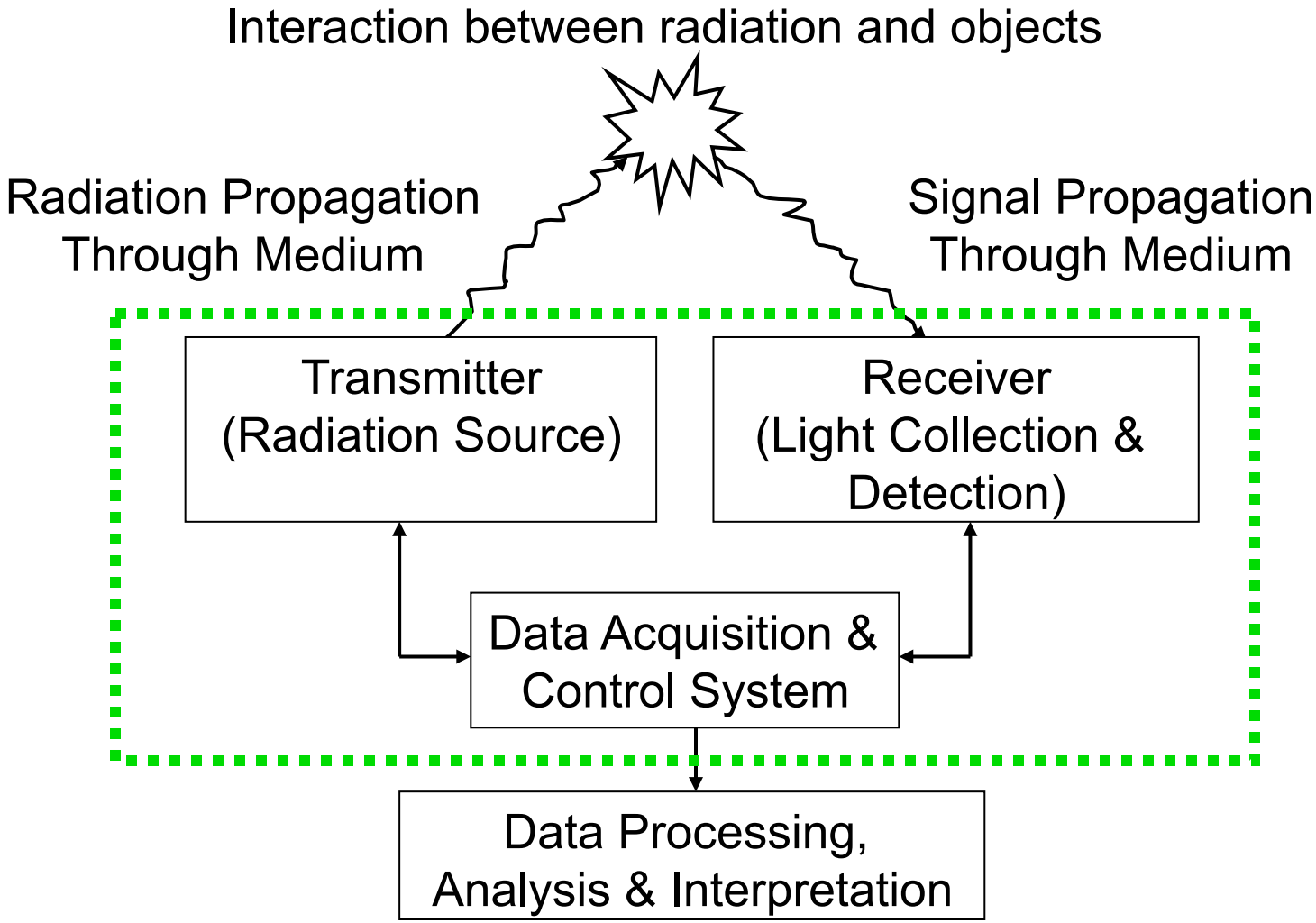
Lecture 17. Temperature Lidar (6) Na Resonance-Doppler Lidar Instrumentation

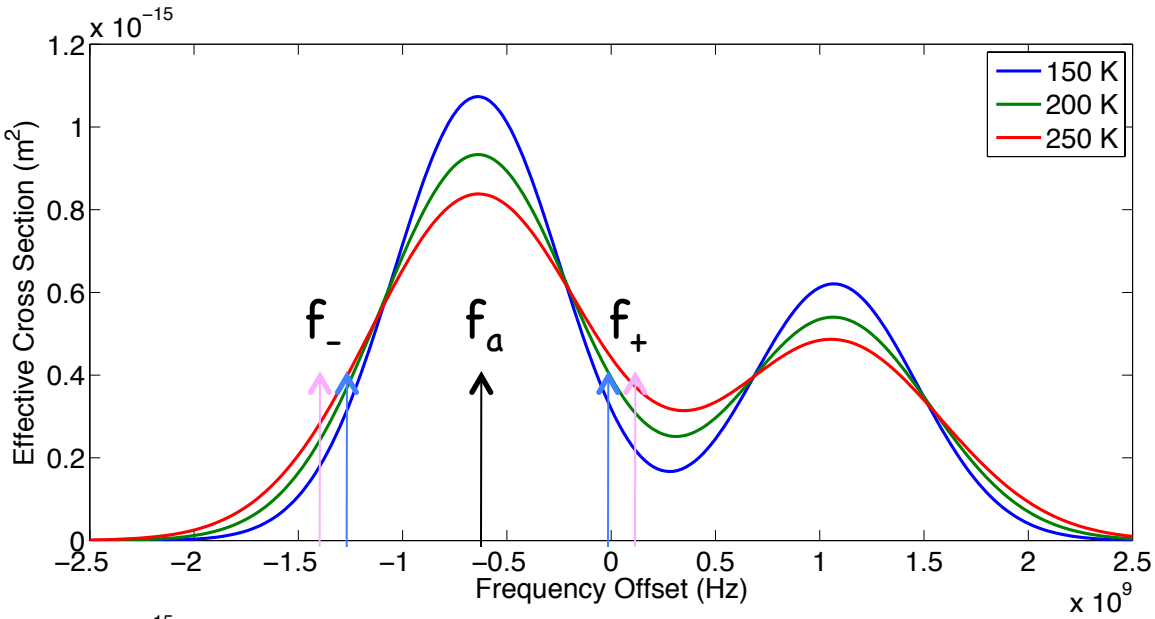
- Introduction: Requirements for Na Doppler Lidar
- Classic Na Doppler Lidar Instrumentation
  - Na Doppler Lidar System
  - Key Technologies in Classic Na Doppler Lidar
  - High-Efficiency Lidar Receivers
  - Narrowband Filters for Daytime Measurements
- More Options for Na Doppler Lidar Instrumentation
- Summary

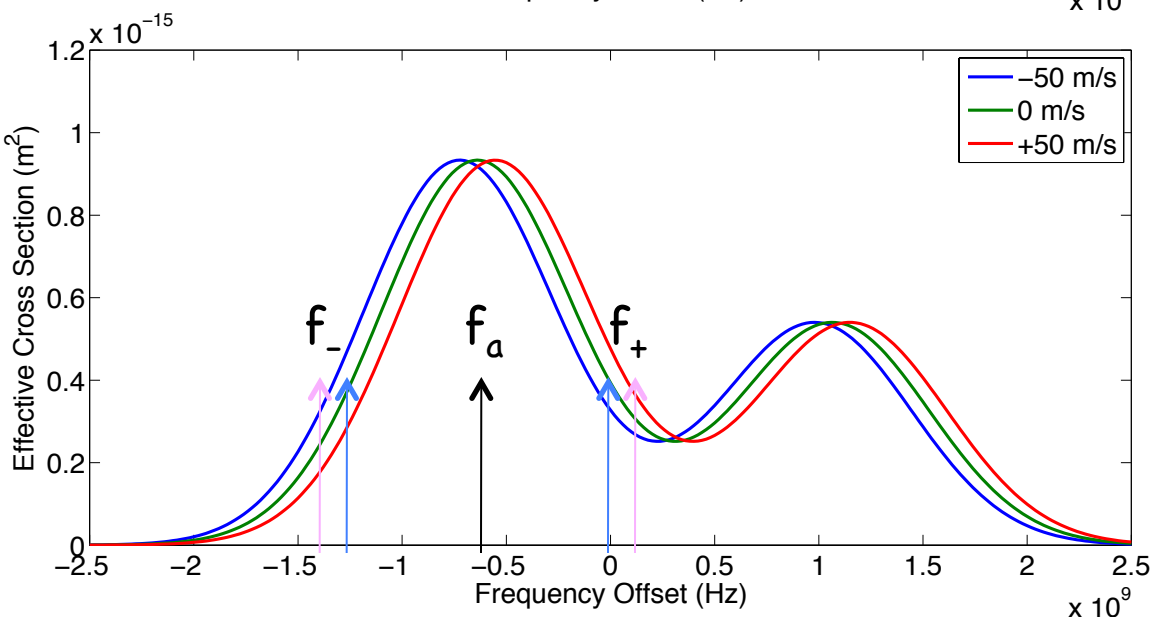
Introduction



- 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!

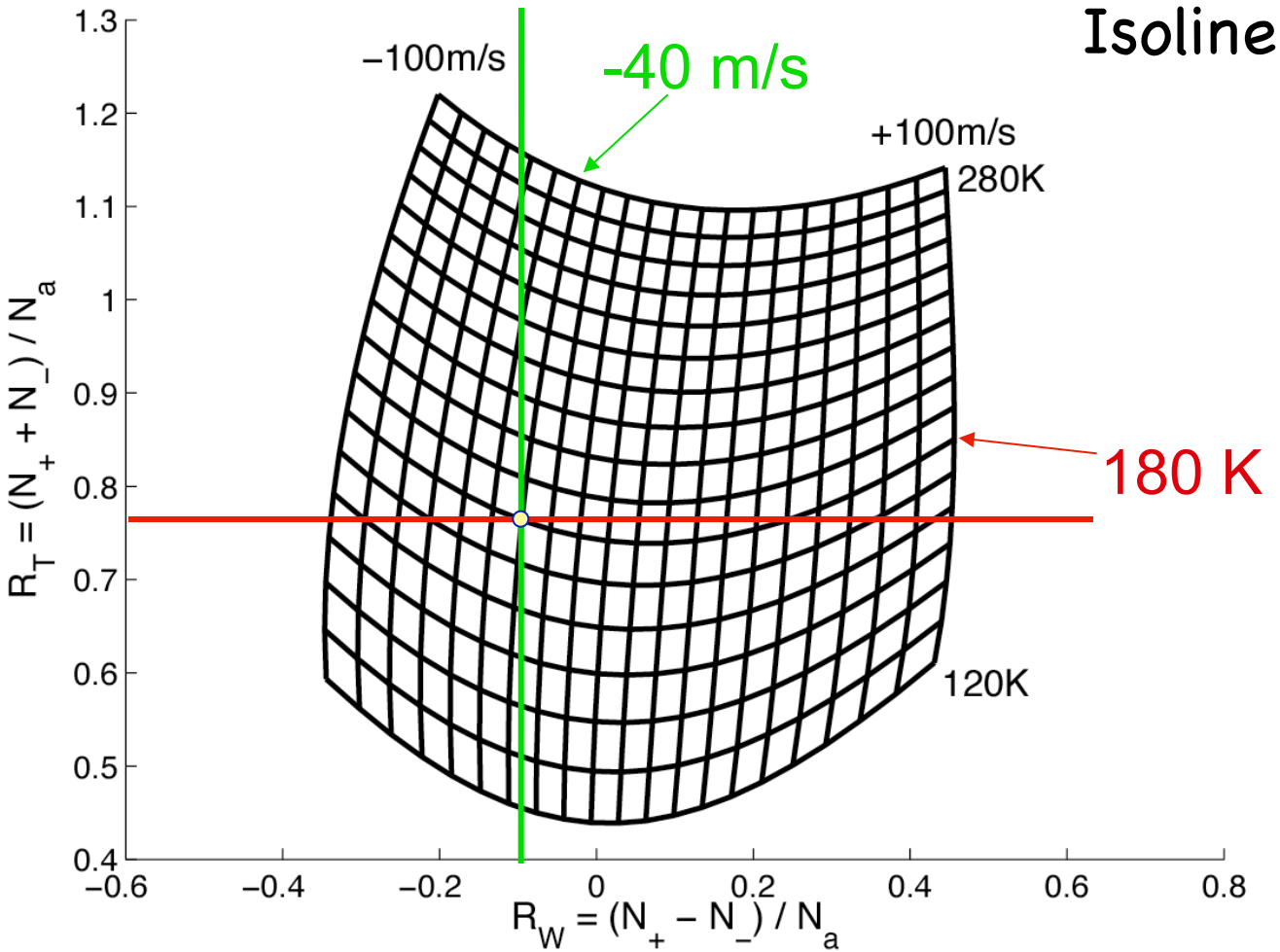
Recall "3-Frequency Ratio Doppler Tech"





Recall "Calibration Curves for 3-Freq"

- R_T is sensitive to temperature, while R_W is sensitive to wind.
- For given temperatures and winds, we can compute the Doppler lidar calibration curves from atomic physics and lidar physics.



Requirements for Na Doppler Lidar

- To infer Doppler broadening and shift with sufficient accuracy & precision, the lidar transmitter must provide narrowband laser light at three (at least) independent frequencies that are sensitive to temperature and LOS wind.

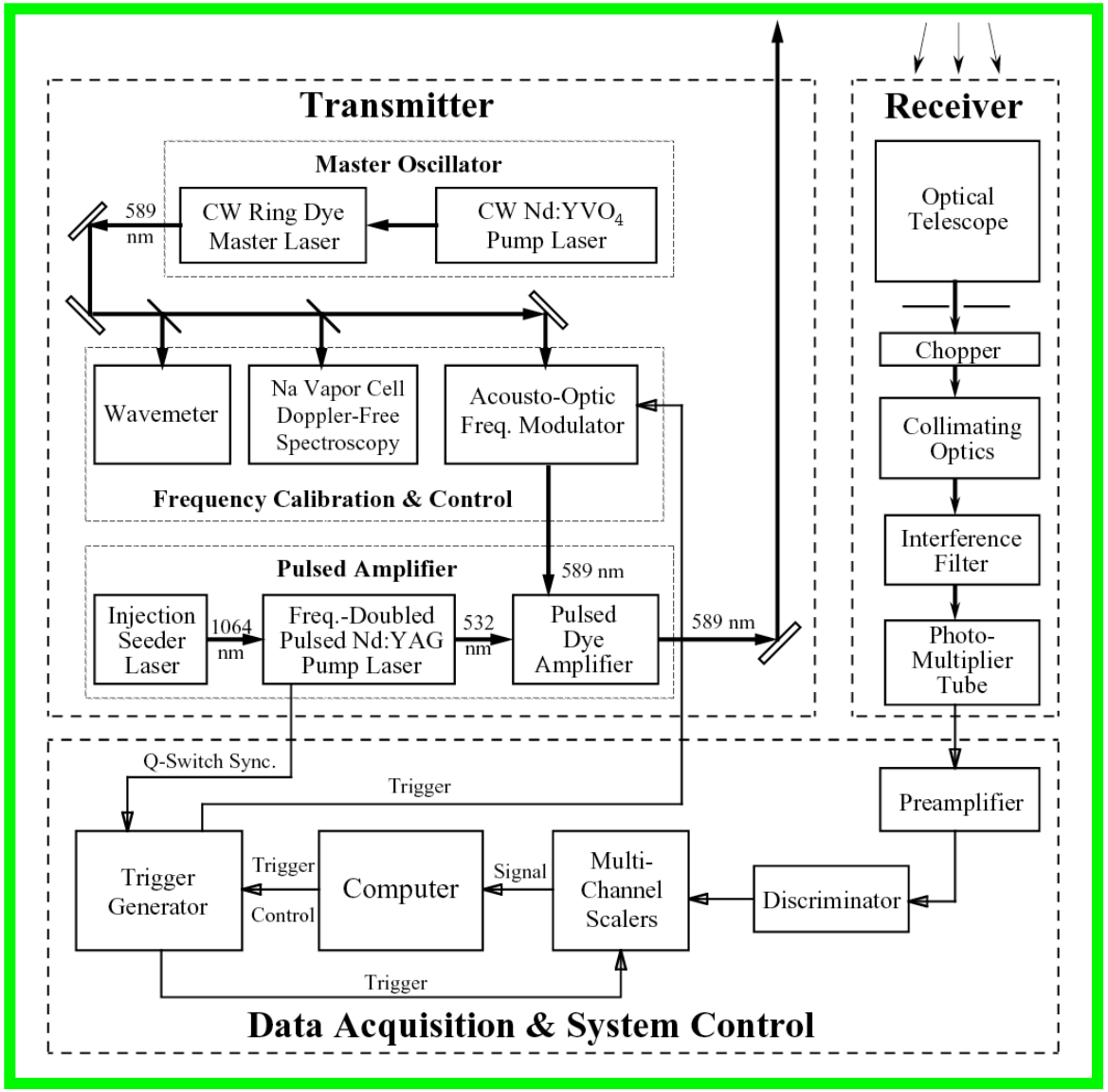
$$\sigma_e = \sqrt{\sigma_D^2 + \sigma_L^2}$$

This is because the return Na fluorescence signal's intensity lineshape is a convolution of Na absorption coefficient lineshape with laser lineshape.

- If $\sigma_L \geq \sigma_D$, the fluctuation of σ_L will dominate the temp errors.
- If $\sigma_L \sim \sigma_D/10$, σ_D dominates the convolution linewidth but laser lineshape still affects the results. So it's important to know laser lineshape well.
- If $\sigma_L \sim \sigma_D/100$, the convolution linewidth is basically determined by σ_D and the laser lineshape doesn't affect the results anymore (minimal).

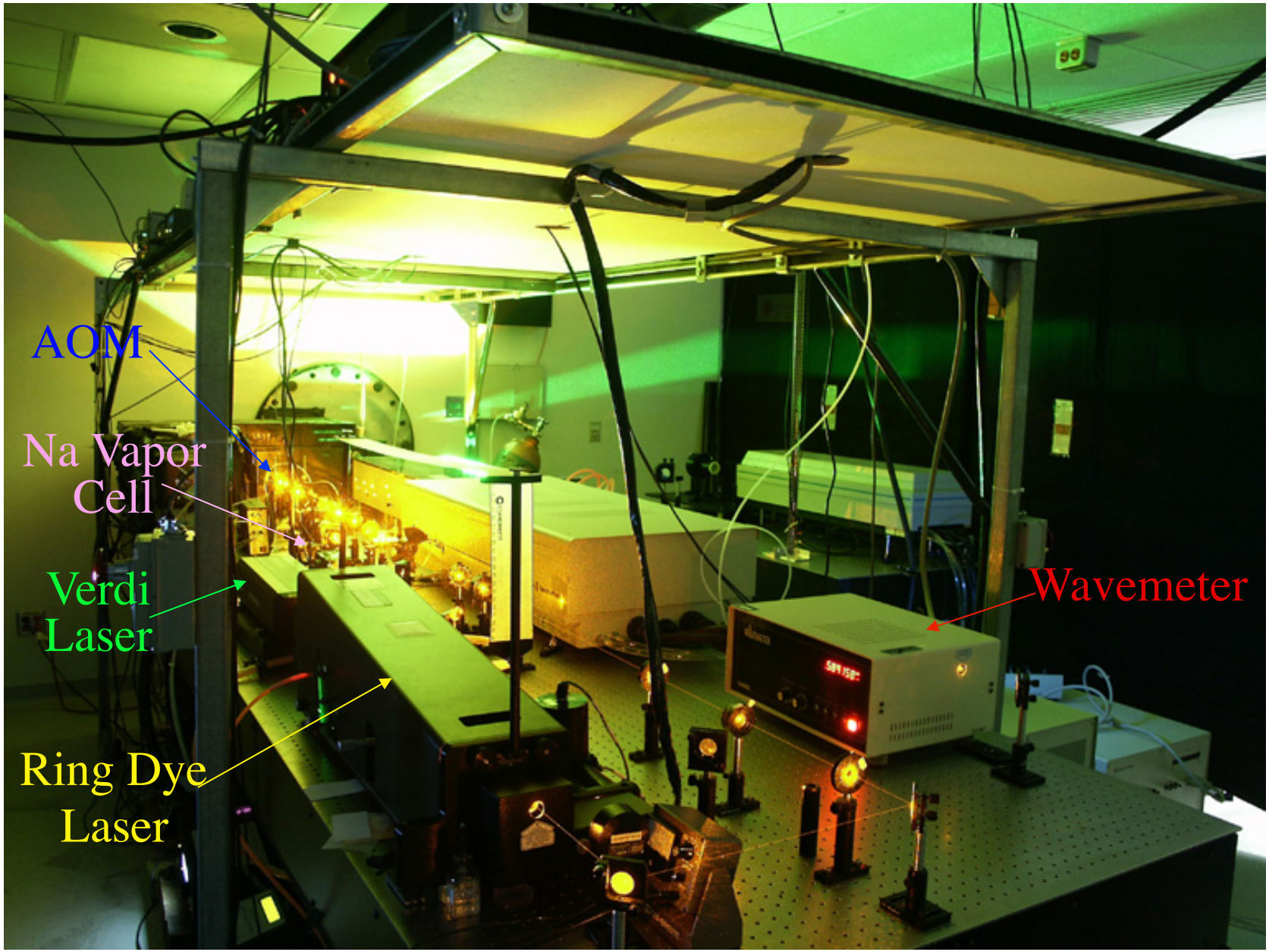
- For temperature measurements, stable and repeatable frequencies must be achieved for all three frequencies.
- An extra and critical requirement for wind measurements is to achieve accurate frequencies, i.e., well-calibrated absolute frequencies.

Classic Na Doppler Lidar

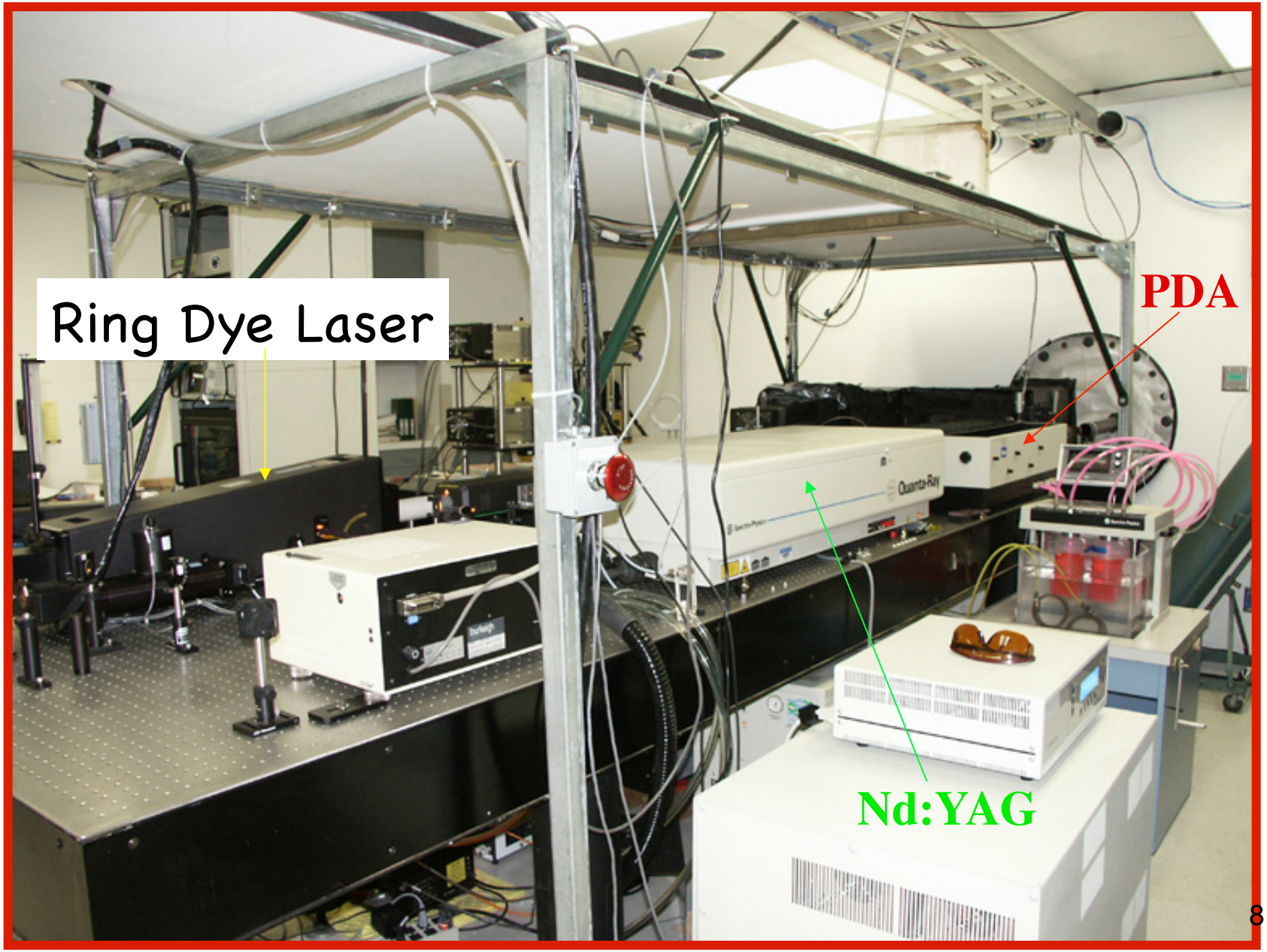


Dye-laser-based Na wind and temperature Doppler Lidar (See details in our textbook Chapter 5)

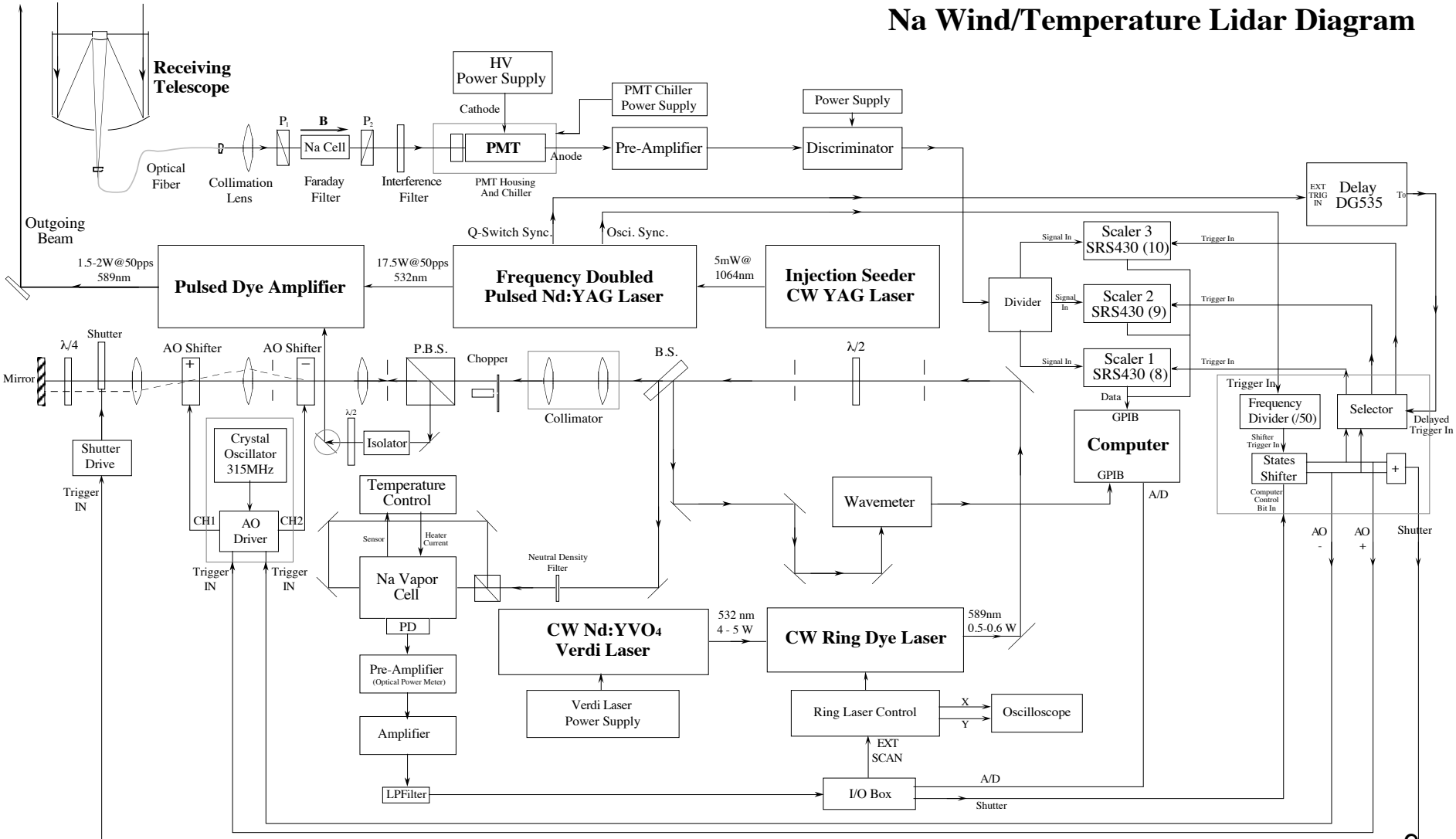
Na Lidar Transmitter Photo 1



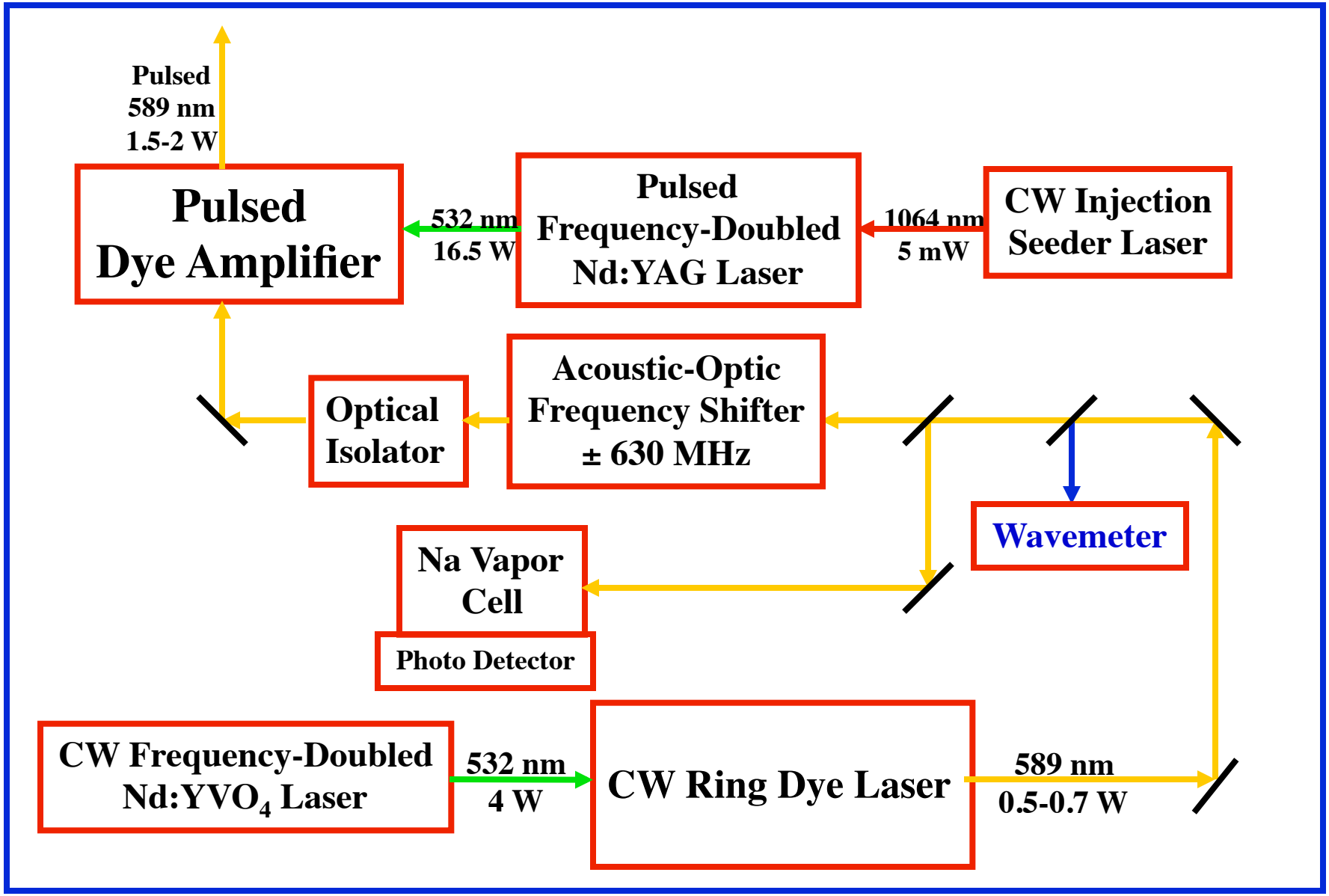
Na Lidar Transmitter Photo 2



Na Wind and Temperature Lidar

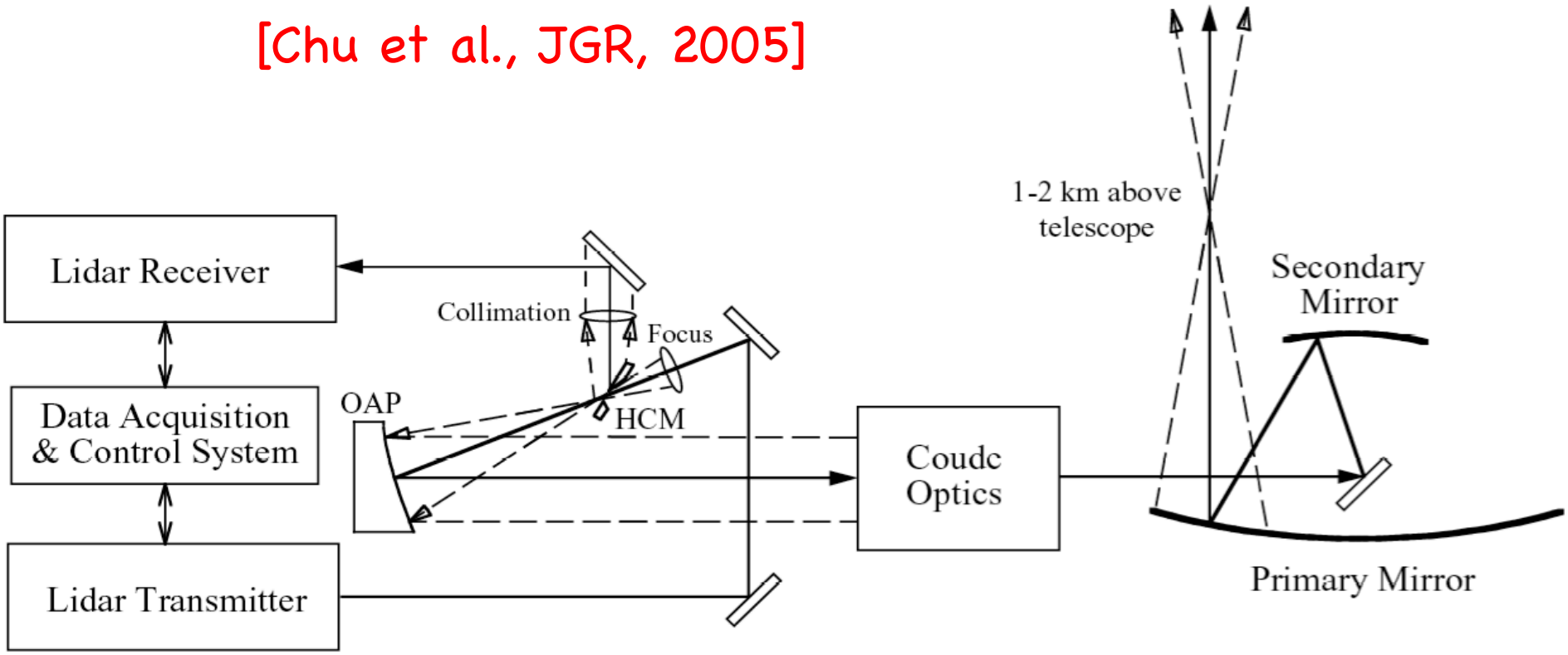


Na Doppler Lidar Transmitter



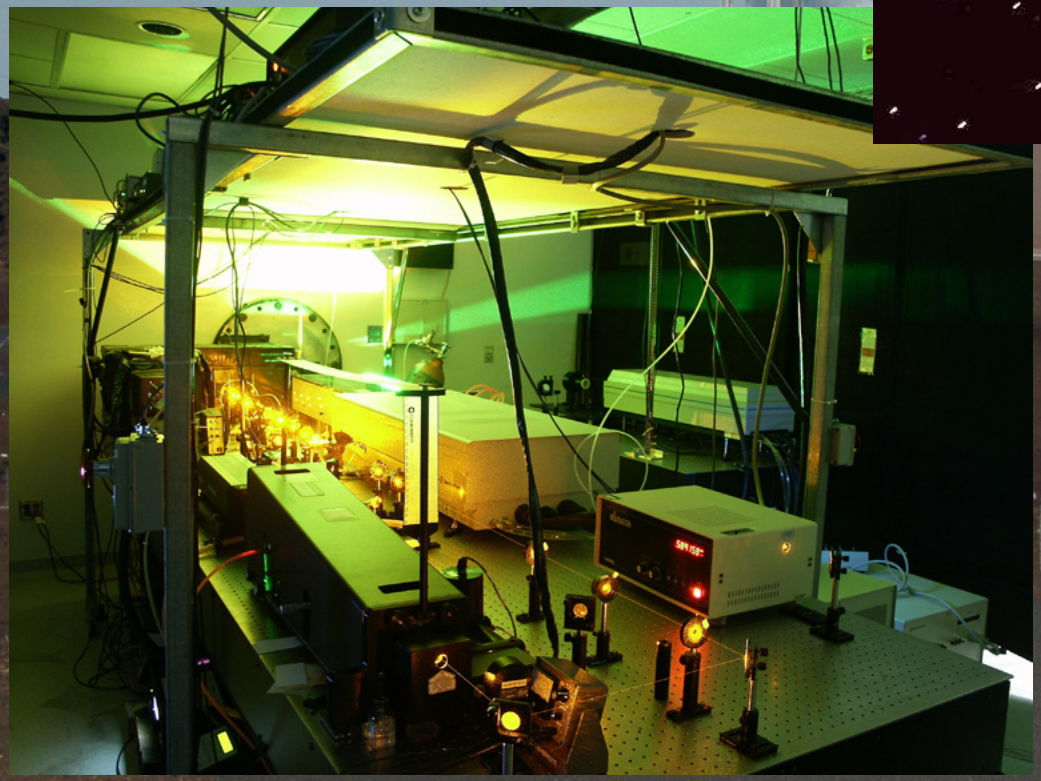
Steerable Na Doppler Lidar

[Chu et al., JGR, 2005]



Large-Aperture (3.5m) Steerable Na Doppler Lidar
Led by Professor Chester S. Gardner of UIUC

Large-Aperture Na Doppler Lidar



Key Technologies in Classic Na Doppler Lidar

1. How to achieve single-frequency CW laser source?

-- Ring Dye Laser (RDL) with sophisticated design

2. How to lock the CW laser frequency to well-calibrated reference?

-- Phase-sensitive detection and servo loop for freq. locking

3. How to achieve an absolute frequency reference?

-- Na vapor cell and Doppler-free saturation-absorption spectroscopy

4. How to achieve wing frequencies after achieving the peak freq?

-- Acousto-Optic Modulators (AOMs), dual channel, double-pass

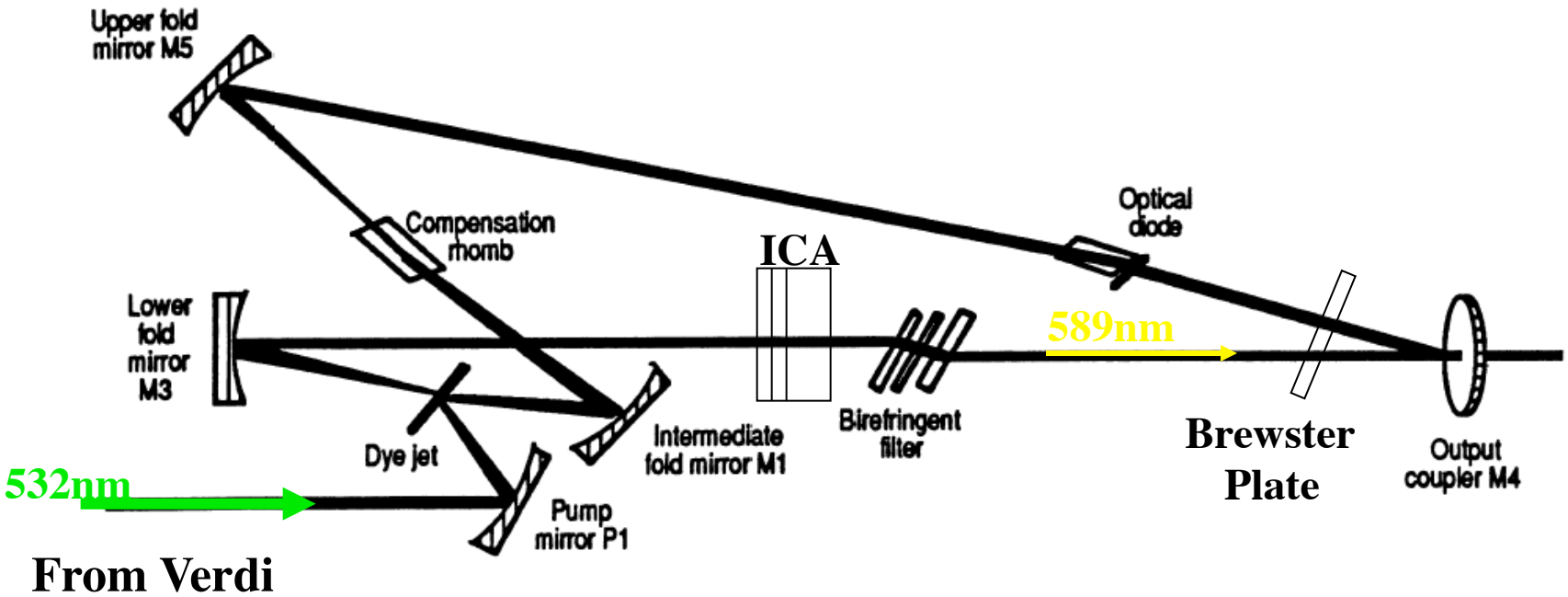
5. How to amplify the CW laser to generate quasi-pulsed laser?

-- Pulsed Dye Amplifier (PDA) pumped by injection-seeded Nd:YAG laser

6. How to compress background to enable daytime measurements?

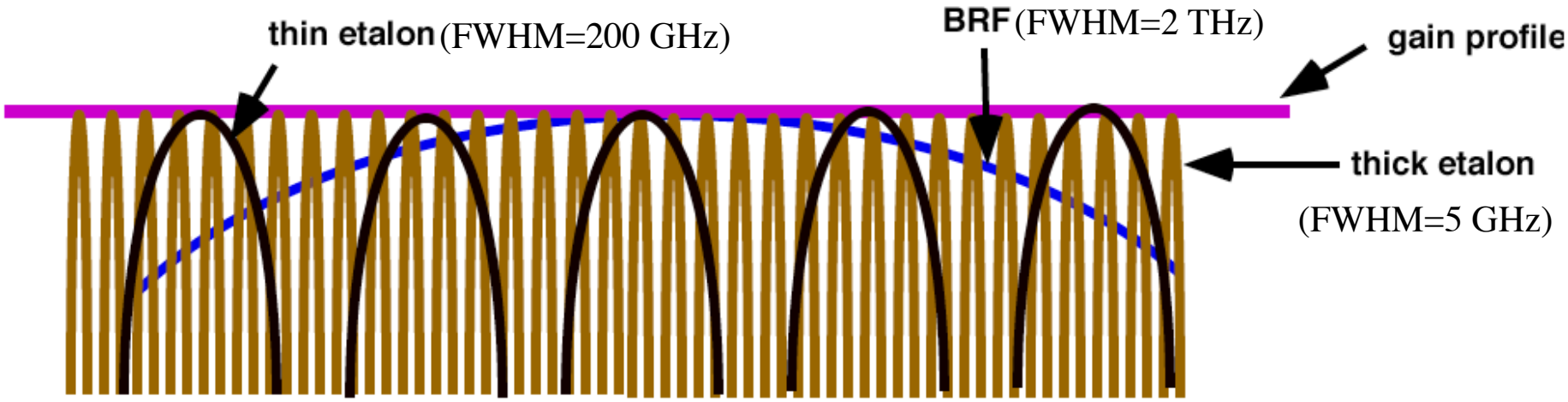
-- Faraday filter or Fabry-Perot etalon with narrowband interference filter

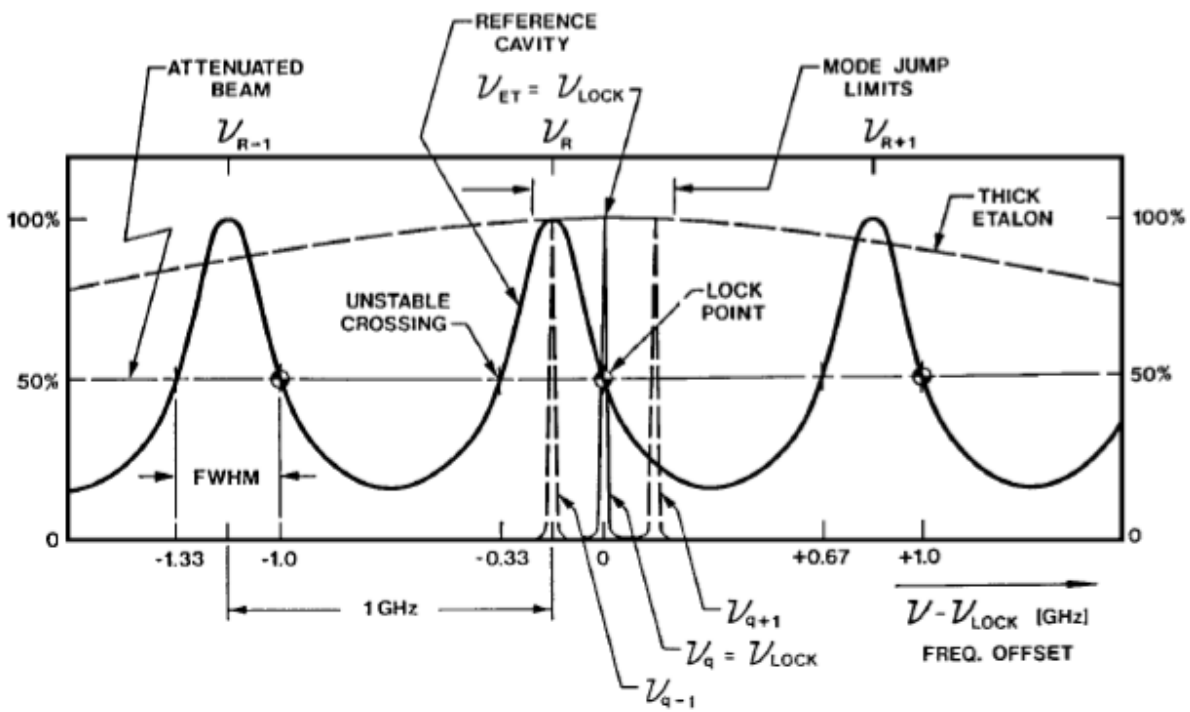
Ring Dye Laser: Single-Frequency



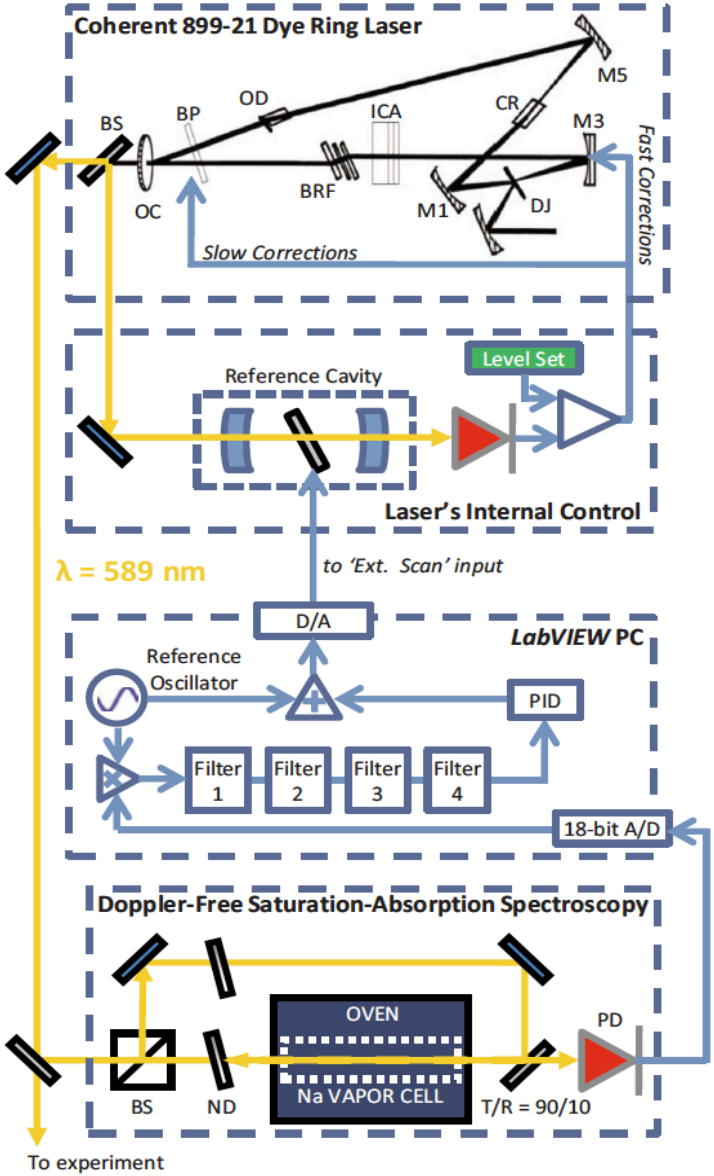
1. "Four mirror + Dye jet" form the laser resonance cavity.
2. Unidirectional lasing prevents spatial hole-burning.
3. Rhomb compensates the astigmatism effect.
4. Optical diode forces the unidirectional lasing.
5. BRF + ICA (etalons) select frequency and narrow bandwidth.
6. "Brewster plate + RCA +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

Frequency Selection in Ring Laser

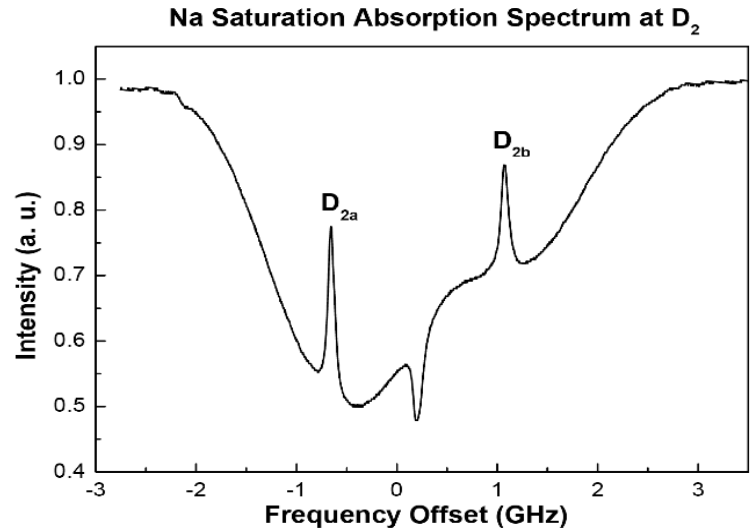




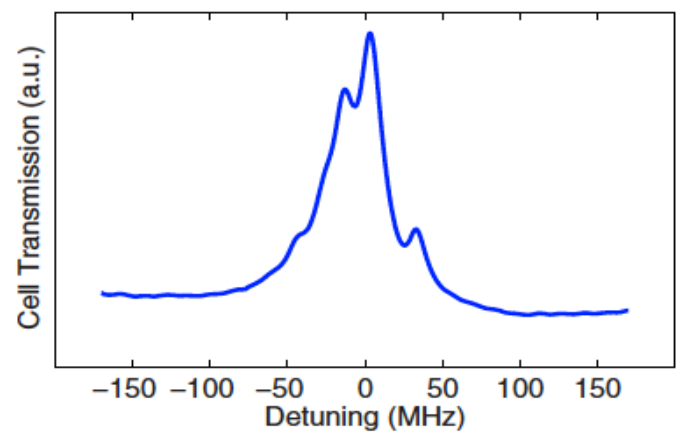
Master Oscillator and Freq Locking with Doppler-Free Spectroscopy



[Smith et al., OE, 2009]

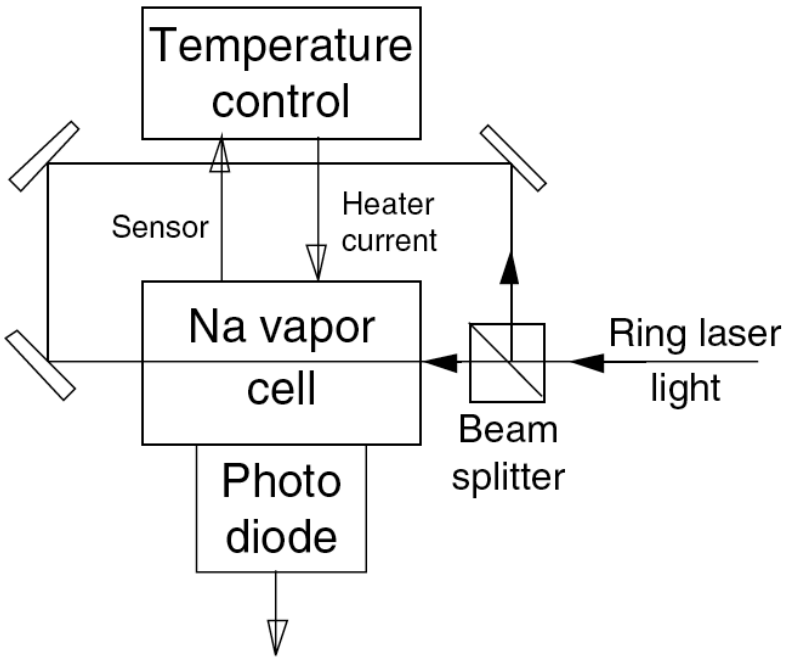


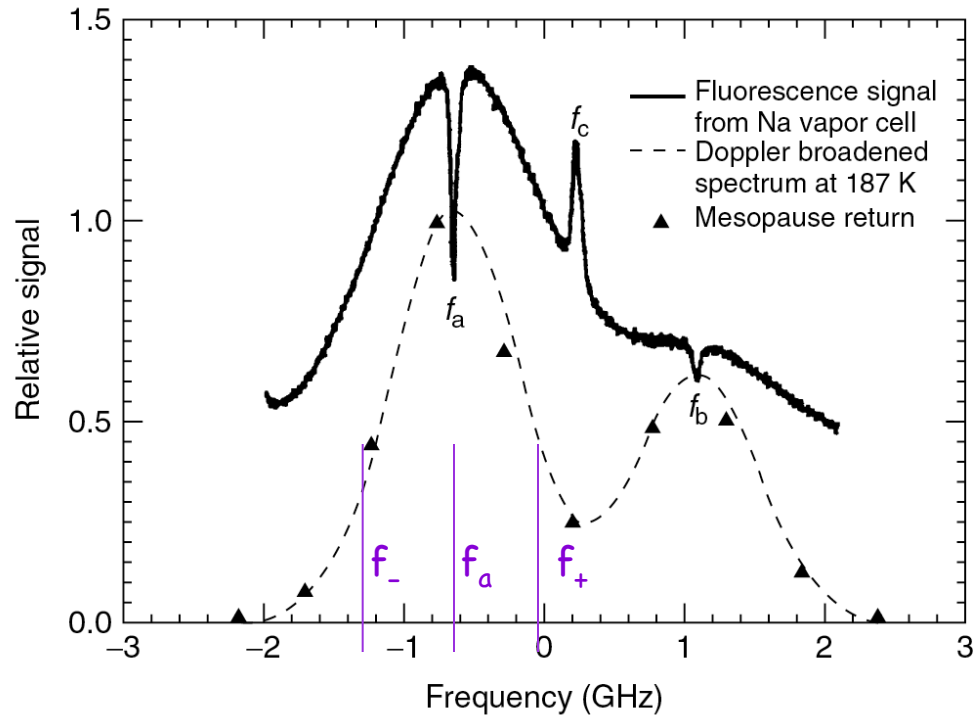
(a) Sodium D_{2a} Doppler–Free Peak



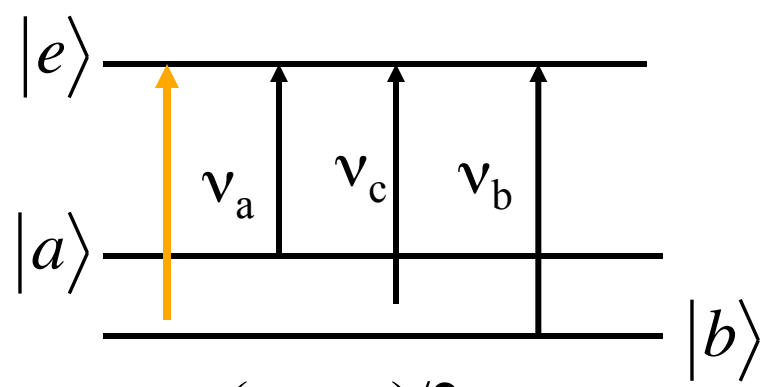
See detailed explanations on Na Doppler-free saturation-fluorescence spectroscopy in Textbook Chapter 5.2.2.3.2

Doppler-Free Na Spectroscopy



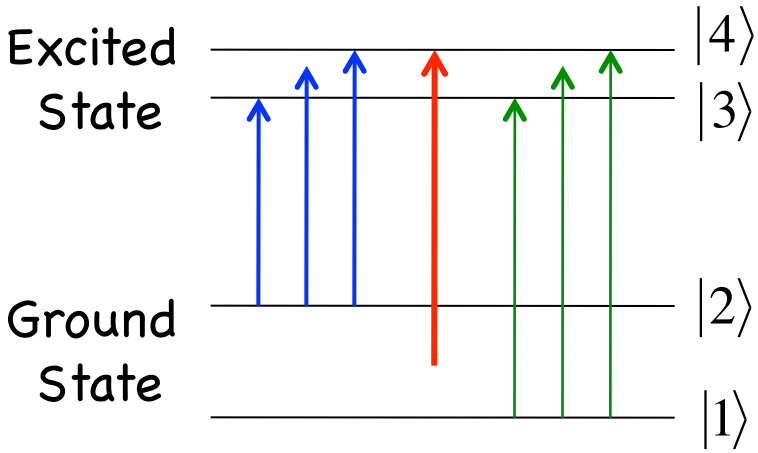


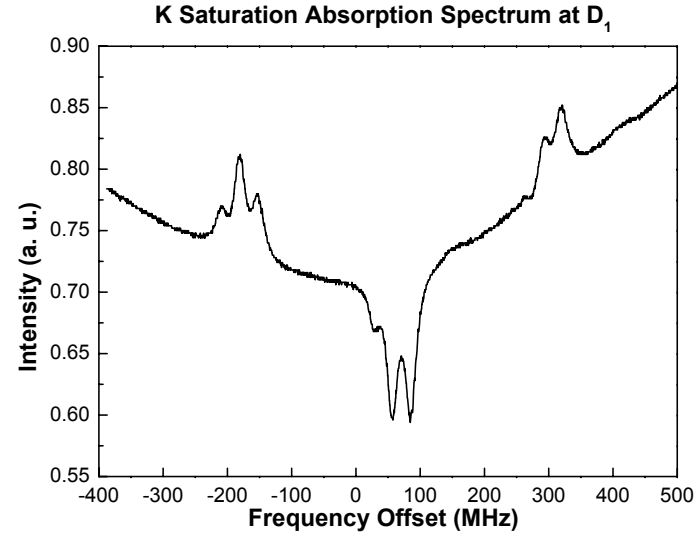
See detailed explanation on Na Doppler-free saturation-fluorescence spectroscopy in Textbook Chapter 5.2.2.3.2

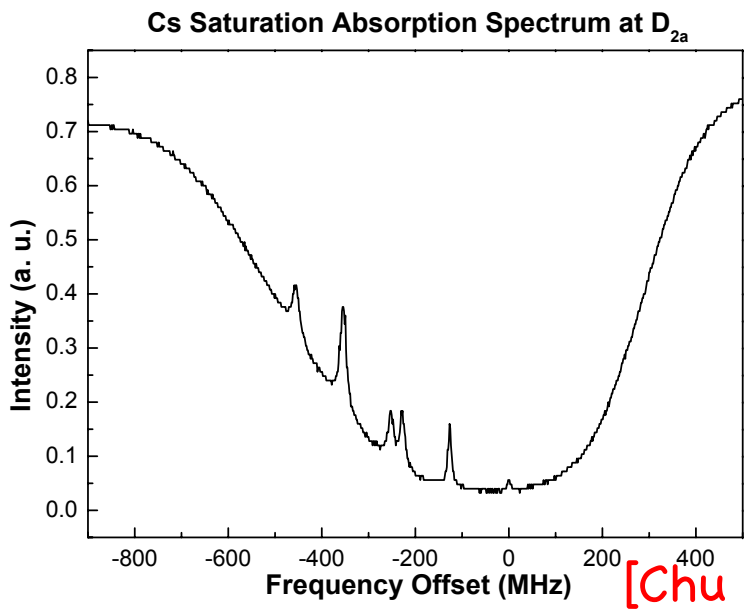


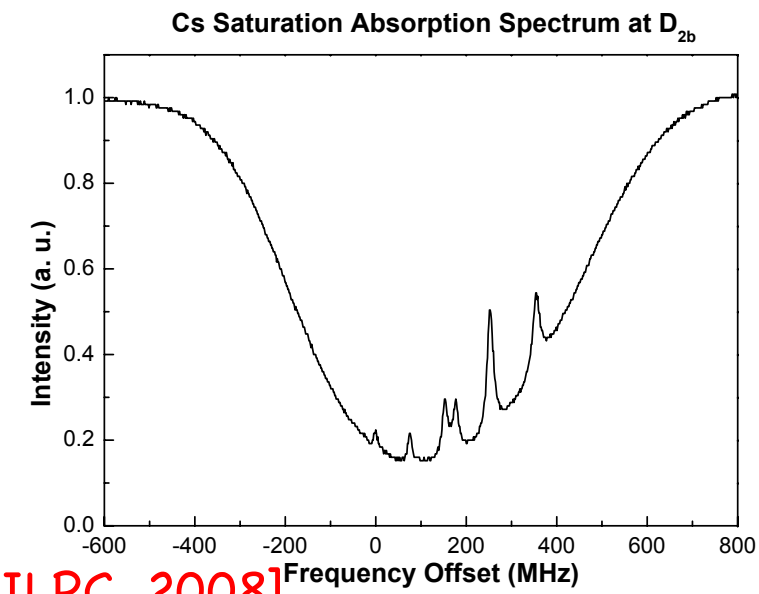
$\nu_c = (\nu_a + \nu_b)/2$

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





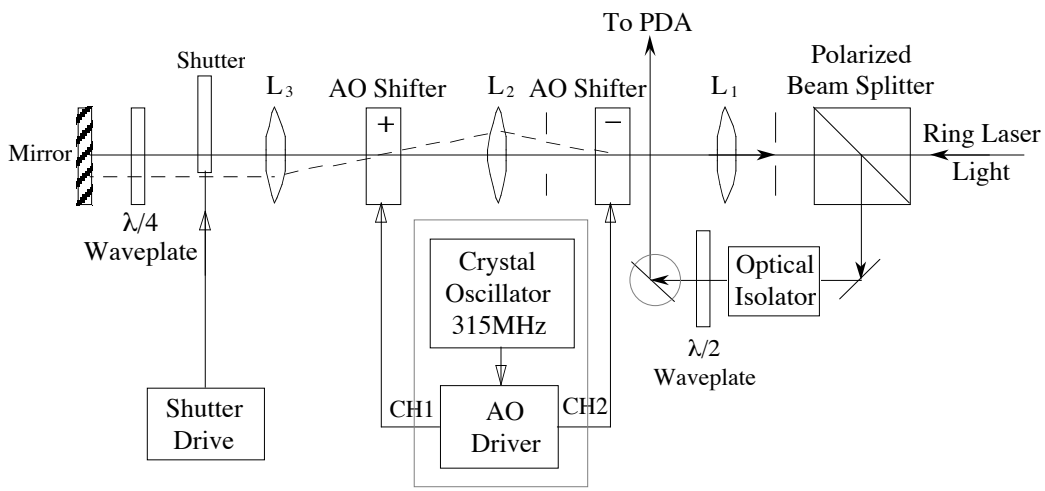




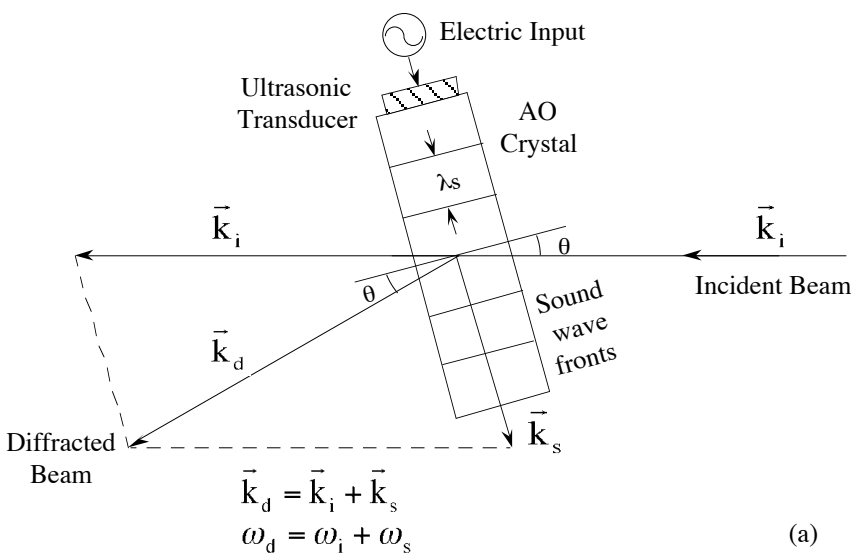
[Chu et al., ILRC, 2008]

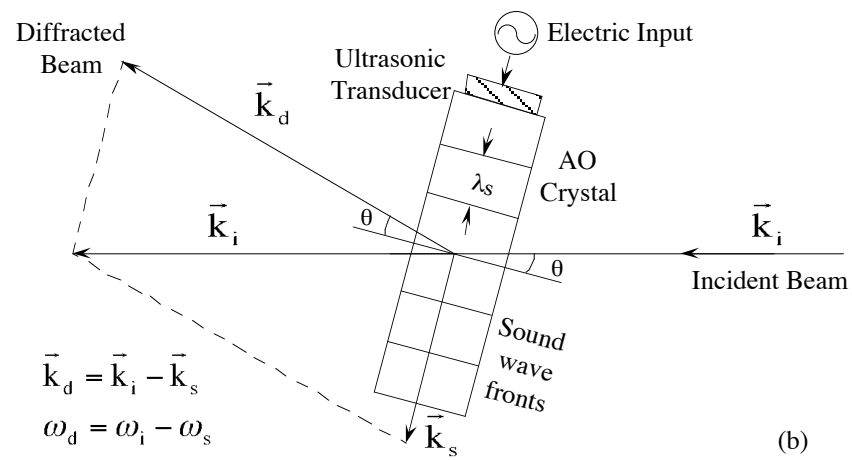
Acousto-Optic Modulator (AOM)

Hardware

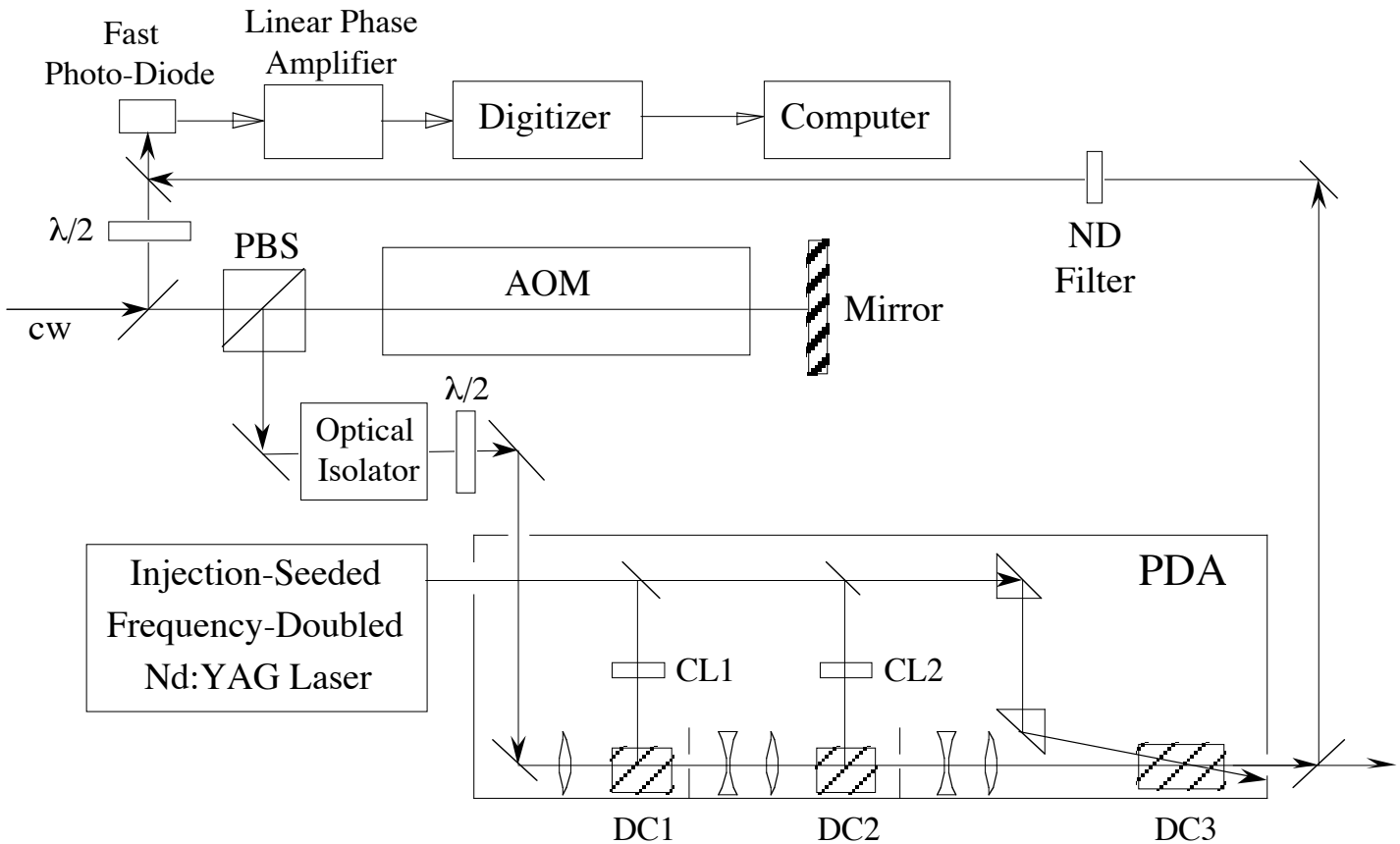


Explanation: Doppler shift or Photon/Phonon Annihilation





Pulsed Amplification: PDA

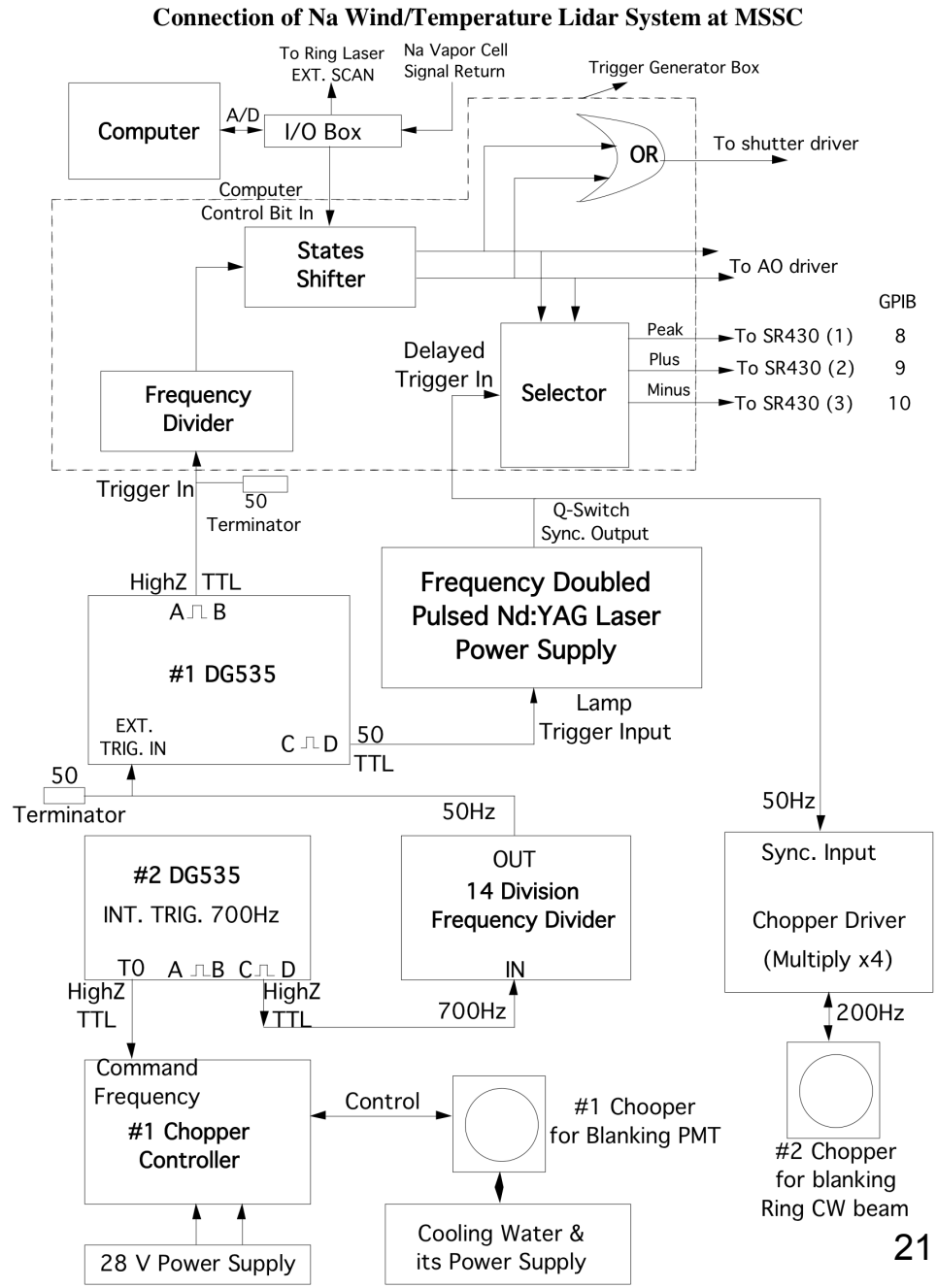


1. **Amplified Spontaneous Emission (ASE)**
2. **Injection-seeded Nd:YAG laser**
3. **PDA chirp caused by pulsed amplification**

Na Doppler Lidar Control System and Data Acquisition

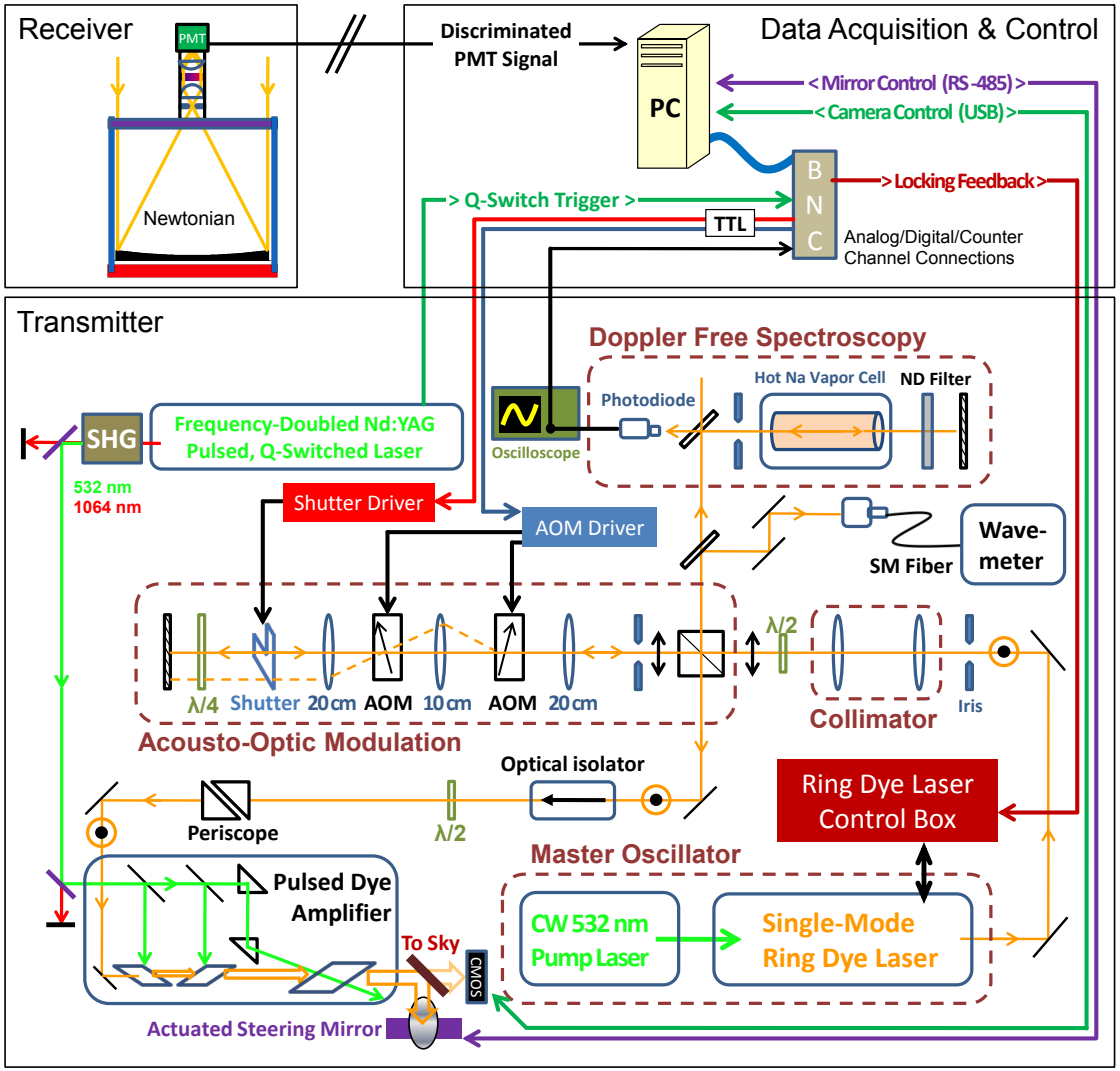
Recent improvements:

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



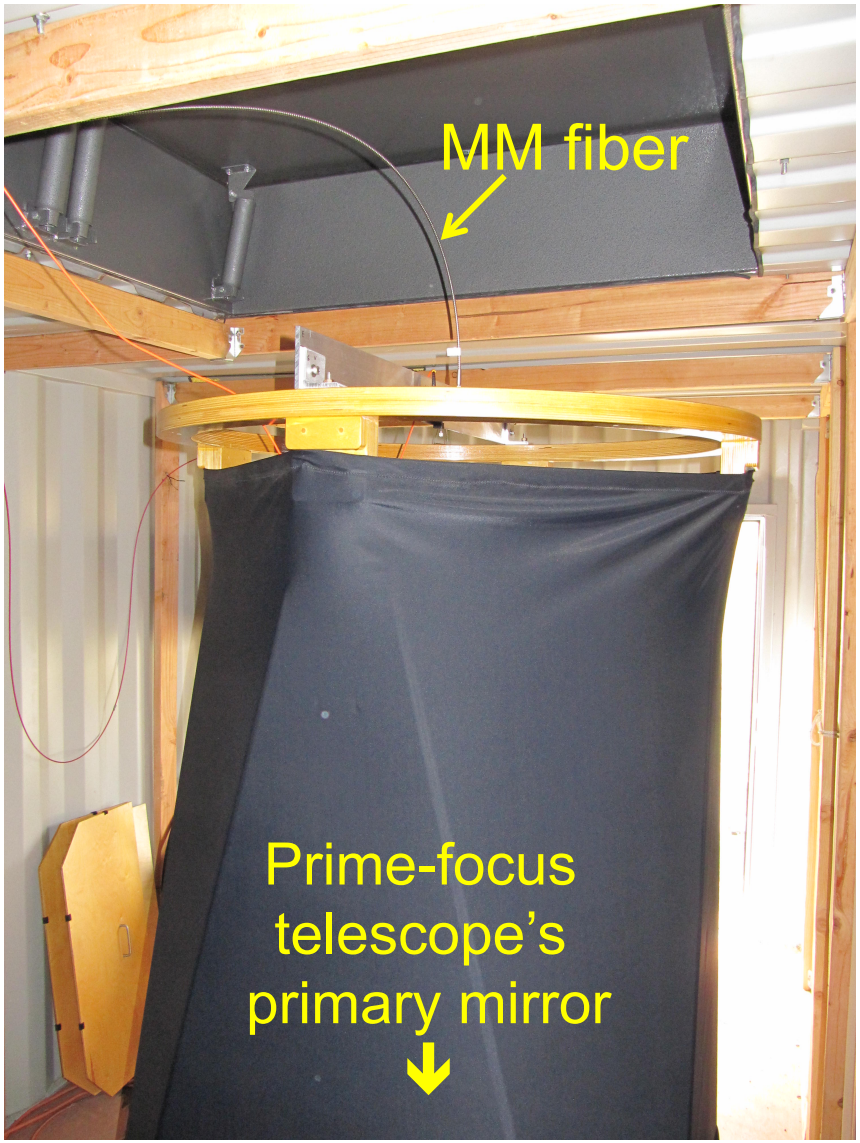
STAR Na LIDAR

Modernized DAQ, System Control, and Receiver

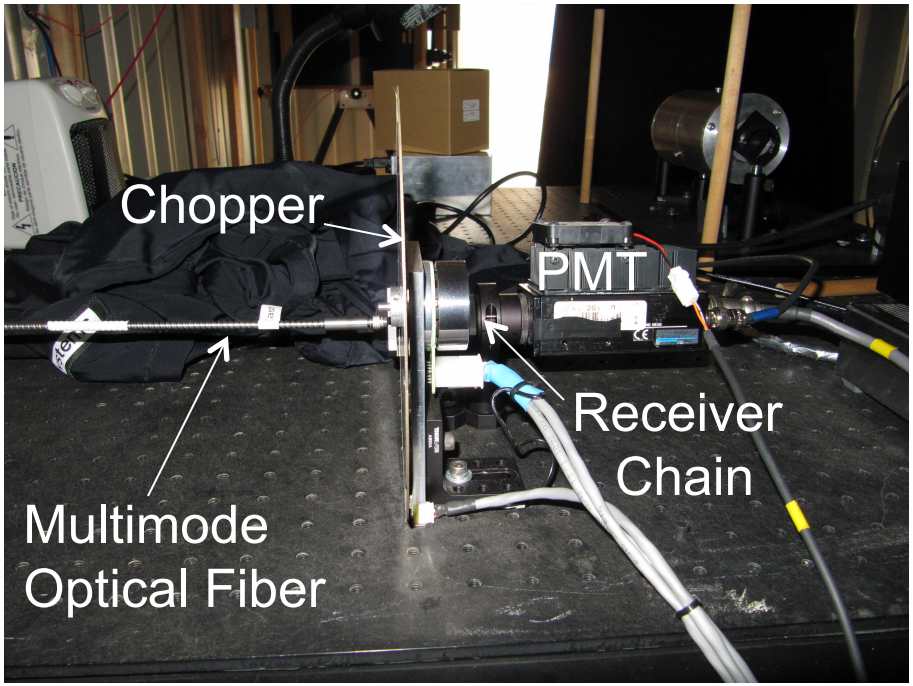


[J. A. Smith, W. Fong, X. Chu, et al., University of Colorado]

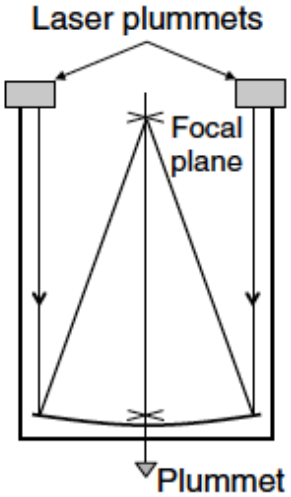
STAR Na Doppler Lidar Receiver

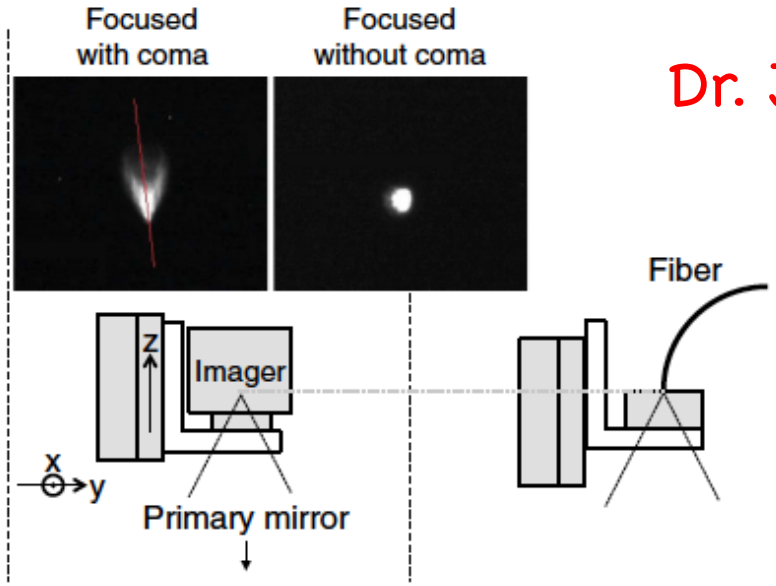


CU-Boulder
STAR Na Doppler Lidar
Primary Focus Telescope
Fiber Coupling



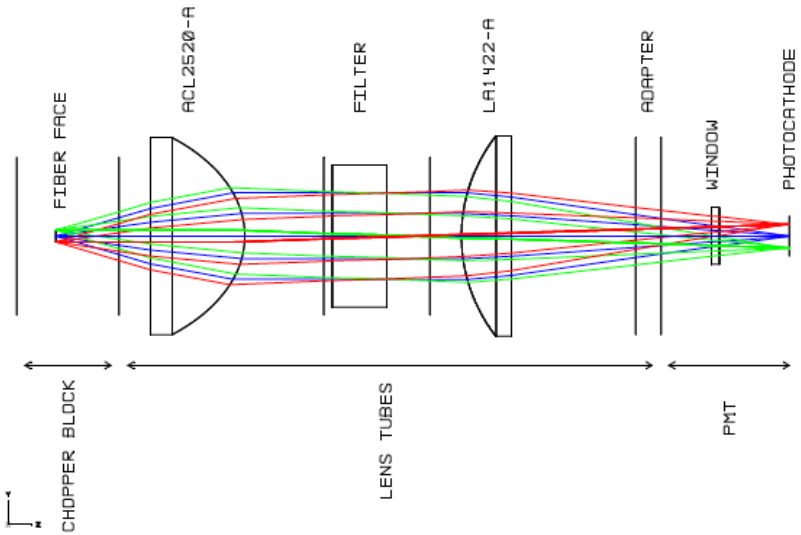
High-Efficiency Lidar Receiver





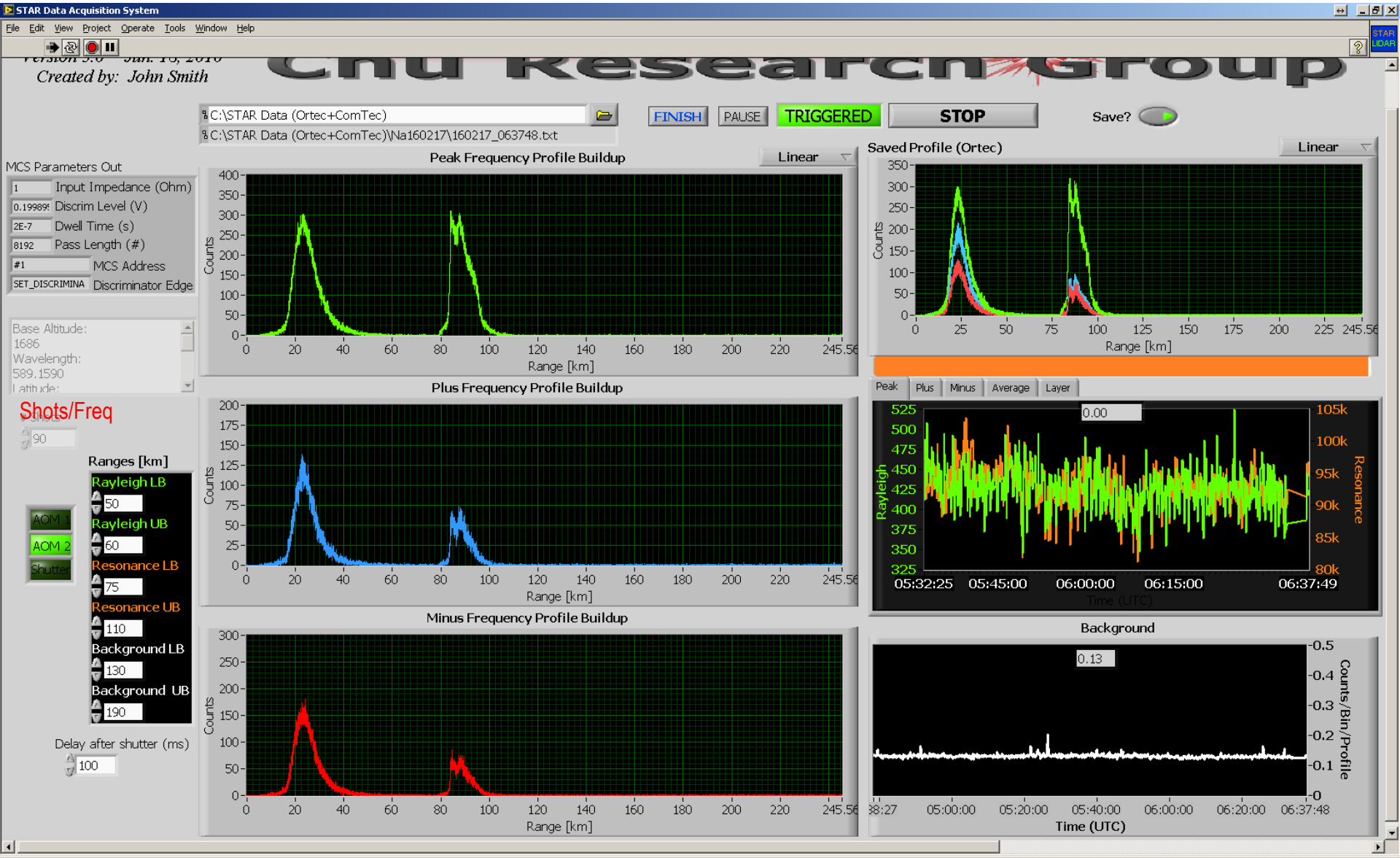
Dr. John Smith's Excellent PhD Research

[Smith and Chu, AO, 2015]



http://cires1.colorado.edu/science/groups/chu/pubs/documents/2015AO_SmithChu_HighEfficiencyLidarArchitecture.pdf

STAR Na Doppler Lidar DAQ



High-Efficiency Lidar Leading to New Science Inquiries

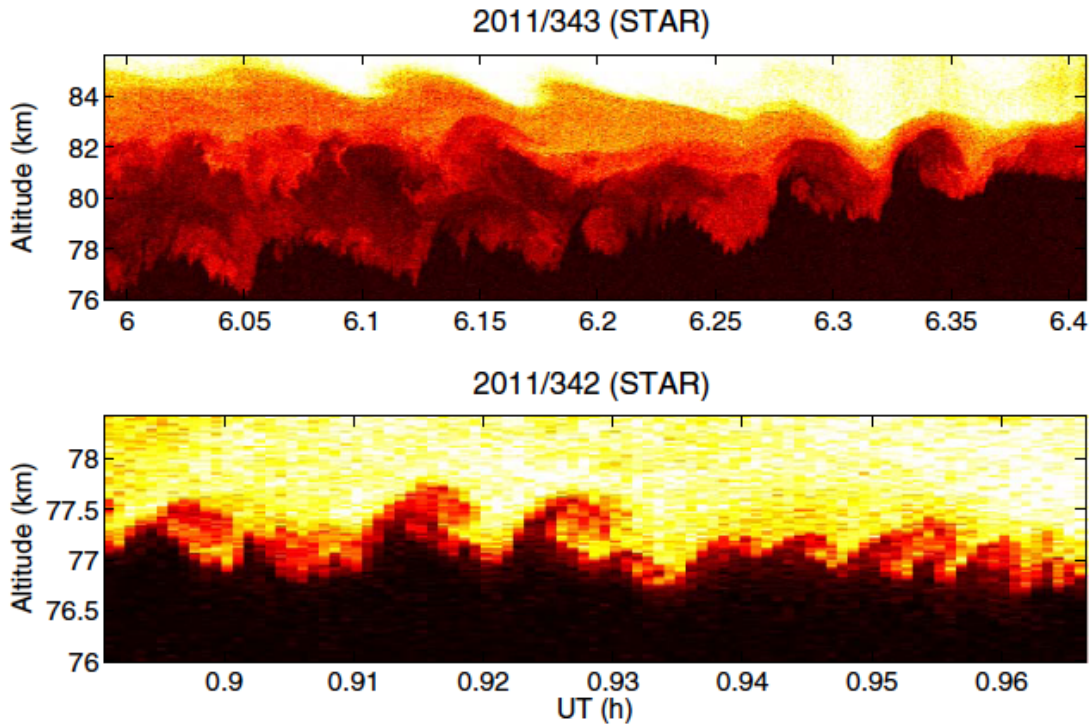
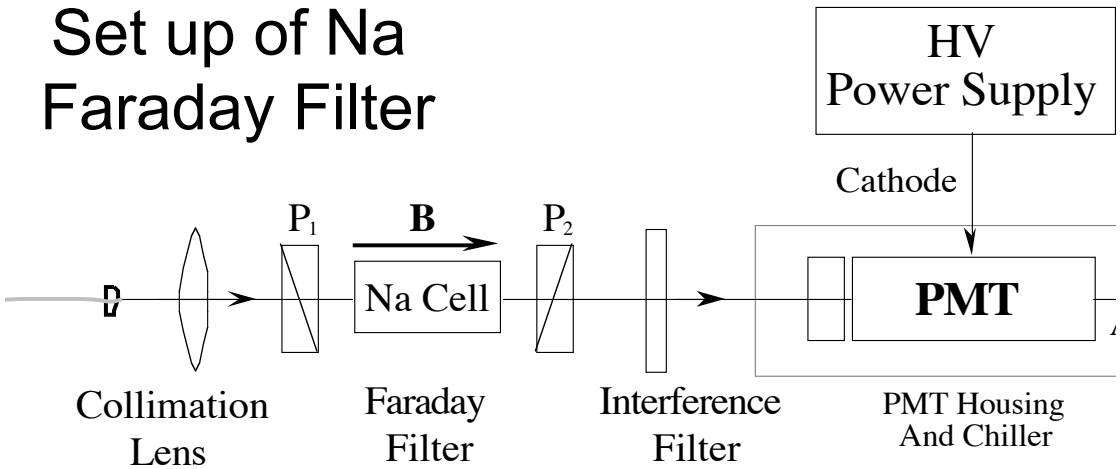


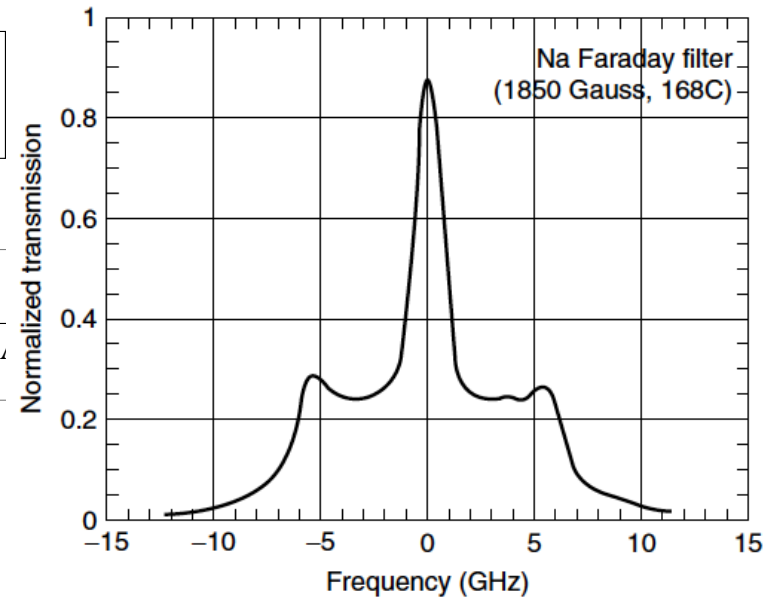
Fig. 10. Turbulence features of the order of 20 s and 24 m in scale are clearly visible on the bottomside of the layer, where the density gradient is large on these nights in December 2011. Data was taken with the STAR Na Doppler lidar, which has a power-aperture product of 0.25 W m^2.

[Smith and Chu, Applied Optics, 2015]

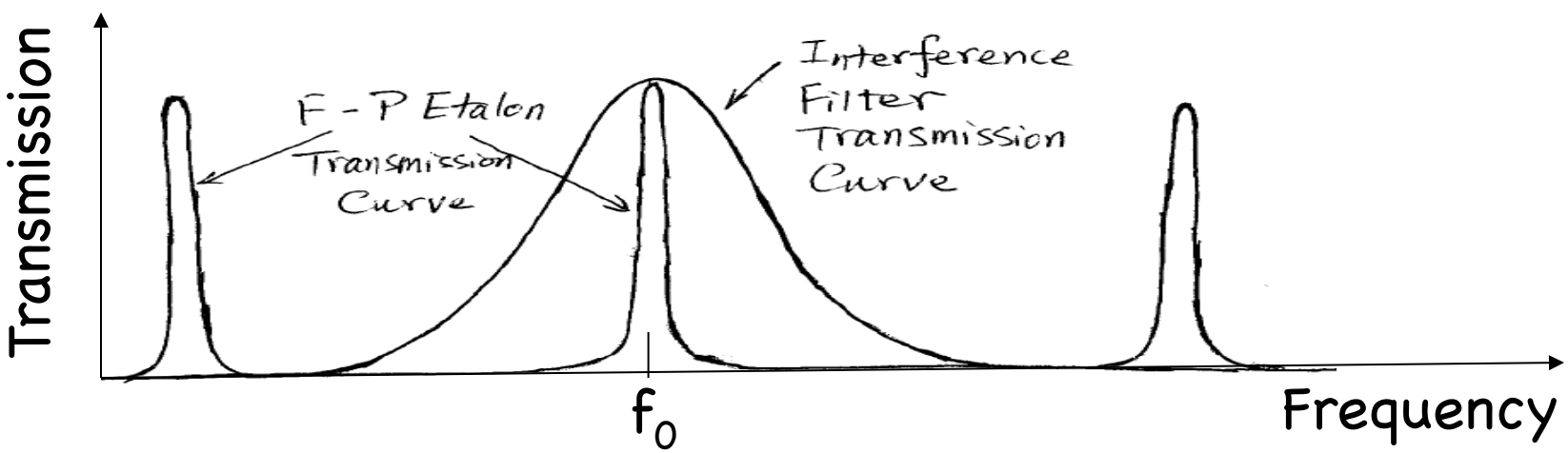
Narrowband Daytime Filter: Faraday Filter for Na Doppler Lidar

Set up of Na Faraday Filter

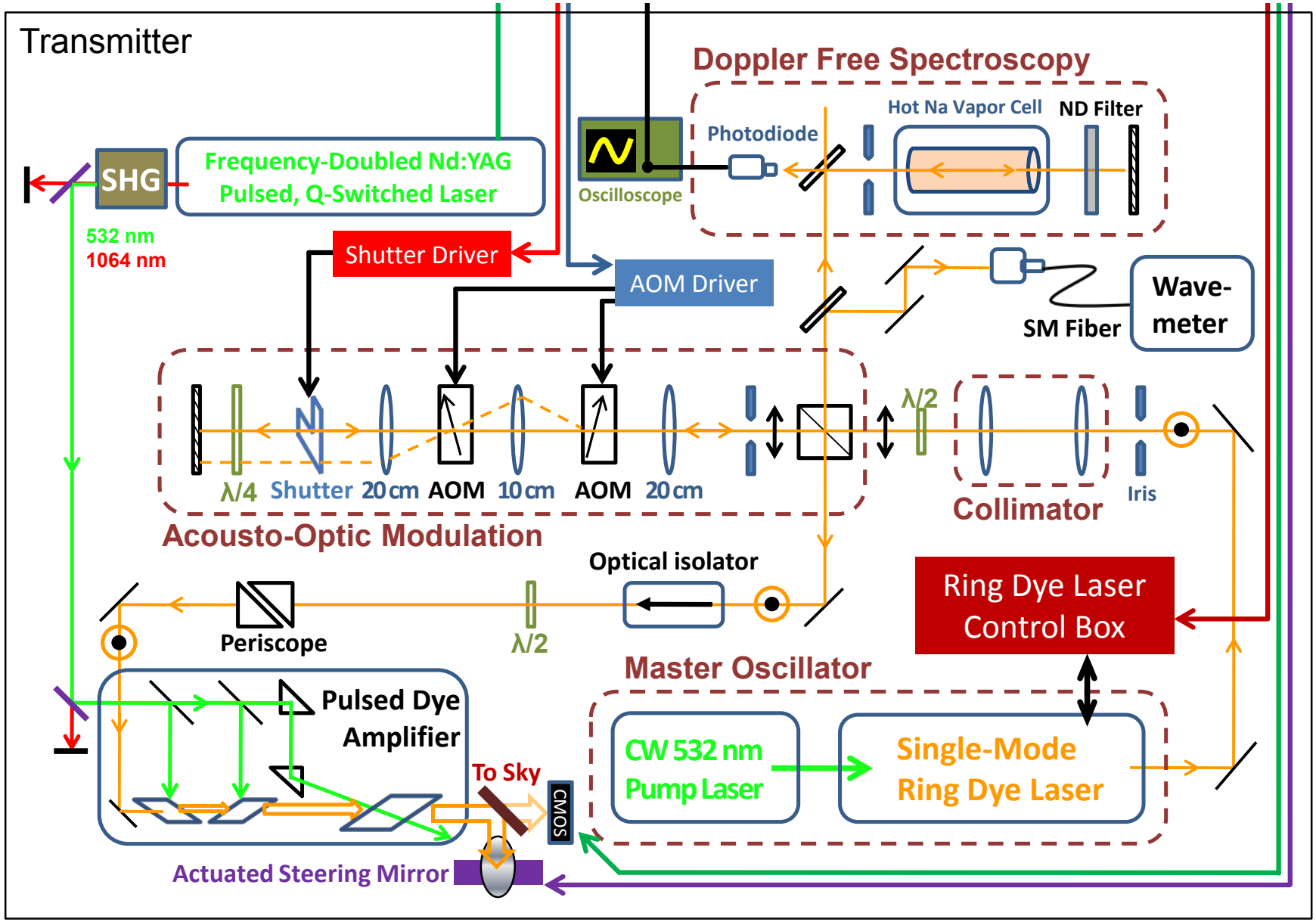




See textbook Chapter 5



STAR Na Doppler LIDAR Transmitter

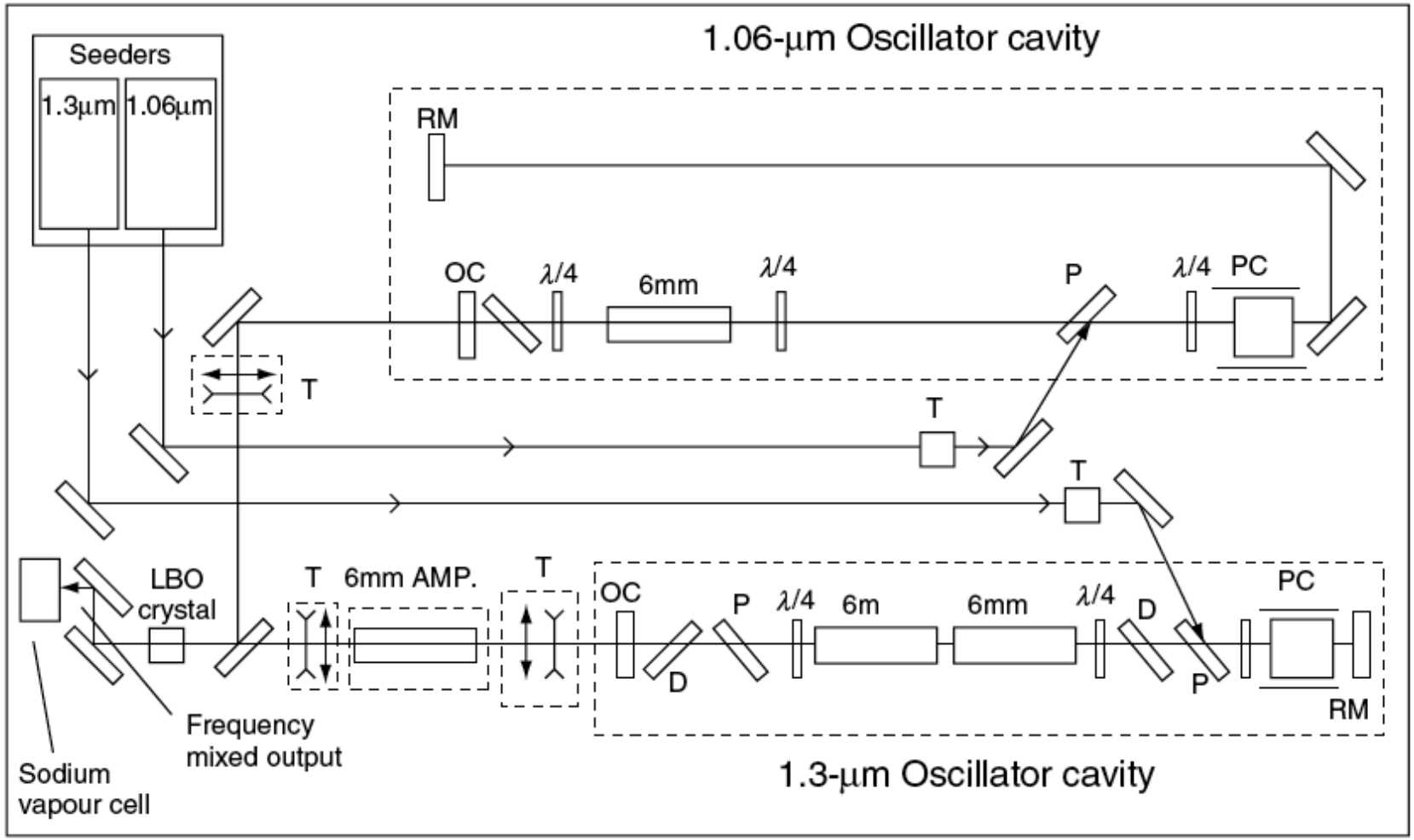


Options for Na Doppler Lidar

- 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

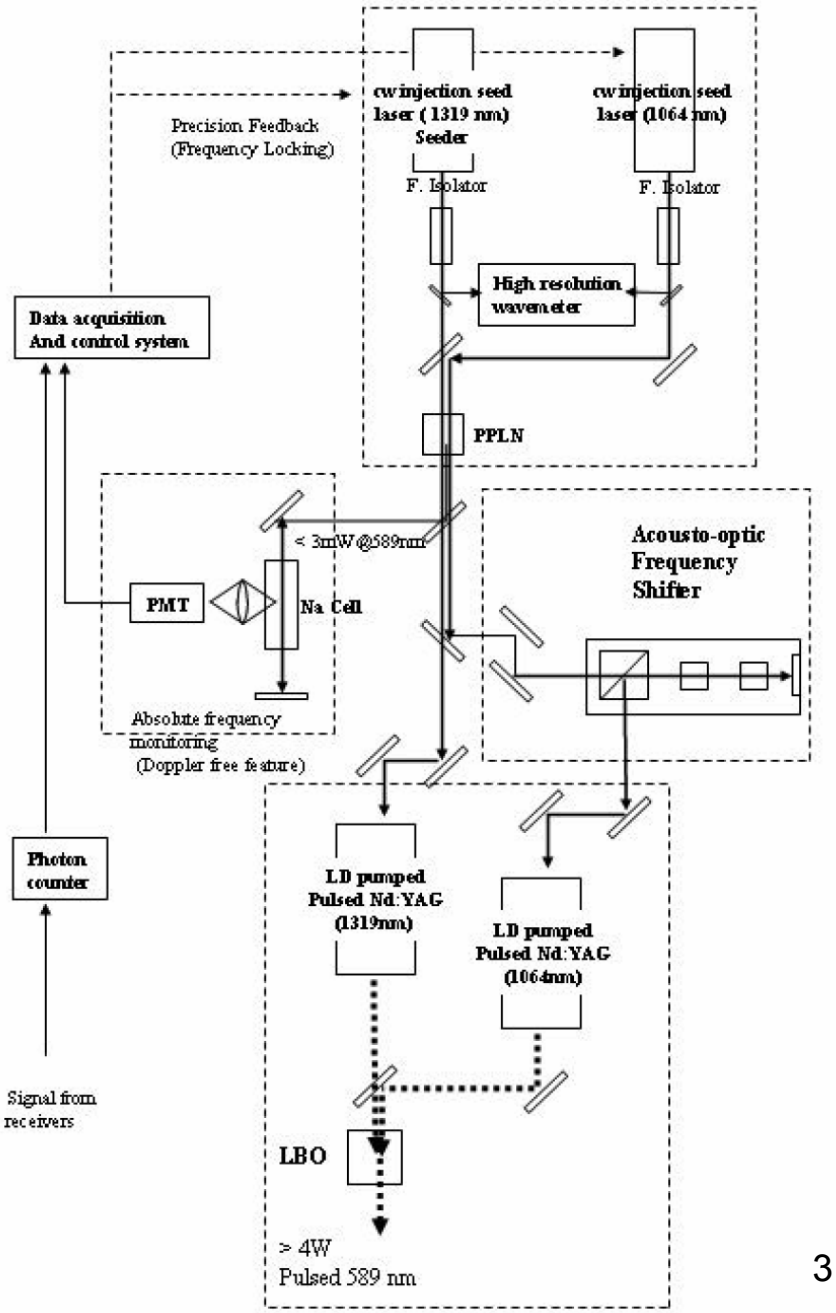
Solid-State Na Doppler Lidar

- 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]



Summary

- A state-of-the-art Na Doppler lidar is the dye-laser-based Na wind and temperature lidar -- "ring dye laser + pulsed dye amplifier" configuration. STAR Na Doppler lidar is a modern version of it.
- A main feature is the narrowband Na lidar transmitter with accurate and precise frequency control and narrowband laser: Na Doppler-free 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. High-efficiency lidar receiver design enables the very high-resolution lidar measurements for new science endeavors.
- Daytime filters based on Faraday filter enable full diurnal cycle measurements, which makes the Na Doppler lidar a golden standard.
- Na Doppler lidar can be realized with many other laser configurations, and its technologies will continue evolving with advancement of laser, electronics, fiber optics, detector, data acquisition, etc. technologies.