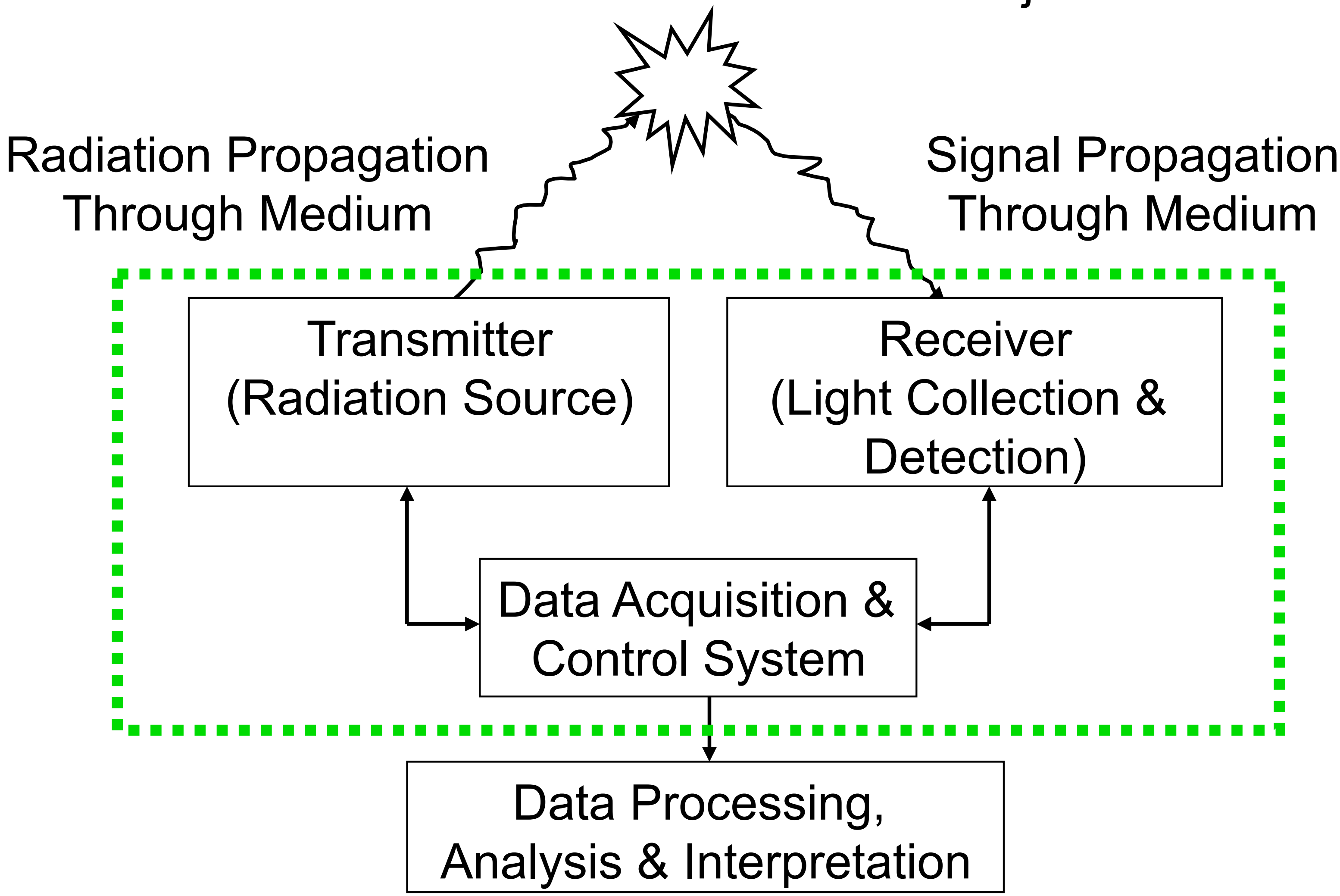
Lecture 14. Temperature Lidar (3)
Resonance Fluorescence Doppler Lidar Instrumentation

- Introduction
- Na Doppler Lidar Instrumentation
  - Classic Na Doppler Lidar
  - Solid-State Na Doppler Lidar
- Other Resonance Fluorescence Doppler Lidars
  - K Doppler Lidar
  - Fe Doppler Lidar
- Summary

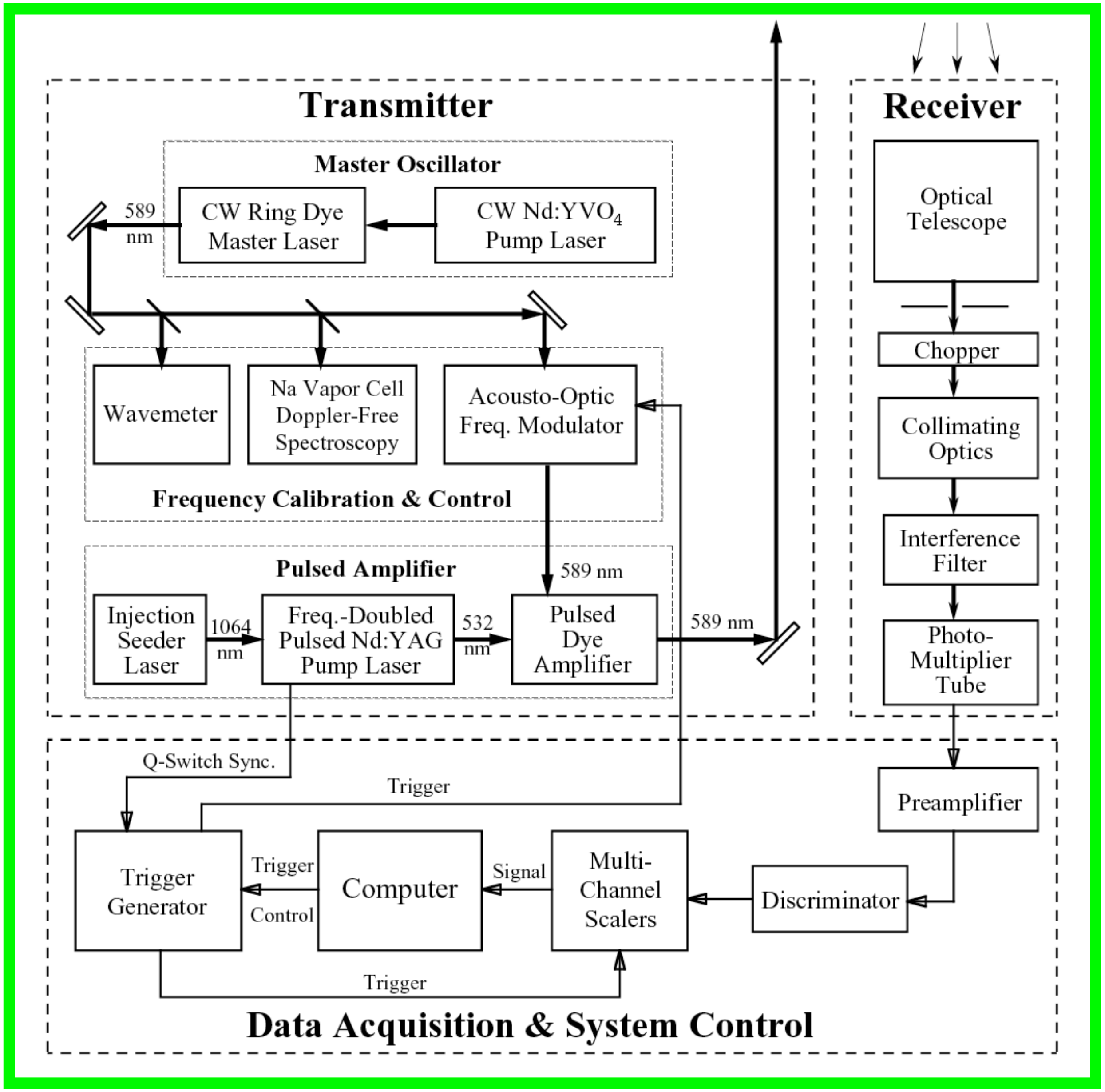
Introduction

Interaction between radiation and objects



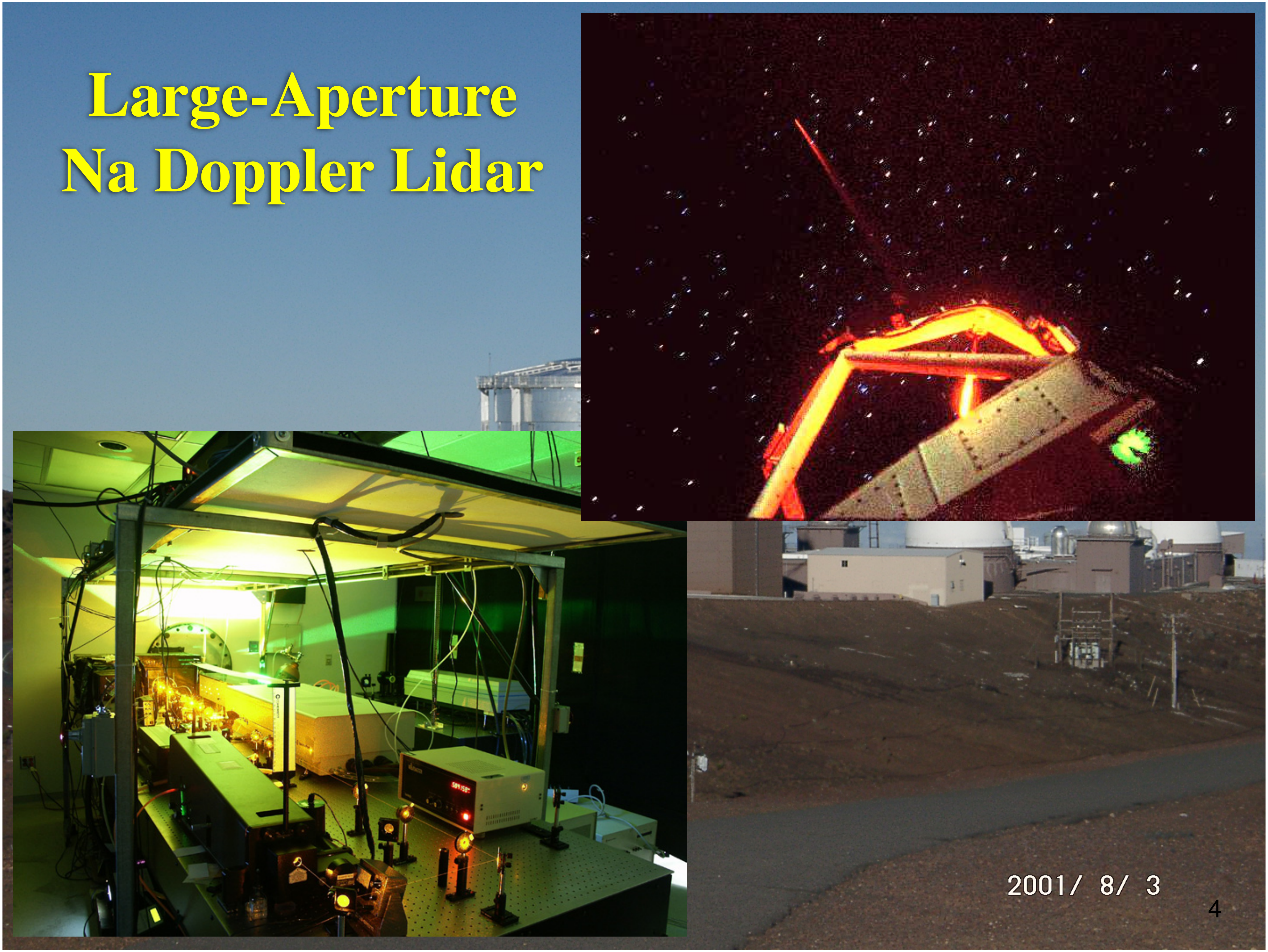
❑ Resonance Doppler lidar has the frequency discriminator in atmosphere – atomic absorption lines! ⇨ Narrowband transmitter, broadband receiver. ⇨ High signal levels and accurate knowledge on the frequency discriminator!

Classic Na Doppler Lidar

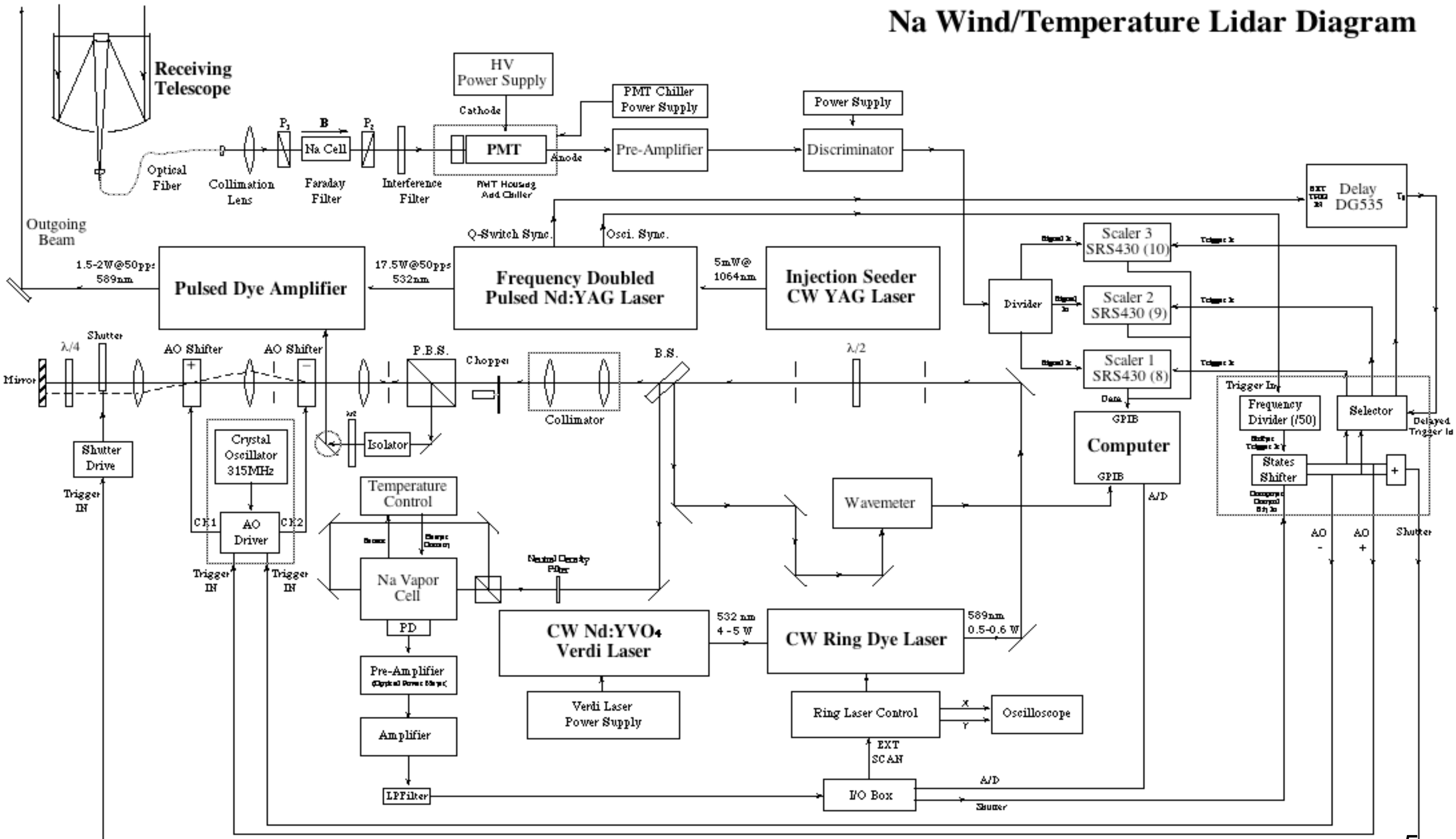


Dye-laser-based Na wind and temperature Lidar (See textbook Chapter 5 by Chu and Papen, 2005)

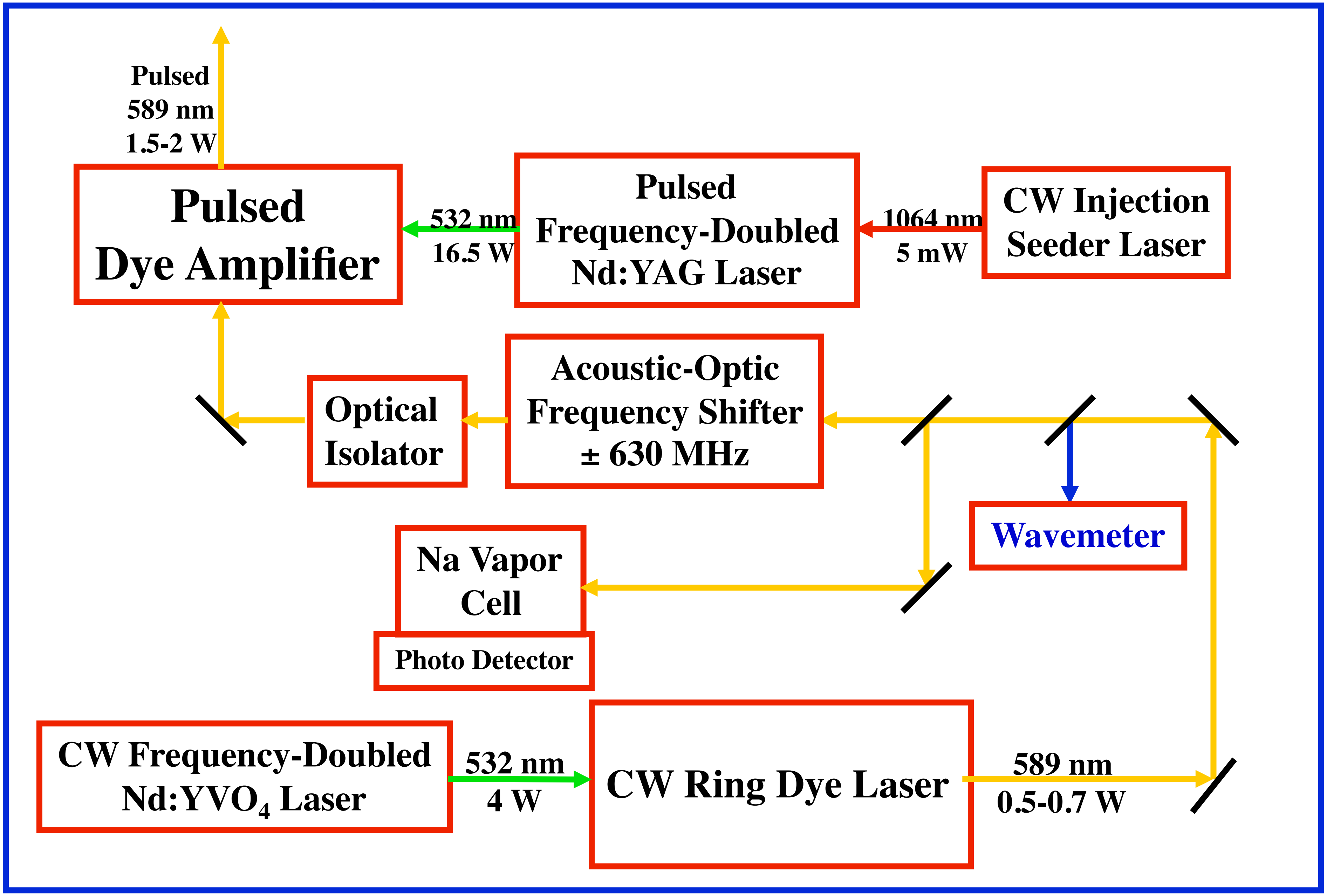
Large-Aperture Na Doppler Lidar



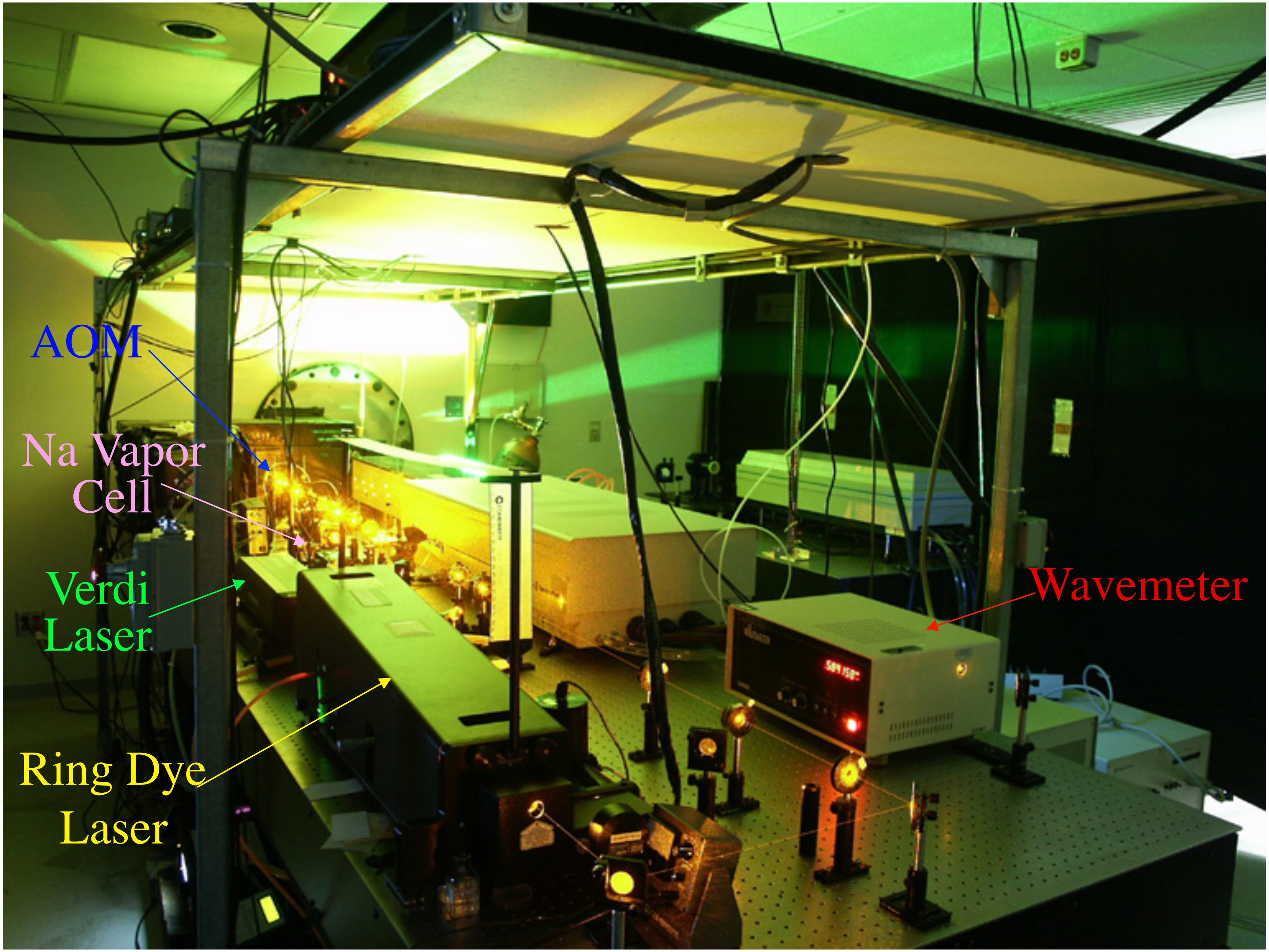
Na Wind and Temperature Lidar



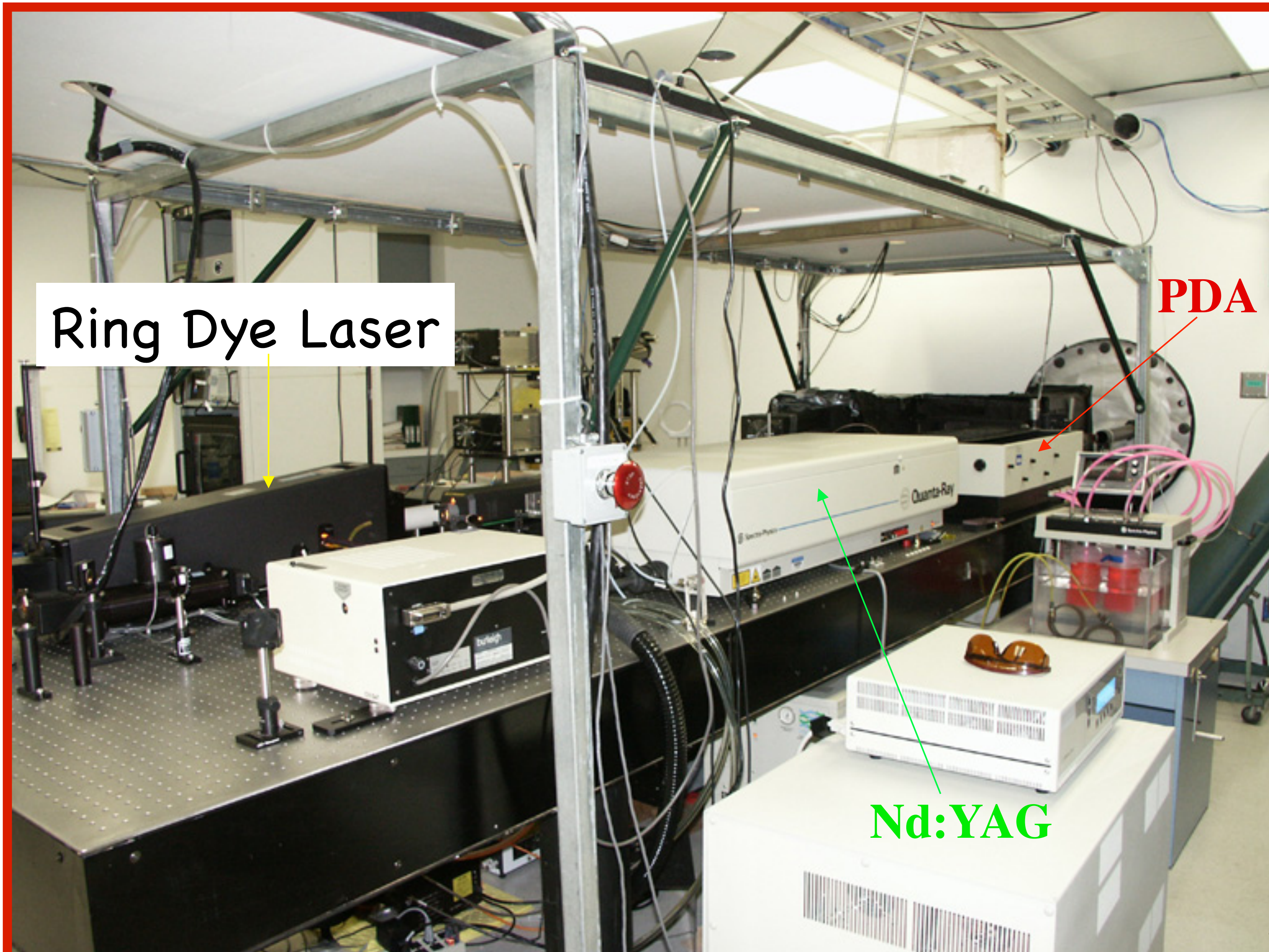
Na Doppler Lidar Transmitter



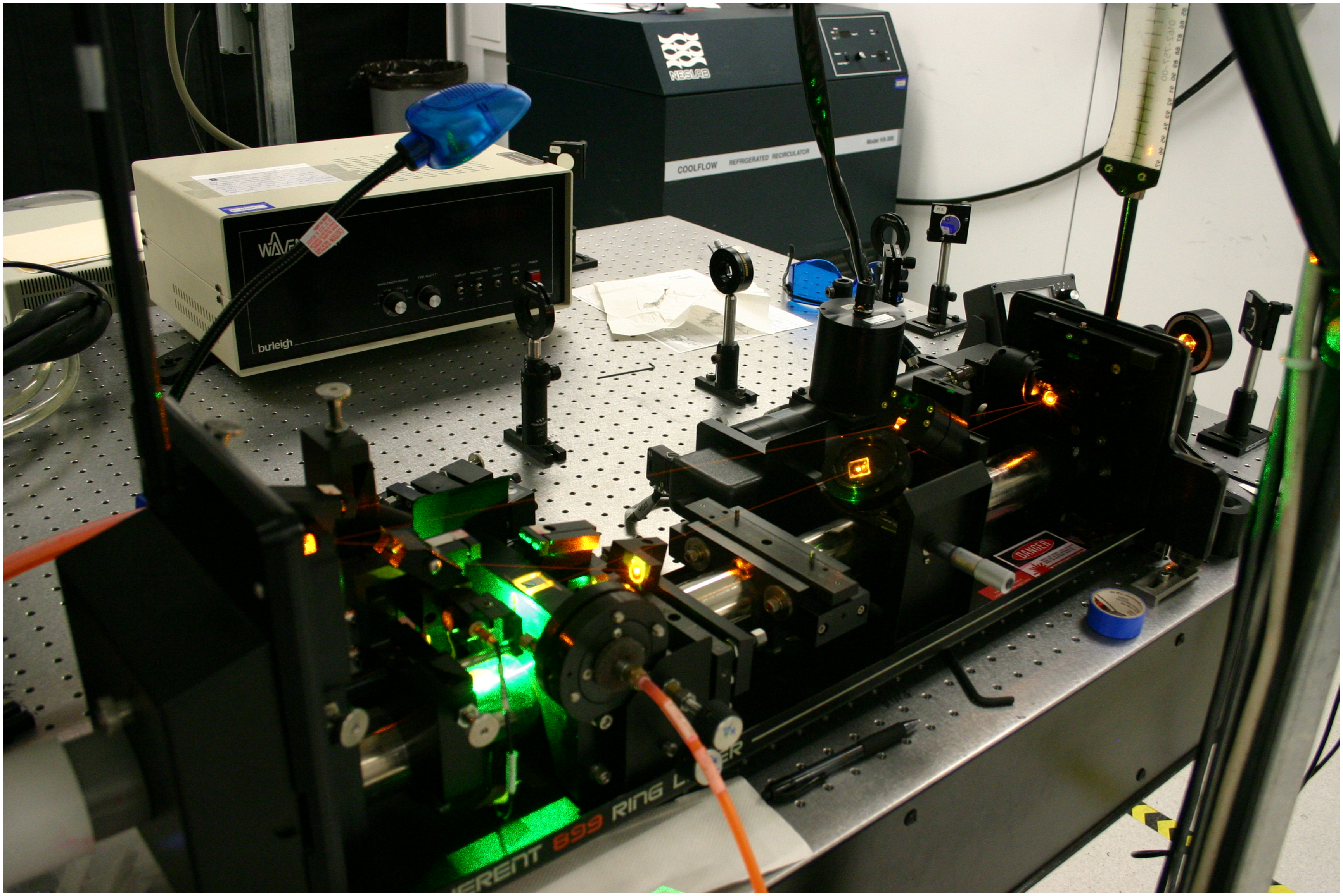
Na Lidar Transmitter Photo 1



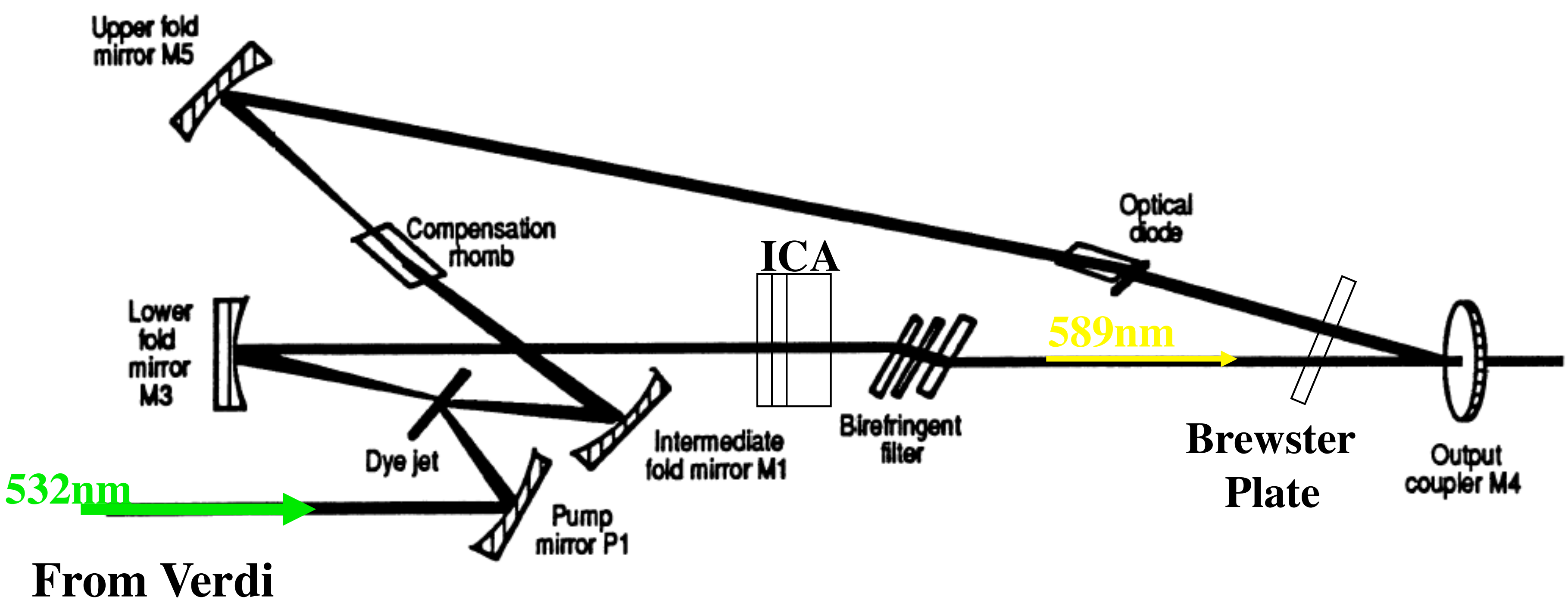
Na Lidar Transmitter Photo 2



Ring Dye Laser

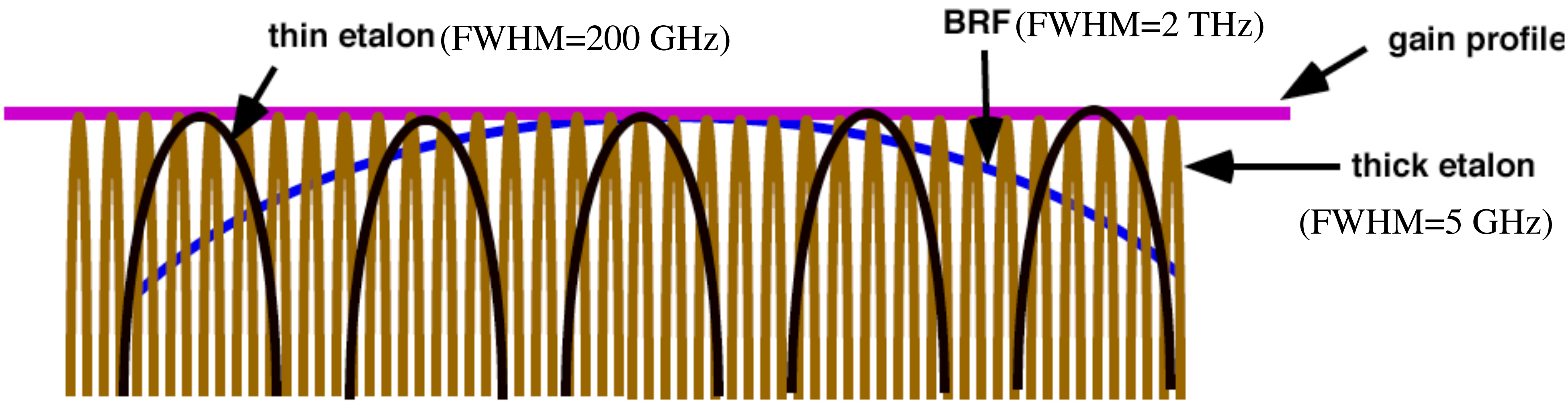


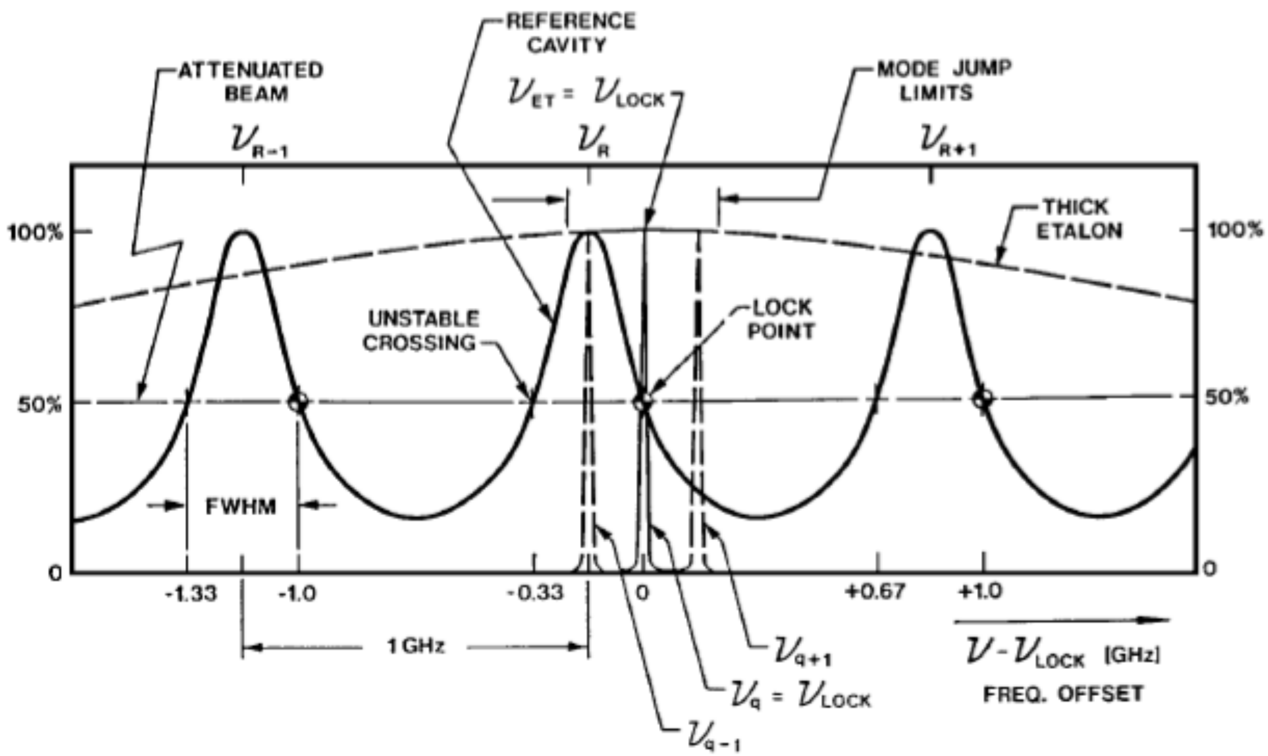
Ring Dye Laser



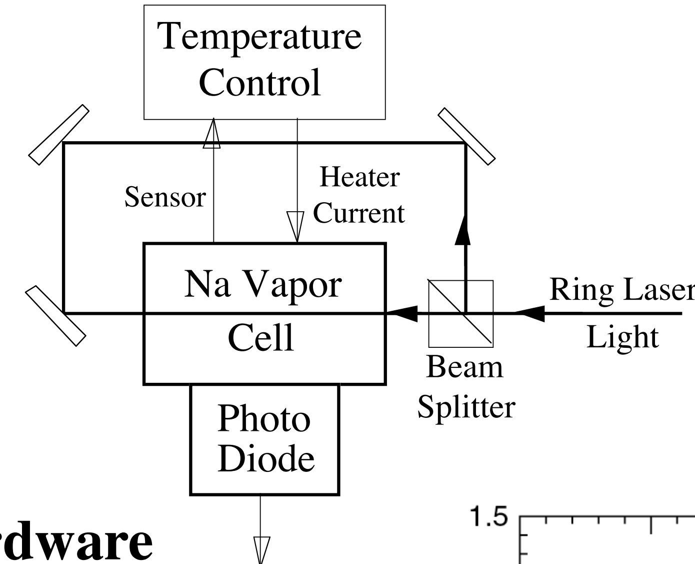
1. "Four mirror + Dye jet" form the laser resonance cavity.
2. Unidirectional lasing prevents spatial hole-burning.
3. Rhomb compensates the astigmatism effect.
4. Optical diode forces the unidirectional lasing.
5. BRF + ICA (etalons) select frequency and narrow bandwidth.
6. "Brewster plate + RCA + M3 PZT" actively control frequency.

Frequency Selection in Ring Laser

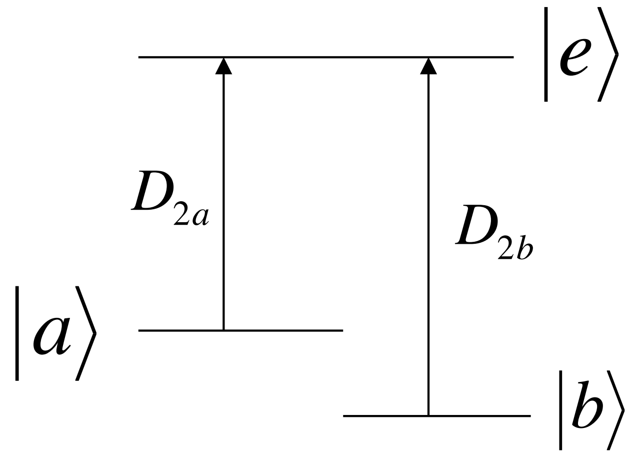




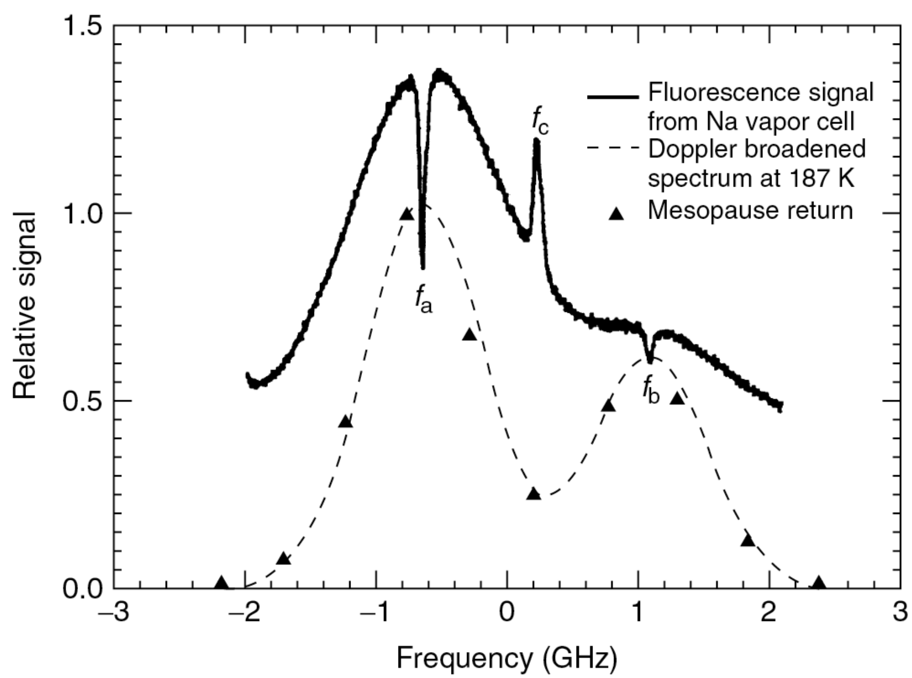
Na Doppler-Free Spectroscopy & Laser Frequency Lock



Hardware

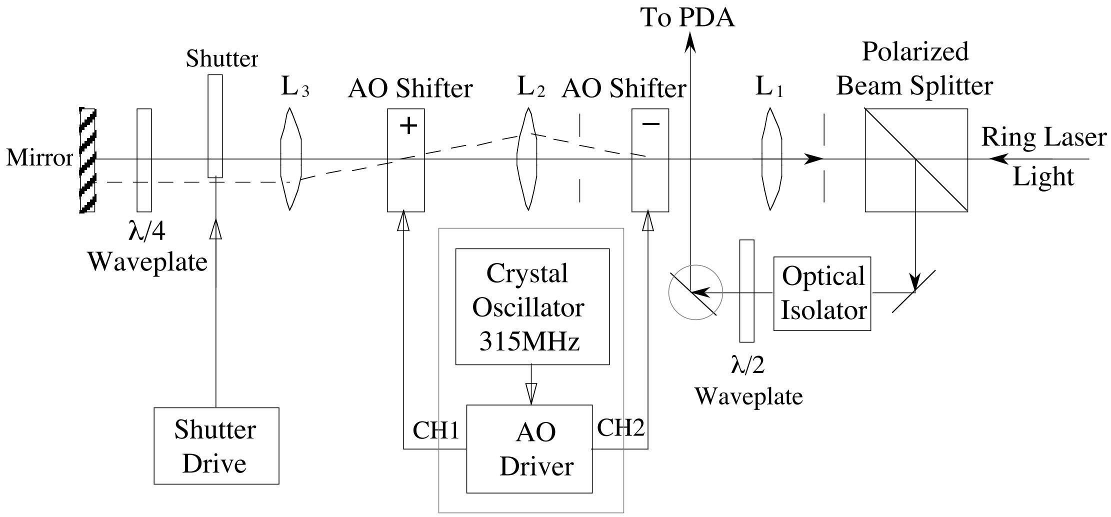


3-Level Explanation

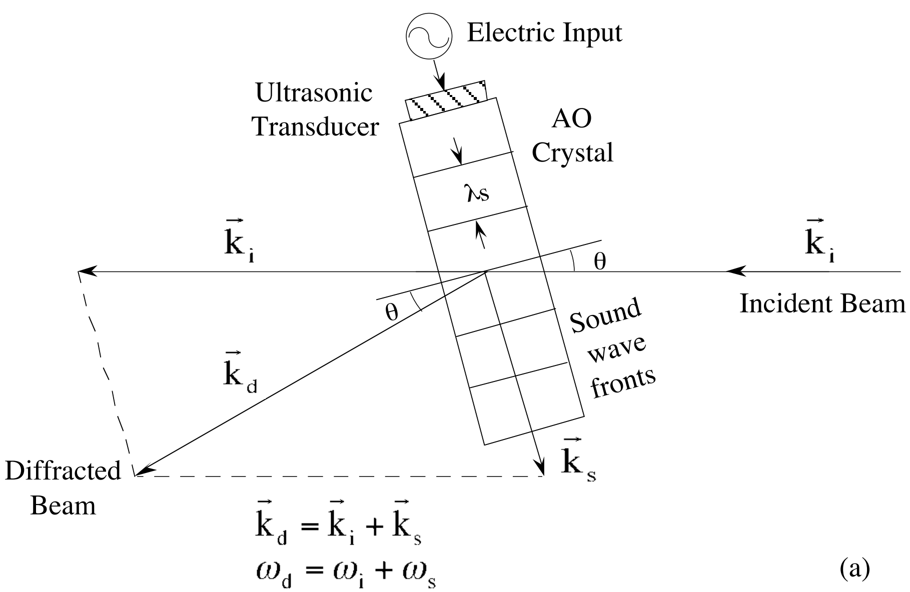


Acousto-Optical Modulator

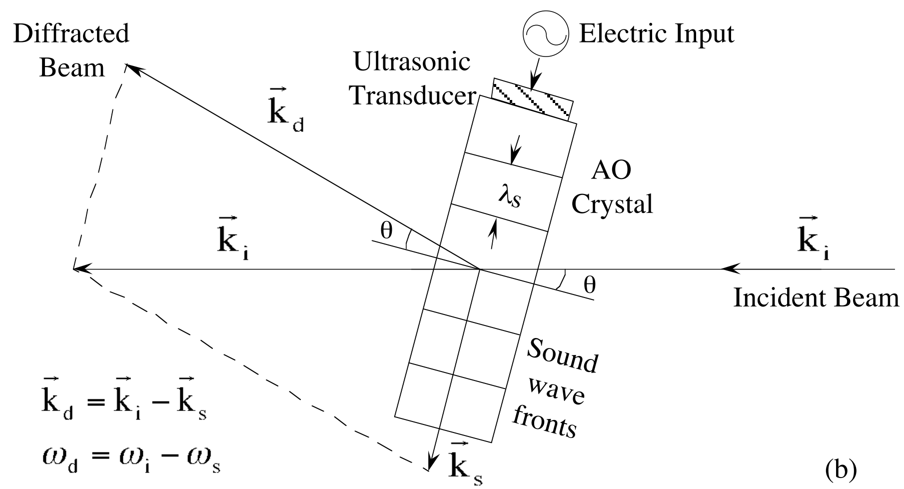
Hardware



Explanation: Doppler shift or Photon/Phonon Annihilation

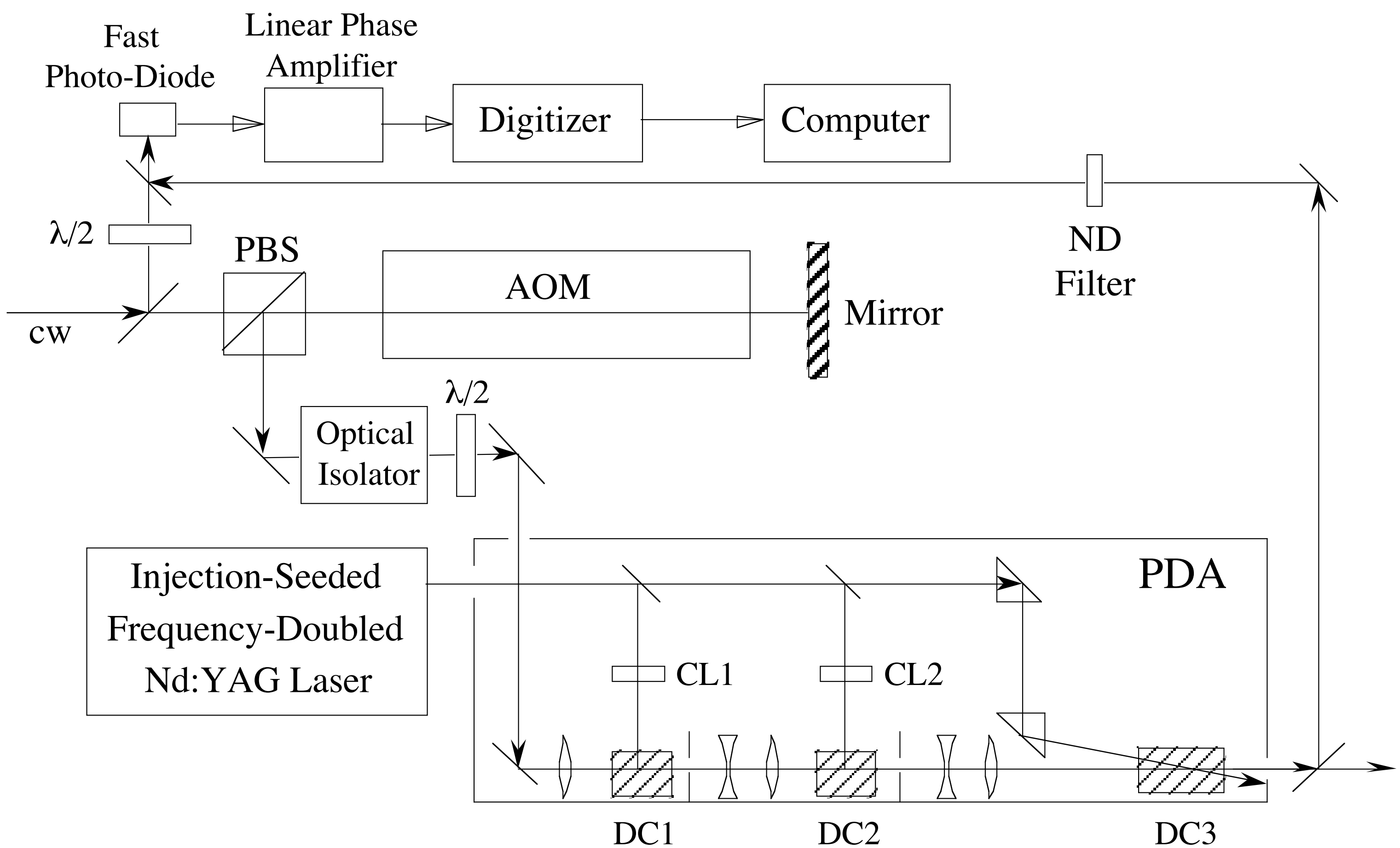


(a)



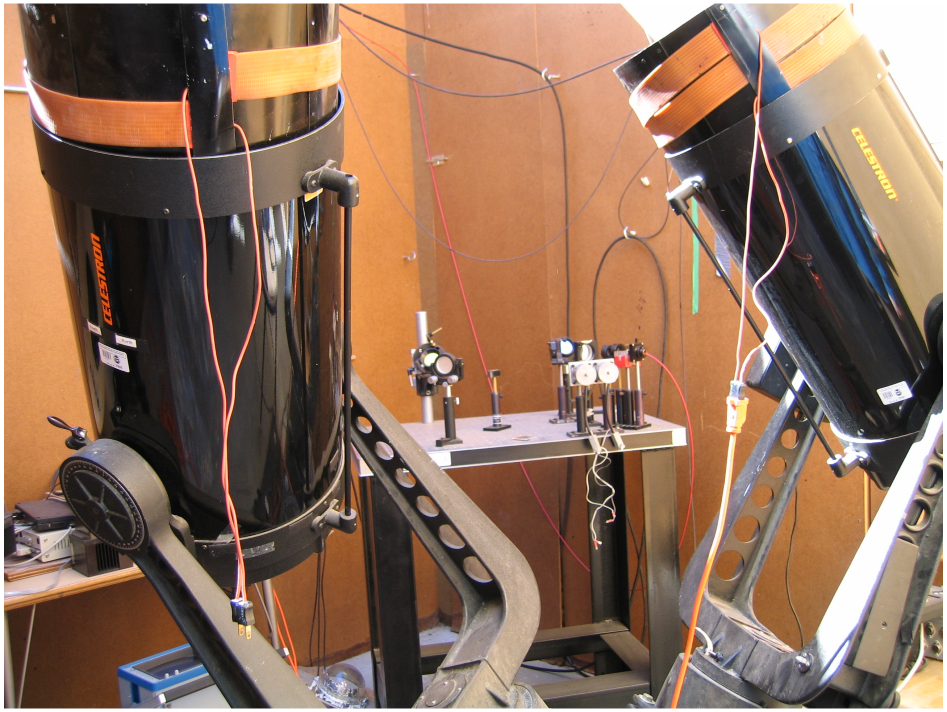
(b)

Pulsed Amplification

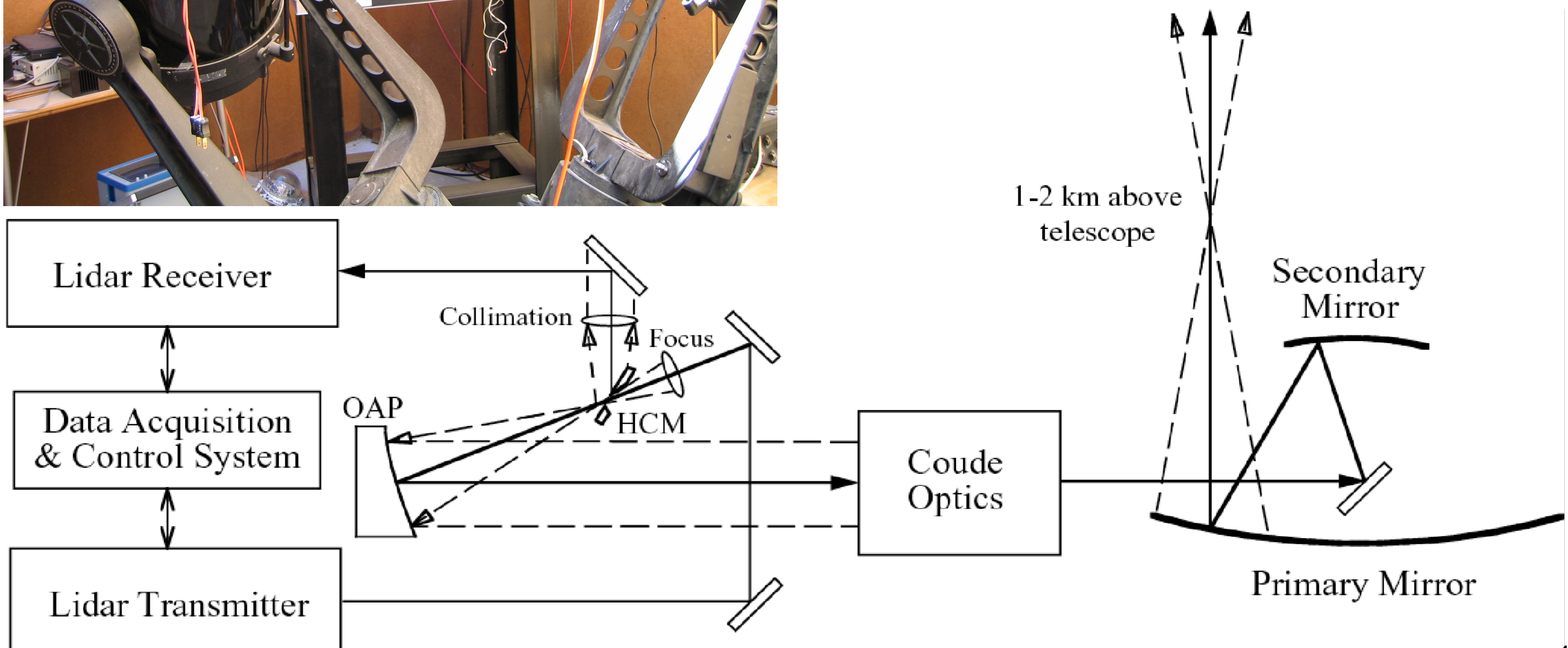


1. **Amplified Spontaneous Emission (ASE)**
2. **Injection-seeded Nd:YAG laser**
3. **PDA chirp caused by pulsed amplification**

Na Doppler Lidar Receiver



CSU Multibeam Receiver
With Fiber coupling



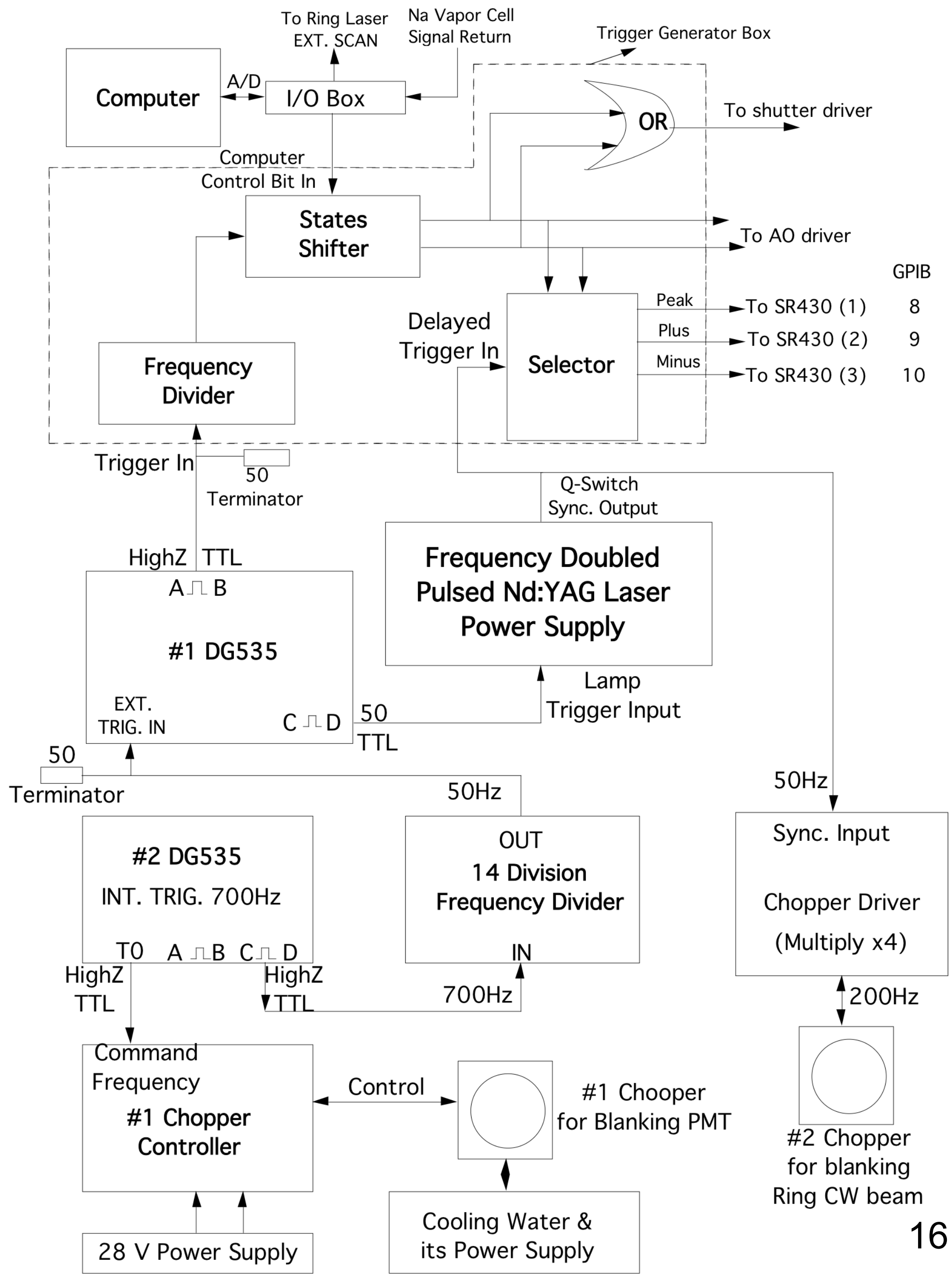
UIUC Large-Aperture Steerable Na Doppler Lidar

Na Doppler Lidar Control System and Data Acquisition

Recent improvements:

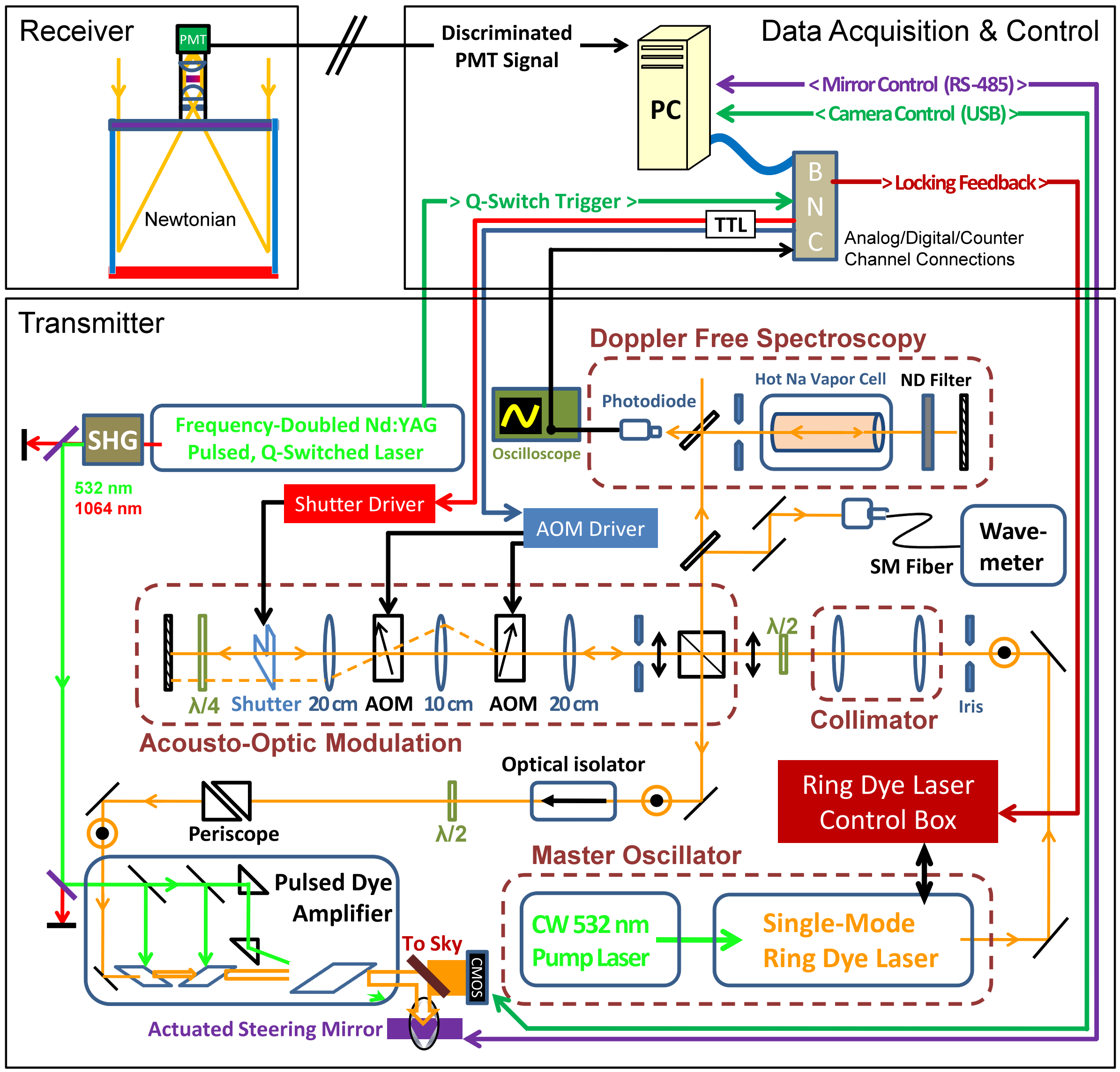
1) Seed laser frequency locking: phase-sensitive
2) Computer-card based multichannel scalers
3) High-QE PMTs (but issues with max cnt rate)
4) Self-made larger aperture telescope
5) LabVIEW-based DAQ
6) Daytime capability …

Connection of Na Wind/Temperature Lidar System at MSSC



STAR Na LIDAR

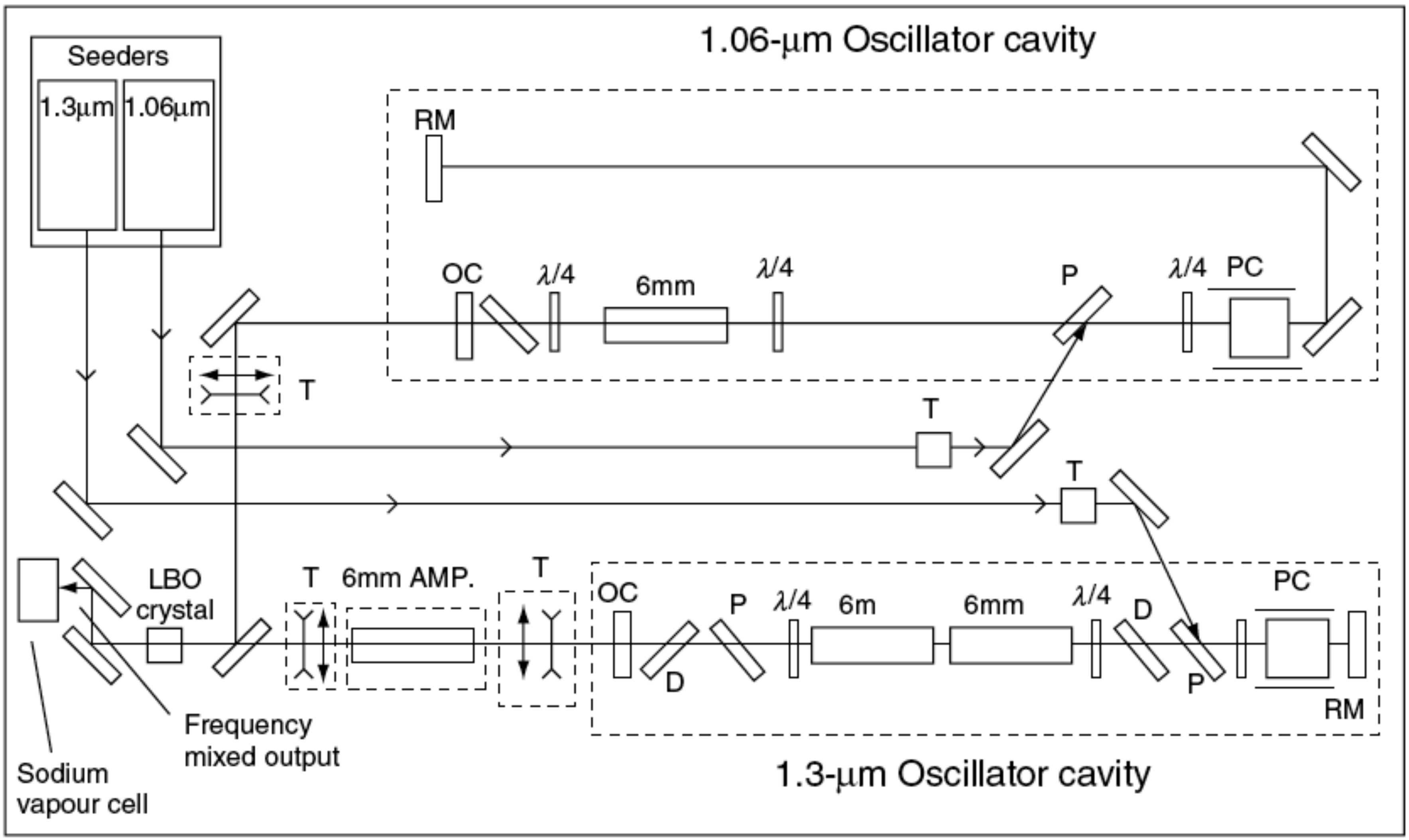
Modernized DAQ, System Control and Receiver



[J. A. Smith, W. Fong, W. Huang, and X. Chu, University of Colorado]

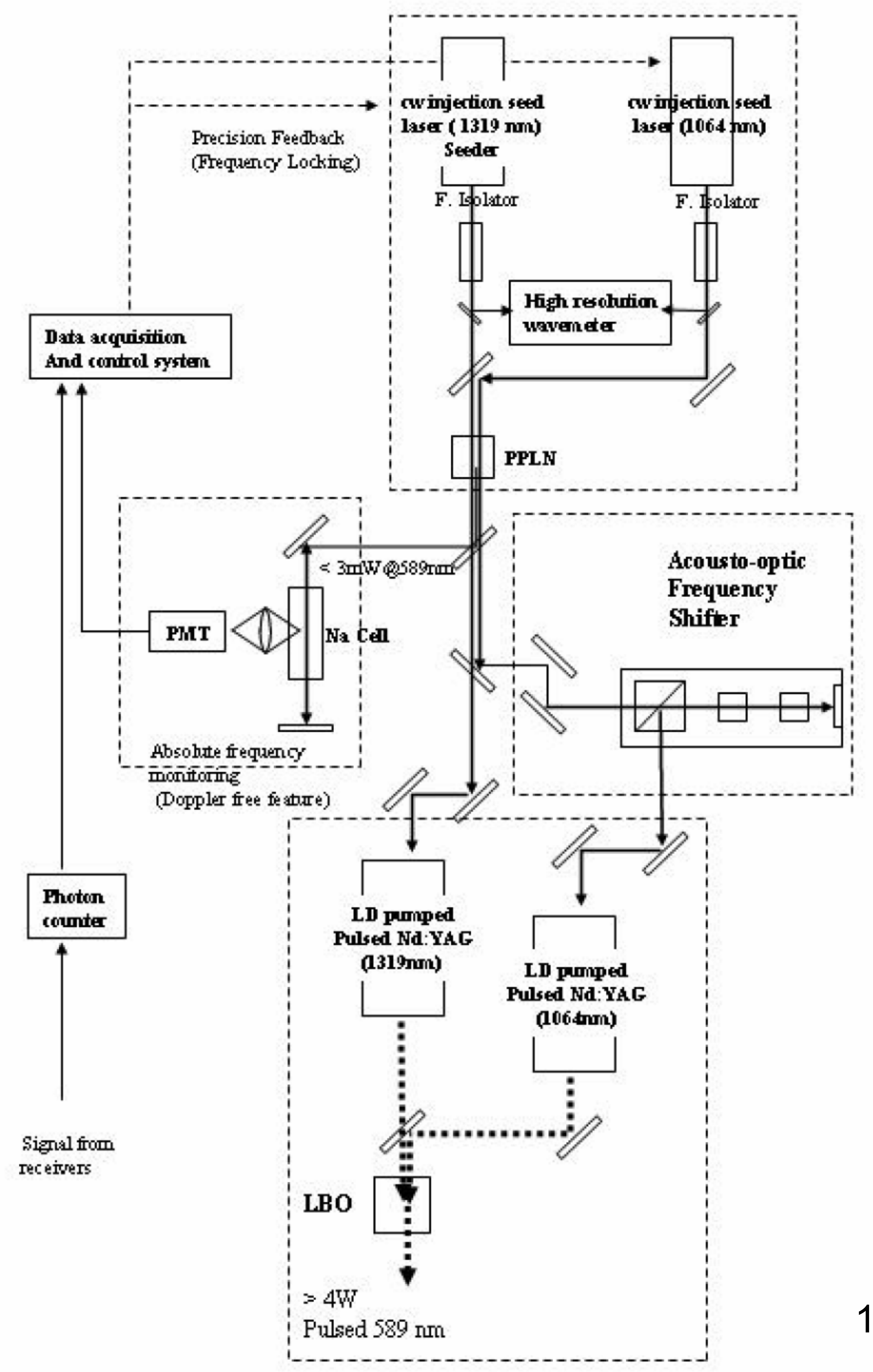
Solid-State Na Doppler Lidar

- Japanese Shinshu system by Kawahara et al.: Frequency mixing of two Nd:YAG lasers at 1064 and 1319 nm



Solid-State Na Doppler Lidar Based on Diode-Laser-Pumped Nd:YAG Lasers

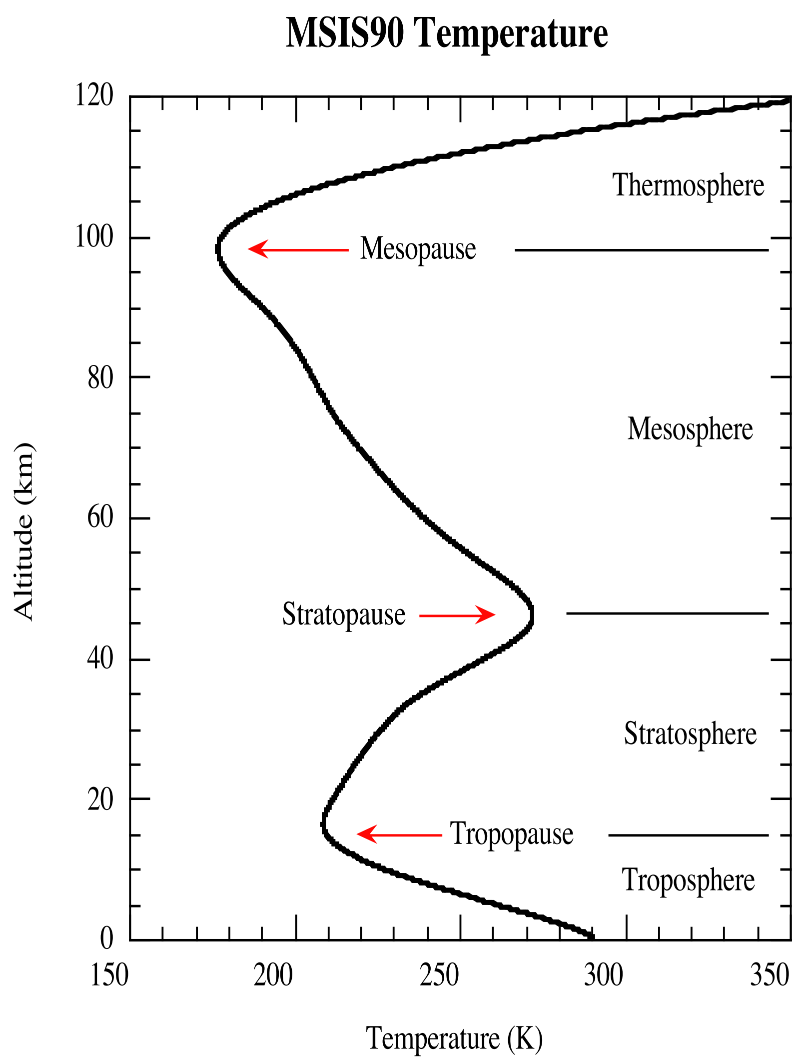
[Kawahara et al., ILRC, 2008]



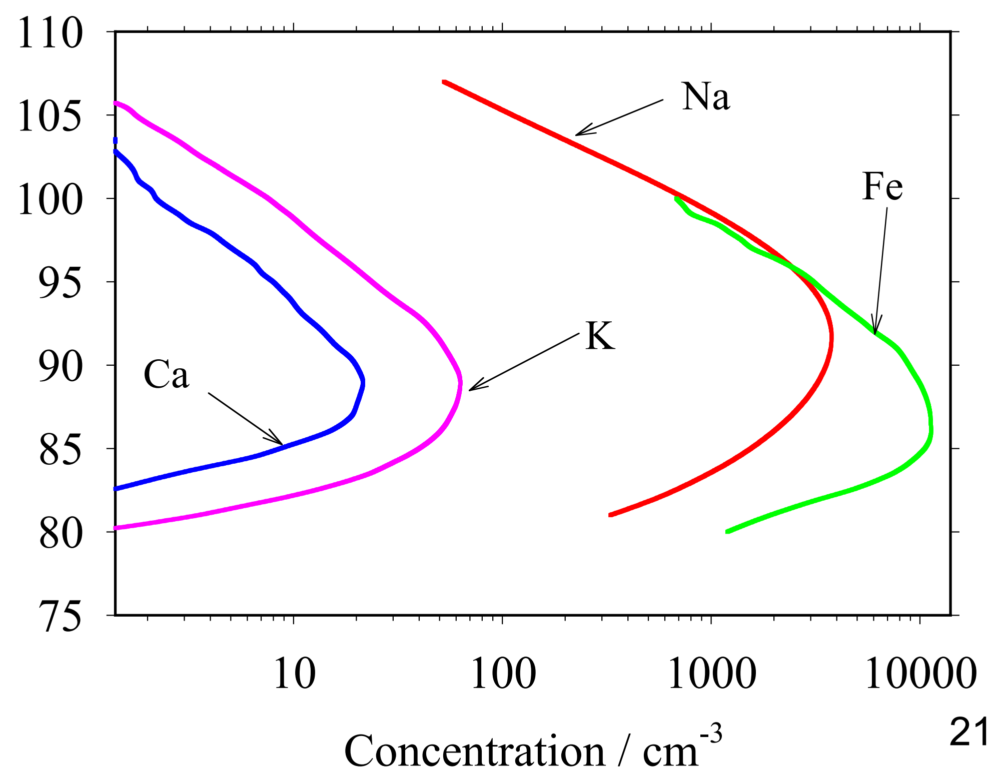
Options for Na Doppler Lidar

- Conventional: Ring Dye Laser + PDA
- Hybrid: Solid-stat cw 589nm source + PDA
  - -- CW Nd:YAG lasers SFG (1064 and 1319 nm)
  - -- CW fiber lasers SFG (1583 and 938 nm)
  - -- Raman shifted fiber laser SHG (1178 nm)
- Full solid-state pulsed 589nm laser
  - -- Flashlamp pumped Nd:YAG lasers SFG
  - -- Diode-laser pumped Nd:YAG laser SFG
  - -- Other laser options
- Solid-state cw 589nm laser + pseudorandom modulation or cw 589nm laser + bistatic configuration

More Resonance Fluorescence Doppler Lidars



- Besides Na, there are more metal species (K, Fe, Ca, Ca^+, Mg, Li, …) from meteor ablation. They can be used as tracers for Doppler lidar measurements in MLT region.

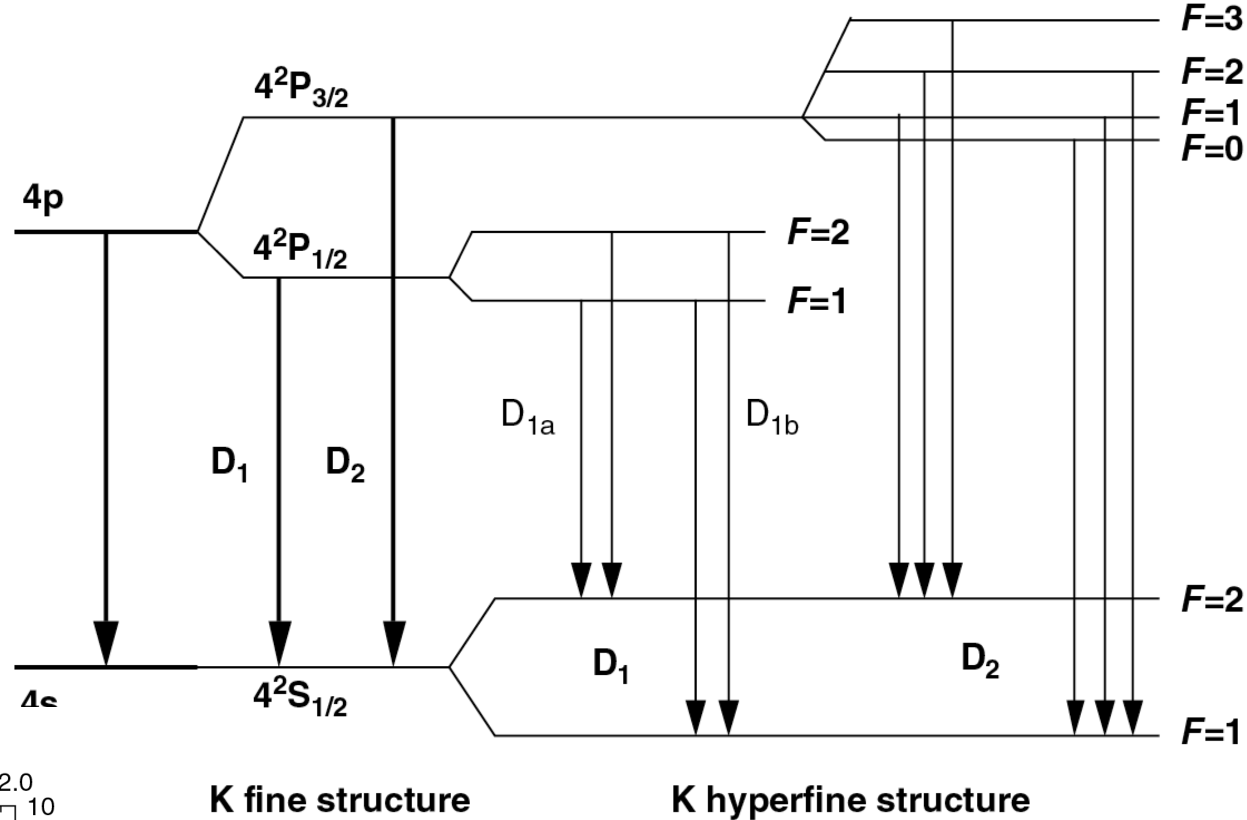


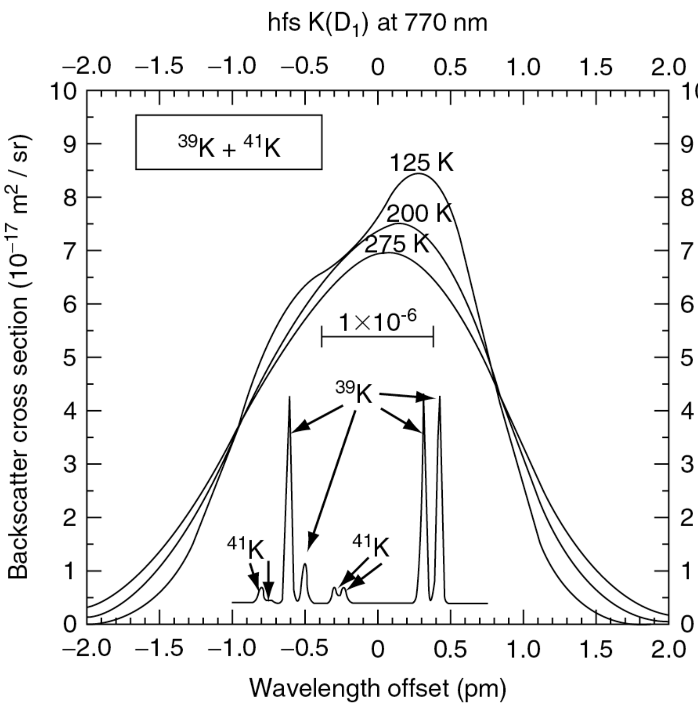
Metal Species in MLT Region

Species	Central wavelength (nm)	A_{ki} ($\times 10^8$ s^{-1})	Degeneracy g_k / g_i	Atomic Weight	Isotopes	Doppler rms Width (MHz)	σ_0 ($\times 10^{-12}$ cm^2)	Abundance ($\times 10^9$ cm^{-2})	Centroid Altitude (km)	Layer rms Width (km)
Na (D_2)	589.1583	0.616	4 / 2	22.98977	23	456.54	14.87	4.0	91.5	4.6
Fe	372.0995	0.163	11 / 9	55.845	54, 56, 57, 58	463.79	0.944	10.2	88.3	4.5
K (D_1)	770.1088	0.382	2 / 2	39.0983	39, 40, 41	267.90	13.42	4.5×10^{-2}	91.0	4.7
K (D_2)	766.702	0.387	4 / 2	39.0983	39, 40, 41	267.90	26.92	4.5×10^{-2}	91.0	4.7
Ca	422.793	2.18	3 / 1	40.078	40, 42, 43, 44, 46, 48	481.96	38.48	3.4×10^{-2}	90.5	3.5
Ca^+	393.777	1.47	4 / 2	40.078	Same as Ca	517.87	13.94	7.2×10^{-2}	95.0	3.6

- In principle, all these species can be used as trace atoms for resonance fluorescence Doppler lidar measurements.
- Whether a Doppler lidar can be developed and used mainly depends on the availability and readiness of laser and electro-optic technologies. In addition, the constituent abundance and absorption cross-section are naturally determined.

K Atomic Energy Levels





Transition	K(D_1)	K(D_2)
Wavelength air [nm]	769.8974	766.4911
Wavelength vacuum [nm]	770.1093	766.7021
Rel. intensity	24	25
A_{ik} [$10^8 s^{-1}$]	0.382 (±10%)	0.387 (±10%)
f-value	0.340	0.682
Terms $^{2S+1}L_J$	$^2S_{1/2} - ^2P^o_{1/2}$	$^2S_{1/2} - ^2P^o_{3/2}$
$g_i - g_k$	2-2	2-4

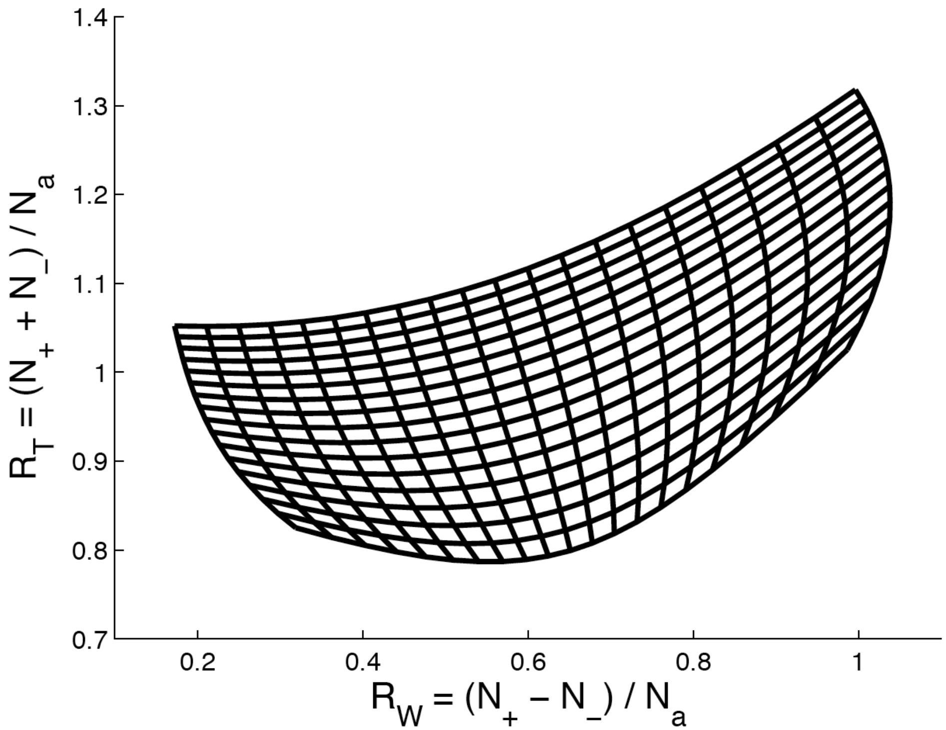
K Atomic Parameters

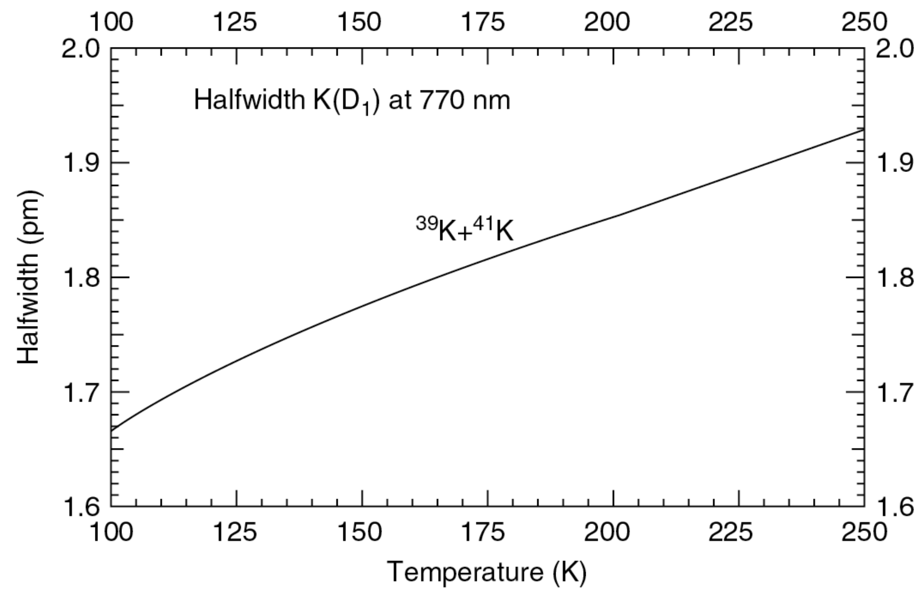
Isotope	Atomic mass	Abundance	Nuclear spin	$K(D_1)$ line shift
39	38.963 706 9(3)	0.932 581(44)	$I = 3/2$	0
40	39.963 998 67(29)	0.000 117(1)	$I = 4$	125.58 MHz
41	40.961 825 97(28)	0.067 302(44)	$I = 3/2$	235.28 MHz

Table 5.8 Quantum Numbers, Frequency Offsets, and Relative Line Strength for K (D_1) Hyperfine Structure Lines

$^2S_{1/2}$	$^2P_{1/2}$	^{39}K (MHz)	^{41}K (MHz)	Relative Line Strength
$F=1$	$F=2$	310	405	5/16
	$F=1$	254	375	1/16
$F=2$	$F=2$	−152	151	5/16
	$F=1$	−208	121	5/16

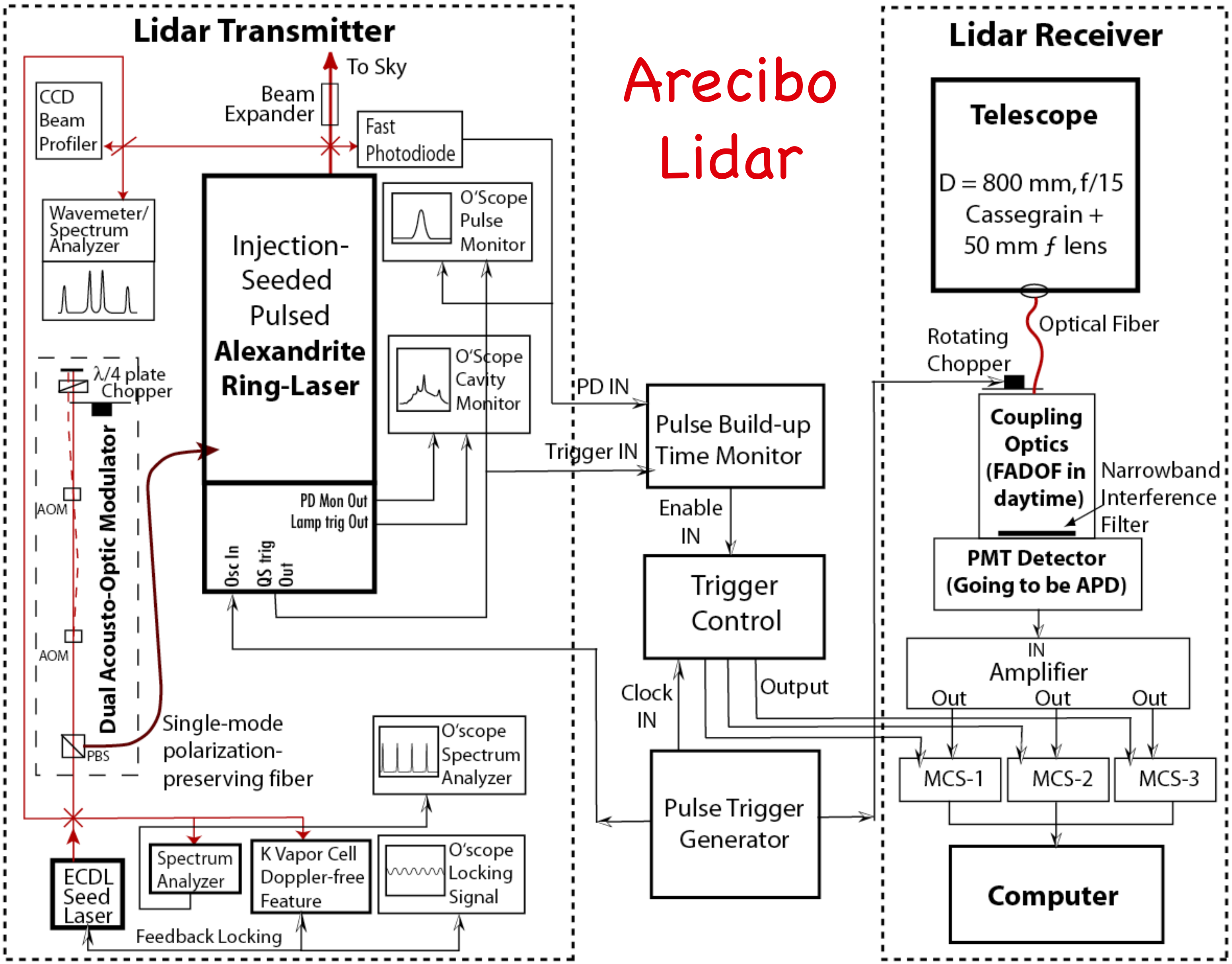
K Doppler Lidar Principle & Metrics





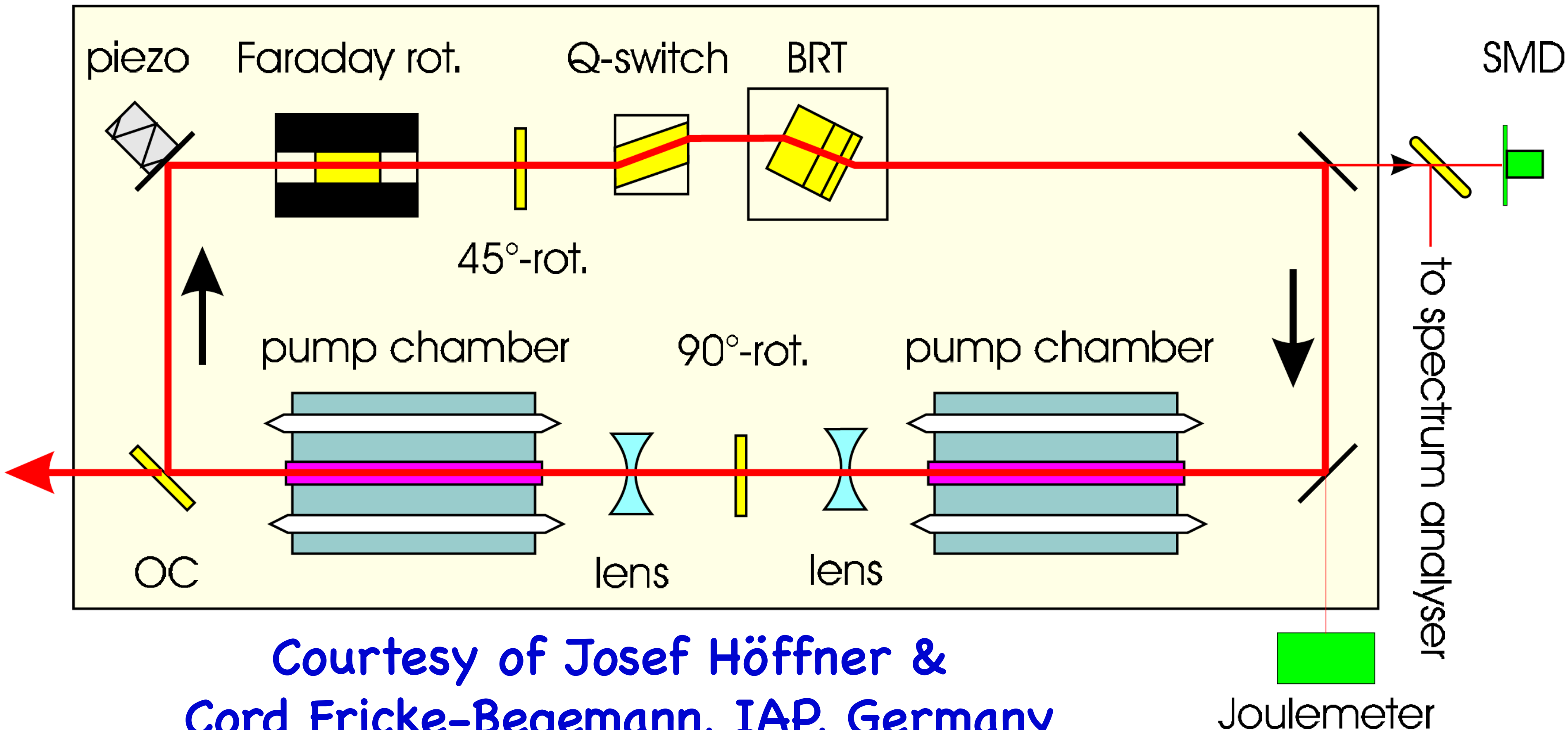
- Ratio technique versus scanning technique
- Scanning technique actually has its advantages on several aspects, depending on the laser system used – whether there is pedestal, background problems, etc.
- Ratio technique usually gives higher resolution.

K Doppler Lidar Instrumentation



[Friedman and Chu, JGR, 2007]

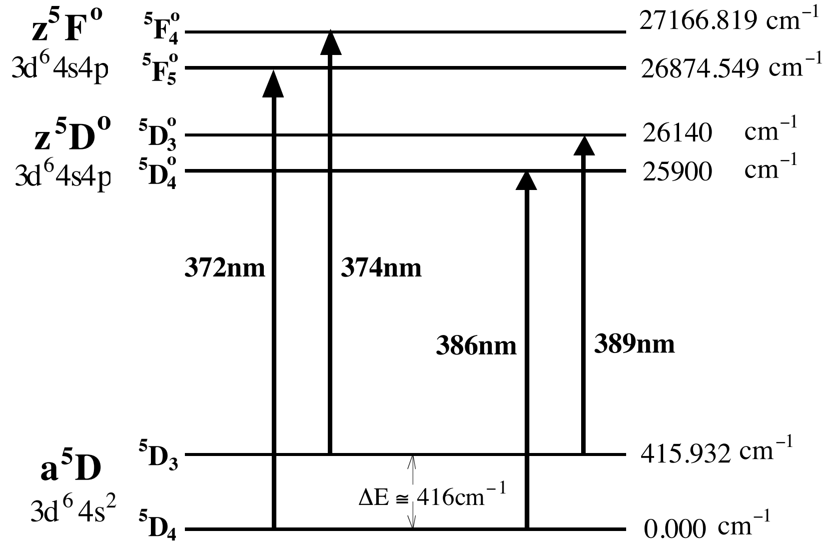
IAP Scanning K Doppler Lidar

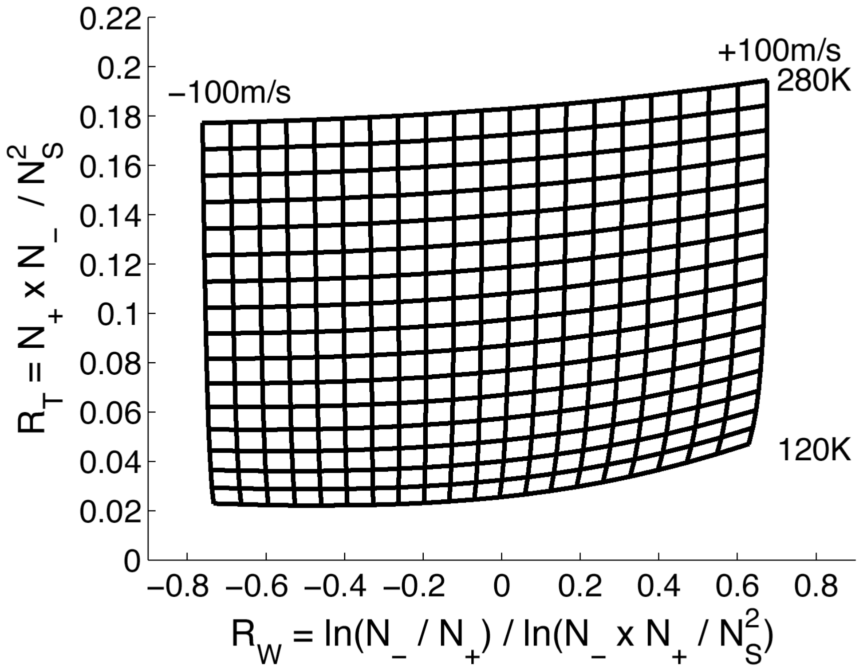


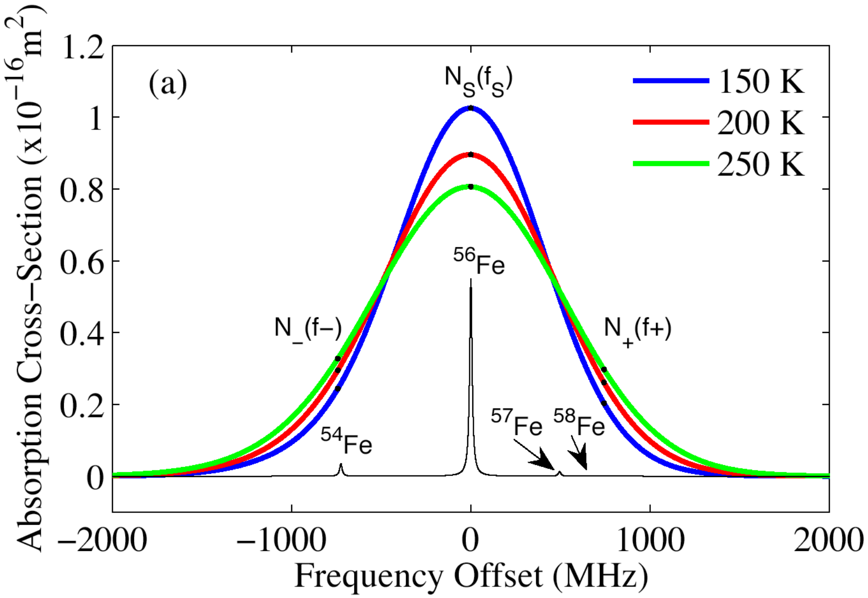
Courtesy of Josef Höffner & Cord Fricke-Begemann, IAP, Germany

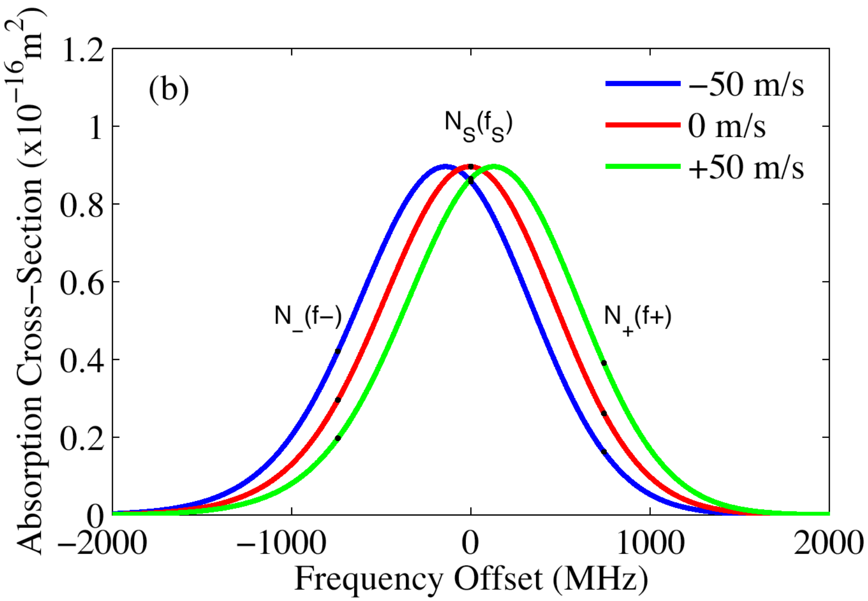
- Based on Light Age, Inc. pulsed alexandrite ring laser, but IAP engineers performed significant in-house development and upgrade.
- The laser frequency is scanned in about 18 channels for temperature-only measurements in MLT region.

Fe Doppler Lidar Principles







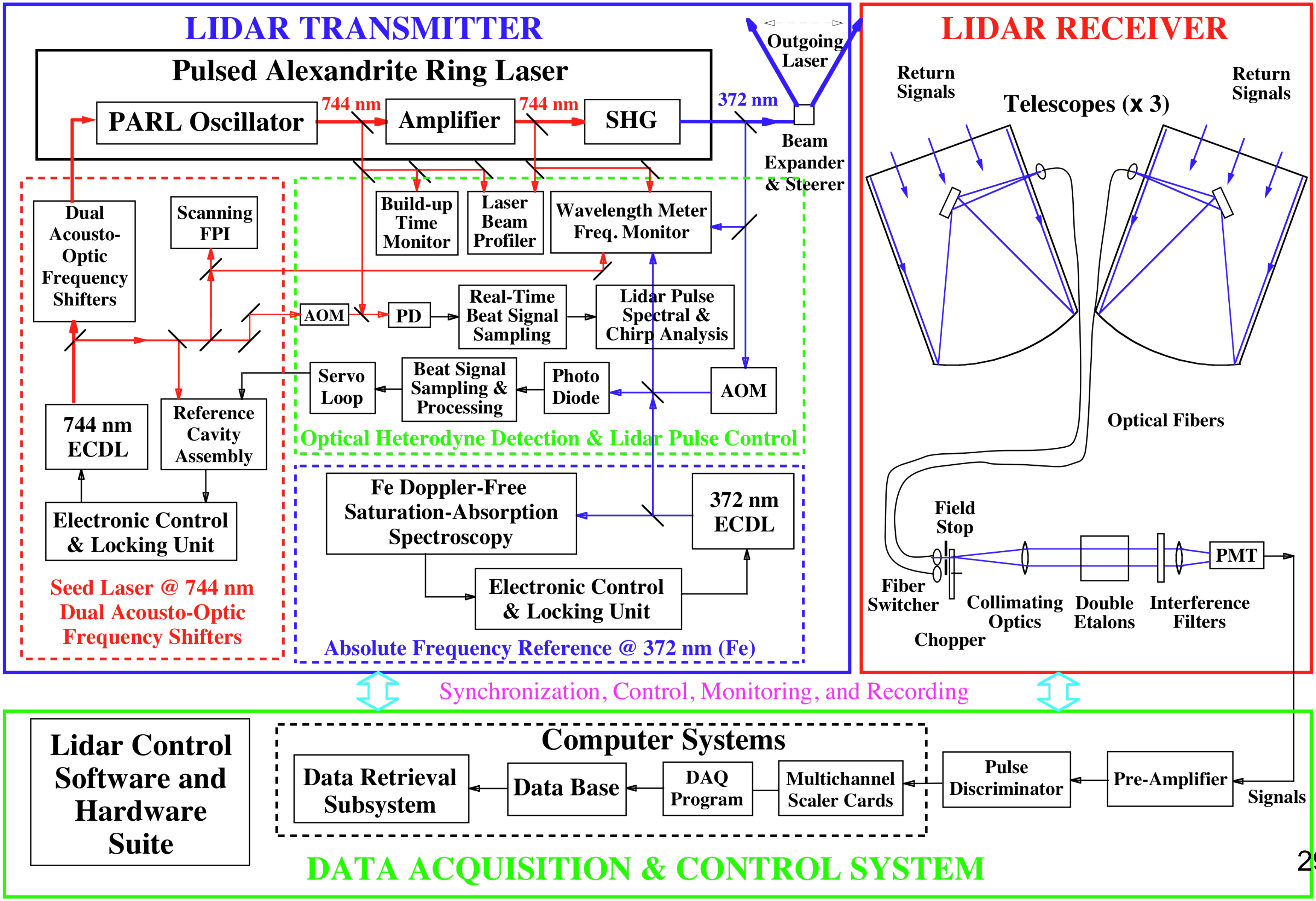


[Chu et al., ILRC, 2008]

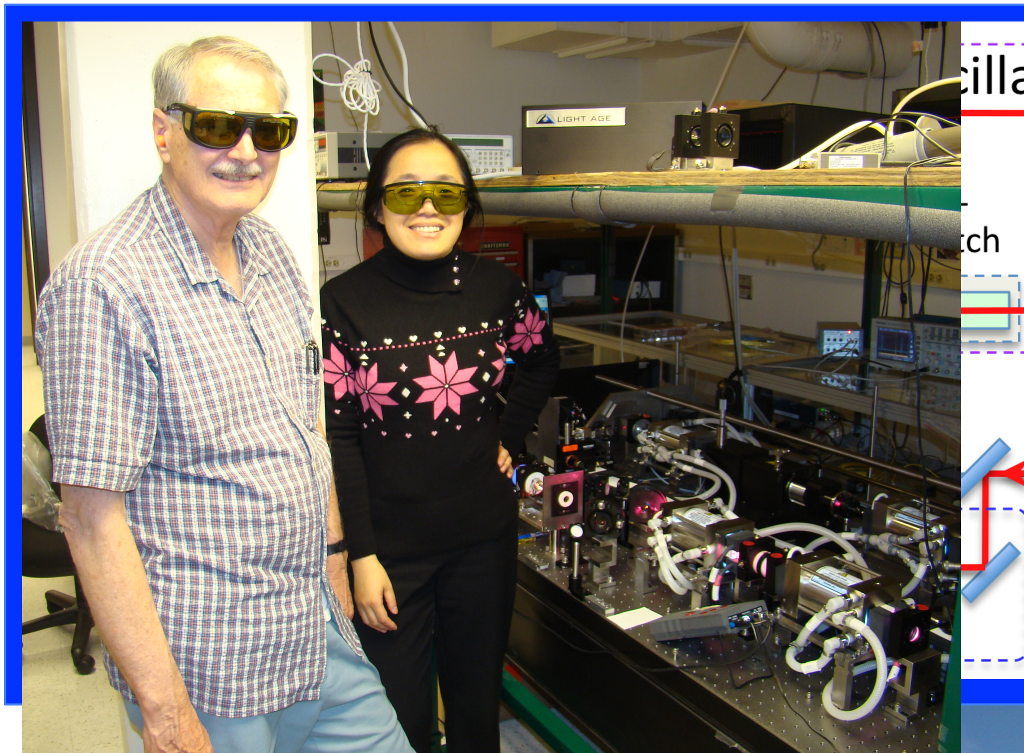
Fe (iron) 372-nm line

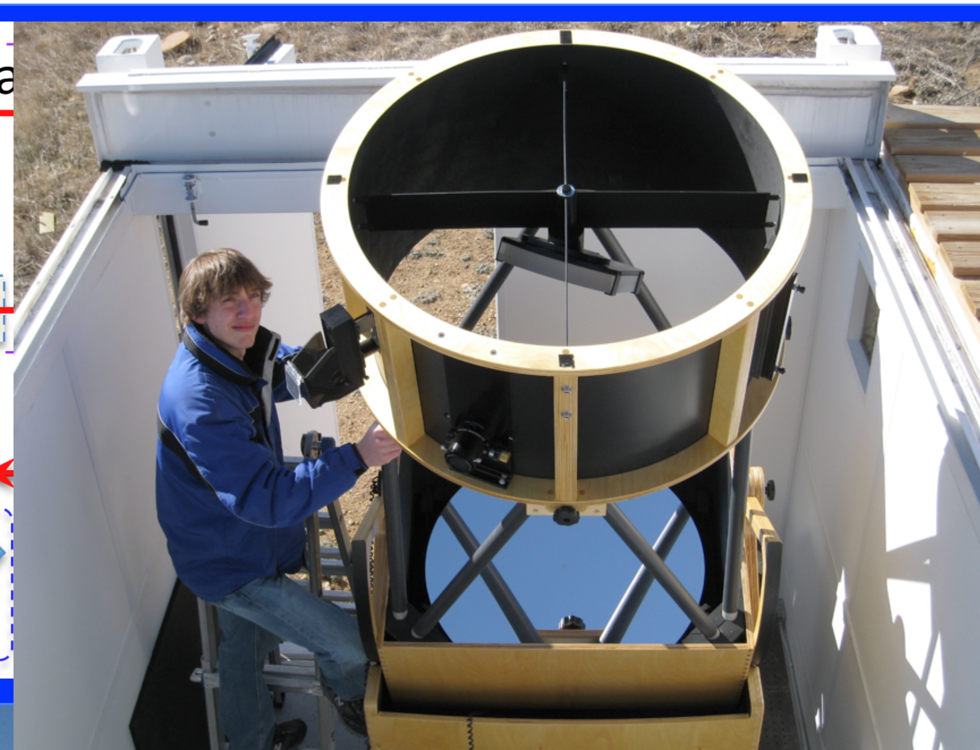
MRI Fe Doppler Lidar

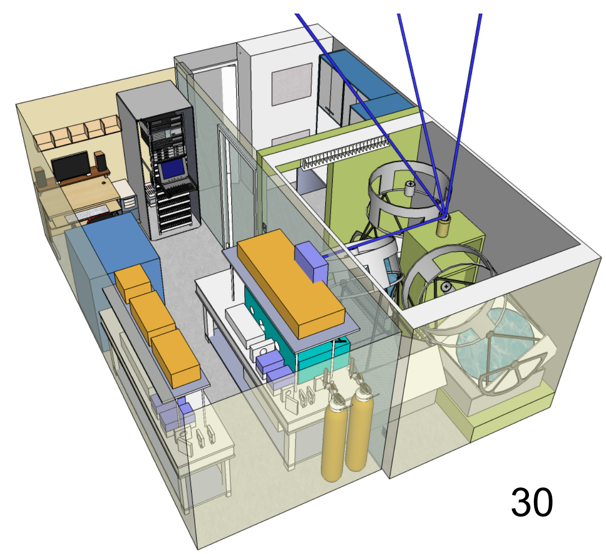
[Chu et al., ILRC, 2010]



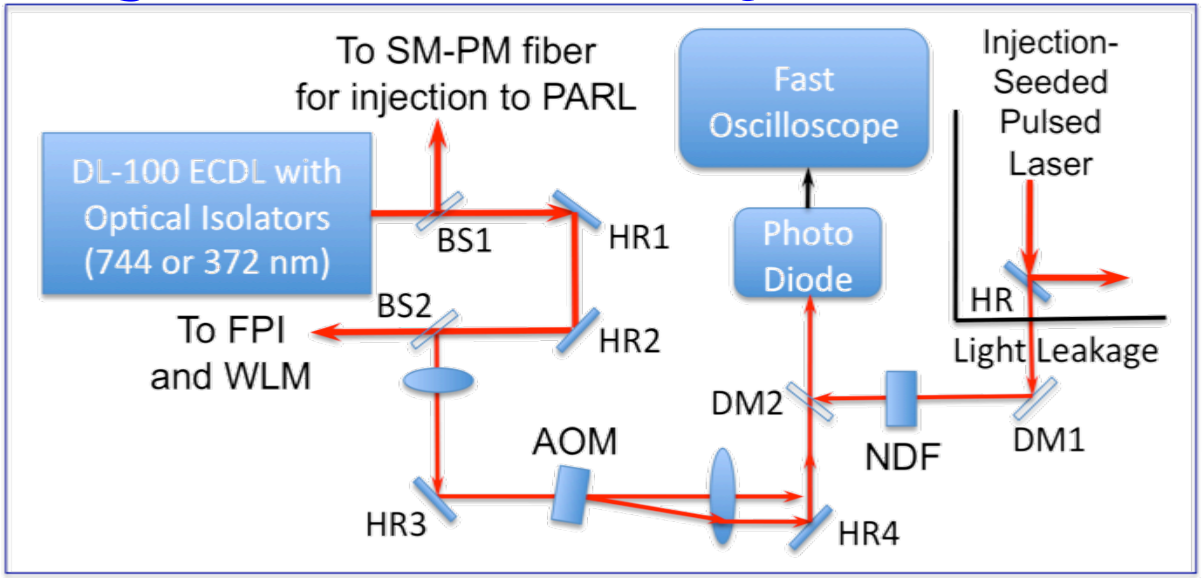
Mobile MRI Fe Doppler Lidar

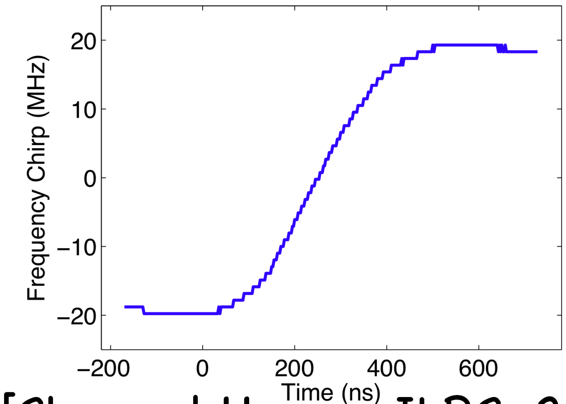




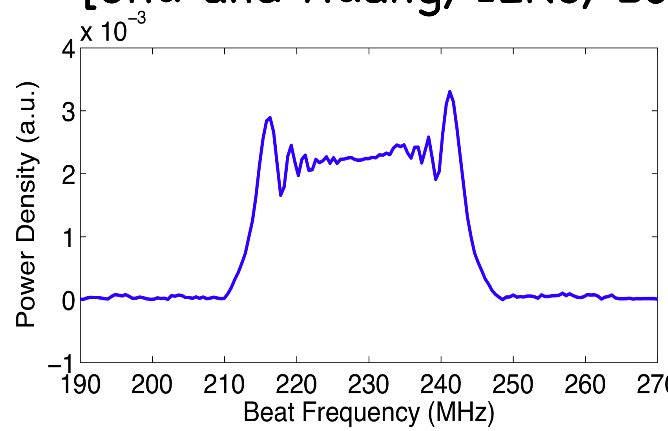


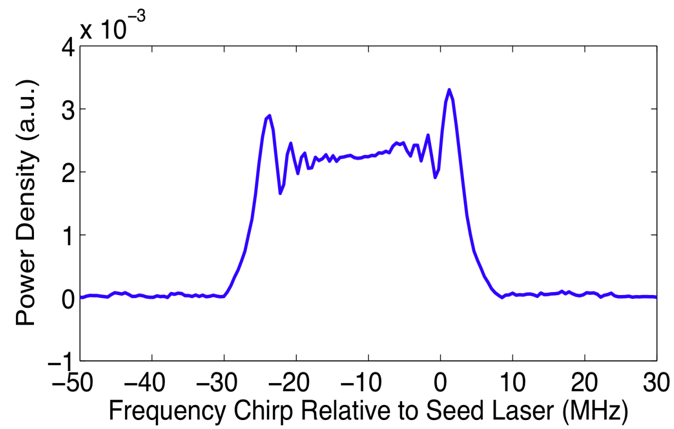
Optical Heterodyne Detection of Laser Pulse

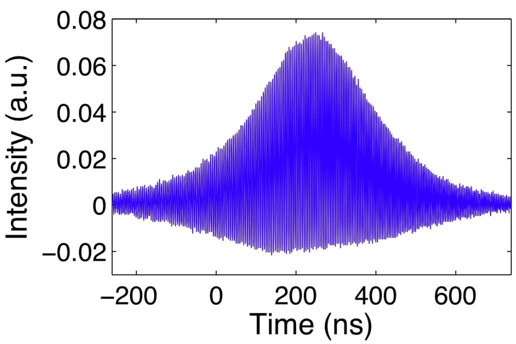


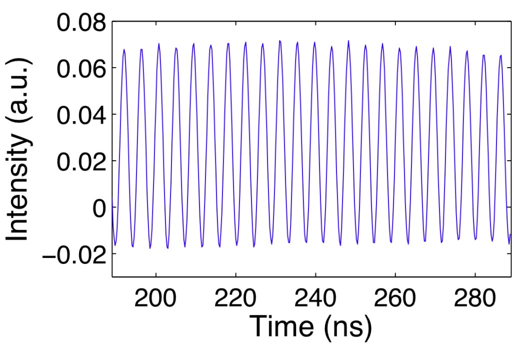


[Chu and Huang, ILRC, 2010]

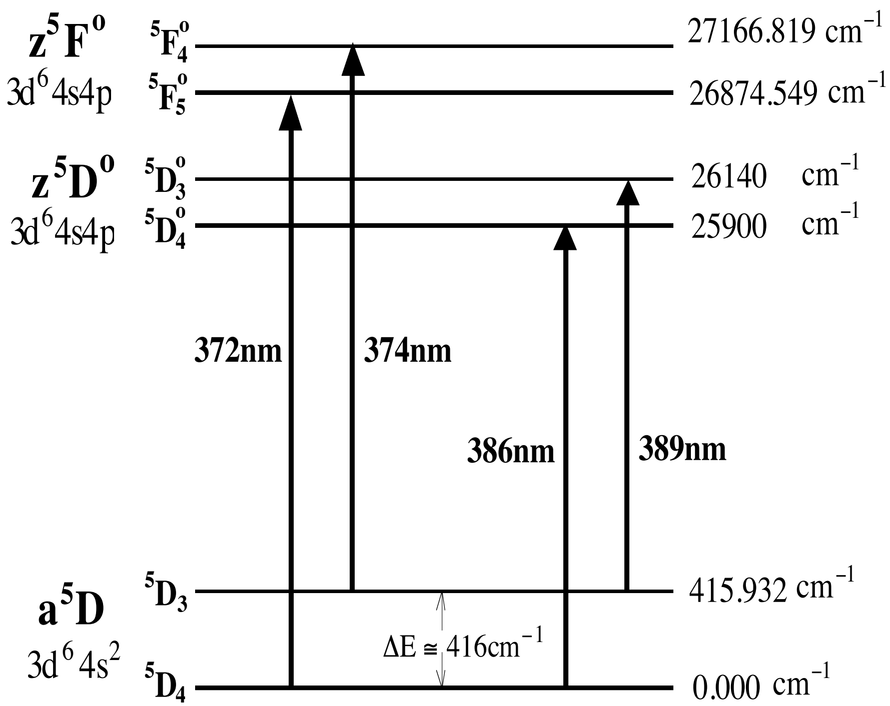


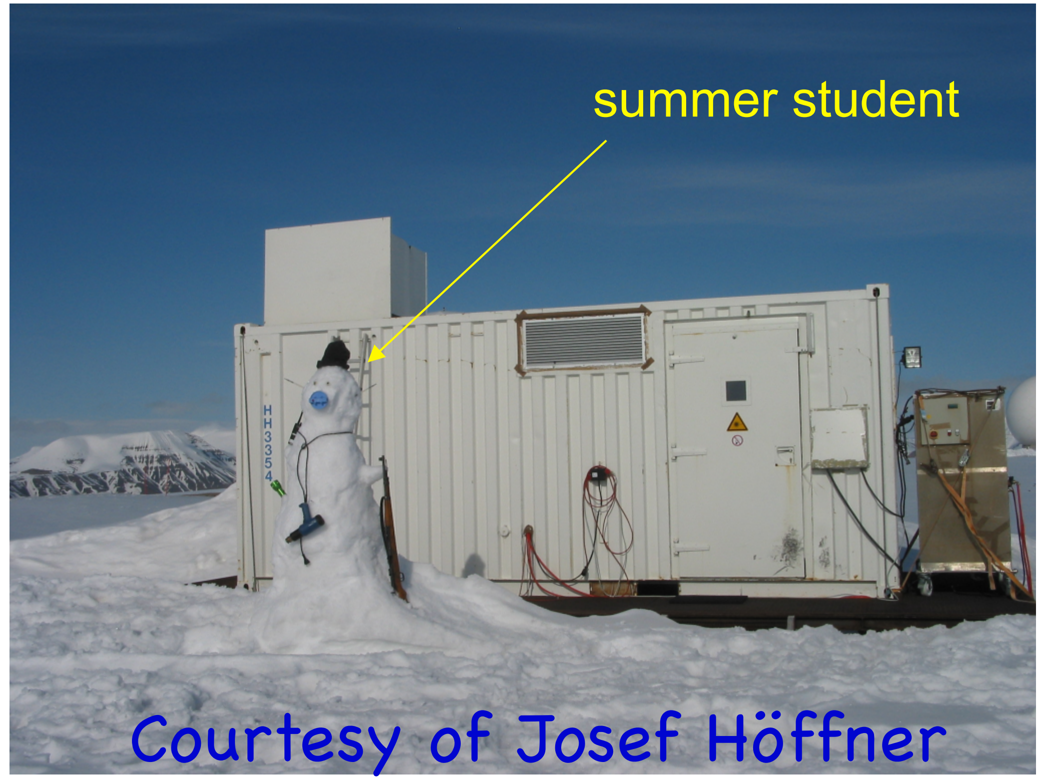






IAP Scanning Fe Doppler Lidar





- 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, …

Summary (1)

- Currently state-of-the-art Na Doppler lidar is the dye-laser-based Na wind and temperature lidar – "ring dye laser + pulsed dye amplifier" configuration.
- One main feature is the narrowband Na lidar transmitter with precise frequency control and narrow laser linewidth: Na Doppler-free fluorescence spectroscopy for frequency calibration and locking, acousto-optic frequency modulator for generating two wing frequencies with high stability and fast switching, pulsed amplification with very low ASE.
- The lidar receiver (broadband) and DAQ subsystems have various styles and forms. They are also progressing rapidly.
- Na Doppler lidar can be realized with other laser configurations, e.g., solid-state Nd:YAG laser frequency mixing, or alexandrite laser Raman shift, etc.

Summary (2)

- There are several different atomic species originating from meteor ablation in the mesosphere and lower thermosphere (MLT) region. They all have the potentials to be tracers for resonance fluorescence Doppler lidars to measure the temperature and wind in MLT region.
- Na and K Doppler lidars are currently near mature status and are making great contributions to MLT science.
- Fe Doppler lidar has very high potential due to the high Fe abundance, advanced alexandrite laser technology, Fe Doppler-free spectroscopy, optical heterodyne detection technology, and bias-free measurement, etc.
- Solid-state Doppler lidars are demanded for science advancement, e.g., space exploration, although dye-laser-based Na Doppler lidar is still the golden standard for now. New Doppler lidar will surpass the classic Na lidar soon!