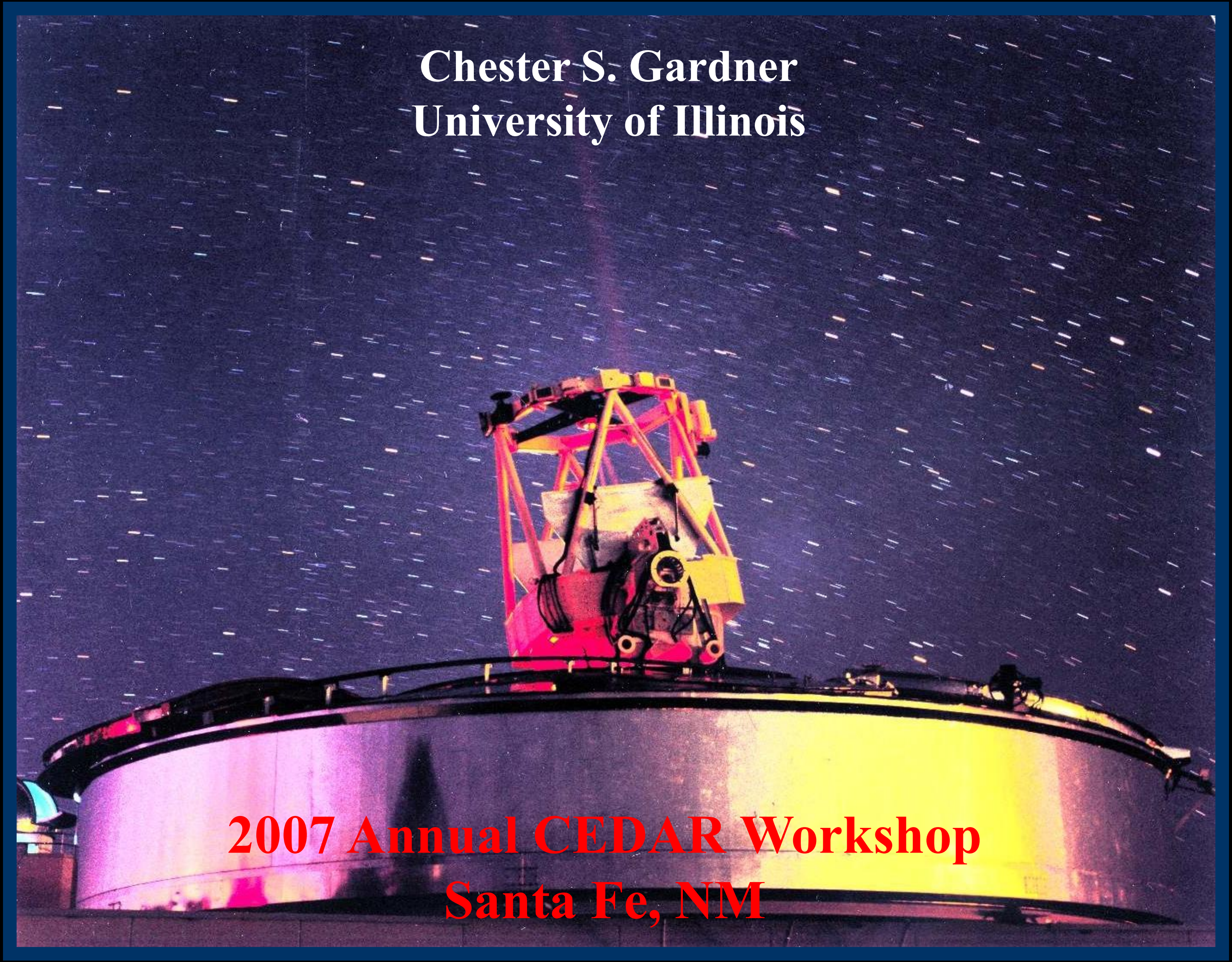
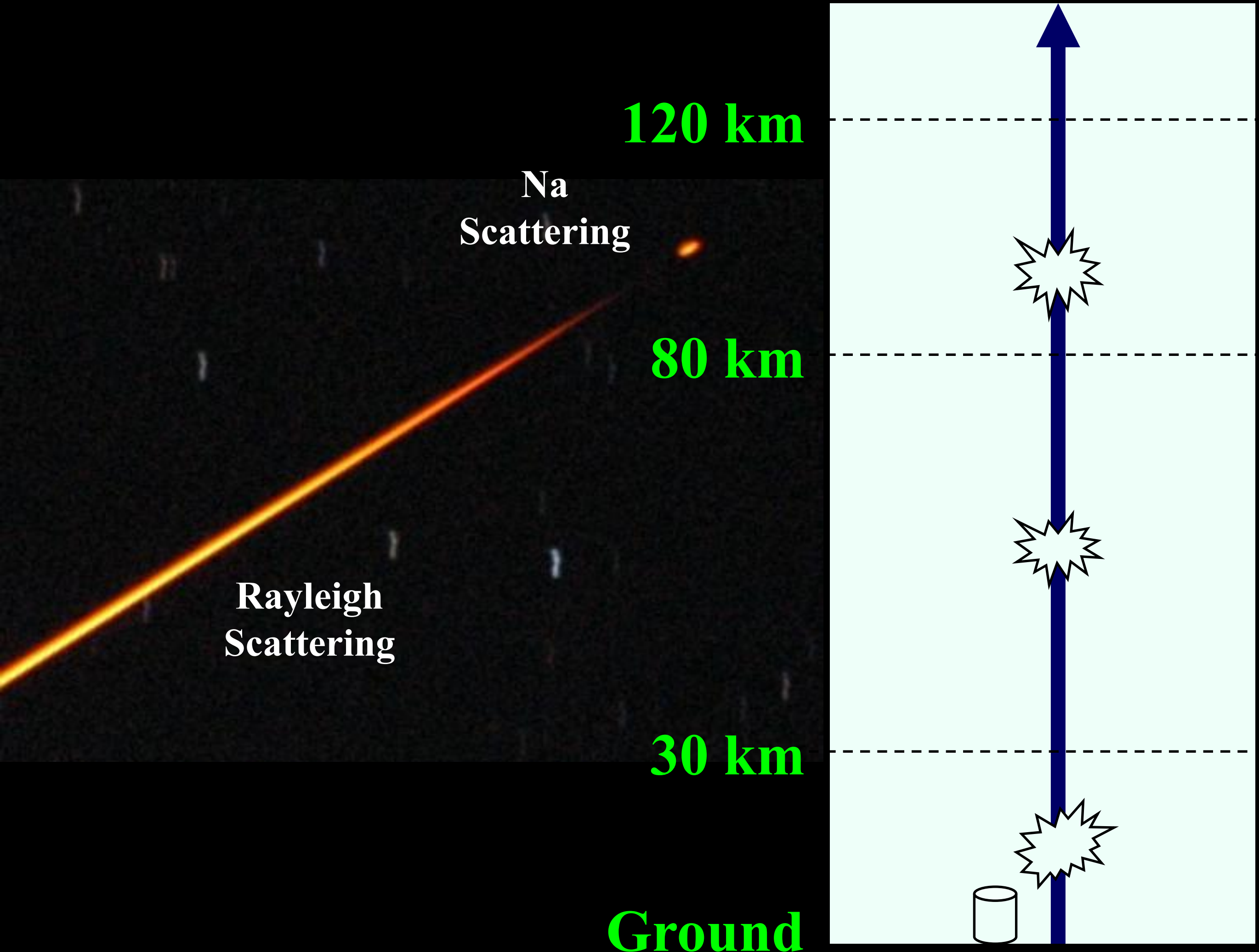
Measuring Middle Atmosphere Winds With Lasers



Chester S. Gardner
University of Illinois

2007 Annual CEDAR Workshop
Santa Fe, NM

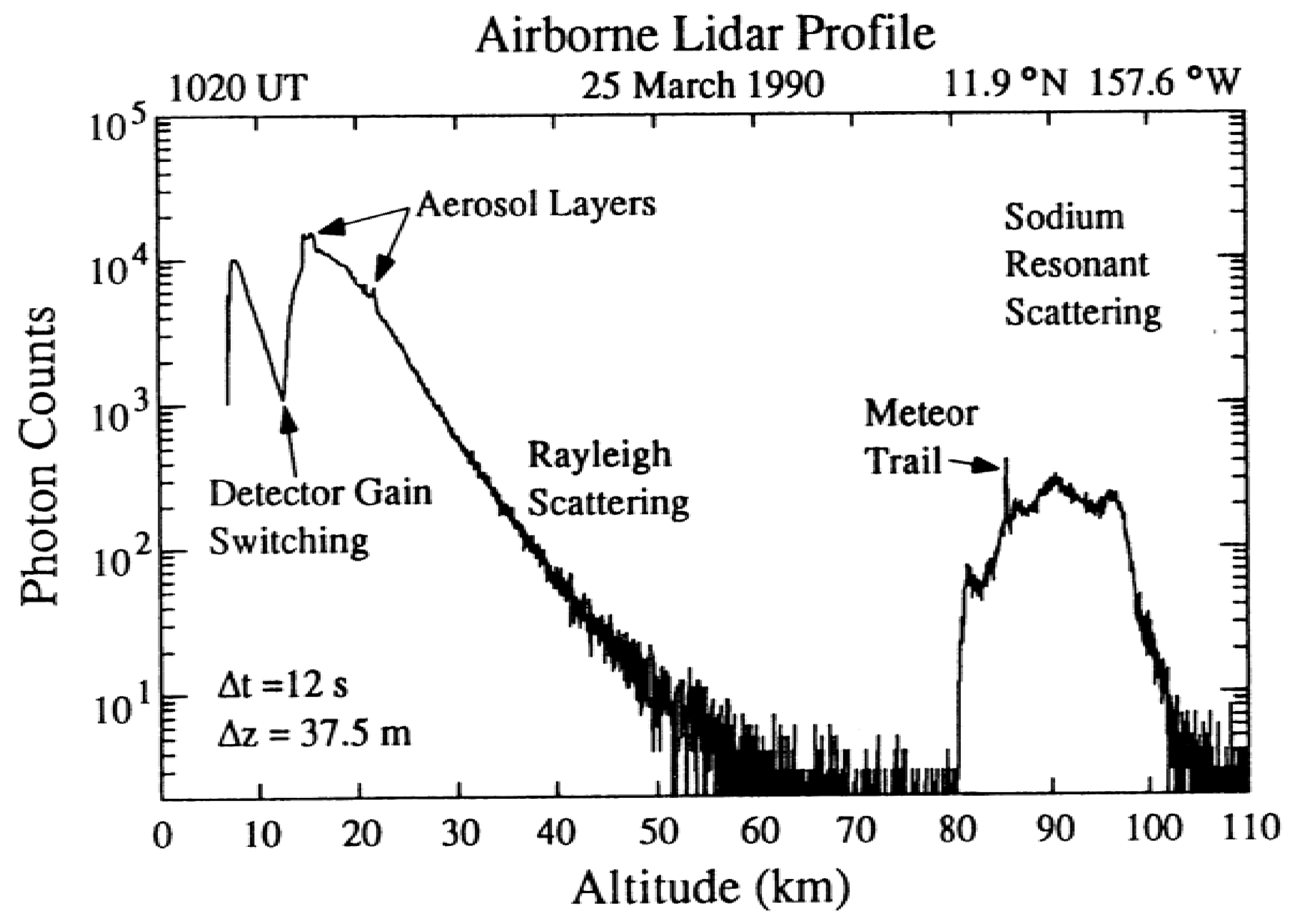
Light Detection and Ranging (LIDAR)



Resonant
Fluorescence
From Metal Atoms

Rayleigh Scattering
From Air Molecules

Mie Scattering
From Aerosols



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**

Rayleigh Scattering

If an atmospheric molecule (or particle) is illuminated by a laser beam of frequency f_L and wavelength λ_L, the Doppler shift is

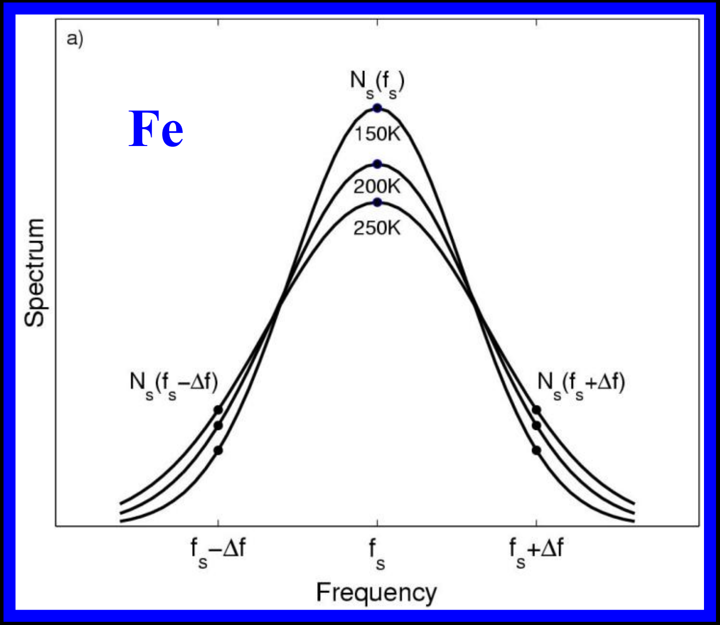
$$f_D = 2V_R/\lambda_L$$

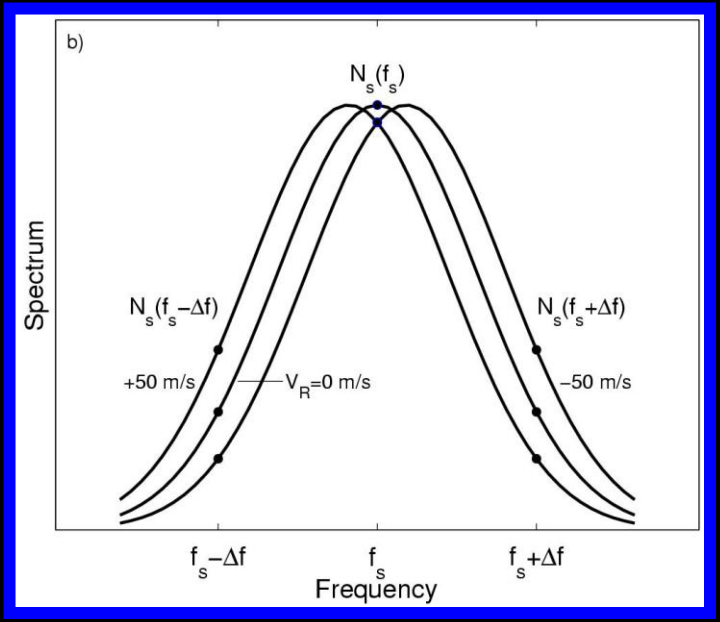
where V_R is the radial velocity of the particle.

Resonance Fluorescence Scattering

If the molecule emits light of frequency f_E and wavelength λ_E, the Doppler shift is

$$f_D = V_R/\lambda_E$$





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

$$Mean-Square\ \ Width\ \ \sigma_S^2=\frac{k_BT}{\lambda_S^2 m_S}\rightarrow\sigma_S\approx 33\sqrt{T}\,MHz=464\,MHz@200K\ \ \ for\ \ Fe$$

$$Temperature\ \ and\ \ Velocity\ \ Sensitivity$$

$$\frac{\partial\sigma_S}{\partial T}=\frac{\sigma_S}{2T}=1.2\,MHz/K=[0.25\%/K]\bullet\sigma_S \quad and \quad \frac{\partial f_D}{\partial V_R}=\frac{1}{\lambda_S}=1.7\,MHz/(m/s)=[0.37\%/(m/s)]\bullet\sigma_S$$

- **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)**

Rayleigh Scattering

$$Doppler\ \ Shift\ \ f_D = \frac{2V_R}{\lambda_L} \qquad Mean - Square\ \ Width\ \ \sigma_{Ray}^2 = \frac{4k_B T}{\lambda_L^2 m_{Atmos}}$$

$$\sigma_{Ray} \approx 64\sqrt{T}\, MHz = 905\, MHz\ \ @\ T = 200K\ \ and\ \ \lambda_L = 532\ \ nm$$

$$Temperature\ \ and\ \ Velocity\ \ Sensitivity$$

$$\frac{\partial \sigma_{Ray}}{\partial T} = \frac{\sigma_{Ray}}{2T} = 2.3\, MHz/K = [0.25\%/K] \bullet \sigma_{Ray}$$

$$\frac{\partial f_D}{\partial V_R} = \frac{2}{\lambda_L} = 3.8\, MHz/(m/s) = [0.42\%/(m/s)] \bullet \sigma_{Ray}$$

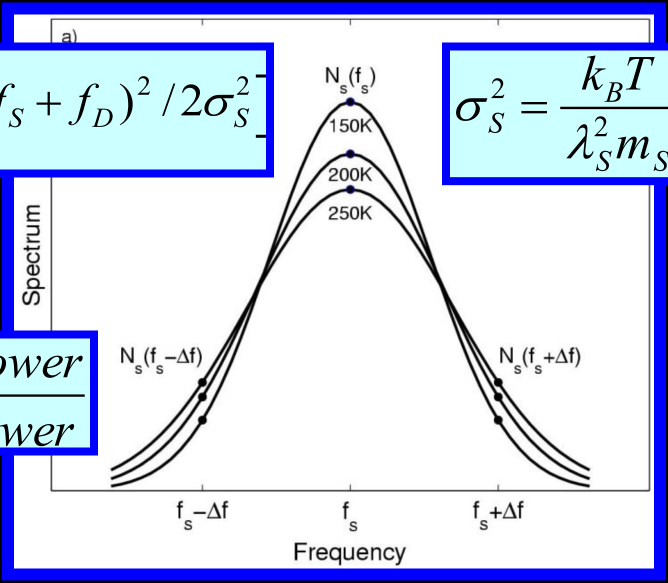
Although the temperature and velocity sensitivity for Rayleigh scattering is about double that for resonance fluorescence, because the backscattered linewidth is also about double, the measurement accuracies are comparable for comparable SNRs.

Signal Processing

Temperature and Winds can be measured by:

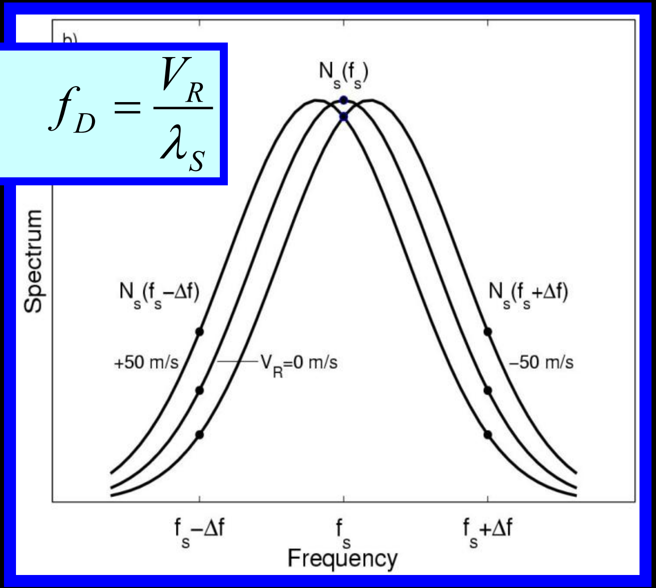
1) **Measuring full spectrum of backscattered signal (RF & Ray)**
2) **Scanning laser through full fluorescence spectrum and measuring backscattered signal at each frequency (RF only)**
3) **Probing fluorescence spectrum with laser at 3-frequencies and measuring backscattered signal at each frequency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

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



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

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



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

$$\hat{V}_R = -\frac{\lambda_S}{N_S}\sum_{i=1}^{N_S}(f_i - f_S) \qquad \Delta\hat{V}_R = \frac{\lambda_S\sigma_S}{\sqrt{N_S}} = \frac{173m/s}{\sqrt{SNR}} \rightarrow SNR = 30{,}000 = 45dB \ \ for \ \ Fe$$

$$\hat{T} = \frac{\lambda_S^2 m_S}{k_B N_S}\sum_{i=1}^{N_S}(f_i - f_S + \hat{V}_R / \lambda_S)^2 \qquad \Delta\hat{T} = \frac{\sqrt{2}T}{\sqrt{N_S}} = \frac{283K}{\sqrt{SNR}} \rightarrow SNR = 80{,}000 = 49dB$$

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

Optimized 3-Frequency Resonance Fluorescence Lidar

Laser probes fluorescence line at three frequencies (f_S and $f_S \pm \Delta f$)

Dwell time at each frequency and offset Δf~600 MHz are both chosen to minimize error

Optimization different for temperature and wind and for day and night observations

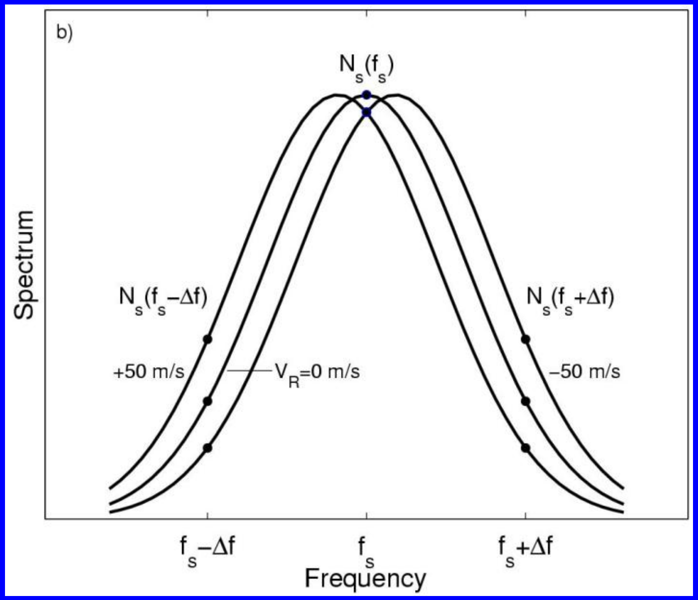
$$R_T = \frac{N_S^2(f_S)}{N_S(f_S+\Delta f)N_S(f_S-\Delta f)} = \exp\left(\Delta f^2/\sigma_S^2\right) = \exp\left(\Delta f^2/\gamma T\right)$$

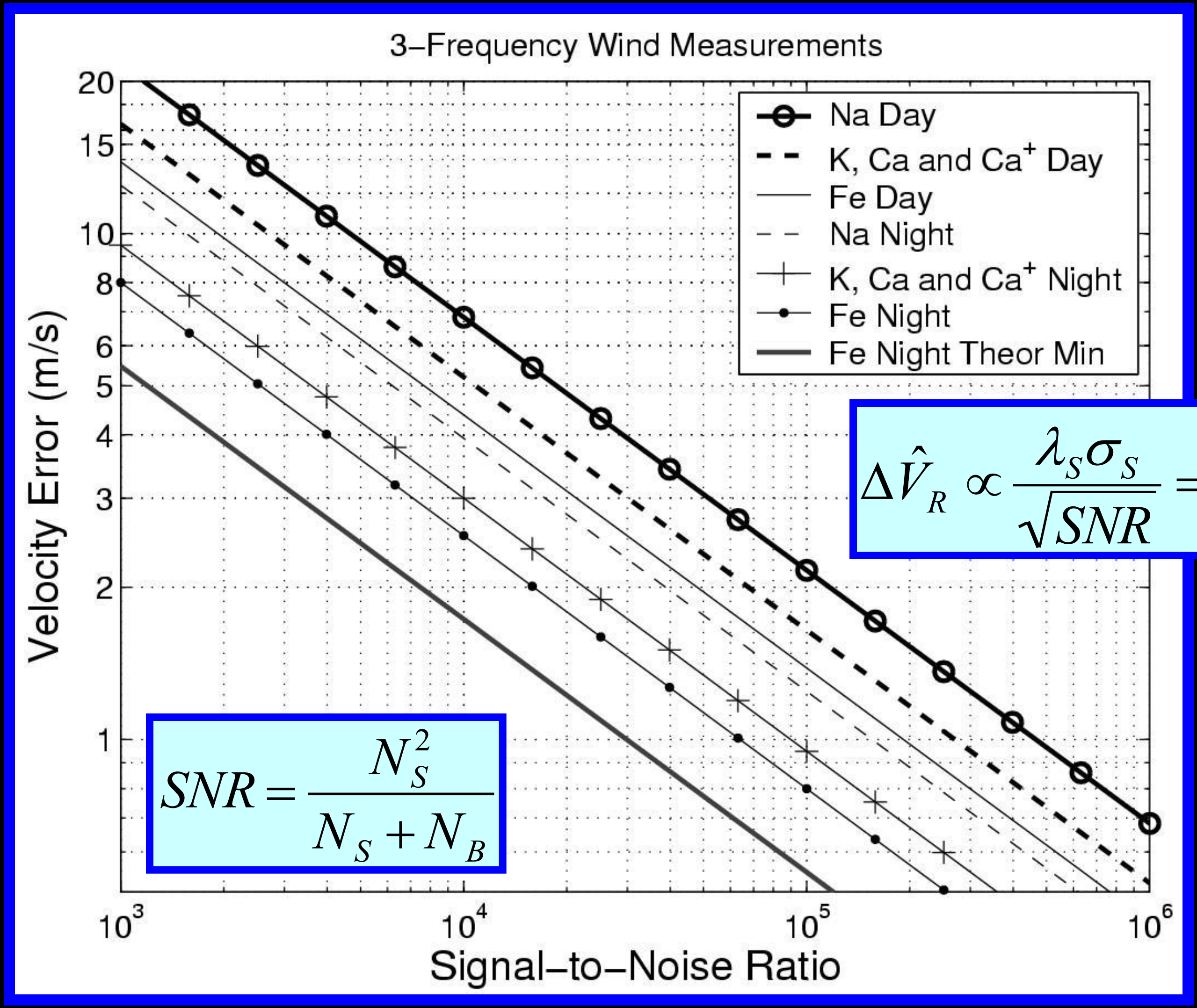
$$R_V = \frac{N_S(f_S-\Delta f)}{N_S(f_S+\Delta f)} = \exp\left(\frac{2\Delta f}{\lambda_S\sigma_S^2}V_R\right) \qquad V_R = \frac{\lambda_S\Delta f}{2}\frac{\ln(R_V)}{\ln(R_T)}$$

[*Gardner*, *Applied Optics*, 2004]

Rayleigh Lidar

3 narrowband filters centered at f_S and $f_S \pm \Delta f$ can be used to process Rayleigh scattered signals. Filter bandwidths and offset frequency Δf are chosen to minimize error.





3–Frequency Wind Measurements

$$\Delta \hat{V}_R \propto \frac{\lambda_S \sigma_S}{\sqrt{SNR}} = \frac{\sqrt{k_B T / m_S}}{\sqrt{SNR}}$$

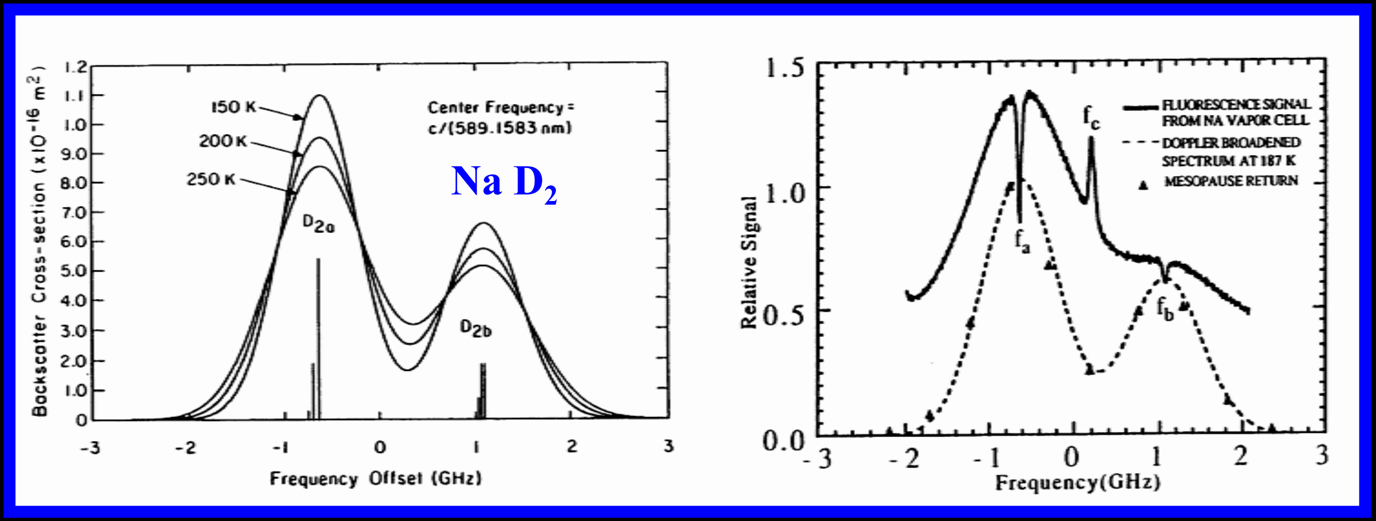
$$SNR = \frac{N_S^2}{N_S + N_B}$$

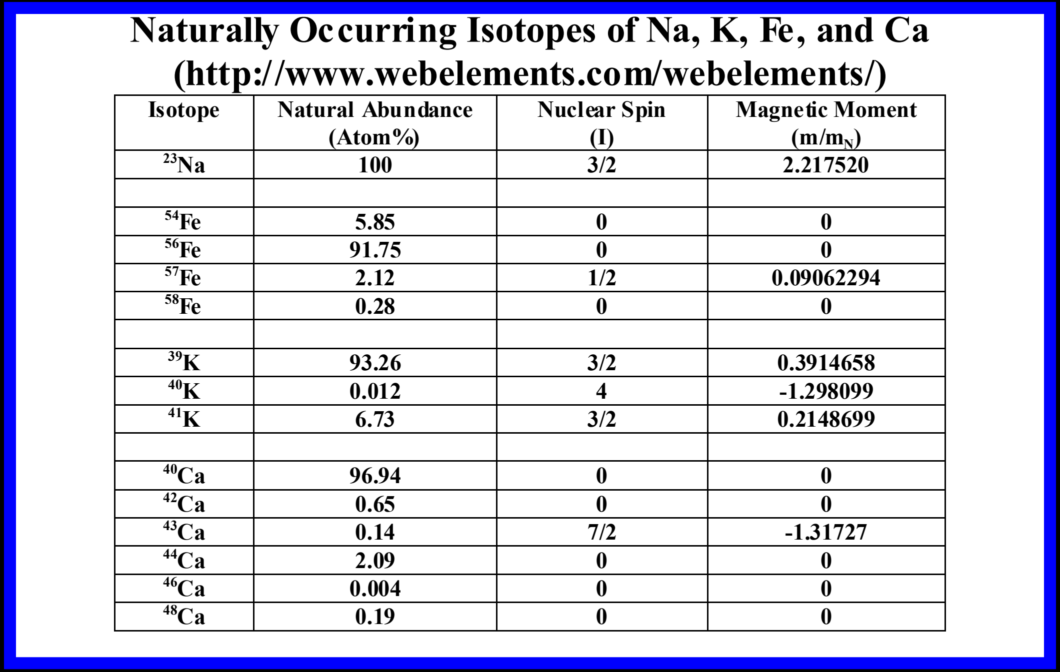
Fe lidar has smallest error because Fe is heaviest atom

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~ 64,000= 48 dB @ Night and SNR~ 130,000 = 51 dB @ Day

Hyperfine Lines and Isotopes

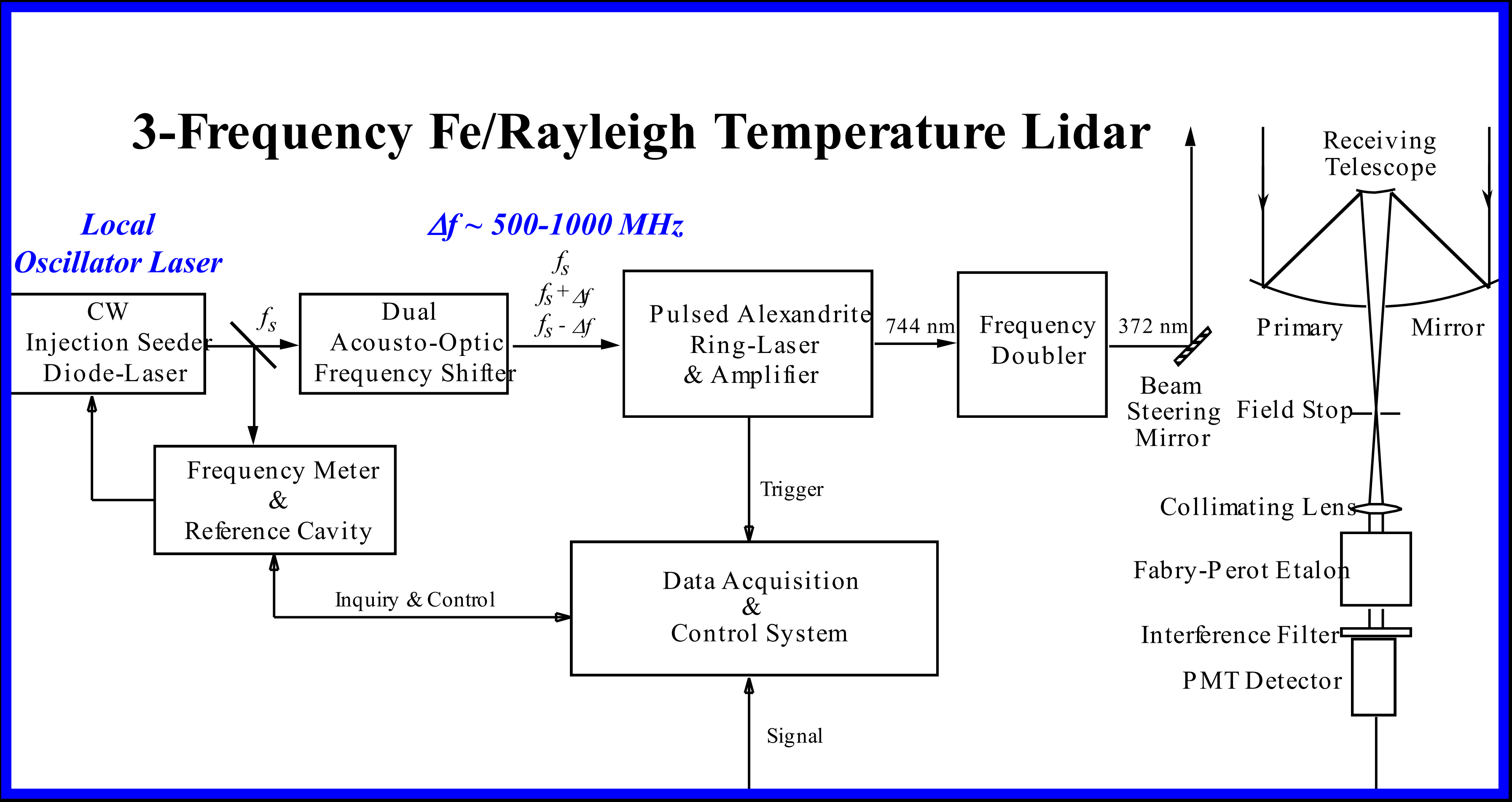




Naturally Occurring Isotopes of Na, K, Fe, and Ca (http://www.webelements.com/webelements/)

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



3-Frequency Fe/Rayleigh Temperature Lidar

Local Oscillator Laser

Δf ~ 500-1000 MHz

CW
Injection Seeder
Diode-Laser

f_s

Dual
Acousto-Optic
Frequency Shifter

f_s
$f_s + \Delta f$
$f_s - \Delta f$

Pulsed Alexandrite
Ring-Laser
& Amplifier

744 nm

Frequency
Doubler

372 nm

Beam
Steering
Mirror

Receiving
Telescope

Primary Mirror

Field Stop

Collimating Lens

Fabry-Perot Etalon

Interference Filter

PMT Detector

Frequency Meter
&
Reference Cavity

Trigger

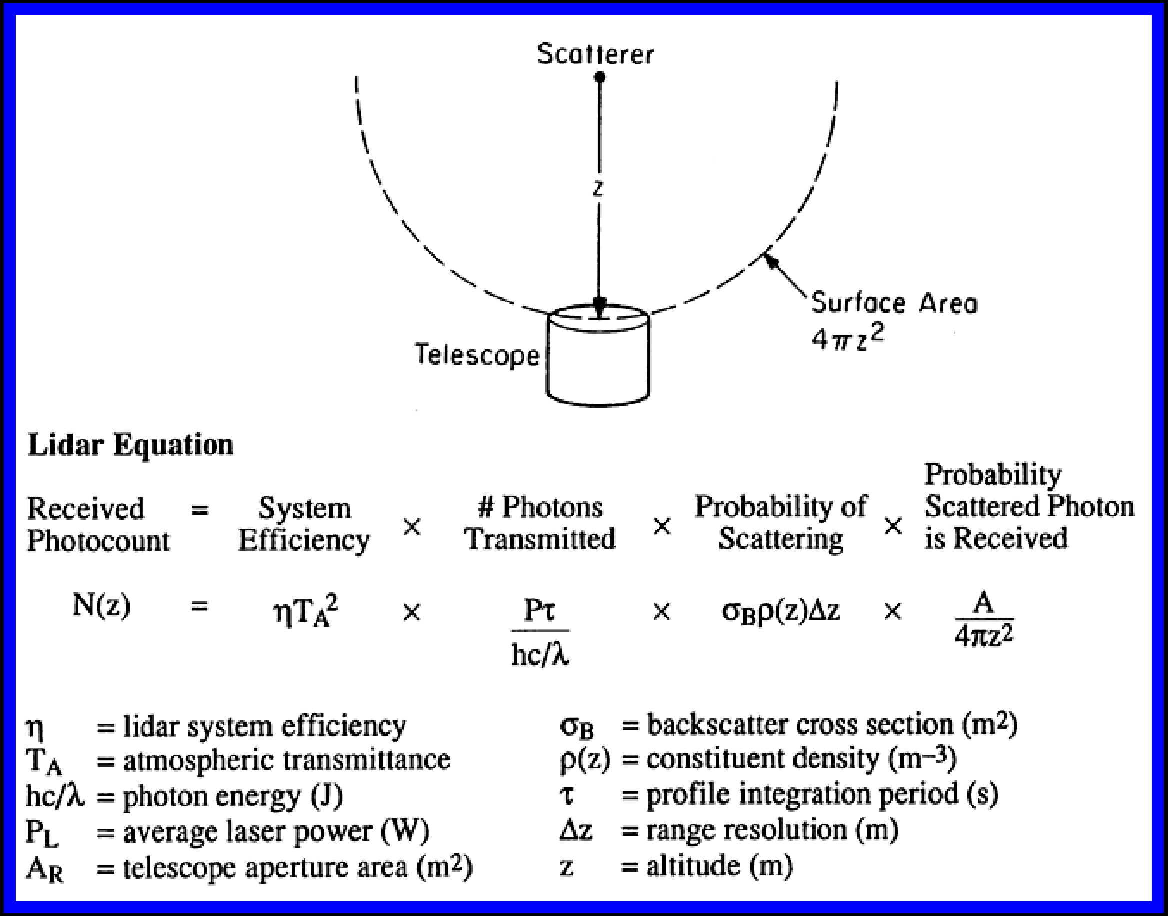
Inquiry & Control

Data Acquisition
&
Control System

Signal

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

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

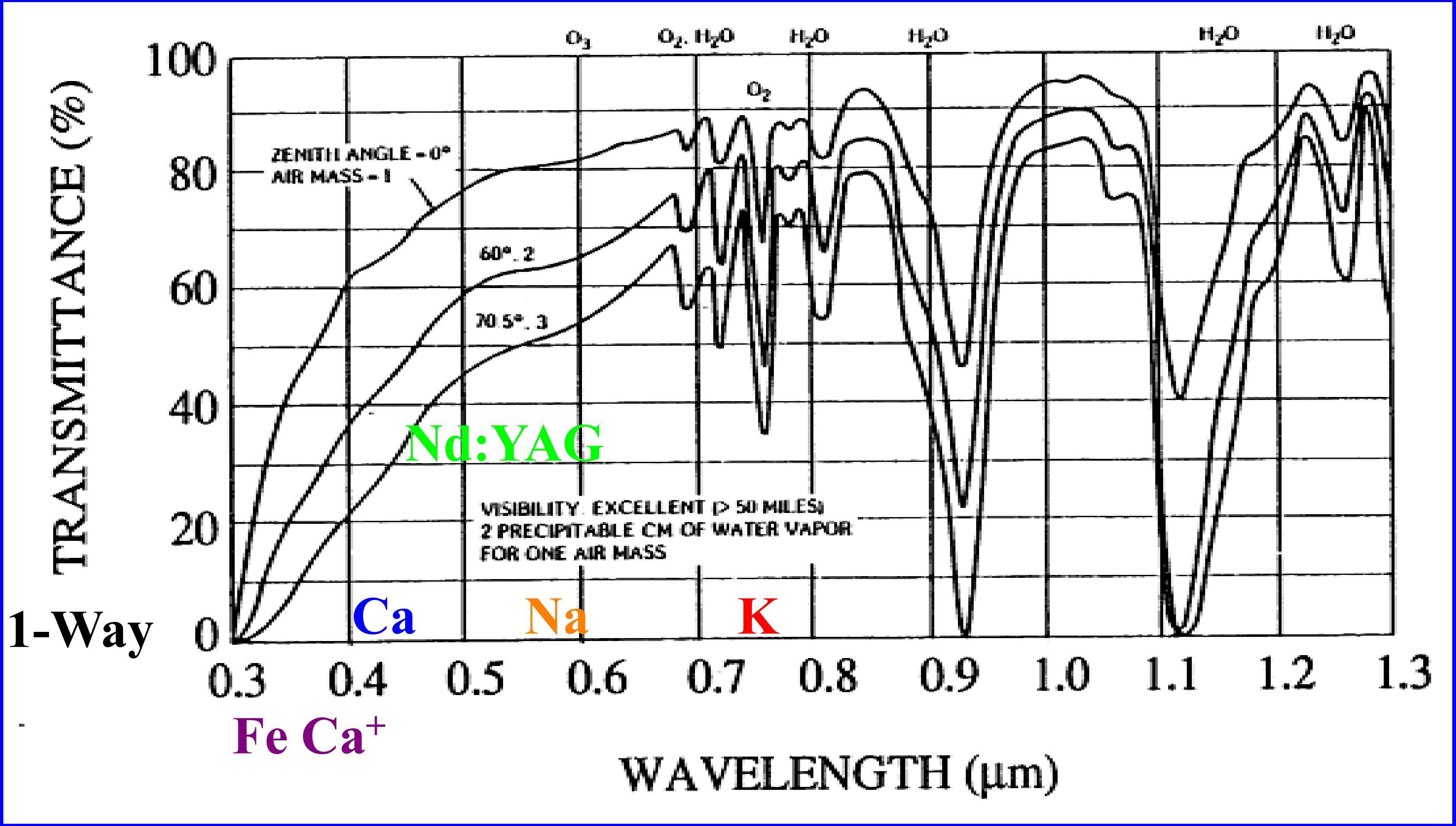
Backscatter Parameters

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}	7.1×10^{13}	90.0	0.0054
Rayleigh	532.070	7.6×10^{-15}	6.4×10^{15}	60.0	0.49
Rayleigh	532.070	7.6×10^{-15}	3.8×10^{17}	30.0	29

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

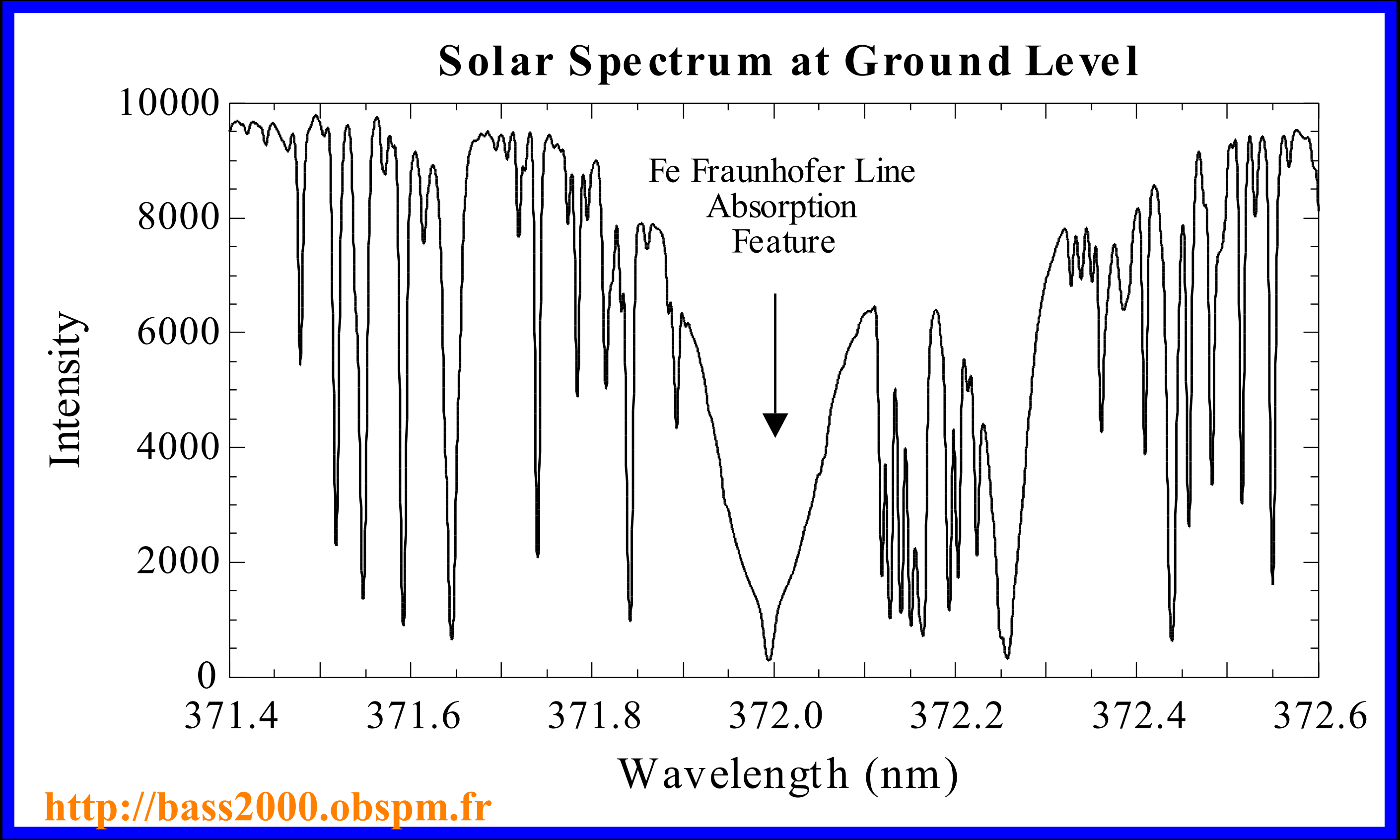
$$N_S(z) \propto (PA\Delta z\Delta t)[T_A^2\sigma_B\rho_S(z)]$$

Atmospheric Transmittance



Atmospheric attenuation decreases with increasing altitude

Sky Brightness and Background Noise



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

Sky brightness decreases with increasing altitude

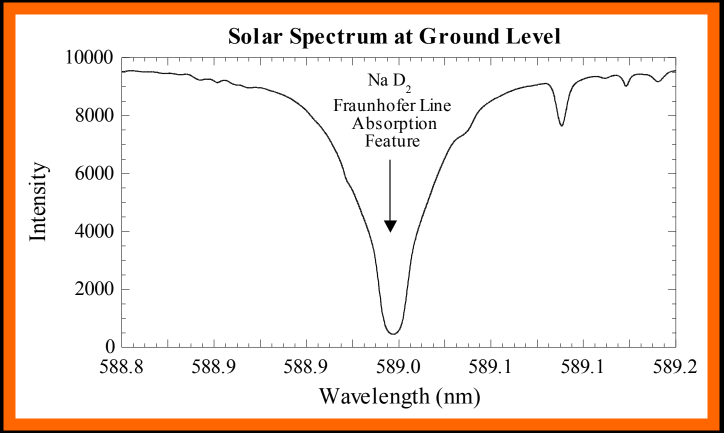
Atmospheric Parameters

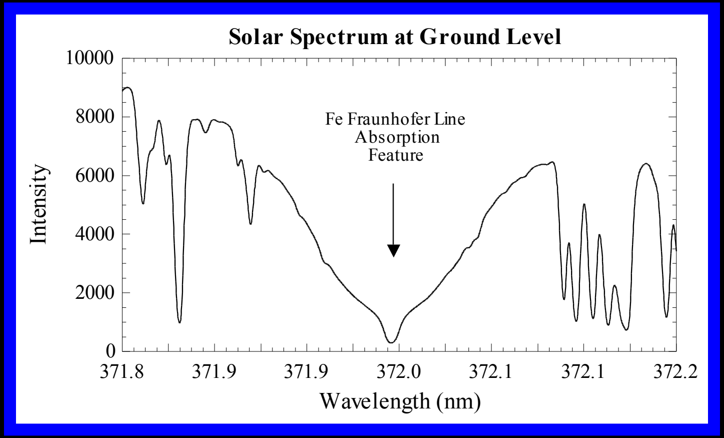
Species or Laser	λ_S (nm)	2-Way Atmospheric Transmittance T_A^2	Sky Spectral Radiance Continuum[1] (10^{-3} W/m^2/nm/sr)	Fraunhofer Line Relative Depth[2] (% Continuum)	Fraunhofer Linewidth[3] (GHz)	Narrowband Sky Spectral Radiance[1,4] (10^{-3} W/m^2/nm/sr)
Na	588.995	0.49	86.3	9.6	14.5	8.28
Fe	371.994	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

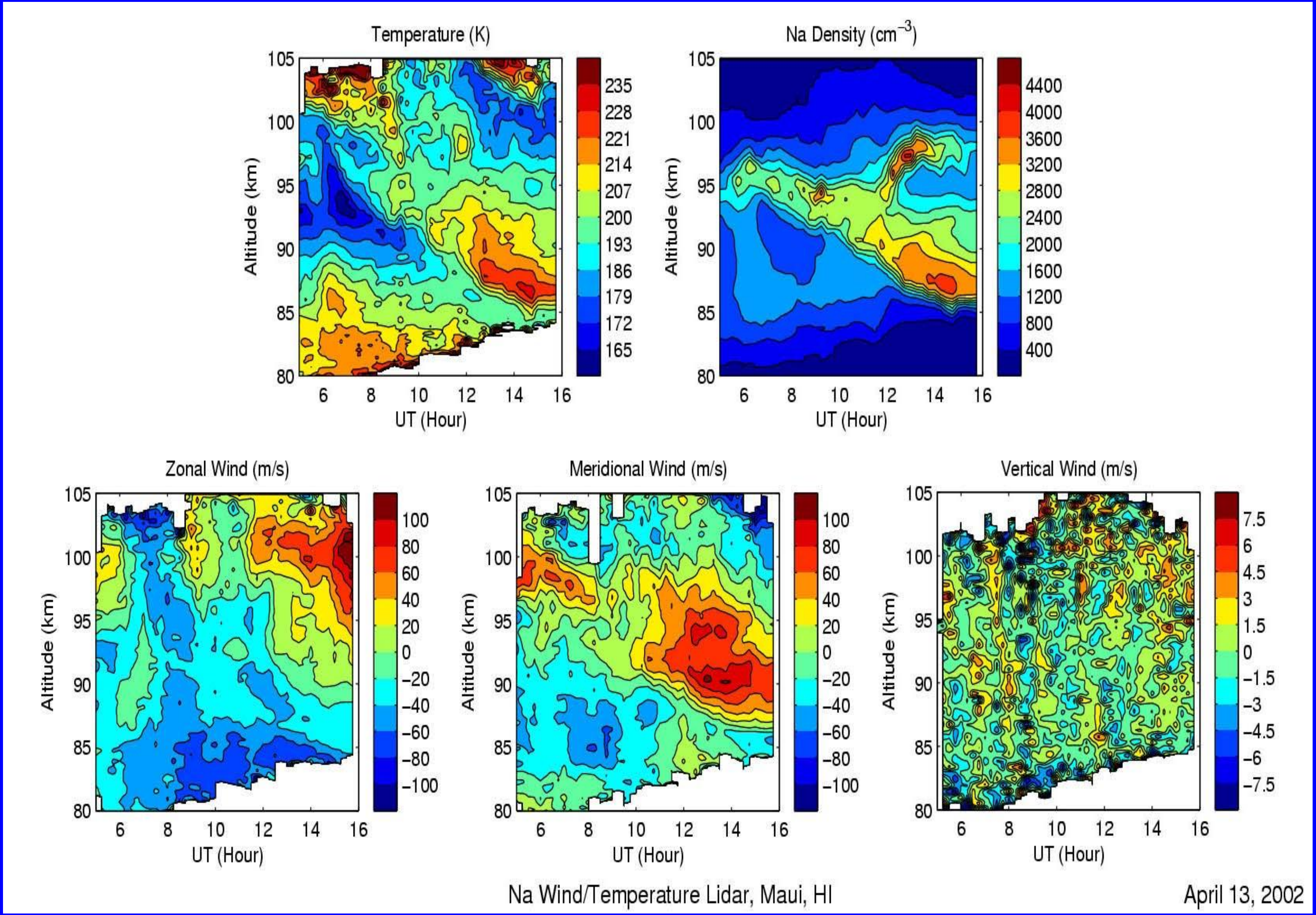
[2] Includes 5% Ring effect for all lines, [3] Full width @ twice depth

[4] Receiver bandwidth much smaller than Fraunhofer linewidth





Maui:MALT Na Lidar @ Haleakala, HI


Temperature (K)

Na Density (cm^{-3})

Zonal Wind (m/s)

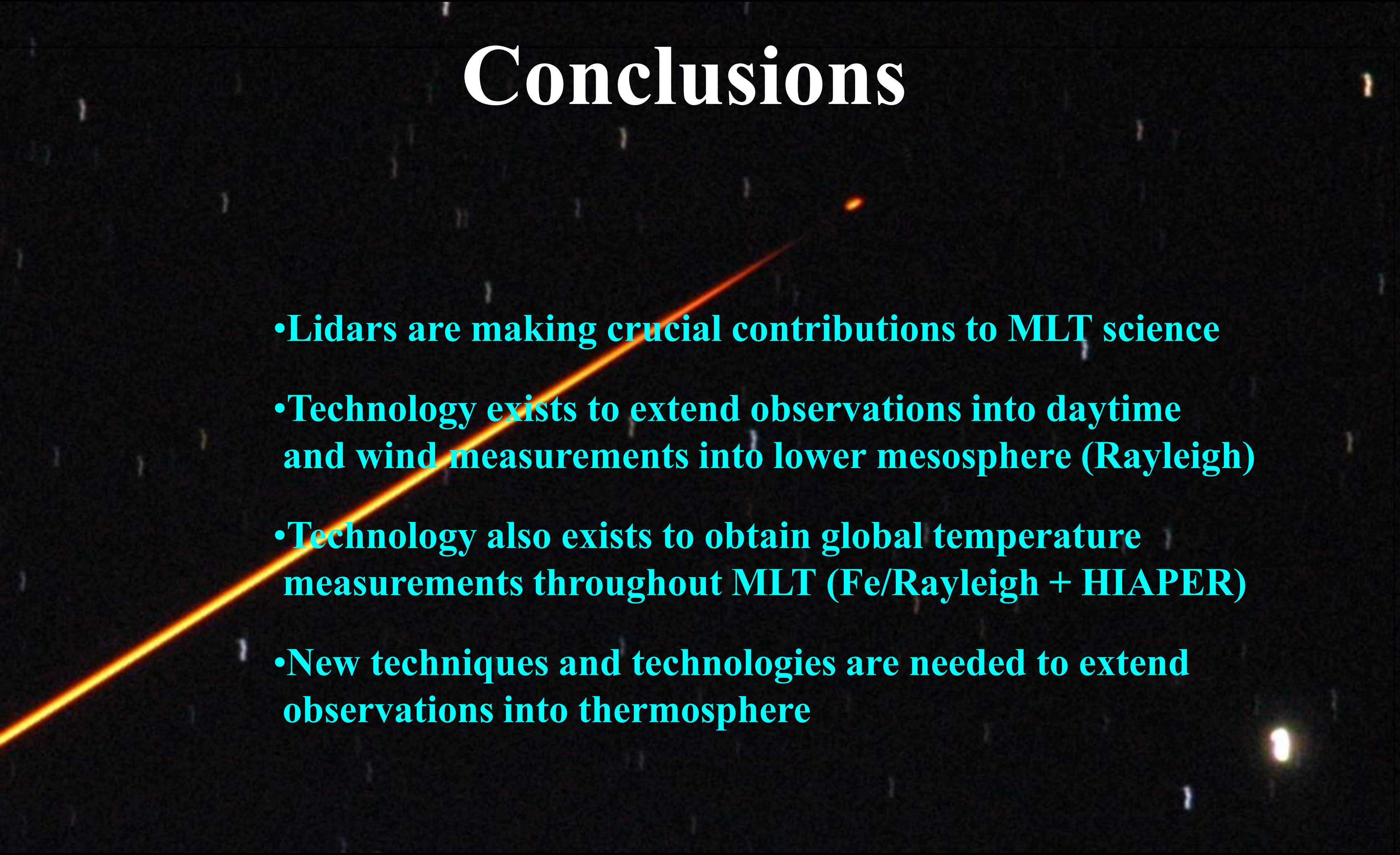
Meridional Wind (m/s)

Vertical Wind (m/s)

Na Wind/Temperature Lidar, Maui, HI

April 13, 2002

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