Middle Atmosphere Wind and Temperature Lidars: Current Capabilities and Future Challenges

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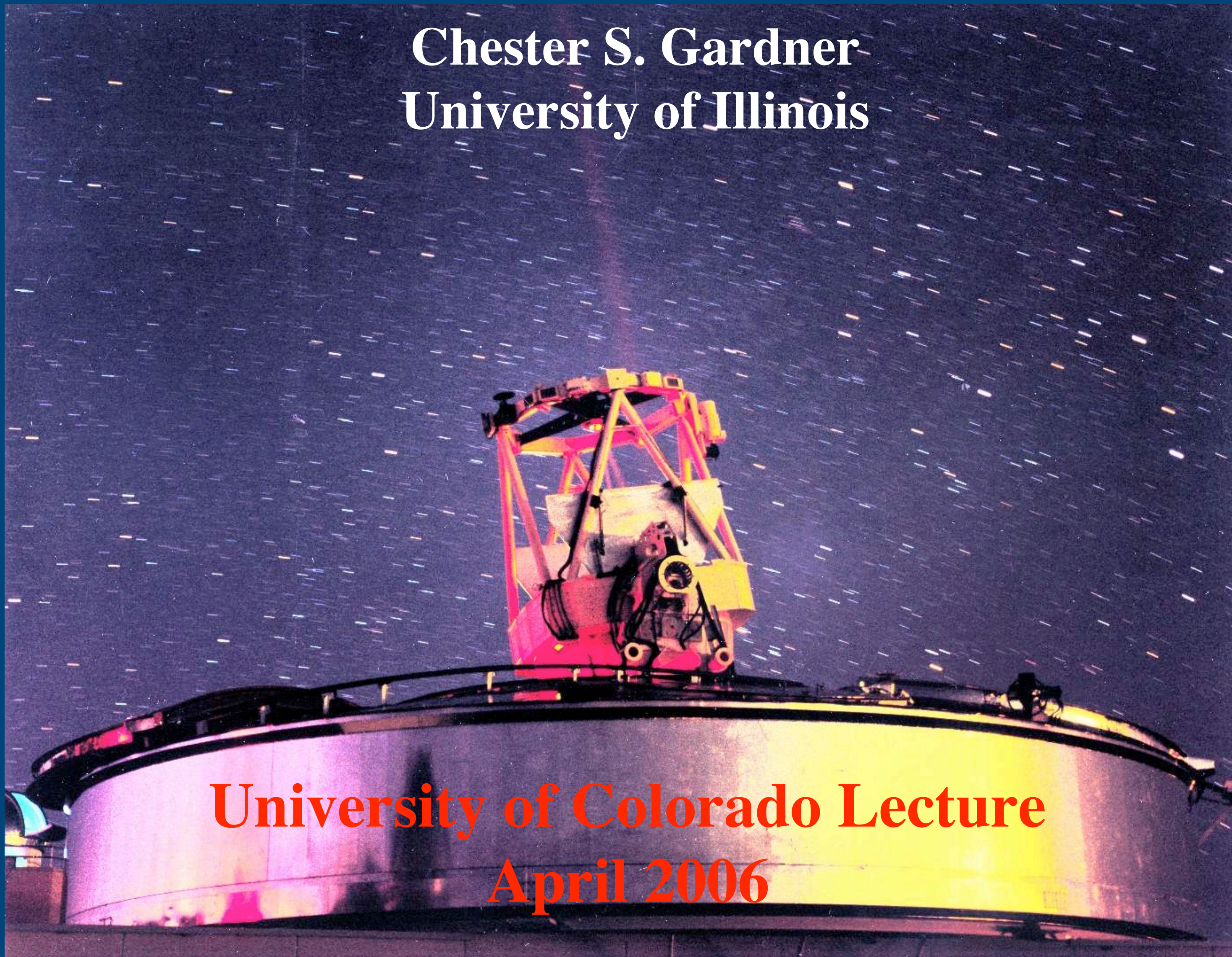
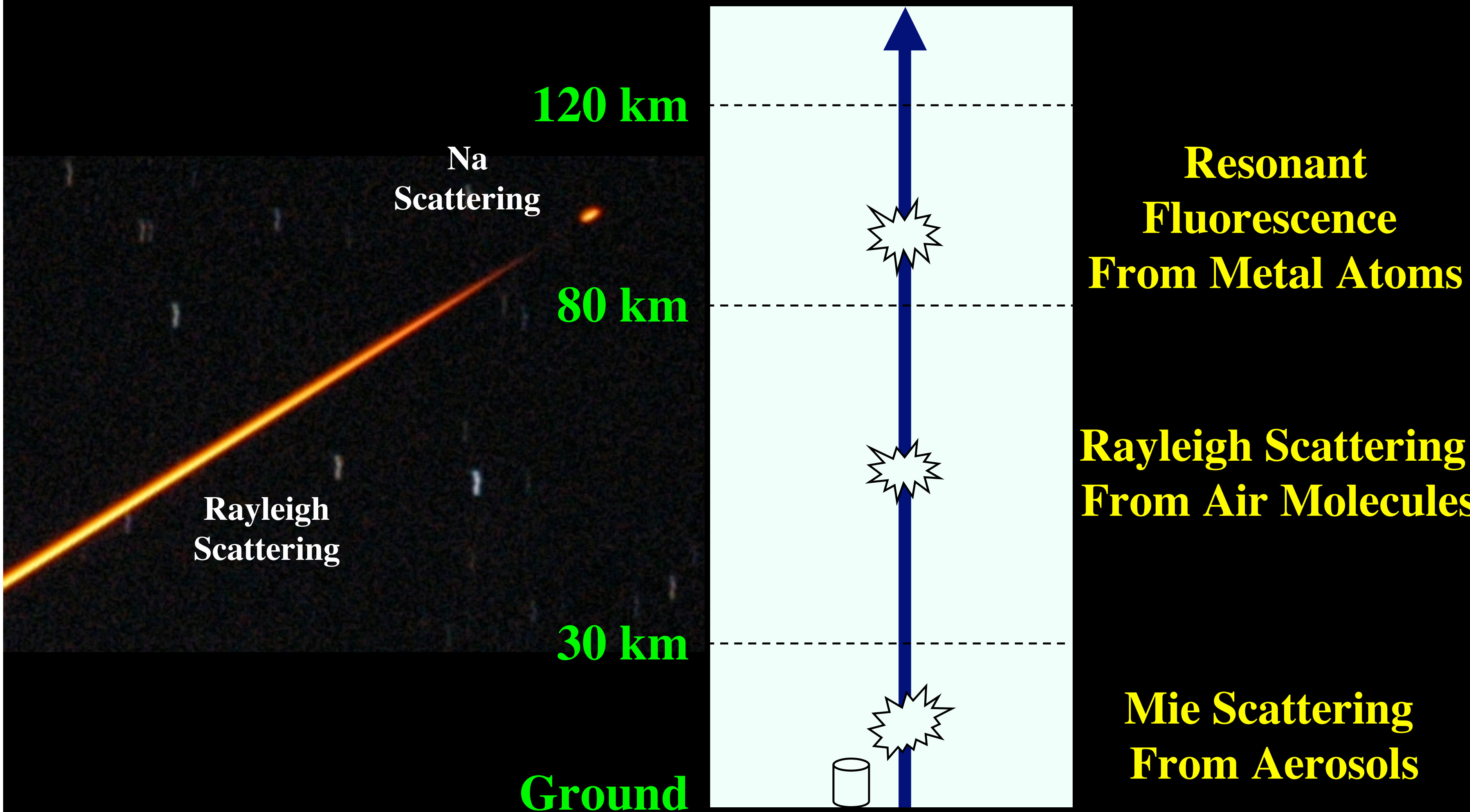
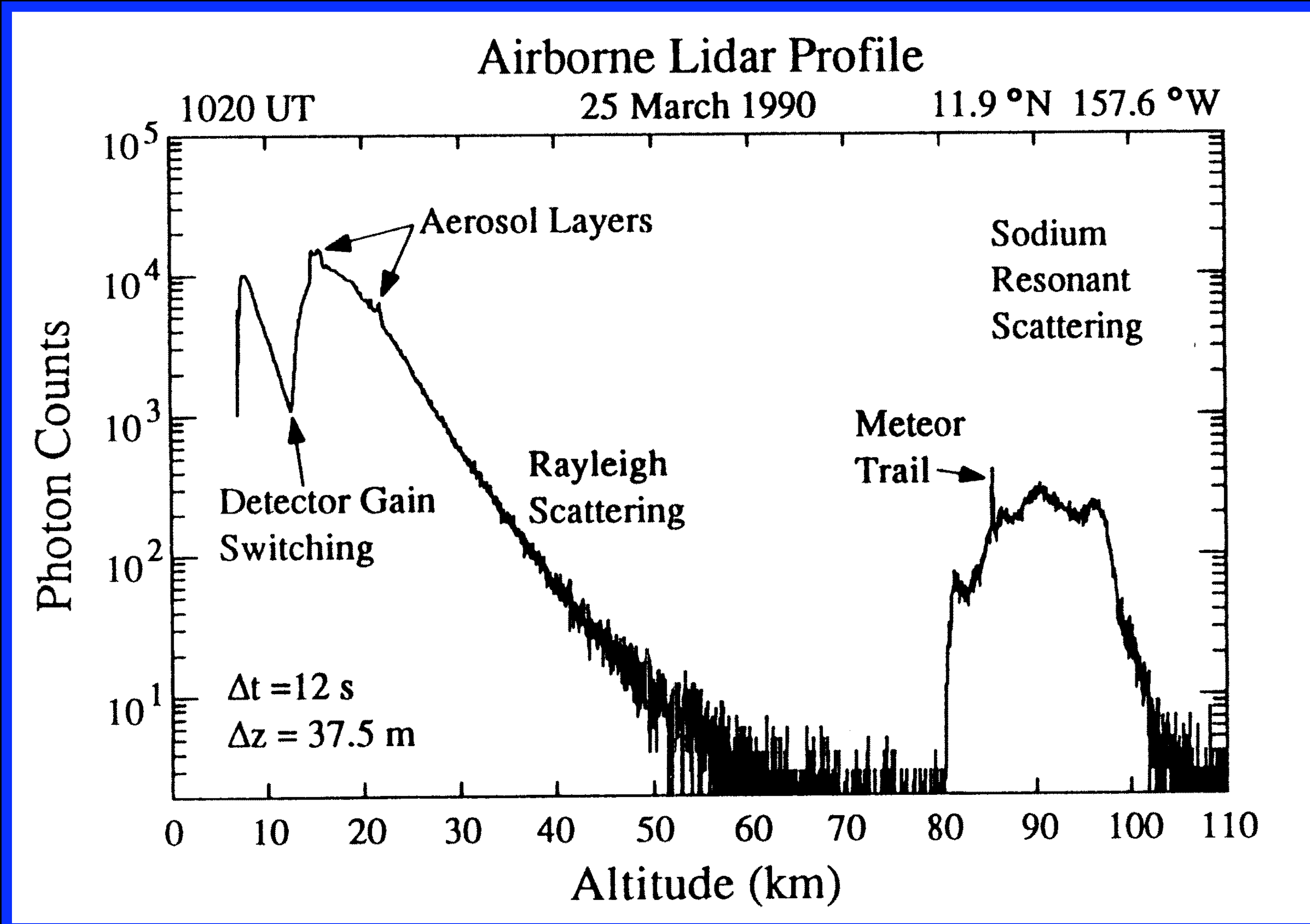


University of Colorado Lecture
April 2006

Light Detection and Ranging (LIDAR)





This photon count profile illustrates the rich variety of atmospheric constituents and processes that can be studied with lidar systems

Historical Perspective

- First lidar systems constructed in 1930s and 40s using mechanically modulated searchlights to study clouds, aerosols, and stratospheric temperatures [*Elterman, J. Geophys. Res., 1951a,b; 1953*]

- In 1980s M. L. Chanin and colleagues used frequency-doubled Nd:YAG lasers to measure stratospheric temperatures and winds (Rayleigh scattering) [*Chanin and Hauchecorne, J. Geophys. Res., 1981; Chanin et al., GRL, 1989*]

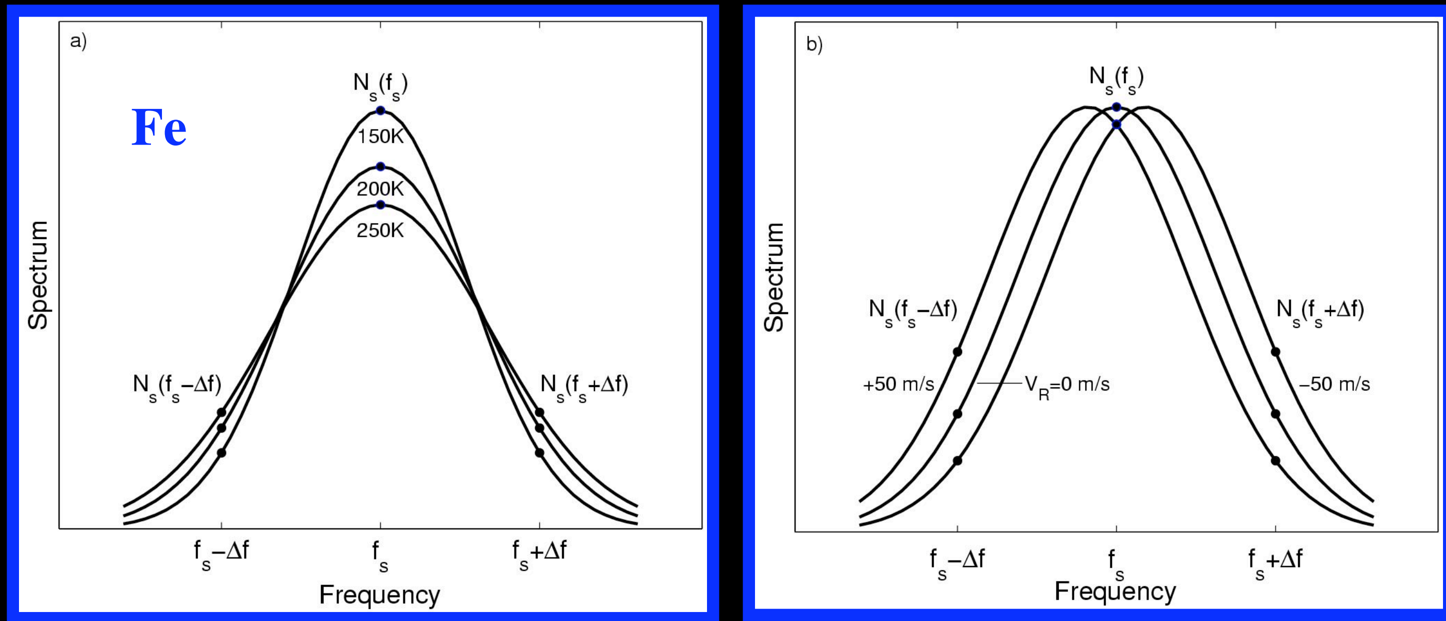
- First lidar in space (aerosol/Rayleigh) flew aboard the shuttle Discovery in September 1994 and provided global measurements of tropospheric/stratospheric clouds, aerosols, and temperatures [*McCormick et al., Bul. Am. Met. Soc., 1993*]

- Today powerful UV laser-based Rayleigh lidars can measure winds in the stratosphere to ~50 km and temperatures to altitudes in excess of 85 km

- First resonance fluorescence lidar measurements were conducted in late 1960s when Bowman et al. [*Nature, 1969*] reported measurements of mesospheric Na profiles using a tunable dye laser; since then Fe, K, Ca, Ca^+, and Li have also been measured

- A crude Na temperature lidar was first demonstrated in late 1970s [*Gibson et al., Nature, 1979*]

- Today Na, K, and Fe lidars are used routinely to measure mesopause region (80~105 km) temperatures while several Na systems are also capable of measuring wind velocities



$$S(f) = \frac{N_S}{\sqrt{2\pi}\sigma_S}\exp\left[-(f - f_S + f_D)^2 / 2\sigma_S^2\right]$$

$$\sigma_S^2 = \frac{k_B T}{\lambda_S^2 m_S} = 1076(MHz^2/K)T(K) \rightarrow \sigma_S = 464 MHz @ 200K \quad for \quad Fe$$

$$f_D = \frac{V_R}{\lambda_S} = 1.7(MHz/m/s)V_R(m/s) \rightarrow 1.7 MHz @ 1 m/s \quad for \quad Fe$$

$$\frac{\partial \sigma_S}{\partial T} = \frac{\sigma_S}{2T} = 1.2 MHz/K \quad and \quad \frac{\partial f_D}{\partial V_R} = 1.7 MHz/(m/s)$$

•Spectra of isolated fluorescence lines and Rayleigh scattered light are approximately Gaussian

•Width is related to temperature (Thermal Broadening)

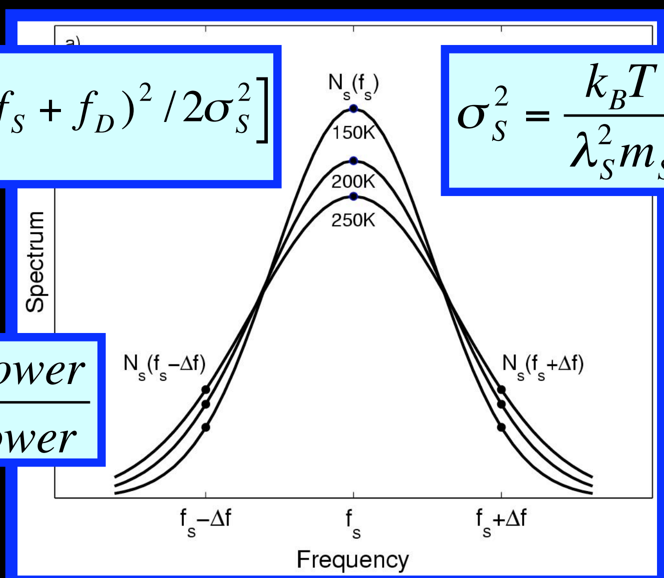
•Center frequency is related to velocity (Doppler Shift)

Signal Processing

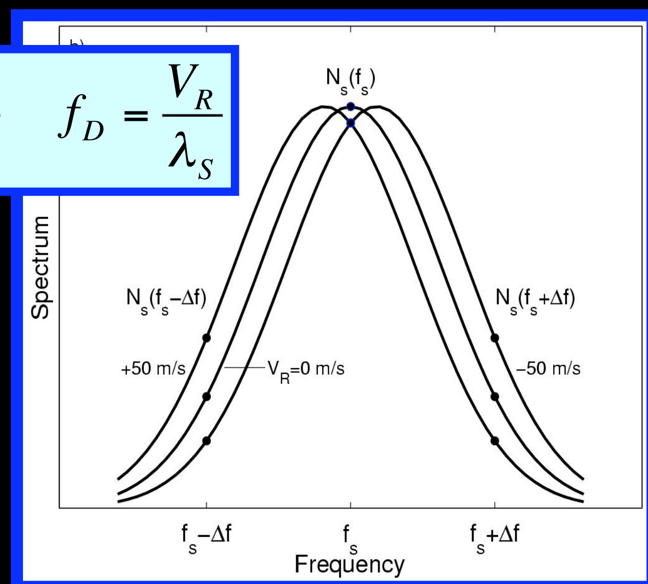
Temperature and Winds can be measured by:

1) **Measuring full spectrum of backscattered signal**
2) **Scanning laser through full fluorescence spectrum and measuring backscattered signal at each frequency**
3) **Probing fluorescence spectrum with laser at 3-frequencies and measuring backscattered signal at each frequency**
4) **Measuring spectrum of backscattered signal at 3-frequencies**

$$\frac{N_S}{\sqrt{2\pi}\sigma_S}\exp\left[-(f-f_S+f_D)^2/2\sigma_S^2\right]$$



$$\sigma_S^2=\frac{k_B T}{\lambda_S^2 m_S}\qquad f_D=\frac{V_R}{\lambda_S}$$



$$SNR=\frac{Signal\ \ Power}{Noise\ \ Power}$$

Theoretical Optimum

Ideal Receiver

No background noise (Nighttime)

Receiver measures precise frequency of each detected photon (Infinite Spectral Resolution Receiver)

Detected photon frequency is Gaussian distributed random variable

$$p(f_i) = \exp\left[-(f_i - f_S + f_D)^2 / 2\sigma_S^2\right] / \sqrt{2\pi}\sigma_S$$

Mean frequency = f_S-f_D Frequency variance = σ_S^2

Minimum-mean-square-error estimators of velocity and temperature are related to sample mean frequency and sample frequency variance

$$\hat{V}_R = -\frac{\lambda_S}{N_S}\sum_{i=1}^{N_S}(f_i - f_S) \qquad \Delta\hat{V}_R = \frac{\lambda_S\sigma_S}{\sqrt{N_S}} = \frac{\lambda_S\sigma_S}{\sqrt{SNR}}$$

$$\hat{T} = \frac{\lambda_S^2 m_S}{k_B N_S}\sum_{i=1}^{N_S}(f_i - f_S + \hat{V}_R / \lambda_S)^2 \qquad \Delta\hat{T} = \frac{\sqrt{2}T}{\sqrt{N_S}} = \frac{\sqrt{2}T}{\sqrt{SNR}}$$

[*Gardner*, *Applied Optics*, 2004] $SNR = N_S$ @ *Night*

Frequency Scanning Lidar

Laser is scanned over full fluorescence spectrum with same dwell time at each frequency
Receiver records photon counts versus laser frequency
Model spectrum is fitted to photon count data to determine T

$$\Delta\hat{T} = \left[\sqrt{\frac{2}{\pi}}\alpha_{scan}\right]^{1/2} \frac{T}{\sqrt{SNR}} \quad @ \ night \qquad \Delta\hat{T} = \left[\frac{2}{\pi}\alpha_{scan}^2\left(1 - \frac{\alpha_{scan}^2}{6} + \frac{\alpha_{scan}^4}{80}\right)\right]^{1/2} \frac{T}{\sqrt{SNR}} \quad @ \ day$$

$$\alpha_{scan} = \frac{\Delta f_{scan}}{\sigma_S} \approx 6 \qquad SNR = \frac{N_S^2}{N_S + N_B} \qquad [Gardner, \ Applied \ \ Optics, \ 2004]$$

Optimized 3-Frequency Lidar

Laser probes fluorescence line at three frequencies (f_S and $f_S \pm \Delta f$)
Dwell time at each frequency and Δf~600 MHz are both chosen to minimize error
Optimization different for temperature and wind and for day and night observations

$$\Delta\hat{T} = G_{3-freq}(\alpha,\beta)\frac{T}{\sqrt{SNR}} \qquad G_{3-freq}(\alpha,\beta) = \frac{2}{\alpha}\left(1 + e^{\alpha/4}\sqrt{\frac{e^{\alpha/2}+\beta}{1+\beta}}\right)$$

$$\alpha = \frac{\Delta f^2}{\sigma_S^2} \qquad \beta = \frac{N_S}{N_B} \qquad [Gardner, \ Applied \ \ Optics, \ 2004]$$

Fe Boltzmann Lidar

Ground state population of Fe responsible for 374 nm line determined by Boltzmann distribution
Temperature is derived from ratio of Fe densities measured at 372 nm and 374 nm using 2 lidars

$$\hat{T} = \frac{\Delta E / k_B}{\ln\left[\frac{7}{9}\frac{\rho_{Fe}(372nm)}{\rho_{Fe}(374nm)}\right]} \qquad [Chu\ et\ al.,\ Applied\ Optics,\ 2002]$$

$$\Delta\hat{T} = G_{Boltzmann}(T, SNR_{372nm}/SNR_{374nm})\frac{T}{\sqrt{SNR_{372nm}}}$$

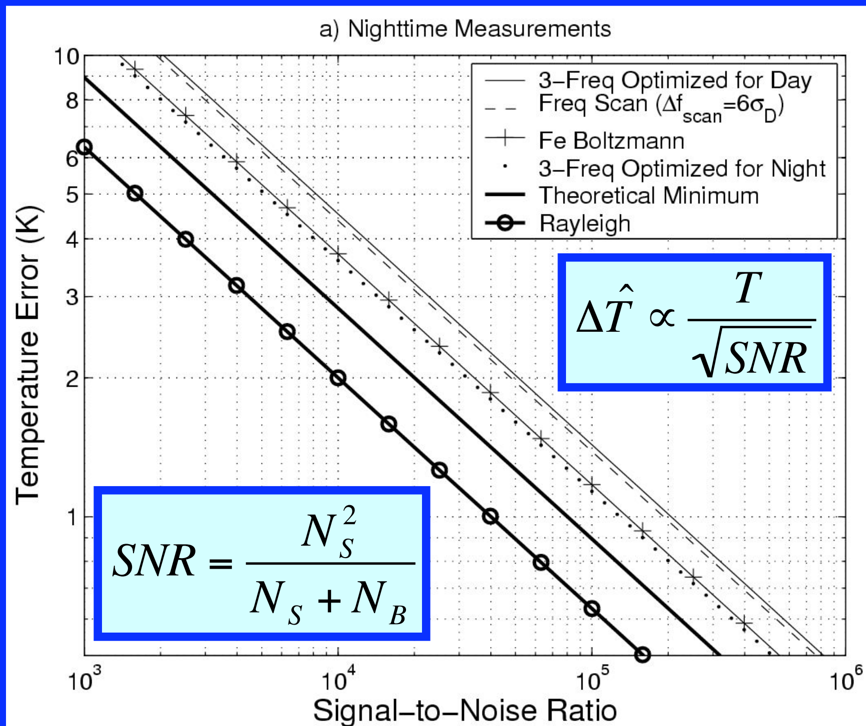
$$G_{Boltzmann}(T, SNR_{372nm}/SNR_{374nm}) = \frac{T}{598.44K}\sqrt{1+\frac{SNR_{372nm}}{SNR_{374nm}}}$$

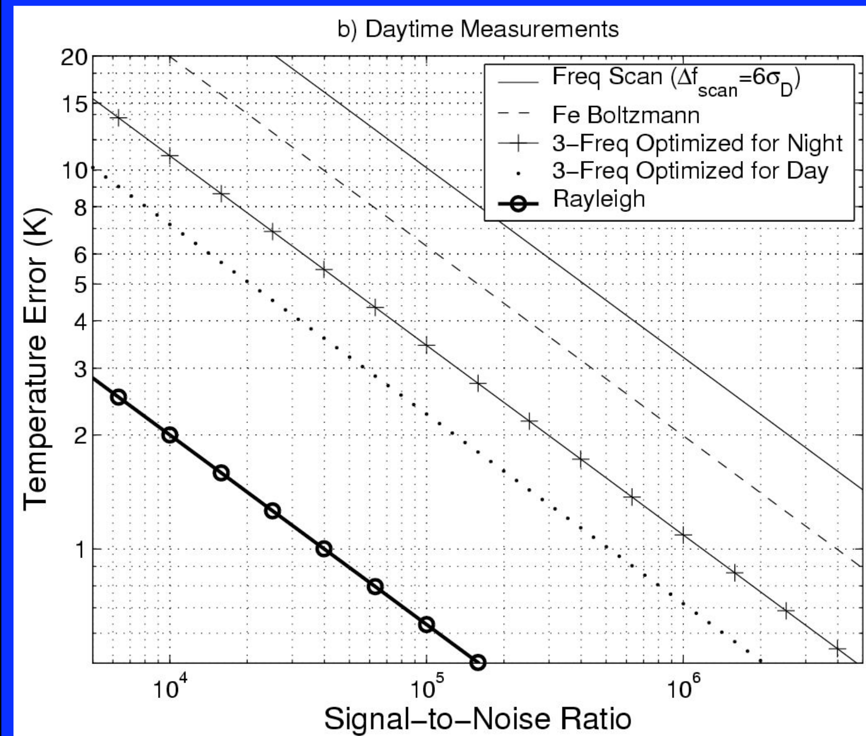
Rayleigh Lidar

When atmosphere is in hydrostatic equilibrium temperature is derived
from relative atmospheric density profile and temperature estimate at top of profile

$$\hat{T}(z) = \frac{T(z_0)\rho_A(z_0)}{\rho_A(z)} + \frac{M}{R}\int_z^{z_0}\frac{g(r)\rho_A(r)}{\rho_A(z)}dr$$

$$\Delta\hat{T} = \frac{T}{\sqrt{SNR}} \qquad [Gardner,\ Applied\ Optics,\ 2004]$$

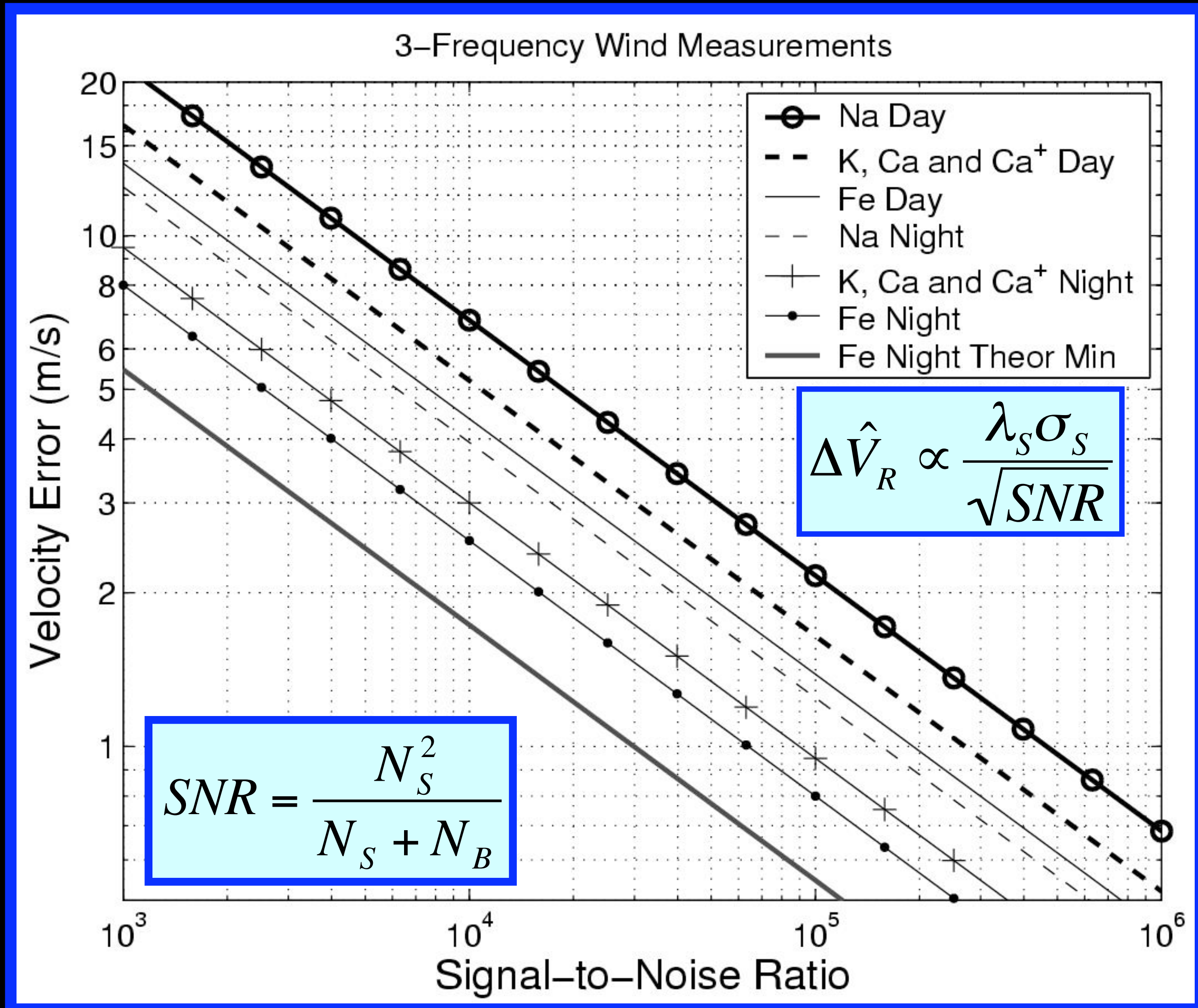




To achieve ±1 K accuracy with optimized 3-frequency lidar requires SNR~ 1.3 x 10^5 = 51 dB @ Night and SNR~ 5.2 x 10^5 = 57 dB @ Day

Signal Processing Gain Factors for Temperature Lidars

Technique	Day	Night
Ideal Receiver $\Delta\hat{T} = \sqrt{2T}/\sqrt{SNR}$	na	+2.1 dB
Optimized 3-Frequency	0 dB	0 dB
Frequency Scanning	-13.0 dB	-1.7 dB
Fe Boltzmann	-8.8 dB	-0.3 dB
Rayleigh	+11.1 dB	+5.1 dB



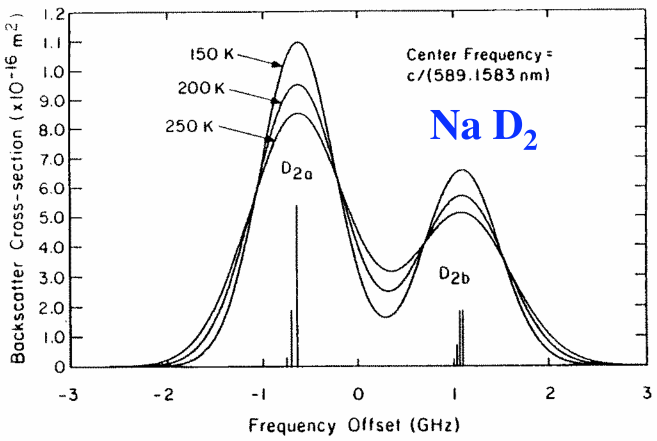
Fe lidar has smallest error because Fe is heaviest atom and wavelength is shortest

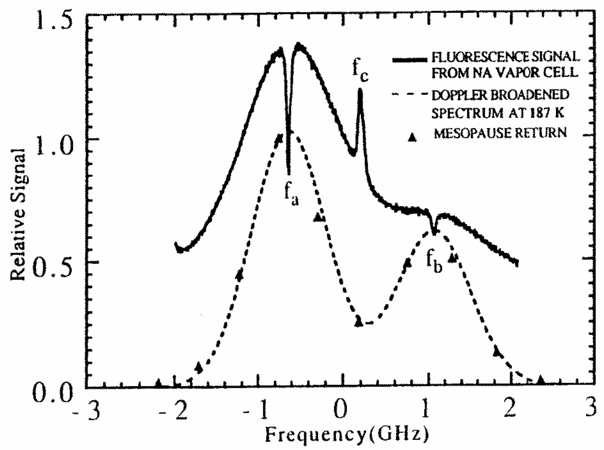
Optimized 3-frequency Fe lidar performs within 3.3 dB of Theoretical Min @ night

To achieve ±1 m/s accuracy with optimized 3-frequency Fe lidar requires

SNR~ 6.4×10^4 = 48 dB @ Night and SNR~ 1.3×10^5 = 51 dB @ Day

Hyperfine Lines and Isotopes

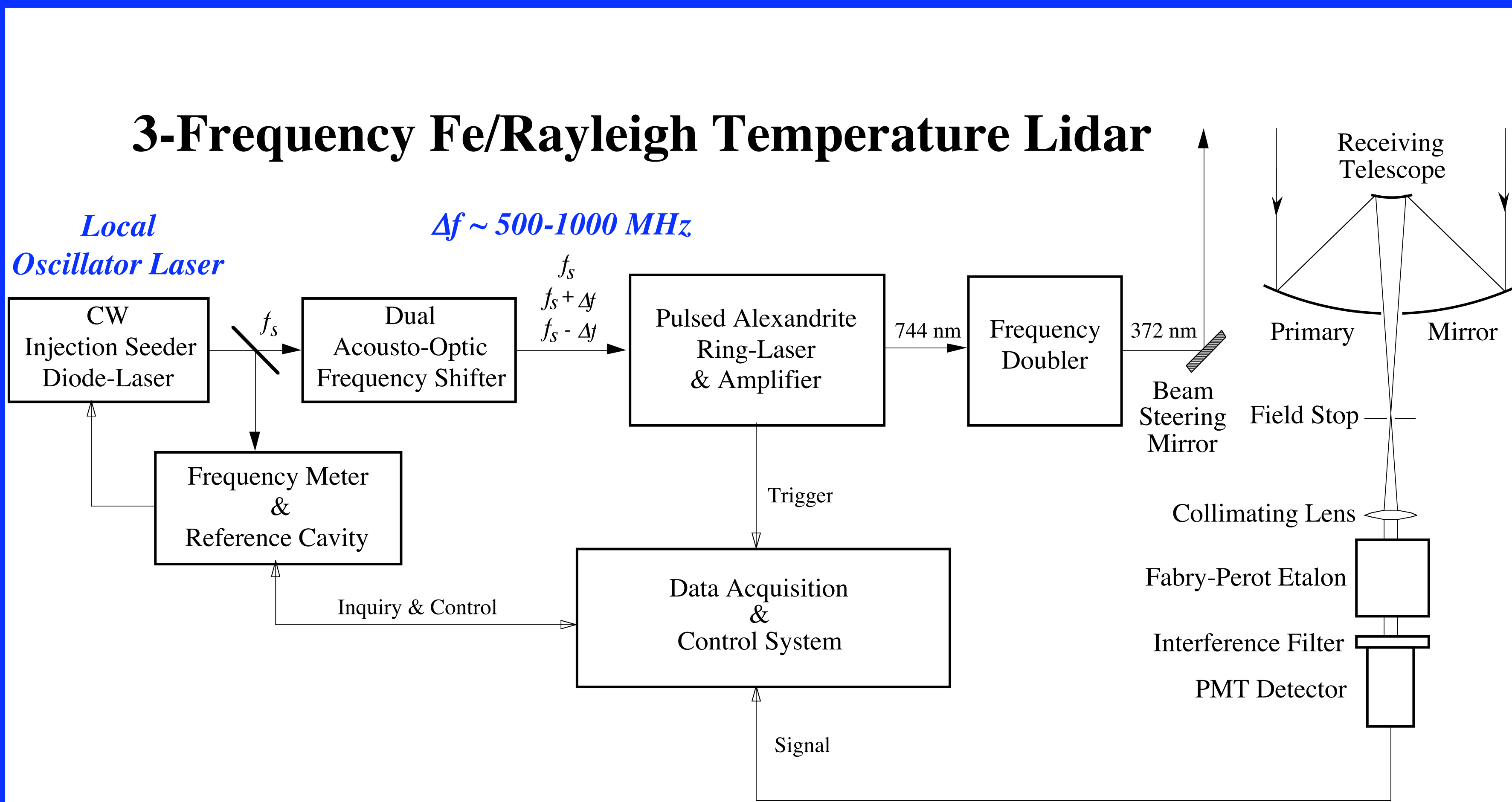




Naturally Occurring Isotopes of Na, K, Fe, and Ca
(http://www.webelements.com/webelements/)

Isotope	Natural Abundance (Atom%)	Nuclear Spin (I)	Magnetic Moment (m/m_N)
^{23}Na	100	3/2	2.217520
^{54}Fe	5.85	0	0
^{56}Fe	91.75	0	0
^{57}Fe	2.12	1/2	0.09062294
^{58}Fe	0.28	0	0
^{39}K	93.26	3/2	0.3914658
^{40}K	0.012	4	-1.298099
^{41}K	6.73	3/2	0.2148699
^{40}Ca	96.94	0	0
^{42}Ca	0.65	0	0
^{43}Ca	0.14	7/2	-1.31727
^{44}Ca	2.09	0	0
^{46}Ca	0.004	0	0
^{48}Ca	0.19	0	0

System Architecture

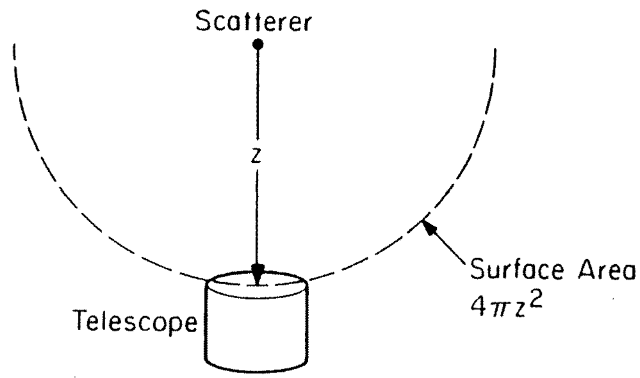


Na systems employ dye ring-laser for local oscillator and pulsed dye amplifier

Maui:MALT
Na Lidar
Haleakala, HI

Laser Power 1-2 W @ 50 pps
Δf = 630 MHz
Telescope Diameter 3.7 m
Power Aperture Product
~15 Wm^2

Lidar Equation



Lidar Equation

Received Photocount	=	System Efficiency	×	# Photons Transmitted	×	Probability of Scattering	×	Probability Scattered Photon is Received
$N(z)$	=	ηT_A^2	×	$\dfrac{P\tau}{hc/\lambda}$	×	$\sigma_B \rho(z) \Delta z$	×	$\dfrac{A}{4\pi z^2}$

η = lidar system efficiency
T_A = atmospheric transmittance
hc/λ = photon energy (J)
P_L = average laser power (W)
A_R = telescope aperture area (m^2)

σ_B = backscatter cross section (m^2)
$\rho(z)$ = constituent density (m^{-3})
τ = profile integration period (s)
Δz = range resolution (m)
z = altitude (m)

$$SNR_{Night} = \frac{N_S^2(z)}{N_S(z) + N_B} \cong N_S(z) \qquad SNR_{Day} = \frac{N_S^2(z)}{N_S(z) + N_B} \cong \frac{N_S^2(z)}{N_B} \cong \frac{SNR_{Night}^2}{N_B}$$

$$N_S(z) \propto (PA\Delta z \Delta t)[T_A^2 \sigma_B \rho_S(z)] \qquad N_B \propto S_{Sky}(\lambda)\Delta\lambda\Omega_{Field-of-View}$$

Backscatter Cross-Section

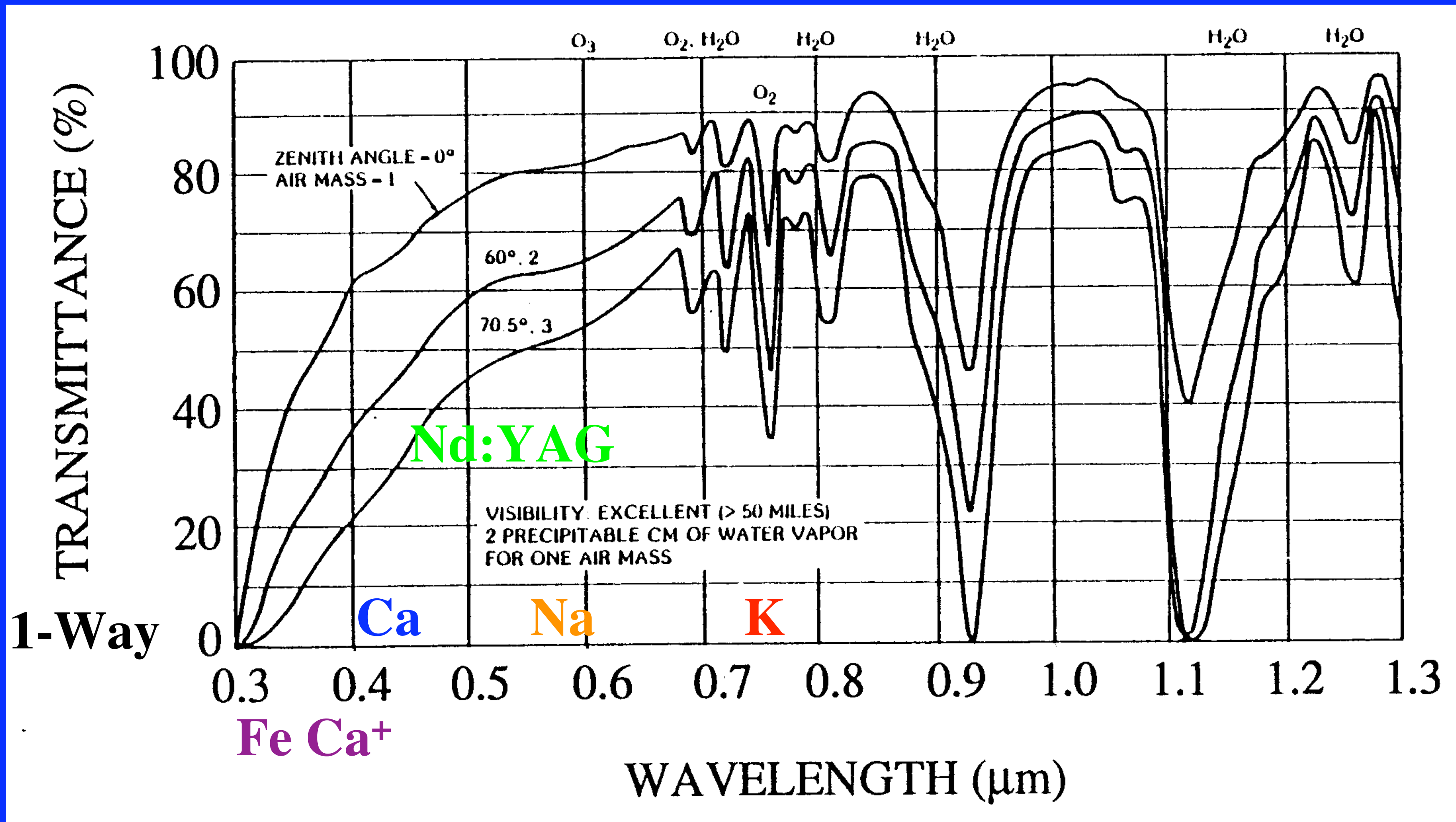
Backscatter Parameters

Species	Central Wavelength λ_S (nm)	Peak Cross-Section σ_B (10^{-12} cm^2)	Peak Density ρ_S (cm^{-3})	Altitude (km)	$\sigma_B \rho_S$ (10^{-8} m^{-1})
Na (D_2)	588.995	14.87	3500	91.5	520
Fe	371.994	0.944	9000	88.3	85
K (D_1)	769.896	13.42	40	91.0	5.4
Ca	422.673	38.48	40	90.5	15
Ca^+	393.366	13.94	80	95.0	11
Rayleigh	532.070	7.6×10^{-15}	1.7×10^{14}	85.0	0.013
Rayleigh	532.070	7.6×10^{-15}	3.4×10^{15}	65.0	0.26
Rayleigh	532.070	7.6×10^{-15}	4.1×10^{16}	45.0	3.1

$$\sigma_{Rayleigh}\rho_{Atmosphere}(z) = 3.7x10^{-31}\frac{P(mb)}{T(K)}\frac{1}{\lambda(m)^{4.0117}}$$

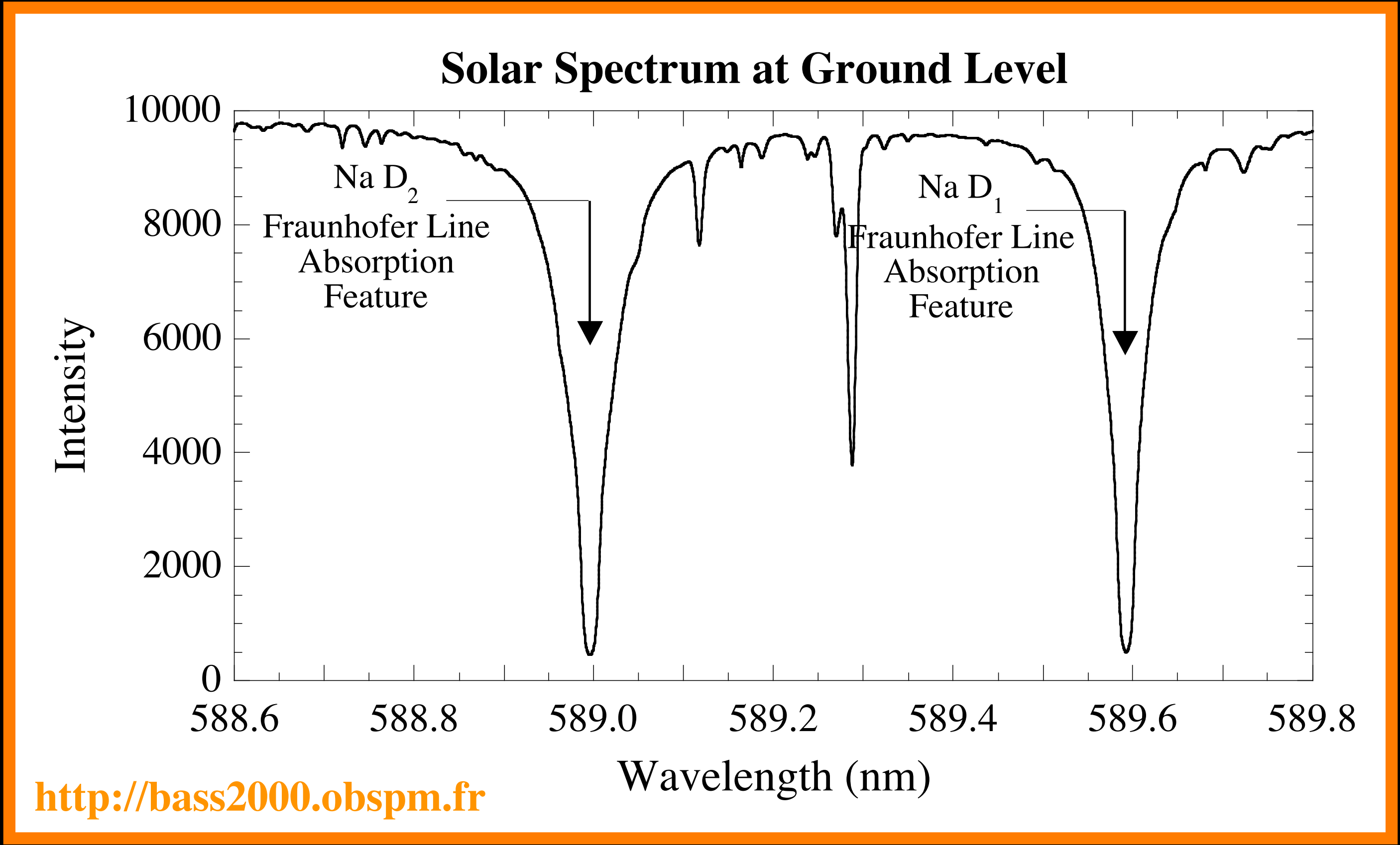
$$N_S(z) \propto (PA\Delta z\Delta t)[T_A^2\sigma_B\rho_S(z)]$$

Atmospheric Transmittance



Atmospheric attenuation decreases with increasing altitude

Sky Brightness and Background Noise



$$N_B \propto S_{Sky}(\lambda)\Delta\lambda\Omega_{Field-of-View}$$

Sky brightness decreases with increasing altitude

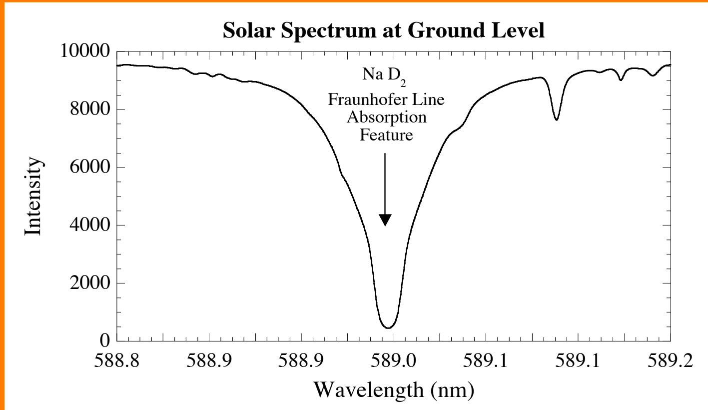
Atmospheric Parameters

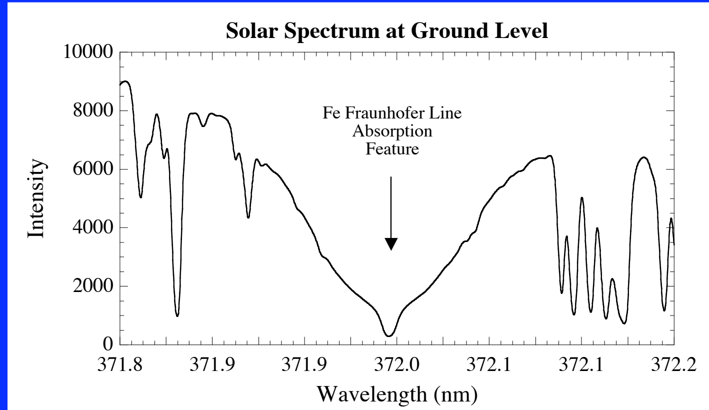
Species or Laser	λ_S (nm)	2-Way Atmospheric Transmittance T_A[2]	Sky Spectral Radiance Continuum[1] (10^{-3} W/m^2/nm/sr)	Fraunhofer Line Relative Depth[2] (% Continuum)	Fraunhofer Linewidth[3] (GHz)	Narrowband Sky Spectral Radiance[1,4] (10^{-3} W/m^2/nm/sr)
Na	588.995	0.49	86.3	9.6	14.5	8.28
Fe	371.994	0.25	34.8	8.1	36.0	2.82
K	769.896	0.64	67.7	21.7	5.9	14.69
Ca	422.673	0.37	67.7	7.6	23.2	5.15
Ca^+	393.366	0.30	41.0	9.9	554.0	4.06
Frequency Doubled Nd:YAG	532.070	0.46	90.0	na	na	90.0
Frequency Tripled Nd:YAG	354.713	0.23	27.9	na	na	27.9

[1]Zenith viewing at sea level, solar zenith angle 45^0, excellent visibility

[2]Includes 5% Ring effect for all lines, [3]Full width @ twice depth

[4]Receiver bandwidth much smaller than Fraunhofer linewidth





Relative Nighttime Signal-to-Noise Ratios

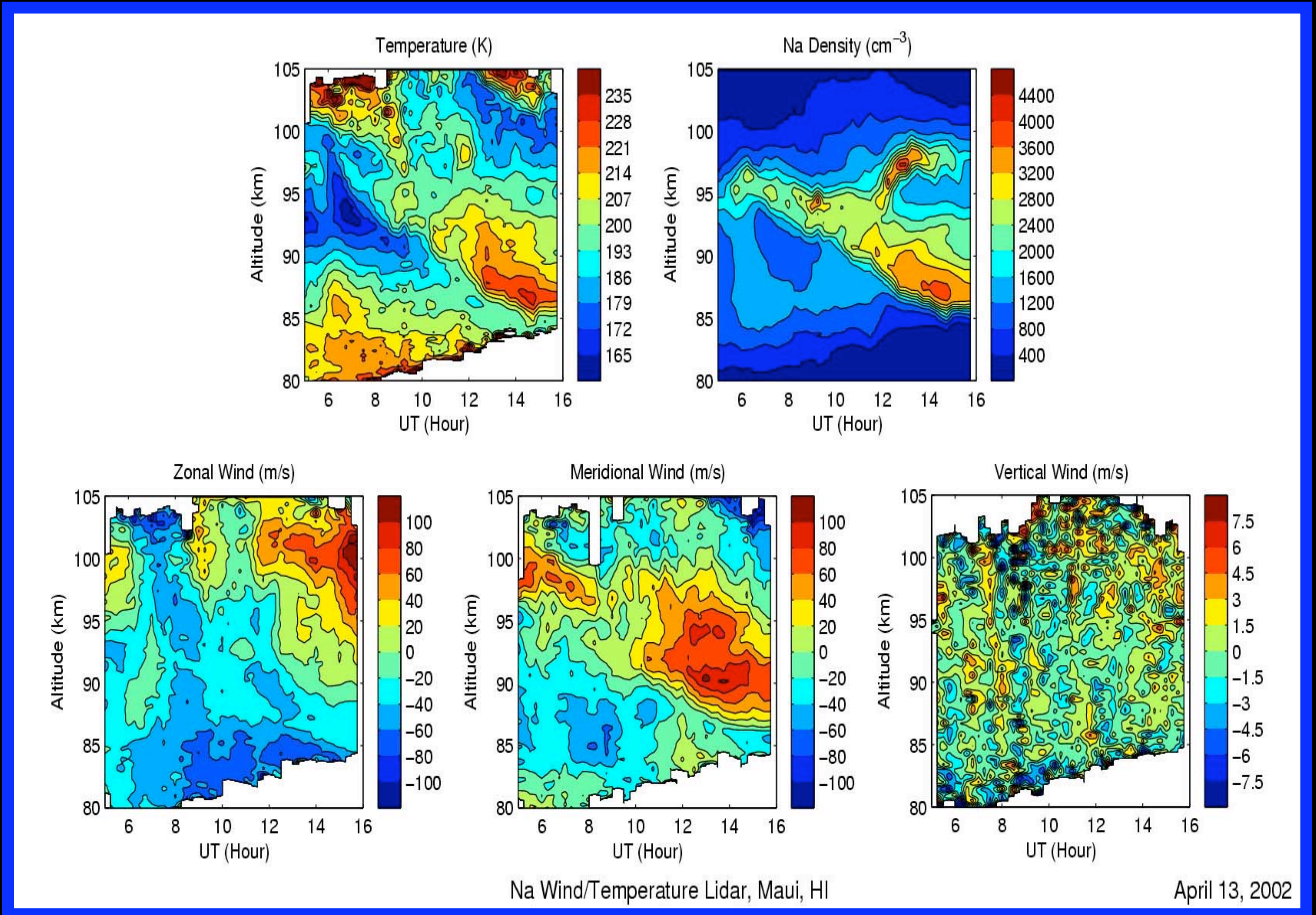
Species or Laser	Wavelength (nm)	Fluorescence SNR_S/SNR_{Na}	Rayleigh SNR_λ/SNR_{532}
Na	588.995	0 dB	-1.1 dB
Fe	371.994	-12.5 dB	+2.0 dB
K	769.896	-17.6 dB	-3.4 dB
Ca	422.673	-19.1 dB	+2.1 dB
Ca^+	393.366	-21.9 dB	+2.1 dB
Frequency-Doubled Nd:YAG	532.070	na	0 dB
Frequency-Tripled Nd:YAG	354.713	na	+2.3 dB

Relative Daytime Signal-to-Noise Ratios

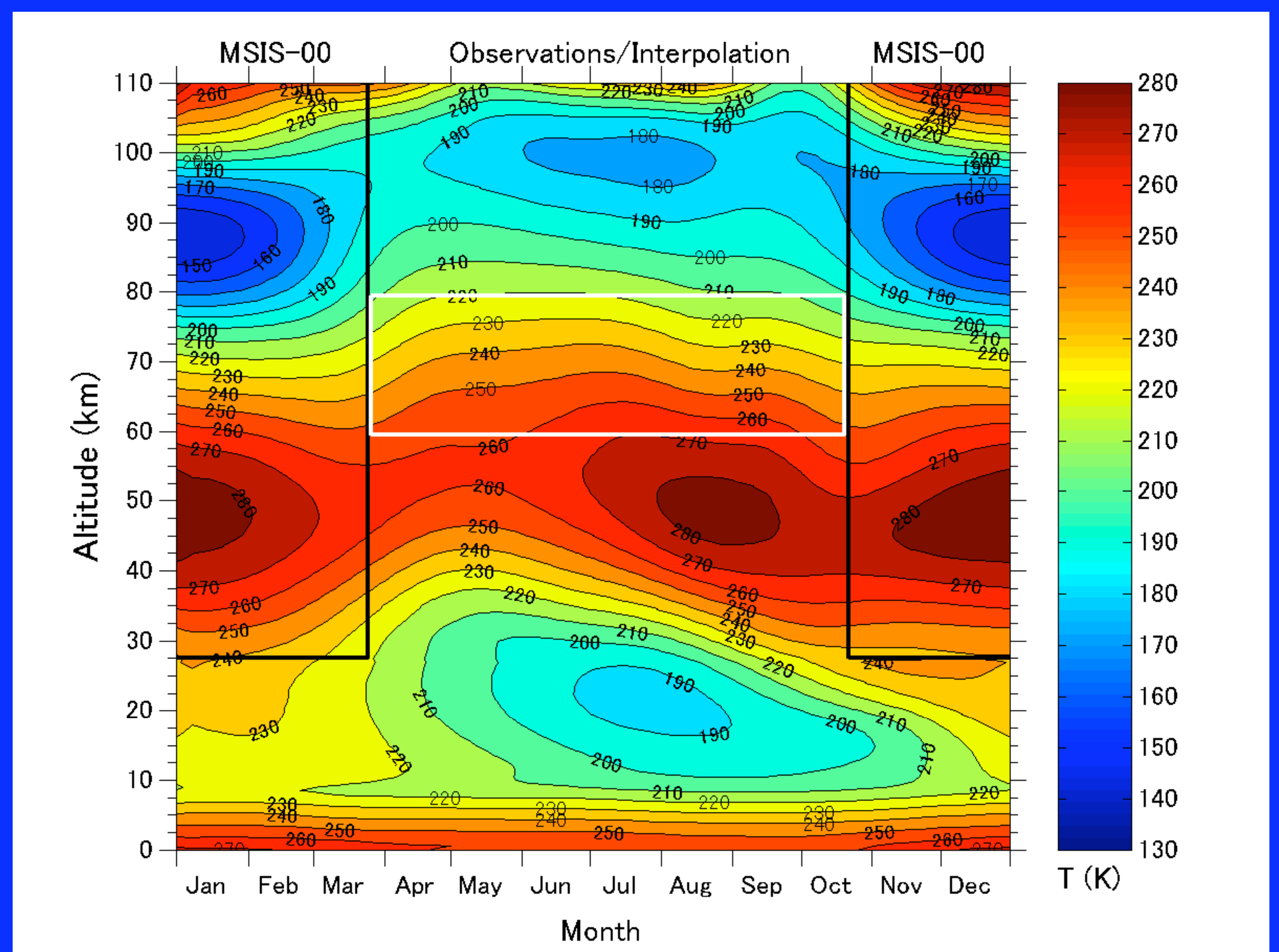
Species or Laser	Wavelength (nm)	Fluorescence SNR_S/SNR_{Na}	Rayleigh SNR_λ/SNR_{532}
Na	588.995	0 dB	+7.8 dB
Fe	371.994	-18.4 dB	+20.7 db
K	769.896	-38.8 dB	-0.5 dB
Ca	422.673	-34.8 dB	+17.6 dB
Ca^+	393.366	-39.0 dB	+19.0 dB
Frequency-Doubled Nd:YAG	532.070	na	0 dB
Frequency-Tripled Nd:YAG	354.713	na	+11.5 dB

$$Error \propto 2^{-ratio(dB)/6}$$

Maui:MALT Na Lidar @ Haleakala, HI

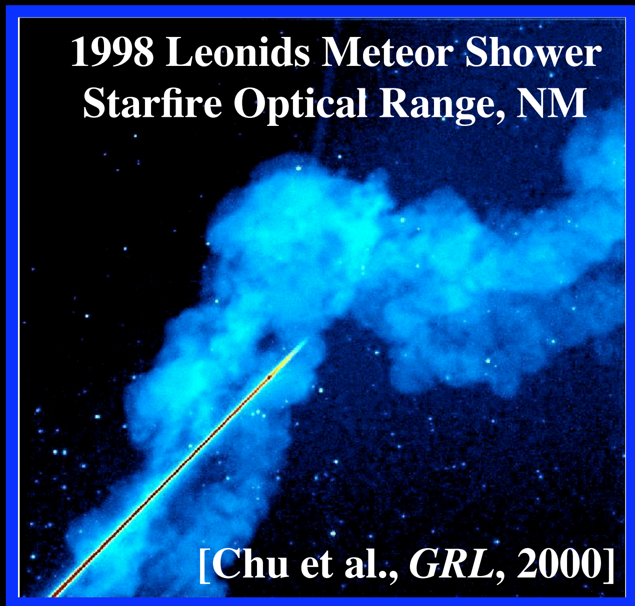


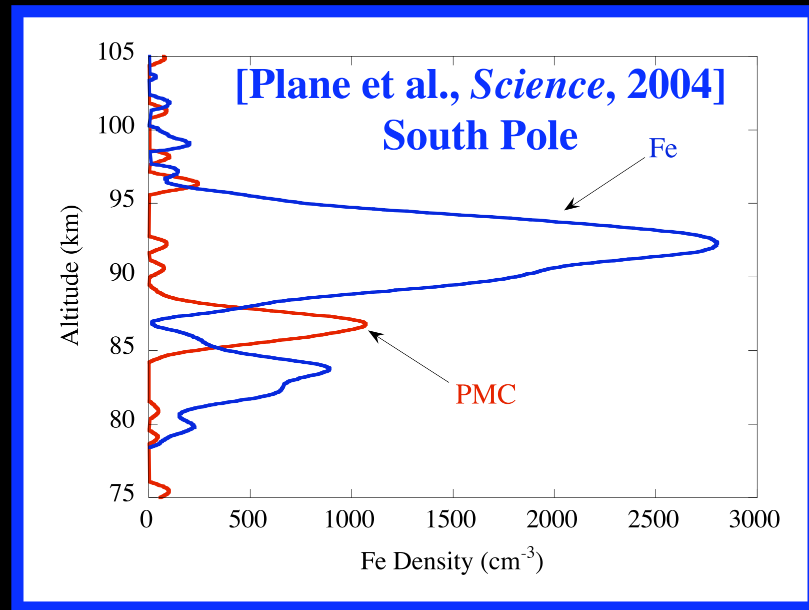
Balloon (0-28 km), Rayleigh Lidar (28-58 km), Na Lidar (80-105 km) Temperature Observations @ Syowa, Antarctica

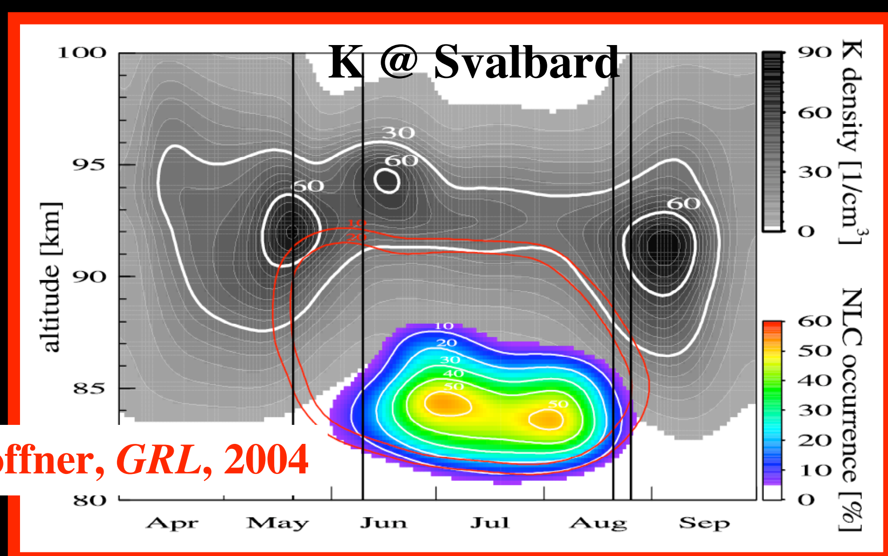


Kawahara et al. [*JGR*, in press 2004]

Lidars are also being used to study Meteor Trails and Polar Mesospheric Clouds

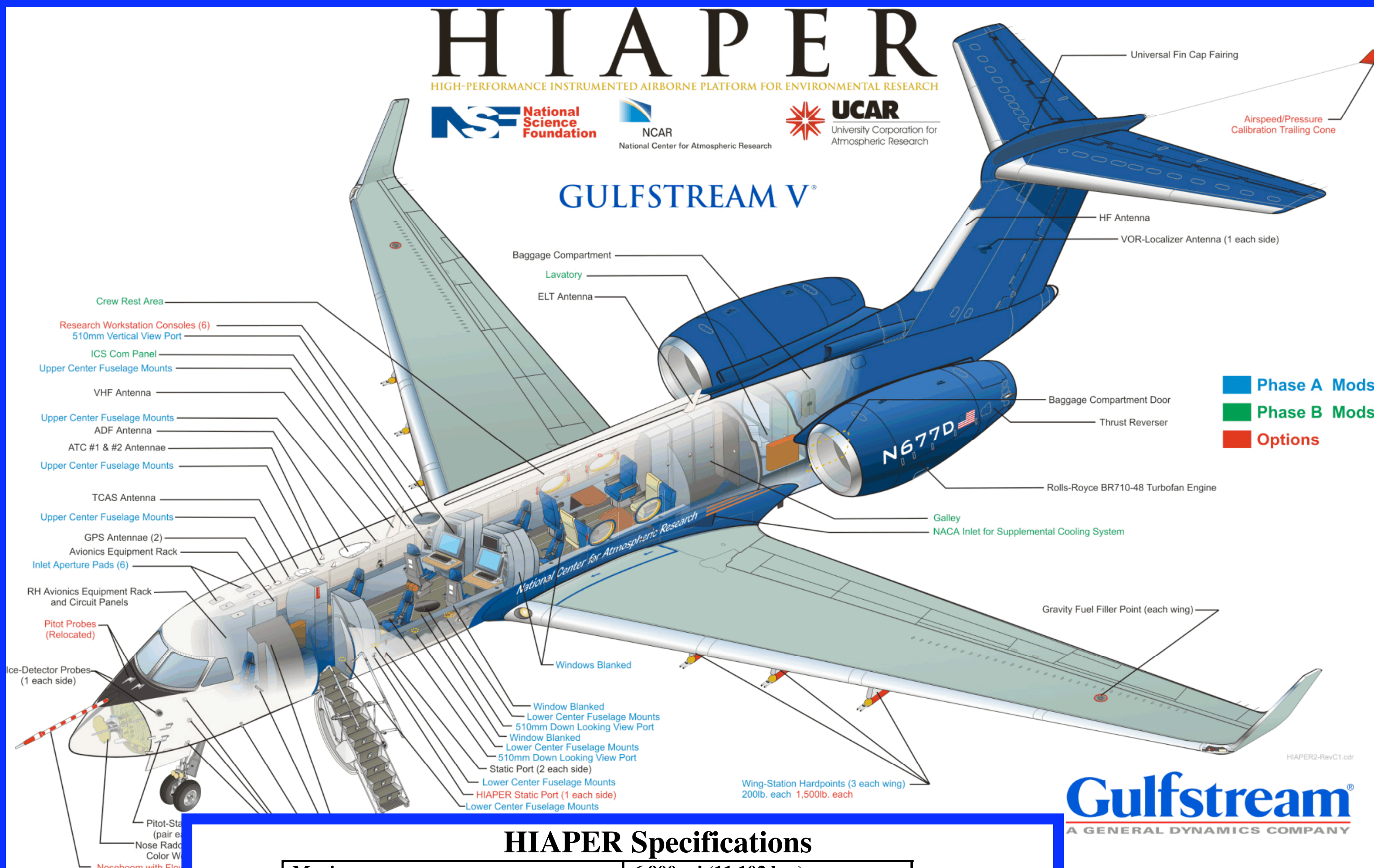






[Lubken and Hoffner, *GRL*, 2004

Future Challenges (Mobile/Global Capabilities)



HIAPER Specifications

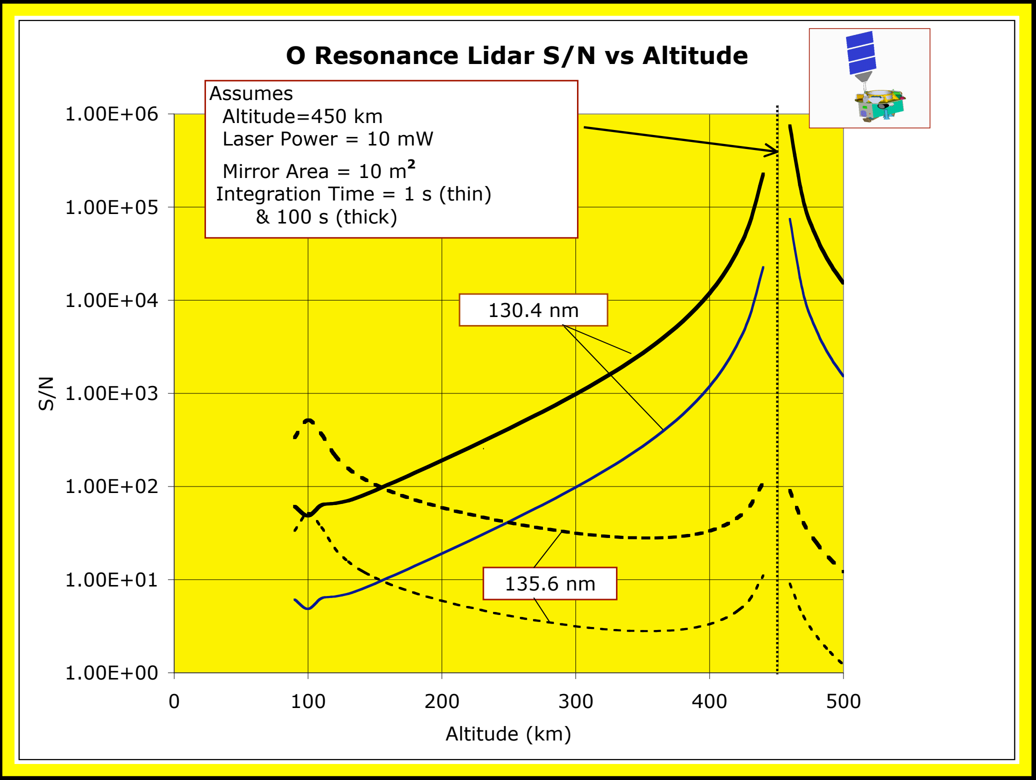
Maximum range	6,900 mi (11,102 km)
Long range cruise speed	Mach 0.80 (850 km/hr)
Flight duration	13.4 hr
Maximum cruise altitude	51,000 ft (15.545 km)
Scientific payload at maximum range	5,500 lbs (2,495 kg)
Cabin length	50 ft 1 in (15.3 m)
Cabin height	6 ft 2 in (1.9 m)
Cabin width	7 ft 4 in (2.2 m)
Passengers	13-15 max including flight crew

Future Challenges (Thermospheric Capabilities)

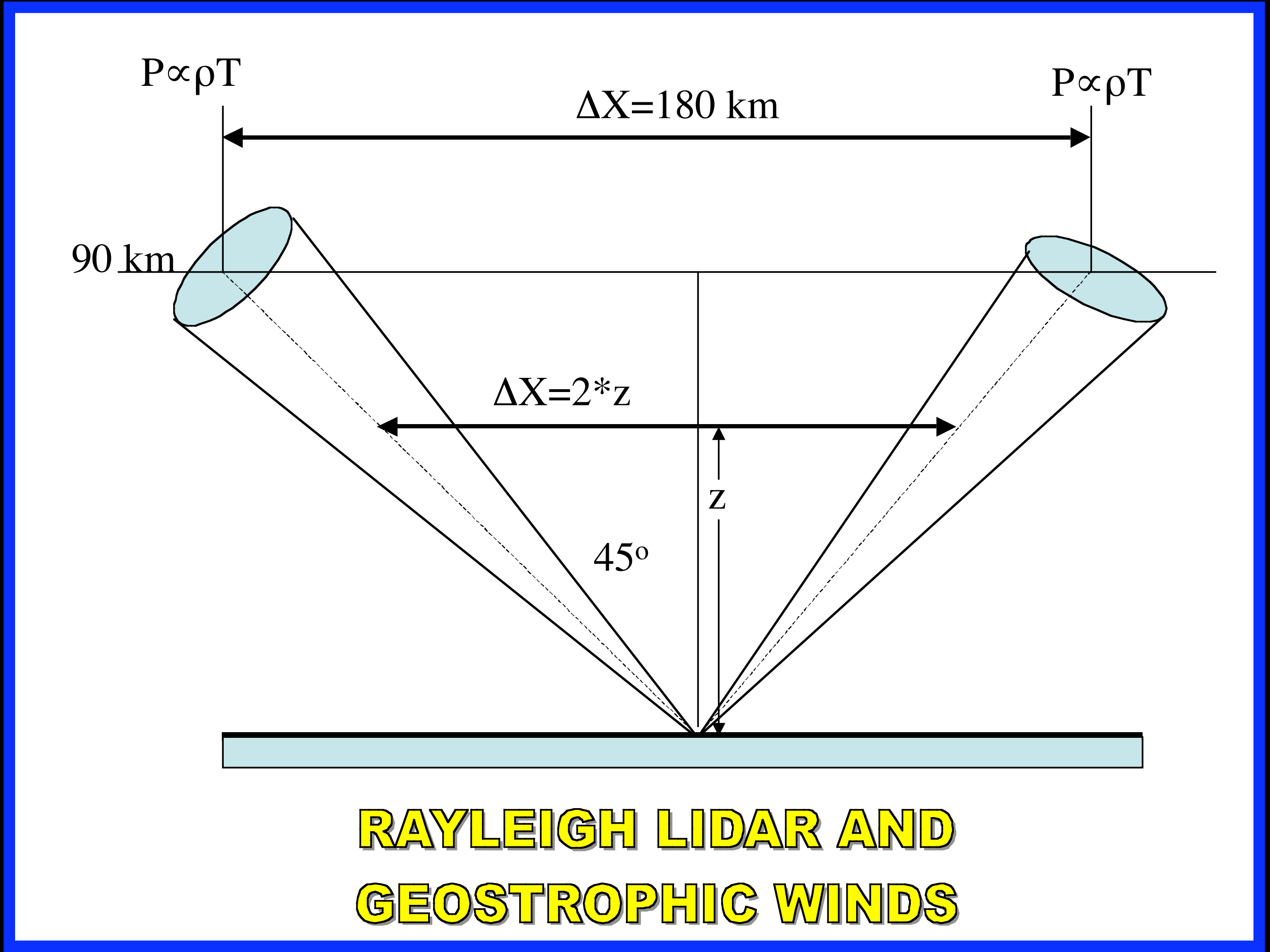
•Helium Fluorescence Lidar @ 587.56 nm (R. Kerr)

•Aurorally-Excited Nitrogen Lidars @ 888.3, 391.2, and 337.0 nm [R. Collins et al., *Applied Optics*, 1997]

•Topside O Fluorescence Lidar @ 130.4 and 135.6 nm (G. Swenson et al.)



Future Challenges (Novel Techniques)



Hundred Watt fiber lasers and several meter diameter Fresnel lens telescopes
Measure pressure gradients from which geostrophic winds are computed
(Swenson, Liu, and Dragic)

Conclusions

- Lidars are making crucial contributions to MLT science
- Technology exists to extend observations into daytime and wind measurements into lower mesosphere (Rayleigh)
- Technology also exists to obtain global temperature measurements throughout MLT (Fe/Rayleigh + HIAPER)
- New techniques and technologies are needed to extend observations into thermosphere