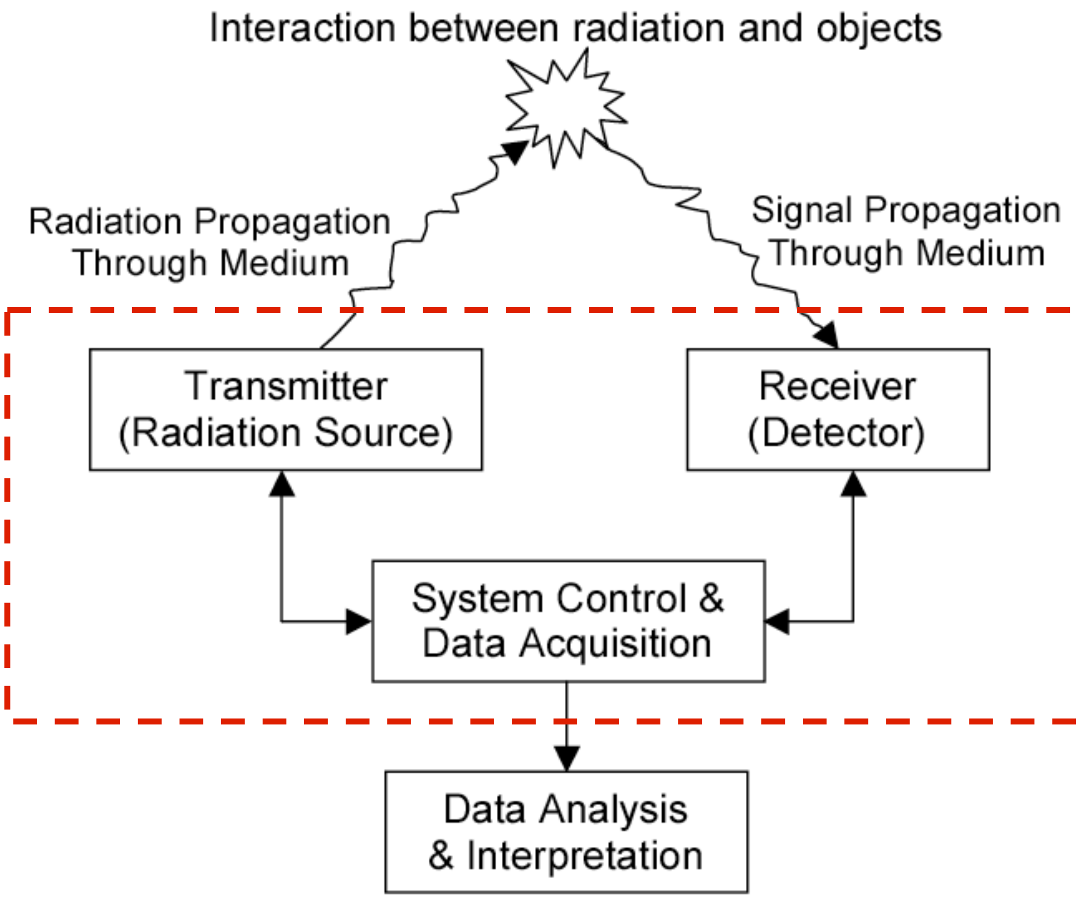
Lecture 39. Lidar Architecture and Lidar Design

- Introduction
- Lidar Architecture: Configurations & Arrangements
- Lidar Design: Basic Ideas and Basic Principles
- Considerations on Various Aspects of Lidar Design
- An Example of Lidar Design and Development
- Lidar Calibration
- Summary

Introduction

- Lidar architecture is the art of lidar system instrumentation (including hardware and software).



- Refer to Lecture 07 on lidar architecture fundamentals

Introduction

- Lidar design is to design a lidar system that meets our measurement goals. Lidar design is based on our understanding of the physical interactions and processes involved and utilizes the lidar simulations to assess the lidar performances, errors, and sensitivities.
- Lidar design includes

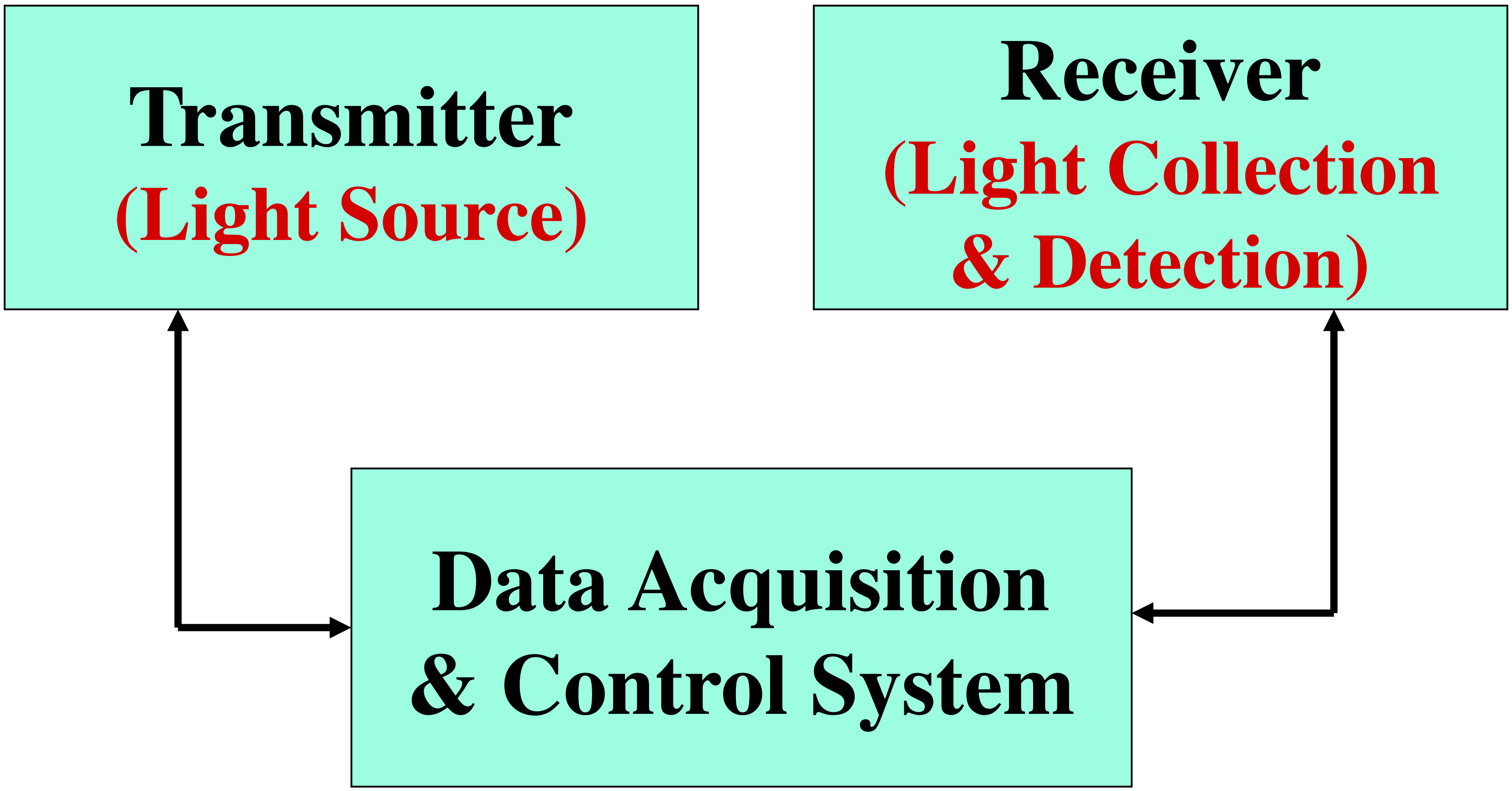
(1) Choice of what type of lidar to use, based on measurement objectives (subject), measurement requirements (accuracy, precision, and resolution) and operation requirements (reliability, stability, operation difficulty), considering physical interactions and processes involved (how well we know the details), potential signal levels, and available hardware, etc.

(2) Choice of what kind of wavelength, bandwidth, and diurnal coverage to use, based on potential return SNR, available hardware, etc.

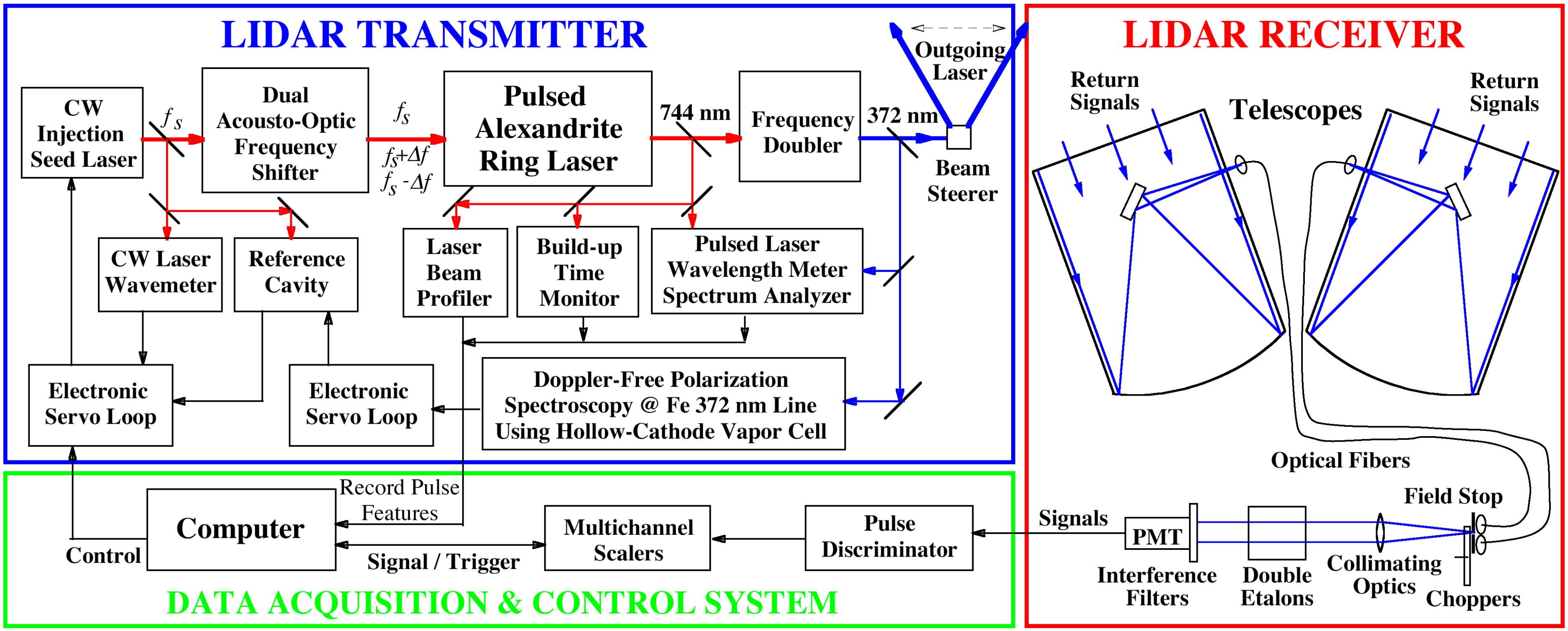
(3) Choice of what kind of laser, frequency control, receiver, filter, detector, DAQ to use, based on measurement requirements, available hardware, etc.

(4) Design the lidar system based on above choices, and run simulations or basic tests or prototypes to predict the lidar performance.

LIDAR Architecture



MRI LIDAR Architecture



- Functions for each sub-system:

  transmitter, receiver, DAQ & control

Novel Architecture of LIDAR

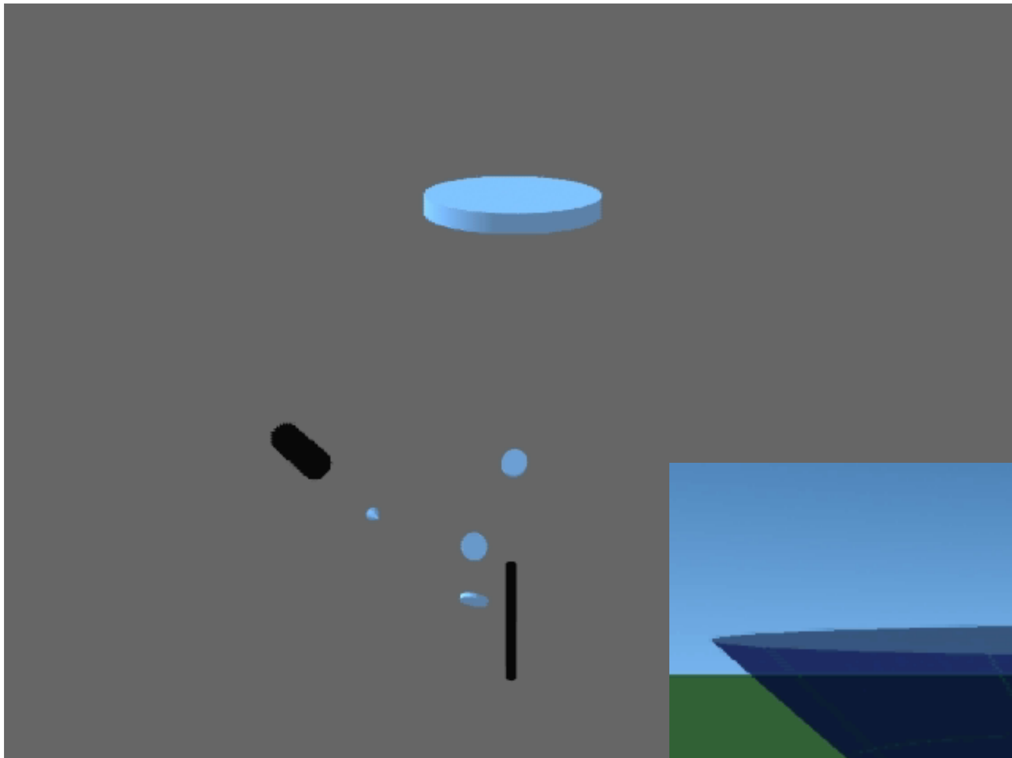
Transceiver
(Light Source and Light Collection/Detection)

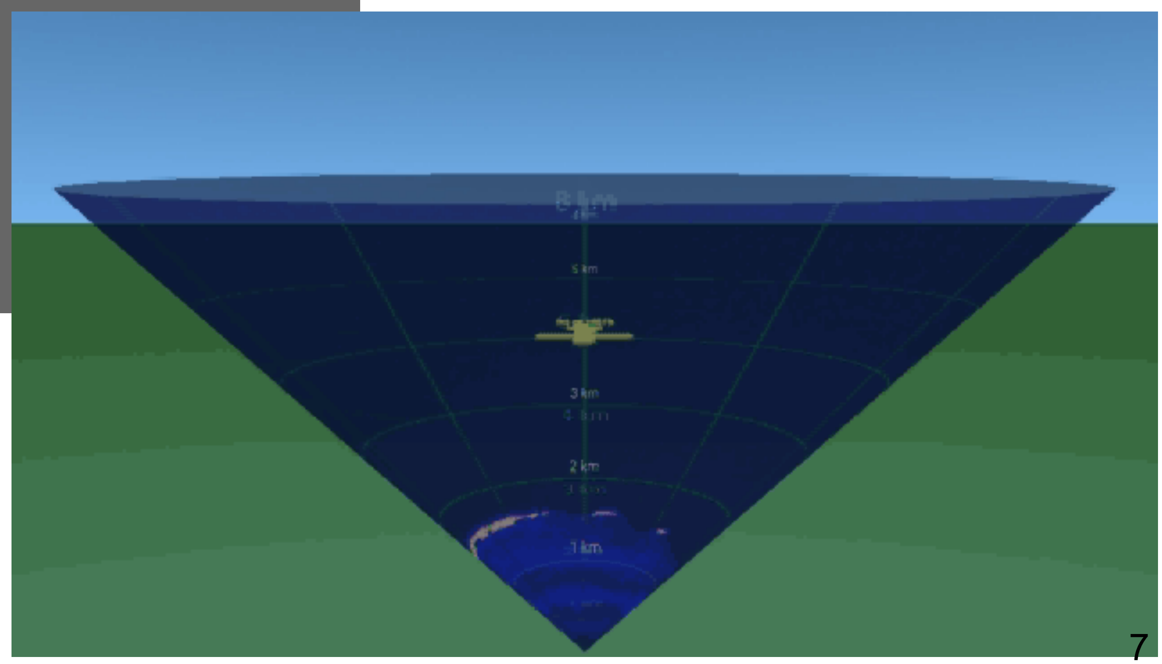
↑

Data Acquisition & Control System

- ❑ Transceiver is becoming more and more popular for compact lidars in mobile systems, like ground-based mobile lidars or airborne and spaceborne lidars for the lower atmosphere detection.

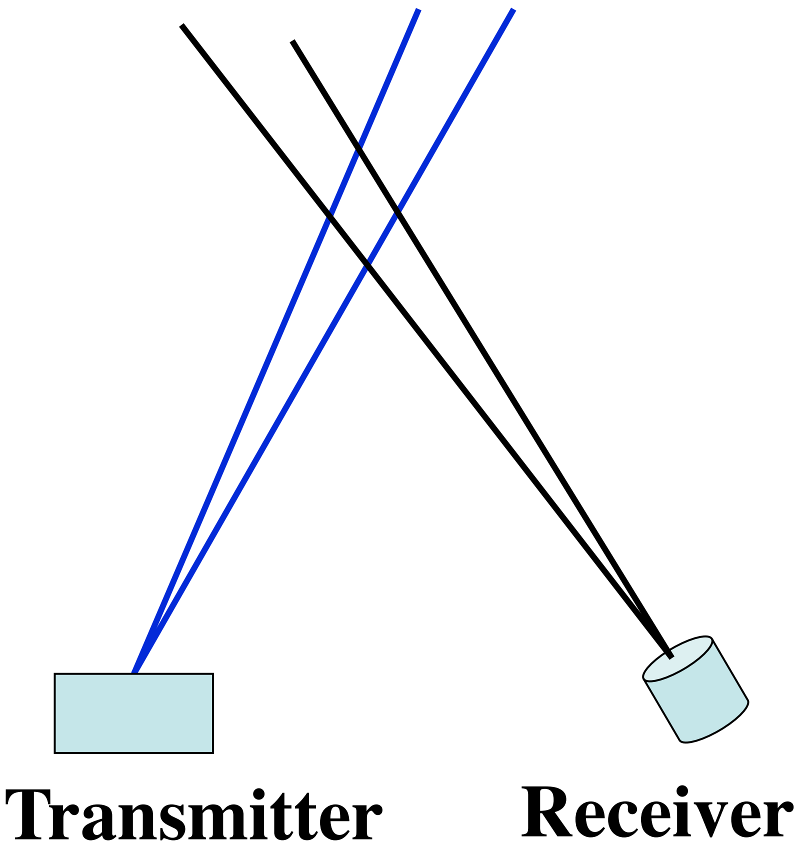
Lidar with Holographic Optical Element





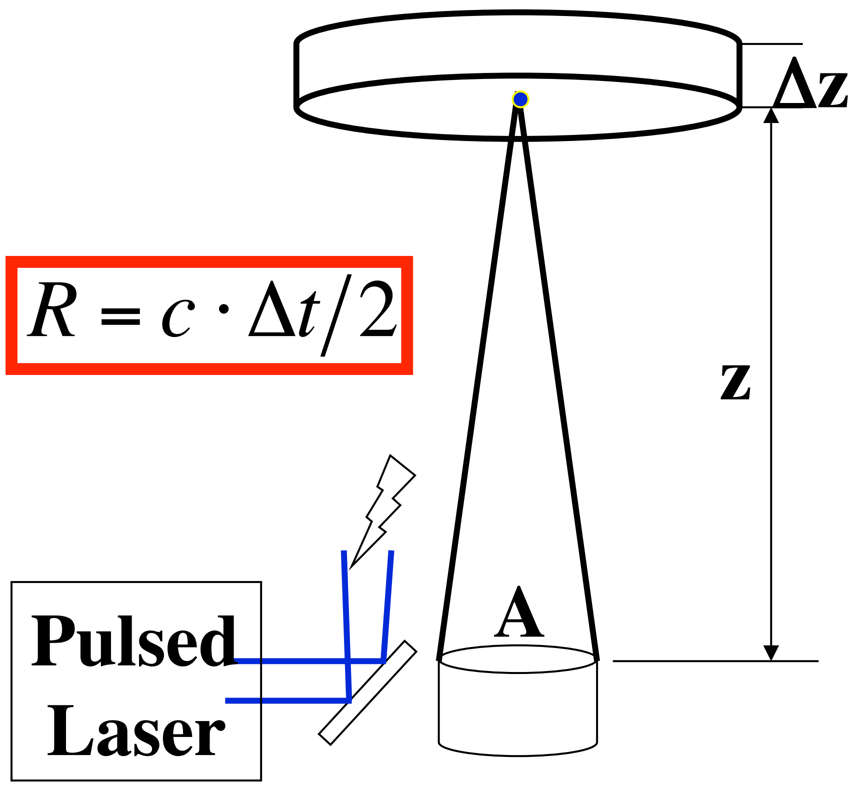
Courtesy of
Geary Schwemmer

LIDAR Configurations: Bistatic and Monostatic



Bistatic Configuration

$$R = c \cdot \Delta t / 2$$

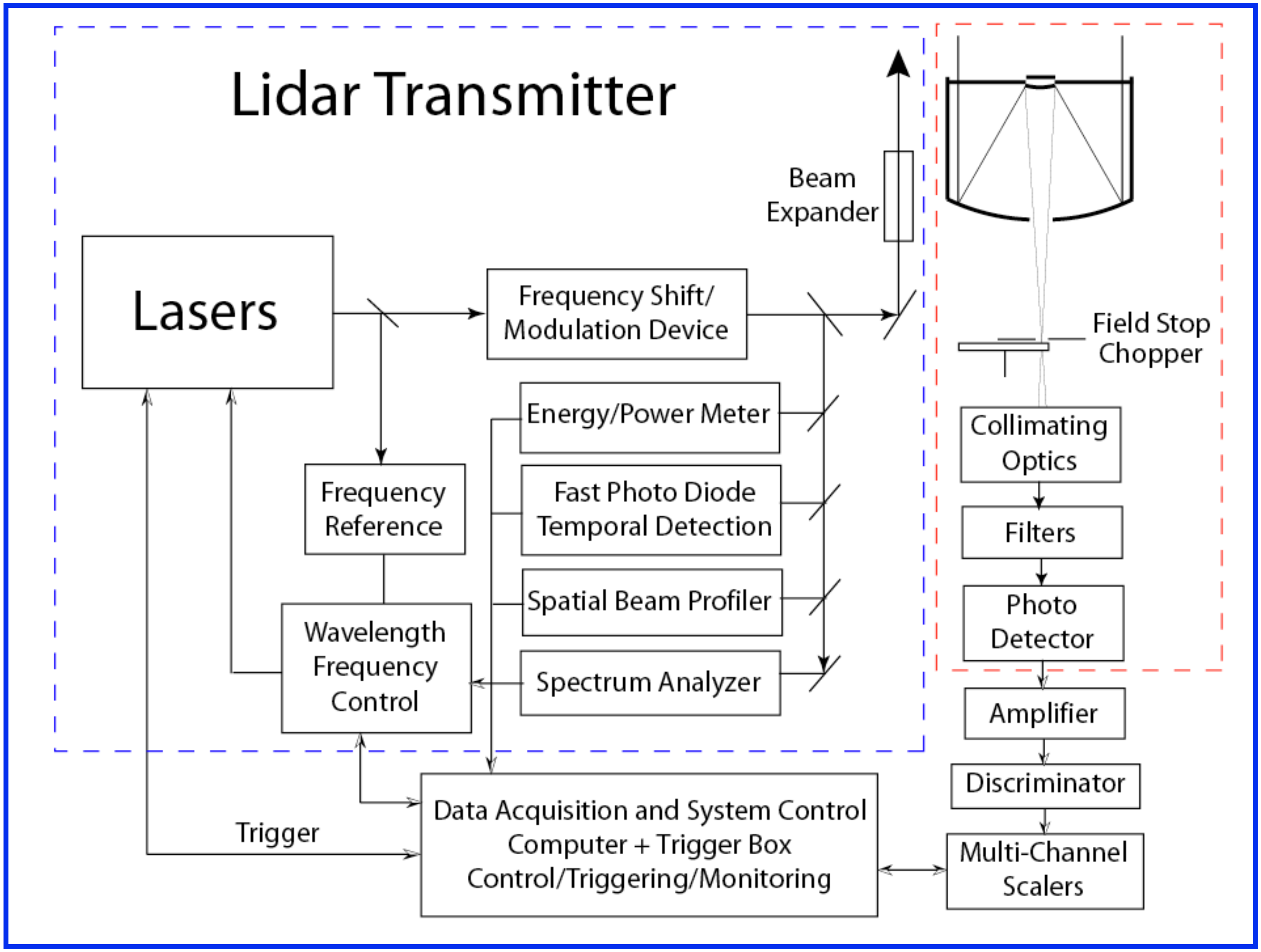


Monostatic Configuration

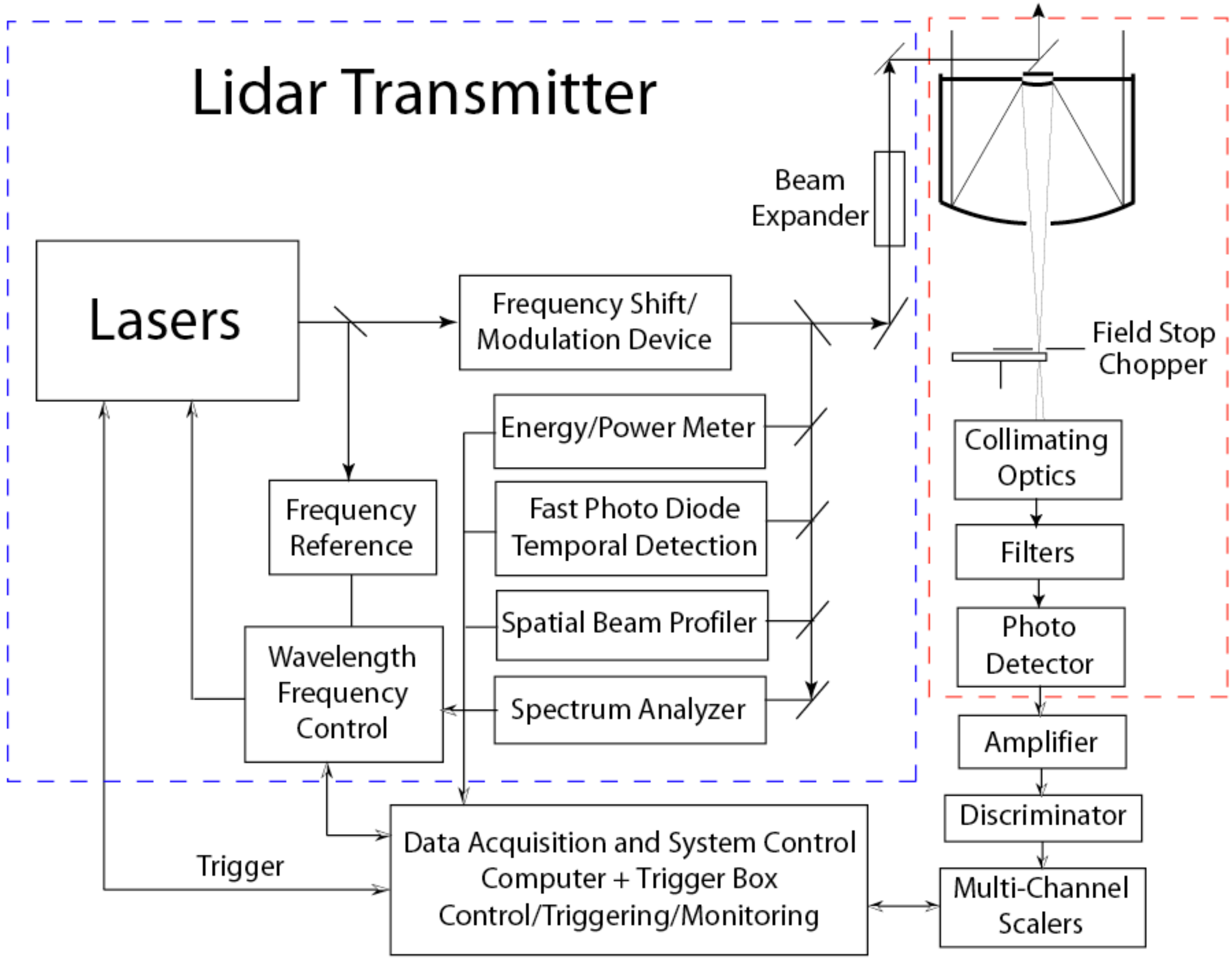
LIDAR Arrangements: Biaxial and Coaxial

- There are considerable amount of lidars using biaxial arrangements although they have monostatic configurations.
- In the biaxial arrangement, the laser beam and the receiver axis are separated, and the laser beam only enters the field of view of the receiver optics beyond some predetermined range.
- Biaxial arrangement helps avoiding near-field backscattered radiation that may saturate photo-detector.
- In the coaxial arrangement, the axis of the laser beam is coincident with the axis of the receiver optics.
- Therefore, the receiver can see the laser beam since the zero range bin. (There are debates on this point - depending on the telescope structure!)
- The near-field backscattering problem in a coaxial system can be overcome by either gating of the photo-detector or use of a fast shutter or chopper to block the near-field scattering.

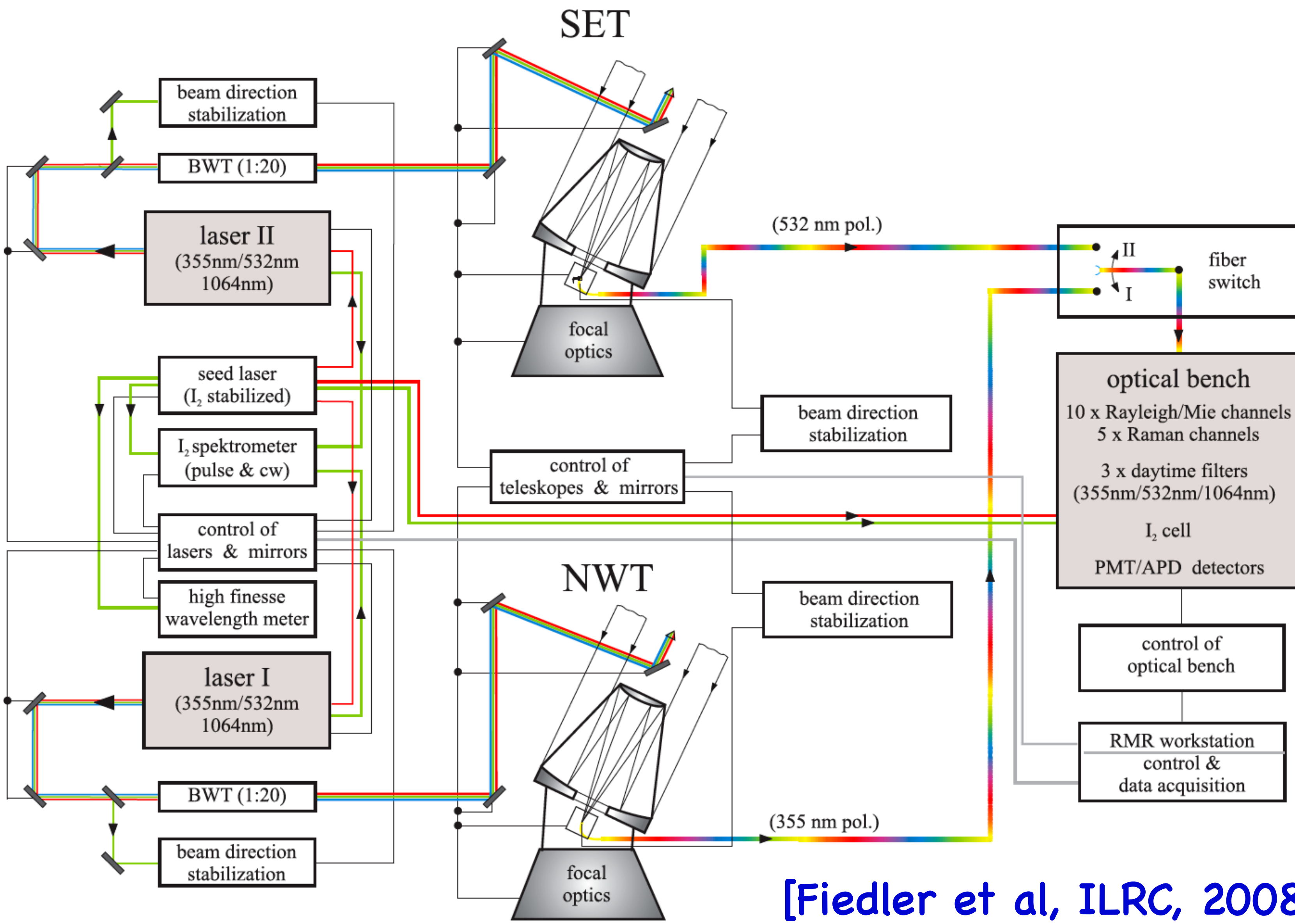
Biaxial Arrangement



Coaxial Arrangement



ALOMAR RMR Lidar @ Andoya



[Fiedler et al, ILRC, 2008]

ALOMAR RMR Lidar Transmitter

- The ALOMAR RMR lidar is optimized for maximum receiving signal to measure atmospheric temperatures, winds and aerosols simultaneously. Therefore, it is a complex twin-lidar system consisting of two power lasers, two receiving telescopes, and one optical bench for spectral separation and filtering of the light received from the atmosphere.

- The power lasers are pulsed Nd:YAG lasers emitting the fundamental (1064 nm), second (532 nm), and third (355 nm) harmonic wavelengths simultaneously. Both power lasers are seeded by a single external cw laser, which is frequency stabilized to iodine absorption spectroscopy, to generate laser pulses of high spectral stability. Using beam direction stabilization systems the laser beams are guided into beam widening telescopes (BWT) for reduction of the beam divergence by a factor of 20. After that the beams with 20-cm diameters are guided by a second set of beam direction stabilization systems into the atmosphere.

- For collection of the backscattered light two quasi-Cassegrain telescopes with 1.8-m primary mirrors are used which can be tilted up to 30° off-zenith while covering an azimuth range of 90° each. They are installed in such a way that one telescope is able to access the north-to-west quadrant (NWT), the other one the south-to-east quadrant (SET). The light received from the atmosphere is guided by optical fibers to the input of the optical bench. For investigations of the polarization characteristics of the light in the visible and ultraviolet spectral range, polarizers are integrated in the focal optics of the receiving telescopes.

ALOMAR RMR Lidar Receivers

- At the input of the optical bench a rotating segmented mirror (fiber switch) is used to feed the light of both telescopes synchronized to the laser pulses into the single set of receiving optics.
- In the following, the light is separated and filtered by spectral range and intensity to produce 15 different channels:
- 1064 nm (two channels, Rayleigh-/Mie-scattering on air molecules & aerosols),
- 532 nm (three channels, Rayleigh-/Mie-scattering on air molecules & aerosols),
- 355 nm (three channels, Rayleigh-/Mie-scattering on air molecules & aerosols),
- 608 nm (two channels, N2 vibrational Raman-scattering excited by 532 nm),
- 387 nm (one channel, N2 vibrational Raman scattering excited by 355 nm),
- 530.4 nm and 529.1 nm (two channels, N2 + O2 rotational Raman-scattering excited by 532 nm).
- Two additional channels at 532 nm are placed behind an iodine absorption cell for analyzing the Doppler shift.
- Using photomultipliers (PMT) and avalanche photodiodes (APD) the light is converted into electrical signals which are altitude resolved by counters and processed and stored on a computer.

[Fiedler et al, ILRC, 2008]

Basic Ideas of Lidar Design

- The key of lidar design is the understanding of physical interactions and processes involved, the lidar simulations, and the choices of lidar type, configuration, arrangement, hardware and software to meet the measurement goals (subject, accuracy, precision, resolution, coverage).
- The basic procedure of lidar design includes

(1) Study of physical interactions, processes, and spectroscopy for their applications in the lidar field. Study of lidar principles and technologies.

(2) Choice of what type of lidar to use, based on measurement objectives and requirements (subject, accuracy, precision, resolution, reliability, stability, operation difficulty, etc).

(3) Choice of what kind of wavelength, bandwidth, and diurnal coverage to use, based on potential return SNR, available hardware, etc.

(4) Choice of what kind of laser, frequency control, receiver, detector, filter, and DAQ to use, based on measurement requirements, available hardware, etc.

(5) Design the lidar system based on above choices, and run simulations or basic tests or prototypes to predict the lidar performance.

Considerations on Lidar Design

- What type of lidar: Mie, Rayleigh, Raman, resonance fluorescence, DIAL, coherent, direction-detection Doppler, fluorescence, rangefinder, altimeter, HSRL?
- Bistatic or monostatic?
- Biaxial or coaxial?
- Geometrical overlap
- Uplooking or downlooking?
- Care about only scattering or only timing or both?
- Wavelength for transmitter and receiver
- Tunable or not?
- Bandwidth for transmitter and receiver
- Frequency stability for transmitter and receiver
- Power/energy consideration
- Nighttime or full diurnal capability?
- Mobile or not?
- Volume, mass, cost, reliability, robustness, operation, etc?

Further Considerations

- Doppler shift and how much?
- Polarization detection or not?
- Pulse repetition rate
- Beam divergence
- Layer saturation
- Photo detector dynamic range
- Bin width and resolution
- Record every pulse or not?
- Record system parameters or not?
- Timing control
- Need precise beam point control or not?
- Need real time data reduction or not?
- Eye safe or not?
- … …

Choice of Lidar Types

- To choose the right type, we have to know how many types of lidars are available and the capabilities and limitations/issues of each type of lidar. This is why we have gone through all types of lidars in our class to give you a comprehensive overview.
- The choice of lidar type is mainly driven by the measurement goals, available expertise, and available hardware.
- Conventional Mie and Rayleigh lidar
- Pure Rotational Raman lidar
- Vibrational-Rotational Raman lidar
- Differential absorption lidar
- Broadband resonance fluorescence lidar
- Narrowband resonance-fluorescence Doppler lidar
- Coherent Doppler lidar
- Direct-detection Doppler lidar
- High-spectral-resolution lidar
- Fluorescence lidar
- Range-finder and Altimeter

Capabilities and Limitations

- Conventional Mie/Rayleigh lidar: aerosol/cloud occurrence, geometry, size, shape (with polarization or multi-wavelength detection), density; atmospheric density and temperature (with Rayleigh integration technique) in aerosol-free region, …
- Pure-Rotational Raman lidar: temperature in lower atmosphere, aerosols, species
- Vibrational-Rotational Raman lidar: temperature in lower atmosphere when aerosols present, species, …
- Differential absorption lidar: various species in lower atmosphere, temperature
- Broadband resonance fluorescence lidar: various species and/or temperature in MLT (Boltzmann), Rayleigh temperature above 30 km, aerosol/cloud
- Narrowband resonance-fluorescence Doppler lidar: various species, temperature and wind in MLT, Rayleigh temperature above 30 km, aerosol/cloud from 10-100 km
- Coherent Doppler lidar: high-resolution wind in lower atmosphere
- Direct-detection Doppler lidar: wind and/or temperature in lower and middle atm
- High-spectral-resolution lidar: aerosol optical properties, wind, or temp
- Fluorescence lidar: species in liquid or solid states
- Range-finder and Altimeter: range and altitude determination

Configuration, Arrangement, Direction

- Most modern lidars (consisting of pulsed lasers) use monostatic configuration with either biaxial or coaxial arrangement. Lidars consisting of cw laser transmitters usually take bistatic configuration, in order to distinguish range, if coding technique is not applied.
- The choice of biaxial or coaxial arrangement is usually determined by the detection range. If near-field range is desired, coaxial arrangement is preferred as it provides full overlap of receiver field-of-view with laser beam. If near-field range is not desired, biaxial arrangement may help prevent the saturation of photo-detector by strong near-field scattering. Scanning capability can also come into play for the selection of biaxial or coaxial.
- Groundbased lidars are usually uplooking, while spaceborne lidars are usually downlooking. Airborne lidars can be either uplooking or downlooking, depending on application needs.
- The reason to care about up- or down-looking is the fact that atmospheric density decreases with altitude nearly exponentially. So the signal strength for up- or down-looking lidars will be quite different.

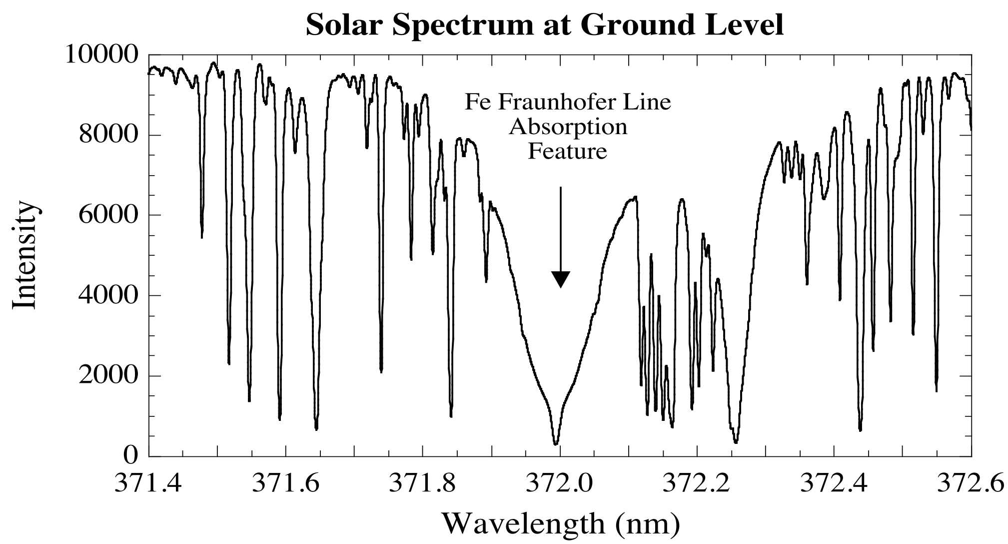
Wavelength Considerations

- Many factors determine the wavelength selection:

- First, the detection subject - whether a specific wavelength is required, e.g., Na or Fe atomic transition wavelength, or H_2O differential absorption wavelength.
- Second, signal-to-noise ratio considerations: Rayleigh (λ^{-4}), Mie (λ^{-2} to λ): e.g., Coherent lidar (Mie vs Rayleigh); VR Raman lidar (N_2 vs. O_2)
- Third, transmission of laser light through the medium (e.g., atmosphere or water).
- Fourth, the solar background intensity - low solar radiation is desirable to benefit signal-to-noise ratio (SNR) in daytime. Usually UV solar radiation is lower than visible and IR.
- Fifth, available hardware (wavelength vs. power/energy) is often to be a major limitation.
- Another important factor in determining wavelength is eye-safety. UV and far IR are safer for people because our eyes cannot focus the light with wavelengths in these regions. Our eyes have much higher damage threshold in these wavelengths than visible light or near IR.

Fraunhofer Lines

- Fraunhofer lines are named after the German physicist Joseph von Fraunhofer (1787–1826). Fraunhofer lines in solar radiation are a set of several hundred dark lines appearing against the bright background of the continuous solar spectrum. They are produced by absorption of light by the cooler gases in the Sun's outer atmosphere at frequencies corresponding to the atomic transition frequencies of these gases, such as atomic H, Fe, Na, K, Ca, Mg, Li, etc, or by oxygen of the Earth's atmosphere.
- Lidar operating at the wavelengths in deep Fraunhofer lines benefits from the lower solar background for daytime operations.



http://bass2000.obspm.fr/solar_spect.php?PHPSESSID=b1fb4b5e30286b1698ae5b2f330b3318

Bandwidth Considerations

- Possible combinations of transmitter and receiver

Transmitter		Receiver	Lidar types
Broadband Transmitter	+	Broadband Receiver	Conventional Mie, Rayleigh, Raman Scatter lidar, Broadband Resonance Fluorescence lidar, Differential Absorption lidar
Narrowband Transmitter	+	Broadband Receiver	Narrowband Resonance Fluorescence Doppler lidar, Differential Absorption lidar
Narrowband Transmitter	+	Narrowband Receiver	Coherent Doppler lidar, Direct-Detection Wind lidar, Rayleigh Doppler lidar. High-Spectral-Resolution lidar
Broadband Transmitter	+	Narrowband Receiver	Potential broadband resonance fluorescence temperature lidar, Potential Rayleigh and Raman temperature lidar

Nighttime-Only & Full Diurnal

- This is mainly a consideration on background suppression to ensure sufficient signal-to-noise ratio (SNR).
- Even for nighttime-only operation, interference filters are necessary to suppress background (like moon or star or city light) and ensure safe operation of photo detectors.
- Daytime operation needs extra suppression on much stronger solar background. Usually extra spectral filters with very narrow bandwidth are needed. Two major narrowband spectral filters: F-P etalons and atomic/molecular spectral filters (like Faraday filter or iodine filter).
- Spatial filter or minimized field-of-view (FOV) is also very necessary to largely suppress the solar background. Of course, this may be limited by layer saturation, geometrical overlap and alignment issues.
- FOV usually should be larger than the laser beam divergence to ensure that the receive sees the full lidar beam. When a tight FOV is used, active alignment/stabilization (beam steering) system may be necessary to ensure the FOV contains the full beam at all times.

Transmitter & Receiver

- Depending on application needs and lidar types, there may be several possible combinations of transmitter and receiver to satisfy the same goal. Choose the best one depending on science need, technical feasibility, cost, performance, reliability, etc.

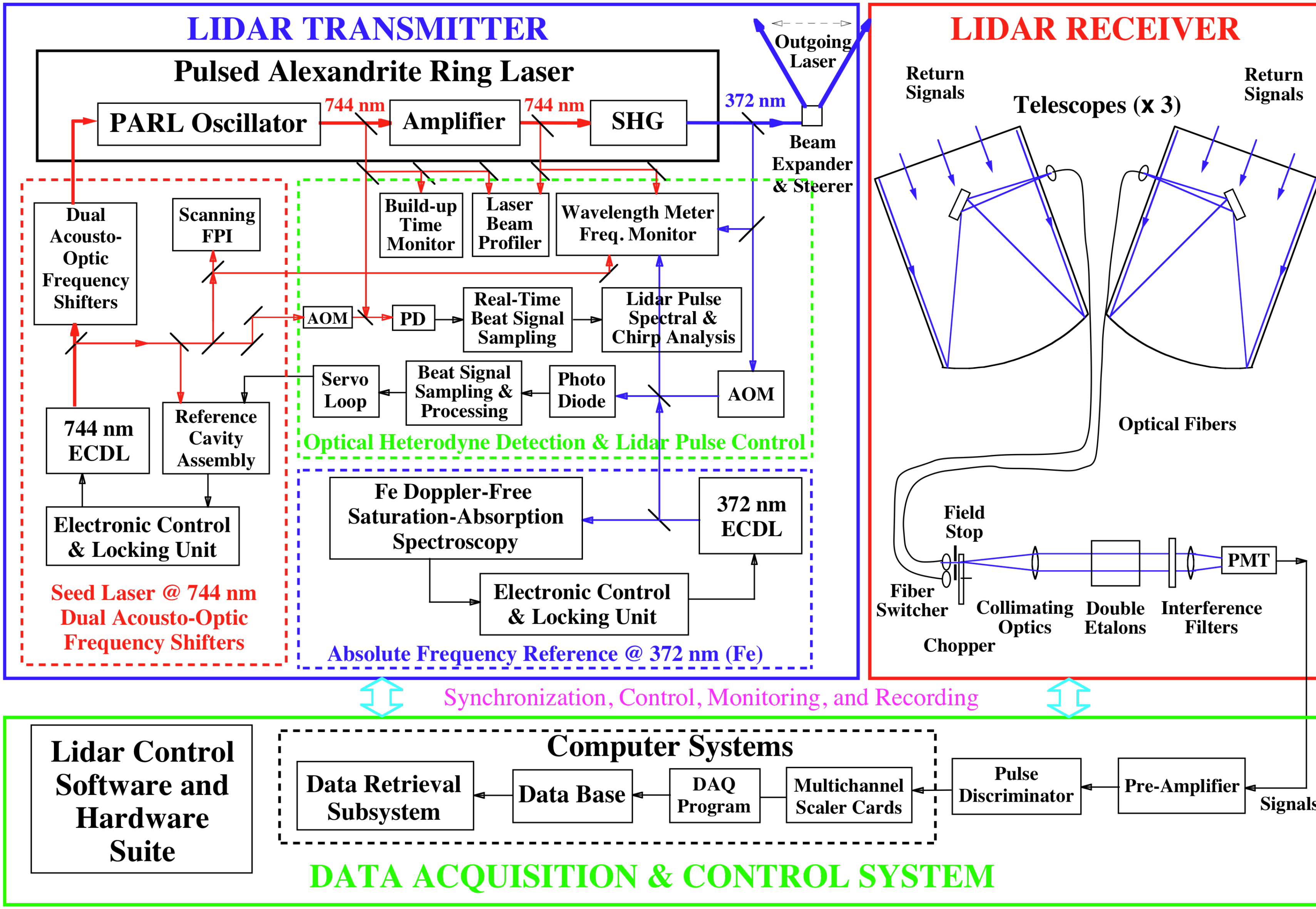
- To choose tunable lasers or not depends on the application needs, e.g., resonance fluorescence and DIAL lidars usually need to be tunable, while conventional Mie, Rayleigh, and Raman scattering lidars can use fixed wavelengths.

- Selection of pulse energy, repetition rate, and duration time, mainly concerns the SNR, measurement resolution, as well as cost, volume, mass, etc. to the entire system.

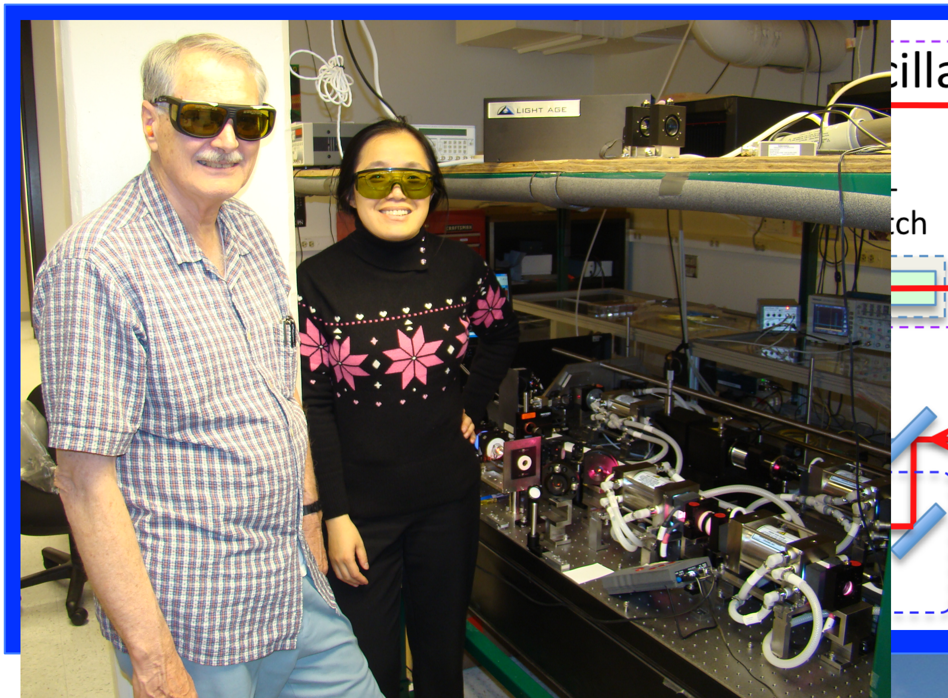
- Selection of telescope area, type, configuration; detector type, size, quantum efficiency, maximum count rate; filter type, size, bandwidth, transmission, mainly concerns the SNR, measurement resolution, as well as cost, volume, mass, etc. to the entire system.

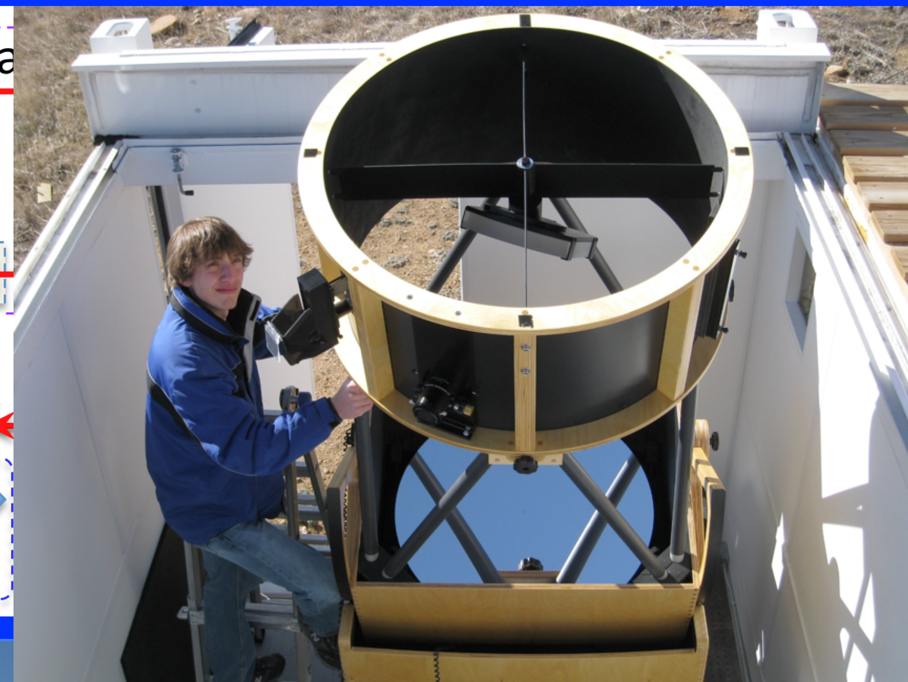
MRI Fe Doppler Lidar

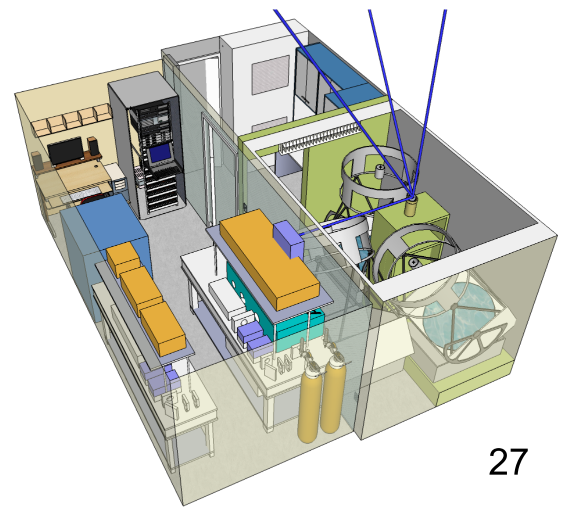
[Chu et al., ILRC, 2010]

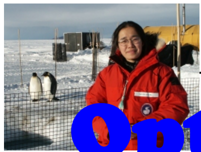


Mobile MRI Fe Doppler Lidar

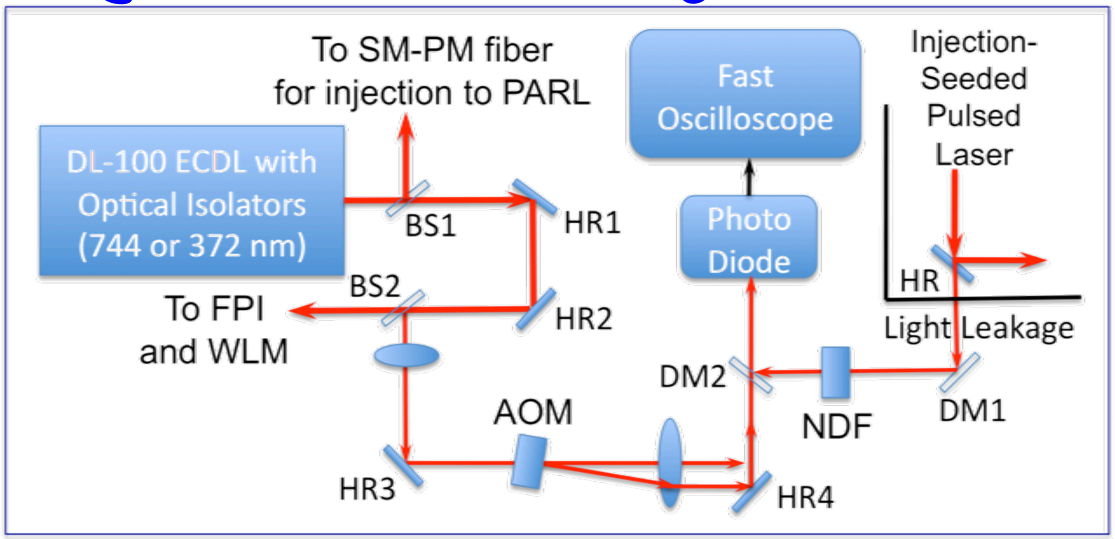


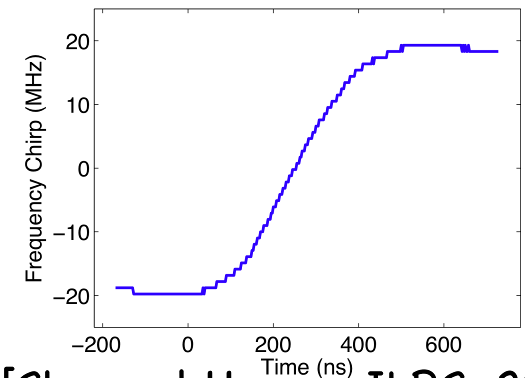




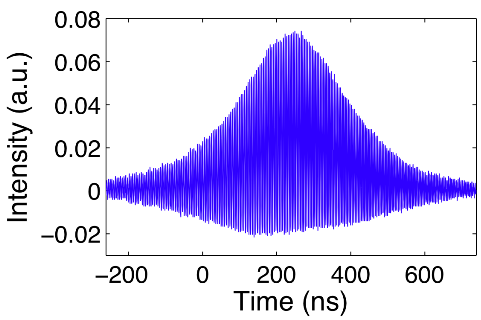


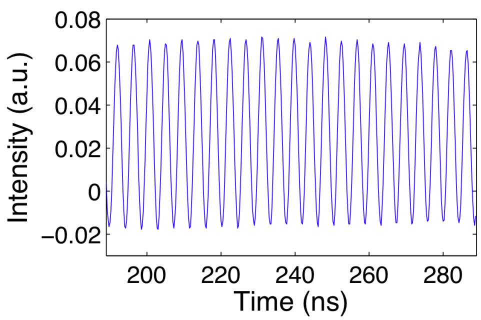
Optical Heterodyne Detection of Laser Pulse

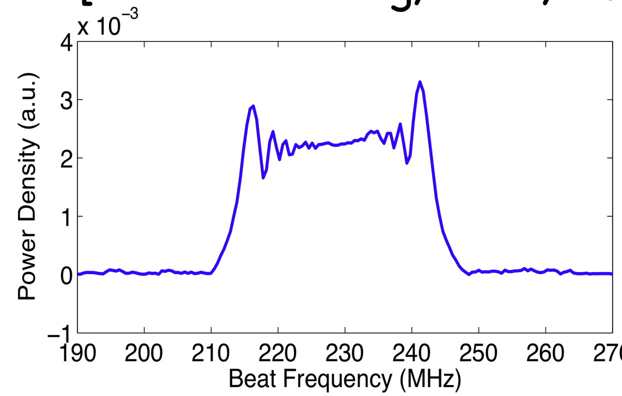


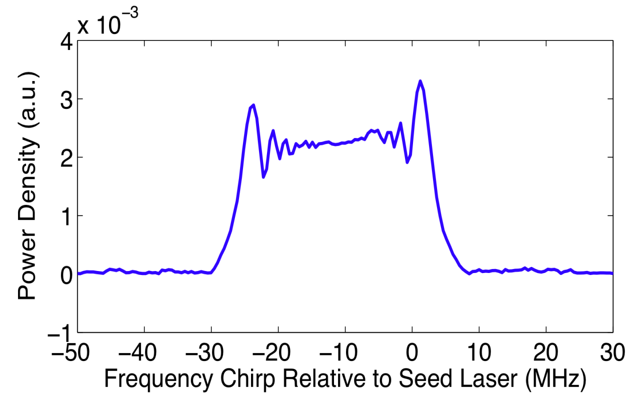


[Chu and Huang, ILRC, 2010]

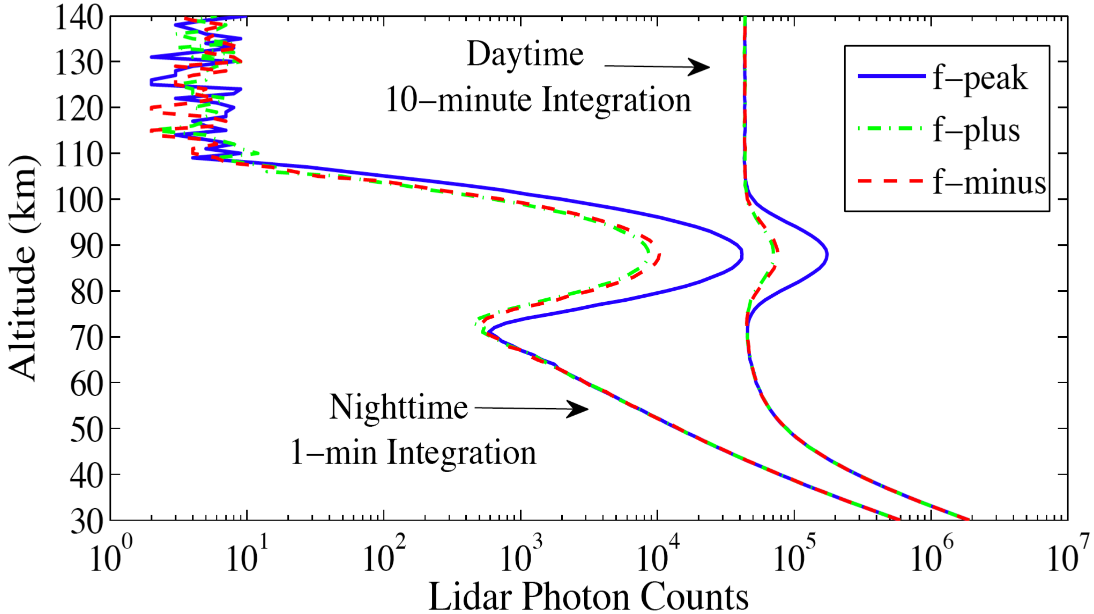


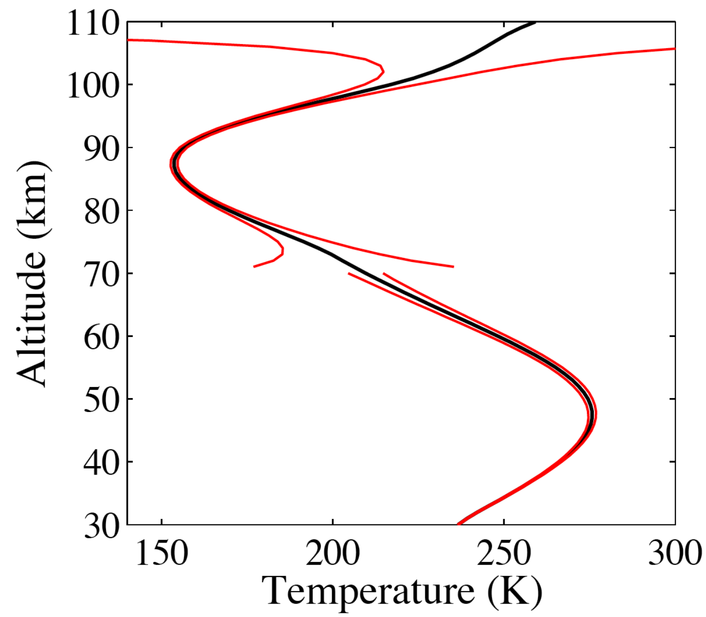


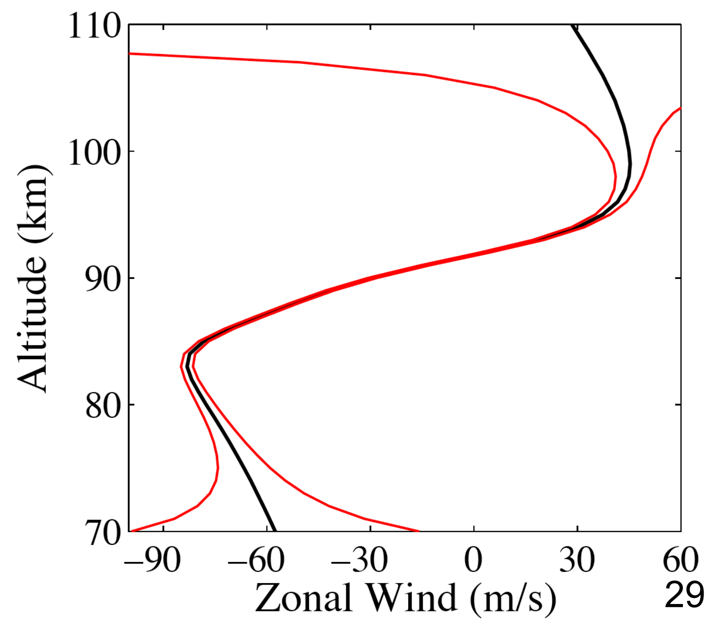




Lidar Simulations







Simulated MRI lidar photon count returns for both day and night measurements and simulated MRI Doppler lidar measurements of temperature and wind for 1-km resolution and 1-min integration at an off-zenith angle of 35° in nighttime configuration. The errors are less than 1 K and 1 m/s at the Fe layer peak. Comparable features can be achieved with 10-min integration in daytime conditions.

Lidar Calibration

- Lidar calibration is a difficult issue for cases when we try to push technology/measurement envelope, because existing instruments have not been able to achieve what you design to achieve. For these cases, you have to fully understand your own system and the entire lidar sensing procedure, including every possible interaction or process involved, and then do a thorough analysis on all possible measurement errors (accuracy, precision, resolution, and stability).
- Understanding your own system and entire procedure is also the key for all cases of lidar calibration. A self-calibration must be made before cross-calibrations with others.
- Make sure your lidar system and data processing are human-error-free!
- In all cases, try to find any possible existing measurements (even not as accurate or resolution as yours) and theoretical/model predictions, and then compare your measurements with them to figure out the similarity and differences. Then analyze the reasons why so.
- Try to operate your lidars with an existing lidar or lidars or other instruments simultaneously and in common-volume, and then compare the measurement results. Be aware of the limitation of each instrument.

Lidar Calibration

- Design your measurements so that you can have some internal calibration or at least do some reality check. For example, temperature profile is usually stable but wind is highly variable. Simultaneous temperature and wind measurements can help determine whether the measurements make sense.
- Before the full system calibration, you may want to calibrate each individual pieces, e.g., PMT, filter, laser, etc. Is your PMT or APD saturated? How is your filter function like and is it stable? How is your laser lineshape like and is it stable? Is there any component in your lidar having day-to-day variability?
- For spaceborne or airborne lidars, it may be necessary to set up some ground-based calibration points. Flight over-passes some ground-based lidar stations for simultaneous and common-volume measurements or over-pass some known objects for altimeter calibration.
- If possible, compare with some in-situ measurements.

Summary

- Lidar architecture is the art of lidar instrumentation, concerning the lidar hardware and software, lidar configuration and arrangement, etc.
- Lidar architecture consists of lidar transmitter, receiver, and data acquisition and control system. Some have merged transceiver. Basic lidar configurations are bistatic and monostatic configurations. Basic lidar arrangements are biaxial and coaxial arrangements.
- Learning existing lidar systems is a good approach to understand the lidar architecture in depth, especially experiences and issues. It will help the design of a new lidar system.
- Lidar design is based on the understanding of physical interactions and processes involved, the lidar simulations, and the choices of lidar type, configuration, arrangement, hardware and software to design a lidar that meets the measurement goals (subject, accuracy, precision, resolution, reliability, coverage, etc).

Summary

- Lidar design is based on the understanding of physical interactions and processes involved, the lidar simulations, and the choices of lidar type, configuration, arrangement, and hardware and software to design a lidar that meets the measurement goals (subject, accuracy, precision, and resolution, coverage, reliability, etc).

- Besides basic architecture, configuration, and arrangement, more considerations should be given to the selection of wavelengths (specific request and solar spectrum intensity), bandwidth of transmitter and receiver (application needs - spectral resolved or not, nighttime-only or full diurnal cycle), laser power/energy, repetition rate, pulse duration time, receiver area, detector efficiency and capability, data acquisition software, and system timing and coordination control. Cost, volume, mass, reliability, etc will also be important when come to reality.

- Lidar calibration is an important but challenging issue. Thorough understanding of your own lidar system and the entire lidar sensing procedure is the key step to calibrate your lidar. Then comparison with other lidars or other instruments is usually necessary for cross-calibration and at least reality check.