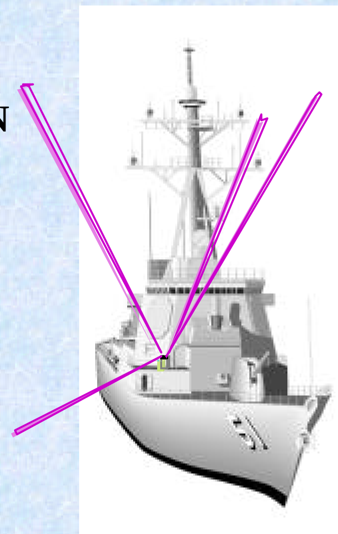
ENVIRONMENT DEFINITION USING RAMAN LIDAR: EM-EO-MET



by

C. Russell Philbrick and Adam Willitsford
Electrical Engineering Department
and Applied Research Lab

BACIMO 2005 Conference
Monterey CA
12–14 October 2005

lidar1.ee.psu.edu

EM /EO/MET Data for Navy METOC Support

E&M (RF refraction) and EO (optical propagation) data products are required for future systems. A new level in type and quality of observational data is needed for assimilation into numerical models.

Lidar profiles provide the best source for high quality meteorological profiles and EM/EO data.

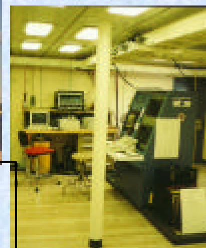
Model prediction capability is based upon constraints provided by gridded fields of measured parameters.

High resolution data - both time and space - are needed to constrain advanced numerical models as they are applied to mesoscale features -- tens to hundreds of kilometers.

"Even if more capable models were available, our ability to suppl y the data needed to drive them is deficient."
Reference: 97 EM/EO Symposium, Edward Whitman (TD for Oceanographer of the Navy)

Our Research Goals . .

– Develop, demonstrate and use capabilities of Raman lidar to foster a wide range of applications that support atmospheric measurements, weather prediction, air quality monitoring, and model development (initialization and assimilation).



Goal of this paper . . .
show capability and status of Raman lidar for providing measurements required for Navy applications in EM/EO/MET.

Presentation

What is Raman lidar?

Why Raman lidar?

- Robust (signal ratios)
- Single wavelength (no tuning)
- Many parameters measured simultaneously
- Continuous time sequence of data
- Horizontal measurements – spatial, evaporation duct
- Real-time data product in engineering units

What are the limitations of Raman lidar?

- Small cross-section (~molecular/1000 – move to UV)
- Need large laser for sufficient photon flux over background

What is the status?

- Research on technique is relatively complete
- Cross-sections are known to < ± 1%
- Long life – 3-4 months continuous
- Sensor is ready to marry with models

Model Development and Application

Models provide the capability to input:
- physics and chemistry
- past climatology

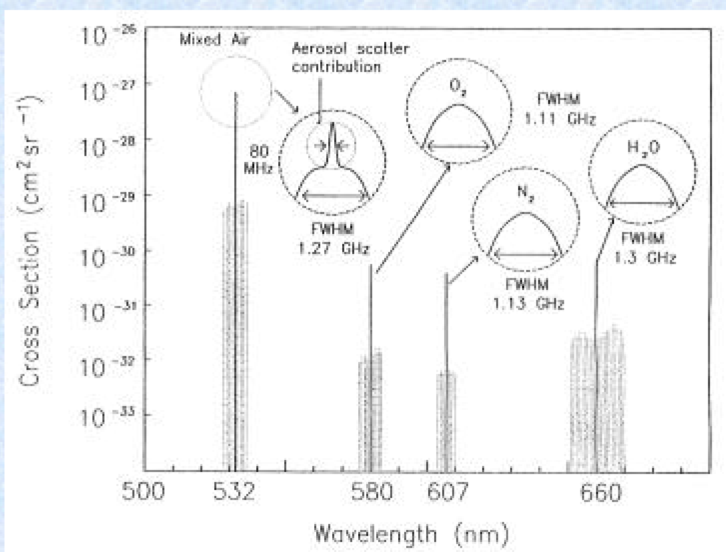
and thereby allow extensions in time and space.
You have seem many advances in models,
NOGAPS, COAMPS and NOWCAST – NRL Monterey
WRF – NCAR

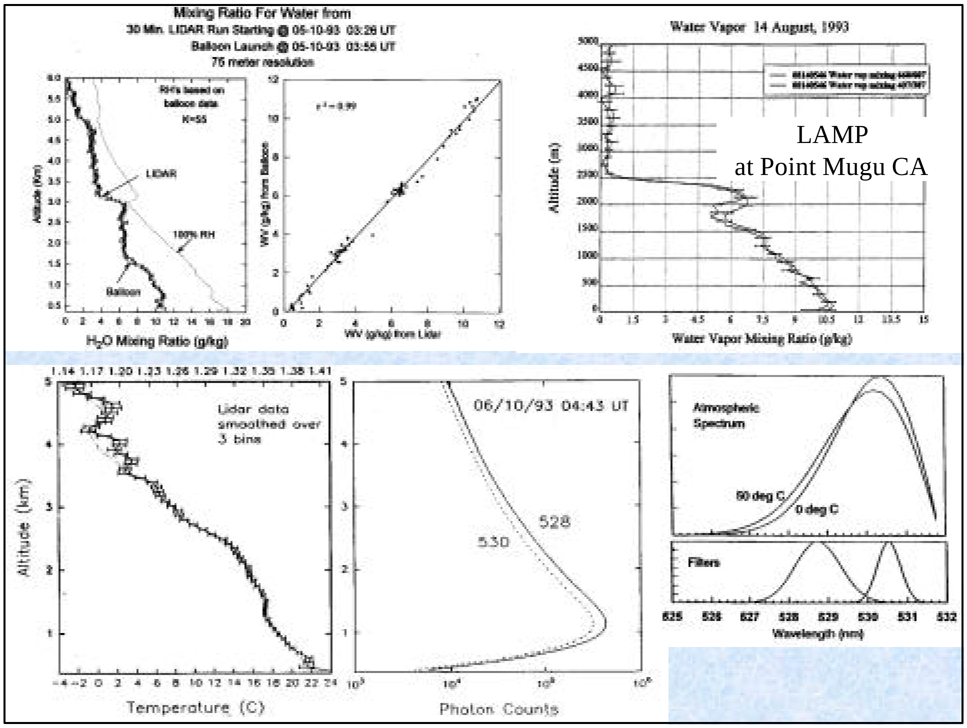
CAUTION
The model output data products generally look the same whether there has been any data input or not.

There needs to be a marriage between sensors and models to be able to really provide the required:
- spatial continuity,
- time projection.

Raman Scatter in Air

(Nd:YAG 2^{nd} Harmonic – 532 nm)





Raman Lidar Development

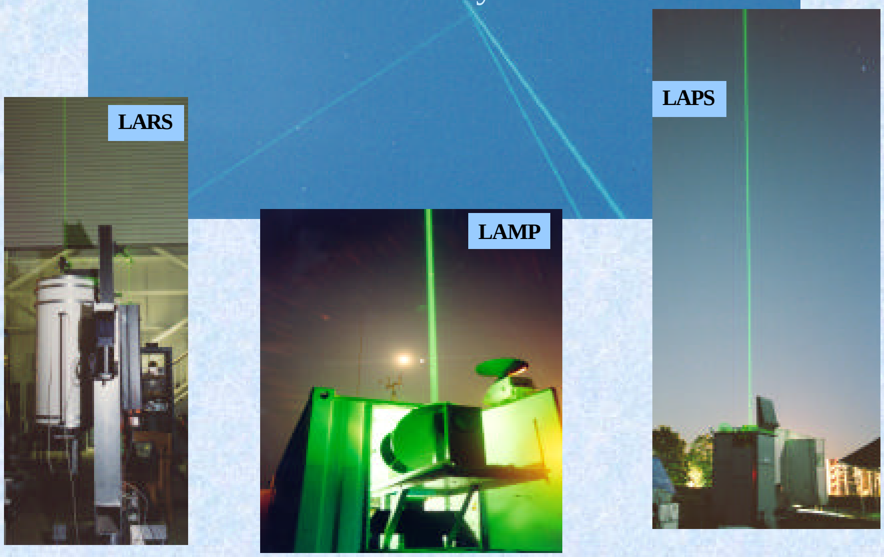
Five generations of Raman Lidar

1st GLEAM (1978)
2nd GLINT (1984)
3rd LAMP (1990)
4th LARS (1994)
5th LAPS (1996)

Breadboard Research Instrument ………….. to ….. Operational Prototype (ADM)

Arctic to Antarctic | **Testing on USNS Sumner**
Testing at Point Mugu | **Advanced Development Model**

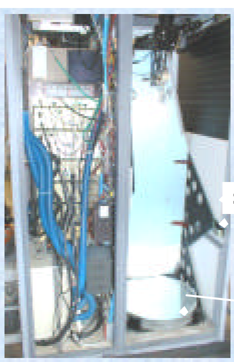
Three Raman Lidar Operating Simultaneously at PSU

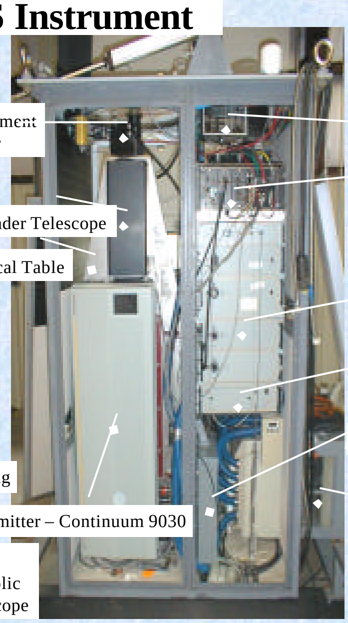


LAPS Instrument

The LAPS instrument is first prototype for an operational system – Rugged, weather-sealed, compact, semi-automated

Backside of LAPS Instrument





LAPS Instrument Characteristics and Measurements

Transmitter	Continuum 9030 (30 Hz) 5X Beam Expander	600 mj @ 532 nm 120 mj @ 266 nm
Receiver	61 cm Dia. Prime Focus Telescope	Fiber optic pickup
Detector	8 PMT Channels Photon Counting	528 + 530 nm – Temperature 660 + 607 nm – Water vapor 294 + 285 nm – Daytime Water Vapor 276 + 285 nm – Raman/DIAL
Data System	DSP 100 MHz	75 m bins (upgrade to 15 meter)
Safety System	Marine R-70 – X-Band	Protect near field

Property	Measurement	Altitude	Time - Resolution
Water Vapor	660/607 (H_2O/N_2) 294/285 (H_2O/N_2)	Surface to 5 km Surface to 3 km	Night -1 min Day & Night -1 min
Temperature	528/530 Rotational Raman	Surface to 5 km	Night 10 to 30 min
Extinction 530 nm	530 nm Rotational Raman	Surface to 5 km	Night 10 to 30 min
Extinction 607 nm	607 nm N_2 1st Stokes	Surface to 5 km	Night 10 to 30 min
Extinction 285 nm	285 nm N_2 1st Stokes	Surface to 3 km	Day & Night 10 to 30 min
Ozone	O_2/N_2 (276/285)Raman/DIAL	Surface to 2 km	Day & Night - 30 min

PENN STATE

EM/EO Requirements for Refractivity and Extinction

EM requirement is for RF-refraction

Water Vapor, Temperature ⇒ n (index of refraction) ⇒ m (modified index) ⇒ TREPS, RPO, RPOT, TPEM

EO requirement is for optical refraction/extinction

Upper Layer - Temperature Dew Point ⇒ Optical Extinction
Lower Layer - Aerosol Description & Visibility

Lidar ⇒ Water Vapor & Temp ⇒ EM Propagation Conditions
Lidar ⇒ Optical Extinction & Temp ⇒ EO Propagation Conditions

EM – RF-refraction

- Index of refraction of air typically 1.00025 to 1.0004
- N units = (n - 1) *10^6 yielding 250 to 400 N units
- M units (modified refractivity) -> N units modified to account for the curvature of earth

  M = N + 0.157*z (z is the altitude in meters)

Condition	N-Gradient (N/km)	M-Gradient (M/km)
Trapping	dN/dz = -157	dM/dz = 0
Superrefractive	-157 < dN/dz = -79	0 < dM/dz = 78
Standard	-79 < dN/dz = 0	78 < dM/dz = 157
Subrefractive	dN/dz > 0	dM/dz > 157

PENN STATE

RF Refractivity Variation

$N = (n - 1) \times 10^6 = 77.6\, P/T + 3.73 \times 10^5\, e/T^2$

$e\ (mb) = (r\, P)/(r + 621.97)$

P - surface pressure r - specific humidity T - temperature

T(K) ~ 295 K P(mb) ~ 1000 mb r ~ 7 g/kg N ~ 310

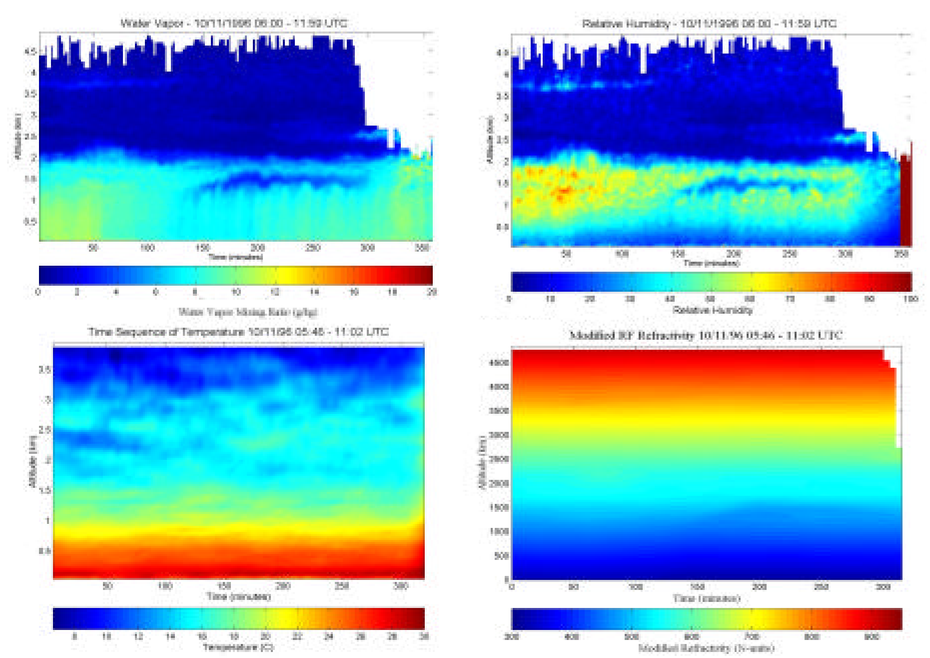
$\Delta N = (\delta N/\delta r)\, \Delta r + (\delta N/\delta T)\, \Delta T + (\delta N/\delta P)\, \Delta P$

$\delta N/\delta r \sim 6.7$ $\delta N/\delta T \sim -1.35$ $\delta N/\delta P \sim 0.35$

$dN/dz = 6.7\, dr/dz - 1.35\, dT/dz + 0.35\, dP/dz$

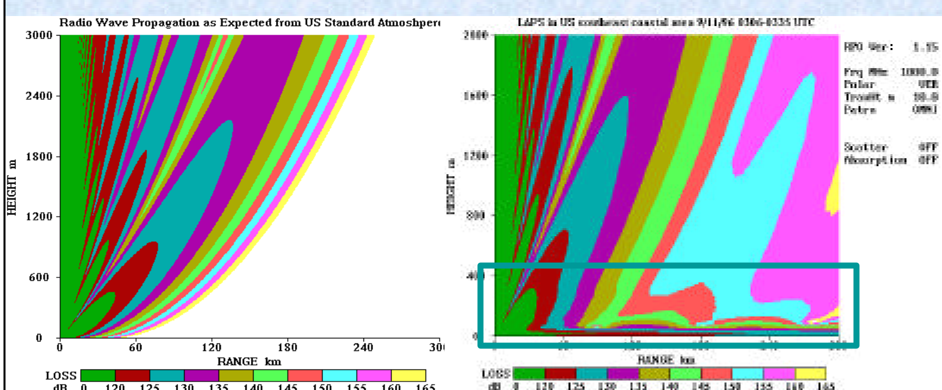
Gradients in water vapor are most important in determining RF ducting conditions.

Water Vapor and Temperature

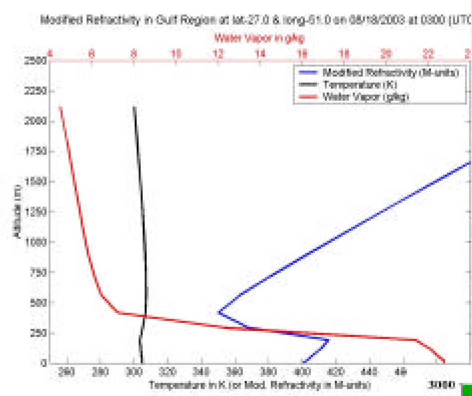


Radar Refraction Effects

- U.S. Standard Atmosphere
- Surface/Evaporative Duct

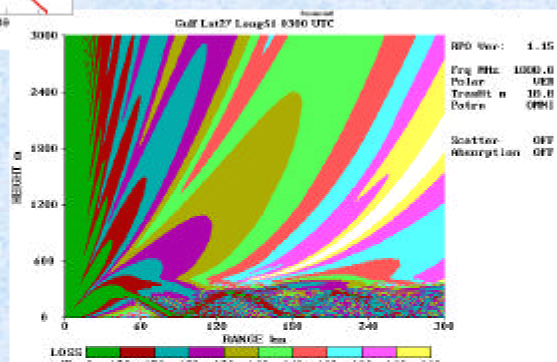


Collier Thesis, 2004



Radar Refraction Vertical Profile

Persian Gulf

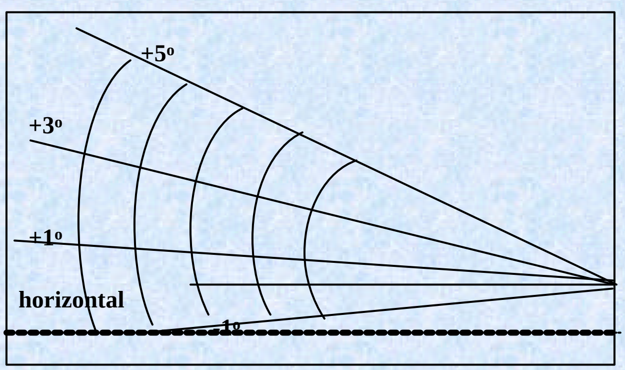


Collier Thesis, 2004

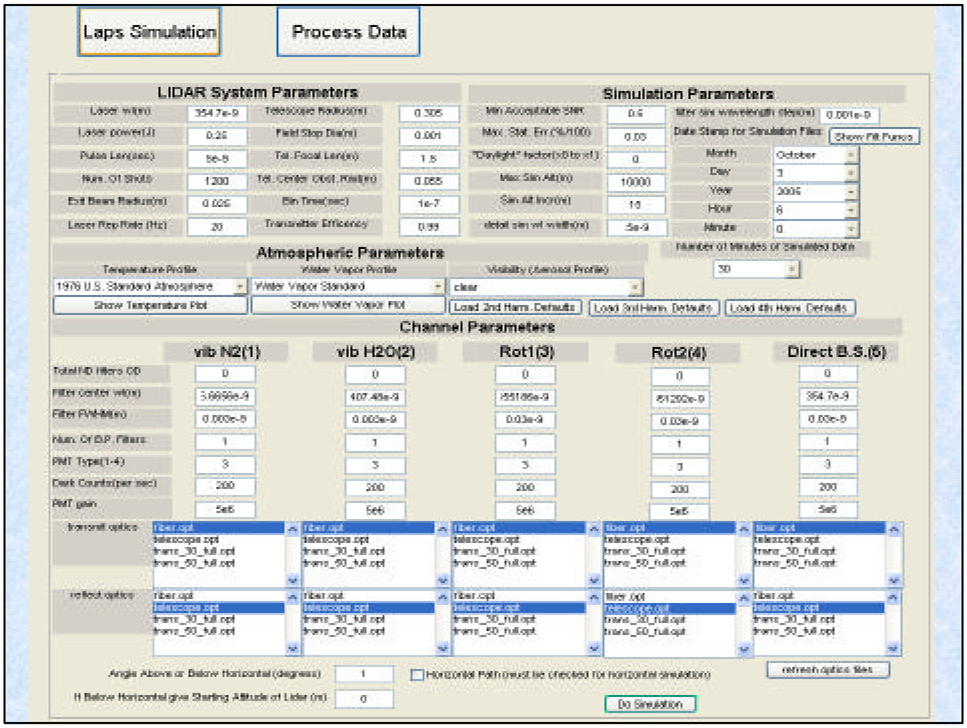
Lidar on a Horizontal Path

for Evaporation Duct and Spatial Data

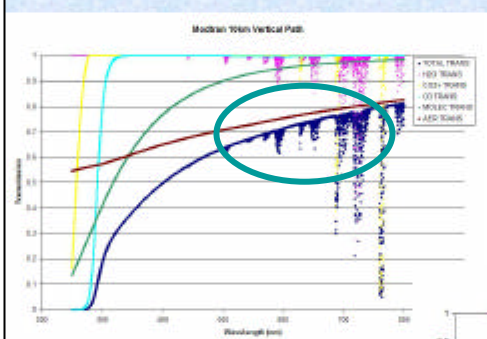
- Adapt vertical lidar instrument using a turning mirror for horizontal propagation (-1 to 5 degrees elevation).
- Tag laser pulses with angle, mapping atmosphere with returns



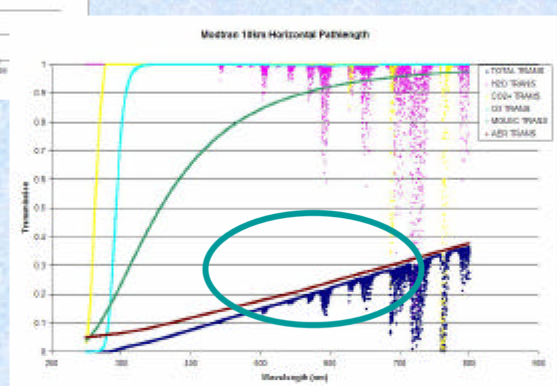
- High vertical resolution for water vapor and temperature (<50cm).



Lidar on a Horizontal Path - Simulation

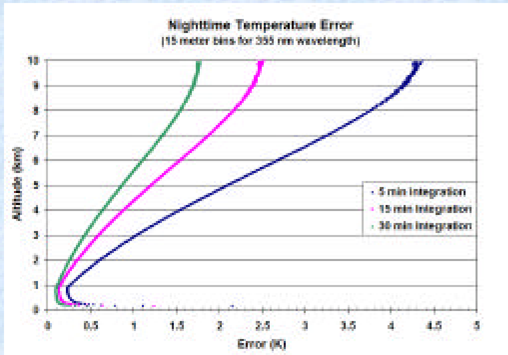


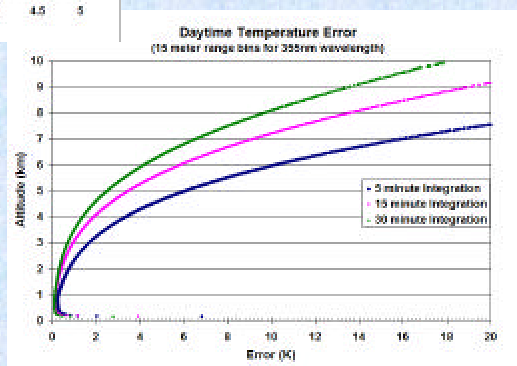
- Comprehensive model for lidar on vertical and horizontal paths
- User may input a large array of variables: Laser power, Pulse frequency, visibility.
- Horizontal Transmission considerably smaller than vertical.



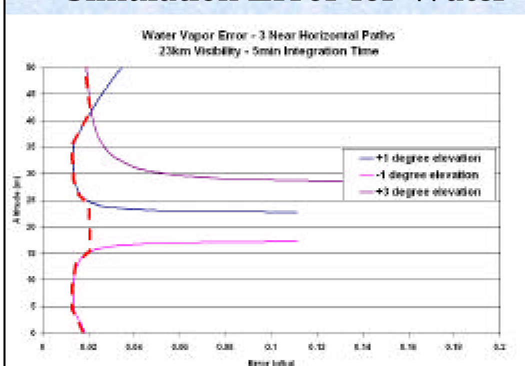
Raman Lidar Temperature Error

Night and Day

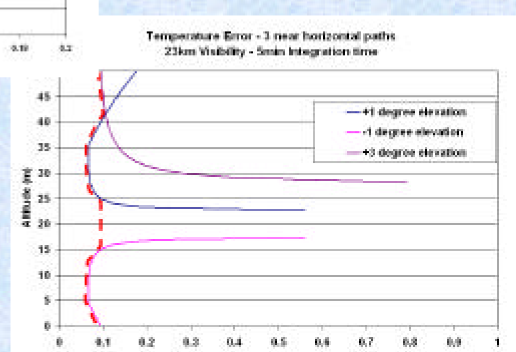




Simulation Error for Water Vapor and Temperature



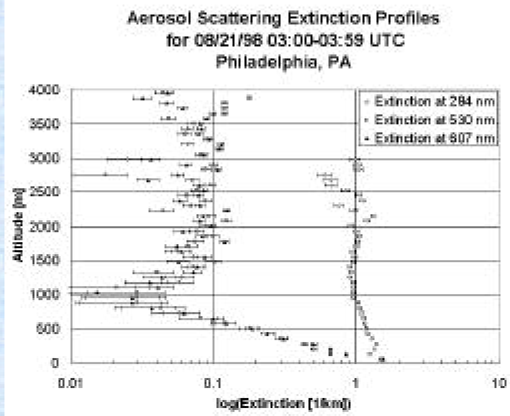
Error < 0.2 M units



EO
Optical Extinction

Extinction is obtained directly from the slope of the molecular profiles, compared to their expected hydrostatic gradient.

N_2 at 607 and 284 nm
N_2 and O_2 in rotational band at 530 nm

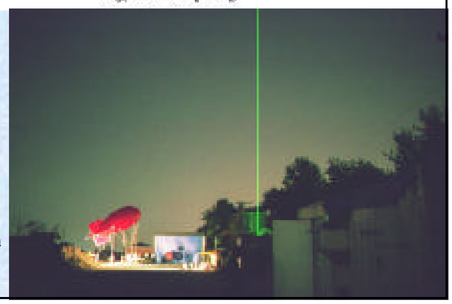


$$a_R^{aer} = \frac{d}{dz}\left[\ln\frac{N_R(z)}{P_R(z)\cdot z^2}\right] - a_0^{mol}(z) - a_R^{mol}(z) - a_0^{aer}(z)$$

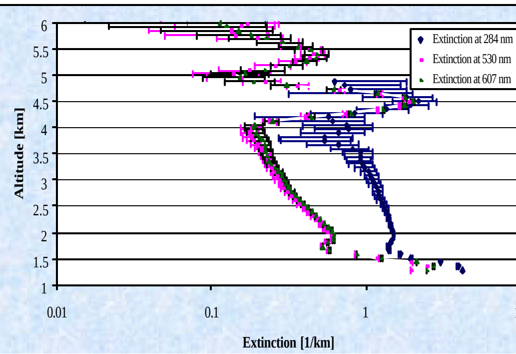
$$a_{532}^{aer} = \frac{d}{dz}\left[\frac{1}{2}\ln\frac{N(z)}{P_{530}(z)\cdot z^2}\right] - a_{532}^{mol}(z)\ .$$

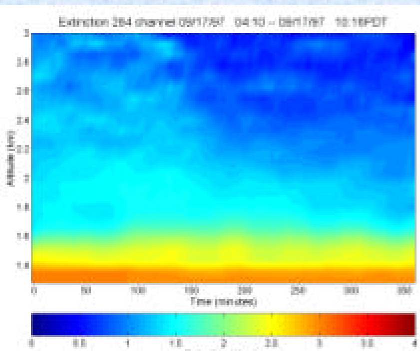
O - outgoing - 532 or 266 nm

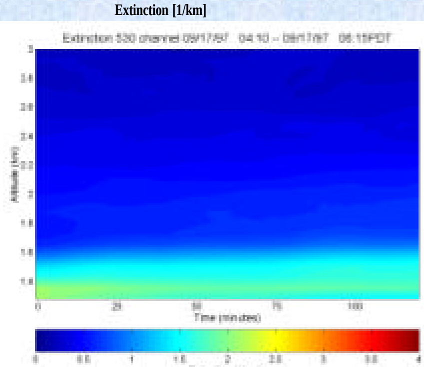
R - return - 530 (rot), 607 (N_2), 285 (N_2) or 276 (O_2) nm

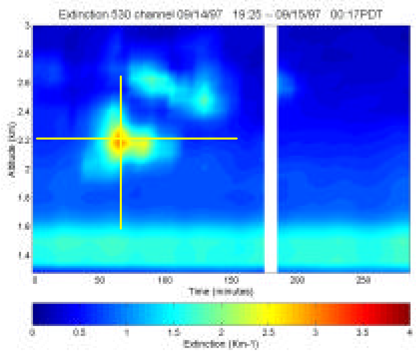


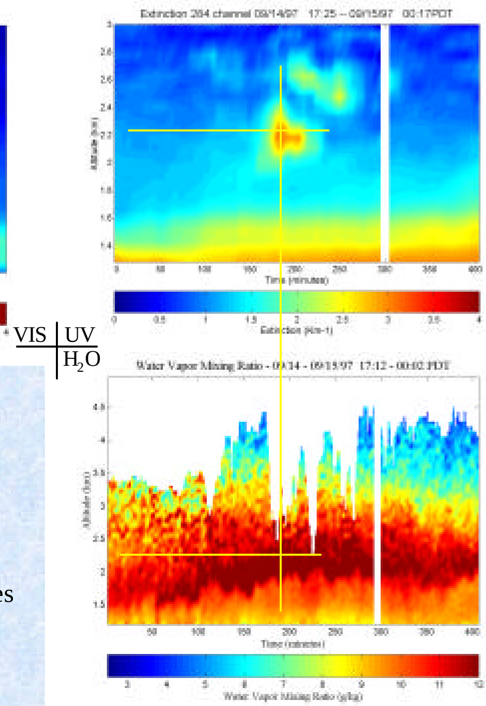
EO
Time sequence profiles of optical extinction









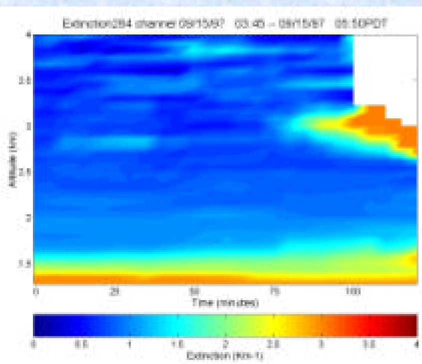


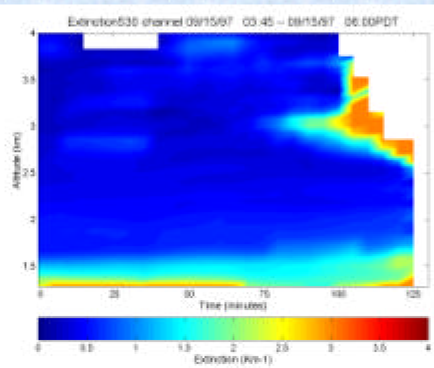
Scattering from Clouds

Cloud scattering at visible and ultraviolet wavelengths -
- multi-λ to infer size variation
- SH in region around cloud indicates growth or dissipation

Cloud Micro-Physics

The ratio of visible and ultraviolet signals provides a measure of the changing particle size in the edges of cloud.

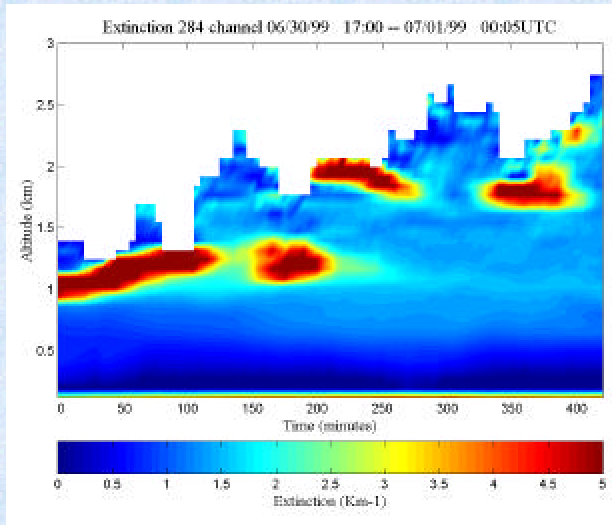


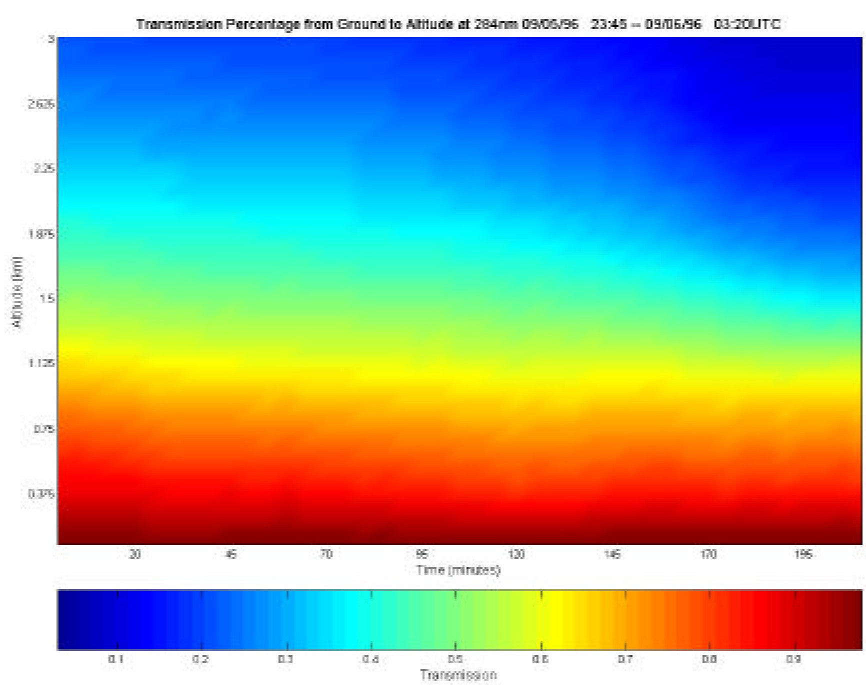


PENNSTATE

Cloud Development

Relatively dense clouds ($\alpha \sim$ 5-7km^{-1} OD ~ 1-1.5) can be measured to observe formation and growth/dissipation of clouds.

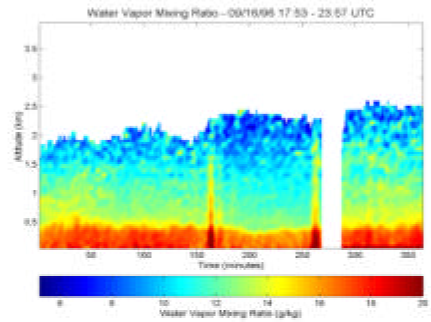


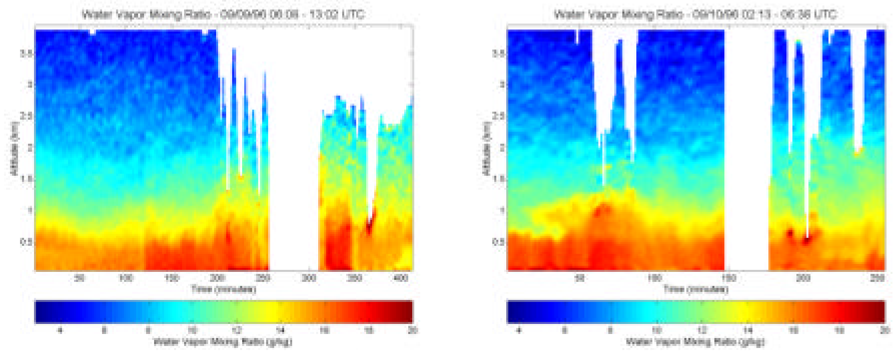


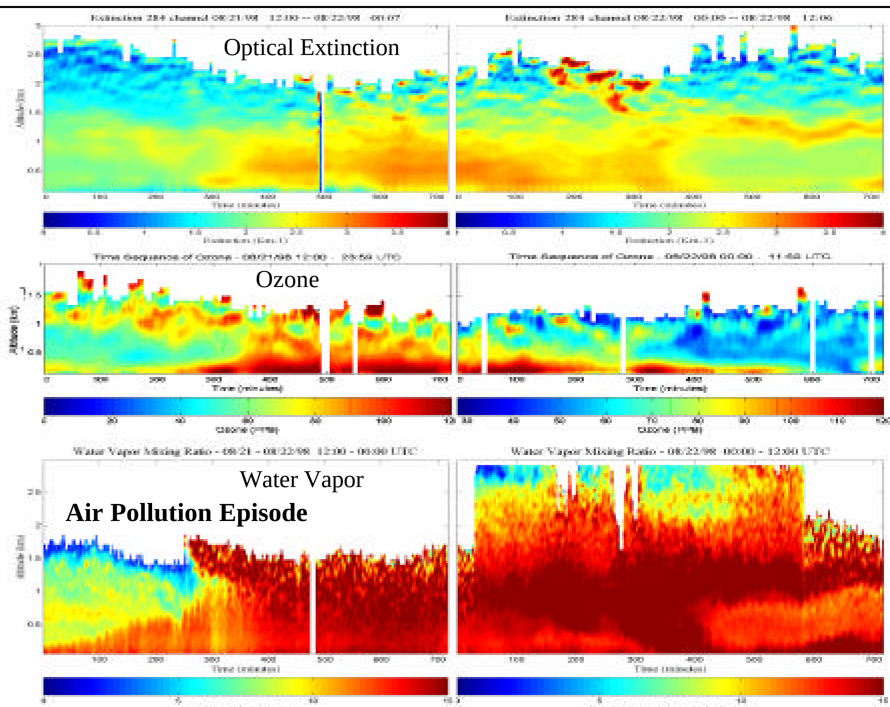
Meteorology

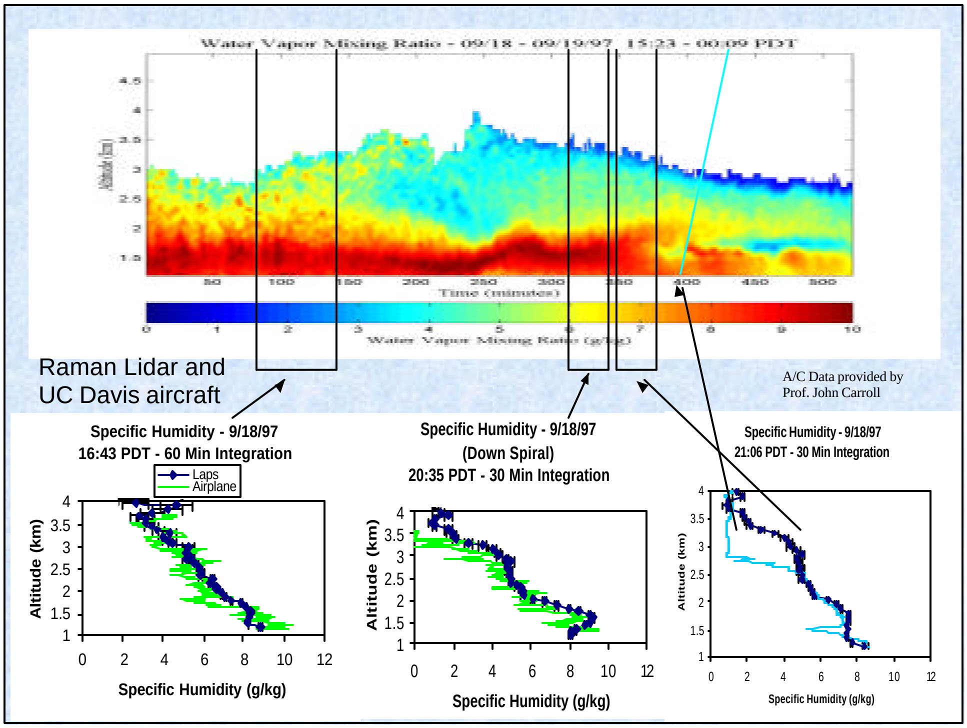
Water Transfer into Cloud Base

Water vapor feeds directly from the marine boundary layer into the base of clouds – example of convective cloud formation over the ocean





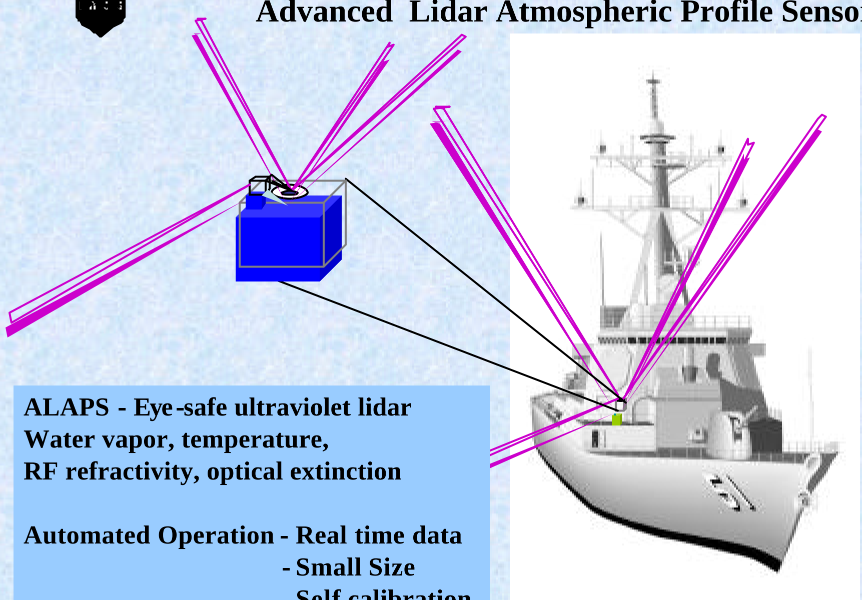




PENNSTATE

ALAPS

Advanced Lidar Atmospheric Profile Sensor



ALAPS - Eye-safe ultraviolet lidar
Water vapor, temperature,
RF refractivity, optical extinction

Automated Operation - Real time data
- Small Size
- Self-calibration

PENNSTATE

Lidar for the Future

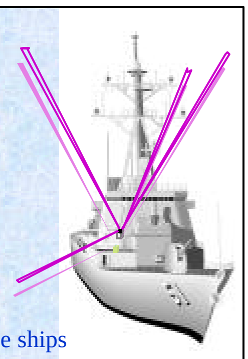
LAMP – Breadboard demonstration of technology - 1990
LAPS – Operational Prototype (ADM) – 1996
Too large – Needs to be covert and eye-safe – Improved resolution
ALAPS – Engineering Model (EDM) – 200?
One-third size of LAPS (<1 m^3)
Uses eye-safe ultraviolet wavelength
Higher speed electronics for improved resolution (1 GHz)
Fully automatic and self-calibrating
Replaces most needs for sonde systems with improved data
Real time continuous data product in scientific/engineering units
Horizontal mode for evaporation duct and spatial data

EM Propagation – Radar Tracking, Detection Gaps, Communications
Lidar Water Vapor & Temperature ⟹ RF Refractivity

EO Propagation – Visibility, Surveillance, Aircraft OPS
Lidar Optical Extinction ⟹ Visual Range, Changing Conditions

PENNSTATE

ALAPS Summary



ALAPS Raman Lidar (EDM)
- 3-D picture of EM/EO environment
- vertical profiles of meteorological properties
- automated operation with real time data
- eye-safe and covert
- self-calibrating optical system and fast electronics
- small and self-contained, choice for future low observable ships

Design work and testing on LAPS since USNS Sumner tests
- upgrade to faster electronics - embedded microprocessor
- design to smaller size (~1/3) and self-contained
- design eye-safe, self-calibration
- investigations of optical extinction, air pollution
- more than 50 papers, 20 MS thesis and PhD dissertations using LAPS for testing, analysis, design, studies of atmospheric properties

Raman Lidar is ready to be used prepared as primary instrument for atmospheric profiling -- with improved data product, high spatial resolution, and continuous data sequence. A key instrument for NOWCAST!

Acknowledgments

The PSU lidar development, testing, and field investigations have been supported by the following organizations: supported by the following organizations: US Navy through SPAWAR PMW-185, NAVOCEANO, NAWC Point Mugu, ONR, DOE, EPA, Pennsylvania DEP, California ARB, NASA and NSF. The vision and support of Carl Hoffman, Ed Harrison and Ed Mozley have been most valuable during this development. The hardware and software development has been possible because of the excellent efforts of several engineers and technicians at the PSU Applied Research Laboratory and the Department of Electrical Engineering. Special appreciation goes to D. Sipler, B. Dix, D.B. Lysak, T.M. Petach, F. Balsiger, T.D. Stevens, P.A.T. Haris, M. O'Brien, S.T. Esposito, K. Mulik, A. Achey, E. Novitsky, G. Li and many graduate students who have made contributed to these efforts. The NE-OPS research investigations have been supported by the USEPA STAR Grants Program #**R826373,** Investigations of Factors Determining the Occurrence of Ozone and Fine Particles in Northeastern USA, and by the Pennsylvania DEP grant for the 2002 program. The efforts and cooperation of the several university investigators and government laboratory researchers is gratefully acknowledged. The effort and contributions of Rich Clark, S.T. Rao, George Allen, Bill Ryan, Bruce Doddridge, Steve McDow, Delbert Eatough, Susan Weirman and Fred Hauptman are particularly acknowledged because of their very significant contributions to these programs.

lidar1.ee.psu.edu