ASEN 5519

Fundamentals of Spectroscopy for Optical Remote Sensing

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Concept of Remote Sensing

- **Remote Sensing** is the science and technology of obtaining information about an object without having the sensor in direct physical contact with the object. -- opposite to *in-situ* methods
- Radiation interacting with an object to acquire its information remotely

Active Remote Sensing

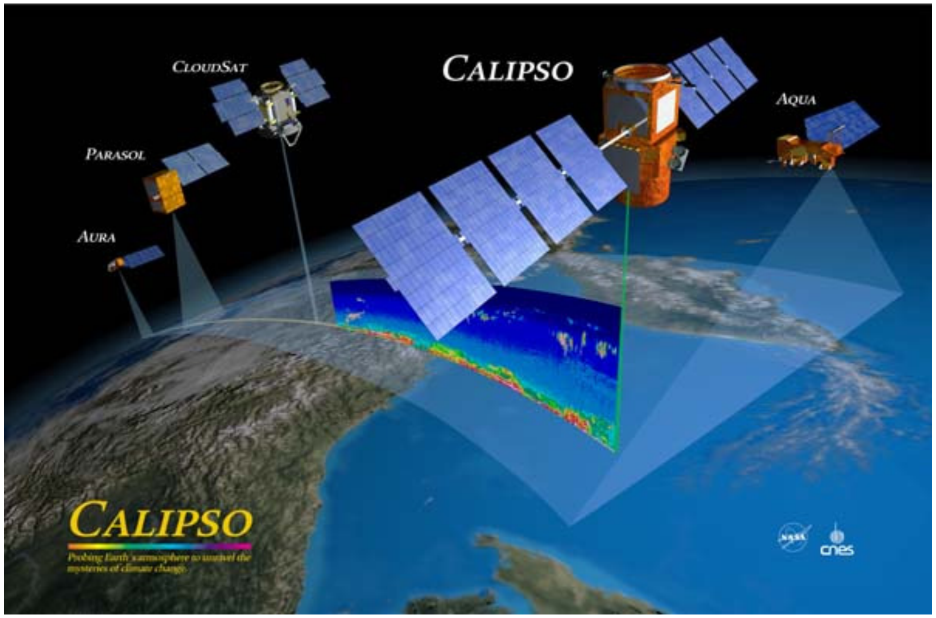
SODAR: Sound Detection And Ranging
RADAR: Radiowave Detection And Ranging
LIDAR: Light Detection And Ranging


DRI, Nevada

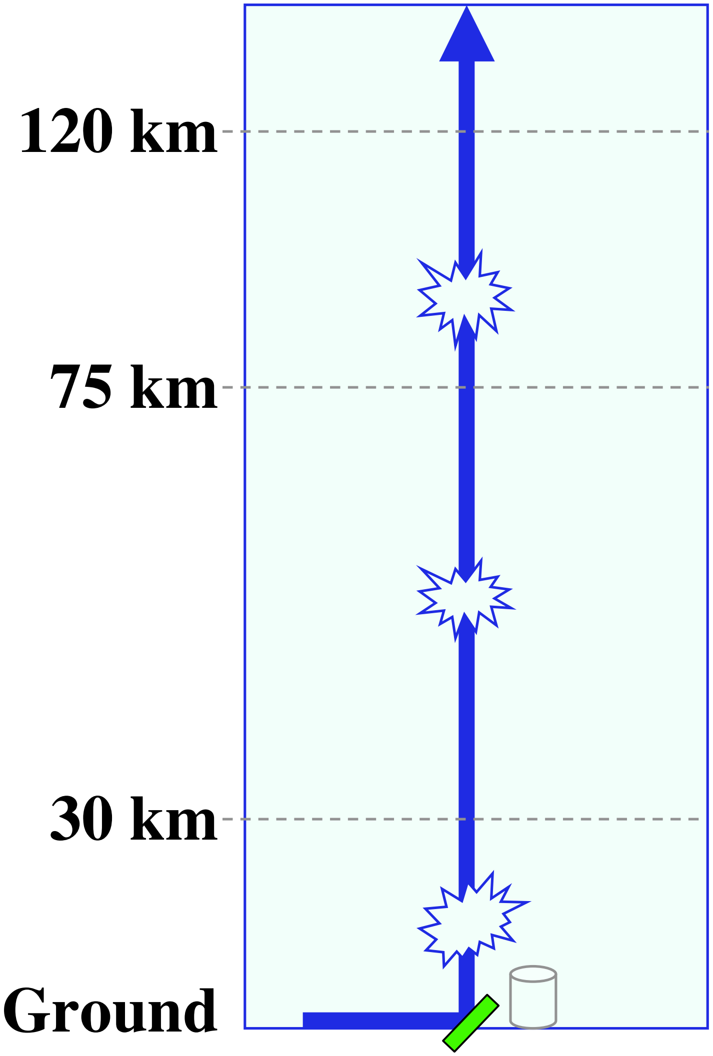

Arecibo

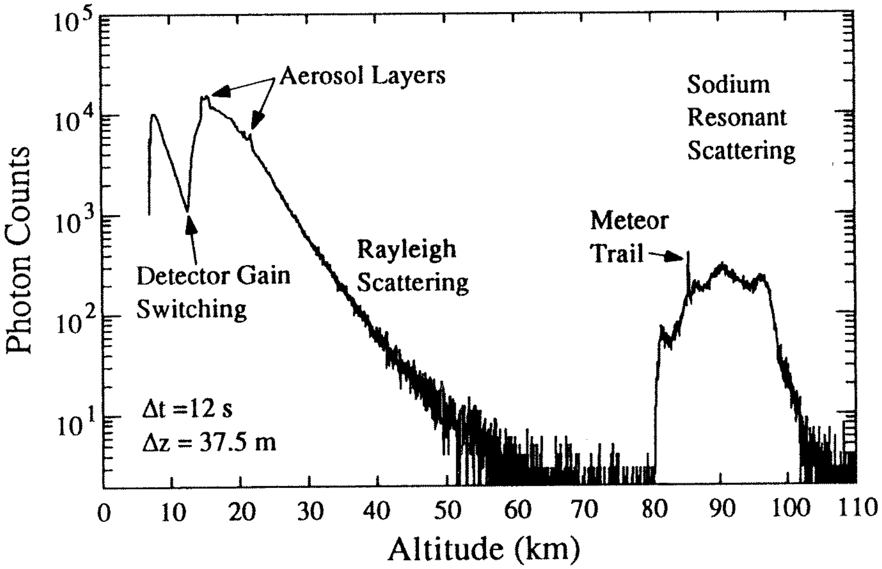
Light Detection And Ranging

- LIDAR is a very promising remote sensing tool due to its high resolution and accuracy.
- In combination of modern laser spectroscopy methods, LIDAR can detect variety of species and key parameters, with wide applications.



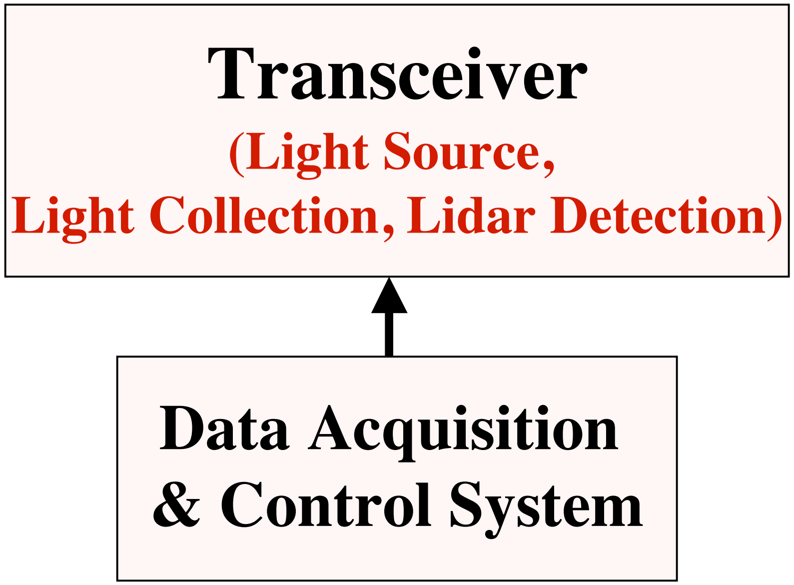
Light Detection And Ranging





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

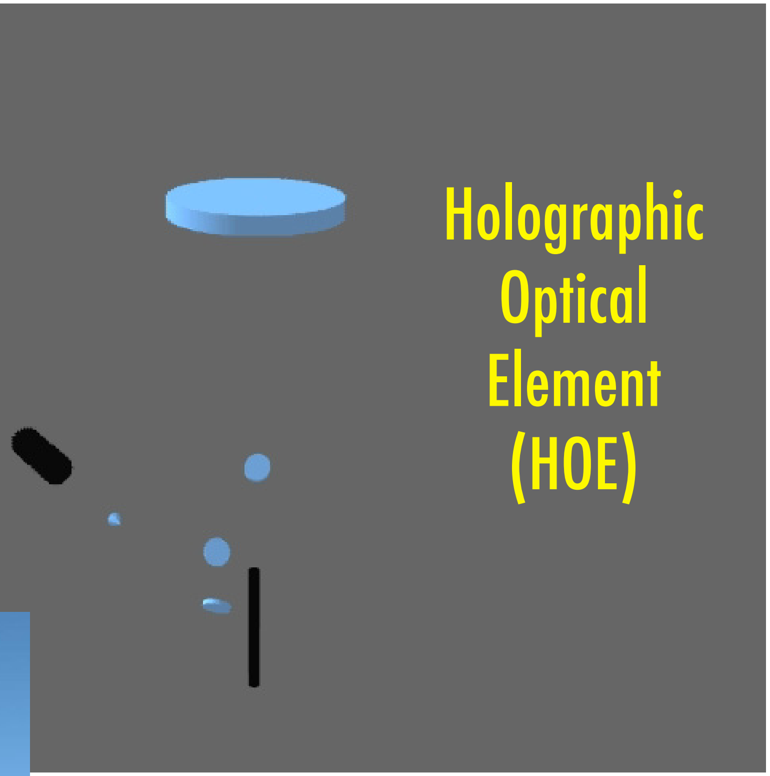
“Fancy” Lidar Architecture

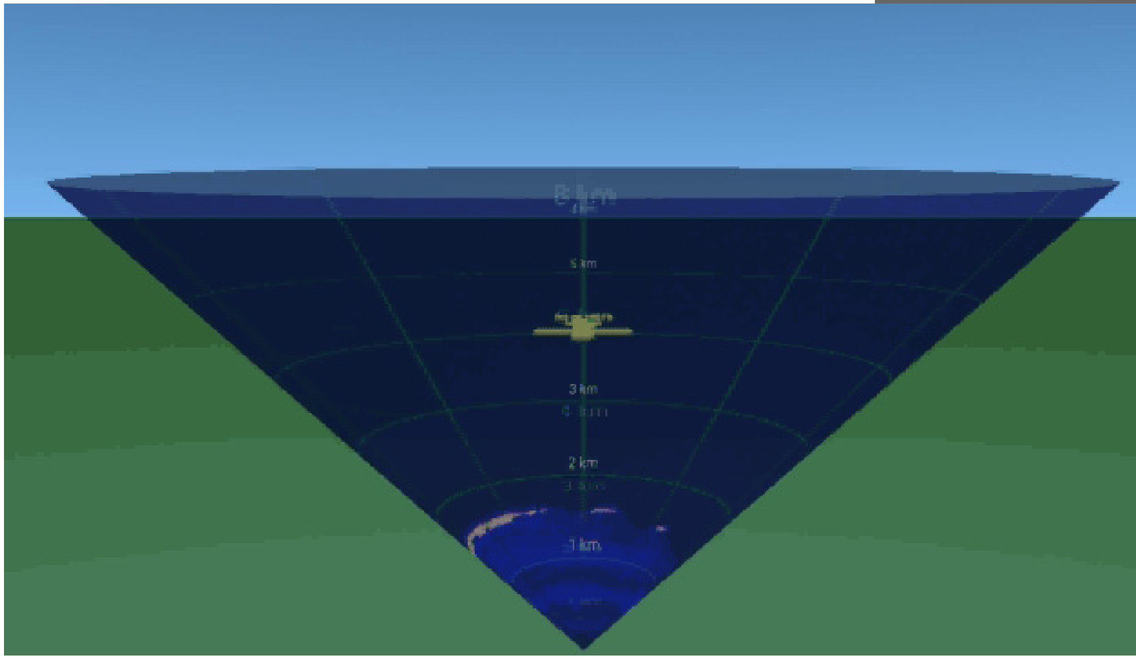


Transceiver

(Light Source,
Light Collection, Lidar Detection)

Data Acquisition & Control System





Courtesy to
Geary Schwemmer

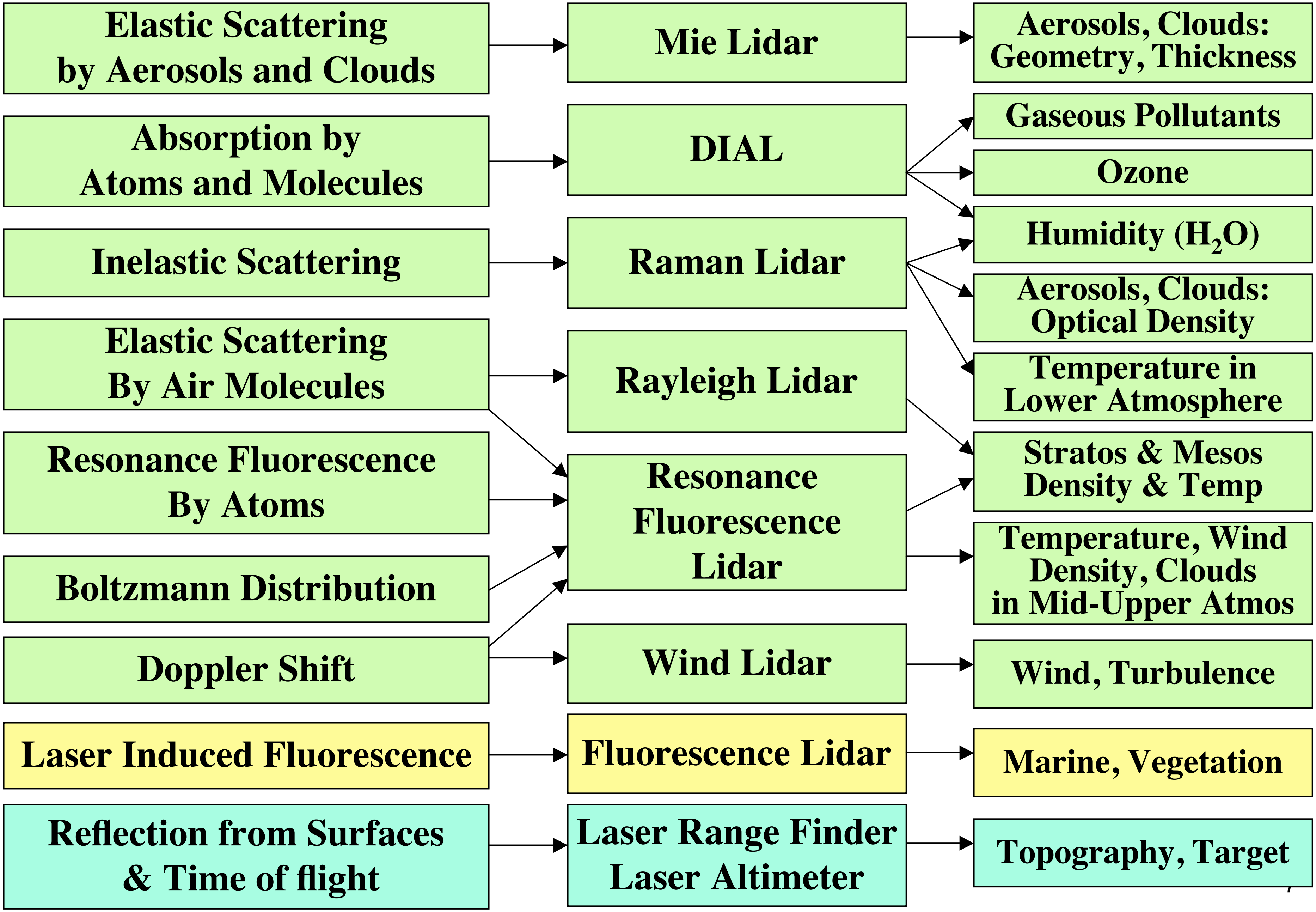
From Searchlight to Modern Lidar

- 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.

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

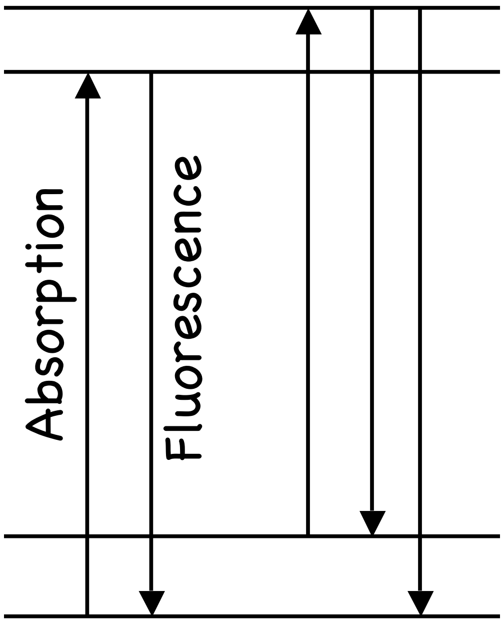
Temperature, Wind Density, Clouds in Mid-Upper Atmos

Wind, Turbulence

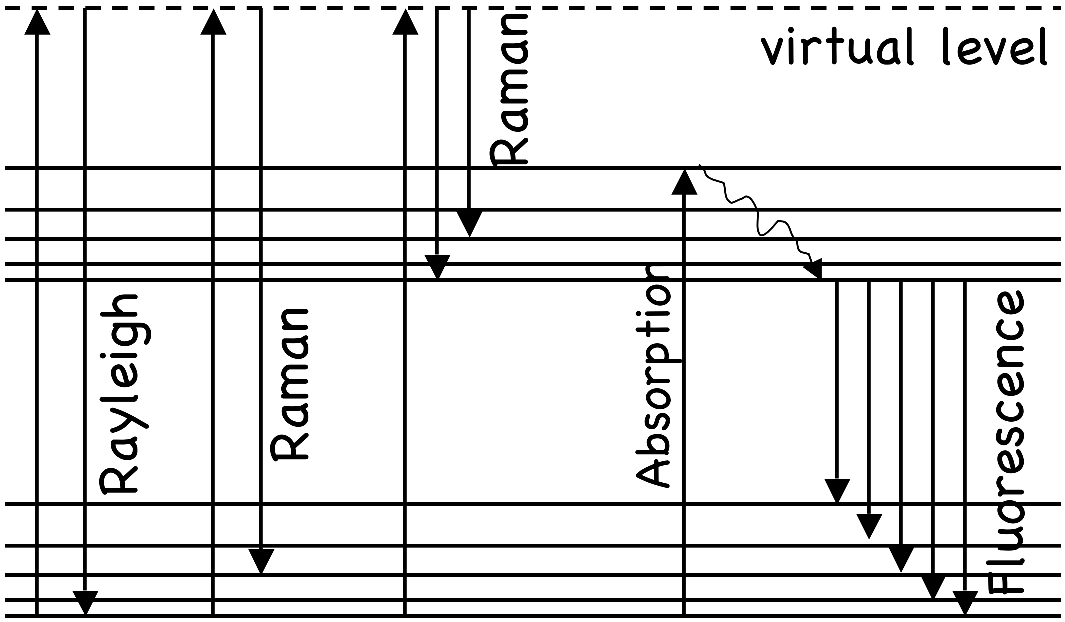
Marine, Vegetation

Topography, Target

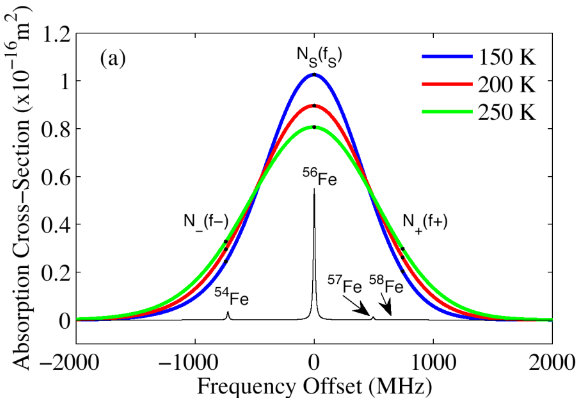
Elastic and Inelastic Scattering

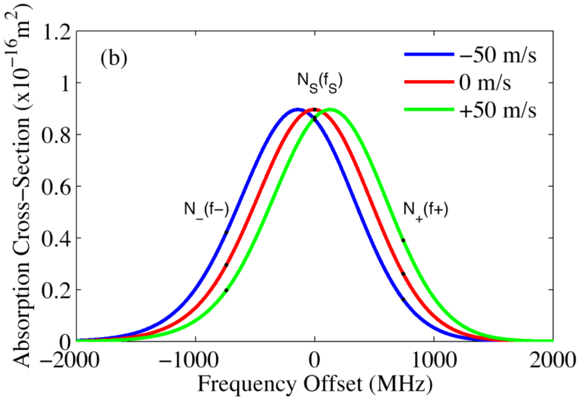


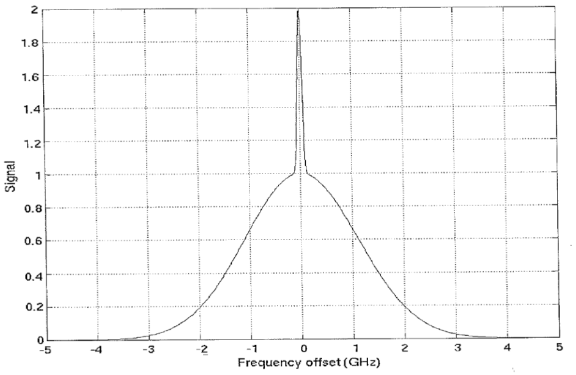
Atomic absorption &
(resonance) fluorescence



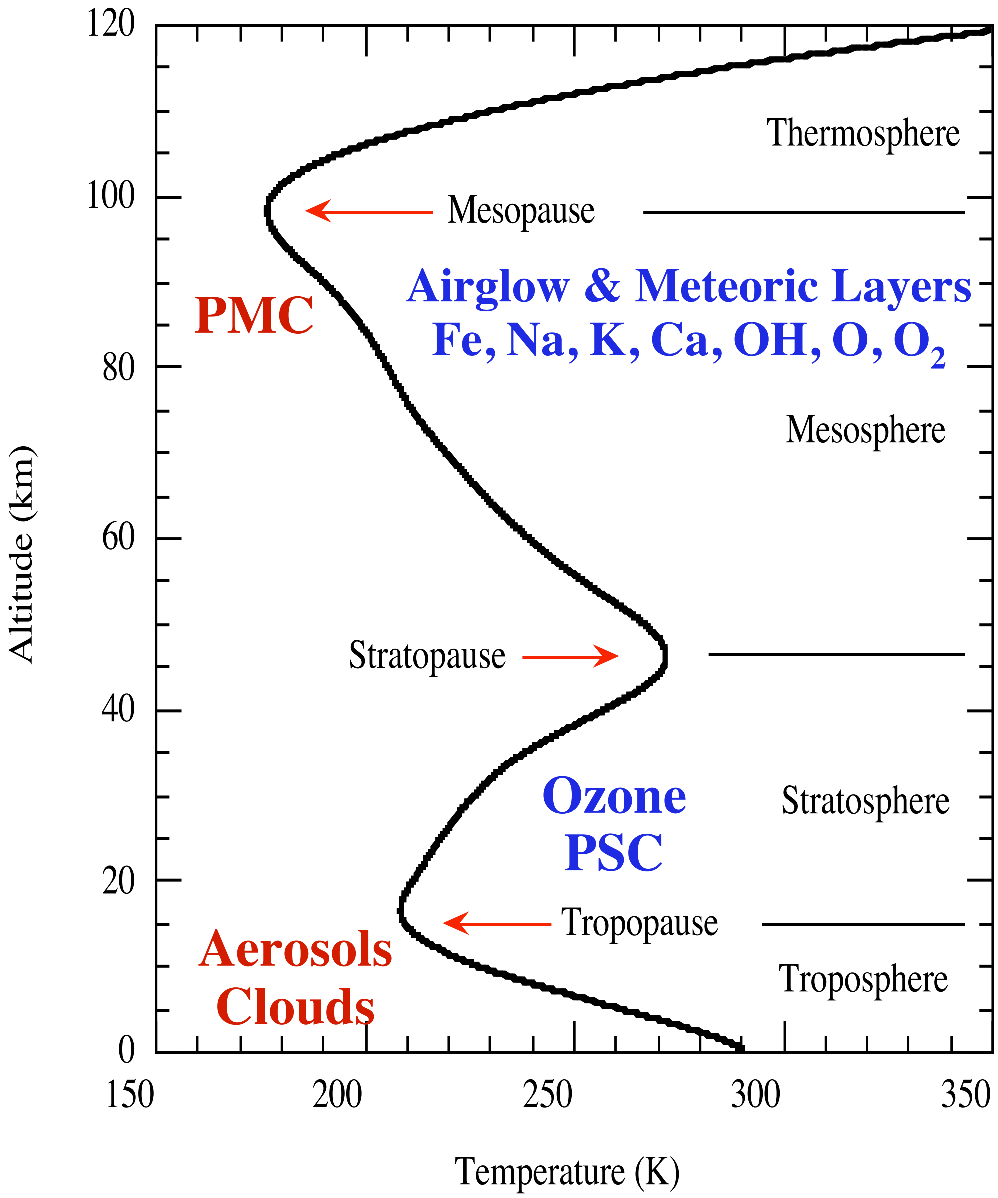
Molecular elastic and inelastic scattering,
absorption and fluorescence





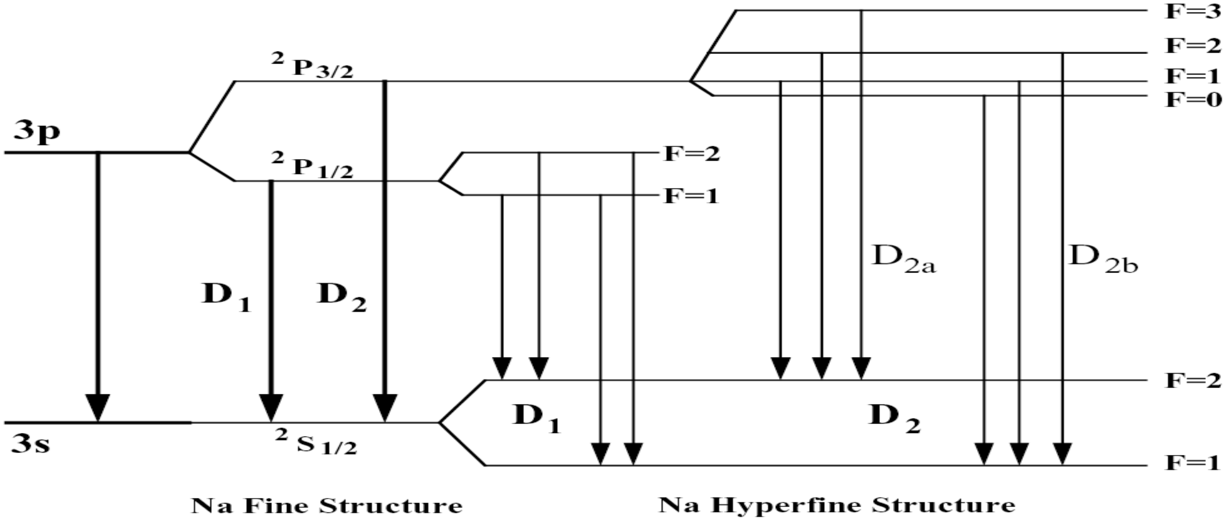


Physical Interactions in Lidar



- ❑ 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)

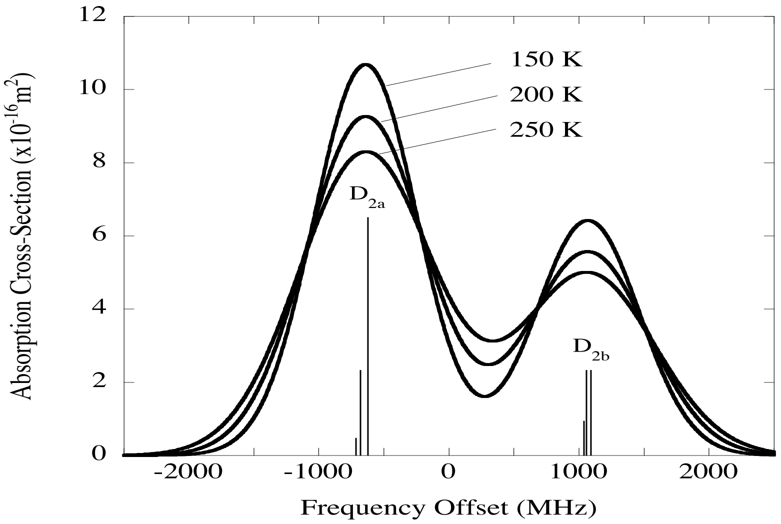
Na Doppler (Wind & Temp) Lidar

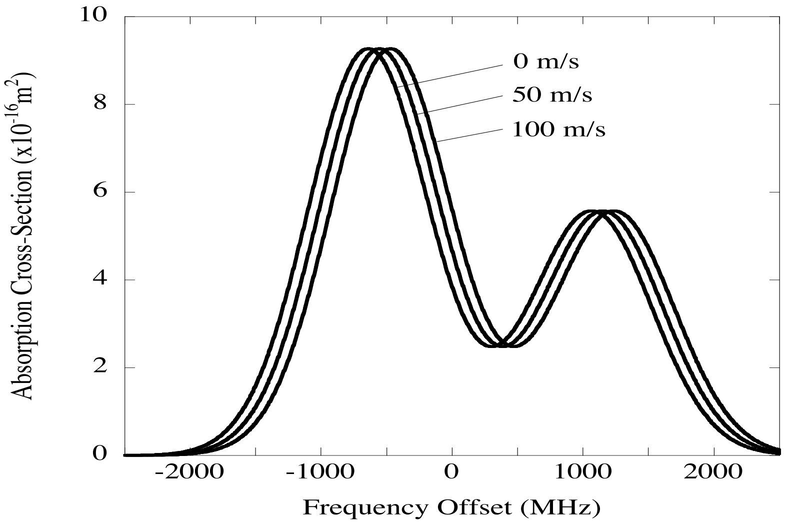


Energy Level Diagram of Atomic Na

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

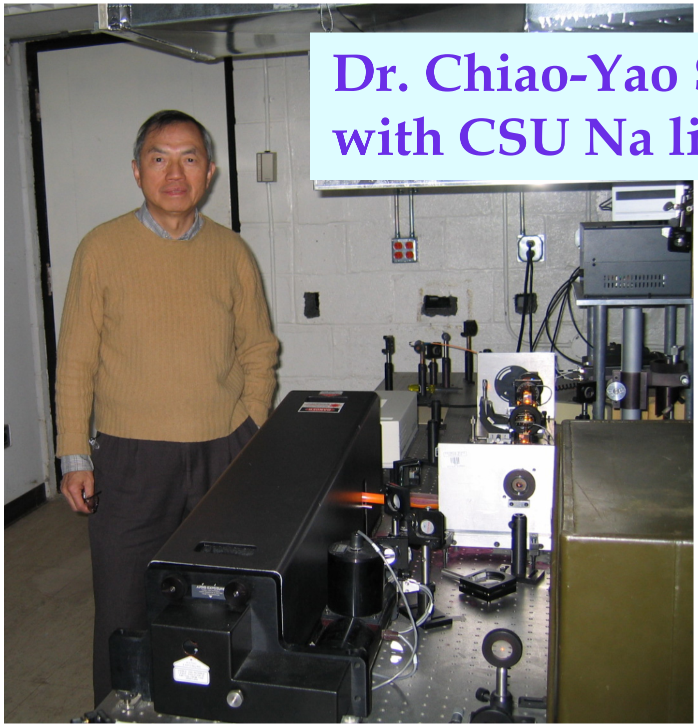
$$\nu' = \nu\left(1-\frac{V_R}{c}\right)$$



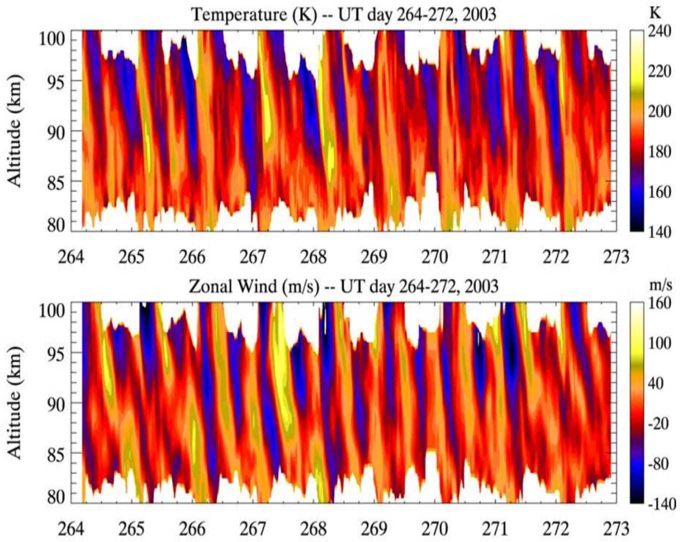


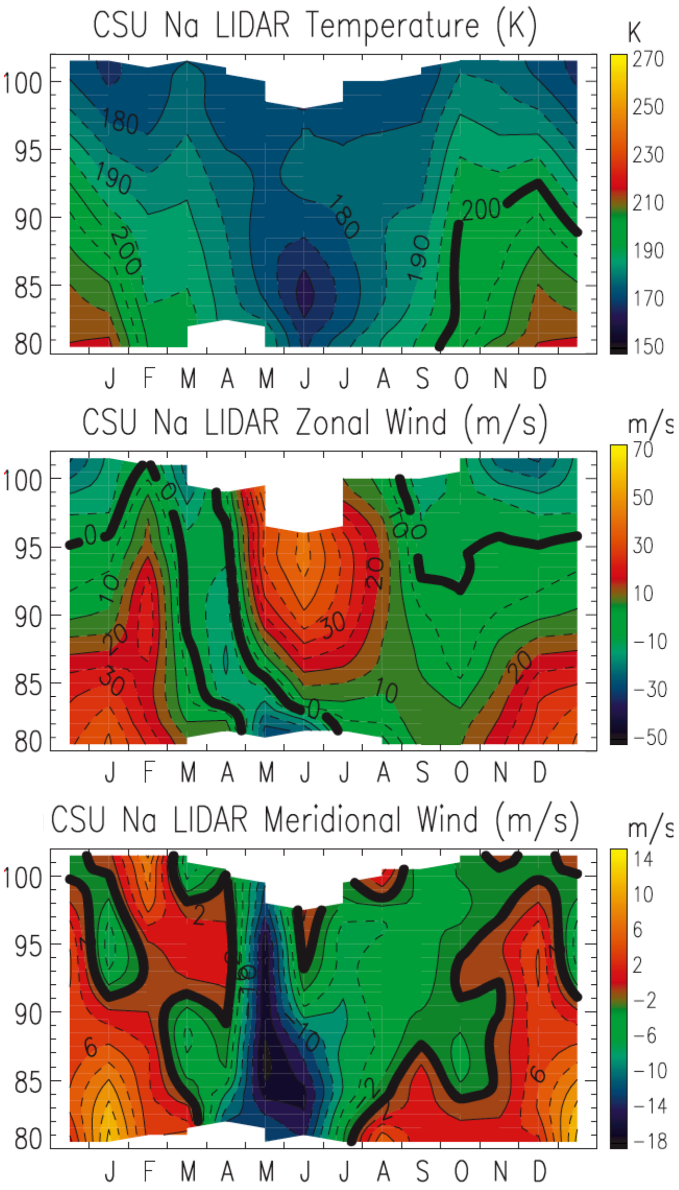
Resonance Fluorescence, Frequency Analyzer in Atmosphere

Full-Diurnal Multiple-Beam Obs.



Dr. Chiao-Yao She with CSU Na lidar

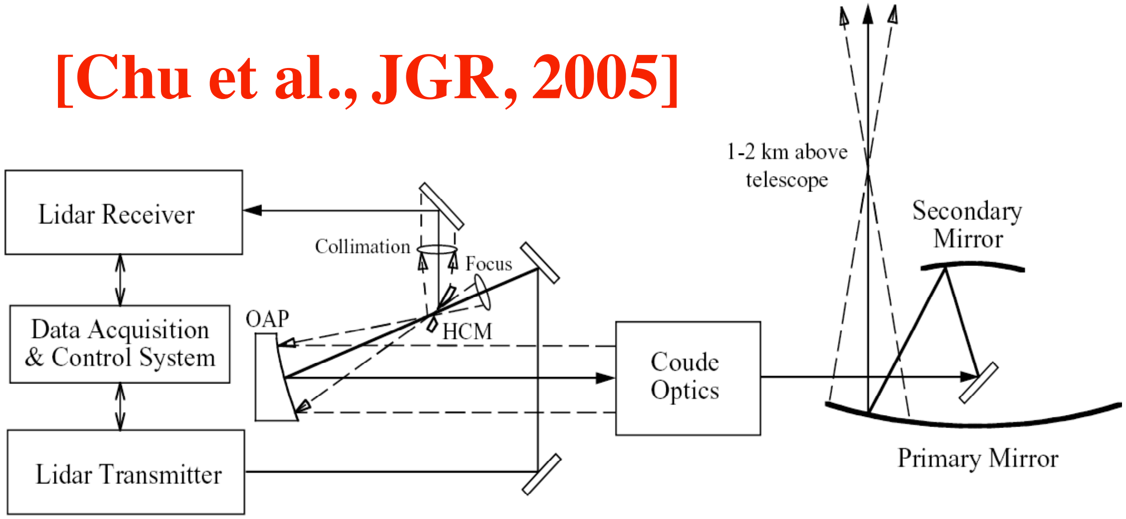


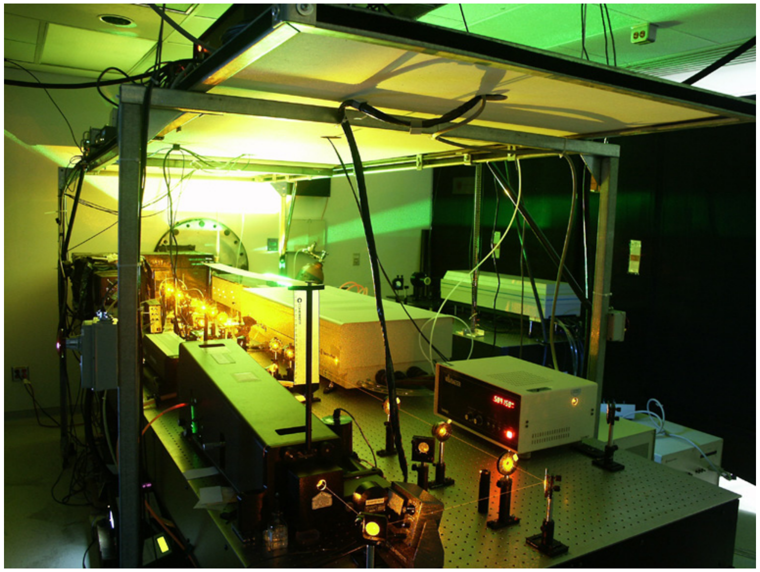


[Yuan et al., JGR, 2008]

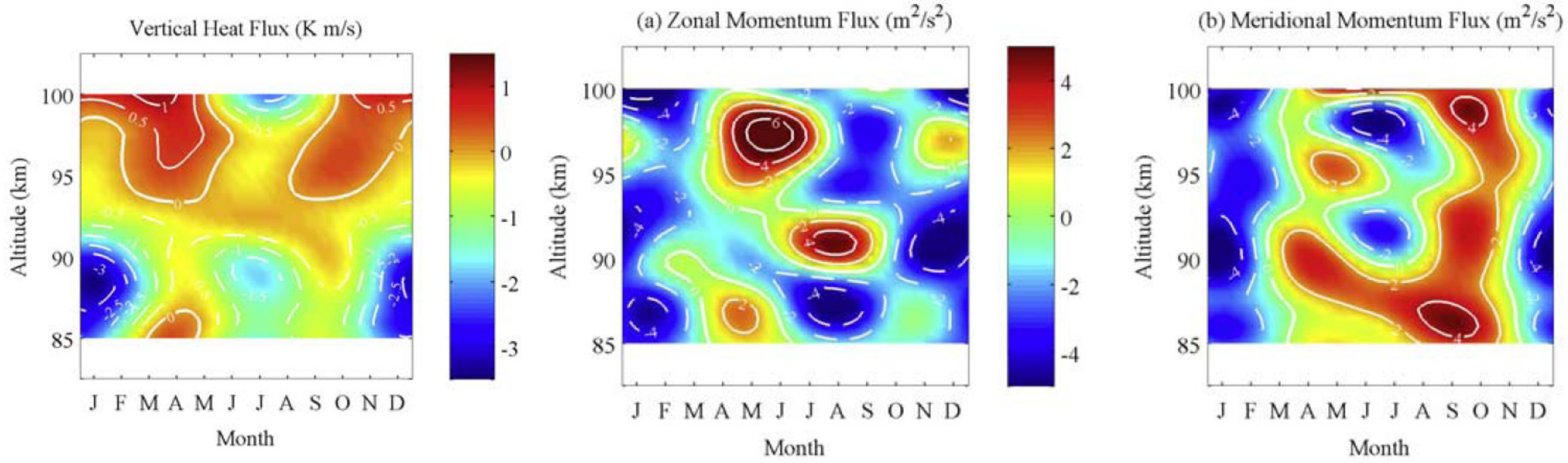
Large Aperture for High Precision

[Chu et al., JGR, 2005]





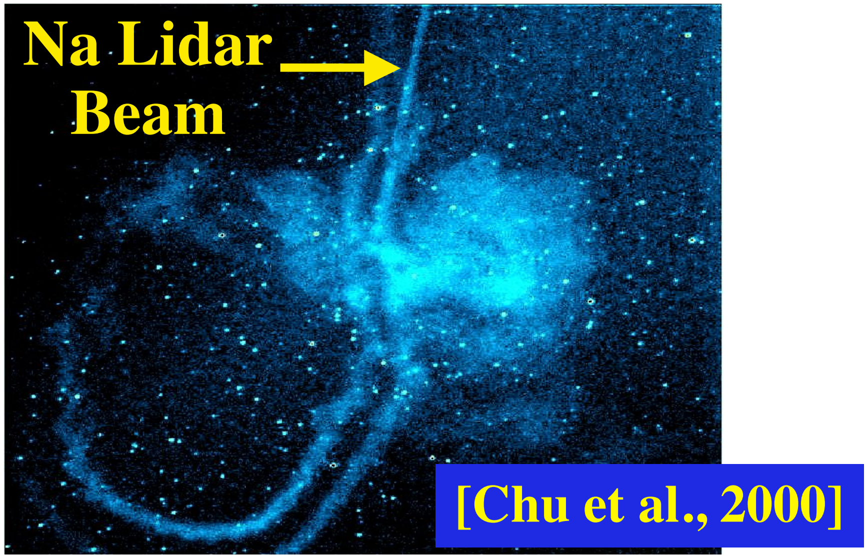
UIUC Na Wind & Temperature Lidar Coupled with Large Telescope



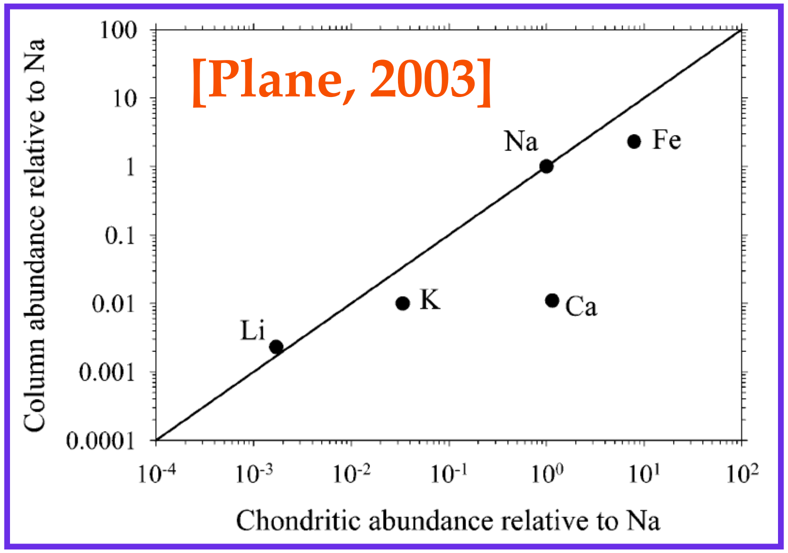
[Gardner and Liu, JGR, 2007]

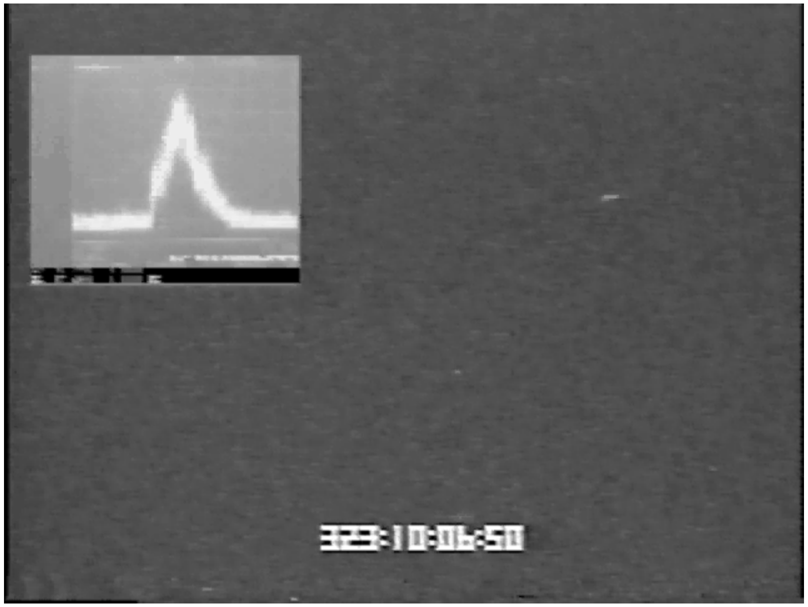
CEDAR Science: Meteor & Metal Species

Meteor ablation deposits metallic atoms

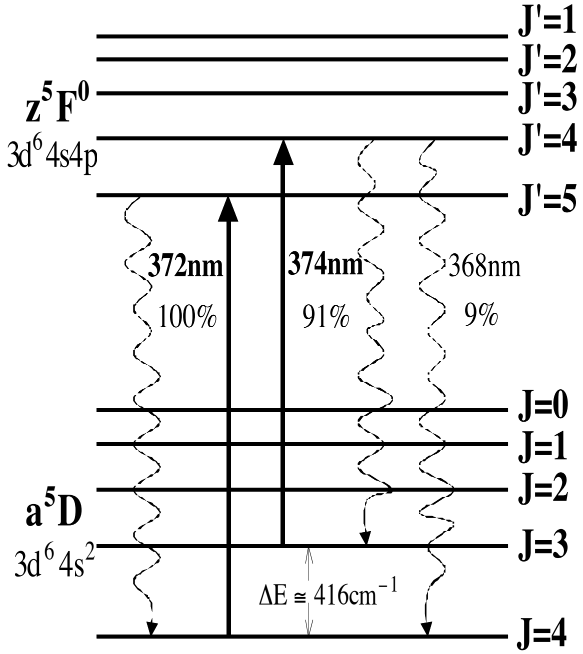


Lidar detection of persistent meteor trails during Leonid Shower 1998





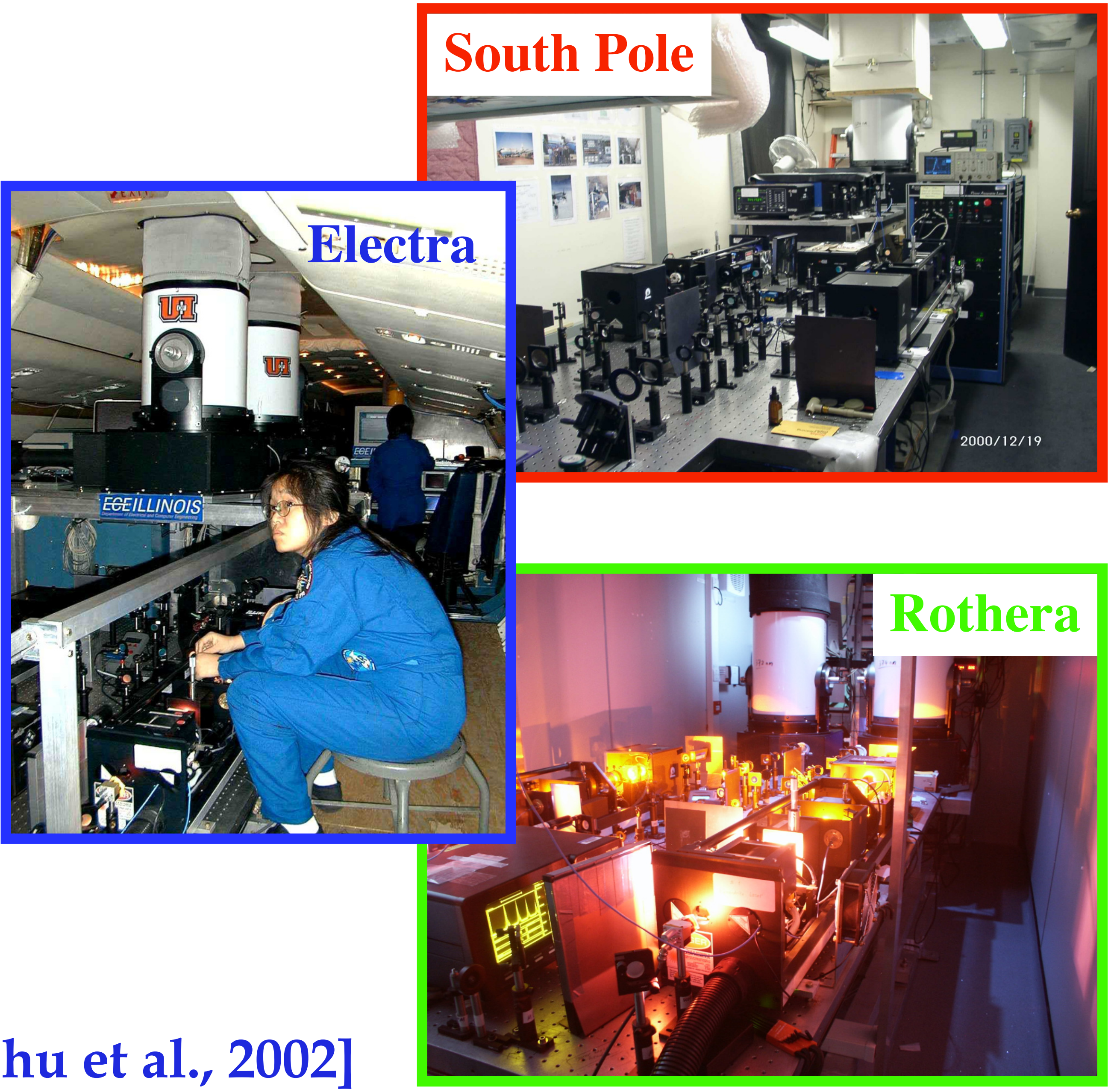
Fe Boltzmann Temperature LIDAR



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

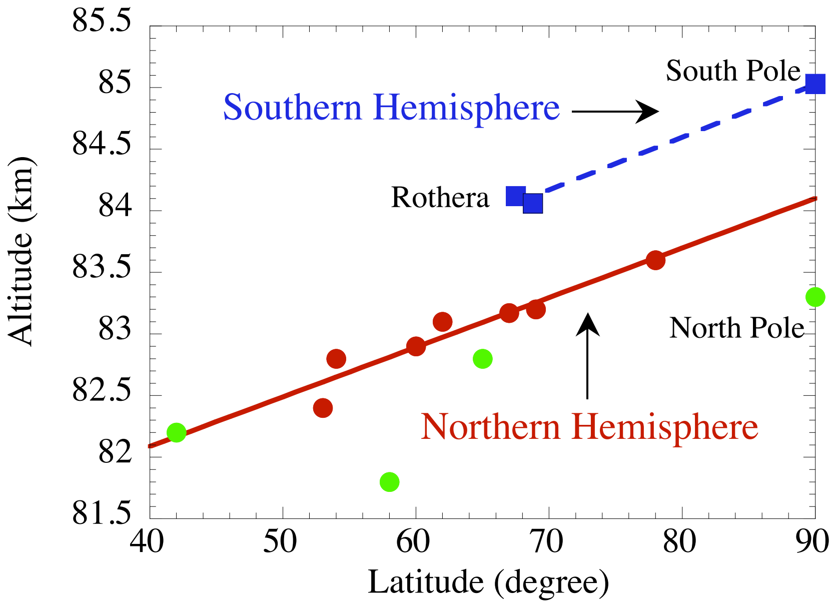
⇓

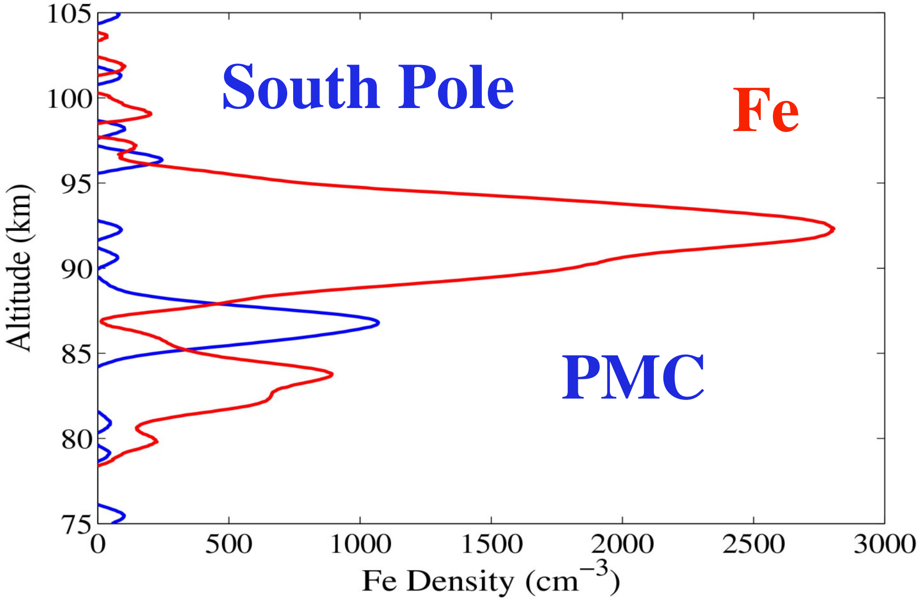
$$T = \frac{\Delta E / k_B}{ln\left(\frac{g_2}{g_1} \cdot \frac{P_1}{P_2}\right)}$$



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

PMC Hemispheric Difference & Fe/PMC Heterogeneous Chemistry





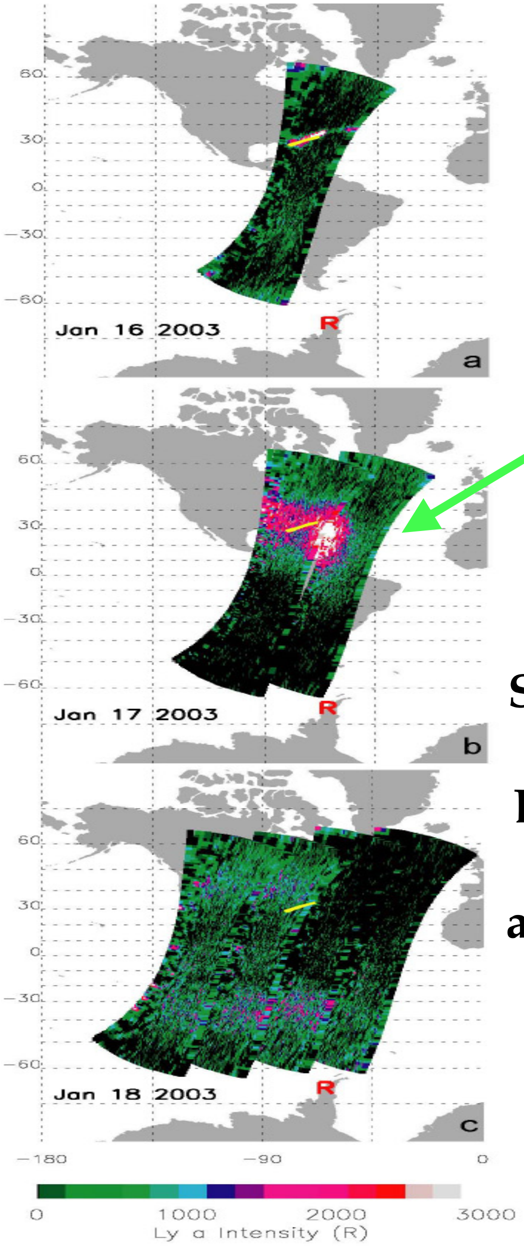
Southern PMC are ~ 1 km Higher than Northern PMC ⇨ Earth Orbital Eccentricity and Gravity Wave Differences

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

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

[Plane et al., Science, 2004]

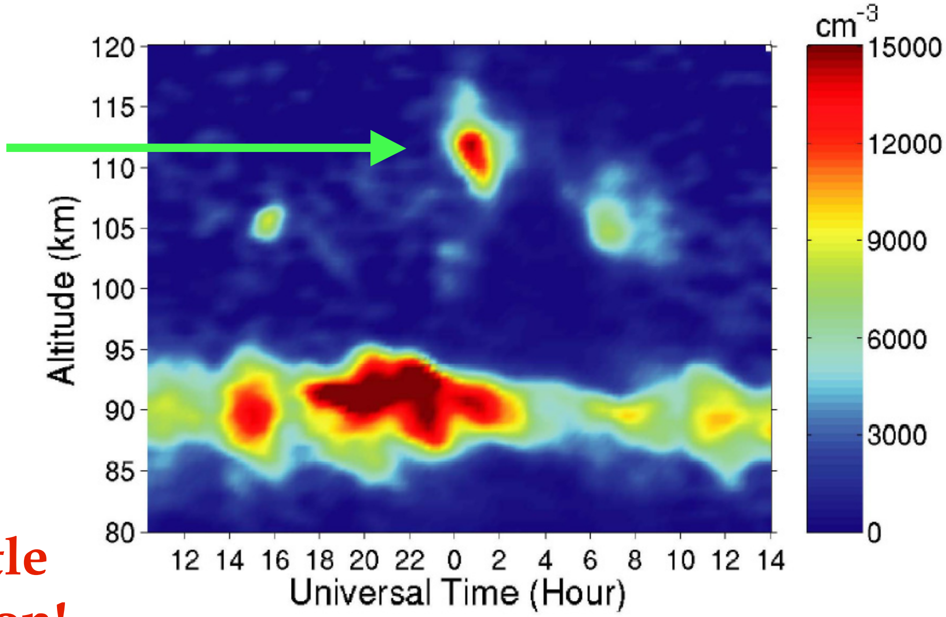
Shuttle Formed High-Z Sporadic Fe



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)

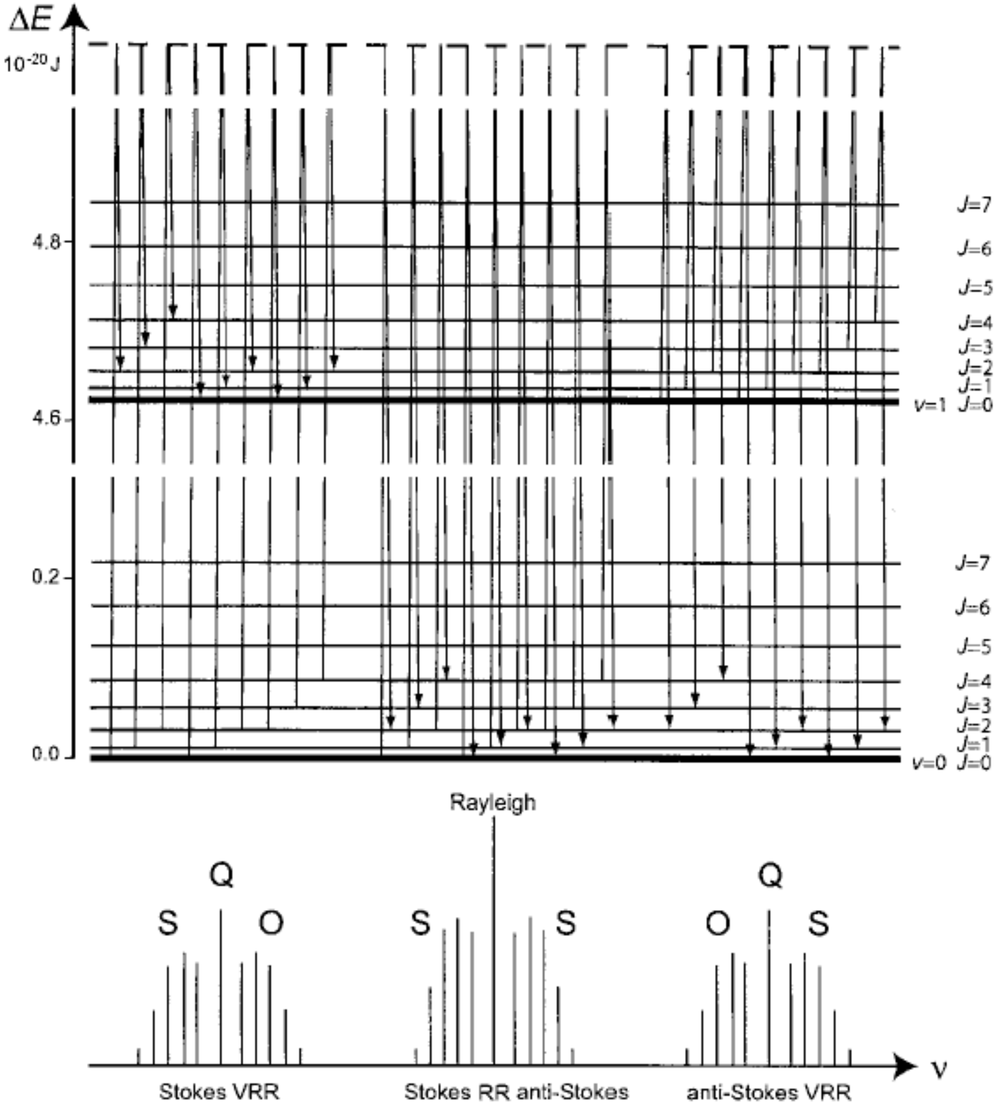


Causes: Shuttle
Engine Ablation!

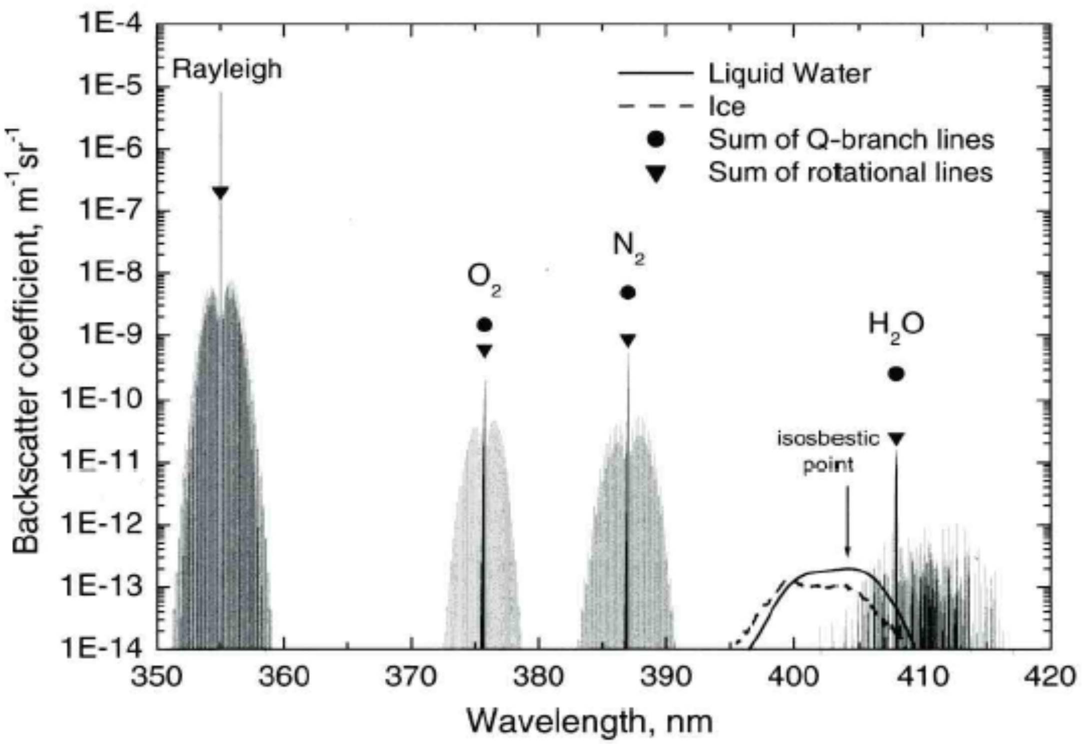
[Stevens et al., GRL, 2005]

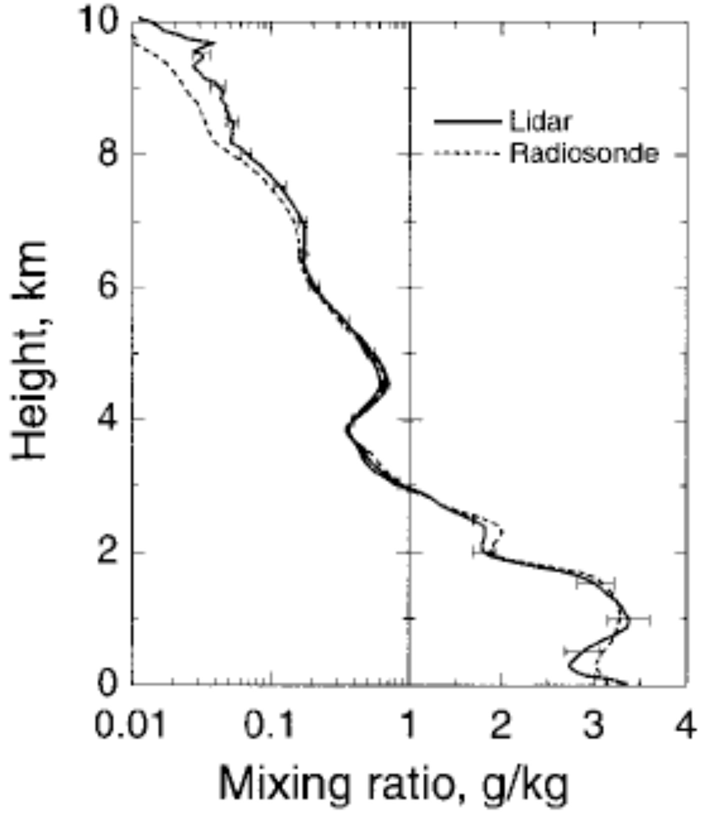
DIAL & Raman Lidar for Trace Gases

- 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!



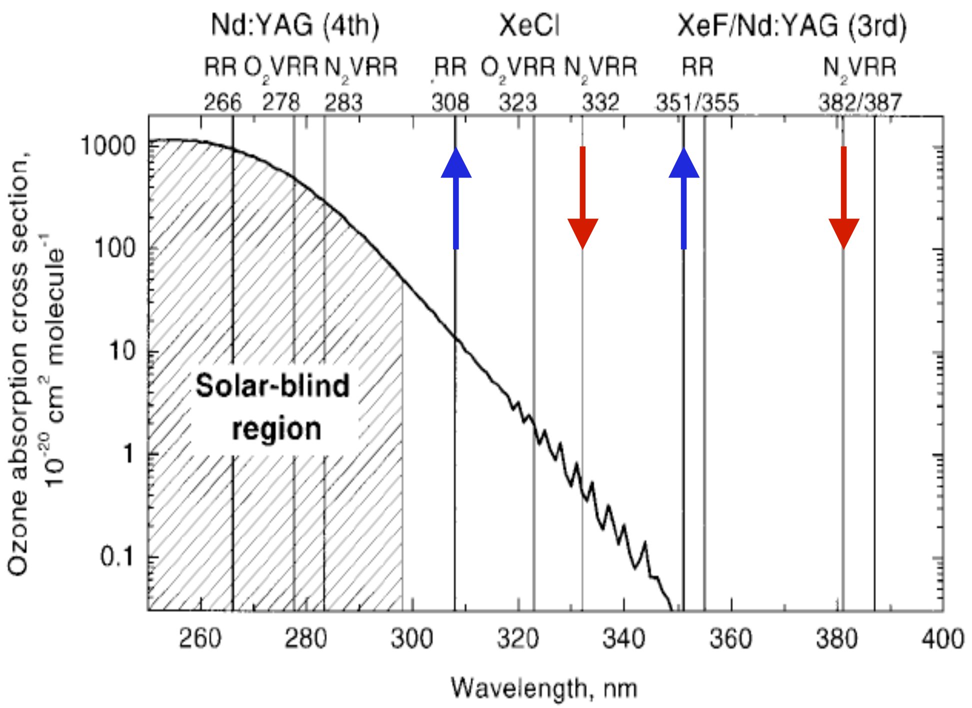
Raman Lidar for Water Vapor





- 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.

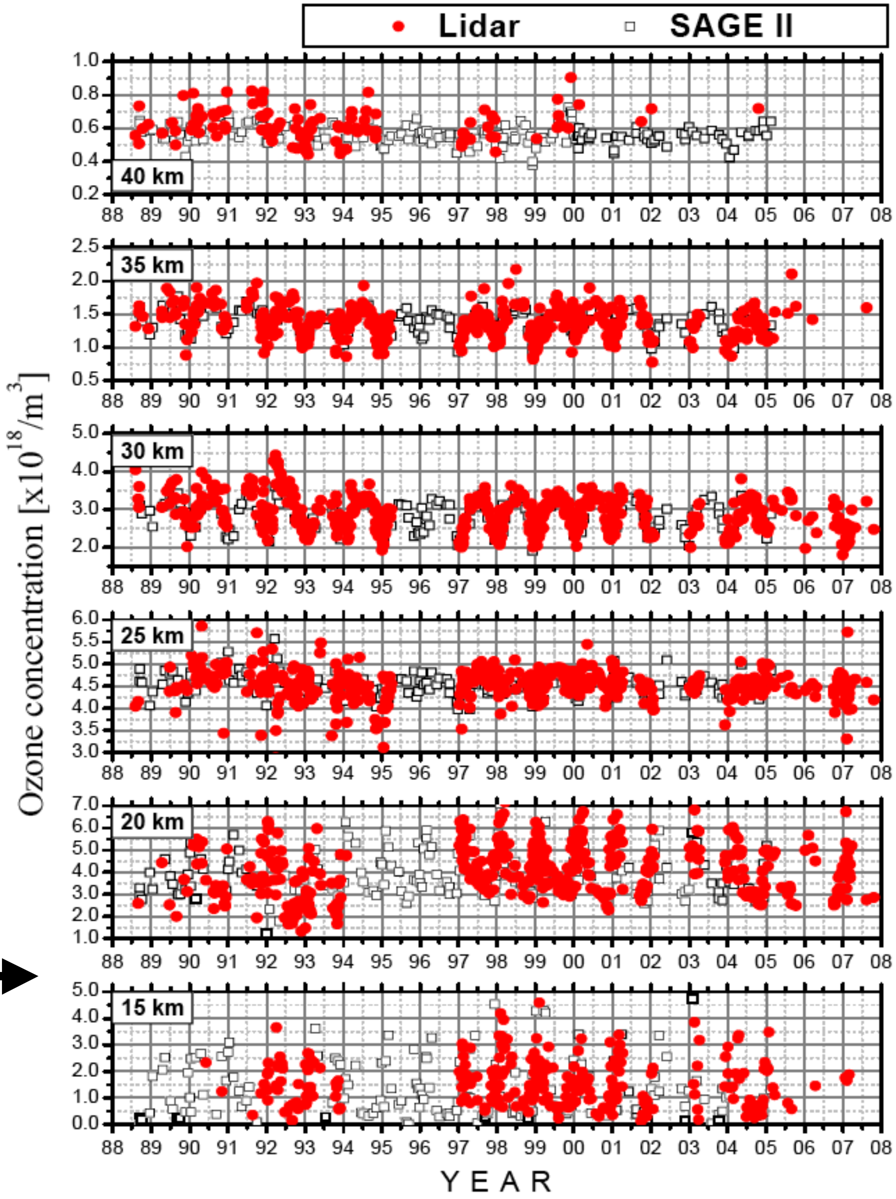
DIAL for Ozone in Two Decades



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

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

→



Rayleigh + Raman Integration Lidar

Hydrostatic Equation

$$dP = -\rho g dz$$

+

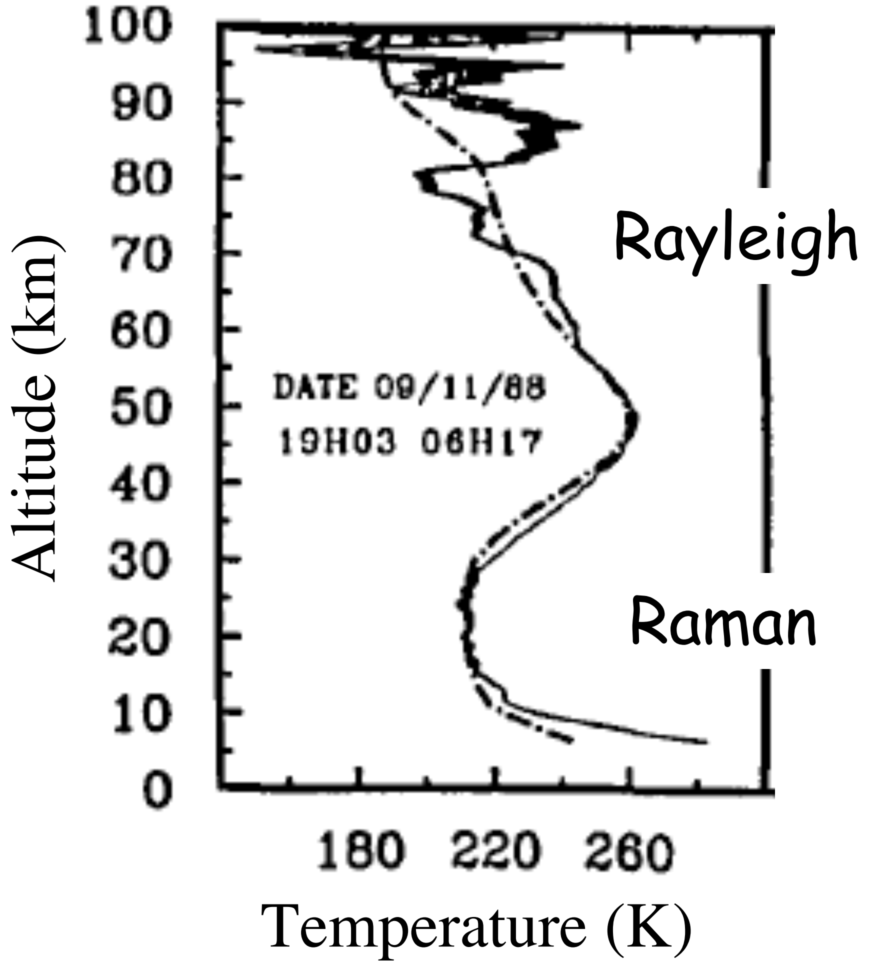
Ideal Gas Law

$$P = \rho RT$$

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

Density Ratio ⇨ Temperature

Searchlight, Falling Sphere
Rayleigh Lidar, VR-Raman Lidar

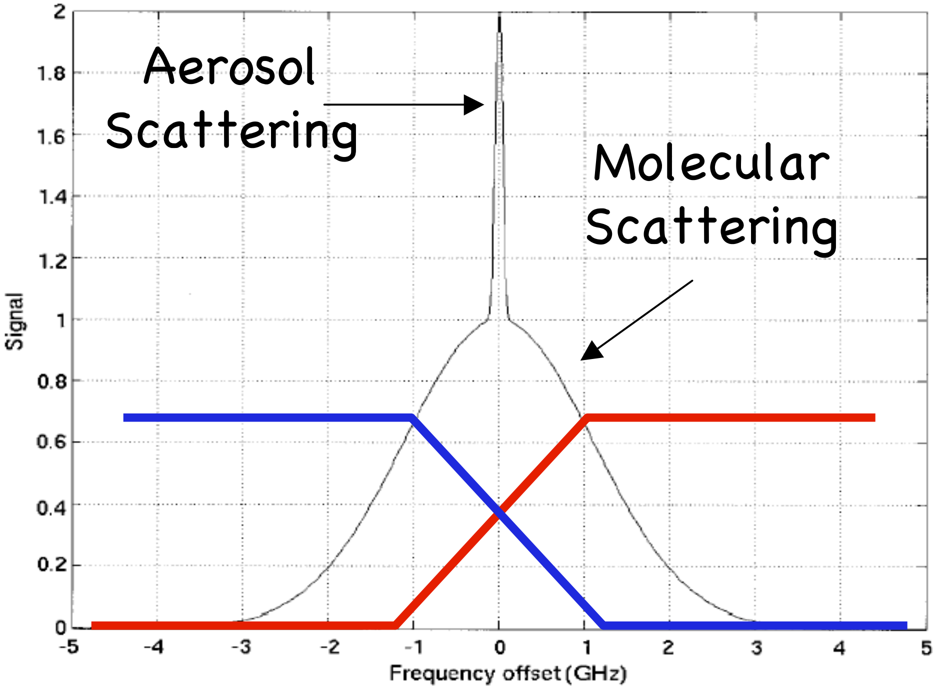


[Keckhut et al., 1990]

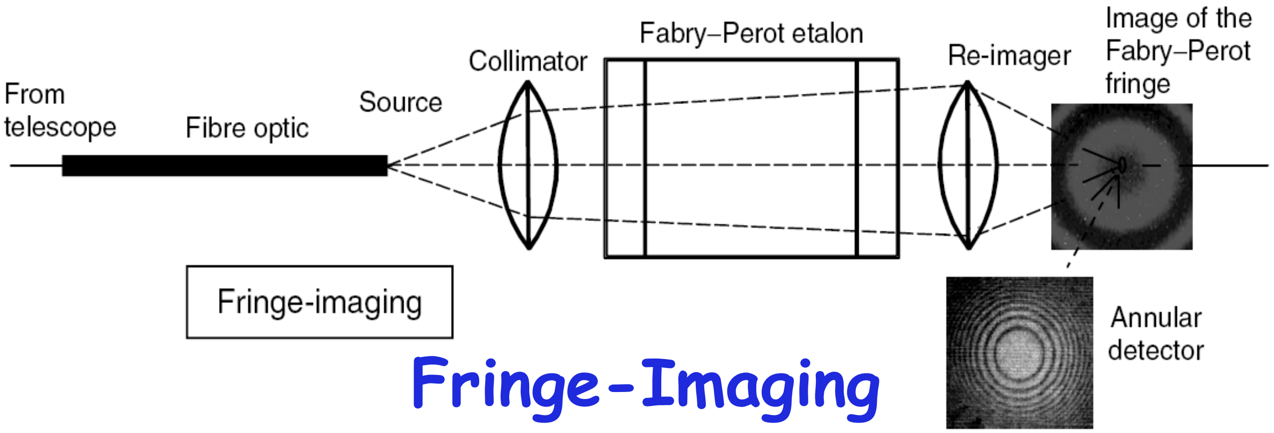
Direction-Detection Doppler Lidar

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.



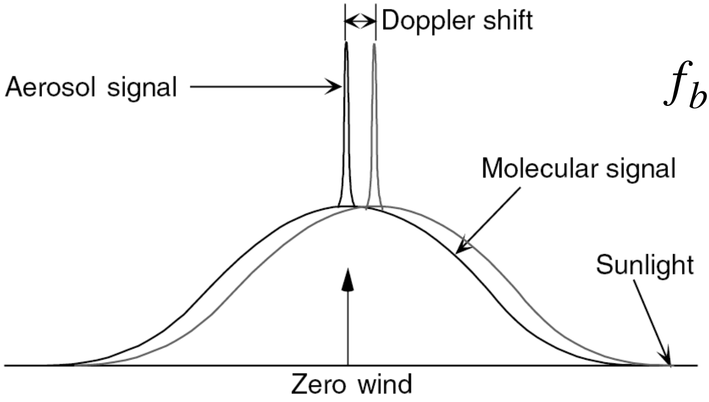
Double-Edge Filter



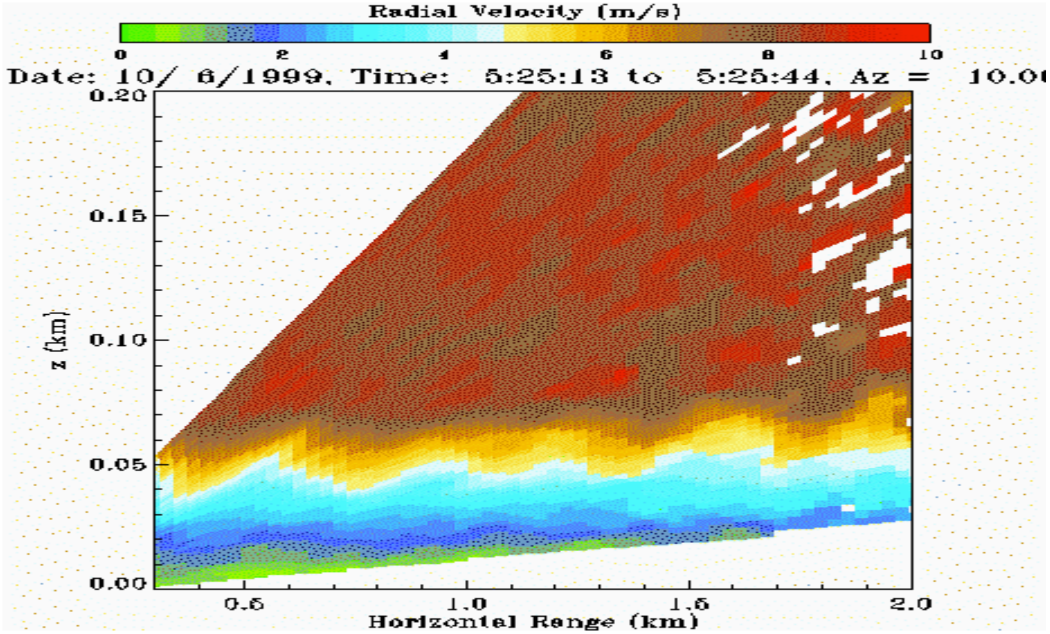
Fringe-Imaging

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.



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

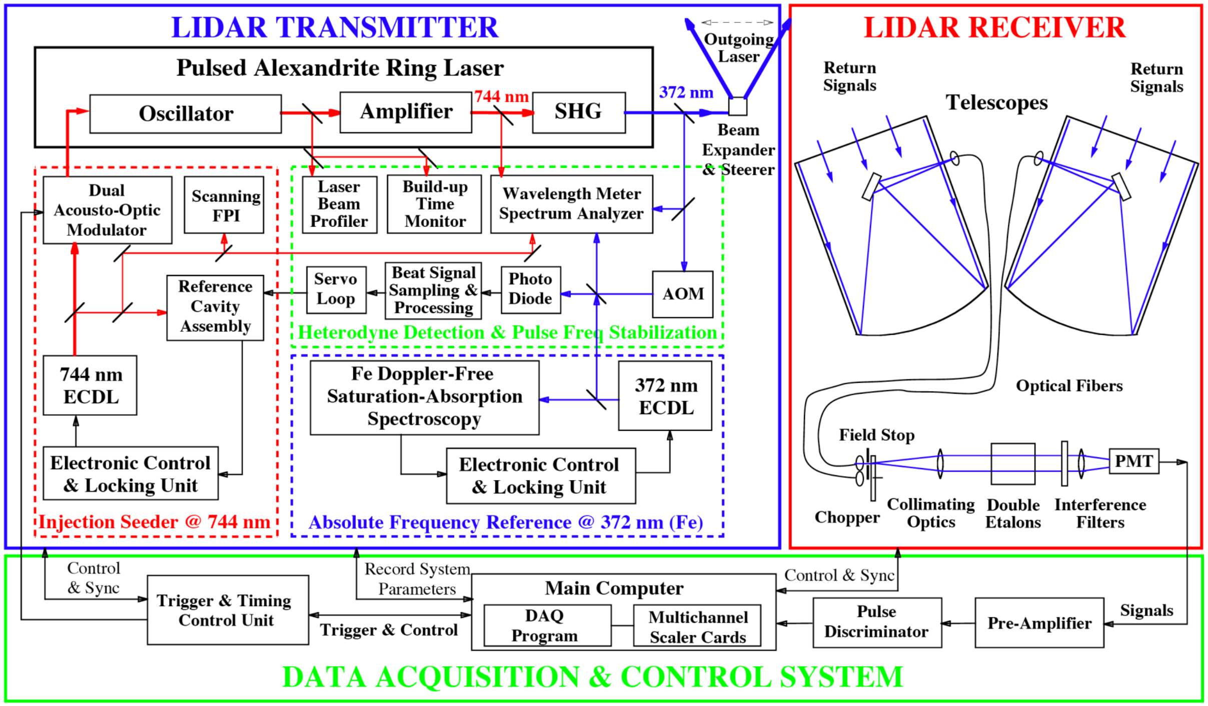


NOAA HRDL

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

Mobile Solid-State Doppler Lidar



LIDAR TRANSMITTER

Pulsed Alexandrite Ring Laser

Oscillator

Amplifier

744 nm

SHG

372 nm

Outgoing Laser

Beam Expander & Steerer

Dual Acousto-Optic Modulator

Scanning FPI

Laser Beam Profiler

Build-up Time Monitor

Wavelength Meter Spectrum Analyzer

Reference Cavity Assembly

Servo Loop

Beat Signal Sampling & Processing

Photo Diode

AOM

Heterodyne Detection & Pulse Freq Stabilization

744 nm ECDL

Fe Doppler-Free Saturation-Absorption Spectroscopy

372 nm ECDL

Electronic Control & Locking Unit

Electronic Control & Locking Unit

Injection Seeder @ 744 nm

Absolute Frequency Reference @ 372 nm (Fe)

LIDAR RECEIVER

Return Signals

Telescopes

Return Signals

Optical Fibers

Field Stop

PMT

Chopper

Collimating Optics

Double Etalons

Interference Filters

Control & Sync

Record System Parameters

Control & Sync

Trigger & Timing Control Unit

Main Computer

DAQ Program

Multichannel Scaler Cards

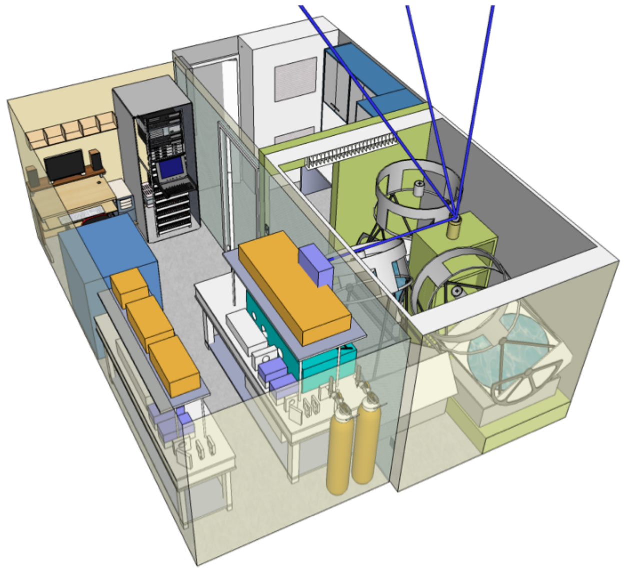
Trigger & Control

Pulse Discriminator

Pre-Amplifier

Signals

DATA ACQUISITION & CONTROL SYSTEM



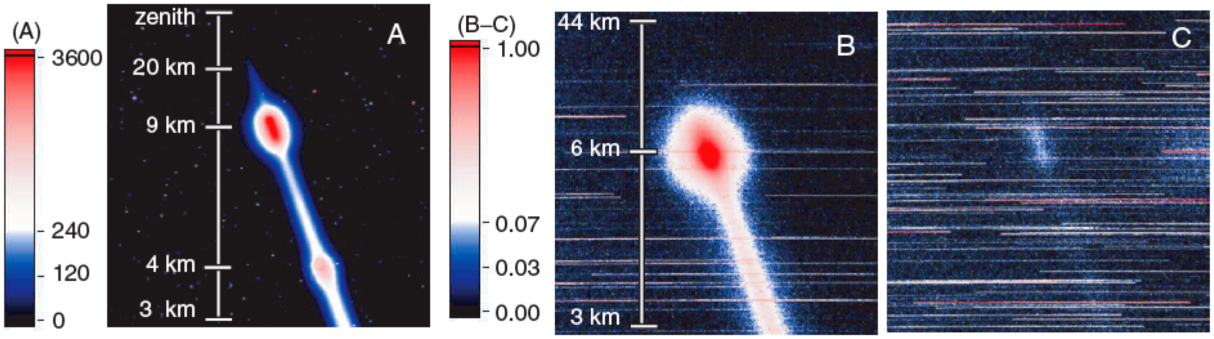
➢ NSF Major Research Instrumentation (MRI) mobile Fe-resonance/ Rayleigh/Mie Doppler lidar is an advanced resonance fluorescence lidar being developed at the University of Colorado, Boulder. It is based on Pulsed Alexandrite Ring Laser (PARL) for simultaneous measurements of temperature (30-110 km), wind (75-110 km), Fe density (75-115 km), aerosols/clouds (10-100 km), and gravity waves in both day and night through an entire year with high accuracy, precision, & resolution.

Extending Measurement Range

- **Extending downward:**

-- Various edge-filter techniques are being developed to probe lower atmosphere wind and temperature simultaneously

-- White-light lidar



[Kasparian et al., 2003]

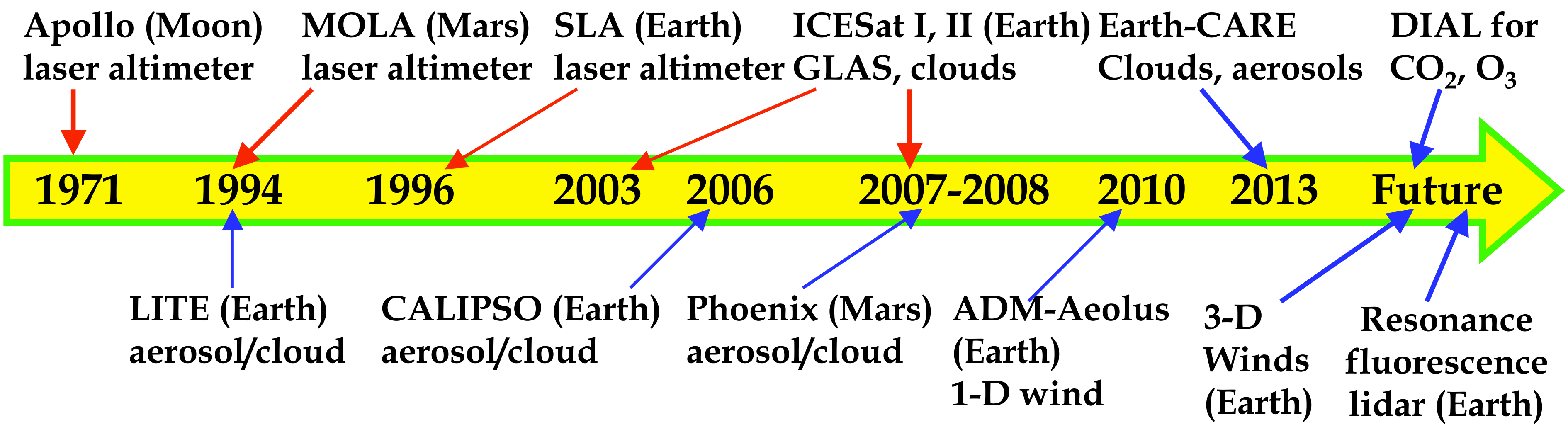
- **Extending upward:**

-- Thermosphere Helium (He) lidar

-- Aurora N_2^+ resonance lidar

Driven by Whole Atmosphere Science !!!

Lidar into Space



Apollo (Moon) laser altimeter

MOLA (Mars) laser altimeter

SLA (Earth) laser altimeter

ICESat I, II (Earth) GLAS, clouds

Earth-CARE Clouds, aerosols

DIAL for CO_2, O_3

1971 1994 1996 2003 2006 2007-2008 2010 2013 Future

LITE (Earth) aerosol/cloud

CALIPSO (Earth) aerosol/cloud

Phoenix (Mars) aerosol/cloud

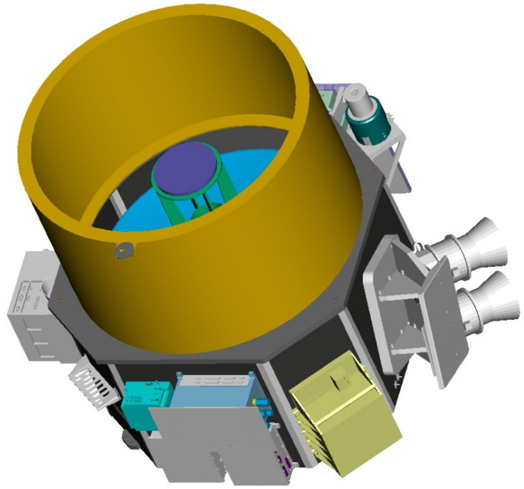
ADM-Aeolus (Earth) 1-D wind

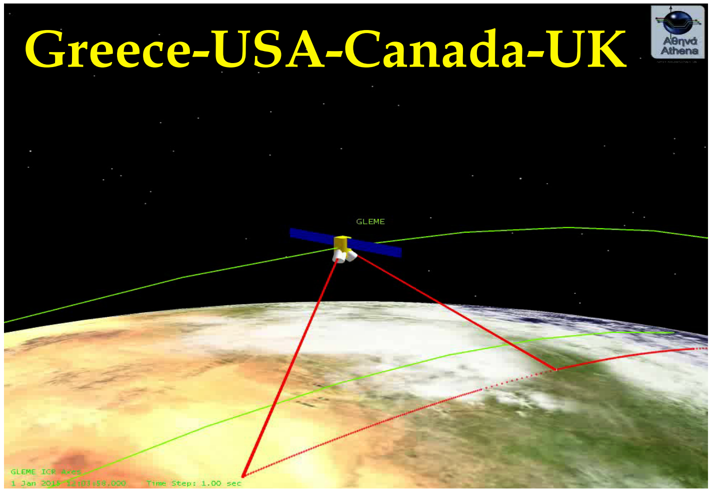
3-D Winds (Earth)

Resonance fluorescence lidar (Earth)

Laser altimeter ⇨ Aerosol/cloud ⇨ DIAL & wind ⇨ Resonance fluorescence

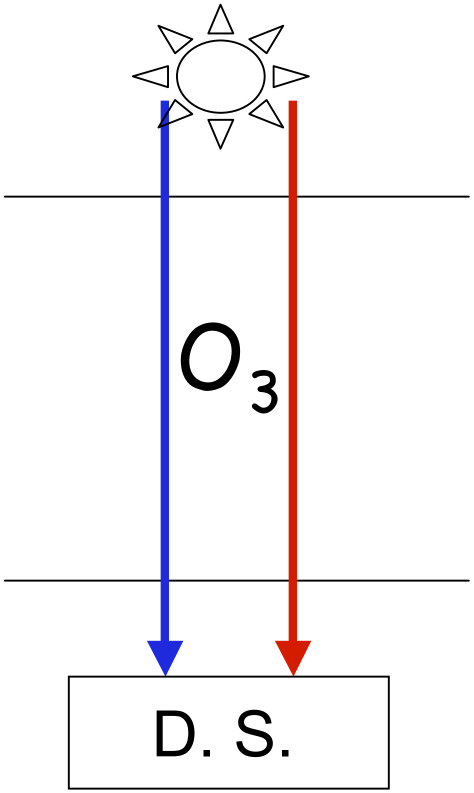
CALIPSO





ESA feasibility study: to develop a resonance fluorescence Doppler lidar to profile wind & temperature in MLT for wave dynamics, thermal & chemistry studies.

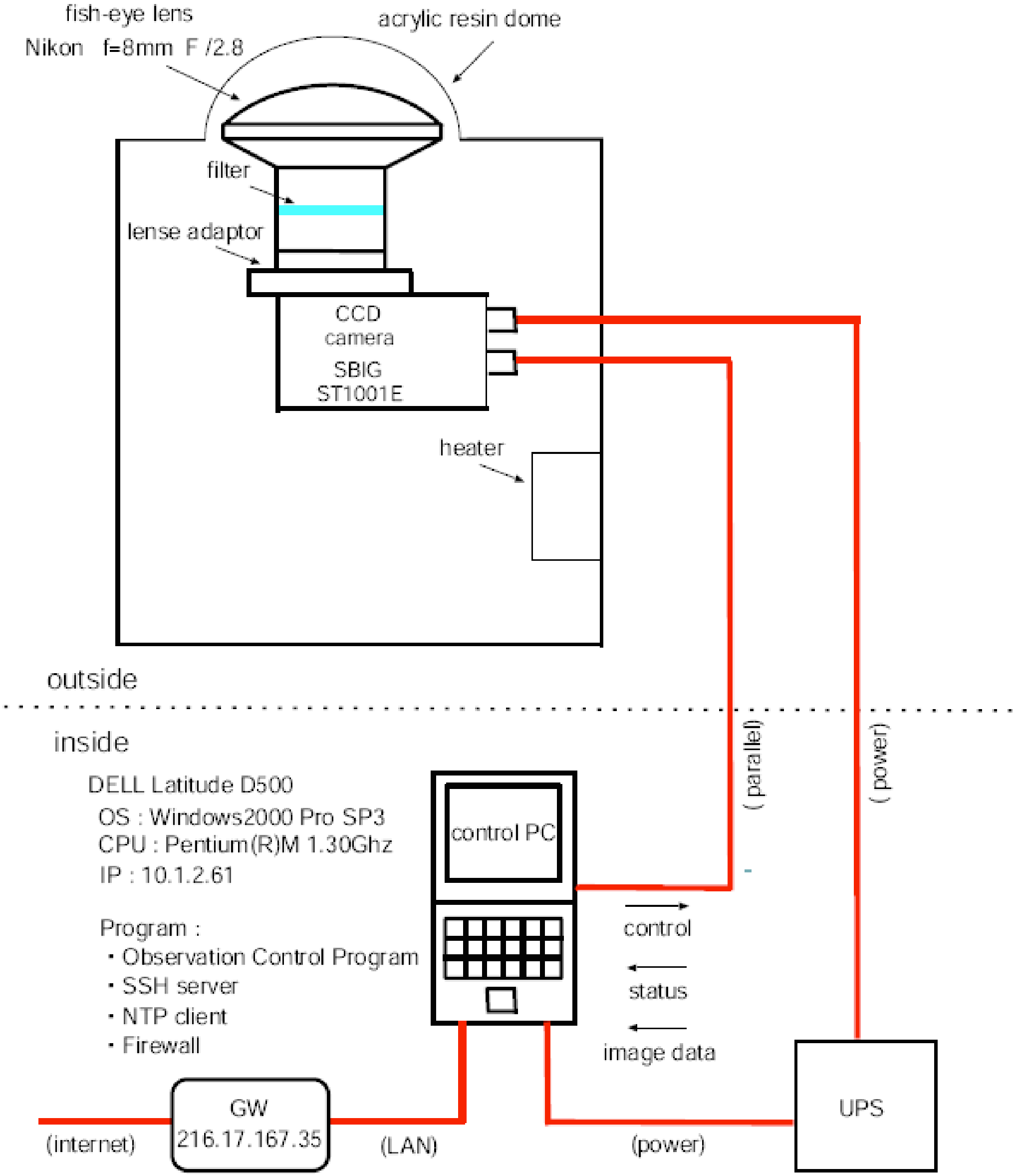
Passive Optical Remote Sensing



305 and 325 nm

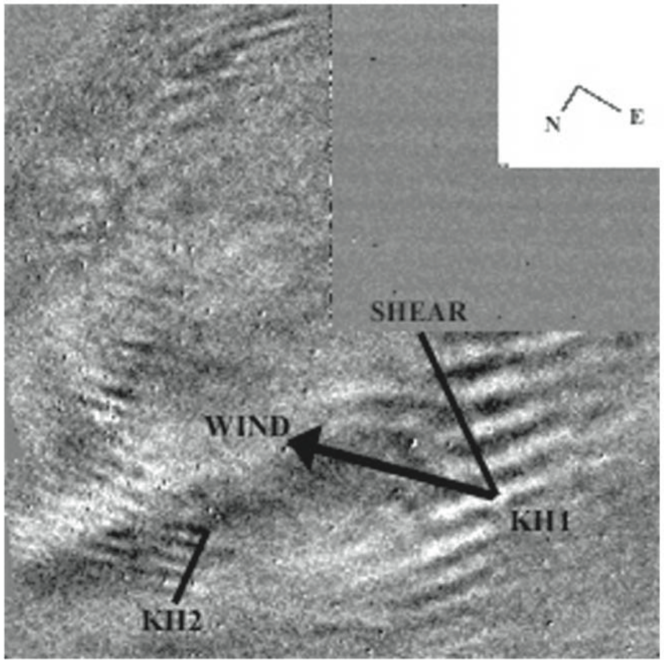
NOAA Dobson Spectrometer
to measure ozone
from the ground

Passive: All-Sky-Camera for Airglow



DELL Latitude D500
OS : Windows2000 Pro SP3
CPU : Pentium(R)M 1.30Ghz
IP : 10.1.2.61

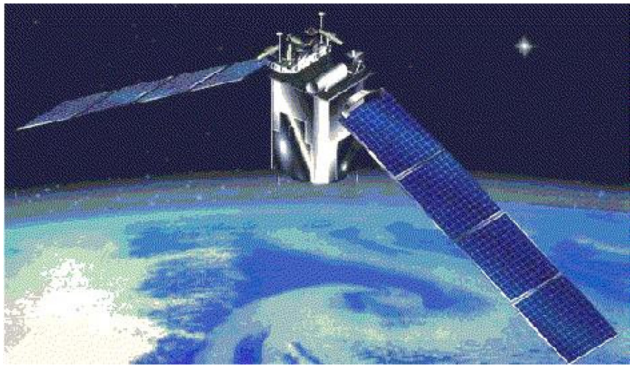
Program :
- Observation Control Program
- SSH server
- NTP client
- Firewall



Courtesy of Takuji Nakamura (NIPR) and Jia Yue (CSU)

The SABER Instrument Aboard the TIMED Satellite

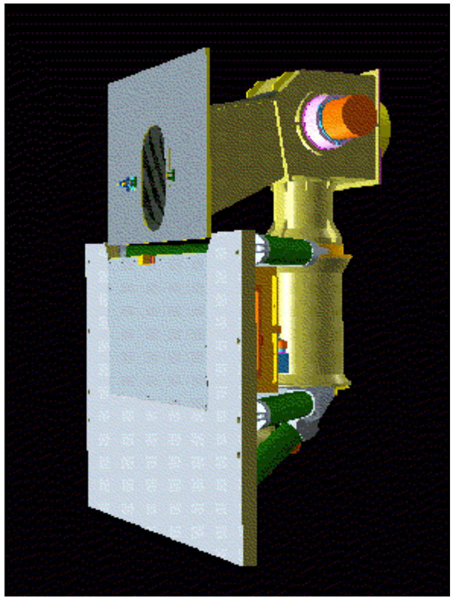
TIMED: Thermosphere, Ionosphere, Mesosphere Energetics & Dynamics



SABER: Sounding of the Atmosphere Using Broadband Emission Radiometry

SABER instrument:

- **Limb scanning infrared radiometer**
- **10 broadband channels (1.27-17 µm)**
- **Products: kinetic temperature, CO_2, O_3, H_2O, NO, O_2, OH, O, H**



[Courtesy of Dr. *Artem Feofilov et al.,* NASA, 2007]

Concepts of Spectroscopy

- Spectroscopy is the study of the interaction between radiation (photons, phonons, or particles) and matter.
- Spectroscopy is the study of matter by investigating radiation (photons, phonons, or particles) that is absorbed, emitted, or scattered by the matter under investigation.
- The radiation includes all forms of electromagnetic radiation and non-electromagnetic radiation.

-- EM radiation (photons): radiowaves, microwaves, infrared light, visible light, ultra-violet light, X-ray, etc.

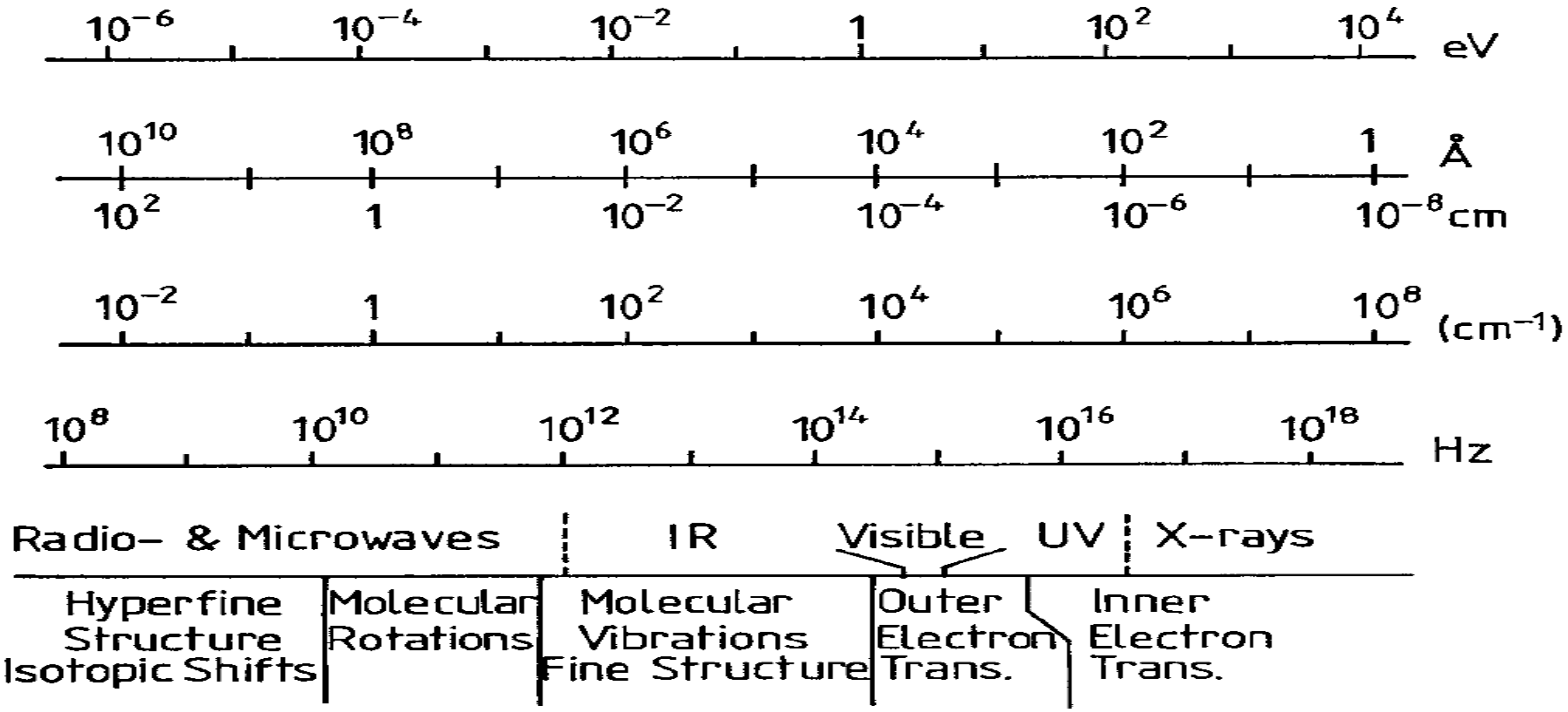
-- Non-EM radiation: phonons (acoustic wave), electrons, etc.

Classification of Spectroscopy

- According to radiation used in the study, spectroscopy can be classified to three main types of spectroscopy:

  EM spectroscopy, Acoustic Spectroscopy, Mass Spectroscopy.

- We deal with EM spectroscopy here.



Methods to Study Spectroscopy

Two main types of study of spectroscopy -

1. **Fundamental study of matter structure (e.g., atomic or molecular structure, etc.)**

   Spectrum study (wavelength, transition probability, etc.) is the fundamental method to study atomic and molecular structures.

2. **Applied study of environmental properties (e.g., remote sensing of atmosphere parameters, chemical analysis)**

   Identification of chemical composition and measurement of their quantity using spectroscopy.

   Measurement of environmental conditions like wind and temperature through spectroscopy analysis.

Why to Study Spectroscopy?

- Spectroscopy is the fundamental for many modern sciences and technologies. Spectroscopy has found very wide applications.

-- Spectroscopy is an very important approach to study the fundamental matter (fundamental particles, atoms, molecules, etc.) structure and internal interaction.

-- Spectroscopy is often used in physics and analytical chemistry for the identification of substances through the spectrum emitted from them or absorbed in them.

-- Spectroscopy is also heavily used in astronomy and remote sensing. They are used either to measure the chemical composition and physical properties of objects or to measure related environmental properties like velocities and temperatures from the Doppler shift and broadening of spectral lines.

- Spectroscopy is the fundamental for all remote sensing technologies.
- We want to give students the abilities and fundamental knowledge to learn more things -

"Teach students the skills to learn new things".

Lidar & Atmosphere Research

AMO Physics and Lidar Theory:

Spectroscopy, Principles, Laser, Optics, Simulation

Instrumentation: to produce lidar tools

Design, development, test, calibration

Deployment: ⇨new lidar data

Installation, operation, data collection

Data Analysis: ⇨new atmosphere data

Data retrieval, data analysis

Science Study: ⇨new atmosphere knowledge

Literature survey, ideas generation, simulation

Data Analysis: ⇨new modeling data

Simulation run, data analysis, …

Numerical Modeling: to produce model tools

…

Atmospheric Theory and Space Physics:

Principles, Equations, …

Concluding Remarks

- Spectroscopy is the fundamental for lidar and passive optical remote sensing, which is very important in full understanding of the principles and technologies, innovation of new technologies and instrumentation, and fully utilizing these remote sensing approaches to study environment, atmosphere, and space.
- Spectroscopy has also found wide applications in many other modern sciences and technologies, making it a “must-learn” knowledge.
- Study of spectroscopy will inspire us for future lidar innovation or even revolution so that we can answer many open questions in atmosphere and space research.
- Through the spectroscopy class, we try to help you to gain the high abilities and skills to learn new things.