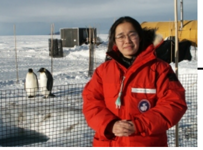


Lecture 27. Wind Lidar New Development & Resonance DDL

- Multi-Frequency Edge-Filter DDL

-- Na-DEMOF and I_2 Filter-based

- New Developments of DDL Using Optical Interferometer

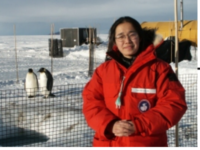
-- Optical Auto-covariance Wind Lidar (OAWL)

- Resonance DDL

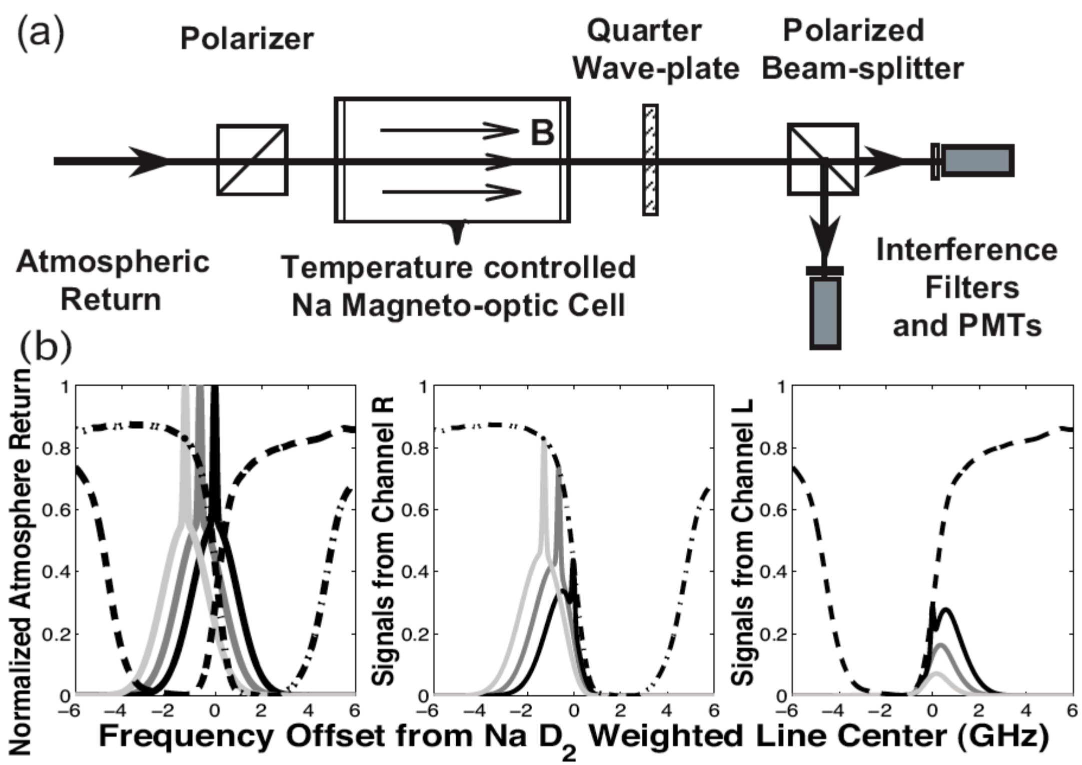
-- Na, Fe, and K Doppler Lidars

- Comparison of Wind Techniques

- Summary



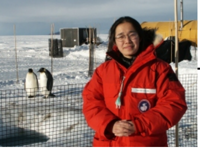
Na/K Double-Edge Magneto-Optic Filter DDL



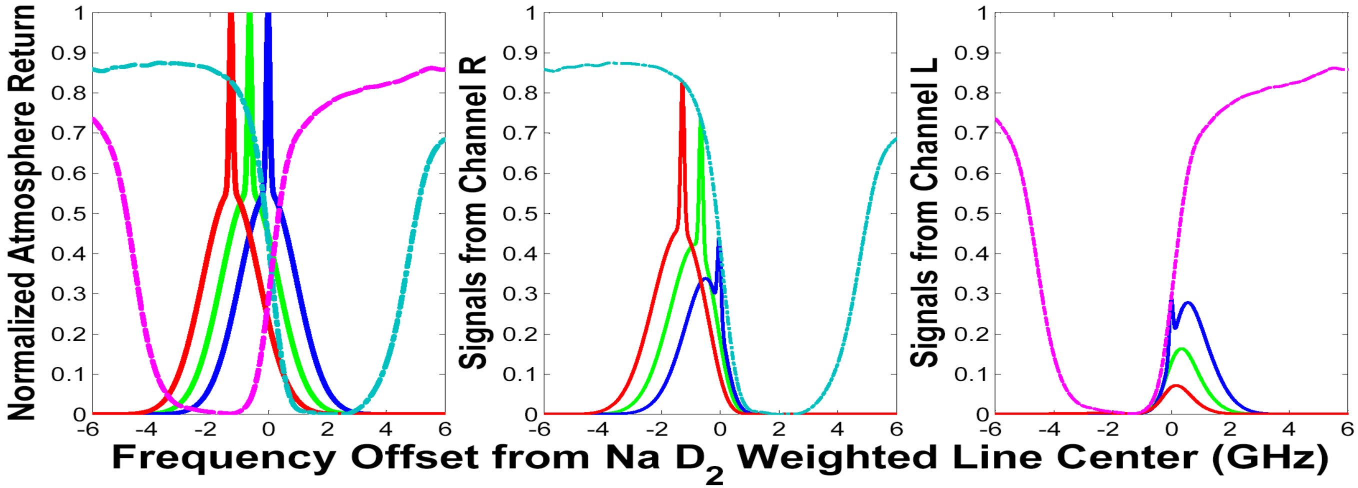
Na Double-Edge Magneto-Optic Filter (Na-DEMOF)

- With a 3-freq Na or K Doppler lidar, it is possible to measure wind, temperature, and aerosol simultaneously with a Na-DEMOF or K-DEMOF.

[Huang, Chu, Williams, et al., Optics Letters, 34, pp.199, 2009]



DEMOF with a 3-freq Na Doppler Lidar

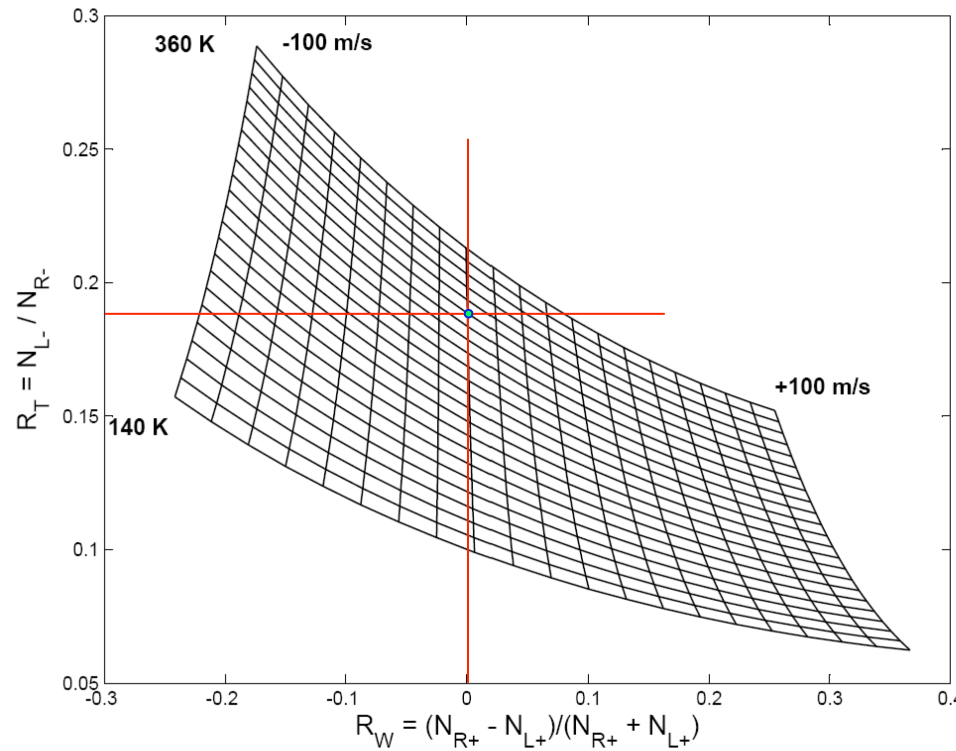


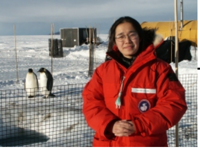
Calibration curves for ratio technique with Na-DEMOF

$$R_W(V_{LOS},T,R_b) = \frac{N_{R+} - N_{L+}}{N_{R+} + N_{L+}}$$

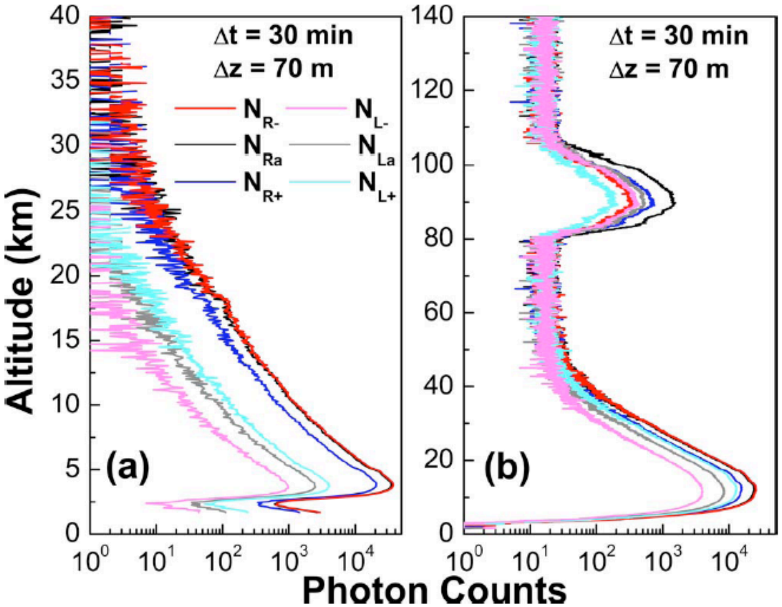
$$R_T(V_{LOS},T,R_b) = \frac{N_{L-}}{N_{R-}}$$

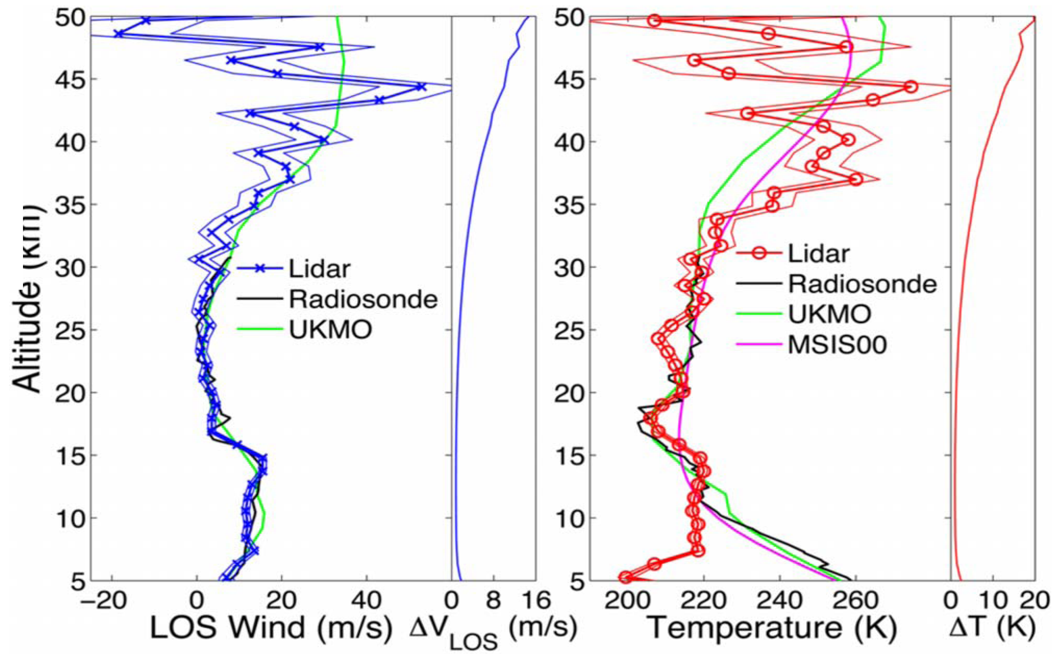
- Temperature and wind are determined simultaneously from two ratios.



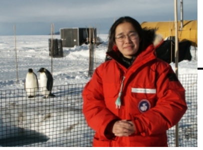


Field Demonstration of Simultaneous Wind and Temperature Measurements (10-45 km) with Na-DEMOF and 3-Frequency Na Lidar





[Huang, Chu, et al., Optics Letters, 34, pp. 1552, 2009]



Doppler Rayleigh Iodine Spectrometer-Based Doppler Rayleigh/Mie/Raman Lidar to Profile Wind and Temperature up to 80 km

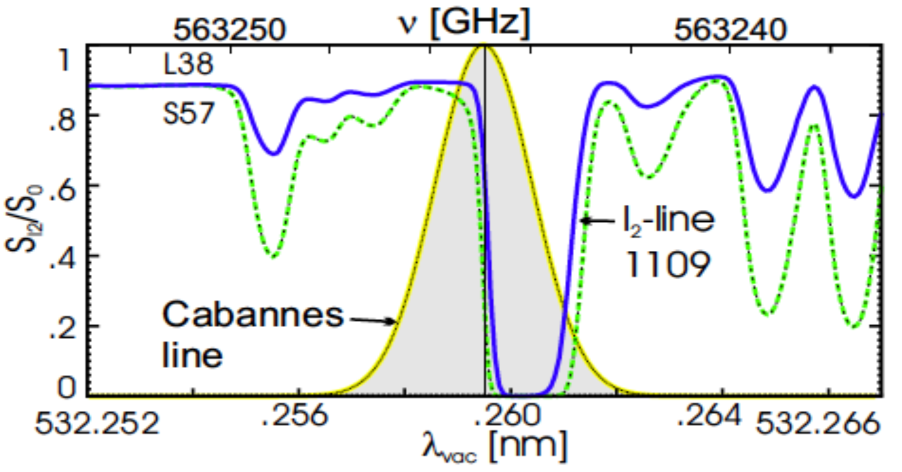
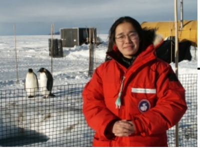


Fig. 2. Measured transmission spectrum of iodine for two cells of different length at different temperatures: 38 °C (blue L38: 15 cm long), 57 °C (green S57: 10 cm long). For reference, the Doppler broadened Cabannes line for 230 K is shown. The wavelength of the seed laser is indicated by a dotted vertical line.

Currently the data retrieval is for molecular scattering (Rayleigh) only, but since rotational and vibrational Raman as well as multiple wavelength aerosol scatterings are also detected, in principle aerosol and temperature information can be derived, so can be used to derive Doppler wind more precisely in the aerosol-loaded regions.

[Baumgarten, Atmos. Meas. Tech., 3, 1509-1518, 2010]



Doppler Rayleigh Iodine Spectrometer-Based Doppler Rayleigh/Mie/Raman Lidar to Profile Wind and Temperature up to 80 km

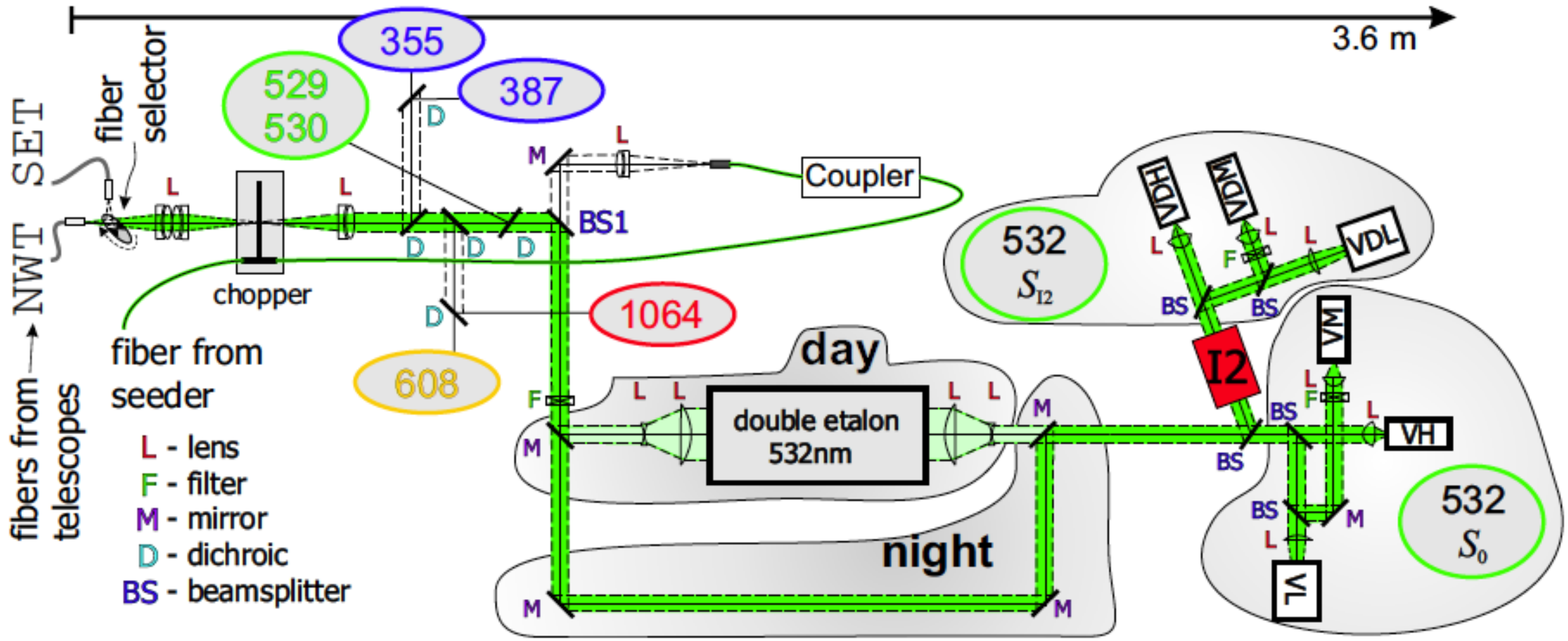
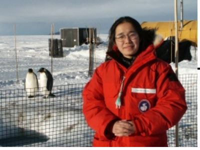


Fig. 4. Polychromatic detection system of the ALOMAR RMR lidar with emphasis on 532 nm channels. Light from the telescopes (NWT or SET) is split by wavelength and intensity. Light for the DoRIS system is detected by the channel groups 532-S_0 and 532-S_{I_2}. The system can be operated during day using a double etalon system (bandpass ~4 pm).

[Baumgarten, Atmos. Meas. Tech., 3, 1509–1518, 2010]



Doppler Rayleigh Iodine Spectrometer-Based Doppler Rayleigh/Mie/Raman Lidar to Profile Wind and Temperature up to 80 km

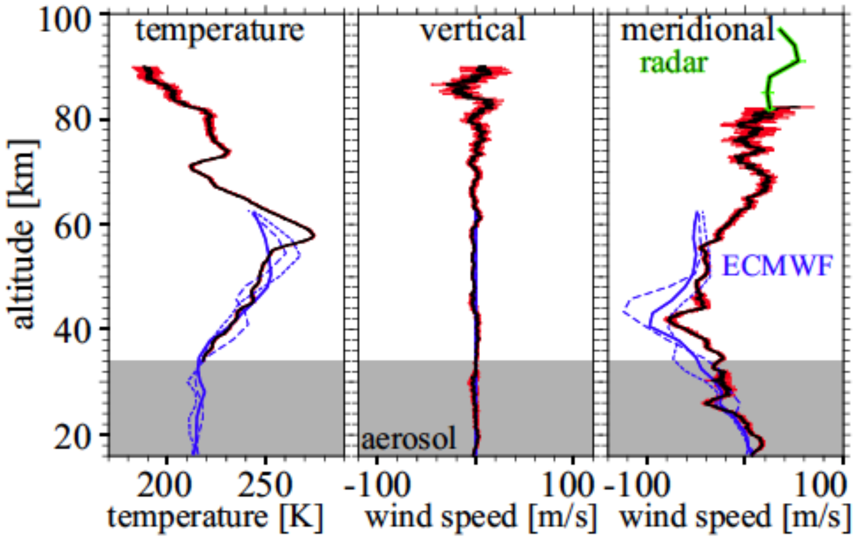


Fig. 9. Temperature, vertical and meridional wind on 17 January 2009 between 17:00 and 19:00 UT. ECMWF data from 18:00 UT (solid) and 12:00, 24:00 UT (dashed) are shown. Simultaneous observations by the collocated Meteor radar are shown. The gray area indicates altitudes with aerosol contribution as measured by the lidar.

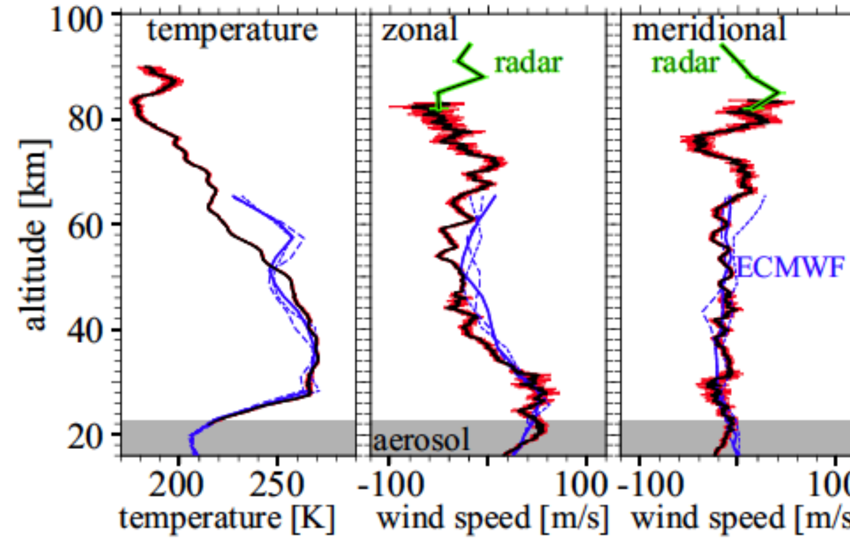
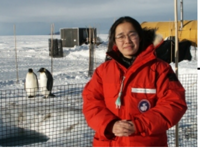


Fig. 10. Temperature and horizontal wind on 23 January 2009 be-

Temperatures are derived from the integration technique combining Rayleigh and VR Raman scatterings.

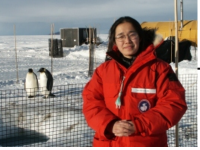
$\Delta t = 2$ h, ΔV_{LOS} = 0.6 m/s @ 49 km, 10 m/s @ 80 km
P_L = 14 W @ 532 nm, $D_{telescope}$ = 1.8 m

[Baumgarten, Atmos. Meas. Tech., 3, 1509-1518, 2010]



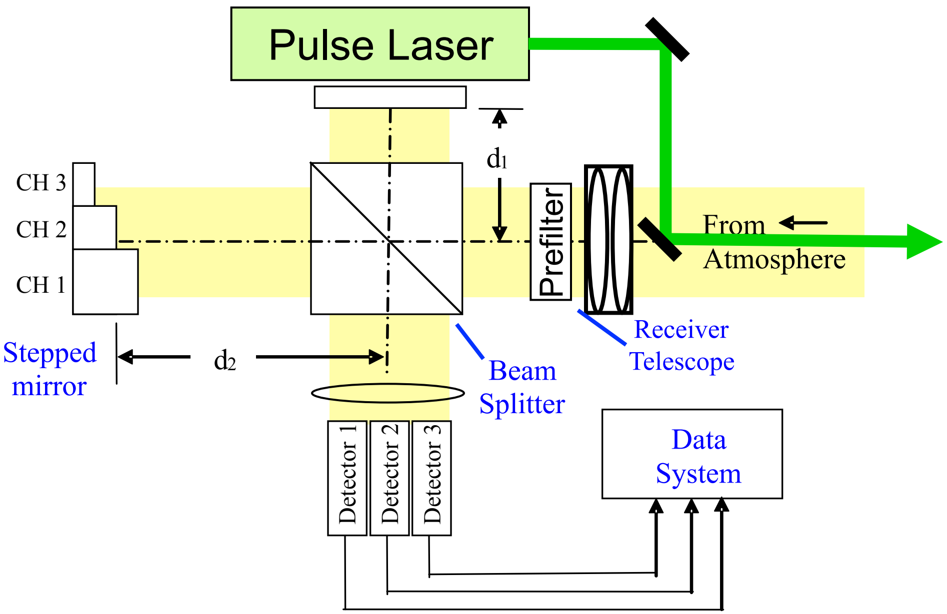
Considerations for DDL

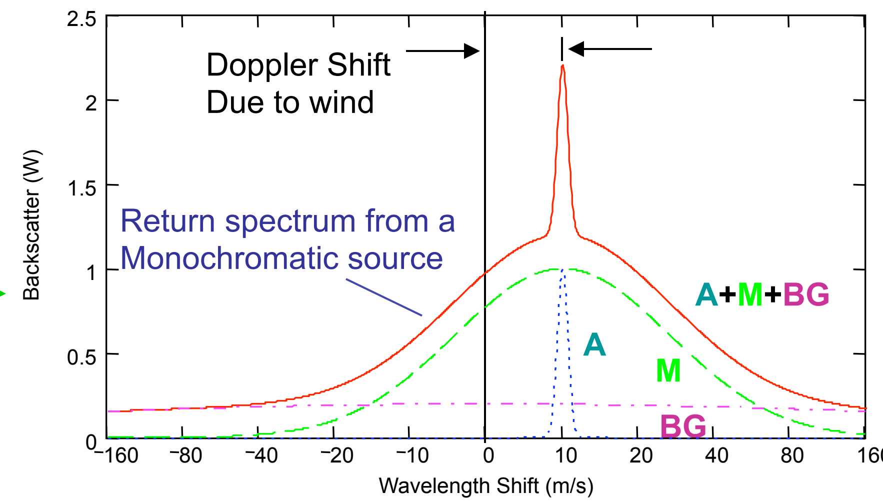
- Multiple-frequency edge-filter-based DDL provides a new idea of measuring wind and temperature simultaneously with DDL.
- The combination of Rayleigh Doppler wind with Rayleigh integration temperature provides another idea of measuring wind and temperature simultaneous with DDL.
- Adding Raman channels (both vibrational-rotational and pure-rotational) and independent aerosol channels will help to retrieval aerosol information (β and α), so enabling the wind retrieval in the aerosol-loaded regions.
- Comparing to Na or K-DEMOF, the advantage of iodine filter is the availability of high-power laser at 532 nm. By integrating our multiple-frequency idea formed from Na-DEMOF investigation to the iodine-filter lidar, it may be even more powerful.
- Nevertheless, all edge-filter DDLs suffer significant signal loss. This is because the peak of the return signals is cut or attenuated in order to have sufficiently high sensitivity to wind. That's why people look into other possibilities to do DDL.

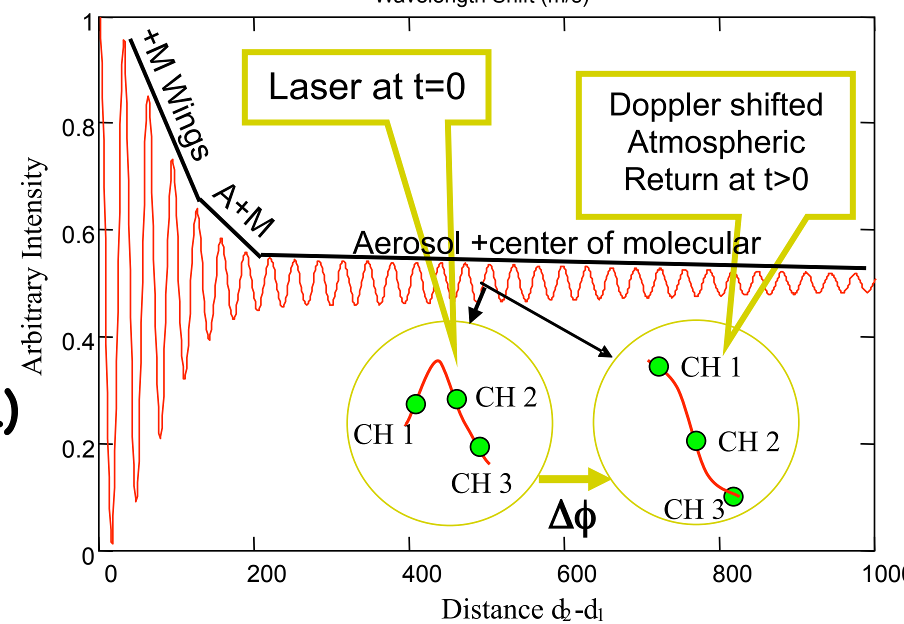


New Development of DDL Recently

- Michelson interferometer-based DDL by Ball Aerospace







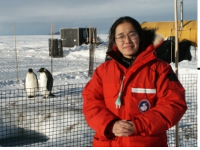
$$V_{LOS} = \lambda * \Delta\phi * c / (4 * (d_2 - d_1))$$

Measured as a fraction

Optical Autocovariance Wind Lidar (OAWL)

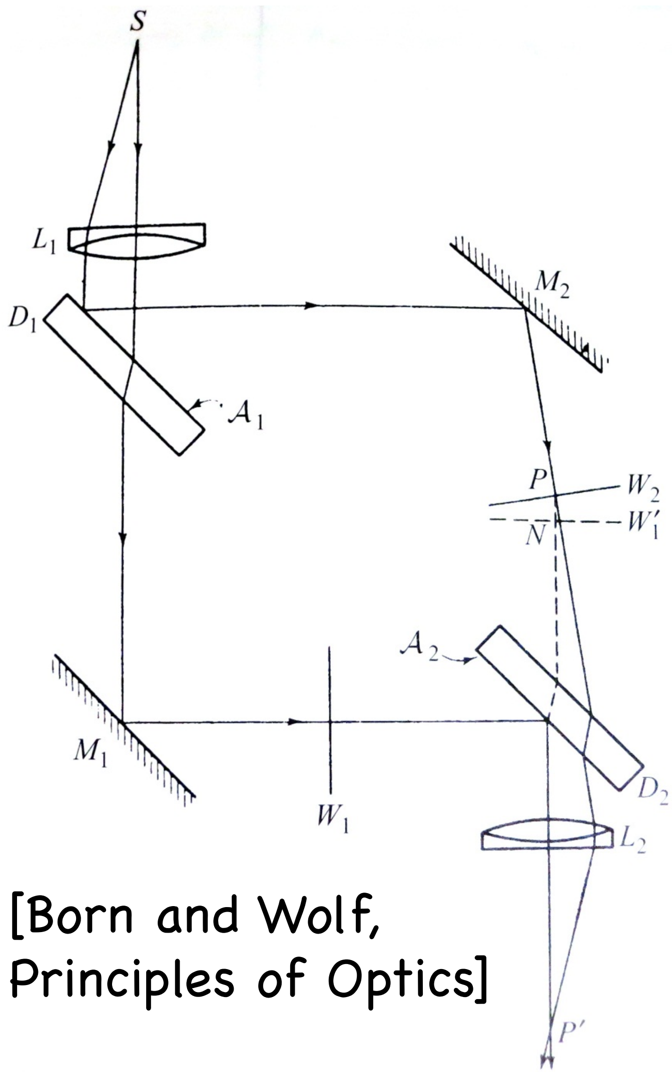
By Christian J. Grund et al., ILRC, 2008

Conceptualized by Grund, Tucker, et al.



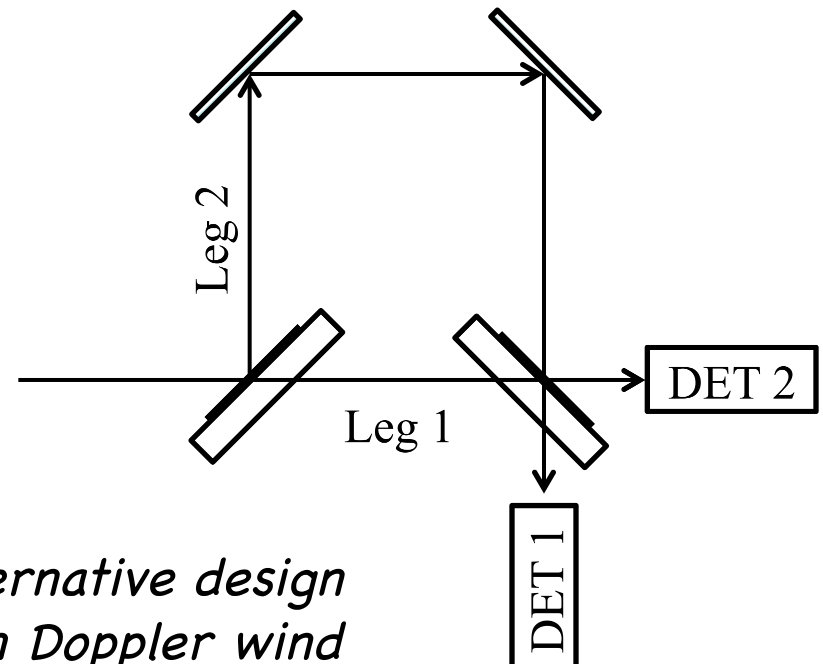
New Development of DDL Recently

- Mach-Zehnder interferometer-based DDL by John A. Smith (UCB)

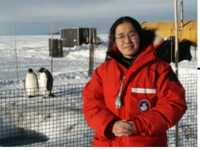


[Born and Wolf, Principles of Optics]

A Mach-Zehnder interferometer (MZI) consists of two (usually 50/50) beam splitters and two high reflectance mirrors in a fixed geometry. The optical path difference between each leg is related to the free spectral range and therefore analogous to the spacing of an etalon.



An alternative design used in Doppler wind lidars

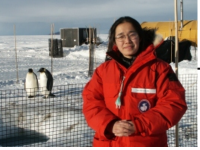


Resonance Fluorescence DDL

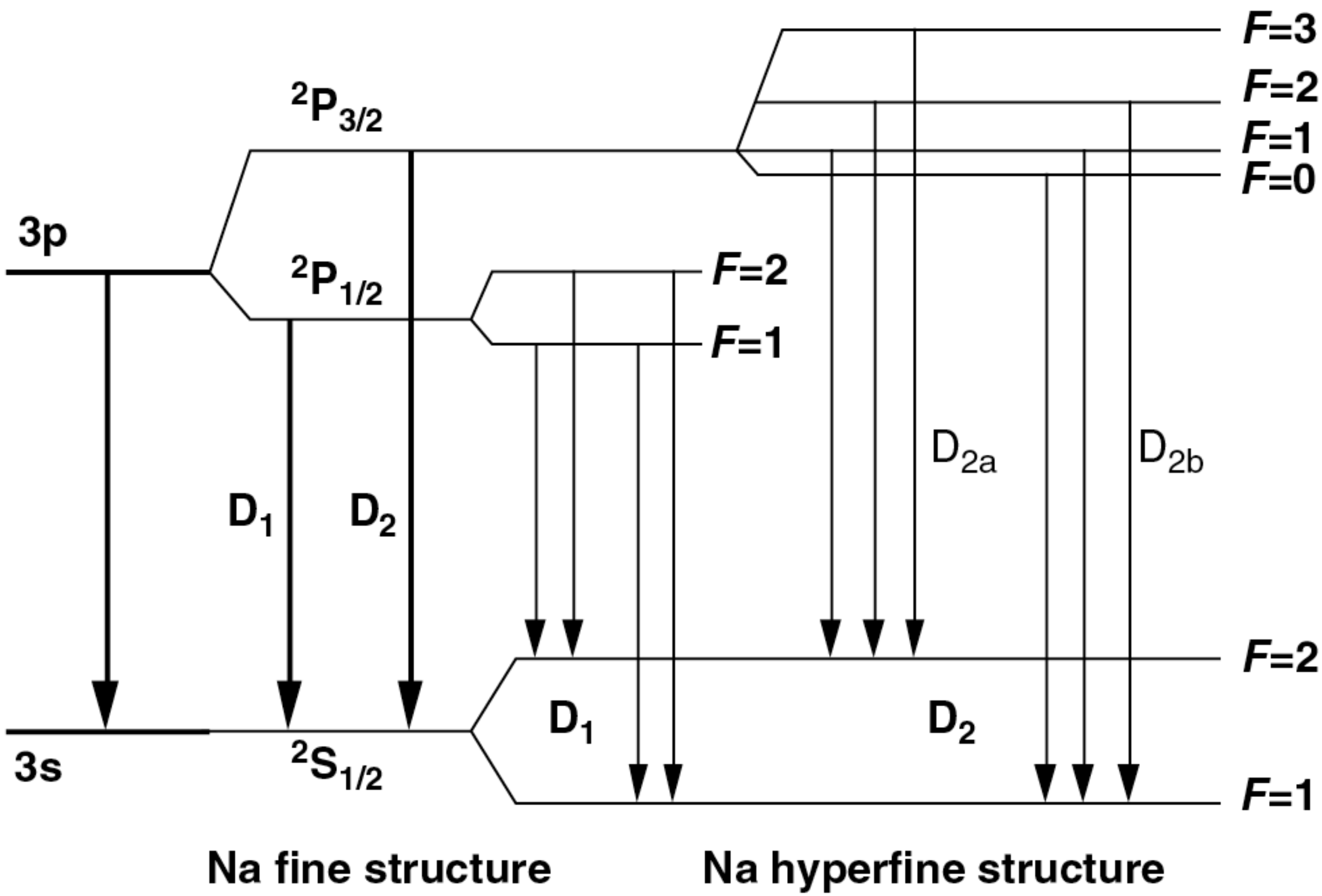
- Atomic Fe, Na, K, etc. absorption lines undergo Doppler frequency shift and Doppler linewidth broadening, so acting as an frequency analyzer or frequency discriminator in the atmosphere – given by mother Nature!

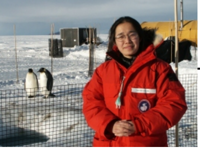
- Consequently, the lidar receiver is broadband so can receive all return signal photons. Plus the high effective absorption and scattering cross-sections (at least 14 orders of magnitude higher than Rayleigh scattering), resonance fluorescence DDL provides much higher signal-to-noise ratios than non-resonance DDL in the upper atmosphere where quenching isn't an issue.

- As a price we have to pay, the effective cross-section of resonance absorption and fluorescence as well as laser frequency and line shape must be known to a great accuracy and precision in order for resonance DDL to derive unbiased wind and temperature.

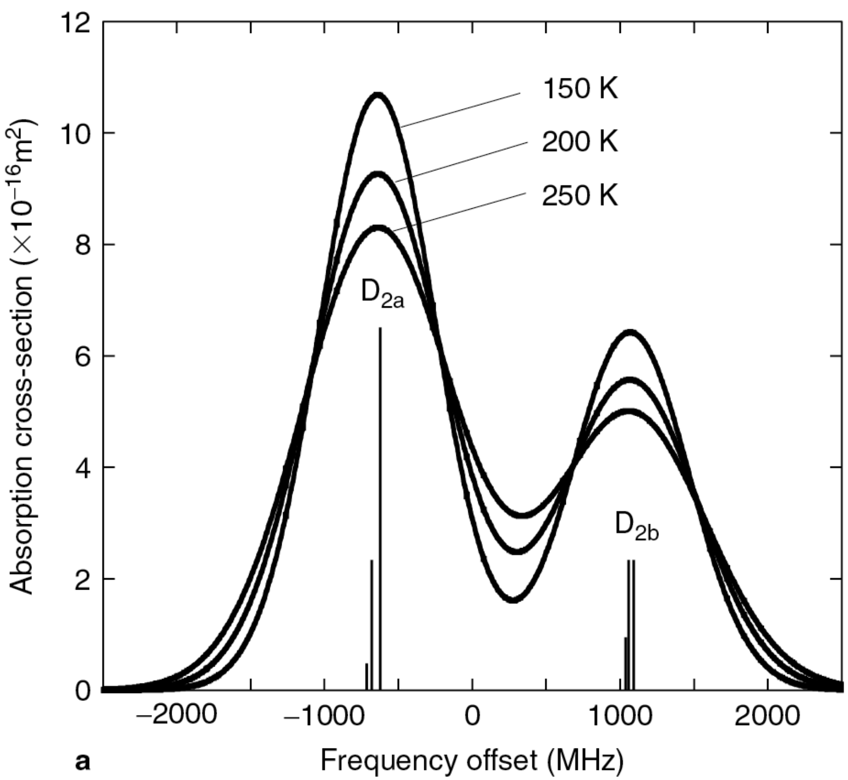


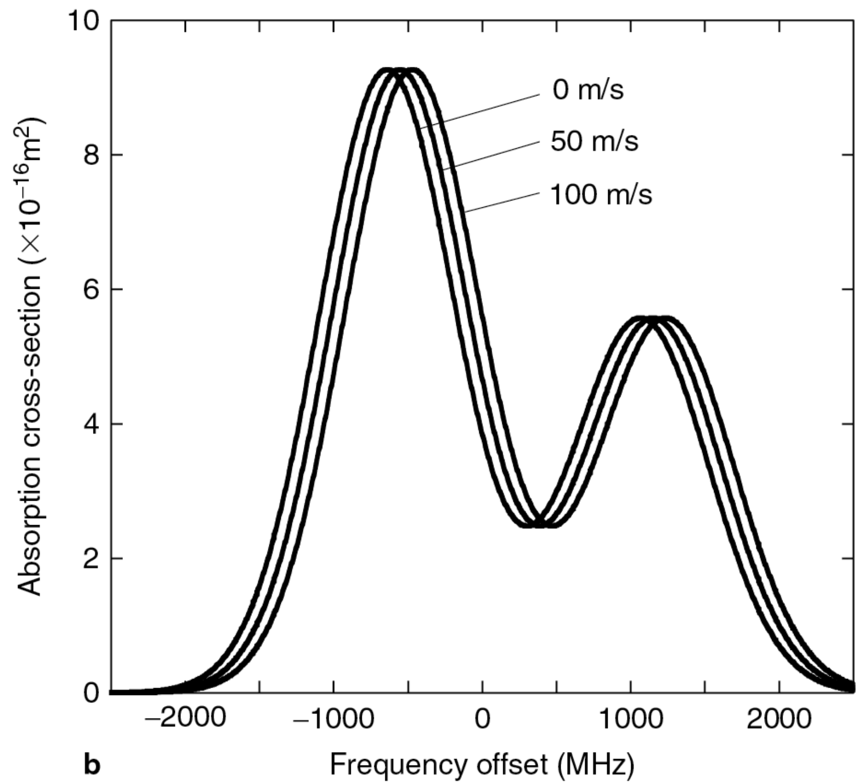
Na Atomic Energy Levels





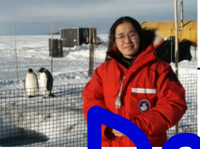
Doppler Effect in Na D_2 Line Resonance Fluorescence





Na D_2 absorption linewidth is temperature dependent

Na D_2 absorption peak freq is wind dependent



Doppler-Limited Na Spectroscopy

- Doppler-broadened Na absorption cross-section is approximated as a Gaussian with rms width σ_D

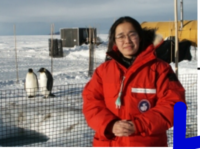
$$\sigma_{abs}(\nu) = \frac{1}{\sqrt{2\pi}\sigma_D}\frac{e^2 f}{4\varepsilon_0 m_e c}\sum_{n=1}^{6} A_n \exp\left(-\frac{[\nu_n - \nu(1 - V_R/c)]^2}{2\sigma_D^2}\right)$$

- Assume the laser lineshape is a Gaussian with rms width σ_L
- The effective cross-section is the convolution of the atomic absorption cross-section and the laser lineshape

$$\sigma_{eff}(\nu) = \frac{1}{\sqrt{2\pi}\sigma_e}\frac{e^2 f}{4\varepsilon_0 m_e c}\sum_{n=1}^{6} A_n \exp\left(-\frac{[\nu_n - \nu(1 - V_R/c)]^2}{2\sigma_e^2}\right)$$

where $\sigma_e = \sqrt{\sigma_D^2 + \sigma_L^2}$ and $\sigma_D = \sqrt{\frac{k_B T}{M\lambda_0^2}}$

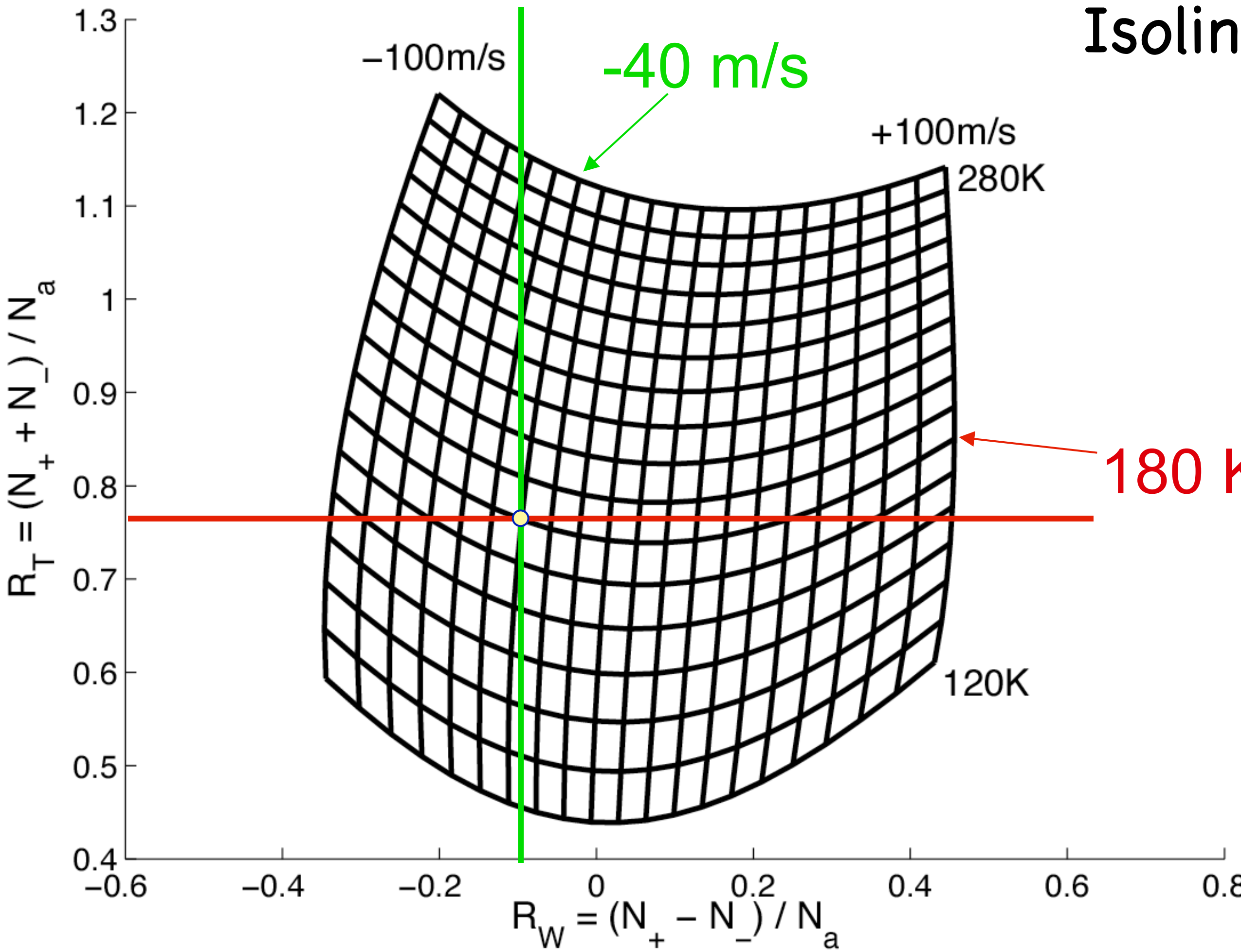
The frequency discriminator/analyzer is in the atmosphere!

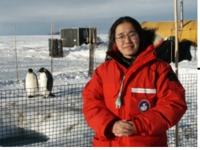


How Does Ratio Technique Work?

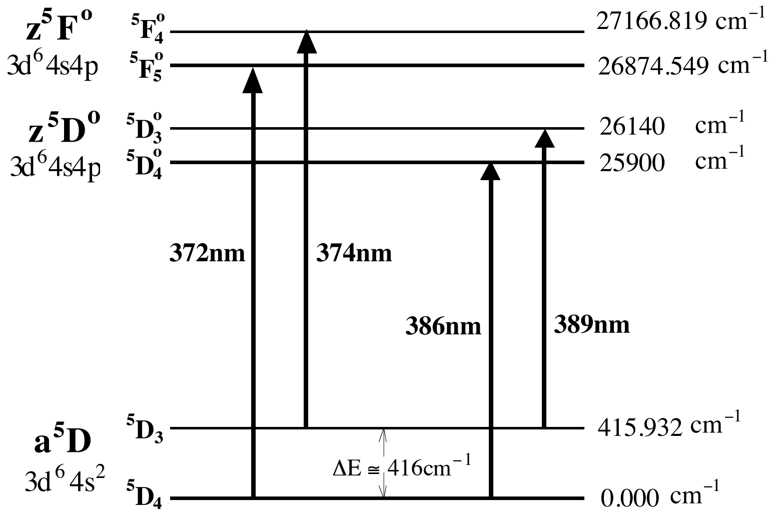
- Compute Doppler calibration curves from physics
- Look up these two ratios on the calibration curves to infer the corresponding Temperature and Wind from isoline/isogram.

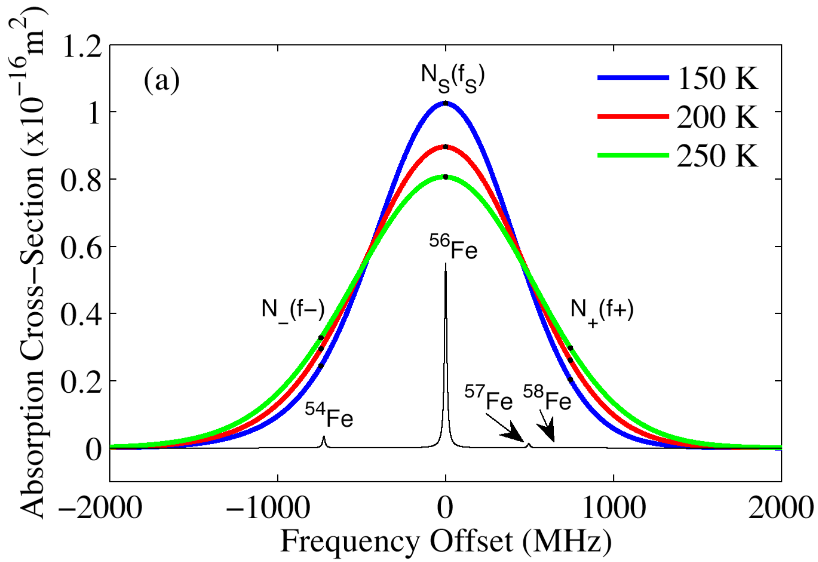
Isoline / Isogram

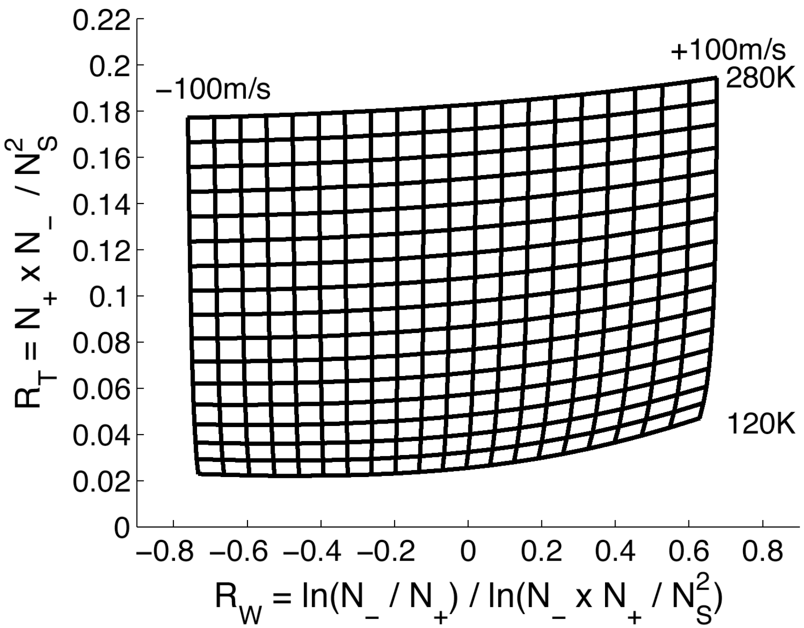


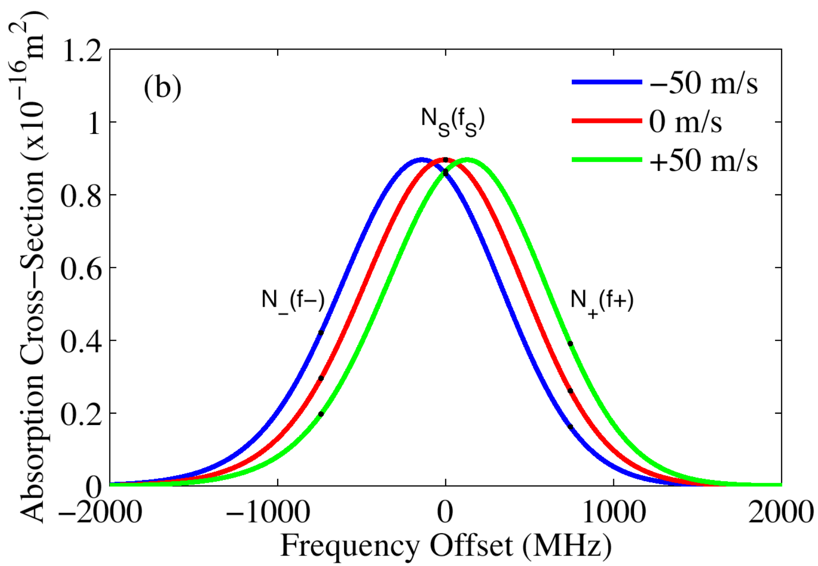


Fe Doppler Lidar Principles



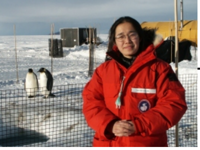






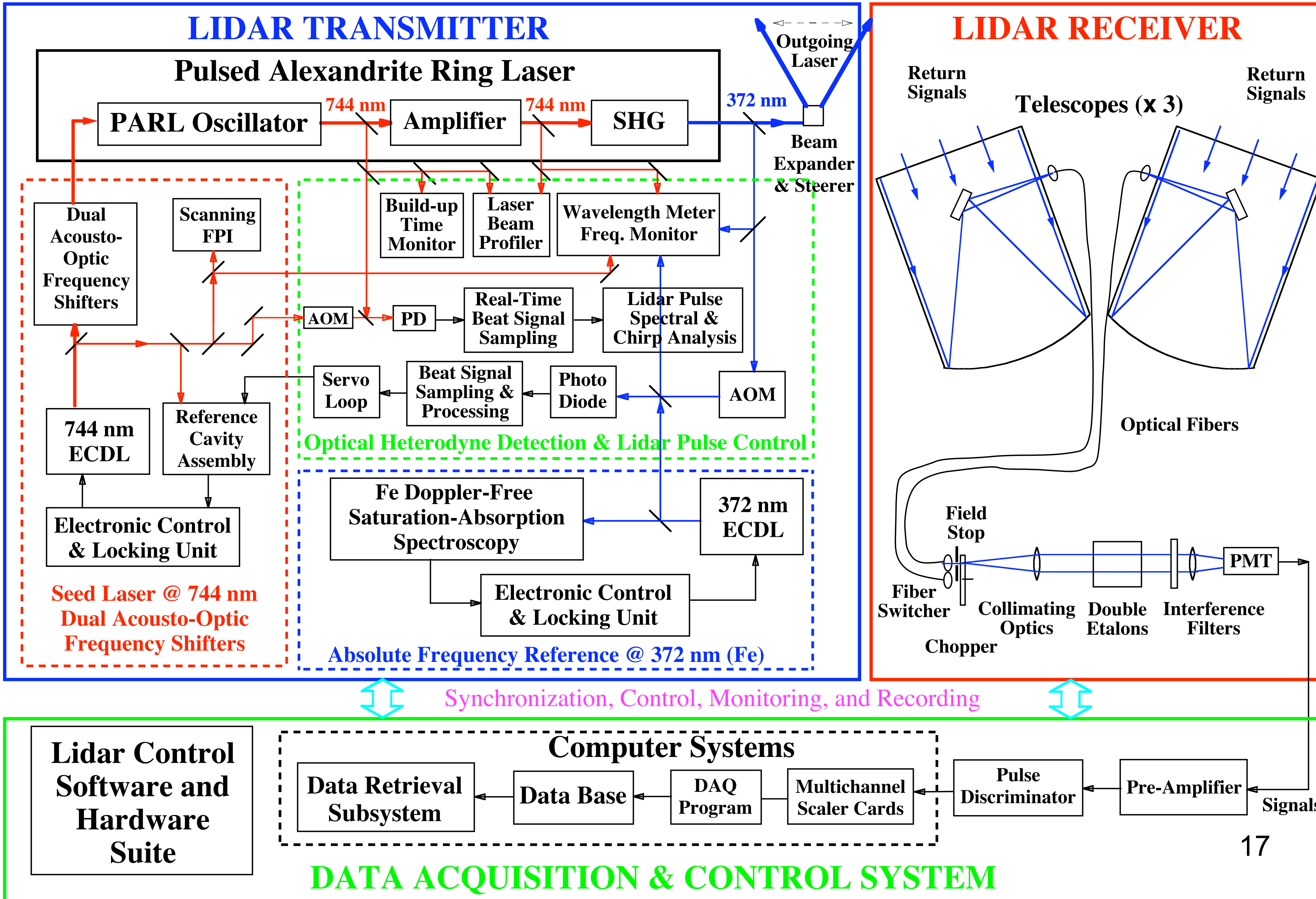
[Chu et al., ILRC,

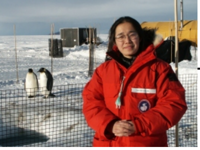
Fe (iron) 372-nm line



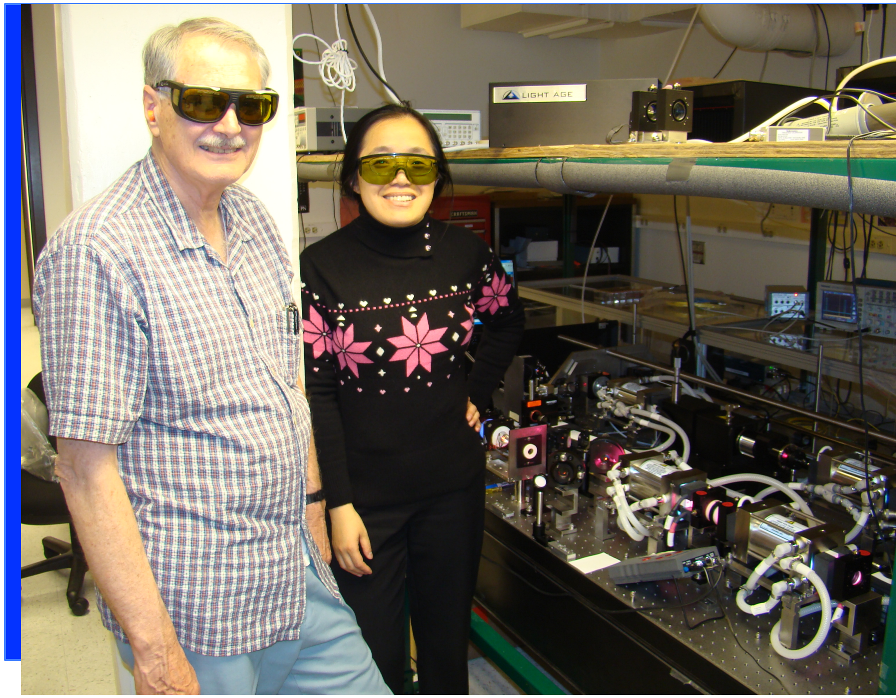
MRI Fe Doppler Lidar

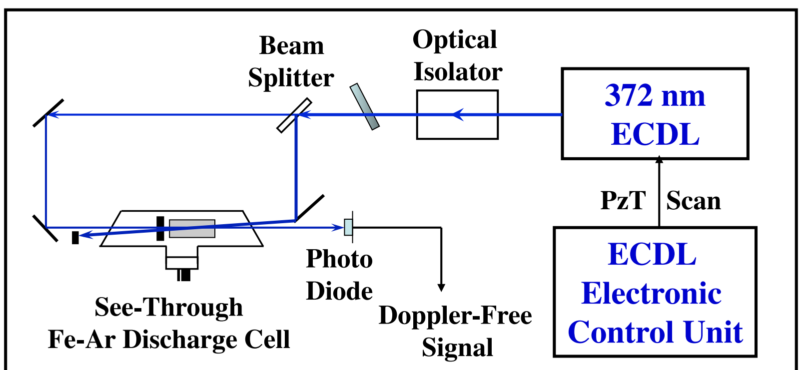
[Chu et al., ILRC, 2010]

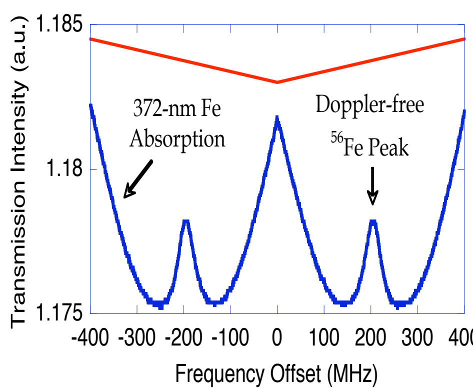


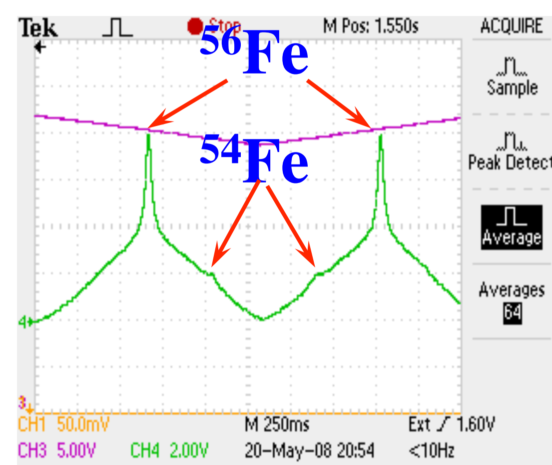


Mobile MRI Fe Doppler Lidar

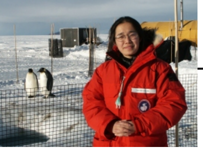




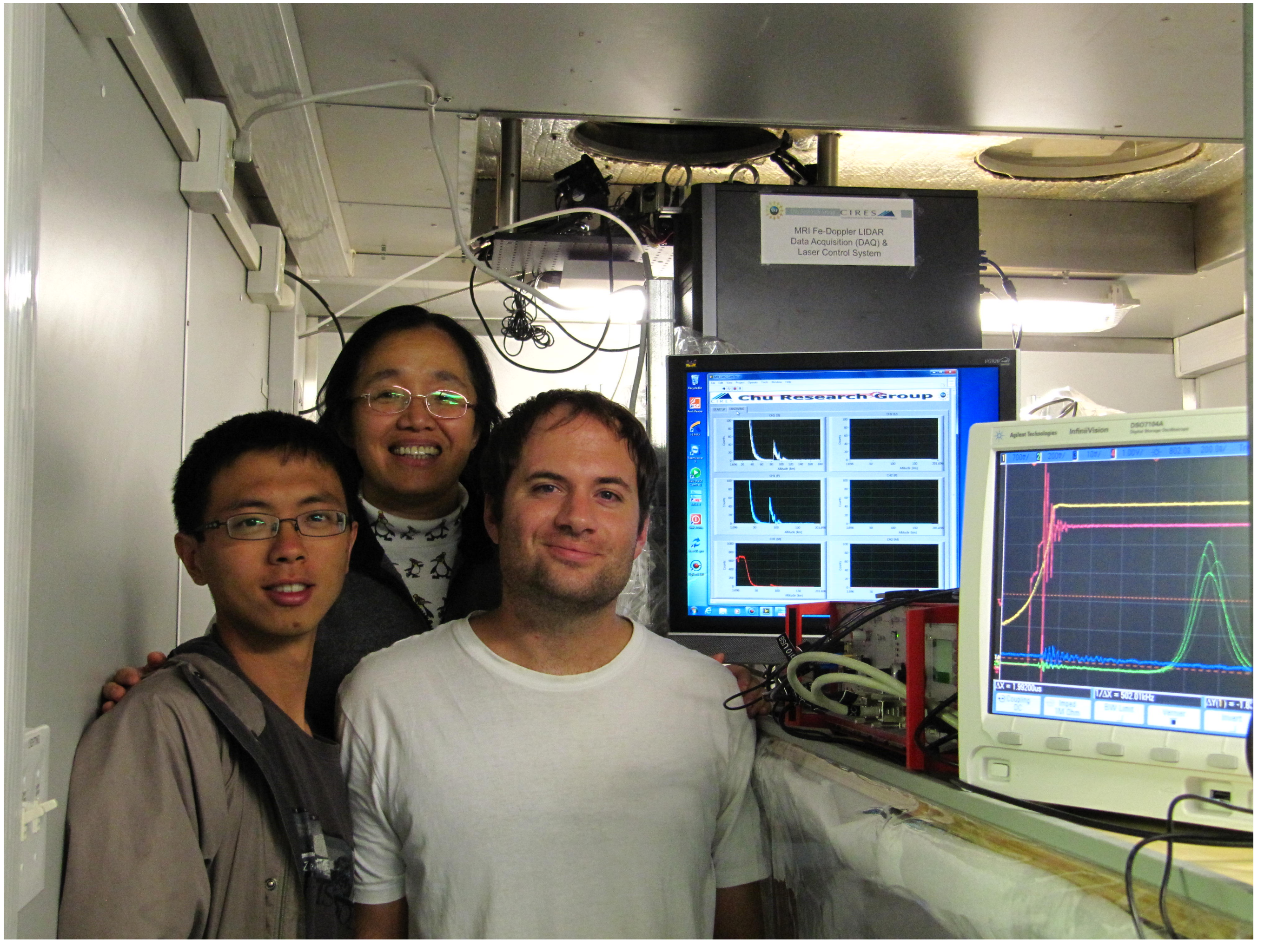




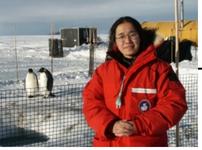
Fe Doppler-free spectroscopy at 372 nm and isotope identification obtained with the MRI Fe Doppler lidar.



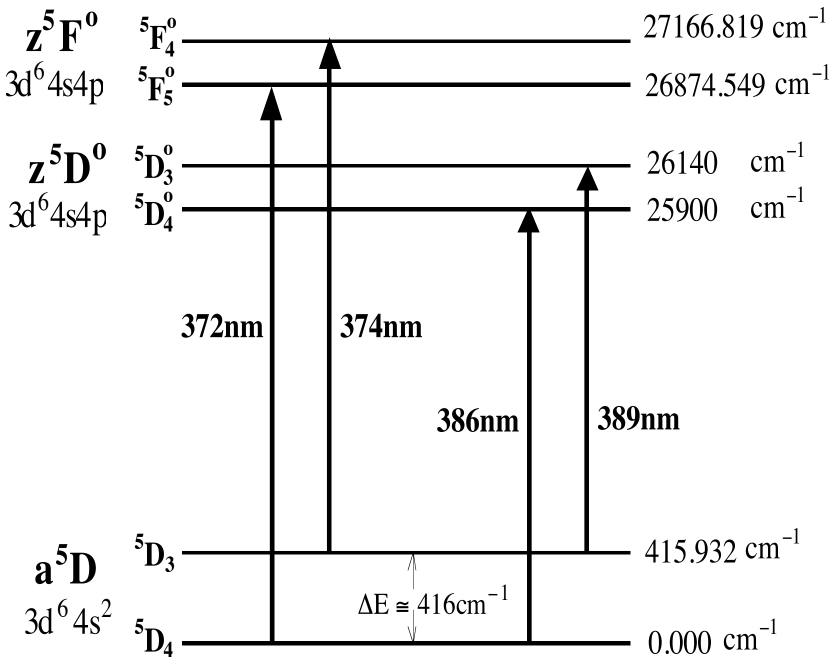
MRI Fe Doppler LIDAR – First Light

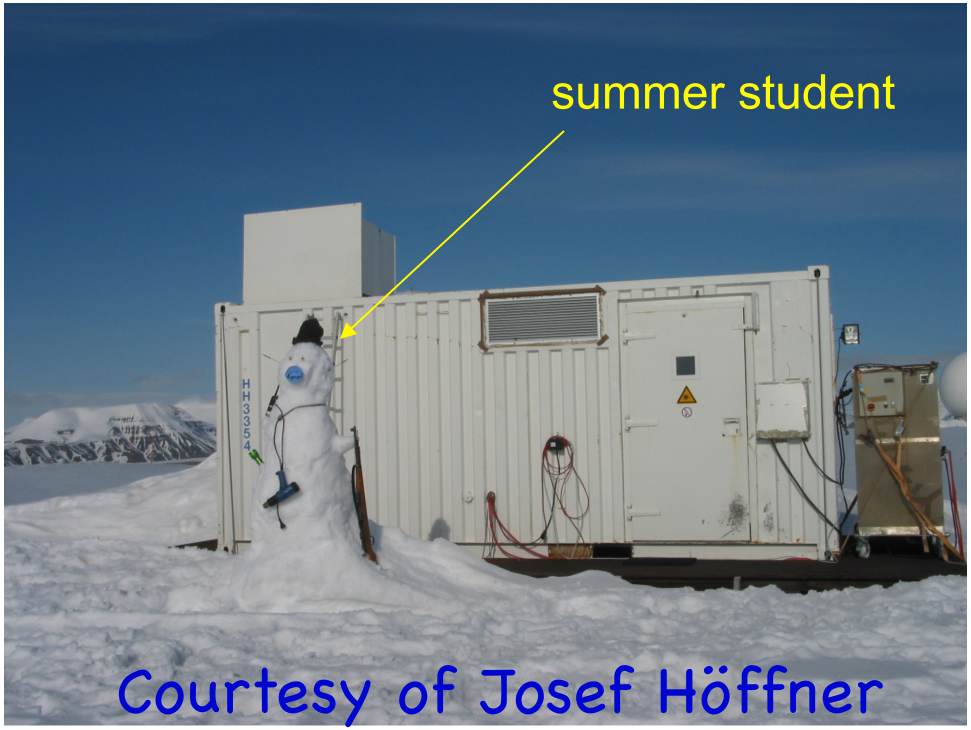


Containerized MRI lidar – hard to take photos
Come to Table Mountain to see it by your own eyes!

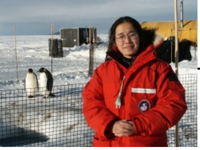


IAP Scanning Fe Doppler Lidar





- IAP pulsed alexandrite ring laser was tuned from 770 nm to 772 nm, and then frequency doubled to probe the 386-nm Fe absorption line for temperature measurements with scanning technique developed for K Doppler lidar.
- Superior performance over K lidar due to Fe abundance, ...



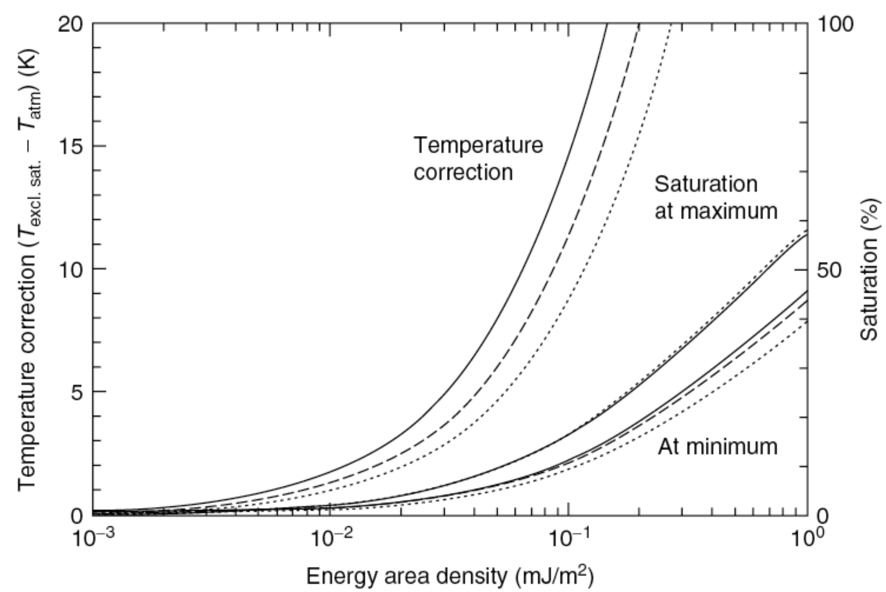
Challenges in Resonance DDL

- 1) Atomic absorption cross-section: isotope shifts, Hanle effects, atomic layer saturation and optical pumping effects
- 2) Laser absolute frequency calibration: frequency chirp and broadening
- 3) Laser lineshape: Convolution of atomic absorption with laser lineshape

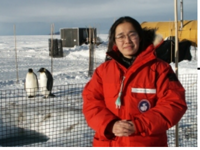
- Determination of $\sigma_{abs}(\nu)$: QM calculation, convolution of Gaussian with Lorentzian, Hanle effect, Na layer saturation, and optical pumping effect.

Hanle effect modified A_n:
5, 5, 2, 14, 5, 1 $\rightarrow$
5, 5.48, 2, 15.64, 5, 0.98

- Absolute laser frequency calibration and laser lineshape.
- Isotope shifts: measured independently, or scanning to more frequencies to infer from atmosphere.



Na Layer Saturation



Na Atomic Parameters

Table 5.1 Parameters of the Na D_1 and D_2 Transition Lines

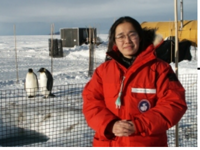
Transition Line	Central Wavelength (nm)	Transition Probability ($10^8\ s^{-1}$)	Radiative Lifetime (nsec)	Oscillator Strength f_{ik}
D_1 ($^2P_{1/2} \rightarrow {}^2S_{1/2}$)	589.7558	0.614	16.29	0.320
D_2 ($^2P_{3/2} \rightarrow {}^2S_{1/2}$)	589.1583	0.616	16.23	0.641

Group	$^2S_{1/2}$	$^2P_{3/2}$	Offset (GHz)	Relative Line Strength[a]
D_{2b}	$F=1$	$F=2$	1.0911	5/32
		$F=1$	1.0566	5/32
		$F=0$	1.0408	2/32
D_{2a}	$F=2$	$F=3$	−0.6216	14/32
		$F=2$	−0.6806	5/32
		$F=1$	−0.7150	1/32

Doppler-Free Saturation–Absorption Features of the Na D_2 Line

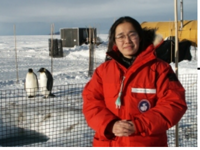
f_a (MHz)	f_c (MHz)	f_b (MHz)	f_+ (MHz)	f_- (MHz)
−651.4	187.8	1067.8	−21.4	−1281.4

[a]Relative line strengths are in the absence of a magnetic field or the spatial average. When Hanle effect is considered in the atmosphere, the relative line strengths will be modified depending on the geomagnetic field and the laser polarization.



Comparison of Wind Techniques

Technique	Lidars	Applications
Doppler Wind Technique (Direct Detection or Coherent Detection): wind dependence of Doppler frequency shift (1 time Doppler shift for single absorption or emission process) (2 times Doppler shift for Mie and Rayleigh scattering)	Resonance Fluorescence Doppler Lidar: Doppler frequency shift and broadening of resonance fluorescence absorption cross-section (scan and ratio techniques)	Mesosphere and Lower Thermosphere temperature and wind (75-120 km); possible in thermosphere with other species
	Rayleigh/Mie Direct Detection Doppler Lidar : Doppler frequency shift of molecular and/or aerosol scattering using edge filters (absorption lines or etalons) or fringe imaging or scanning FPI or Michelson Interferometer	Lower mesosphere, stratosphere and troposphere wind (up to 50-60-70 km if there are enough photon counts)
	Coherent Detection Doppler Lidar: Doppler frequency shift of aerosol scattering using heterodyne detection technique	Troposphere wind, especially in boundary layers (up to 15 km), where aerosols are abundant
Direct Motion Detection Technique: derivative of displacement (the definition of velocity) (direct application of velocity definition or cross-correlation coefficient)	High-Spectral-Resolution Lidar: tracking aerosol / cloud motion through time	Troposphere wind, where aerosols and clouds are abundant
	(Scanning) Aerosol Lidar: tracking aerosol motion through time	Troposphere wind, where aerosols and clouds are abundant
	Laser Time-of-Flight Velocimeter: measuring time-of-flight of aerosol across two focused and parallel laser beams	Within the first km range, laboratory, machine shop, etc.
	Laser Doppler Velocimeter: measuring the frequency of aerosol scattering across the interference fringes of two crossed laser beams	Within the boundary layers, wind tunnel, production facility, machine shop, fluid mechanics research, etc



Summary

- Direct detection Doppler lidar uses atomic/molecular absorption lines, the edge filters, or fringe-imaging techniques to discriminate or analyze the of the return lidar signals (Doppler shifted and/or broadened). Potentially, DDL can measure both wind and temperature if sufficient spectral information is provided or inquired.
- For non-resonance DDL, a major issue is how to improve the signal level or collection efficiency. New developments based on various interferometers are under the way.
- For atmospheric science study, especially for waves coupling from lower to upper atmosphere, DDLs have very high potentials for the future, especially the combination of resonance DDL in MLT region with non-resonance DDL in the troposphere, stratosphere and lower mesosphere, we may be able to profile the wind and temperature from ground all the way up to 170 km. This will be a breakthrough for atmospheric science community.

Please read our textbook Chapter 7 for direct-detection Doppler lidar and for coherent-detection Doppler lidar.
Please read our textbook Chapter 5 for resonance DDL.