Spaceborne Aerosol and Ozone Lidars for Air Quality Applications

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Outline

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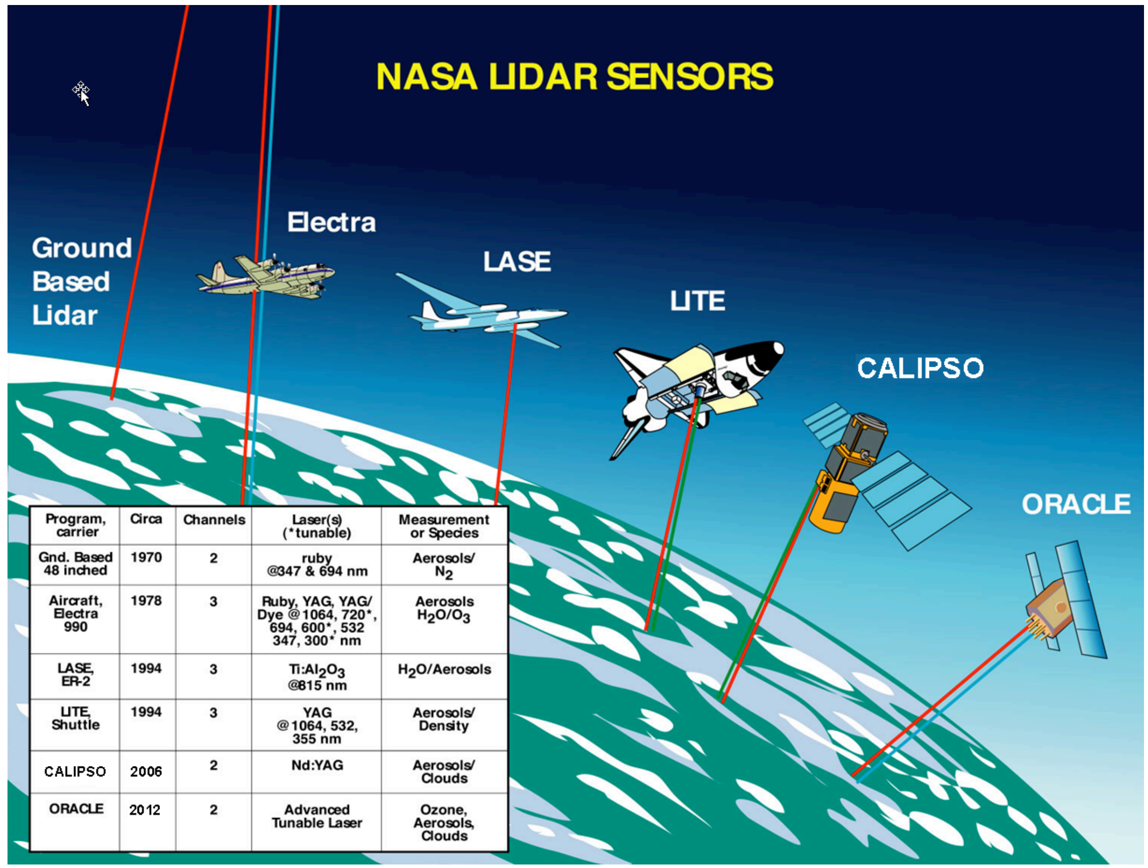
- Aerosols
  - Current capabilities of spaceborne aerosol lidars
  - High Spectral Resolution Lidar (HSRL)
  - Multiwavelength ("3β+2α") Aerosol Retrievals
- Ozone
  - Differential Absorption Lidar (DIAL) Technique
  - Heritage and path to space
- Summary



Program, carrier	Circa	Channels	Laser(s) (*tunable)	Measurement or Species
Gnd. Based 48 inched	1970	2	ruby @347 & 694 nm	Aerosols/ N_2
Aircraft, Electra 990	1978	3	Ruby, YAG, YAG/ Dye @1064, 720*, 694, 600*, 532 347, 300* nm	Aerosols H_2O/O_3
LASE, ER-2	1994	3	Ti:Al_2O_3 @815 nm	H_2O/Aerosols
LITE, Shuttle	1994	3	YAG @1064, 532, 355 nm	Aerosols/ Density
CALIPSO	2006	2	Nd:YAG	Aerosols/ Clouds
ORACLE	2012	2	Advanced Tunable Laser	Ozone, Aerosols, Clouds

Science Objectives

Understanding Global Atmospheric Composition and Predicting Future Evolution

Specific Science Questions:

- What are impacts of natural and anthropogenic aerosols on air pollution?
- What are key local and transported aerosol sources?
- How can we improve our ability to model aerosol-mediated heterogeneous chemistry that impacts O_3, OH, etc. ?
- What is global distribution of tropospheric ozone and how does it change seasonally and interannually?
- What is the relative contribution of photochemical and dynamical processes in determining the distribution of tropospheric ozone?
- What is the impact of ozone on global tropospheric chemistry?

Aerosol – Current Capabilities and Limitations

+ GLAS, CALIOP provide vertical distribution of aerosol
  - Layer heights via backscatter profiles
  - Extinction profiles via inversion
+ CALIOP
  - Extinction profiles constrained with A-train (e.g. MODIS) data
  - Aerosol type can be inferred from backscatter color ratio, depolarization
  - Altitude and back-trajectories to sources also give clues to composition

— Calibration
  - Must calibrate in some region assumed to be free of aerosols and clouds; CALIPSO calibrates at 30-34 km.
  - Can limit calibration to night only; calibration may drift during day

— Measures attenuated total backscatter
  - Aerosol backscatter retrieval requires extinction-to-backscatter ratio S_a
    - Depends on aerosol composition, size, and shape which are variable
    - Uncertainty in profile of Sa raises potential for structural error in backscatter lidar retrieval

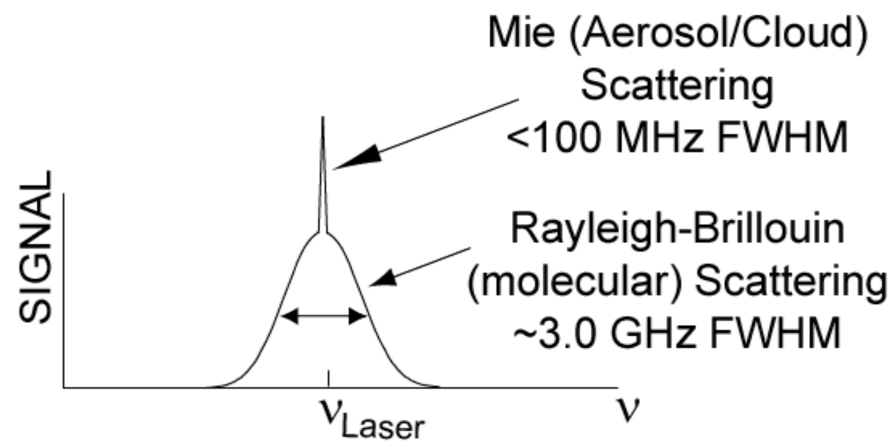
High Spectral Resolution Lidar (HSRL)

HSRL relies on spectral separation of aerosol and molecular backscatter in lidar receiver.

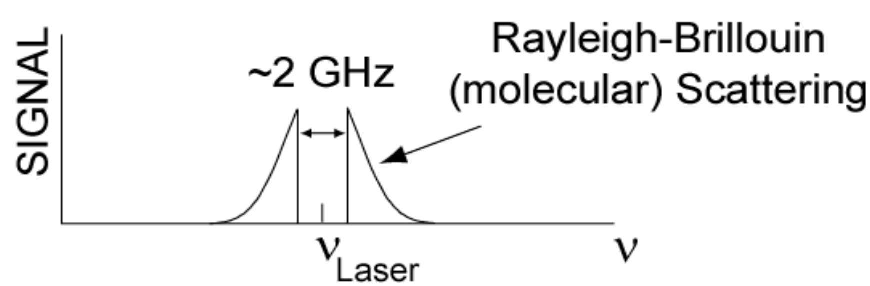
- HSRL independently measures aerosol and molecular backscatter
  - Can be internally calibrated
  - No correction for extinction required to derive backscatter profiles
  - More accurate aerosol layer top/base heights

- HSRL enables independent estimates of aerosol backscatter and extinction
  - Extinction and backscatter estimates require no S_a assumptions
  - Provide *intensive* optical data from which to infer aerosol type
  - Measurements of extinction at 2 wavelengths and backscatter at 3 wavelengths enables retrieval of aerosol microphysical parameters and concentration

Atmospheric Scattering



Effect of Iodine Vapor Notch Filter



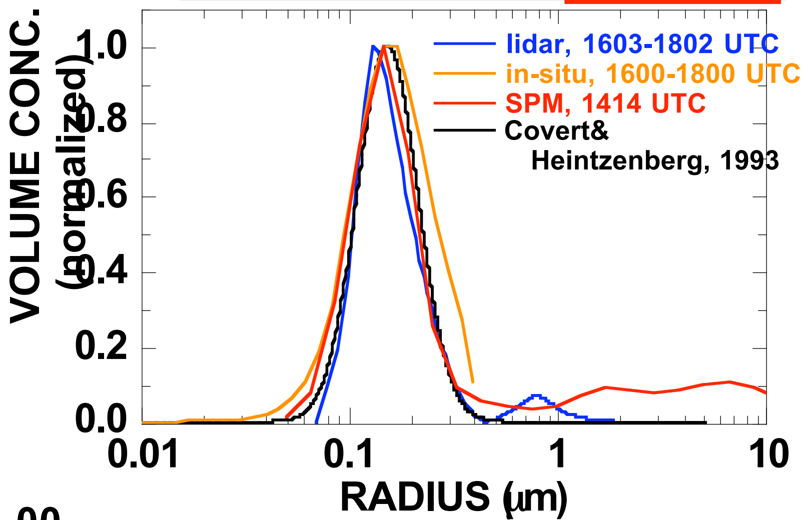
Next Step: "3β+2α" HSRL retrievals

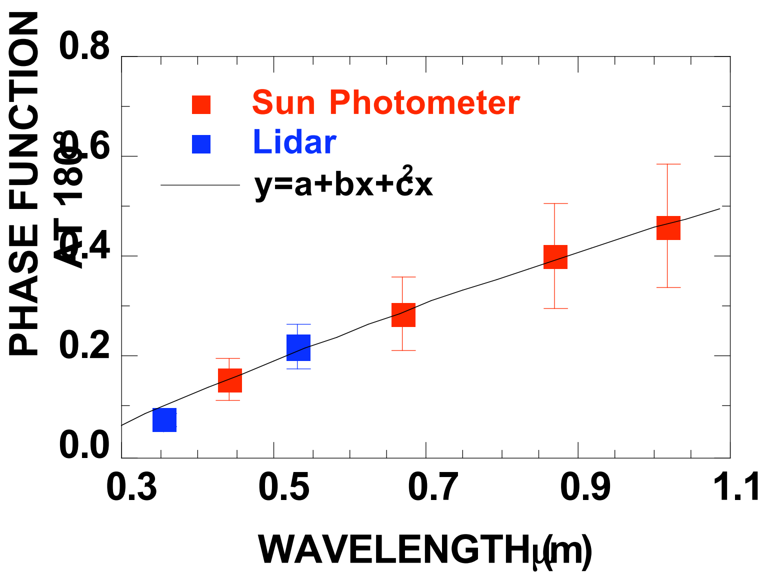
- Fundamental data products
  - Backscatter at 3 wavelengths (3β) : 355, 532, 1064 nm – 120 m vert., 20 km horiz
  - Extinction at 2 wavelengths (2α) : 355, 532 nm – 900 m vert., 20 km horiz.
  - Depolarization at 355, 532, and 1064 (dust and contrails/cirrus applications)
- Retrieved, layer-resolved, aerosol microphysical/macrophysical parameters (Müller et al., 1999, 2000, 2001; Veselovskii et al.,2002,2004)
  - Effective and mean particle radius (errors < 30-50%)
  - Concentration (volume, surface) (errors < 50%)
  - Complex index of refraction
    - real (±0.05 to 0.1)
    - imaginary (order of magnitude if < 0.01; <50% if > 0.01)
  - Single scatter albedo (±0.05; error increases for $r_{eff} > 0.3\ \mu m$)
- Microphysical retrieval issues
  - Constraining assumptions: positivity, smoothness of size distribution, consistency between retrieved parameters and input optical data
  - Assumes wavelength independent and size independent refractive index
  - Assumes spherical particles; upgrade to spheroids is planned
  - Retrieval is restricted to particle radii > 50 nm
  - Not operational: requires extensive computation time and expert operator, software package in alpha version has been developed for more general use

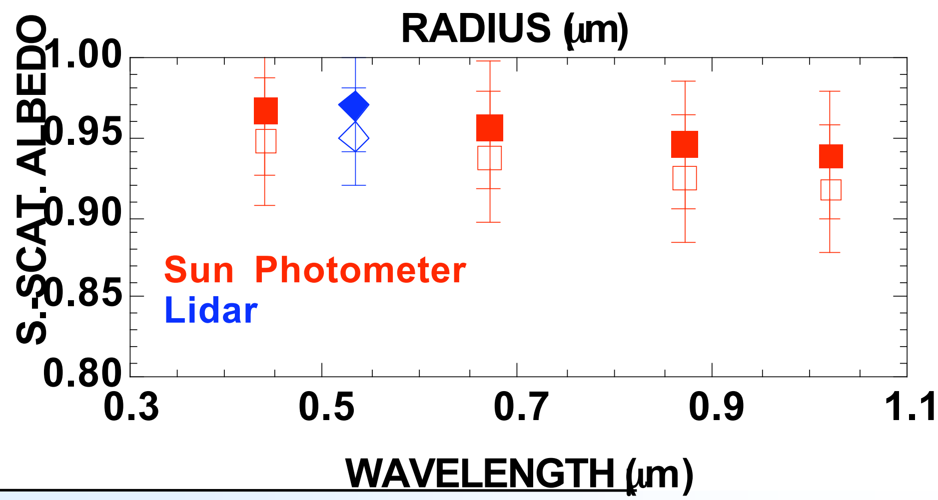
“3β+2α” Example microphysical retrieval

- Mixture of urban and Arctic haze
- Leipzig, Germany during April 2002
- Comparison of retrievals and measurements
  - Lidar (3β + 2α) retrieval
  - AERONET Sun photometer sun and sky radiance retrieval (Dubovik et al., 2000)
  - In situ measurements
- Müller, Dubovik et al., JGR, 2004

	Time, UTC	r_{eff}, μm
SPM	1415	0.18 ± 0.05
	1616	0.22 ± 0.06
Lidar	1603 – 1802	0.18 ± 0.02
	1823 – 1922	0.19 ± 0.04
In Situ	1600 – 1800	0.14 ± 0.03
	1829 – 1929	0.14 ± 0.01







Aerosol Lidar Data Product Evolution

Backscatter Lidar (GLAS, CALIPSO)

Backscatter Lidar + Passive (CALIPSO + A Train)

$3\beta+2\alpha$ Advanced HSRL (AEGIS)

- Aerosol layer heights
- Qualitative vertical distribution (backscatter profile)
- Aerosol type vs. altitude
- Extinction profile from backscatter
- Extinction profile with column constraint
- Fine-coarse mode fraction vs. altitude
- Extinction profile
- Complex refractive index vs. altitude
- Aerosol size vs. altitude
- SSA vs. altitude
- Concentration vs. altitude

Further enhanced by addition of passive sensors

HSRL Technology maturity

Transmitter

- In general, higher average power is required for HSRL technique over current backscatter lidars (e.g., ~5x over CALIPSO, GLAS)
  - Injection-seeded Nd:YAG laser capable of up to 50 W can be built using current technology
  - Space qualified seed lasers are currently available
  - Required spectral purity and frequency agility have been demonstrated
- Frequency doubling to 532 nm has been demonstrated
- Frequency tripling to 355 nm must be assessed
  - Optical damage due to contamination poses greater problems in UV

Receiver

- Iodine absorption cell (532 nm)
  - Used on ground-based systems for many years
  - Poses no technical problem for space
- Multiple Fabry Perot interferometer (355 nm)
  - Demonstrated in the 1970s (Eloranta)
  - Planned for ESA EarthCare
  - Systematic errors associated with spectral characterization of etalon passbands may be an issue
- Mach Zehnder interferometer
  - Demonstrated for ground-based wind measurements
  - CNES developing Mach Zehnder system
  - Systematic errors associated with spectral characterization of etalon passbands may be an issue

Spaceborne Ozone Lidar

- Simultaneous tropospheric and stratospheric ozone profiles with simultaneous aerosol & cloud backscatter & depolarization profiles.

- Will address key global environmental issues including tropospheric chemistry & dynamics and associated ozone and aerosol production & transport for air quality applications; climate change and radiation budget contributions from ozone, aerosols and clouds; and stratospheric chemistry & dynamics and associated surface UV forcing and weather forecasting.

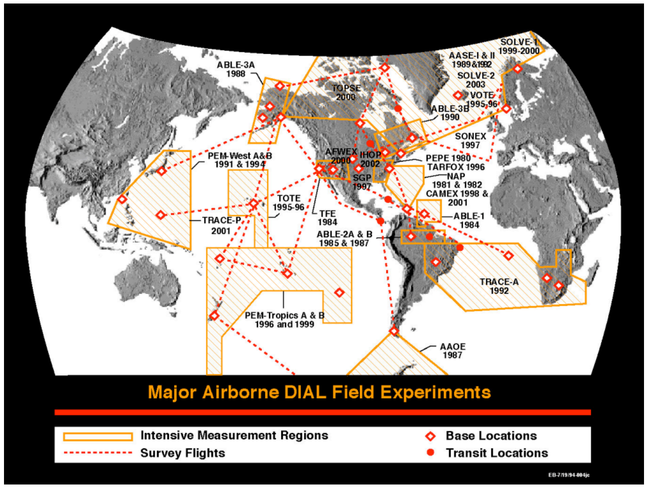
- Measurement resolutions and accuracy goals:

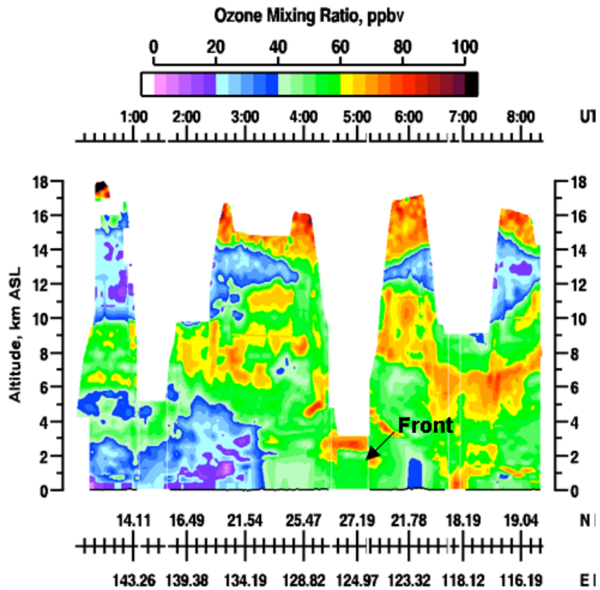
Ozone -	Trop.:	Night: $\leq$2.5 km x 200 km (10%)	
		Day: $\leq$3.0 km x 300 km (10%)	
	Strat.:	$\leq$1 km x 100 km (10%)	
Aerosols -	Trop.:	60 m x 1 km (10%) at 2λ	Backscatter not HSRL
	Strat.:	100 m x 10 km (10%) at 2λ	

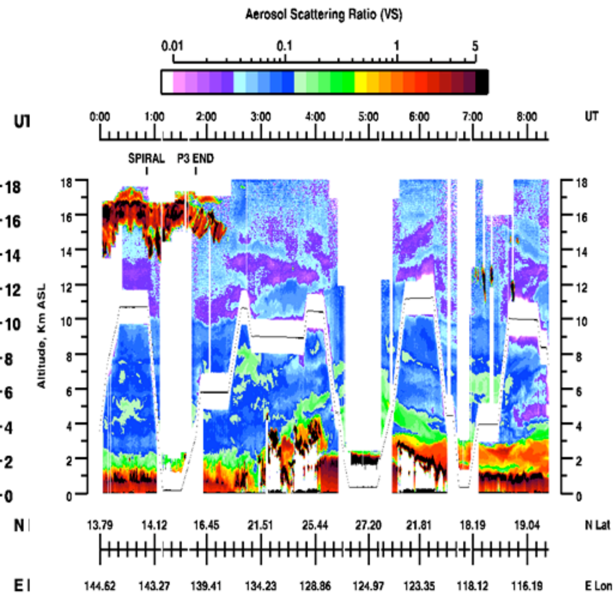
- Spectral Regions: 305-320 nm with 10-12 nm $\Delta\lambda$ DIAL with two aerosol/cloud channels (λ_{off} & visible/near IR λ) & one with depolarization.

- Deployment: Small satellite in polar, low Earth orbit with 3 year life.

Ozone Lidar Heritage

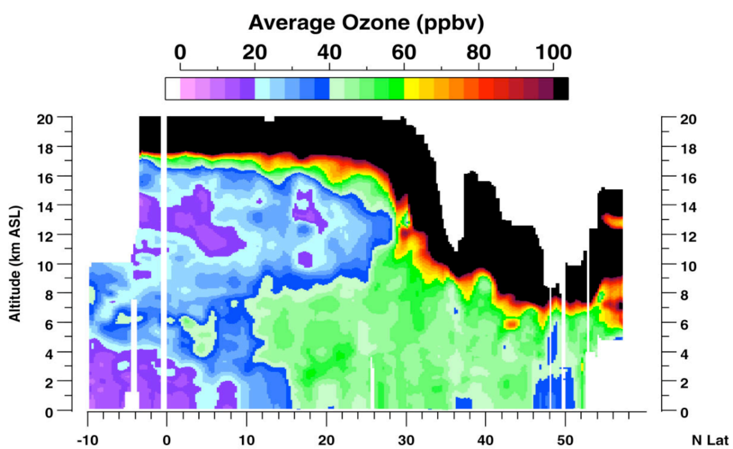






PEMWEST-B

Latitudinal Ozone Distribution Over Western Pacific



NASA airborne ozone and aerosol lidar measurements have long (~30 year) heritage of global measurements characterizing spatial and vertical distributions of ozone and aerosols for stratospheric and tropospheric applications

Space-based Ozone Lidar

Major Technological Challenges:

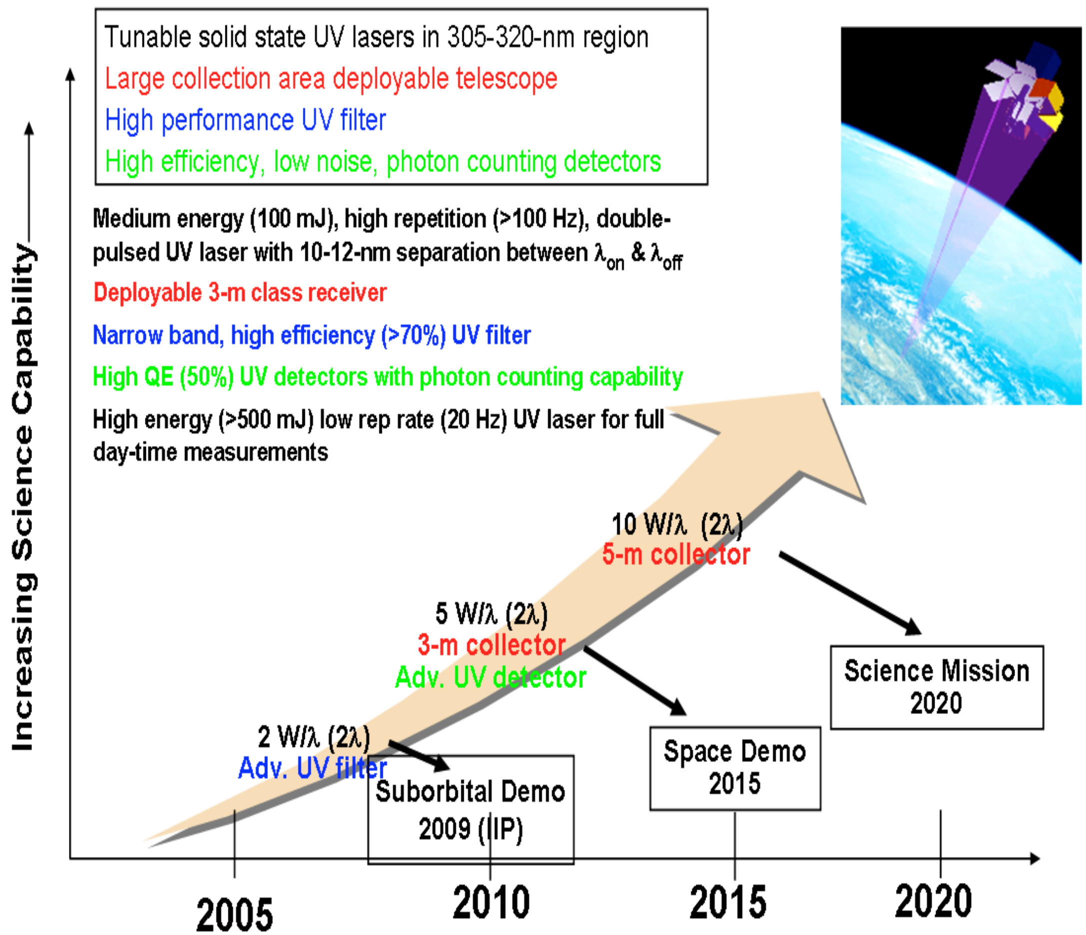
- Transmitter
  - Wavelengths: on-line: 305-308 nm; off-line: 315-320 nm; aerosol wavelength: visible or near IR
  - High-power: >10 W/wavelength with pulse energies of 10 mJ-1 J at pulse rep rates 1 kHz-10 Hz
  - Lifetime: $\geq$3 year

- Receiver
  - Large-effective aperture telescope with area > 4 m^2
  - High-performance UV filters: T >70% with narrow bandwidth
  - High-efficiency (QE >50%), low noise, photon counting detectors

Space-based Ozone & Aerosol Lidar Evolution

Progression to Space

- Current airborne
  - DIAL (ozone)
  - HSRL (aerosol)
    - MILAGRO/INTEX B – air quality/climate
- Instrument Incubator (IIP)
  - Ozone – UAV-based Global Ozone Lidar Demonstrator (GOLD)
  - Ozone+Aerosol – Combined HSRL/Ozone DIAL
- Support
  - NASA (HQ, LaRC, GSFC, ESTO, LRR, CALIPSO)
  - DOE ASP



Summary

- Aerosol lidars (current)
  - Measure aerosol layer heights and thickness
  - Permit inference of aerosol type
  - Retrieval uncertainties due to relating aerosol backscatter and extinction
- HSRL (future)
  - Unambiguous measurement of extinction and backscatter
  - Possible to implement 2-extinction, 3-backscatter wavelength system for retrieval of microphysical properties and concentration
  - Only known demonstrated remote sensing method for obtaining vertically resolved information on aerosol microphysical properties
- Ozone
  - DIAL technique provides higher vertical resolution than passive techniques
  - Long heritage from airborne measurements
- Potential future spaceborne systems
  - Global, vertically (HSRL) and horizontally (MSPI) resolved measurements of aerosol optical and microphysical properties – Aerosol Global Interactions Satellite (AEGIS)
  - Global, vertically resolved measurements of tropospheric and stratospheric ozone and aerosol distributions - Ozone Research with Advanced Cooperative Lidar Experiments (ORACLE)

Backup Slides

- Backup Slides

Disadvantage of backscatter lidar: 1 equation, 2 unknowns

Measured Signal · **Range from Instrument** · **Calibration Constant** · **Molecular Backscatter Coefficient** · **Molecular Extinction Coefficient** ← **Known**

Determined from measured signals and meteorological data

$$P(r) = \frac{C}{r^2}\left[\beta_m(r) + \beta_p(r)\right]\exp\left\{-2\int_0^r\left[\sigma_m(r') + \sigma_p(r')\right]dr'\right\}$$

Particulate Backscatter Coefficient · **Particulate Extinction Coefficient** ← **Retrieved Parameters**

$$\frac{\sigma_p(r)}{\beta_p(r)} = S_p$$

← Assumption of value for extinction-to-backscatter (S_p) ratio required for backscatter lidar retrieval

HSRL: 2 equations, 2 unknowns

Measured Signal on Molecular Scatter (MS) Channel:

$$P_{MS}(r) = \frac{C_{MS}}{r^2} F(r)\,\beta_m(r)\,\exp\left\{-2\int_0^r \left[\sigma_m(r') + \underbrace{\sigma_p(r')}_{\text{Particulate Extinction}}\right] dr'\right\}$$

Particulate Extinction

Measured Signal on Total Scatter (TS) Channel:

$$P_{TS}(r) = \frac{C_{TS}}{r^2} \left[\beta_m(r) + \underbrace{\beta_p(r)}_{\text{Particulate Backscatter}}\right] \exp\left\{-2\int_0^r \left[\sigma_m(r') + \sigma_p(r')\right] dr'\right\}$$

$$\frac{\sigma_p(r)}{\beta_p(r)} = \underline{S_p}$$

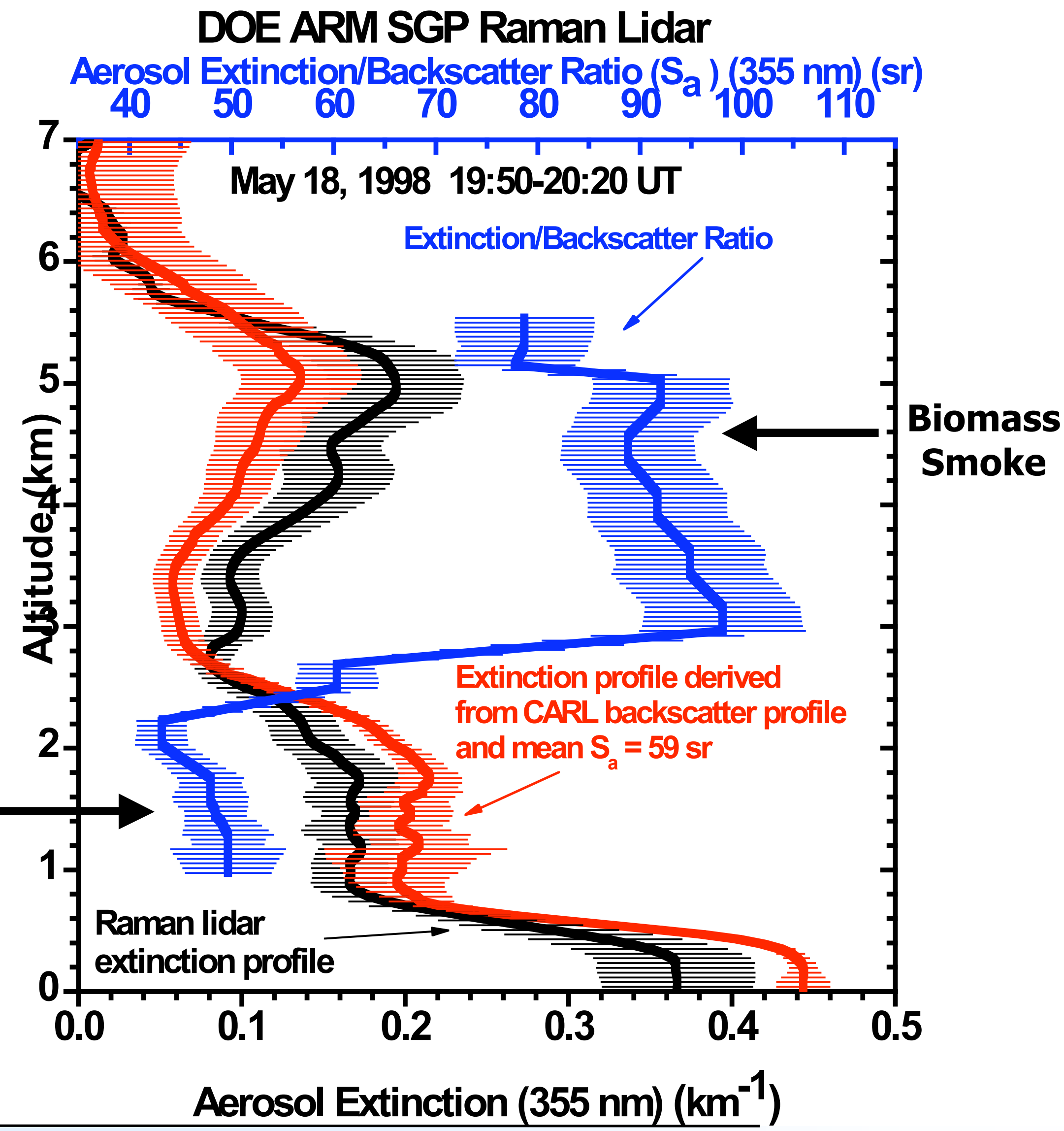
Ext/Backscatter

Particulate Backscatter

Retrieved Parameters

Extinction-to-backscatter ratio variability

- Multiyear Raman lidar measurements over DOE ARM SGP site found large variations in vertical profile of S_a occurred 30% of time
- Significant variability in particle size, composition, and/or shape often occurs
- Uncertainty in profile of S_a raises potential for structural error in backscatter lidar retrieval

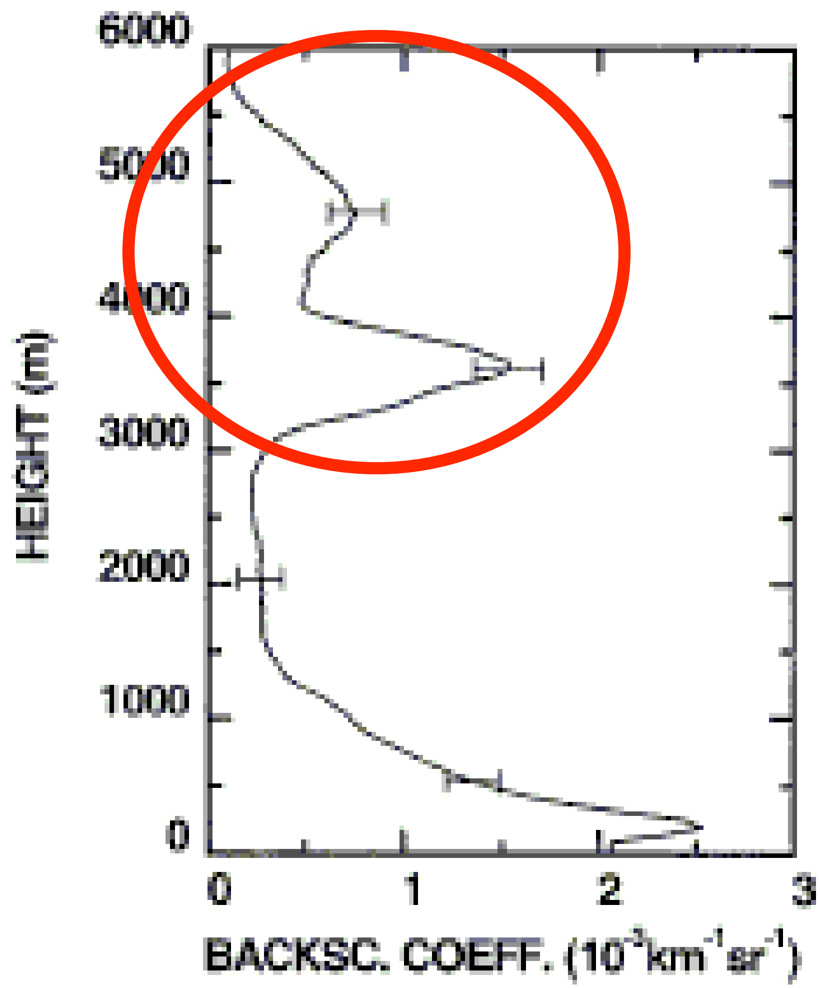


(Ferrare et al.,JGR, 2000)

Heritage and Future Prospects

U. Wisc.- Eloranta 1977 – …	Operating ground-based systems for decades; first etalon-based system; first 532 nm iodine vapor filter system;
Colo. St. - She 1983 – 1998	First vapor filter systems, various wavelengths; first demonstration of temperature measurements
NIES - Liu 1997 – 2001	Ground-based system; 532 nm iodine vapor filter technique
DLR 1998 – 2000	First practical aircraft-based system (no longer functional); 532 nm using iodine vapor filter technique
LaRC 2004 – …	Developed aircraft-based system 532 nm HSRL (iodine filter), 1064 backscatter, and depolarization at both wavelengths. Funded to 355 nm HSRL channels through IIP (to be completed by 2008).
CNES 2005 ? – …	"LNG" -- Leandre upgrade; 355 nm HSRL (Mach Zehnder), 1064 backscatter
ATLID/Earthcare 2012 – …	Spaceborne system; etalon-based receiver; 355 nm

Example microphysical retrieval #1



- From Müller et al., Appl. Opt., 2001
- Data from LACE 98 campaign over Lindenberg, Germany
- Microphysical retrieval performed for upper layer (3-6 km) and compared to in situ aircraft measurements

Ex. #1- Müller et al. (2001) case study using 3-backsatter and 2-extinction wavelengths

Retrieval results compared to in situ measurements for biomass plume.

Parameter	Lidar Retrieval	Aircraft, in situ r>1.5 nm	Aircraft, in situ r>50 nm
r_{eff}, μm	0.27 ±0.04	0.24±0.06	0.25±0.07
Number concentration, cm^{-3}	305±120	640±174	271±74
Surface concentration, $\mu m^2 cm^{-3}$	145±8	110±50	95±55
Volume concentration, $\mu m^3 cm^{-3}$	13±3	9±5	8±5
m_R	1.63±0.09	1.56	1.56
m_I	0.048±0.017	0.07	0.07
SSA (532 nm)	0.81±0.03	0.78±0.02	0.79±0.02
SSA (355 nm)	0.76±0.06	–	–
S_a (532 nm) sr^{-1}	73±4 (75)	–	–
S_a (355 nm) sr^{-1}	51±4 (45)	–	–

Spaceborne 3β+2α HSRL

	CALIPSO	Spaceborne 3β+2α HSRL (rough estimates)
Telescope Diameter	1.0 m	1.5 m
Fundamental Resolution	30 – 60 m vertical, 333 m horizontal	30 m vertical, 70 m horizontal
Backscatter Resolution	120 m vertical, 40 km horizontal	120 m vertical, 20 km horizontal (10% error)
Extinction Resolution	(Indirect) 120 m vertical, 40 km horizontal	(Direct) 900 m vertical, 20 km horizontal (15% error)
Power	200 W @ 700 km	400 W @ 400 km, 825 W at 640 km
Mass	172 kg	265 - 325 kg

Measurement Requirements

- Requirements below are minimums we are currently considering and are driven by
  - 15% accuracy on backscatter and extinction for microphysical retrievals
  - Horizontal and vertical resolutions required to capture relevant aerosol features. Will learn more about relevant aerosol scales with launch of CALIPSO.

Parameter	**Resolution**	**Relative Error**
Backscatter	$\Delta x < 150$ m $\Delta z < 50$ km	< 15%
Extinction	$\Delta x < 1$ km $\Delta z < 50$ km	< 15%

Technology Requirements

- Transmitter
  - SLM, frequency agile Nd:YAG operating at 1064, 532, and 355 nm
    - Average output power > 50W
    - Rep rates 50-200 Hz
      - higher rep rates are acceptable, but puts more stringent requirement on receiver in terms of solar background rejection.
    - High electrical-to-optical efficiency
  - Issues
    - Lifetime
      - Pump diodes
        - Need quantitative database on lifetime vs. diode drive current: determine how derating drive current from nominal specs increase lifetime.
      - UV operation
        - Expect contamination to be a bigger problem in UV than in visible and near IR. Long-term degradation of coatings due to high power UV exposure should be studied. Contamination and contamination control processes should be studied: absorption by trace organic contaminants more of a problem in the UV.

Technology Requirements

- Receiver
  - Interferometric receiver required for 355 nm HSRL measurement (may also be used at 532 if shows merit over iodine vapor filter technique)
    - Spectral resolution ~ 1 GHz
    - Photon efficient
    - Good rejection of solar background
    - High stability/calibration accuracy
      - Accurate calibration of throughput vs. wavelength critical to HSRL application
  - Detectors
    - High QE: >50%
    - Low dark noise
    - Gain sufficient to make amplification noise insignificant
    - Low excess noise factor
  - Telescope
    - Large area: > 1.5 m diameter