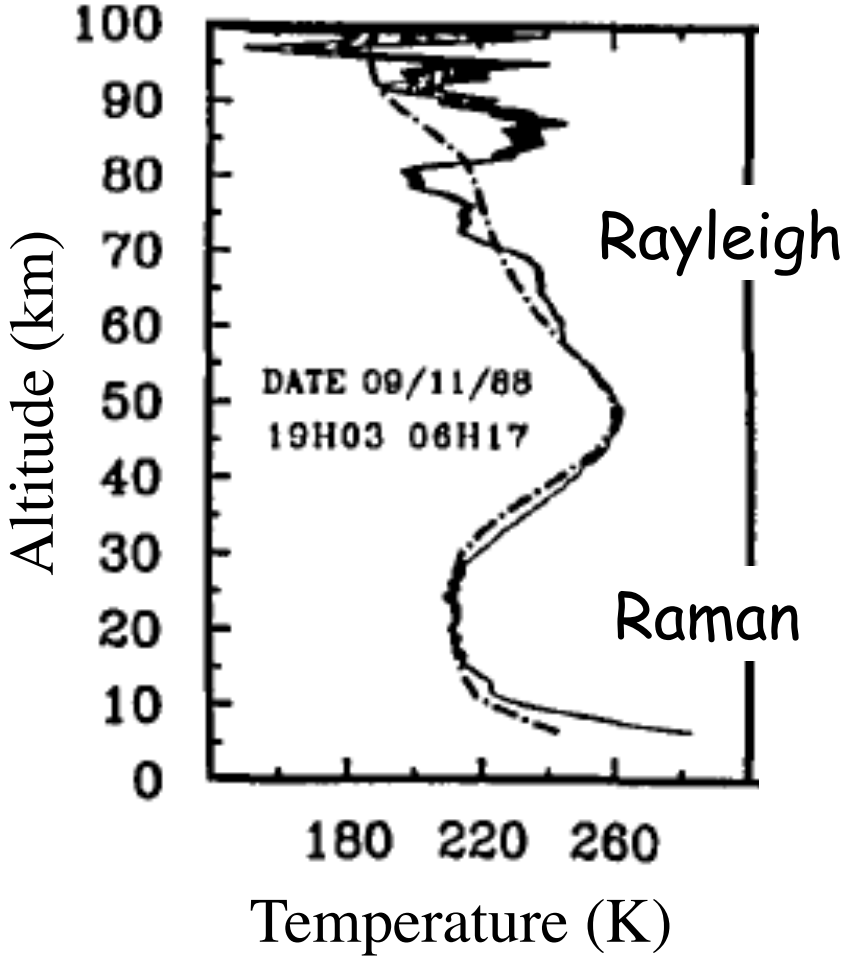
Ideal Gas Law

$$P = \rho R T$$

$$T(z) = T(z_o)\frac{\rho(z_o)}{\rho(z)} + \frac{1}{R}\int_z^{z_o} g(r)dr\,\frac{\rho(r)}{\rho(z)}$$

Density Ratio ⇨ Temperature

Searchlight, Falling Sphere
Rayleigh Lidar, VR-Raman Lidar

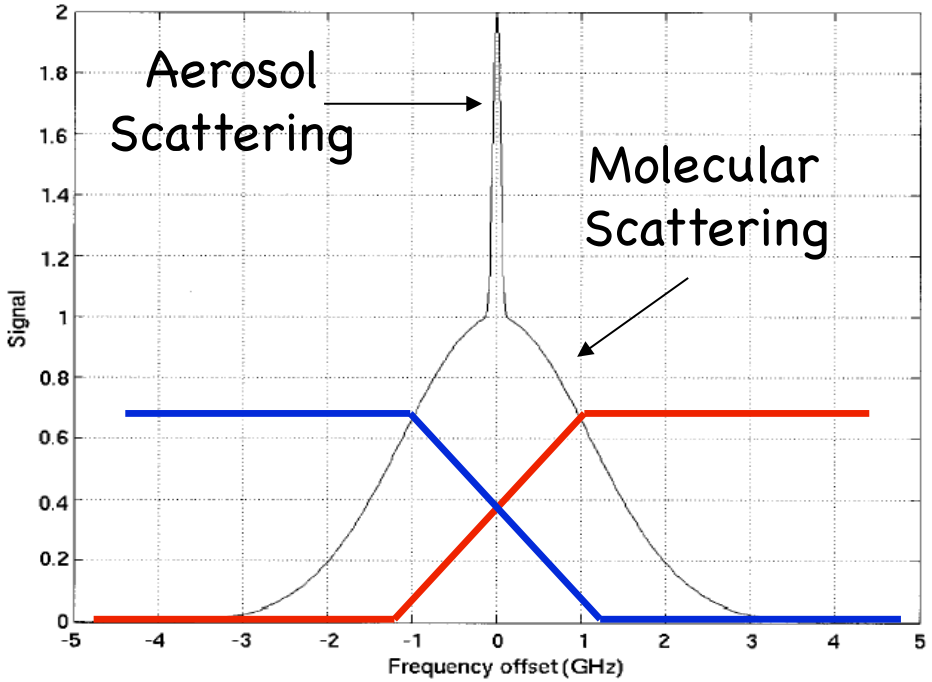


[Keckhut et al., 1990]

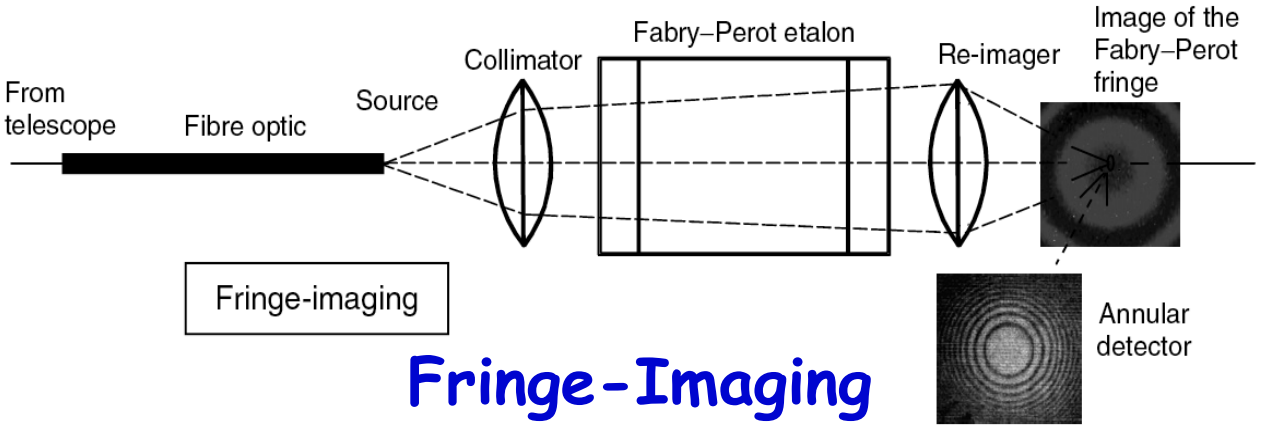
Direction-Detection Doppler Lidar

In lower atmosphere, Rayleigh and Mie scattering experiences Doppler shift and broadening.

However, there is no frequency analyzer in the atmosphere, so the receiver must be equipped with narrowband frequency analyzers for spectral analysis.



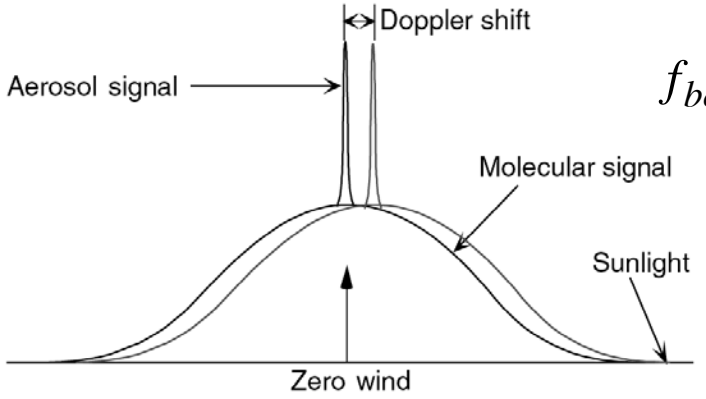
Double-Edge Filter



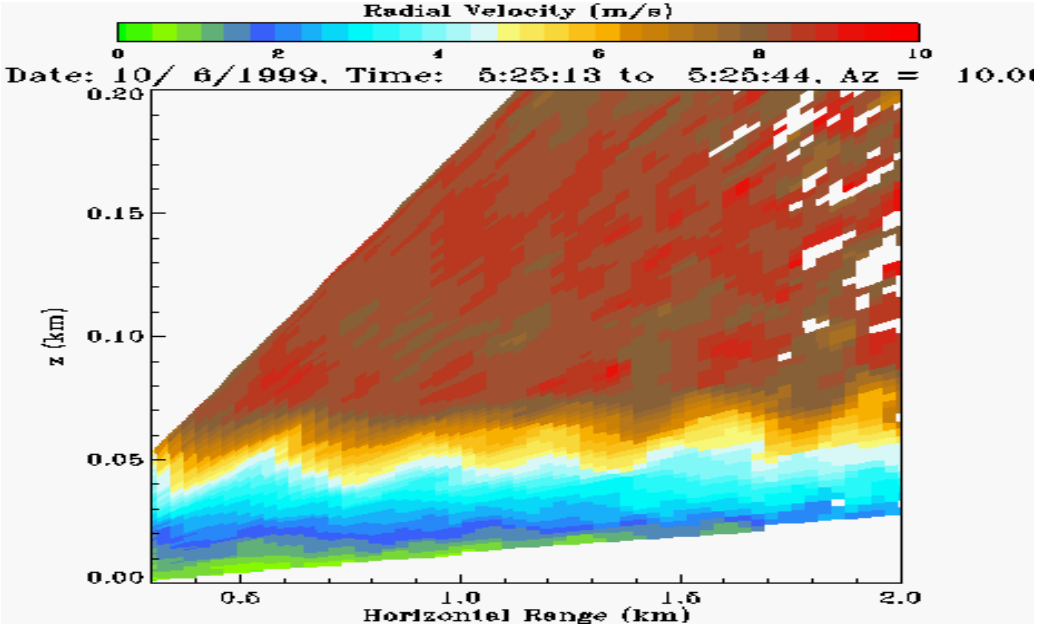
Fringe-Imaging

Coherent Doppler Wind Lidar

- "Heterodyne" Detection from aerosol scattering: the return signal is optically mixed with a local oscillator laser, and the resulting beat signal has the frequency (except for a fixed offset) equal to the Doppler shift.



$$f_{beat} = \left| f_{LO} - f_{Sig} \right|$$
$$= \Delta f + f_{offset}$$



NOAA HRDL

Backscatter Cross-Section Comparison

Physical Process	Backscatter Cross-Section	Mechanism
Mie (Aerosol) Scattering	10^{-8} - 10^{-10} cm^2sr^{-1}	Two-photon process Elastic scattering, instantaneous
Atomic Absorption and Resonance Fluorescence	10^{-13} cm^2sr^{-1}	Two single-photon process (absorption and spontaneous emission) Delayed (radiative lifetime)
Molecular Absorption	10^{-19} cm^2sr^{-1}	Single-photon process
Fluorescence From Molecule, Liquid, Solid	10^{-19} cm^2sr^{-1}	Two single-photon process Inelastic scattering, delayed (lifetime)
Rayleigh Scattering (Wavelength Dependent)	10^{-27} cm^2sr^{-1}	Two-photon process Elastic scattering, instantaneous
Raman Scattering (Wavelength Dependent)	10^{-30} cm^2sr^{-1}	Two-photon process Inelastic scattering, instantaneous

Lidar Data Retrieval

- **Lidar data retrieval varies with lidar systems & detections.**

$$\begin{cases} N_S(\lambda,z) = \left(\dfrac{P_L(\lambda)\Delta t}{hc/\lambda}\right)\left(\sigma_{eff}(\lambda,z)n_c(z)R_B(\lambda)\Delta z\right)\left(\dfrac{A}{4\pi z^2}\right)\left(T_a{}^2(\lambda)T_c^2(\lambda,z)\right)\left(\eta(\lambda)G(z)\right)+N_B \\ N_R(\lambda,z_R) = \left(\dfrac{P_L(\lambda)\Delta t}{hc/\lambda}\right)\left(\sigma_R(\pi,\lambda)n_R(z_R)\Delta z\right)\left(\dfrac{A}{z_R{}^2}\right)T_a{}^2(\lambda,z_R)\left(\eta(\lambda)G(z_R)\right)+N_B \end{cases}$$

Solutions:

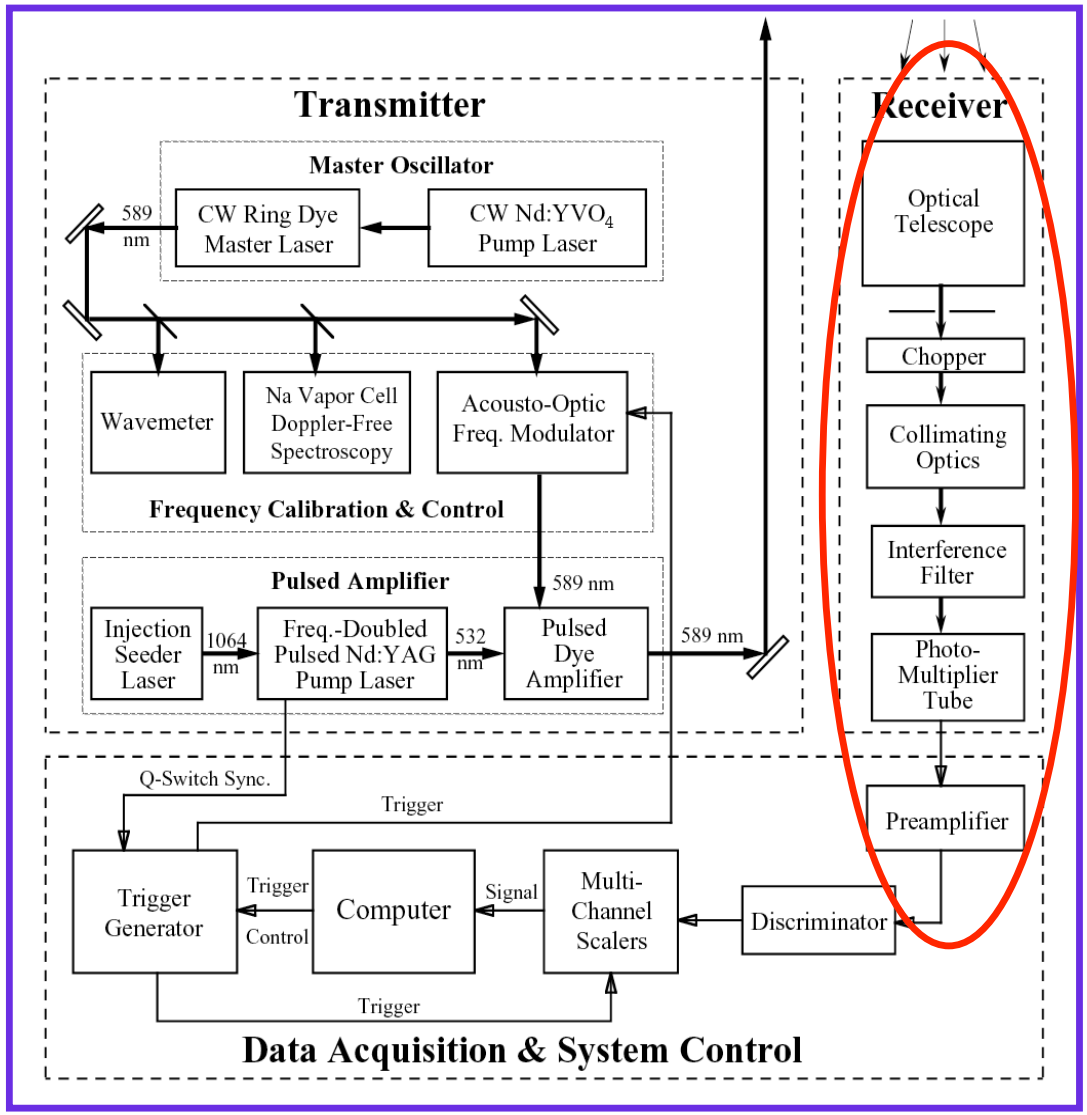
$$n_c(z) = n_R(z_R)\frac{N_S(\lambda,z)-N_B}{N_R(\lambda,z_R)-N_B}\cdot\frac{z^2}{z_R{}^2}\cdot\frac{4\pi\sigma_R(\pi,\lambda)}{\sigma_{eff}(\lambda,z)R_B(\lambda)}\cdot\frac{1}{T_c^2(\lambda,z)}$$

Rayleigh normalization

$$R_T = \frac{N_{Norm}(f_+,z)+N_{Norm}(f_-,z)}{N_{Norm}(f_{pk},z)} = \frac{\sigma_{eff}(f_+,z)+\sigma_{eff}(f_-,z)}{\sigma_{eff}(f_{pk},z)}$$

$$R_W = \frac{N_{Norm}(f_+,z)-N_{Norm}(f_-,z)}{N_{Norm}(f_{pk},z)} = \frac{\sigma_{eff}(f_+,z)-\sigma_{eff}(f_-,z)}{\sigma_{eff}(f_{pk},z)}$$

Preprocess Procedure



[Chu and Papen, Laser Remote Sensing, 2005]

Read Data File

PMT/Discriminator Saturation Correction

Chopper Correction

Subtract Background

Remove Range Dependence (x R^2)

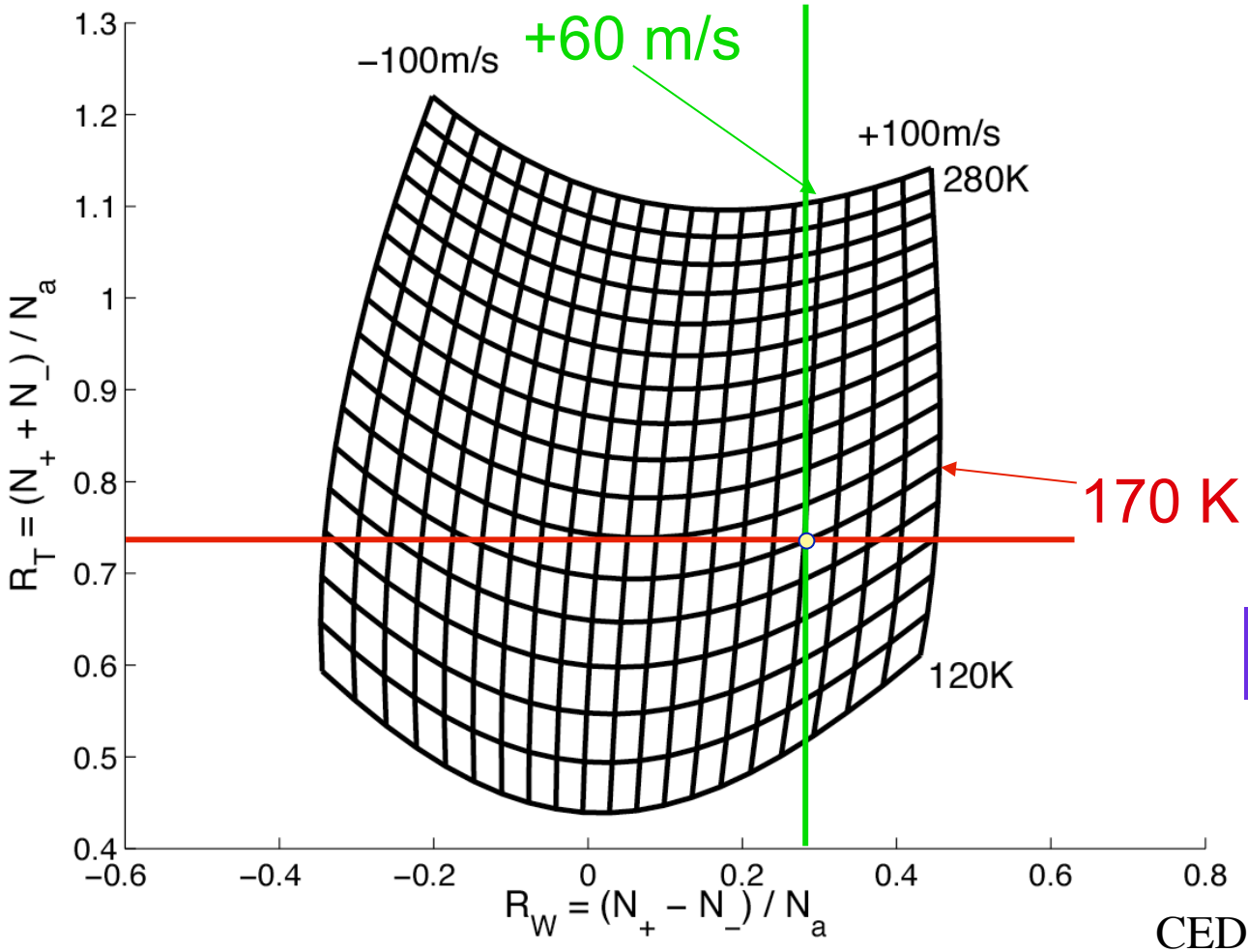
Add Base Altitude

Take Rayleigh Signal @ z_R km

Normalize Profile By Rayleigh Signal @ z_R km

Main Process Procedure

- Compute Doppler calibration curves from physics
- Compute actual ratios R_T and R_W from photon counts
- Look up these two ratios on the calibration curves to infer the corresponding temperature and wind from isoline/isogram.



See poster

Lidar Observables

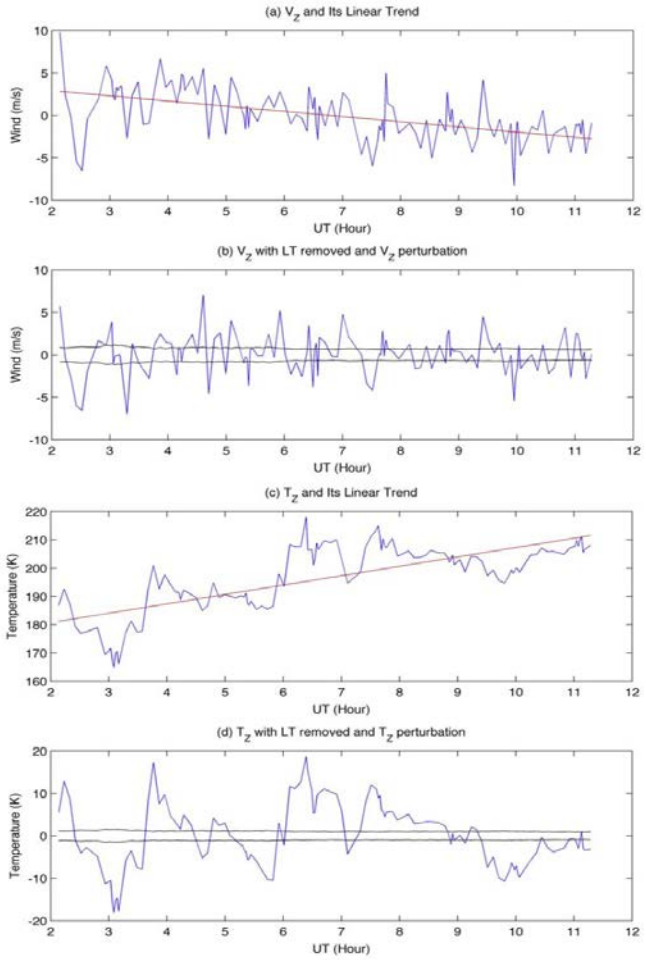
- Lidar raw data are usually photon counts versus time of flight.
- From photon counts, we retrieve directly the backscatter coefficient, density, temperature, wind, and depolarization factor.
- What science can we study from these measured parameters?

-- Thermal structure, dynamics, composition, and chemistry

- Temperature: a key fundamental parameter; essential to thermal structure, climate study, chemical reaction, tides, gravity waves, PW, polar mesospheric and stratospheric clouds, weather forecast, …
- Wind: a key fundamental parameter; essential to dynamical structure, wave dynamics, fluxes, gravity waves, tides, PW, weather forecast, atmospheric coupling, …
- Backscatter coefficient and depolarization factor: aerosols and clouds for their physical, optical, and microphysical characteristics (altitude, width, brightness, particle size, shape, and density) …
- Density: minor species, composition, chemistry, dynamic test, …

CEDAR Science: Thermal & Dynamics

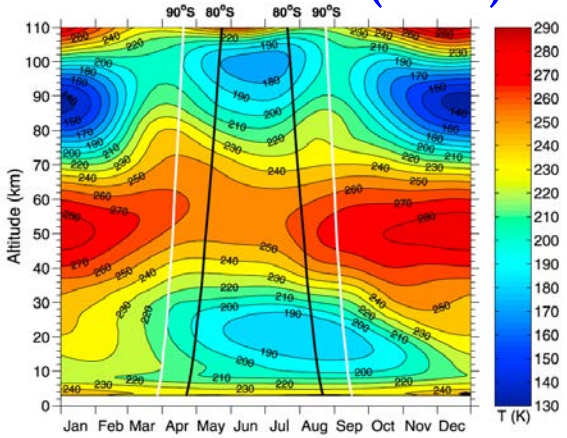
- **Perturbations of temperature, wind, or density ⇨ waves**
  - **How to derive perturbations or how to estimate background? -- Various ways, here is a good one.**
  - **Vertical fluxes are used to characterize momentum, heat and constituent transport by atmospheric gravity waves (AGWs) when waves experience dissipation, due to instability, nonlinear wave-wave interaction and wave-mean flow interactions, and critical level filtering.**
  - **Vertical heat flux <w′T′> is defined as the expected value of the product of the vertical wind and temperature perturbations.**
  - **Vertical fluxes of horizontal momentum <w′u′> and <w′v′> are defined as the expected value of the product of the vertical wind and zonal and meridional wind perturbations.**
  - **Vertical fluxes are very challenging to measure as they require good accuracy at high resolution (~2 min & 1 km), & extremely long averaging time to obtain statistically significant flux estimates.**



[Gardner and Liu, JGR, 2007]
Entire paper with Appendix

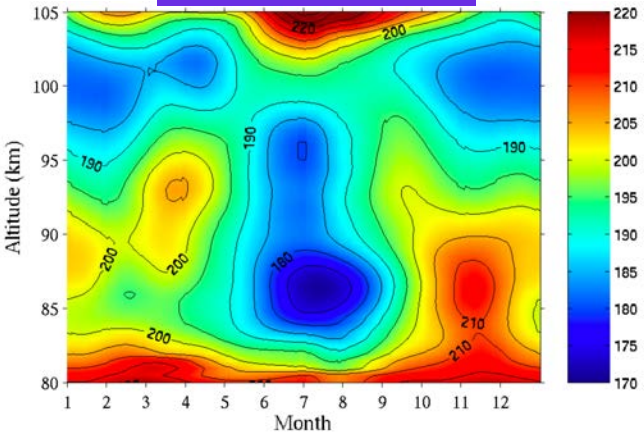
CEDAR Science: Thermal & Dynamics

South Pole (90°S)



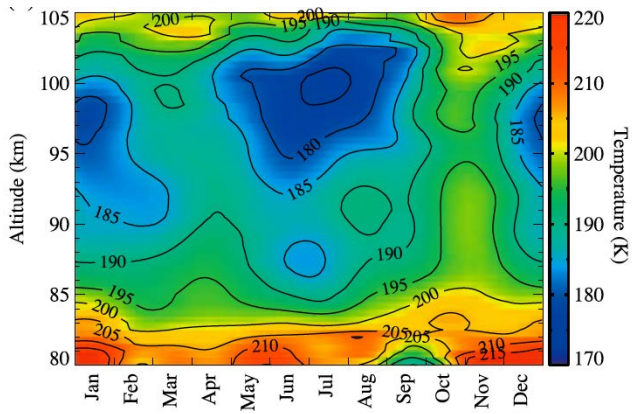
[Pan and Gardner, 2003]

SOR (35°N)



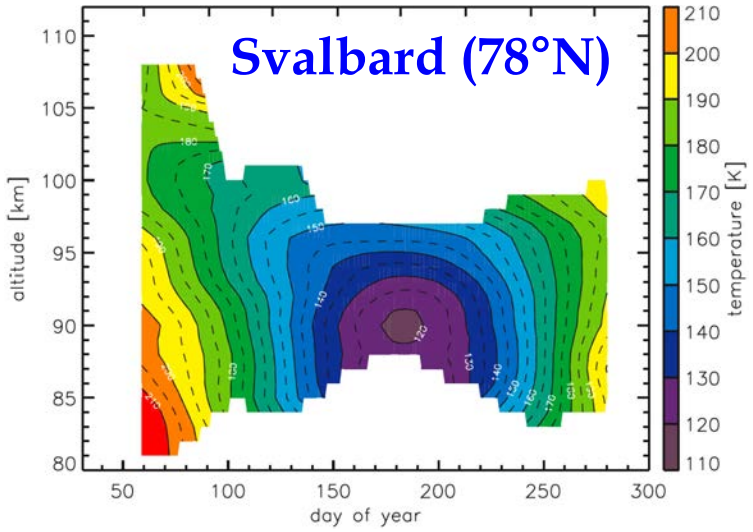
[Chu et al., 2005]

Arecibo (18.35°N)



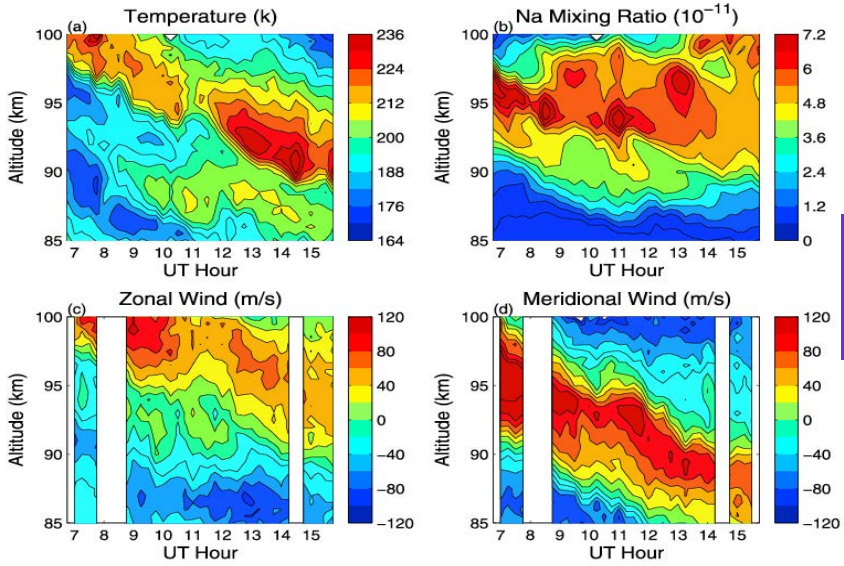
[Friedman and Chu, 2007]

Svalbard (78°N)



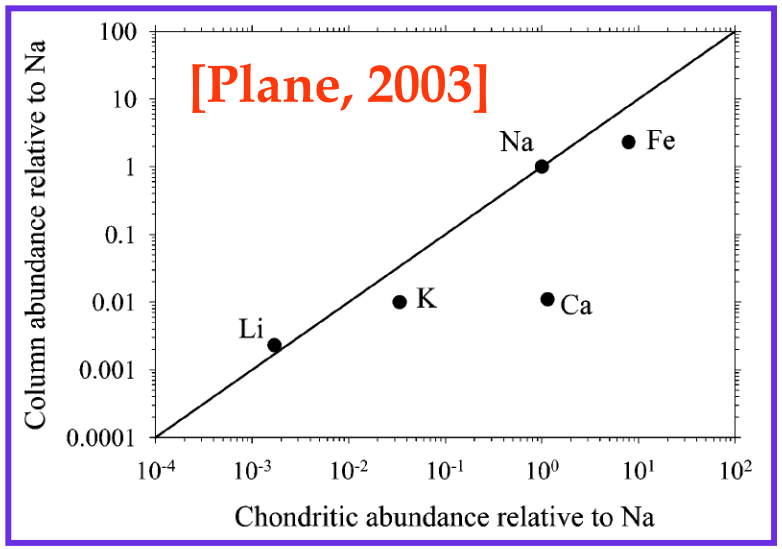
[Höffner and Lübken, 2007]

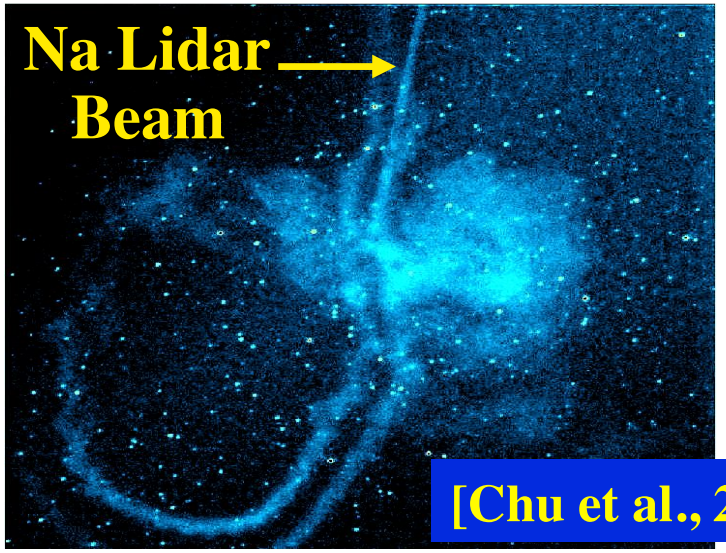
Maui (20.7°N)



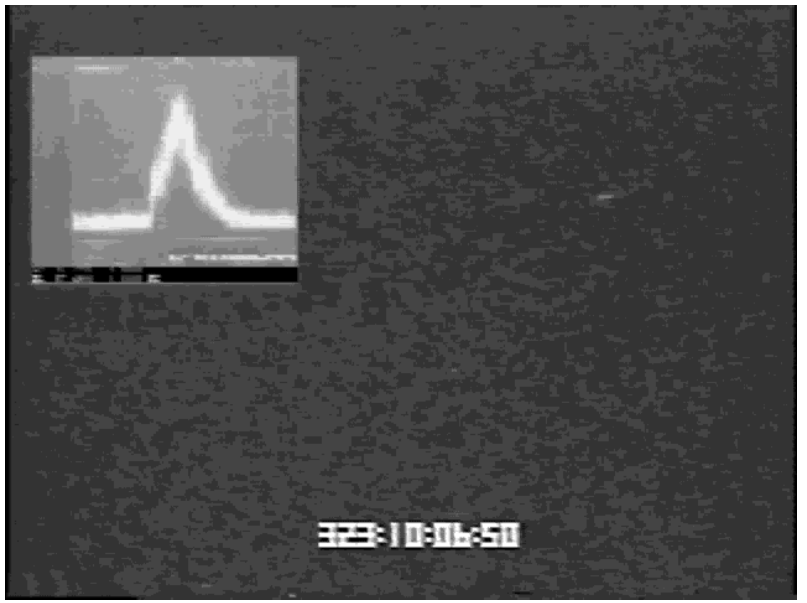
CEDAR Science: Meteor & Metal Species

Meteor ablation deposits metallic atoms

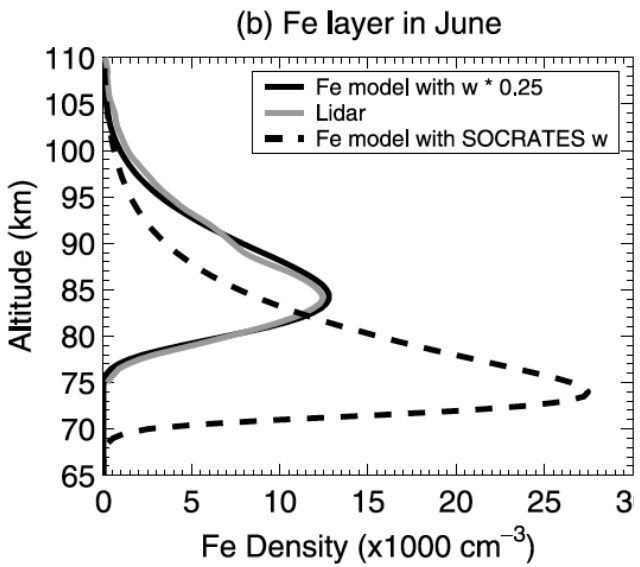


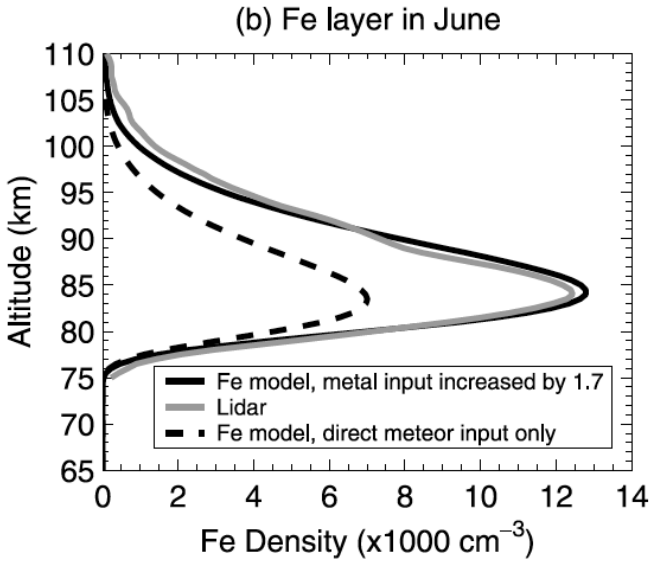


Lidar detection of persistent meteor trails during Leonid Shower 1998



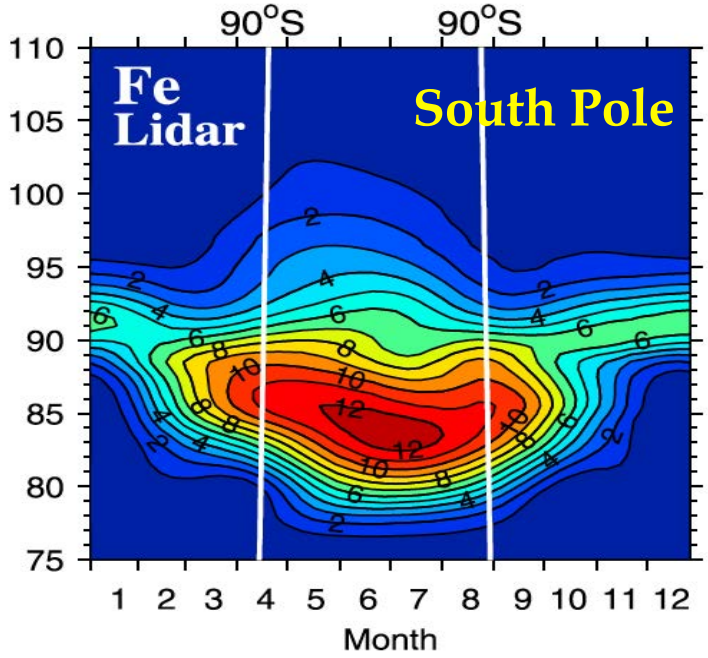
CEDAR Science: Metals, Chemistry, & Dynamics

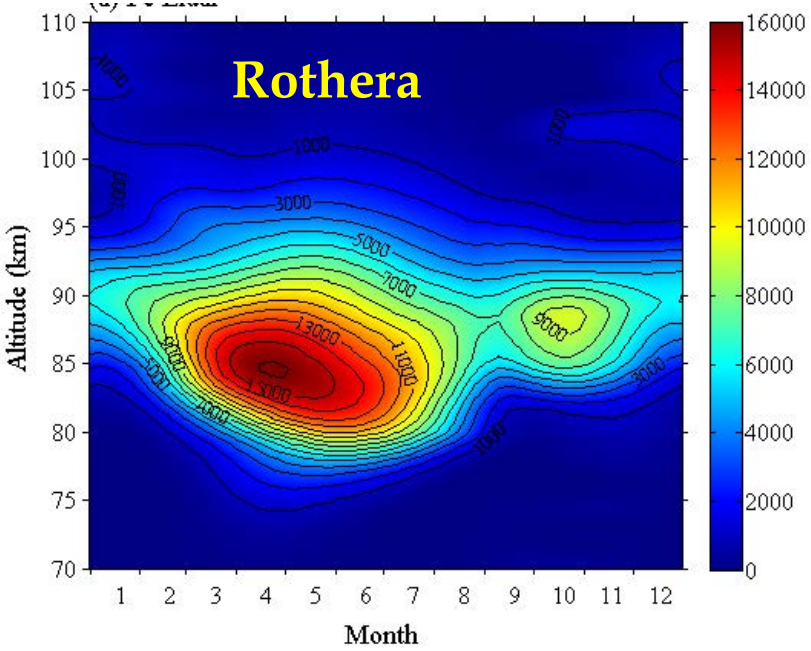




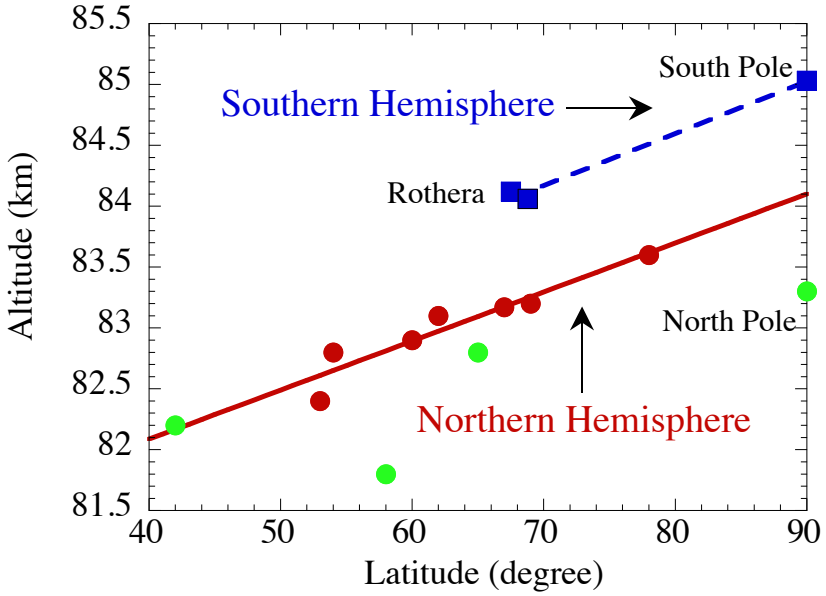
Comparison leads to two empirical corrections: (1) the downward vertical velocity in winter < 1 cm/s in the upper mesosphere;
(2) the wintertime convergence of the meridional flow over the South Pole provides additional input of metallic species .

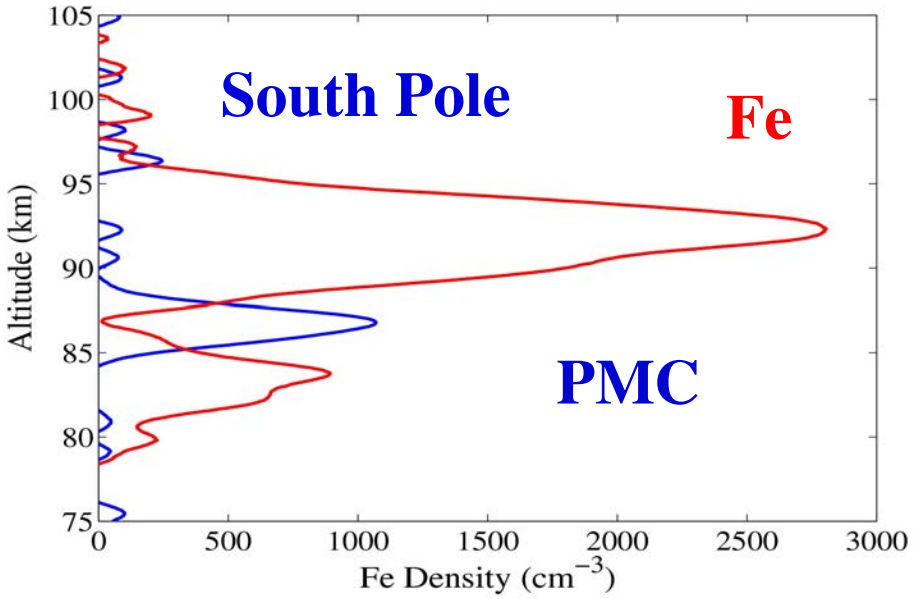
-- [Gardner et al., 2005]





PMC Hemispheric Difference & Fe/ PMC Heterogeneous Chemistry





Southern PMC are ~ 1 km Higher than Northern PMC ⇨ Earth Orbital Eccentricity and Gravity Wave Differences

[Chu et al., JGR, 2003, 2006]

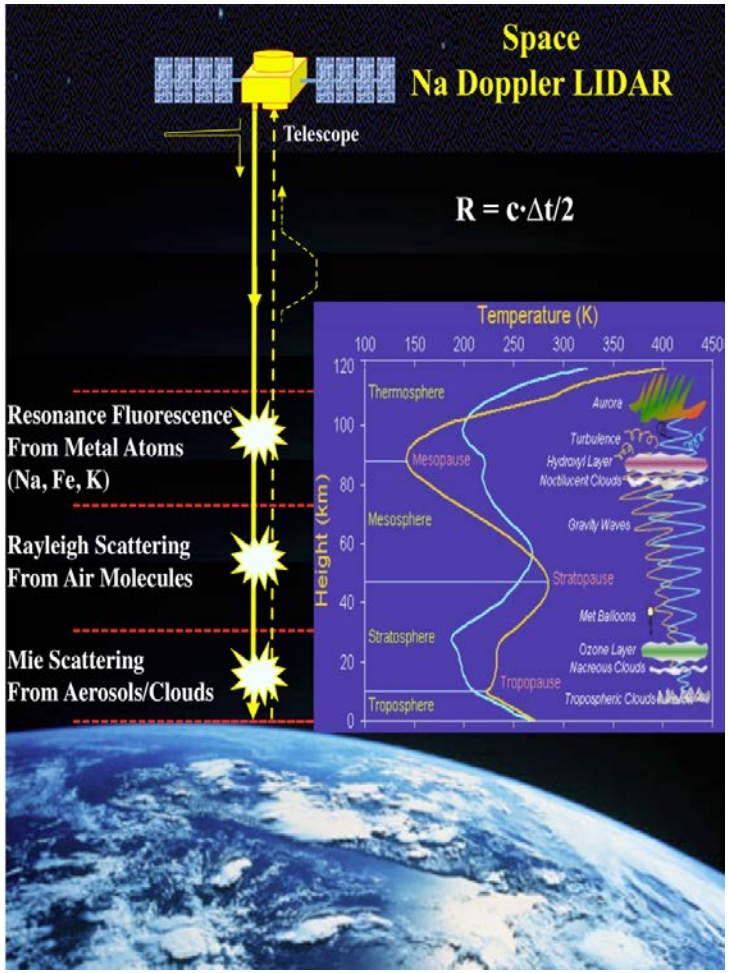
Heterogeneous Removal of Mesospheric Fe Atoms by PMC Ice Particles Observed by the Fe Boltzmann Lidar

[Plane et al., Science, 2004]

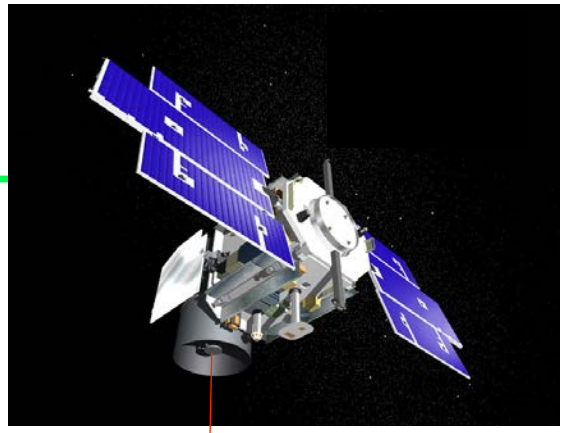
Lidar into Future and Space

Future lidar technology may lie in

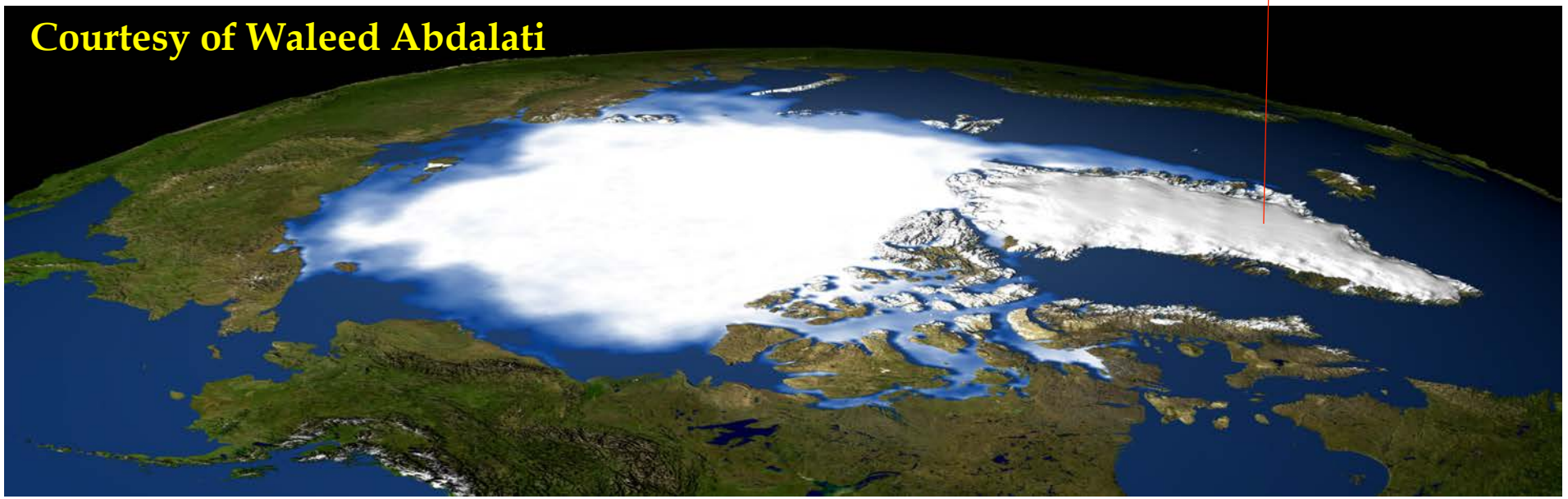
1. **Solid-state resonance and Rayleigh Doppler lidar**, such as the Fe Doppler lidar and Na Doppler lidar
2. **Extending lidar measurement range into the thermosphere,** e.g., He, N2+, and O lidars
3. **Extending to whole atmosphere lidar** by combining resonance Doppler lidars with Rayleigh/Mie/Raman Doppler lidar and DIAL
4. **Spaceborne resonance Doppler lidar**
5. **……**



Laser Altimeter ICESat



- First laser altimeter started in late 1960s.
- Time-of-flight information from a lidar system can be used for laser ranging and altimetry from airborne or spaceborne platforms to measure the heights of surfaces with high resolution and accuracy.
- Apollo laser altimeter in 1971 mapping lunar surface was the first ever lidar in space. ICESat/GLAS provide information on Earth topography and ice coverage.



Conclusions

- **Lidar has made significant contributions to atmosphere and space research owing to its high capabilities to simultaneously measure wind, temperature, density, aerosols/clouds, and minor species with high accuracy, precision, and resolution for both day and night.**
- **New lidar technologies are being proposed and developed to further improve the measurement accuracy, precision, and resolution, the measurement range and capability as well as the mobility to enable new scientific endeavors.**
- **Many open questions remain in atmosphere and space research. Among them the atmospheric coupling and tracking gravity waves from the source regions to the breaking areas are being considered. The whole atmosphere lidar and the space-borne MLT lidar are on the horizon.**
- **Lidar field definitely needs fresh blood, especially creative students and young researchers …**

Standing on the shoulder of giant, we are aiming for the future ……