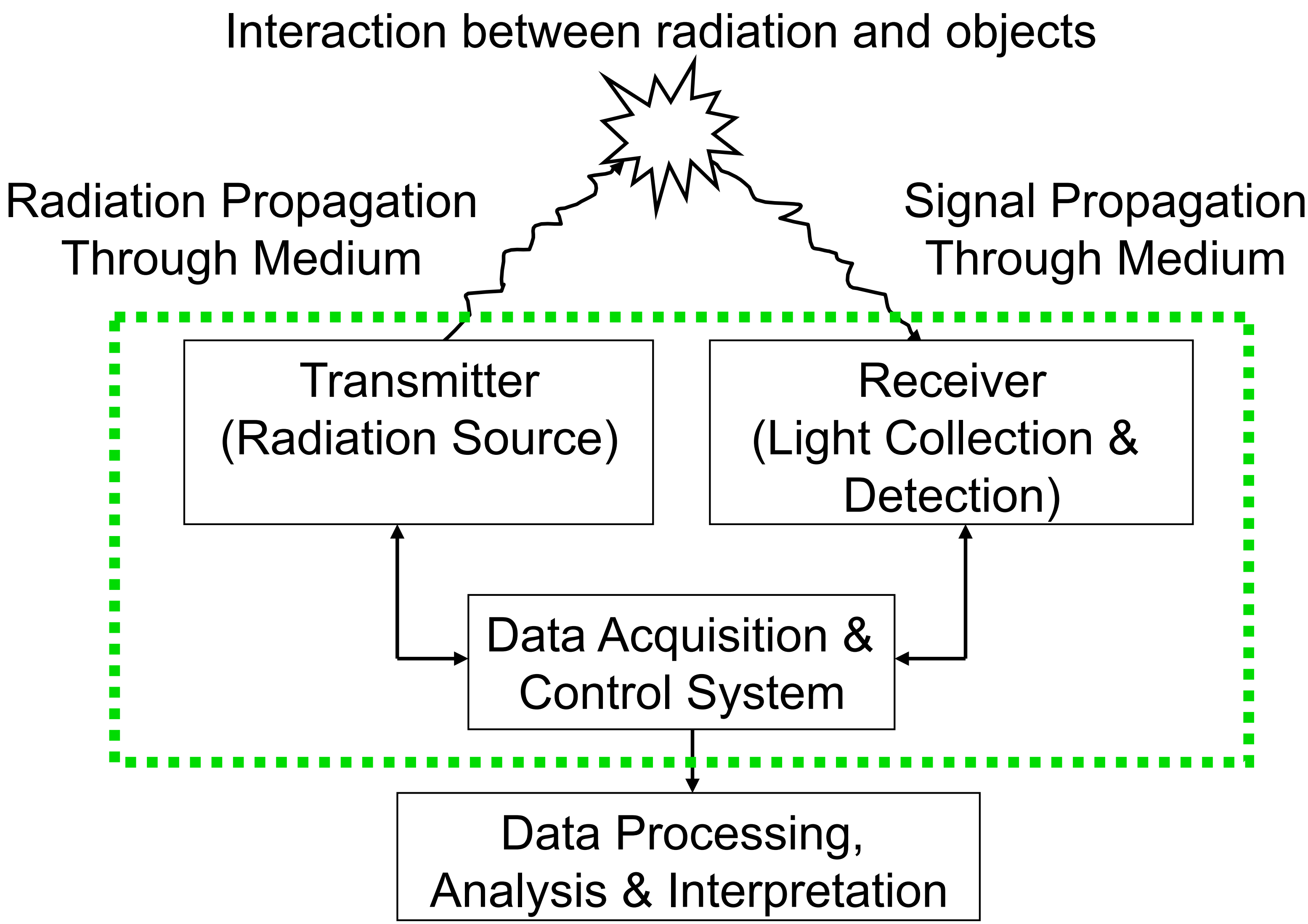
Lecture 13. Temperature Lidar (3)
Resonance Fluorescence Doppler Lidar Instrumentation

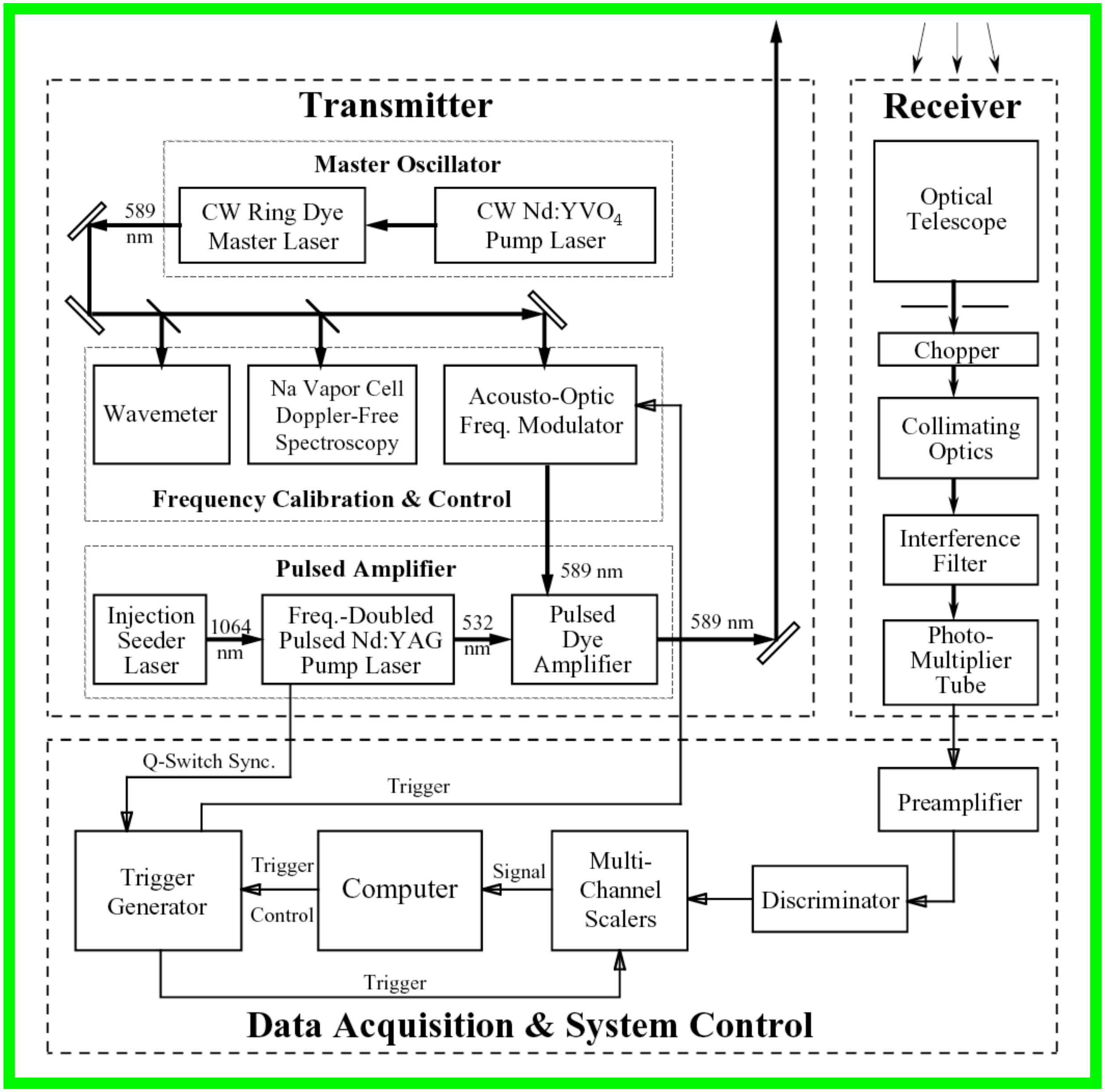
- Introduction
- Na Doppler Lidar Instrumentation
  - Classic Na Doppler Lidar
  - Solid-State Na Doppler Lidar
- Other Resonance Fluorescence Doppler Lidars
  - K Doppler Lidar
  - Fe Doppler Lidar
- Summary

Introduction



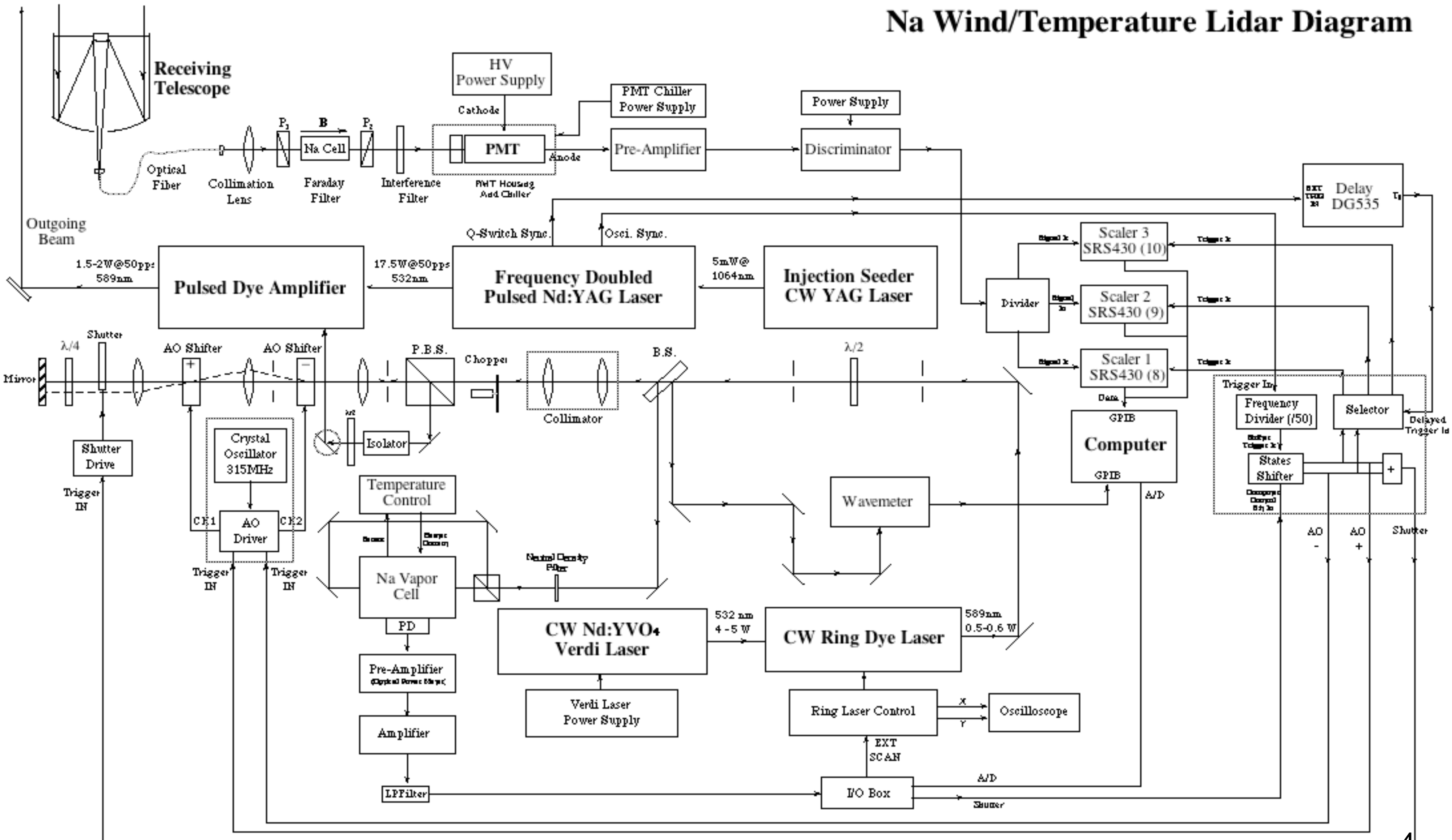
- Resonance Doppler lidar has the frequency discriminator in atmosphere - atomic absorption lines! ⇨ Narrowband transmitter, broadband receiver. ⇨ High signal levels and accurate knowledge on the frequency discriminator!

Classic Na Doppler Lidar

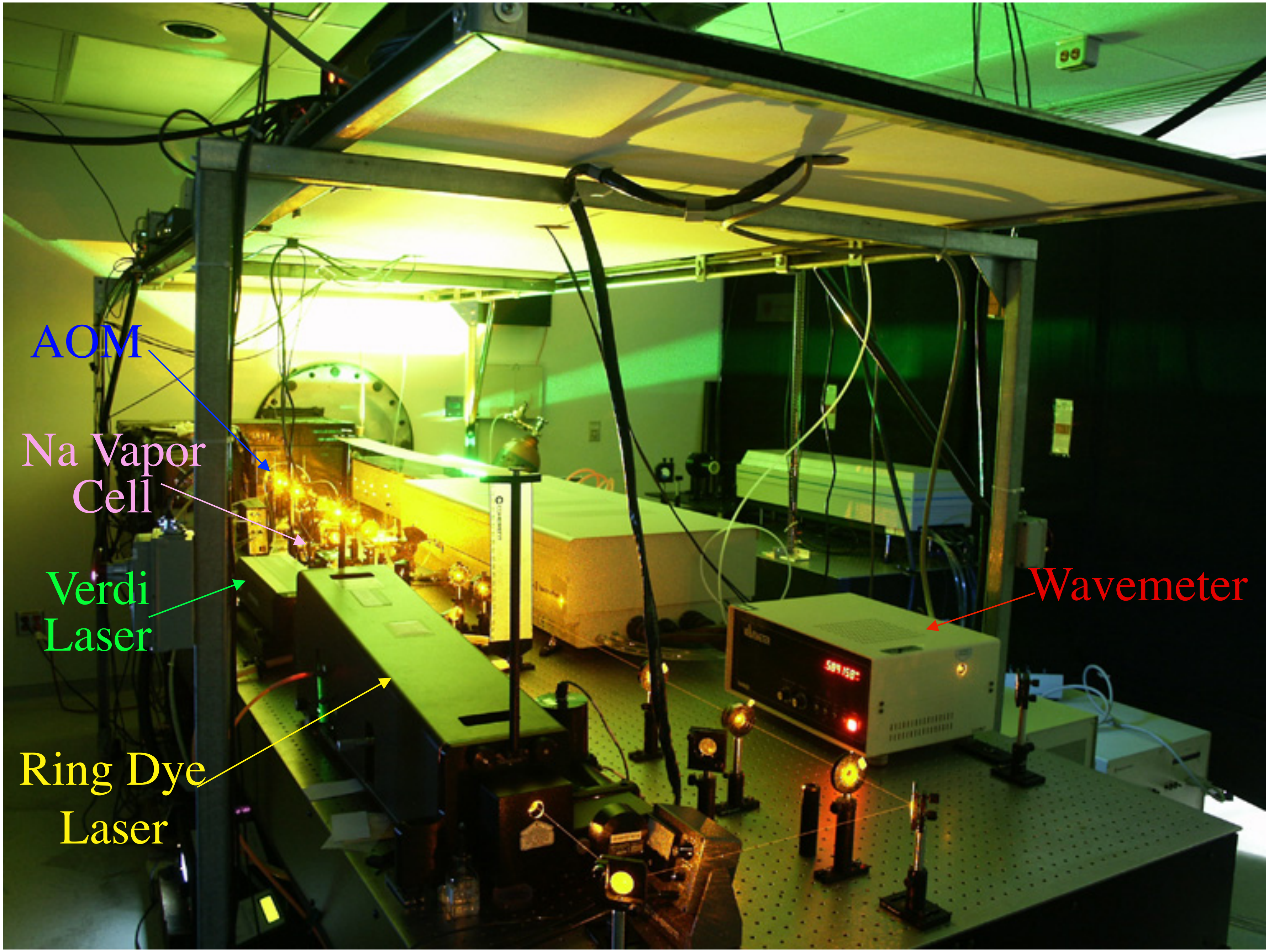


Dye-laser-based Na wind and temperature Lidar (See textbook Chapter 5 by Chu and Papen, 2005)

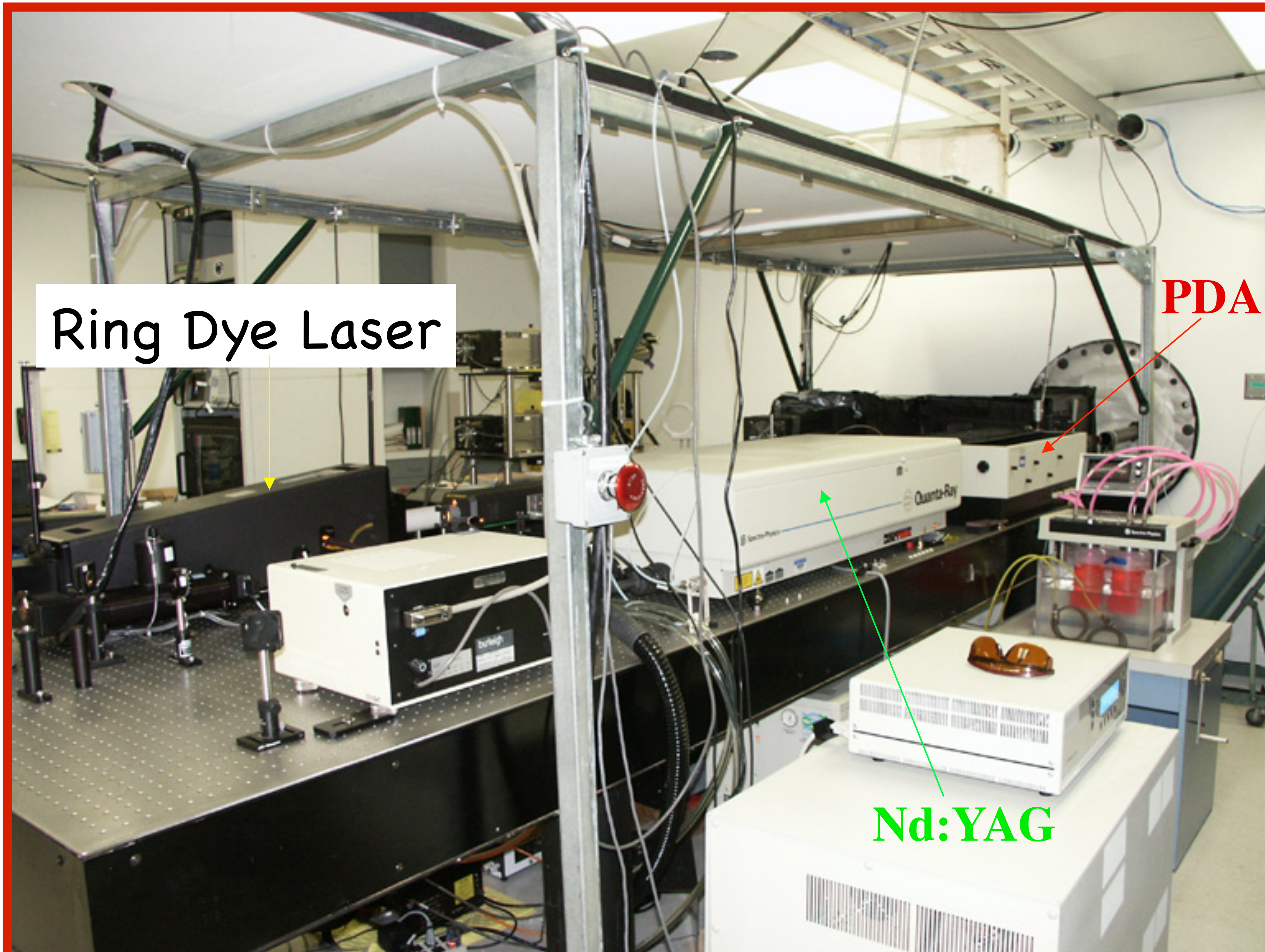
Na Wind and Temperature Lidar



Na Lidar Transmitter Photo 1

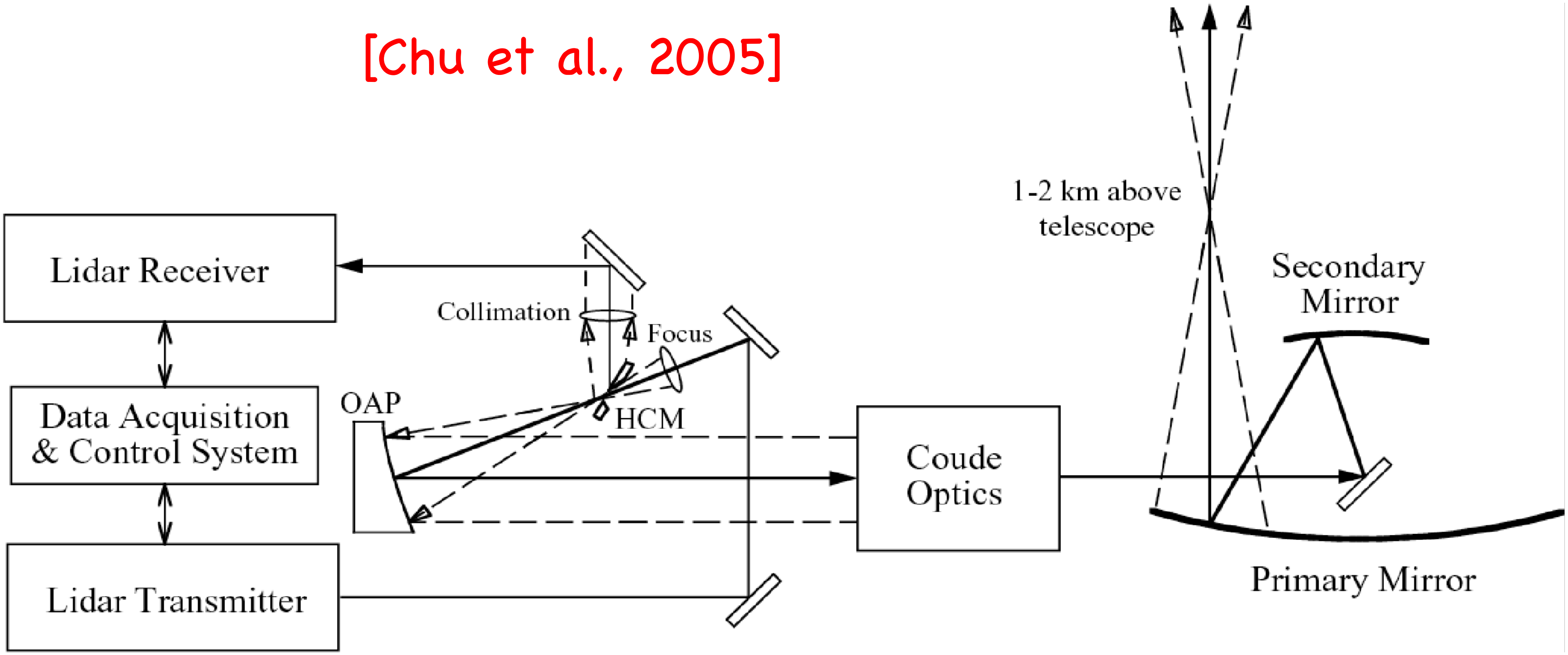


Na Lidar Transmitter Photo 2



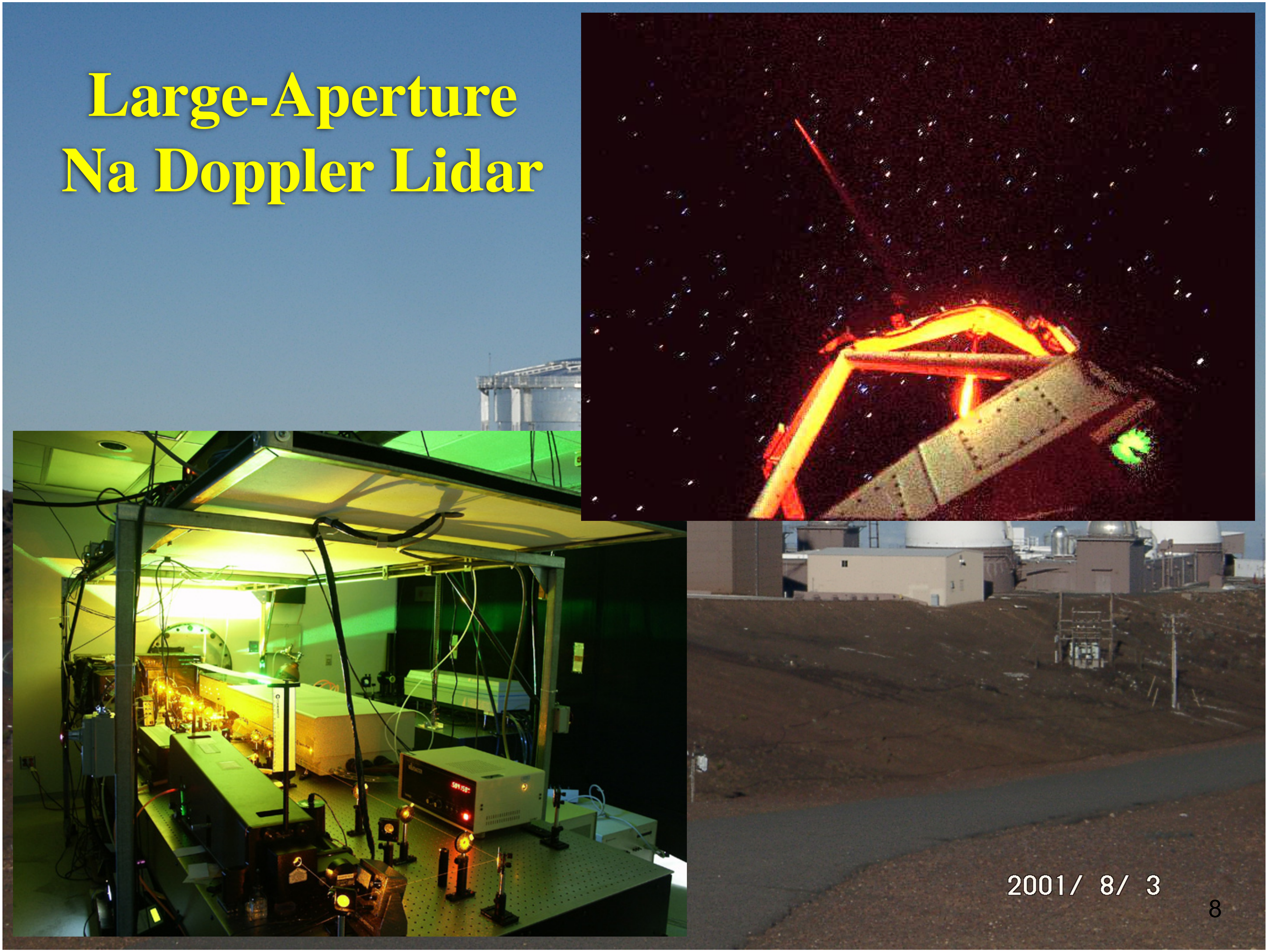
Na Doppler Lidar Receiver

[Chu et al., 2005]



Large-Aperture (3.5m) Steerable Na Doppler Lidar

Large-Aperture Na Doppler Lidar

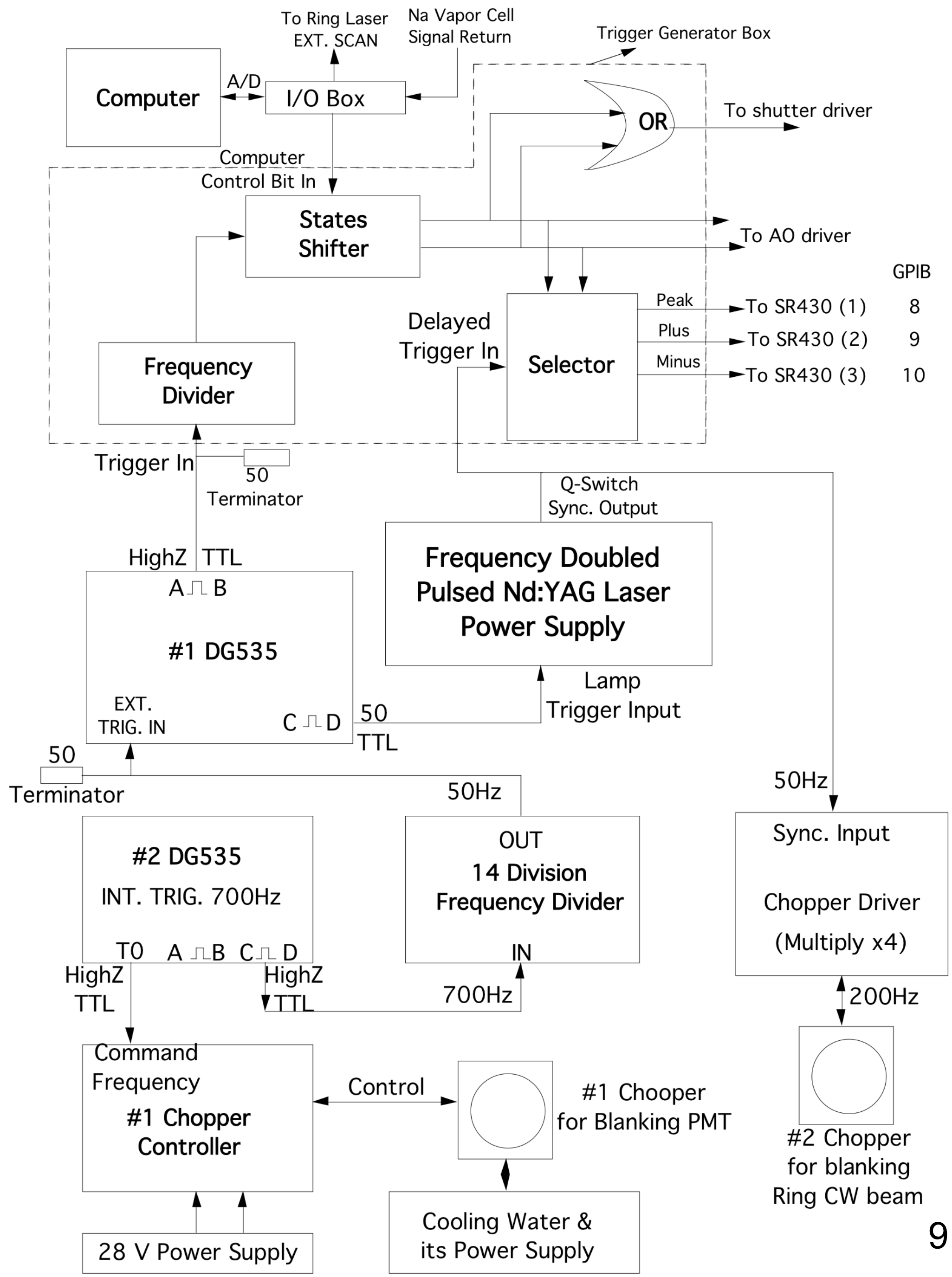


Na Doppler Lidar Control System and Data Acquisition

Recent improvements:

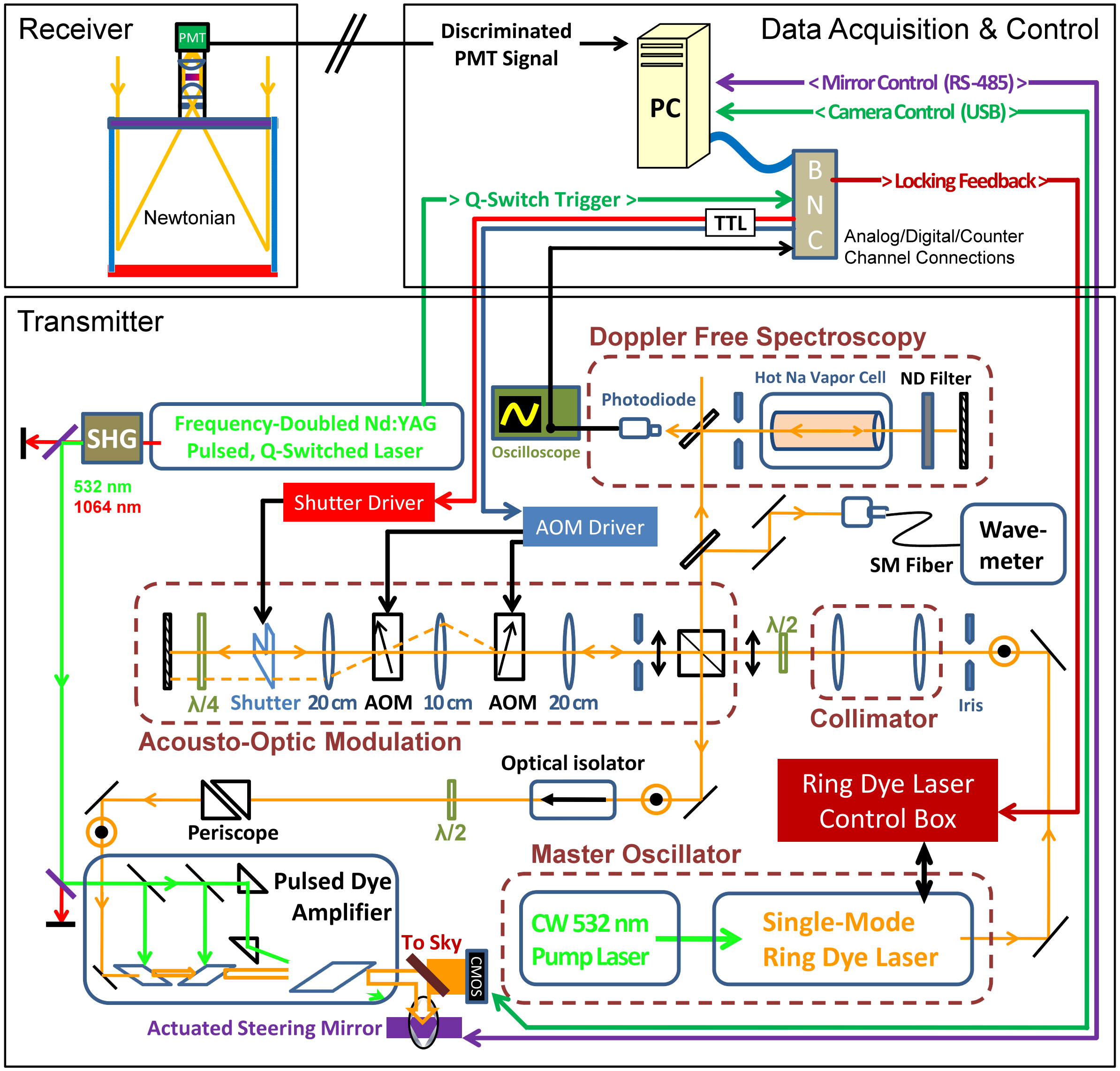
1) Seed laser frequency locking: phase-sensitive
2) Computer-card based multichannel scalers
3) High-QE PMTs
4) Primary-focus larger aperture telescope
5) LabVIEW-based DAQ
6) Daytime capability …

Connection of Na Wind/Temperature Lidar System at MSSC



STAR Na LIDAR

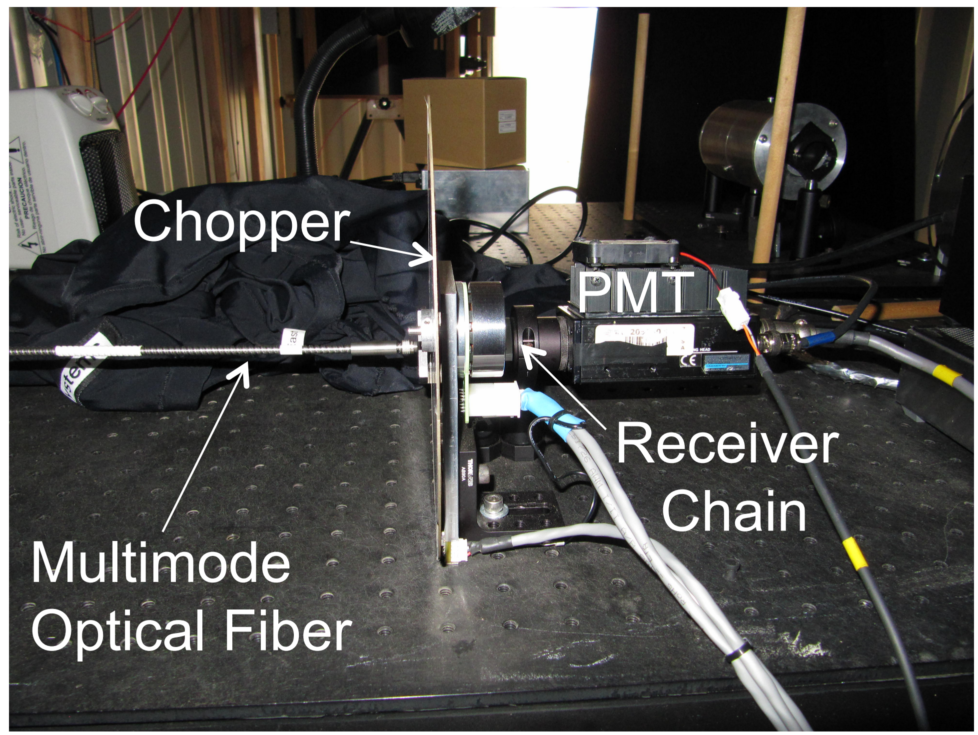
Modernized DAQ, System Control and Receiver



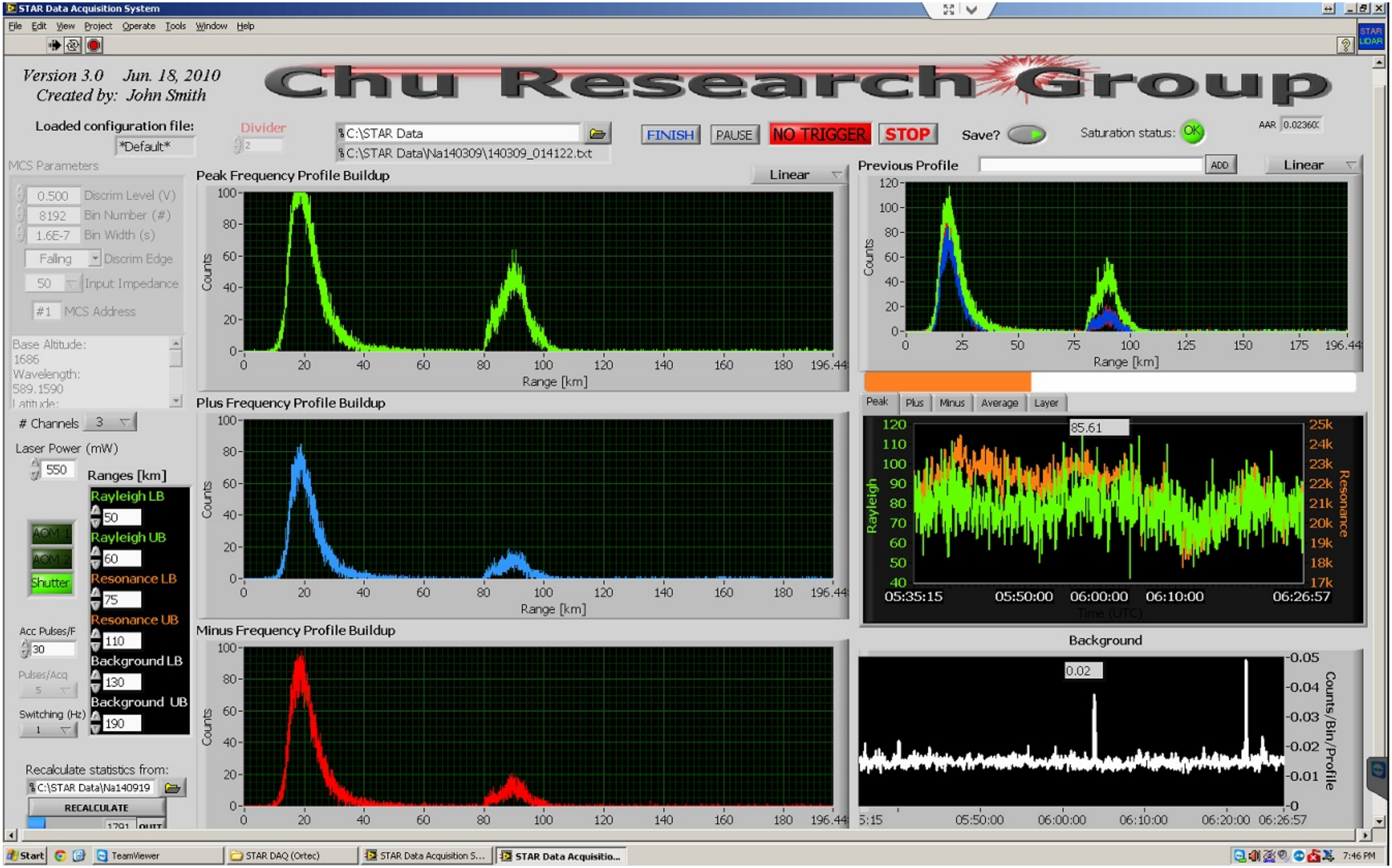
[J. A. Smith, W. Fong, W. Huang, and X. Chu, University of Colorado]

Na Doppler Lidar Receiver

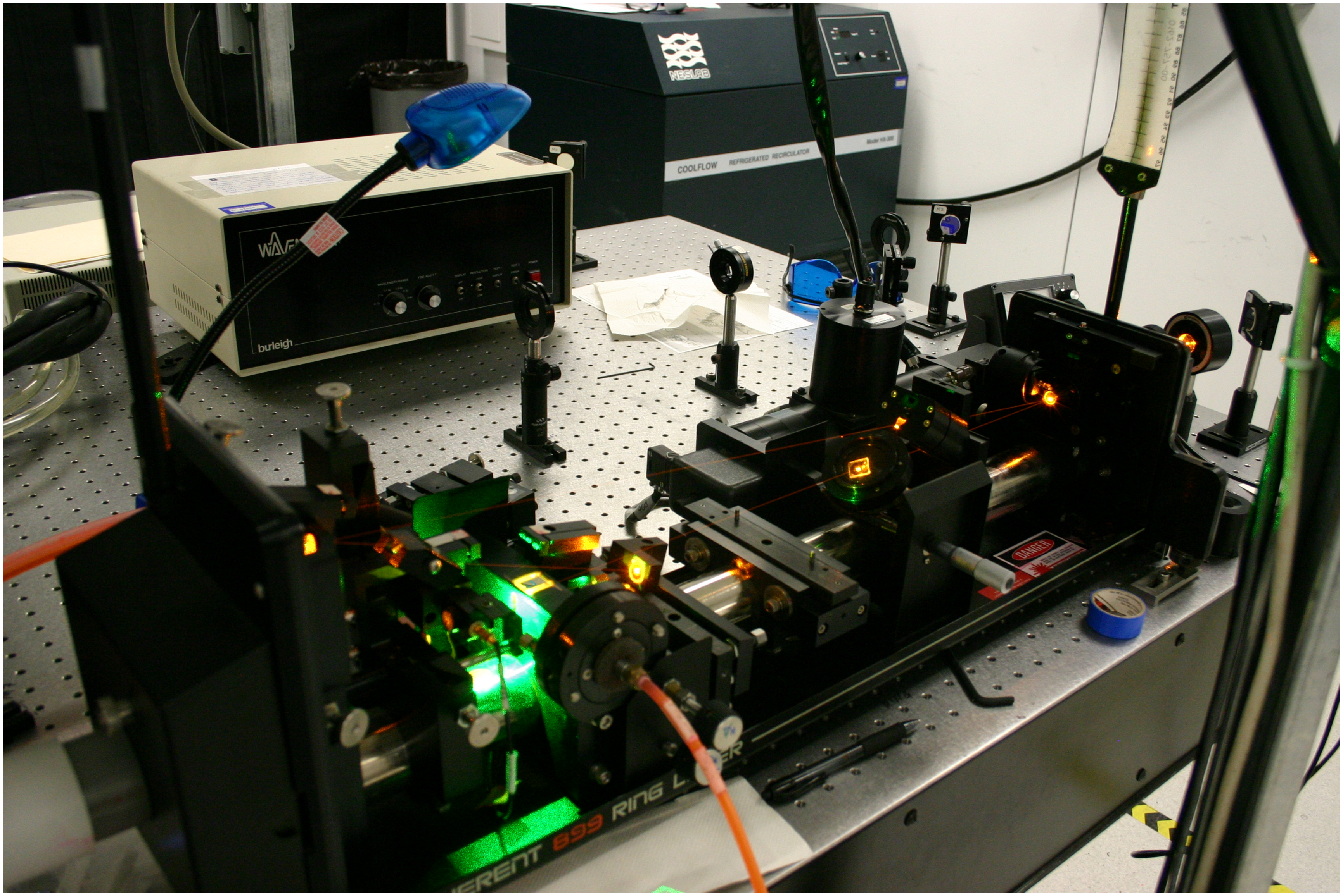
CU-Boulder
STAR Na Doppler Lidar
Primary Focus Telescope
Fiber Coupling



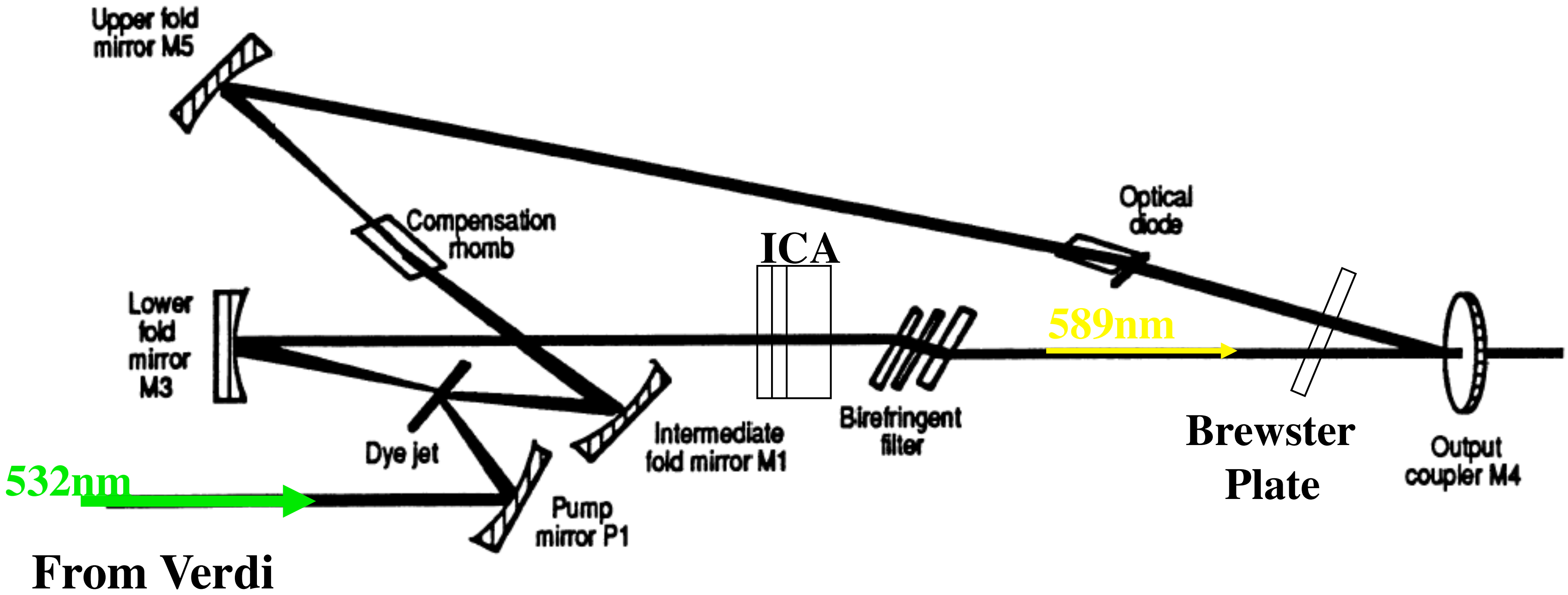
STAR Na Doppler Lidar DAQ



Ring Dye Laser

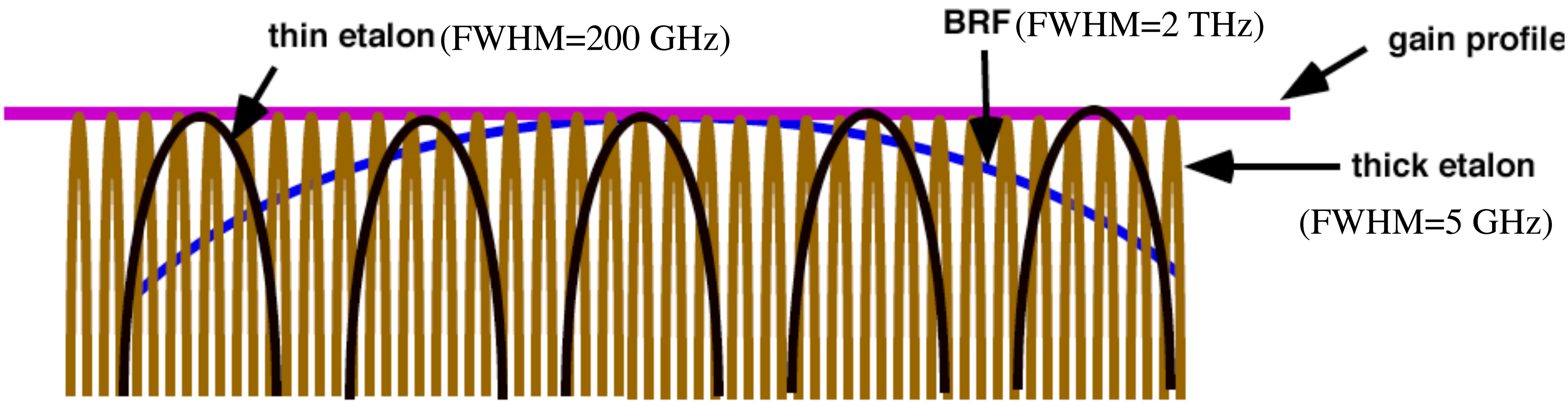


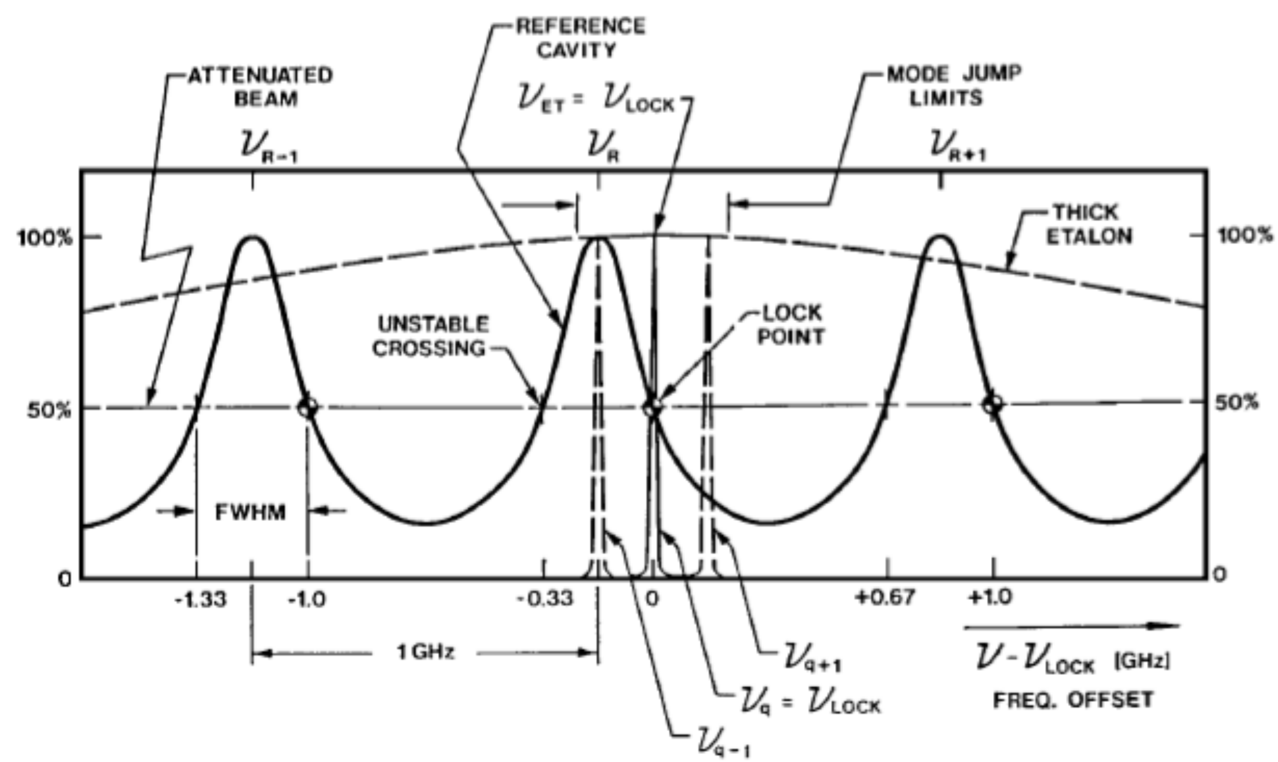
Ring Dye Laser



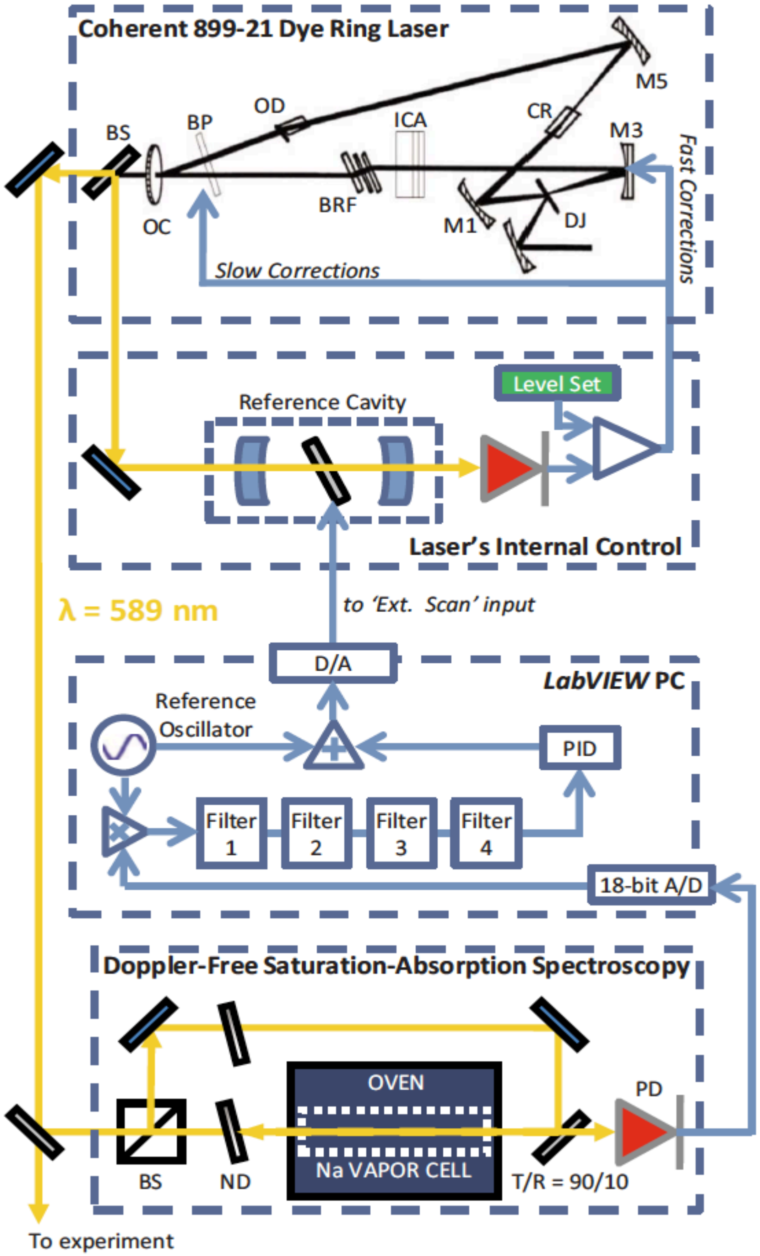
1. "Four mirror + Dye jet" form the laser resonance cavity.
2. Unidirectional lasing prevents spatial hole-burning.
3. Rhomb compensates the astigmatism effect.
4. Optical diode forces the unidirectional lasing.
5. BRF + ICA (etalons) select frequency and narrow bandwidth.
6. "Brewster plate + RCA +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

Frequency Selection in Ring Laser

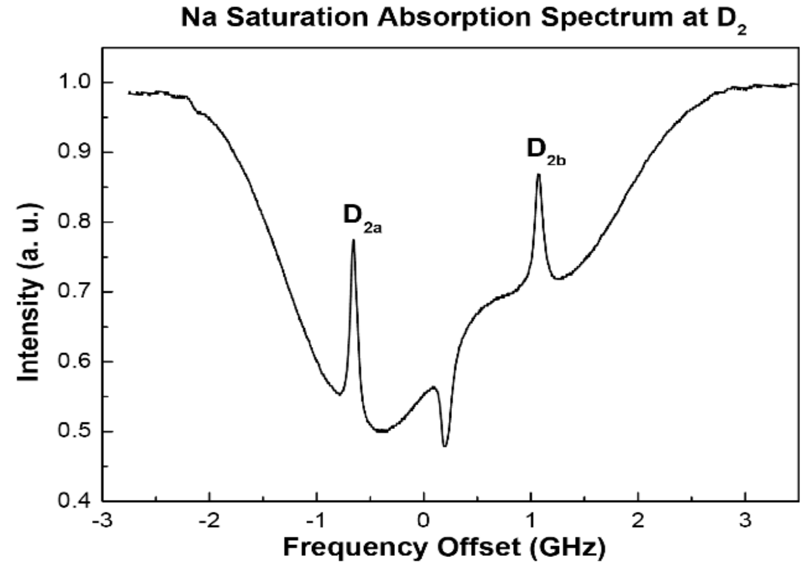




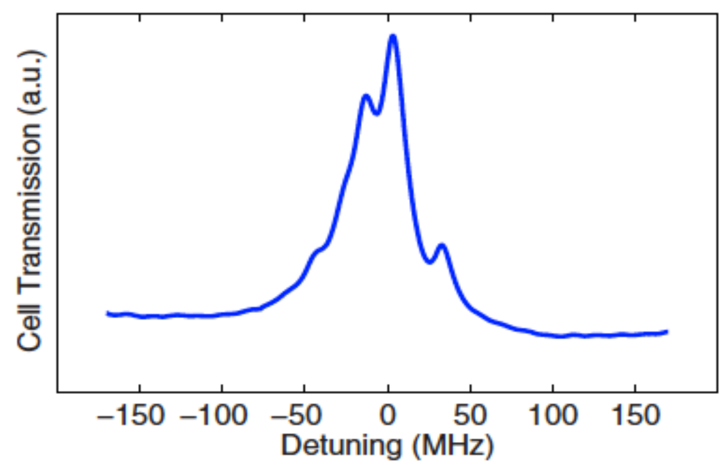
Master Oscillator and Freq Locking with Doppler-Free Spectroscopy



[Smith et al., OE, 2009]

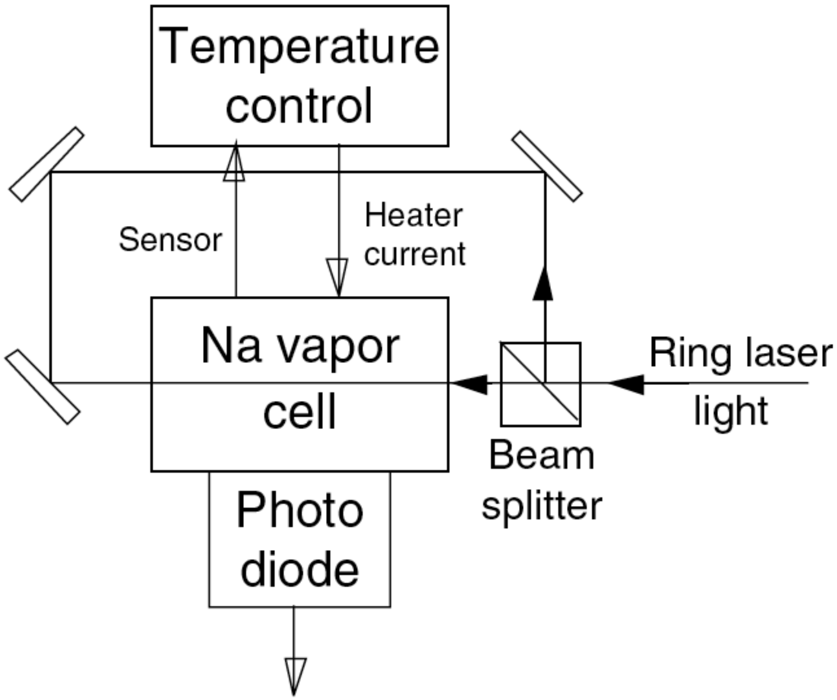


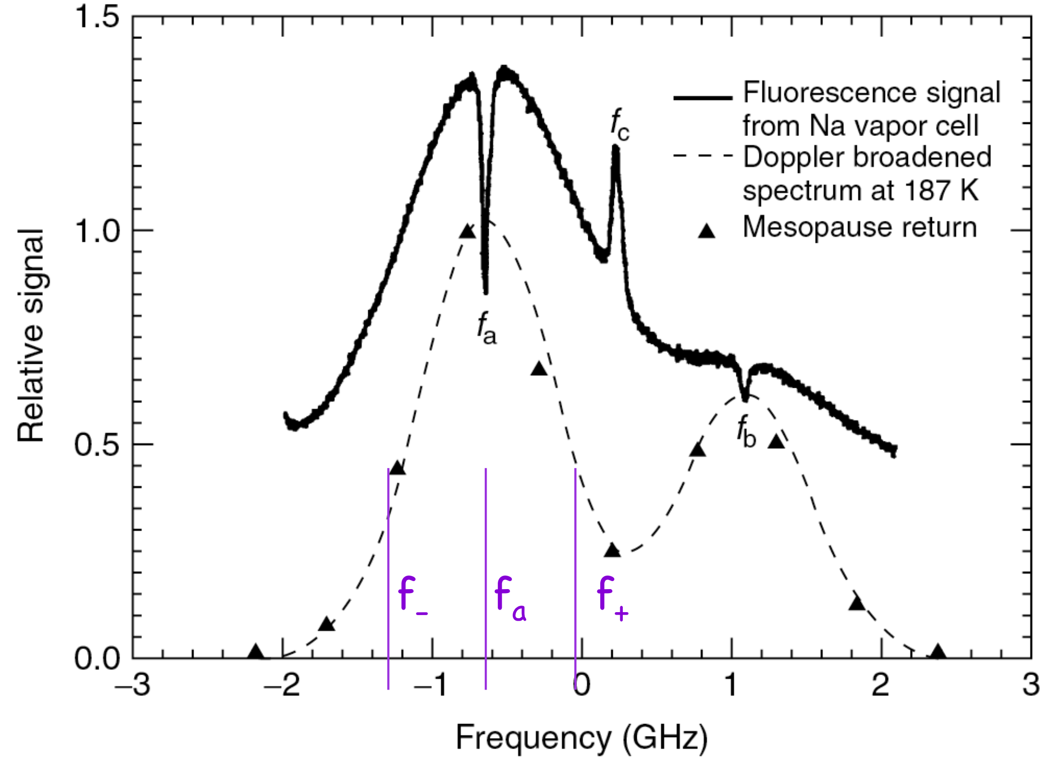
(a) Sodium D_{2a} Doppler–Free Peak



See detailed explanations on Na Doppler-free saturation-fluorescence spectroscopy in Textbook Chapter 5.2.2.3.2

Doppler-Free Na Spectroscopy





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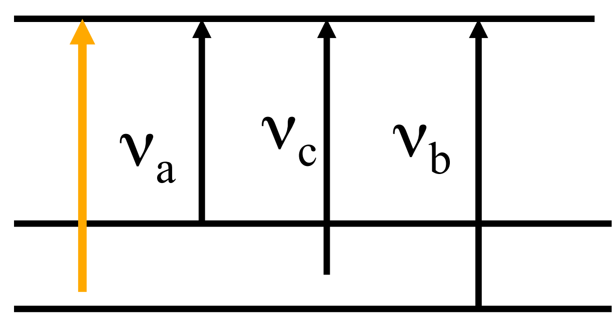
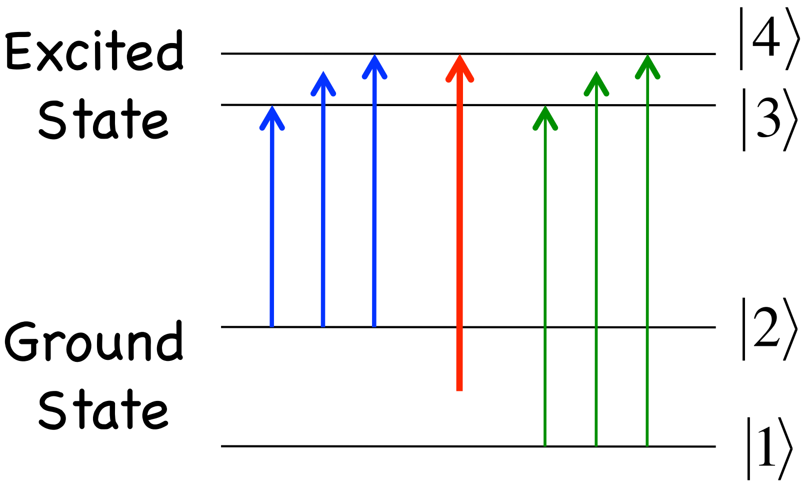
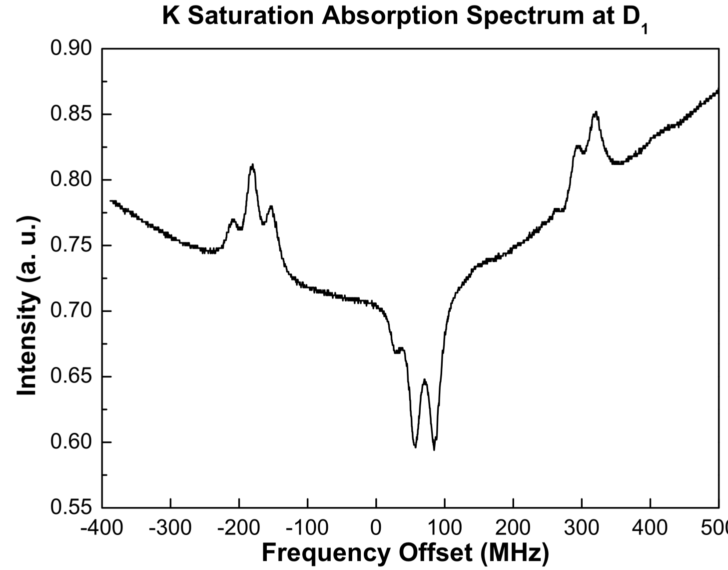
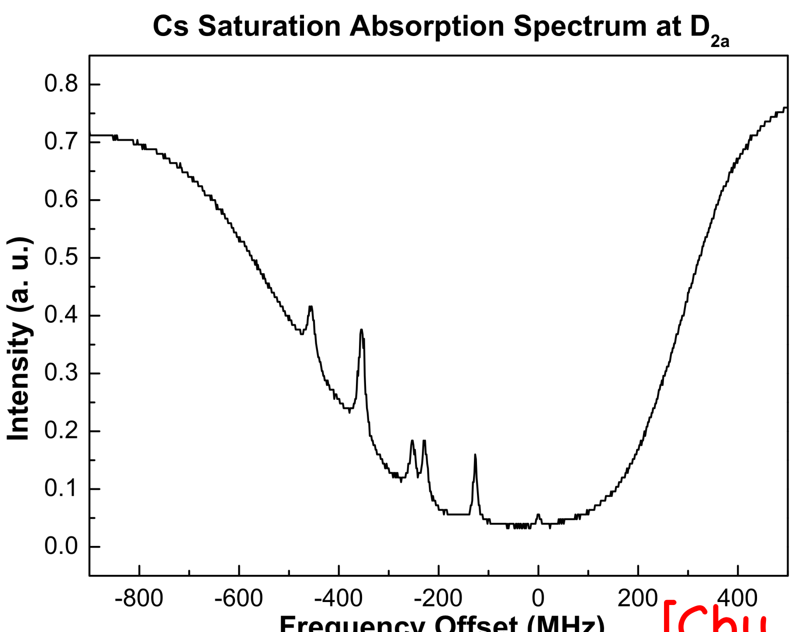


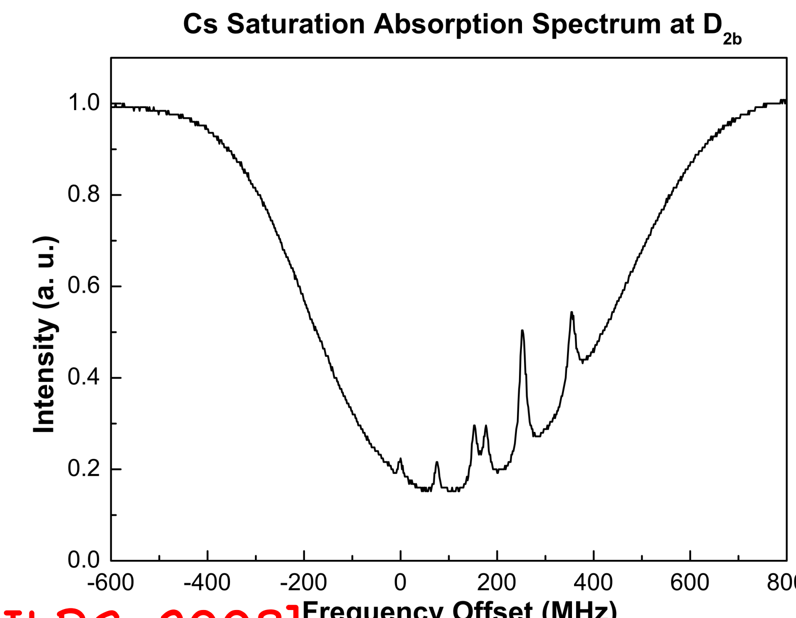
$$\nu_c = (\nu_a + \nu_b)/2$$

Doppler-Free Spectroscopy: Ground-state Cross-over vs. Excited-state Cross-over



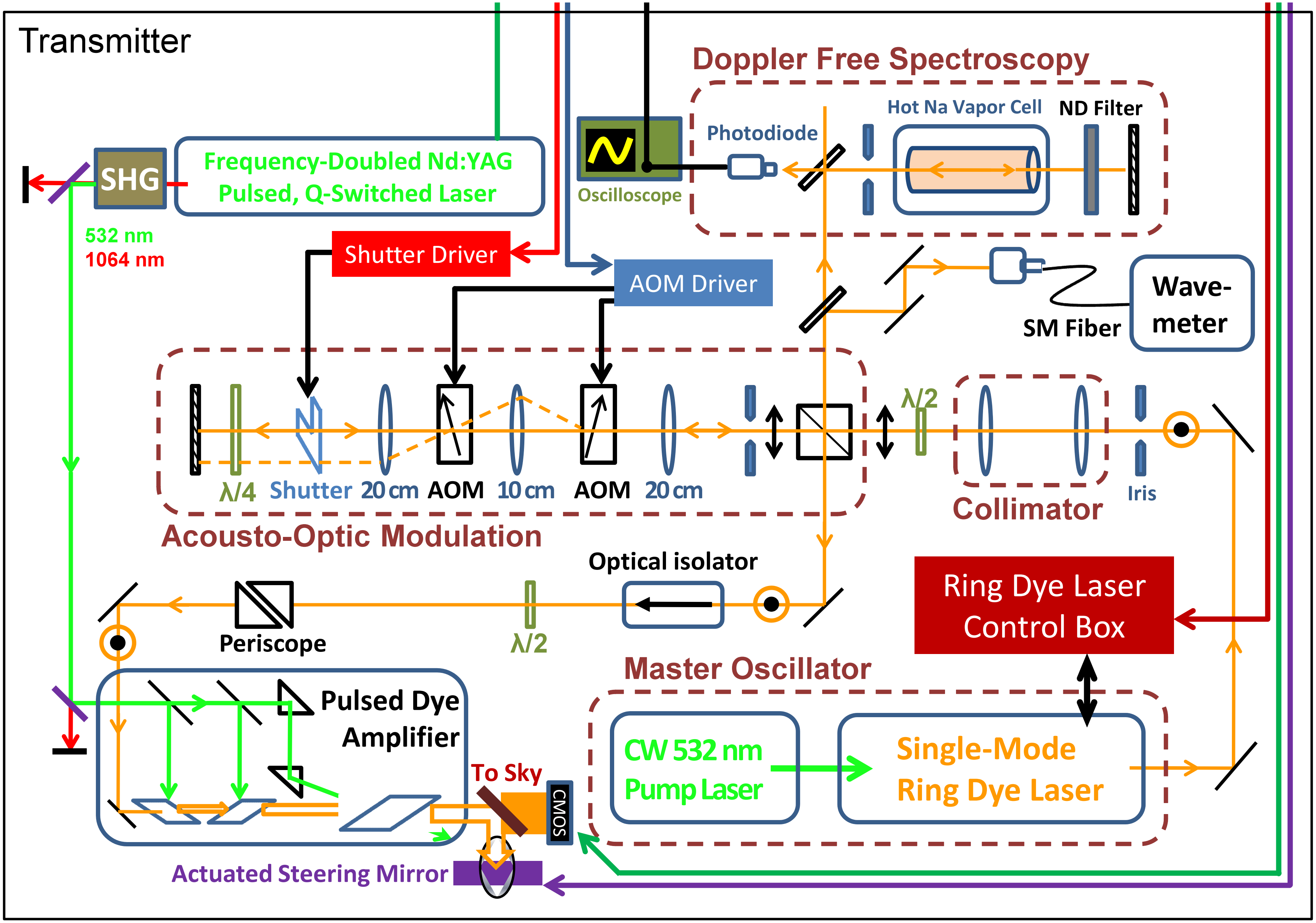






[Chu et al., ILRC, 2008]

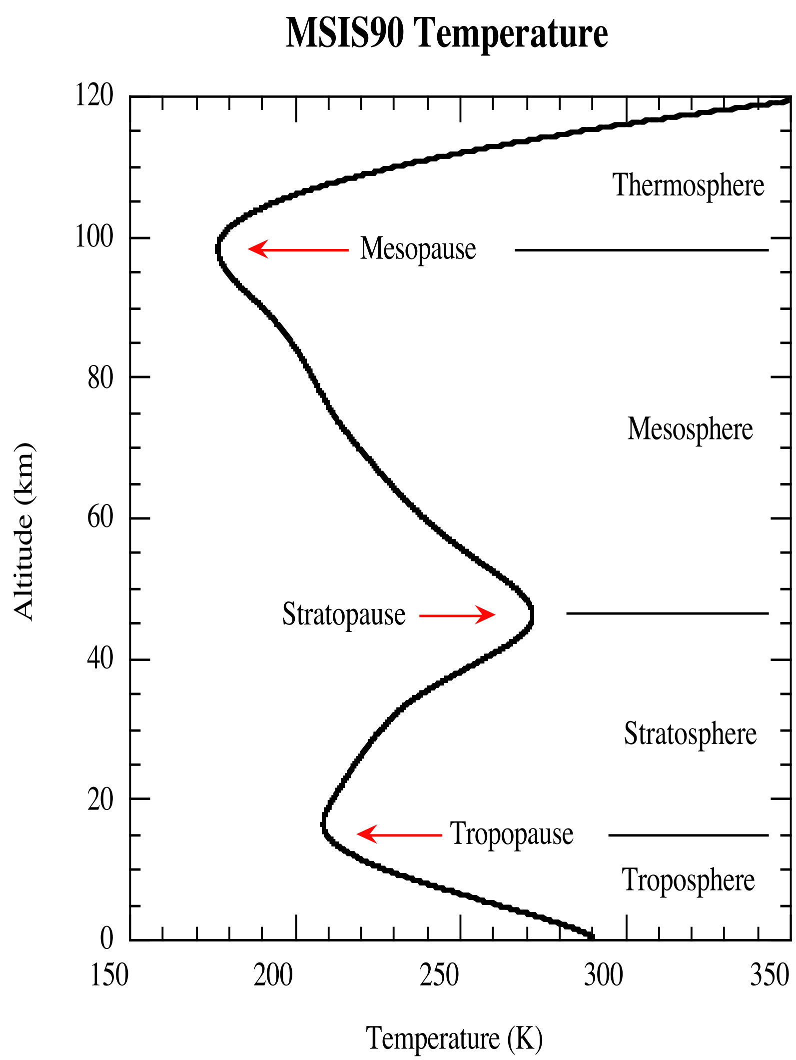
STAR Na Doppler LIDAR Transmitter



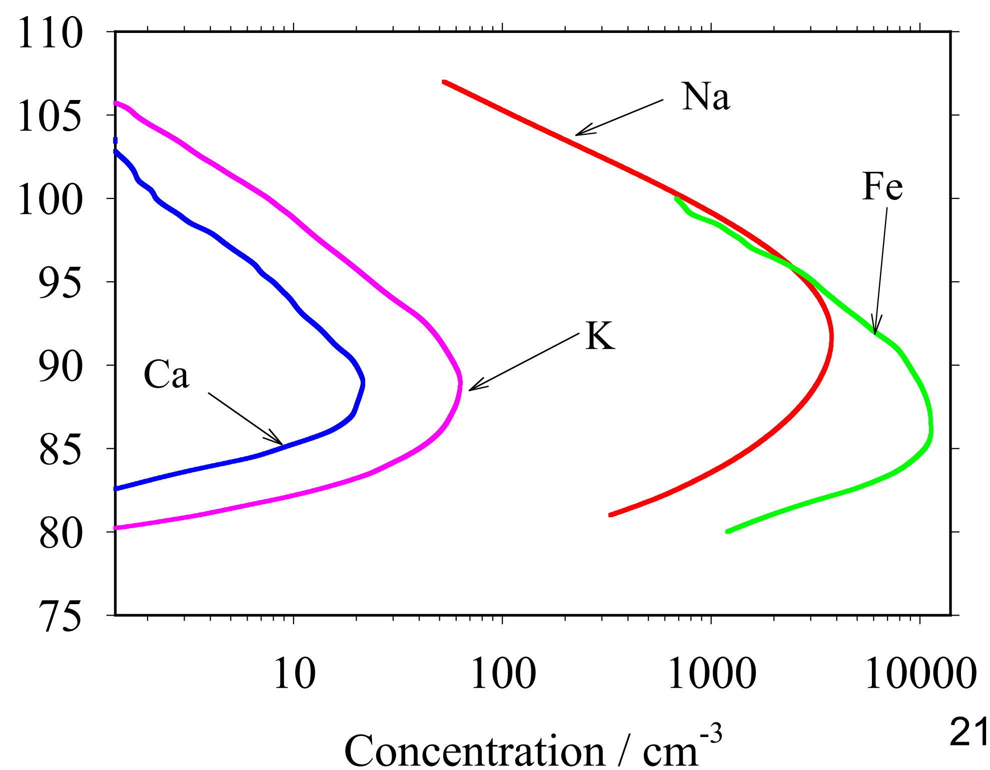
Options for Na Doppler Lidar

- Conventional: Ring Dye Laser + PDA
- Hybrid: Solid-state cw 589nm source + PDA
  - -- CW Nd:YAG lasers SFG (1064 and 1319 -> 589 nm)
  - -- CW fiber lasers SFG (1583 and 938 -> 589 nm)
  - -- Raman shifted fiber laser SHG (1178->589 nm)
  - -- ECDL/DFB + Fiber Amplifier + SHG (1178->589 nm) Toptica
- Full solid-state pulsed 589nm laser
  - -- Flashlamp pumped Nd:YAG lasers SFG
  - -- Diode-laser pumped Nd:YAG laser SFG
  - -- Self-Raman Nd:YVO_4 pulsed laser: 1064->1178->589 nm
- 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.

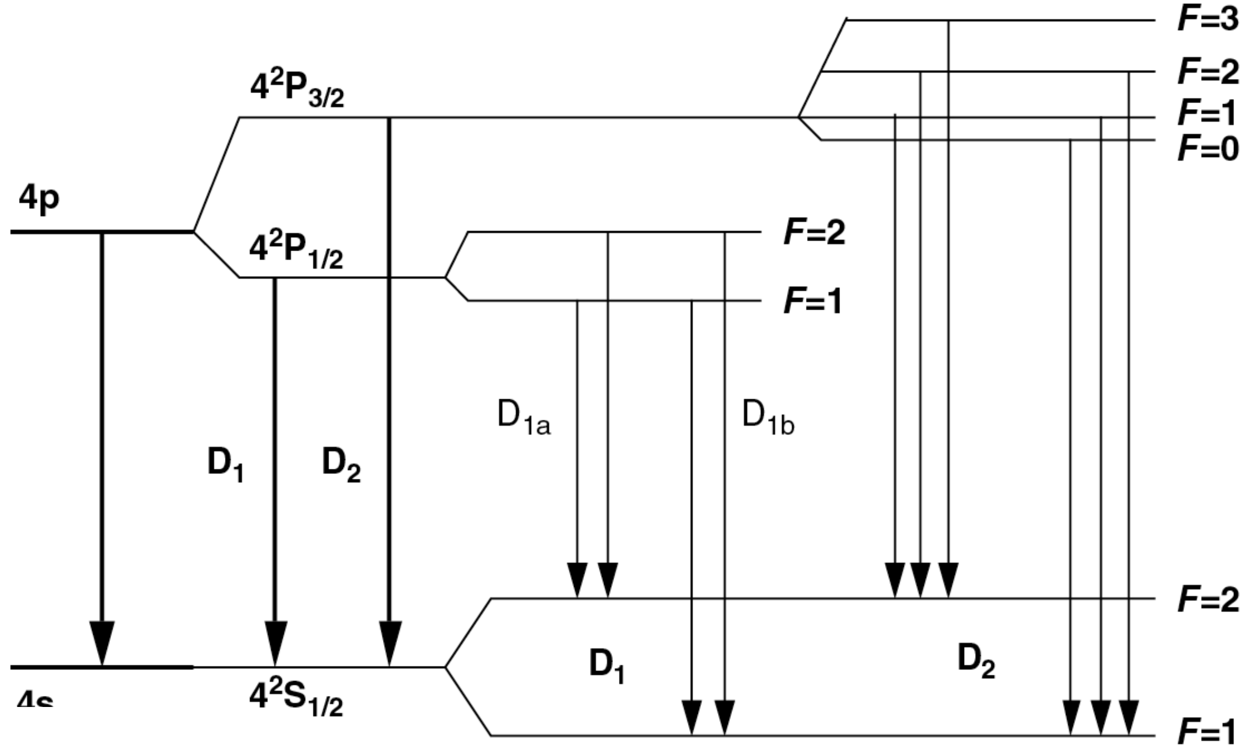


Metal Species in MLT Region

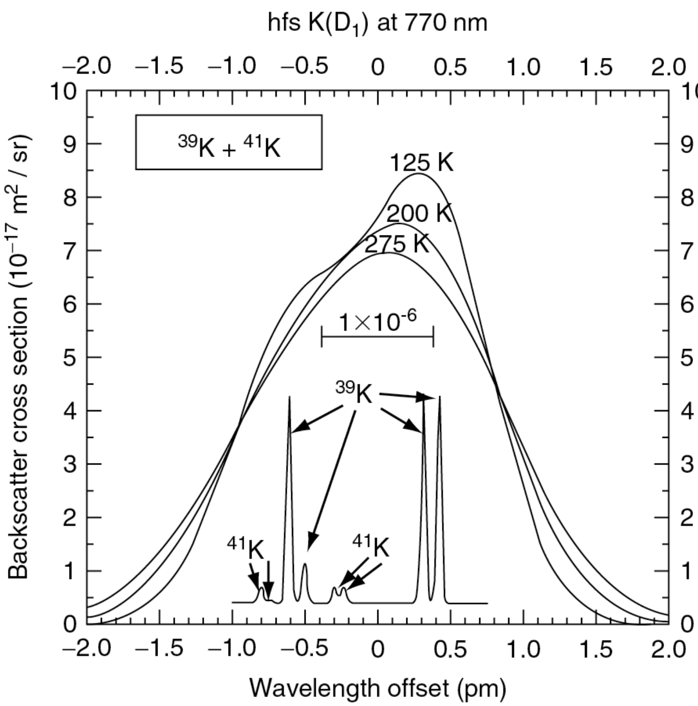
Species	Central wavelength (nm)	A_{ki} ($x10^8$ s^{-1})	Degeneracy g_k / g_i	Atomic Weight	Isotopes	Doppler rms Width (MHz)	σ_0 ($x10^{-12}$ cm^2)	Abundance ($x10^9$ cm^{-2})	Centroid Altitude (km)	Layer rms Width (km)
Na (D_2)	589.1583	0.616	4 / 2	22.98977	23	456.54	14.87	4.0	91.5	4.6
Fe	372.0995	0.163	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



K fine structure K hyperfine structure



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

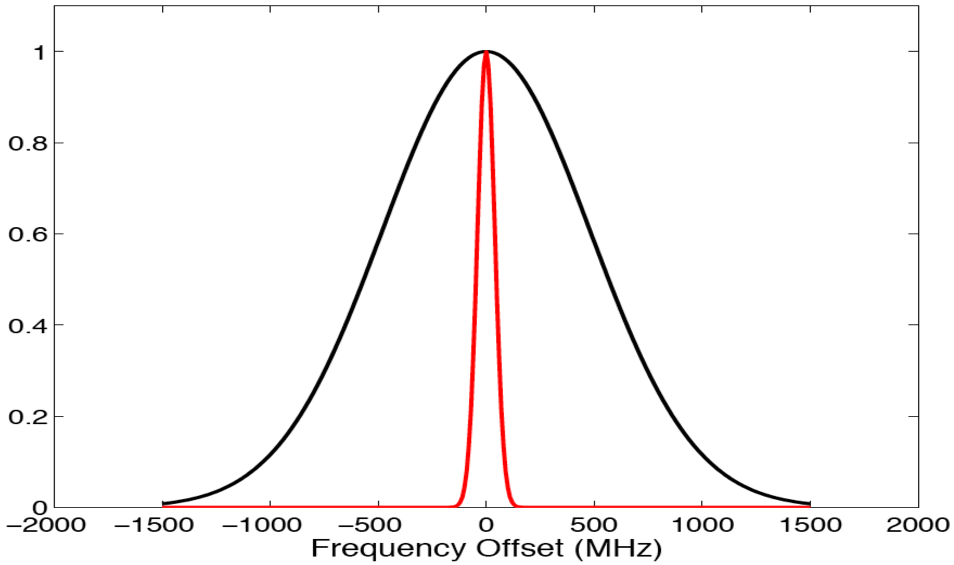
Isotope	Atomic mass	Abundance	Nuclear spin	$K(D_1)$ line shift
39	38.963 706 9(3)	0.932 581(44)	$I = 3/2$	0
40	39.963 998 67(29)	0.000 117(1)	$I = 4$	125.58 MHz
41	40.961 825 97(28)	0.067 302(44)	$I = 3/2$	235.28 MHz

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

Effective Cross Section Computation

- The effective cross section is a convolution of the atomic absorption cross section and the laser line shape.



For Gaussian shapes of atomic absorption and laser lineshape:

$$\sigma_e = \sqrt{\sigma_D^2 + \sigma_L^2}$$

- How would you calculate the effective cross section when atoms have isotopes, e.g., K (potassium) or Fe (iron)?

$$\sigma_{eff}(overall) = \sum_{m=1}^{N}\left[\sigma_{eff,m}(isotope) \times Isotope\ \ Abdn_m\right]$$

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!