A New Horizon:  
LIDAR Exploration of Atmosphere and Space  

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Light Detection And Ranging

- LIDAR Fundamentals
- Physical Interactions in Lidar
- Lidar for CEDAR Science
- Lidar into Future & Space
- Concluding Remarks

CEDAR Lidar Tutorial
**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](image1.jpg)

![Arecibo](image2.jpg)
Light Detection And Ranging

Time of Flight \Leftrightarrow \text{Range} / \text{Altitude} \quad R = C \frac{\Delta t}{2}

\begin{align*}
120 \text{ km} \\
75 \text{ km} \\
30 \text{ km} \\
\text{Ground}
\end{align*}
From Searchlight to Modern Lidar

- Light detection and ranging (LIDAR) started with using CW searchlights to measure stratospheric aerosols and molecular density in 1930s.
- 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**
- **Transmitter**
- **Receiver**

**Monostatic Configuration**
- **Pulsed Laser**

\[ R = c \cdot \Delta t / 2 \]

**CW searchlight → ns laser pulse**
Picture of Lidar Remote Sensing

\[ \beta(\lambda, \lambda_L, \theta, R) \cdot \Delta R \]
Interaction between radiation and objects

Radiation Propagation Through Medium

\[ T(\lambda_L, R) \]

Signal Propagation Through Medium

\[ \eta(\lambda, \lambda_L)G(R) \]

Transmitter
(Radiation Source)

Receiver
(Light Collection & Detection)

Data Acquisition & Control System

Data Processing, Analysis & Interpretation

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Lidar Equation

- General lidar equation with angular scattering coefficient

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

- General lidar equation in angular scattering coefficient \( \beta \) and extinction coefficient \( \alpha \) form

\[ N_S(\lambda, R) = \left[ \frac{P_L(\lambda_L) \Delta t}{hc/\lambda_L} \right] \left[ \beta(\lambda, \lambda_L, \theta, R) \Delta R \right] \left( \frac{A}{R^2} \right) \]
\[ \cdot \exp \left[ -\int_0^R \alpha(\lambda_L, r') \, dr' \right] \exp \left[ -\int_0^R \alpha(\lambda, r') \, dr' \right] \left[ \eta(\lambda, \lambda_L) G(R) \right] + N_B \]
Higher signal level ⇒ high signal-to-noise ratio ⇒ better precision/resolution

Lidar signal level is a game of laser power, telescope aperture, effective cross-section, constituent density, detector and filter performances, etc.
Biaxial vs. Coaxial Arrangements

Lidar Transmitter

Lasers

Frequency Reference

Wavelength Frequency Control

Trigger

Frequency Shift/Modulation Device

Energy/Power Meter

Fast Photo Diode Temporal Detection

Spatial Beam Profiler

Spectrum Analyzer

Data Acquisition and System Control
Computer + Trigger Box Control/Triggering/Monitoring

Beam Expander

Field Stop Chopper

Collimating Optics

Filters

Photo Detector

Amplifier

Discriminator

Multi-Channel Scalers
“Fancy” Lidar Architecture

Transceiver
(Light Source, Light Collection, Lidar Detection)

Data Acquisition & Control System

Holographic Optical Element (HOE)

Courtesy to Geary Schwemmer

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VAD Technique for Vector Wind

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

\[ \mathbf{V} = (u, v, w) = \left( \frac{b \sin \theta_{\text{max}}}{\cos \varphi}, \frac{b \cos \theta_{\text{max}}}{\cos \varphi}, \frac{a}{\sin \varphi} \right) \]

\[ V_R = u \sin \theta \cos \varphi + v \cos \theta \cos \varphi + w \sin \varphi \]
Doppler-Beam-Swinging (DBS) technique: pointing lidar beam to vertical, north, and east, or plus south and west (ZNEZSW).

\( \gamma \) is the off-zenith angle

\[
\begin{align*}
V_{RE} &= u \sin \gamma + w \cos \gamma \\
V_{RN} &= v \sin \gamma + w \cos \gamma \\
V_{RZ} &= w
\end{align*}
\]

\[
\begin{align*}
u &= (V_{RE} - V_{RZ} \cos \gamma) / \sin \gamma \\
v &= (V_{RN} - V_{RZ} \cos \gamma) / \sin \gamma \\
w &= V_{RZ}
\end{align*}
\]

\( V_R > 0, \ w > 0, \ u > 0, \ v > 0 \) for wind towards away, upward, east, and north
**Physical Interaction**

- 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

**Device**

- Mie Lidar
- DIAL
- Raman Lidar
- Rayleigh Lidar
- Resonance Fluorescence Lidar
- Wind Lidar
- Fluorescence Lidar
- Laser Range Finder Laser Altimeter

**Observables**

- Aerosols, Clouds: Geometry, Thickness
- Gaseous Pollutants
- Ozone
- Humidity (H₂O)
- 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

Absorption
Fluorescence

Rayleigh
Raman
Absorption
Fluorescence

virtual level

Atomic absorption & (resonance) fluorescence

Molecular elastic and inelastic scattering, absorption and fluorescence

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The fluorescence signals indicate the presence of high organic (chlorophyll) and enable the dispersion of various kinds of effluent plumes to be remotely mapped.
Laser Rangefinding Techniques

- The basic principle of active noncontact rangefinding systems is to project a wave (radio, ultrasonic, or optical) onto an object and process the reflected signal to determine its range. If a high resolution rangefinder is needed, an optical source must be chosen because radio and ultrasonic waves cannot be focused adequately.

- There are mainly three types of rangefinding techniques: (1) Time of flight techniques: this is for the majority of laser range finder; (2) Geometric-based technique: the classical triangulation by projection of a light beam onto a target; (3) Interferometry: using interferometry principle to measure distance to high accuracy.

- Time-of-flight techniques include 1) pulsed laser rangefinding, 2) cw beam amplitude modulation - the phase-shifting rangefinding technique, and 3) chirp pulse compression.

- The main applications of laser rangefinding techniques, in addition to distance measurements, are obstacle detection for autonomous robots or car safety, nondestructive testing, level control, profilometry, displacement measurements, 3-D vision, and so on.
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.
Altitude Determination

- The reflected pulses from solid surfaces (earth ground, ice sheet, etc) dominate the return signals, which allow a determination of the time-of-flight with much higher resolution than the pulse duration time.
- The range resolution is determined by the resolution of the timer for recording pulses, and can be further improved by computing the centroid.
- Altitude accuracy will be determined by the range accuracy/resolution and the knowledge of the platforms where the lidar is on. Interference from aerosols and clouds can also affect the altitude accuracy.

Altitude = Platform Base Altitude - Range ± Interference of aerosols and clouds
Physical Interactions in Lidar

- 70-120 km and above 120 km: resonance fluorescence (Fe, Na, K, He, O, N₂⁺) 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)

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**Na Doppler (Wind & Temp) Lidar**

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

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

**Energy Level Diagram of Atomic Na**

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

[Chu et al., JGR, 2005]

[Chu et al., JGR, 2005]

[Gardner and Liu, JGR, 2007]
Fe Boltzmann Temperature LIDAR

$\zeta^5 F^0$

3d$^6$4s4p

$J' = 1$

$J' = 2$

$J' = 3$

$J' = 4$

$J' = 5$

$z^5 F^0$

3d$^6$4s4p

$J = 0$

$J = 1$

$J = 2$

$J = 3$

$J = 4$

P$_2 (J = 3)$

P$_1 (J = 4)$

$g_2$

$g_1$

exp(-$\Delta E/k_B T$)

$\Delta E = 416 \text{cm}^{-1}$

P$_2$

P$_1$

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

[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]
The atmosphere has many trace gases from natural or anthropogenic sources, like H₂O, O₃, CO₂, NOₓ, CFC, SO₂, CH₄, NH₃, 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!
- H$_2$O 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$_2$O mixing ratio.
DIAL for Ozone in Two Decades

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

\[ \Delta \sigma_{abs} = \sigma_{abs}(\lambda_{ON}) - \sigma_{abs}(\lambda_{OFF}) \]
Rayleigh + Raman Integration Lidar

Hydrostatic Equation
\[ dP = -\rho gdz \]

+ 

Ideal Gas Law
\[ P = \rho RT \]

\[ T(z) = T(z_0) \frac{\rho(z_0)}{\rho(z)} + \frac{1}{R} \int_{z}^{z_0} g(r)dr \frac{\rho(r)}{\rho(z)} \]

Density Ratio ⇒ Temperature

Searchlight, Falling Sphere
Rayleigh Lidar, VR-Raman Lidar

[Keckhut et al., 1990]
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.
"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.

\[ f_{\text{beat}} = |f_{\text{LO}} - f_{\text{Sig}}| = \Delta f + f_{\text{offset}} \]
# Backscatter Cross-Section Comparison

<table>
<thead>
<tr>
<th>Physical Process</th>
<th>Backscatter Cross-Section</th>
<th>Mechanism</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mie (Aerosol) Scattering</td>
<td>$10^{-8} - 10^{-10}$ cm$^2$sr$^{-1}$</td>
<td>Two-photon process&lt;br&gt;Elastic scattering, instantaneous</td>
</tr>
<tr>
<td>Atomic Absorption and Resonance Fluorescence</td>
<td>$10^{-13}$ cm$^2$sr$^{-1}$</td>
<td>Two single-photon process (absorption and spontaneous emission)&lt;br&gt;Delayed (radiative lifetime)</td>
</tr>
<tr>
<td>Molecular Absorption</td>
<td>$10^{-19}$ cm$^2$sr$^{-1}$</td>
<td>Single-photon process</td>
</tr>
<tr>
<td>Fluorescence From Molecule, Liquid, Solid</td>
<td>$10^{-19}$ cm$^2$sr$^{-1}$</td>
<td>Two single-photon process&lt;br&gt;Inelastic scattering, delayed (lifetime)</td>
</tr>
<tr>
<td>Rayleigh Scattering (Wavelength Dependent)</td>
<td>$10^{-27}$ cm$^2$sr$^{-1}$</td>
<td>Two-photon process&lt;br&gt;Elastic scattering, instantaneous</td>
</tr>
<tr>
<td>Raman Scattering (Wavelength Dependent)</td>
<td>$10^{-30}$ cm$^2$sr$^{-1}$</td>
<td>Two-photon process&lt;br&gt;Inelastic scattering, instantaneous</td>
</tr>
</tbody>
</table>
Lidar Data Retrieval

Lidar data retrieval varies with lidar systems & detections.

\[
N_S(\lambda, z) = \left( \frac{P_L(\lambda)\Delta t}{hc/\lambda} \right) \left( \sigma_{\text{eff}}(\lambda, z)n_c(z)R_B(\lambda)\Delta z \right) \left( \frac{A}{4\pi z^2} \right) T_a^2(\lambda)T_c^2(\lambda, z) (\eta(\lambda)G(z)) + N_B
\]

\[
N_R(\lambda, z_R) = \left( \frac{P_L(\lambda)\Delta t}{hc/\lambda} \right) \left( \sigma_R(\pi, \lambda)n_R(z_R)\Delta z \right) \left( \frac{A}{z_R^2} \right) T_a^2(\lambda, z_R)(\eta(\lambda)G(z_R)) + N_B
\]

Solutions:

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

Rayleigh normalization

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

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

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Preprocess Procedure

[Chu and Papen, Laser Remote Sensing, 2005]
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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.

\[ R_T = \frac{(N_+ + N_-)}{N_a} \]
\[ R_W = \frac{(N_+ - N_-)}{N_a} \]

170 K +60 m/s
See Demo by Bo Tan
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

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)

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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
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CEDAR Science: Meteor & Metal Species

Meteor from extraterrestrial

Meteor ablation deposits metallic atoms

Lidar detection of persistent meteor trails during Leonid Shower 1998

Na Lidar Beam

[Chu et al., 2000]

[Plane, 2003]

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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]
CEDAR Science: Aerosols & Clouds

Polar Mesospheric Clouds (PMC)
Noctilucent Clouds (NLC)

[Chu et al., GRL, 2001]

PMC (water ice particles) ⇒ an early indication of climate change

Polarization detection
[Baumgarten et al., 2002]

\[
\delta_{NLC}(z) = \frac{\beta_{NLC}^\perp(z)}{\beta_{NLC}^\parallel(z)} = \frac{\beta_{NLC}^\perp(z)}{\beta_{NLC}^T(z) - \beta_{NLC}^\perp(z)}
\]
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]
CEDAR Science: Gravity Waves

Derive gravity wave features from Rayleigh signals obtained at Rothera and South Pole [Yamashita et al., JGR, 2009]
Lidar into Future and Space

- Lidar is making more and more contributions to atmospheric and space science, especially in the global & whole atmosphere study with emphasis on atmospheric coupling. -- Driven by scientific needs!
- Lidar advancement is strongly influenced by the advances in laser, spectroscopy, electro-optics, sensor, filter, telescope, automatic control, etc. Robust & energy-efficient solid-state lasers will cover more wavelengths, which will further revolutionize lidar technology.
- Essential lidar technologies that could lead to science breakthrough:
  - Mobile solid-state Doppler wind and temperature lidars
  - Whole atmosphere lidar concept
  - Lidar into space
  - White-light lidar
- More sophisticated lidar applications in ATM & space science are emerging. Global lidar network and mapping with spaceborne lidar would dramatically increase the well-needed database. Lidar data assimilation into atmospheric models should also be considered.
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.
Whole Atmosphere Lidar Concept

Fe Doppler Technique (Temperature & Wind)

Rayleigh Integration Technique (Temp.)

Mie Scattering Technique (Aerosol)

Rayleigh Doppler Edge-Filter Technique with Fabry-Perot Etalons Stabilized to 372-nm ECDL (cw)

Pound-Drever-Hall Locking Technique

Adding extra receiver
Extending Measurement Range

Extending downward:
-- Various edge-filter techniques are being developed to probe lower atmosphere wind and temperature simultaneously
-- White-light lidar

Extending upward:
-- Thermosphere Helium lidar - originally studied by Gerrard et al., JASTP 1997 and is now being developed by UIUC Carlson et al, ILRC, 2008
-- Aurora $N_2^+$ resonance Boltzmann lidar - originally studied by Collins et al., Appl. Opt. 1997 and is now being developed by UAF Collins group

Driven by Whole Atmosphere Science !!!

See Na-DEMOP poster by Wentao Huang et al.

[Kasparian et al., 2003]
From Airborne To Spaceborne

NCAR Electra over North Pole

Auto Pilot

Aim to cover the entire global in real time & continuously

NCAR HIAPER

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Lidar into Space

Apollo (Moon) laser altimeter
MOLA (Mars) laser altimeter
SLA (Earth) laser altimeter
ICESat I, II (Earth) laser altimeter
Earth-CARE Clouds, aerosols
DIAL for CO₂, O₃


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

Greece-USA-Canada-UK

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

- 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.

- I still have no good solutions to Dr. Anne Smith’s request - to measure atomic oxygen density in the upper atmosphere using lidar technology. Far UV laser source, spaceborne, etc. are posing great challenge to lidar community. But it is also an inspiration for future lidar innovation or even revolution ...

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

**Lidar Class:**
A 6000-level graduate class on Lidar Remote Sensing is offered by Professor Xinzhao Chu at University of Colorado. The class is accessible from the web: [http://cires.colorado.edu/science/groups/chu/classes/lidar2008/](http://cires.colorado.edu/science/groups/chu/classes/lidar2008/)

**Lidar Books:**
2). Lidar (2005)
4). Lidar Applications in Remote Sensing (paper collection)
5). Laser Distance Measurements (paper collection)

**Lidar Conference:**
International Laser Radar Conference (ILRC) -- biennial