# Coherent Lidar

Wm. Randall Babbitt
Professor of Physics and Director of Spectrum Lab
Montana State University

CLRC 2022 Tutorial
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## Outline of Tutorial

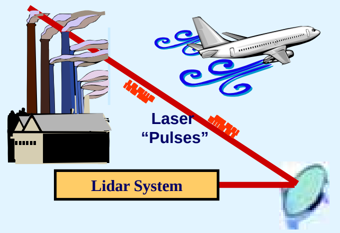
- Coherent Lidar
    - Direct Detection
        - Range Resolution, Precision, and Accuracy
        - Lidar Return
    - Coherent Detection
        - Heterodyne Detection
        - Phase Sensitivity
        - Signal to Noise
        - Speckle
    - FMCW lidar
        - Principles
        - Advantages and Disadvantages
        - Chirped laser generation
        - Optical Metrology and Long Range Lidar
        - Double Sideband FMCW
- Digital Holography

## Lidar versus Ladar

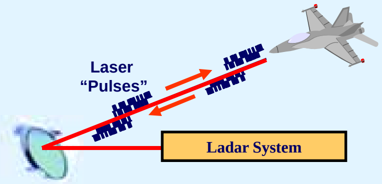
Acronyms:
LIDAR: "Light Detection and Ranging"
or ""laser imaging, detection, and ranging"
LADAR: "Laser Detection and Ranging"
or "Laser Radar"
The "D" doesn't typically stand for "Doppler" ,
but many lidar/ladar systems measure range and velocity

Lidar and Ladar are used interchangeably.
CLRC program: 284 instances of Lidar, 4 instances of ladar, 10 instances of laser radar

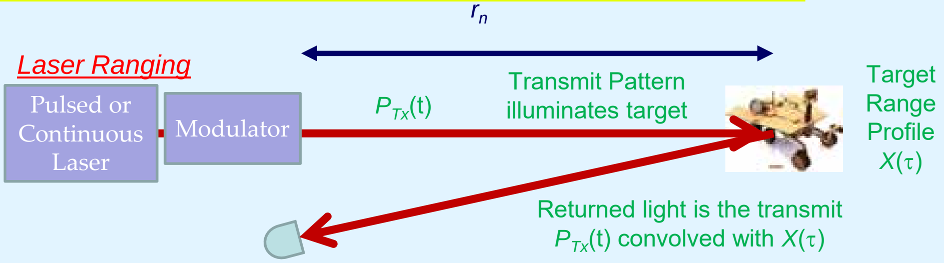
Lidar with Soft target Detection (particles/gases)



Lidar/Ladar/Laser Radar with Hard Targets



## Direct Detection Incoherent Lidar of Hard Targets



$r_n$

*Laser Ranging*

Pulsed or Continuous Laser

Modulator

$P_{Tx}(t)$

Transmit Pattern illuminates target

Target Range Profile $X(\tau)$

Returned light is the transmit $P_{Tx}(t)$ convolved with $X(\tau)$

$$S_{\text{Return}}(t) = \beta \int P_{Tx}(t-\tau) X(\tau) d\tau$$

Assume light is "incoherent"
Ignoring coherent interference effects

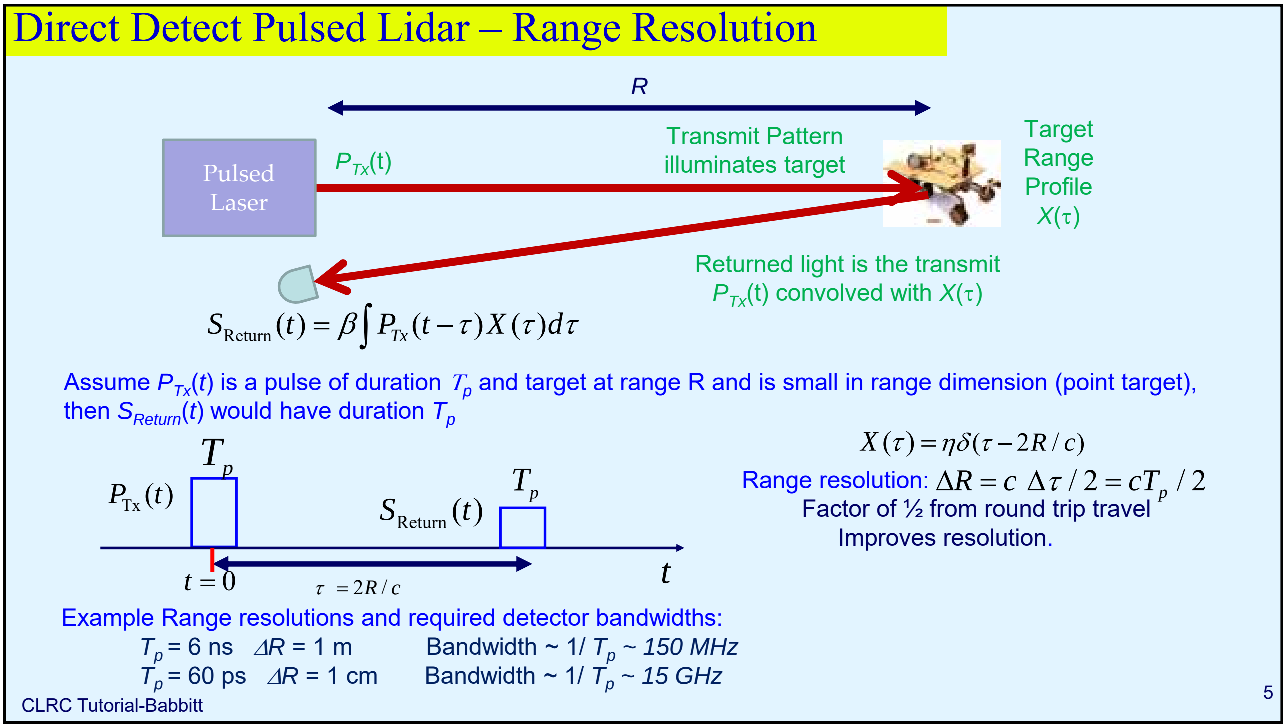
The factor $\beta$ incorporates the losses in transit, beam overlap, and return.

Break target into range "resolvable" elements: $X(\tau) = \sum_n \eta_n \delta(\tau - \tau_n) = \sum_n \eta_n \delta(\tau - 2r_n / c)$
Convert range to delay: $\tau_n = 2r_n / c$
where $r_n$ is range and $\eta_n$ is intensity reflectivity of $n^{th}$ element of target.

$$S_{\text{Return}}(t) = \sum_n \eta_n \beta P_{Tx}(t - 2r_n / c)$$

If the target is a single element, $X(\tau) = \eta_1 \delta(\tau - 2r_1 / c)$

$$S_{\text{Return}}(t) = \eta_1 \beta P_{Tx}(t - 2r_1 / c)$$



# Direct Detect Pulsed Lidar – Range Resolution

$$S_{\text{Return}}(t)=\beta\int P_{Tx}(t-\tau)X(\tau)d\tau$$

Assume $P_{Tx}(t)$ is a pulse of duration $T_p$ and target at range R and is small in range dimension (point target), then $S_{Return}(t)$ would have duration $T_p$

$$X(\tau)=\eta\delta(\tau-2R/c)$$

Range resolution: $\Delta R = c\,\Delta\tau/2 = cT_p/2$

Factor of ½ from round trip travel
Improves resolution.

Example Range resolutions and required detector bandwidths:

$T_p$ = 6 ns $\Delta R$ = 1 m Bandwidth ~ 1/ $T_p$ *~ 150 MHz*
$T_p$ = 60 ps $\Delta R$ = 1 cm Bandwidth ~ 1/ $T_p$ *~ 15 GHz*

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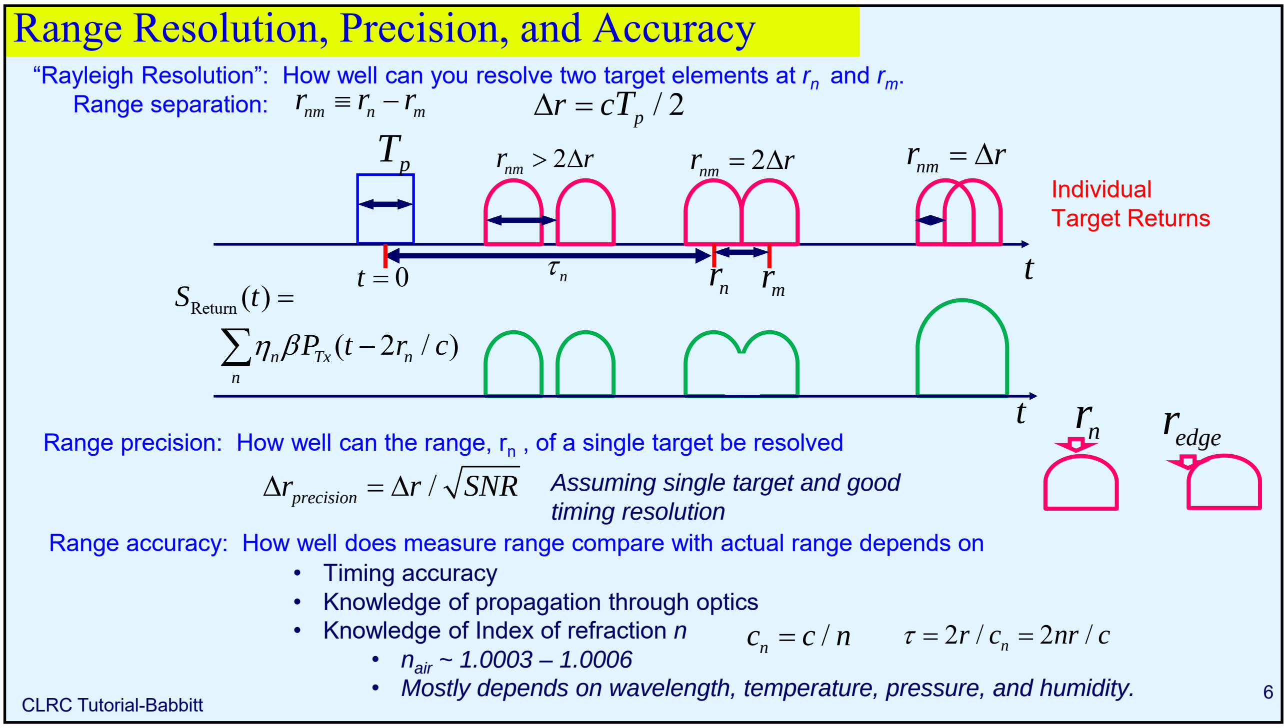

# Range Resolution, Precision, and Accuracy

"Rayleigh Resolution": How well can you resolve two target elements at $r_n$ and $r_m$.

Range separation: $r_{nm}\equiv r_n - r_m$ $\qquad \Delta r = cT_p/2$

$$S_{\text{Return}}(t)=\sum_n \eta_n\beta P_{Tx}(t-2r_n/c)$$

Range precision: How well can the range, $r_n$ , of a single target be resolved

$$\Delta r_{precision}=\Delta r/\sqrt{SNR}$$ *Assuming single target and good timing resolution*

Range accuracy: How well does measure range compare with actual range depends on

- Timing accuracy
- Knowledge of propagation through optics
- Knowledge of Index of refraction *n* $\qquad c_n = c/n \qquad \tau = 2r/c_n = 2nr/c$
    - *$n_{air}$ ~ 1.0003 – 1.0006*
    - *Mostly depends on wavelength, temperature, pressure, and humidity.*

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# Cross range Resolution, Precision, and Accuracy

Scanning Lidar

Galvo Mirrors, Fast Steering Mirrors, MEMs mirror

Trade-offs between scan rates, resolution, linearity/accuracy, aperture, and cost!

Typical good fast scanning mirror

Scan Range: a few degrees => limited field of view

Resolution = sub-arc second ~ 2 microradians => 2mm at 1 km

Linearity : ~1% => 10 m accuracy at 1km

Encoder readouts can help, but take time to readout.

Can't scan too fast to obtain cross range resolution of $\Delta x$

$\Gamma$= rad/sec

$v_{\text{cross scan}} = R\,\Gamma$

Dwell time per spot: $\tau_{\text{dwell}} = \Delta x / v_{\text{cross scan}}$

Round trip time: $\tau_{\text{RT}} = 2R/c$

If transmit and received optics are collinear, must have $\tau_{\text{dwell}} > \tau_{\text{RT}}$

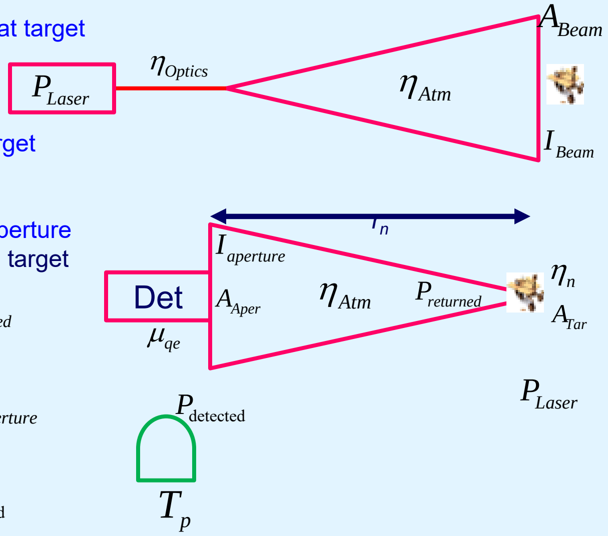
Bistatic can have receiver position "delayed"

Another consideration is number of pixels in image

More pixels => Lower frame rate

# Calculation of Lidar Energy Return

$$S_{\text{Return}}(t) = \eta_1 \beta P_{Tx}(t - 2r_1/c)$$



Intensity of transmit beam at target

$$I_{Beam} = \frac{P_{Laser}\eta_{Optics}\eta_{Atm}}{A_{Beam}}$$

Power returned from n^th target

$$P_{returned} = \eta_n A_{Tar} I_{beam}$$

Intensity at the detection aperture

Assuming Lambertian target

$$I_{aperture} = \frac{\eta_{Atm}}{\pi r_n^2} P_{returned}$$

Power detected

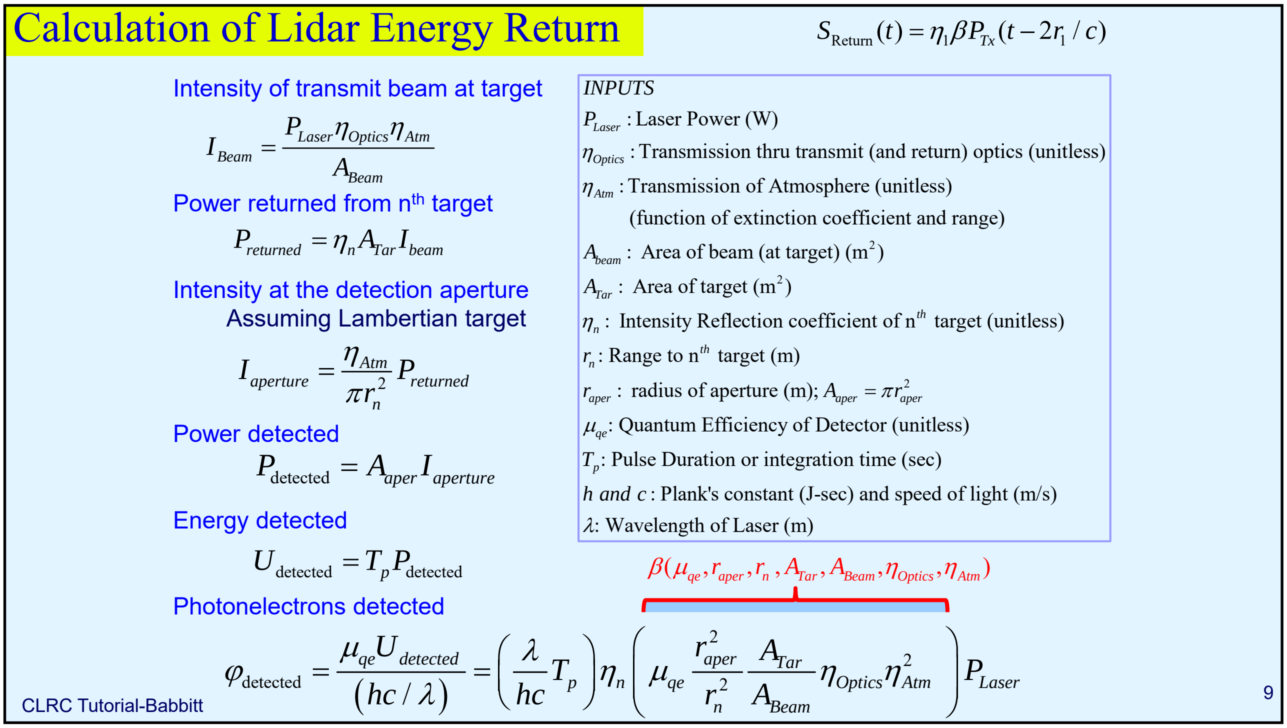
$$P_{\text{detected}} = A_{aper} I_{aperture}$$

Energy detected

$$U_{\text{detected}} = T_p P_{\text{detected}}$$

Photonelectrons detected

$$\varphi_{\text{detected}} = \frac{\mu_{qe} U_{detected}}{(hc/\lambda)} = \left(\frac{\lambda}{hc} T_p\right) \eta_n \left(\mu_{qe} \frac{r_{aper}^2}{r_n^2} \frac{A_{Tar}}{A_{Beam}} \eta_{Optics} \eta_{Atm}^2\right) P_{Laser}$$



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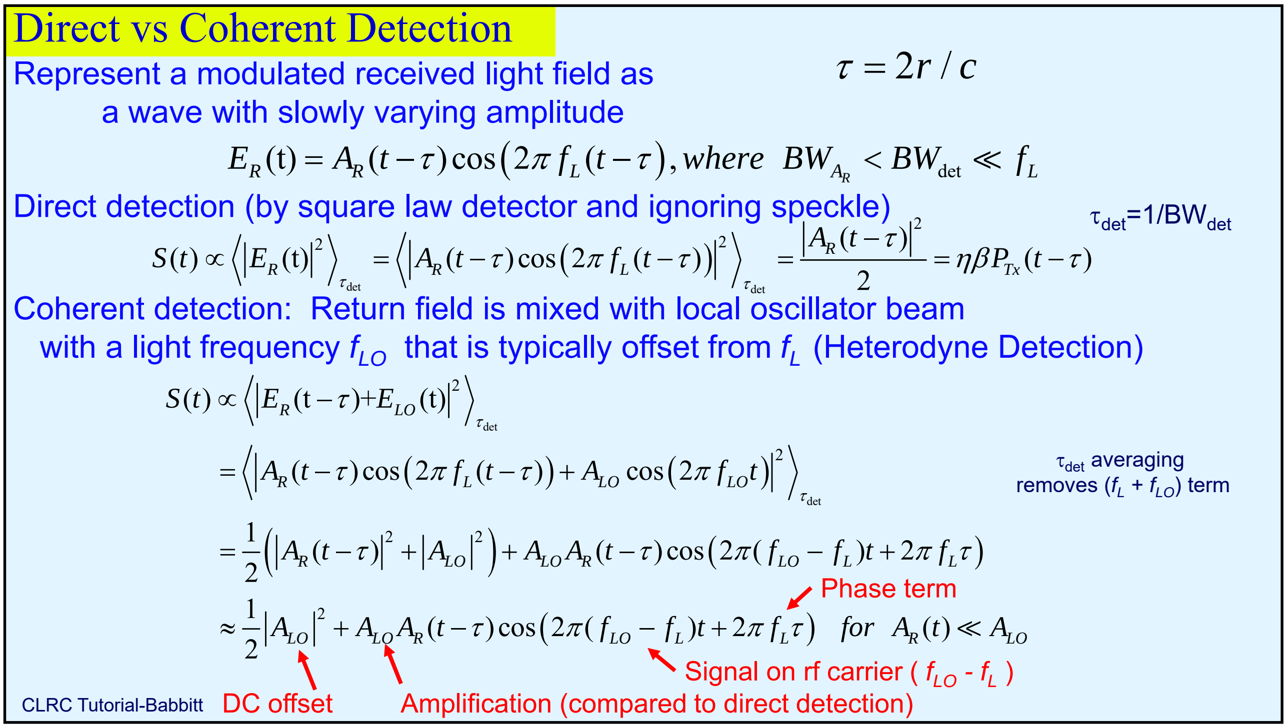
*INPUTS*
$P_{Laser}$ : Laser Power (W)
$\eta_{Optics}$ : Transmission thru transmit (and return) optics (unitless)
$\eta_{Atm}$ : Transmission of Atmosphere (unitless)
(function of extinction coefficient and range)
$A_{beam}$ : Area of beam (at target) (m$^2$)
$A_{Tar}$ : Area of target (m$^2$)
$\eta_n$ : Intensity Reflection coefficient of n$^{th}$ target (unitless)
$r_n$ : Range to n$^{th}$ target (m)
$r_{aper}$ : radius of aperture (m); $A_{aper} = \pi r_{aper}^2$
$\mu_{qe}$: Quantum Efficiency of Detector (unitless)
$T_p$: Pulse Duration or integration time (sec)
*h and c* : Plank's constant (J-sec) and speed of light (m/s)
$\lambda$: Wavelength of Laser (m)



# Direct vs Coherent Detection

$$\tau = 2r / c$$

Represent a modulated received light field as
a wave with slowly varying amplitude

$$E_R(\mathrm{t}) = A_R(t-\tau)\cos\left(2\pi f_L(t-\tau)\right), where \;\; BW_{A_R} < BW_{\text{det}} \ll f_L$$

Direct detection (by square law detector and ignoring speckle)

$\tau_{\text{det}}$=1/BW$_{\text{det}}$

$$S(t) \propto \left\langle \left|E_R(\mathrm{t})\right|^2 \right\rangle_{\tau_{\text{det}}} = \left\langle \left|A_R(t-\tau)\cos\left(2\pi f_L(t-\tau)\right)\right|^2 \right\rangle_{\tau_{\text{det}}} = \frac{\left|A_R(t-\tau)\right|^2}{2} = \eta\beta P_{Tx}(t-\tau)$$

Coherent detection: Return field is mixed with local oscillator beam
with a light frequency $f_{LO}$ that is typically offset from $f_L$ (Heterodyne Detection)

$$S(t) \propto \left\langle \left|E_R(\mathrm{t}-\tau) + E_{LO}(\mathrm{t})\right|^2 \right\rangle_{\tau_{\text{det}}}$$

$$= \left\langle \left|A_R(t-\tau)\cos\left(2\pi f_L(t-\tau)\right) + A_{LO}\cos\left(2\pi f_{LO} t\right)\right|^2 \right\rangle_{\tau_{\text{det}}}$$

$\tau_{\text{det}}$ averaging removes ($f_L$ + $f_{LO}$) term

$$= \frac{1}{2}\left(\left|A_R(t-\tau)\right|^2 + \left|A_{LO}\right|^2\right) + A_{LO}A_R(t-\tau)\cos\left(2\pi(f_{LO} - f_L)t + 2\pi f_L \tau\right)$$

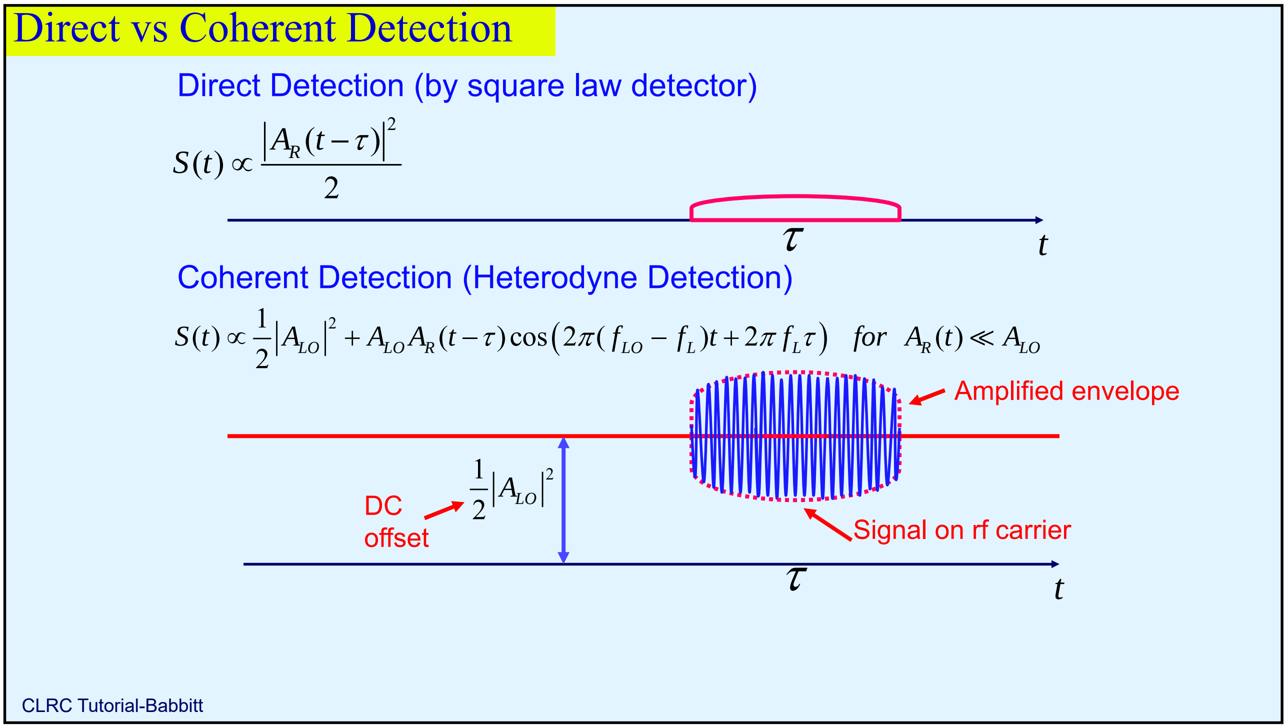
Phase term

$$\approx \frac{1}{2}\left|A_{LO}\right|^2 + A_{LO}A_R(t-\tau)\cos\left(2\pi(f_{LO} - f_L)t + 2\pi f_L \tau\right) \quad for \quad A_R(t) \ll A_{LO}$$

Signal on rf carrier ( $f_{LO}$ - $f_L$ )

DC offset

Amplification (compared to direct detection)



# Direct vs Coherent Detection

Direct Detection (by square law detector)

$$S(t) \propto \frac{|A_R(t-\tau)|^2}{2}$$

Coherent Detection (Heterodyne Detection)

$$S(t) \propto \frac{1}{2}|A_{LO}|^2 + A_{LO}A_R(t-\tau)\cos\left(2\pi(f_{LO}-f_L)t + 2\pi f_L \tau\right) \quad for \quad A_R(t) \ll A_{LO}$$

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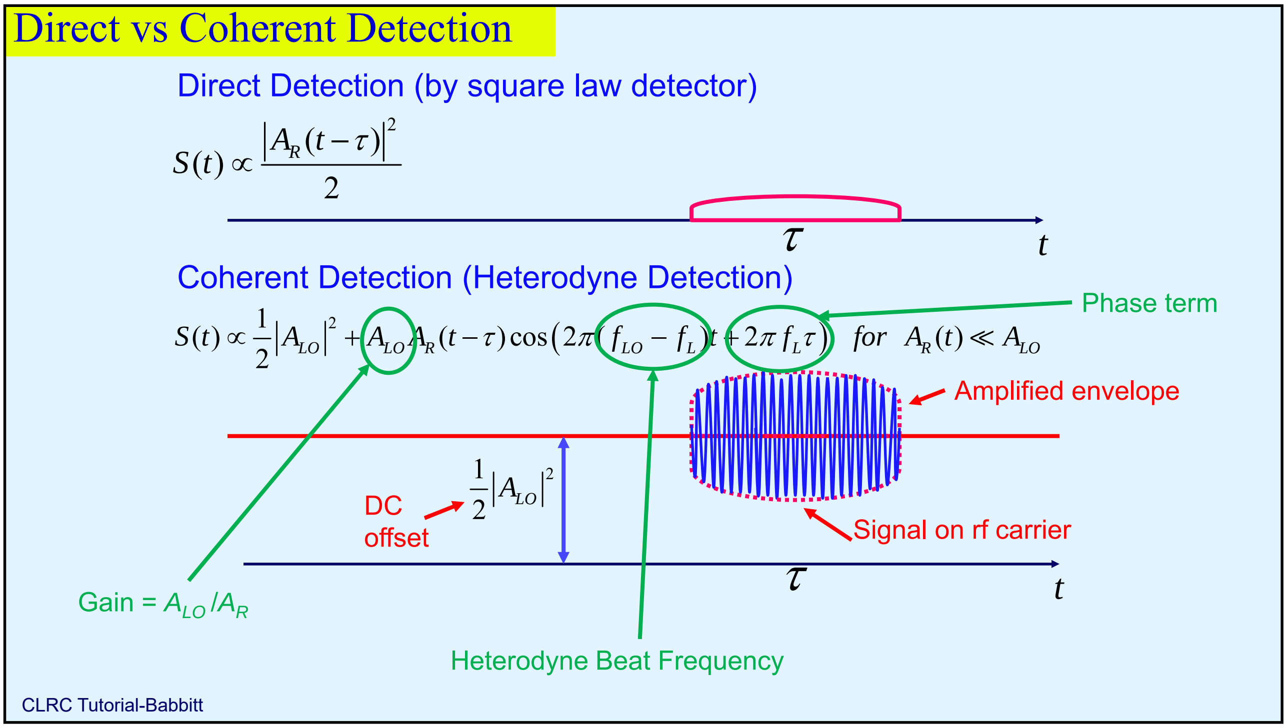

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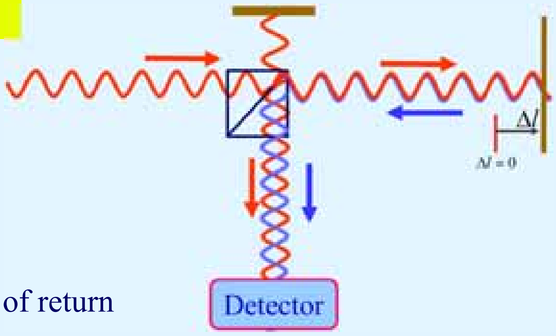
# Phase Term => Coherent Interferometry



Movement of target by just $\Delta l = \lambda / 4$ can flip sign of return

- Pro
  - Doppler measurement => Velocimeter
  - Vibrometry sensor
    - Monitoring phase of return yields vibration info, provided vibration not too severe.
- Con
  - Vibrations or movement can diminish/distort integrated return signal peak
  - Reflection from rough surface will have multiple reflection with different phases => Speckle

# Direct vs Coherent Detection: Signal to Noise Considerations

Direct detected photoelectrons in pulse of duration $T_p$ and power $P_R$:

$$\varphi_R = \eta_{qe} P_R T_p / (hf)$$

Shot noise + thermal noise $\varphi_N = \sqrt{\varphi_R} + \varphi_{kT}$

Signal to Noise Ratio (SNR): $\dfrac{\varphi_R}{\sqrt{\varphi_R} + \varphi_{kT}}$

To get shot noise limit: $\sqrt{\varphi_R} \gg \varphi_{kT}$

Shot noise limited S/N: $\sqrt{\varphi_R}$

Coherently Detected envelope (in photoelectrons)

Signal: $\varphi_S = \sqrt{\varphi_{LO}\varphi_R}$ with signal riding on DC background of $\varphi_{LO}$

Shot noise + thermal noise $\varphi_N = \sqrt{\varphi_{LO}} + \varphi_{kT}$

SNR: $\dfrac{\sqrt{\varphi_{LO}}\sqrt{\varphi_R}}{\sqrt{\varphi_{LO}} + \varphi_{kT}}$

Shot noise limited if $\sqrt{\varphi_{LO}} \gg \varphi_{kT}$ with SNR= $\sqrt{\varphi_R}$

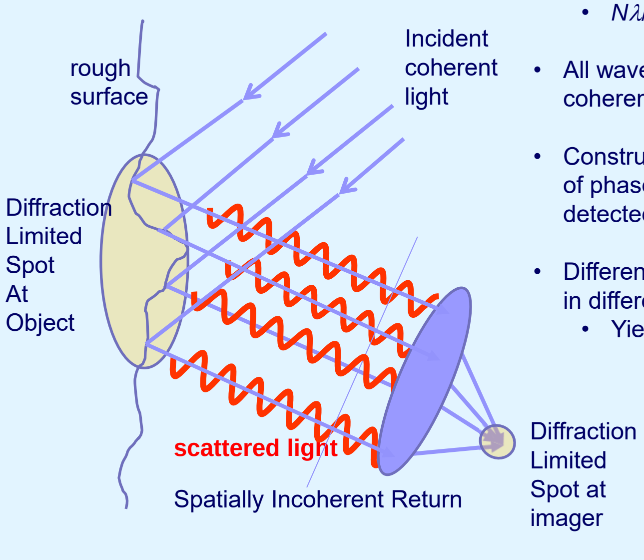
Advantage of coherent detection:

If $\varphi_R \ll \varphi_{kT}$ , still can have shot noise limited SNR still of $\sqrt{\varphi_R}$

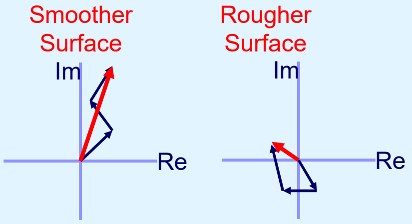
# Direct vs Coherent Detection: Spectral Filtering

Stray/background light
- Direct detection
    - Typically use a wavelength filter (nm widths)
- Coherent Light
    - Only light with frequencies within detector bandwidth are heterodyne detected

# Speckle



- The surface of an object can be “rough”, with variations with a diffraction limited spot of more than a wavelength
    - $N\lambda$/spot for rough surfaces versus $\lambda/N/1$” for mirrors
- All waves scattered from a diffraction limited spot add coherently.
- Constructively and destructive interference due to the spread of phases of the return light causes a reduction in the detected total field.
- Different spots will have different granular patterns, resulting in different measured field amplitudes across the image.
    - Yielding the speckle pattern.



## Size of Speckle Grains

Average size of the speckle grain
(as seen in image, but size w.r.t. object plane)
is the diffraction limited spot size:

$$\Delta x = 1.22 \frac{\lambda R}{D}$$

$\lambda$ = Wavelength of illuminating light
$R$= Distance between the object and the sensor
$D$ = Aperture diameter

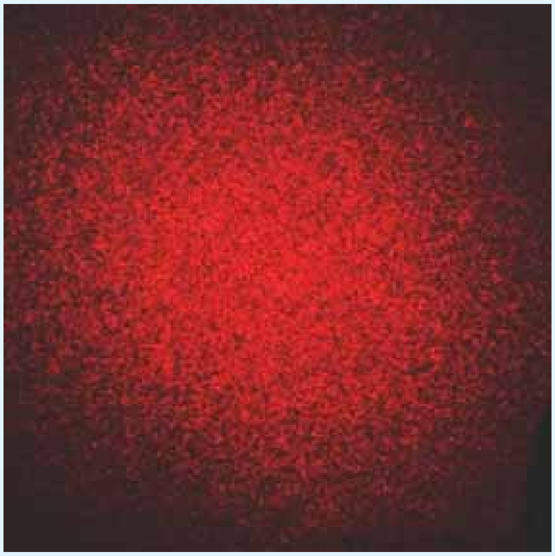
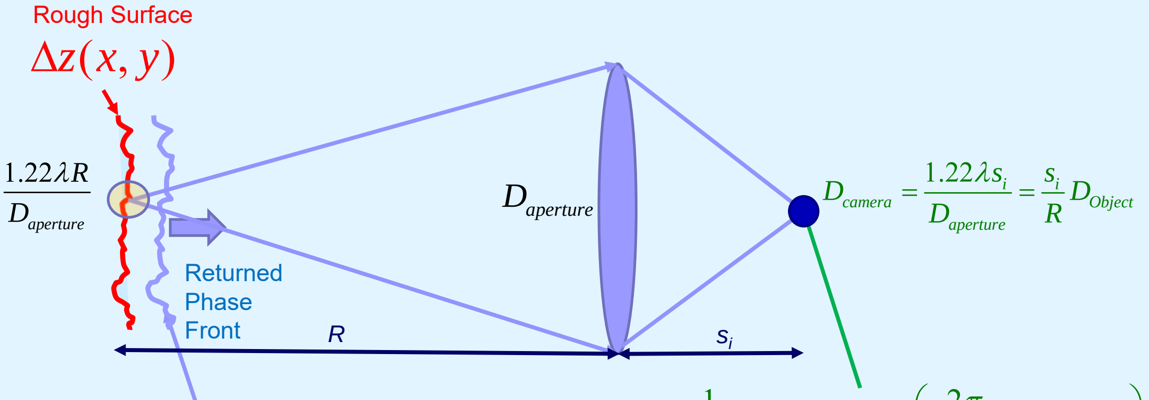


Image from:
https://en.wikipedia.org/wiki/Speckle_(interference)

## Speckle



$$D_{object} = \frac{1.22\lambda R}{D_{aperture}}$$

$$D_{camera} = \frac{1.22\lambda s_i}{D_{aperture}} = \frac{s_i}{R} D_{Object}$$

$$E_{spot}(x,y) = \frac{1}{N} \sum E_i \exp\left( i \frac{2\pi}{\lambda} 2\Delta z(x_i, y_i) \right)$$

Sum over N surfaces in diffraction limited spot about (x,y)

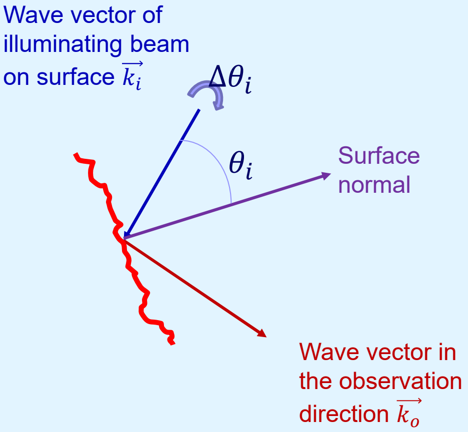
$$E_{return}(x,y) = E_0 \exp(i\phi(x,y)) = E_0 \exp\left( i \frac{2\pi}{\lambda} 2\Delta z(x,y) \right)$$

Assuming each surface has the same reflectivity

## Speckle Dependence

*Speckle pattern depends on*

- *Roughness*
- *Wavelength*
- *Illumination angle*
- *Observation angle*



Wave vector of illuminating beam on surface $\overrightarrow{k_i}$

Surface normal

Wave vector in the observation direction $\overrightarrow{k_o}$

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## Pulsed Nd:YAG Lasers

$$E_{pulse} = P_{peak}\tau_{pulse}$$

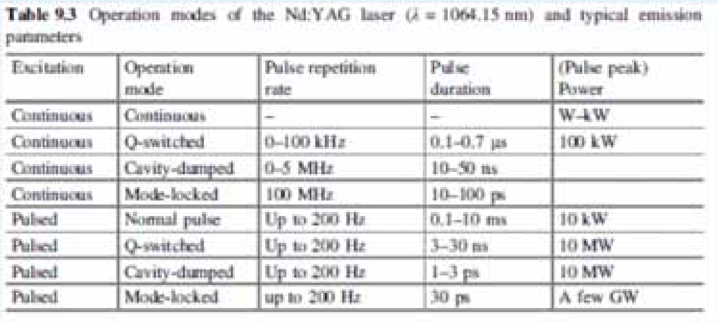


**Table 9.3** Operation modes of the Nd:YAG laser ($\lambda$ = 1064.15 nm) and typical emission parameters

| Excitation | Operation mode | Pulse repetition rate | Pulse duration | (Pulse peak) Power |
|---|---|---|---|---|
| Continuous | Continuous | – | – | W–kW |
| Continuous | Q-switched | 0–100 kHz | 0.1–0.7 μs | 100 kW |
| Continuous | Cavity-dumped | 0–5 MHz | 10–50 ns | |
| Continuous | Mode-locked | 100 MHz | 10–100 ps | |
| Pulsed | Normal pulse | Up to 200 Hz | 0.1–10 ms | 10 kW |
| Pulsed | Q-switched | Up to 200 Hz | 3–30 ns | 10 MW |
| Pulsed | Cavity-dumped | Up to 200 Hz | 1–3 ps | 10 MW |
| Pulsed | Mode-locked | up to 200 Hz | 30 ps | A few GW |

| | | |
|---|---|---|
| **Repetition rate (Hz)** | | **10** |
| **Energy per pulse (mJ)** | **1064 nm** | **850** |
| | **532 nm** | **430** |
| | **355 nm** | **230** |
| | **266 nm** | **100** |
| | **213 nm** | **20** |
| **Pulse duration (ns)** | **1064 nm** | **~ 6** |
| **Beam divergence (mrad)** | **1064 nm** | **< 0.5** |
| **Dimensions in mm (H x L x W)** | **Laser head** | **147 x 526 x 125** |
| | **Harmonic modules** | **99 x 123 x 125** |
| | **Power supply** | **513 x 507 x 283** |
| **Weight in kg** | **Laser head** | **7** |
| | **Power supply** | **27** |

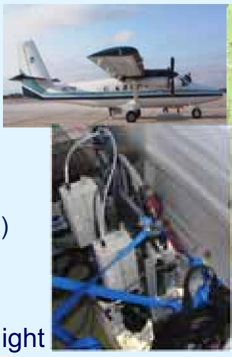
Big Sky Laser
$\Rightarrow$ Quantel
$\Rightarrow$ Lumibird

At 1064nm

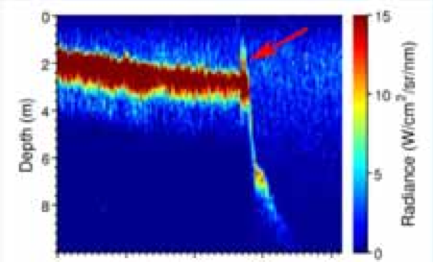
$$P_{peak} = \frac{E_{pulse}}{\tau_{pulse}} = \frac{850mJ}{6ns} = 140MW$$

# Fish Lidar

Airborne fish lidar in Yellowstone lake
Joe Shaw et al, MSU ECE
Laser: Doubled Nd:YAG
532 nm
27 mJ
100 Hz
Lidar depth penetration
(Depending on beam spot parameters)
8-50 meters

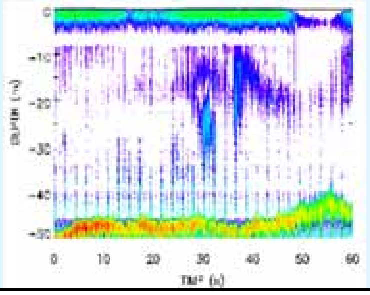


Signal return versus depth during flight

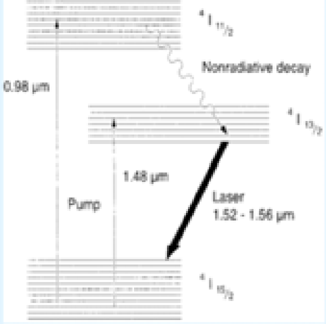


2015 data

2004 data



# "Eye-Safe" Lidar Pulsed Lasers



Erbium Lasers
1.52-1.56 microns, "eye-safe"
Optically-pumped, lamps or diode lasers (0.96 µm)

Thulium-Holmium at 2.1 microns (eye-safe)

Erbium doped fiber amplifiers
Pumped by 0.98 µm diode laser
Can be seeded with diode laser at 1.5 µm
Enables flexible control of pulses

Keopsys (by Lumibird)
- Femto and picosecond pulse amplification
- Pulse distortion free up to 1 KW
- Average power up to 33 dBm (2W)
- Operating wavelength from 1535 to 1565 nm
- Pulse repetition frequency: 10 MHz to 100 GHz
- Polarization maintaining available
- Rack Mounted or OEM

## "Eye-Safe" Lidar Pulsed Lasers

### Mono-Block Laser Resonators

Diode Bar or Flash-lamp pumped

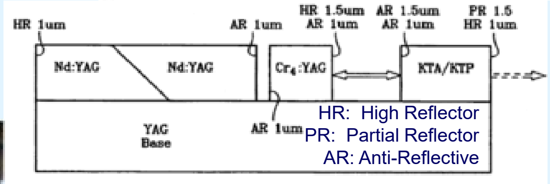
Output

- 1.064 microns or 1.54 microns with OPO
    - Up to 16 mJ
    - 8 nsec – 1 usec pulses
    - Up to 10 Hz
- Weight: less than 0.5 oz

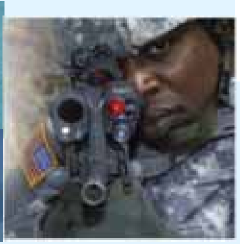
Application Example:

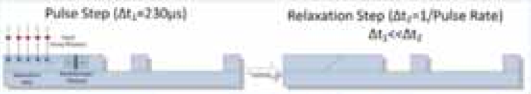
- M16/M14 Rifle Range Finder

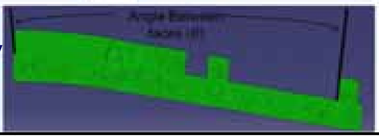
SCIENTIFIC MATERIALS CORP.
A FLIR Systems Company



HR: High Reflector
PR: Partial Reflector
AR: Anti-Reflective







Finite Element Analysis of
Thermal Stress on 1064nm Monoblock cavity
Aaron Anderson,
MSU MS in Mech Eng Thesis 2011

## How to get better Range Resolution

Same "Rayleigh Resolution" for pulses direct detect and coherent lidar:

$$\Delta R = \frac{cT_p}{2} = \frac{c}{2B_p}, \ where \ \ B_p \ \ is \ the \ bandwidth \ of \ \ the \ \ pulse$$

Shorter pulse = increased bandwidth

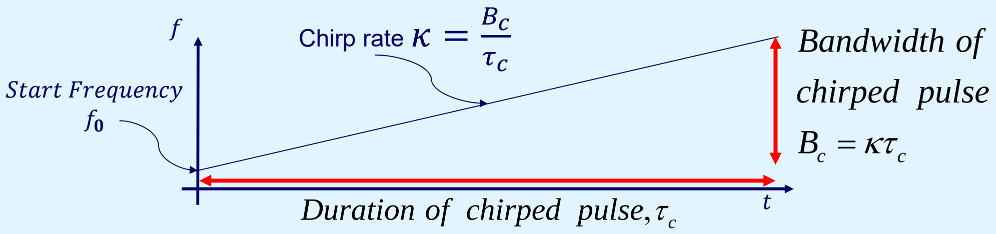
- Less energy, unless pulse power is increased

  => Intense brief pulses
    - Are more expensive and technically difficult
    - Can cause potential optical damage
    - Are less eye safe
    - Require higher bandwidth detectors
    - Can be distorted or have jitter

Another way to increase the bandwidth, without shortening the pulse, is
Frequency Modulated Continuous Wave (FMCW) waveforms

## FMCW Chirps

- FMCW waveforms have constant amplitudes with frequencies that vary in time.
- The most typical FMCW waveform is a linear chirp
  - Start Frequency: $f_0$
  - Frequency Chirp rate: $\kappa$
  - $E(t) = \exp(-i\left[2\pi(f_0 t + \frac{1}{2}\kappa t^2\right])$
- Linear chirps have interesting time-frequency transforming properties.
- Chirped waveforms are used in radar, lidar, ringdown spectroscopy, ….



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## Chirped FMCW Lidar

### Transmit Pulse

$$E(z,t) = \exp\left(ikz - i\left[w_0 t + \tfrac{1}{2}\alpha t^2\right]\right) + c.c$$

$$\omega_0 \Leftrightarrow 2\pi f_0$$

$$\alpha \Leftrightarrow 2\pi\kappa$$

### Received Pulse ($\tau$ = 2R/c)

$$E(z,t-\tau) = \exp\left(ikz - i\left[w_0(t-\tau) + \tfrac{1}{2}\alpha(t-\tau)^2\right]\right) + c.c$$

### Coherent Detection (cross term only, ignore dc)

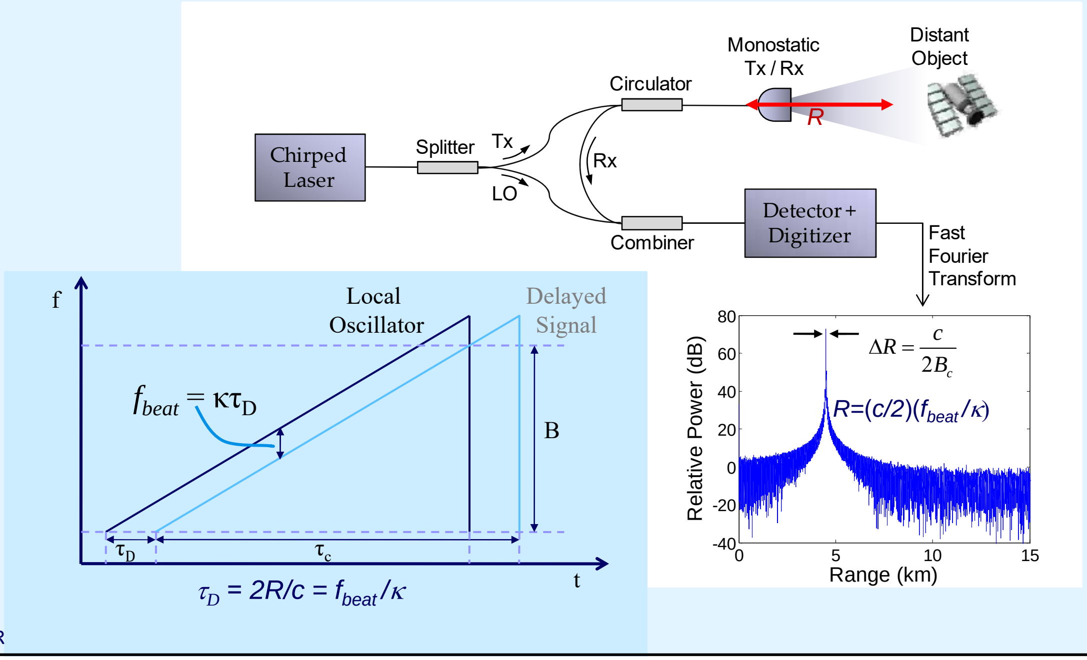
$$\langle E(z,t)E(z,t-\tau)\rangle = \exp\left(-i\left[w_0\tau + \tfrac{1}{2}\alpha(2t\tau - \tau^2)\right]\right) + c.c$$

$$f_{beat} = \alpha\tau/(2\pi) = \alpha\left(2R/c\right)/(2\pi)$$

a.k.a.

$$f_{beat} = \kappa\tau = \kappa\left(2R/c\right)$$

# Chirped FMCW Ranging



# Advantages and Disadvantages of FMCW

Chirped Lidar, a.k.a Frequency Modulated Continuous Wave (FMCW) lidar

FMCW lidar has similar “Rayleigh Resolution” equation as pulses direct detect and coherent lidar:

$$\Delta r = \frac{c}{2B_p}, \text{ but now we can have } \tau_c \gg \frac{1}{B_c}$$

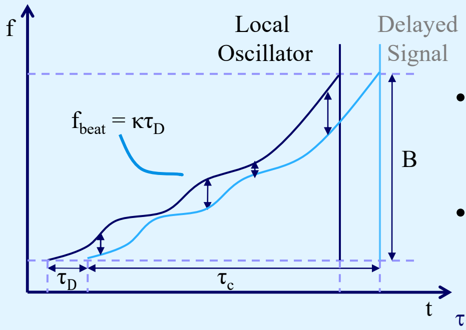
Advantages of FMCW Lidar

- More energy, with much less peak power
  - Higher energy => better SNR
  - Less chance of optical damage
  - More eye safe
  - Requires much lower bandwidth detectors and digitizers
  - Can be well characterized to reduce distortion or jitter

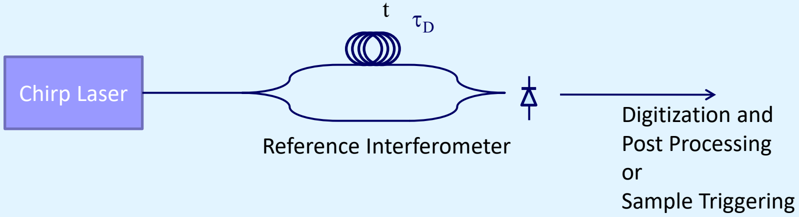
Disadvantage

- More expensive and technically difficult,
  - Though volume and new techniques are quickly reducing cost and improving performance.

# Chirp Nonlinearities



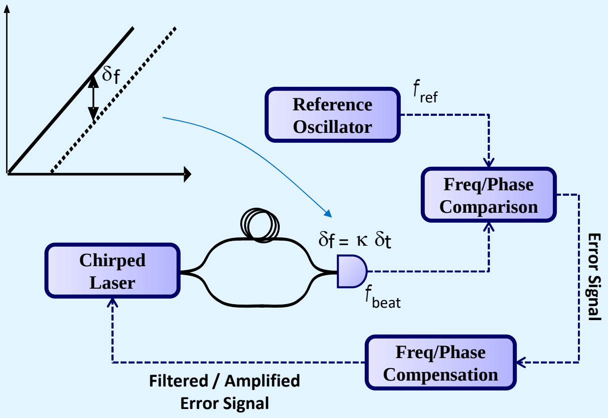
- Chirp nonlinearities lead to variations in beat note frequency
  => Broadened peaks
- Variation worse with longer delays
  => Limits useful range



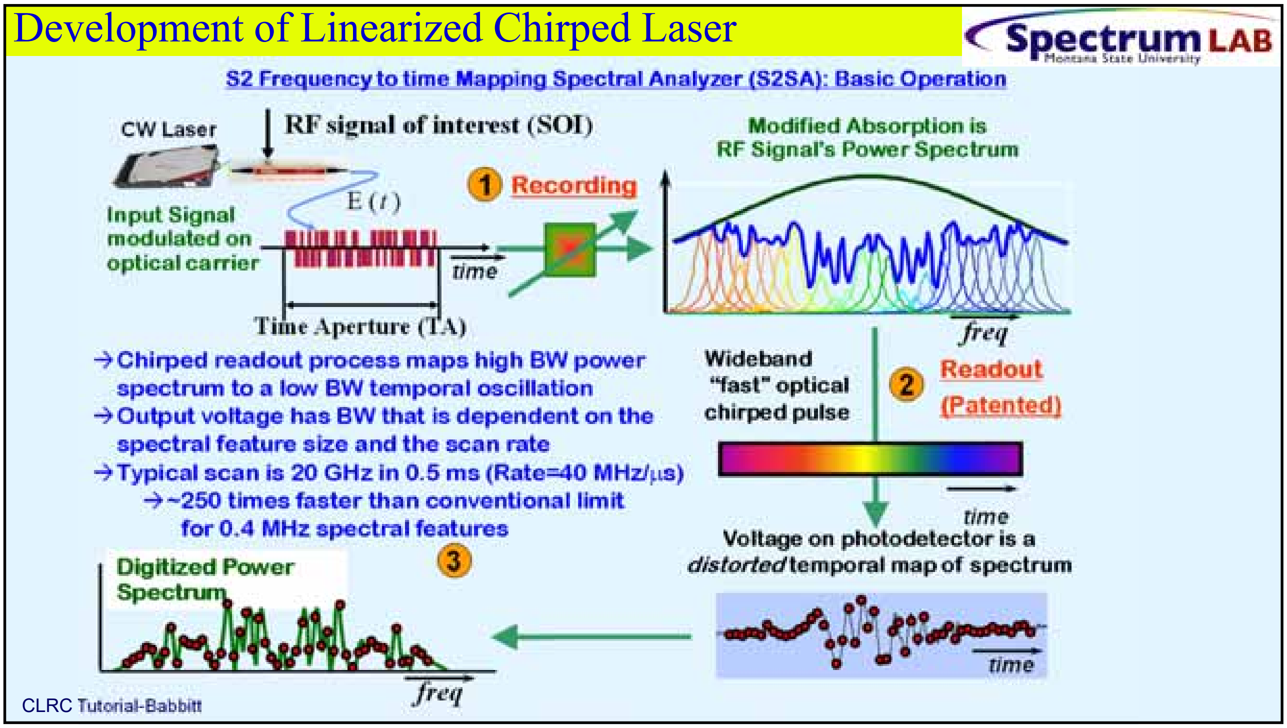
[1] E. D. Moore and R. R. McLeod, Optics Express **16**, 13139 (2008).
[2] T.-J. Ahn, J. Y. Lee, and D. Y. Kim, Applied Optics **44**, 7360–7634 (2005).

# Linearization Technique

- Use stable reference delay to generate “perfect” beat note
  - Measure $\delta f$ on photodetector (proportional to chirp rate)
  - Phase/frequency lock chirp to produce stable reference oscillator
    - Actuator to adjust laser frequency/phase



C. Greiner, B. Boggs, T. Wang, and T. Mossberg, Optics Letters **23**, 1280–1282 (1998).



## Development of Linearized Chirped Laser

S2 Frequency to time Mapping Spectral Analyzer (S2SA): Basic Operation

→Chirped readout process maps high BW power spectrum to a low BW temporal oscillation

→Output voltage has BW that is dependent on the spectral feature size and the scan rate

→Typical scan is 20 GHz in 0.5 ms (Rate=40 MHz/μs)

  →~250 times faster than conventional limit for 0.4 MHz spectral features

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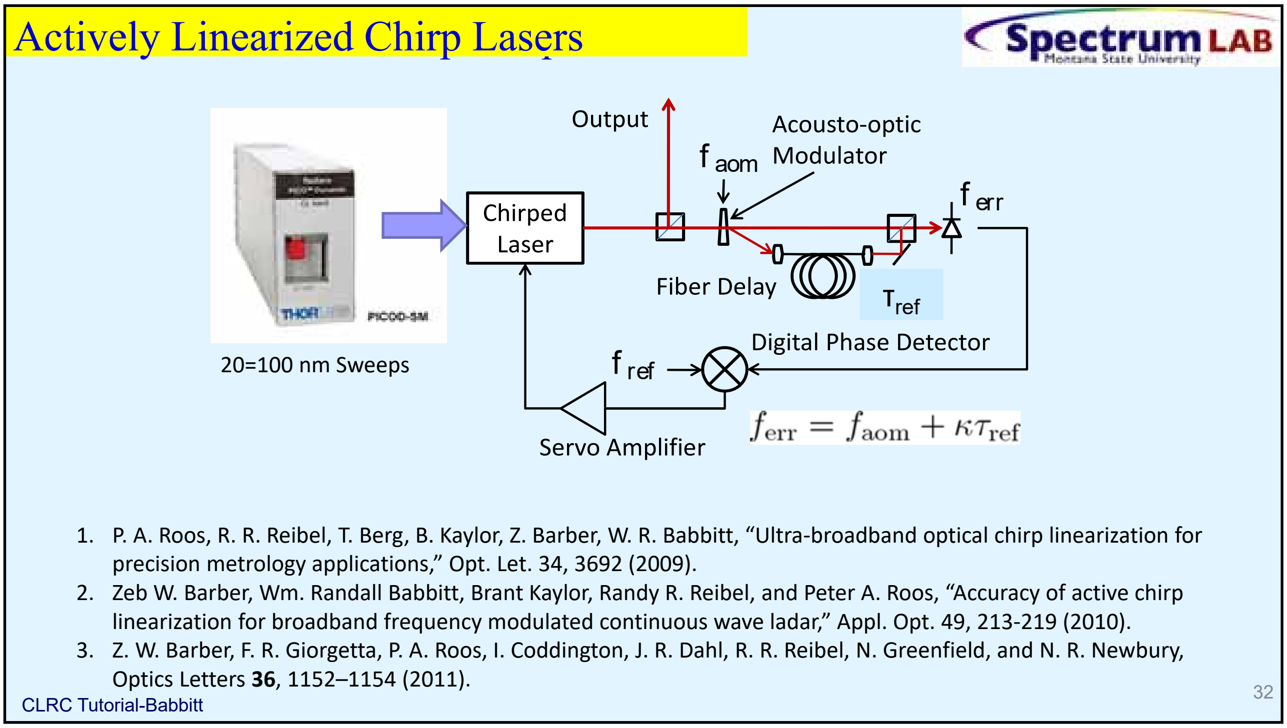


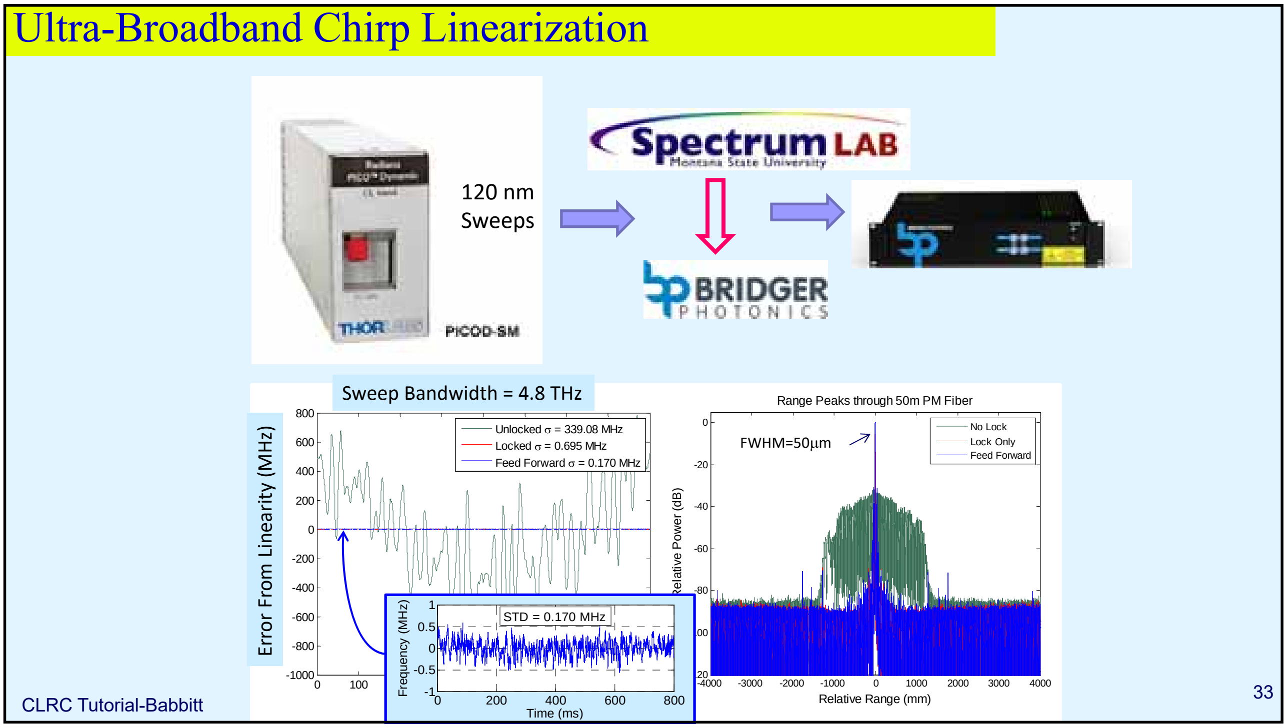
## Actively Linearized Chirp Lasers

20=100 nm Sweeps

$$f_{\text{err}} = f_{\text{aom}} + \kappa\tau_{\text{ref}}$$

1. P. A. Roos, R. R. Reibel, T. Berg, B. Kaylor, Z. Barber, W. R. Babbitt, “Ultra-broadband optical chirp linearization for precision metrology applications,” Opt. Let. 34, 3692 (2009).
2. Zeb W. Barber, Wm. Randall Babbitt, Brant Kaylor, Randy R. Reibel, and Peter A. Roos, “Accuracy of active chirp linearization for broadband frequency modulated continuous wave ladar,” Appl. Opt. 49, 213-219 (2010).
3. Z. W. Barber, F. R. Giorgetta, P. A. Roos, I. Coddington, J. R. Dahl, R. R. Reibel, N. Greenfield, and N. R. Newbury, Optics Letters **36**, 1152–1154 (2011).

CLRC Tutorial-Babbitt



# Ultra-Broadband Chirp Linearization

120 nm Sweeps

Sweep Bandwidth = 4.8 THz

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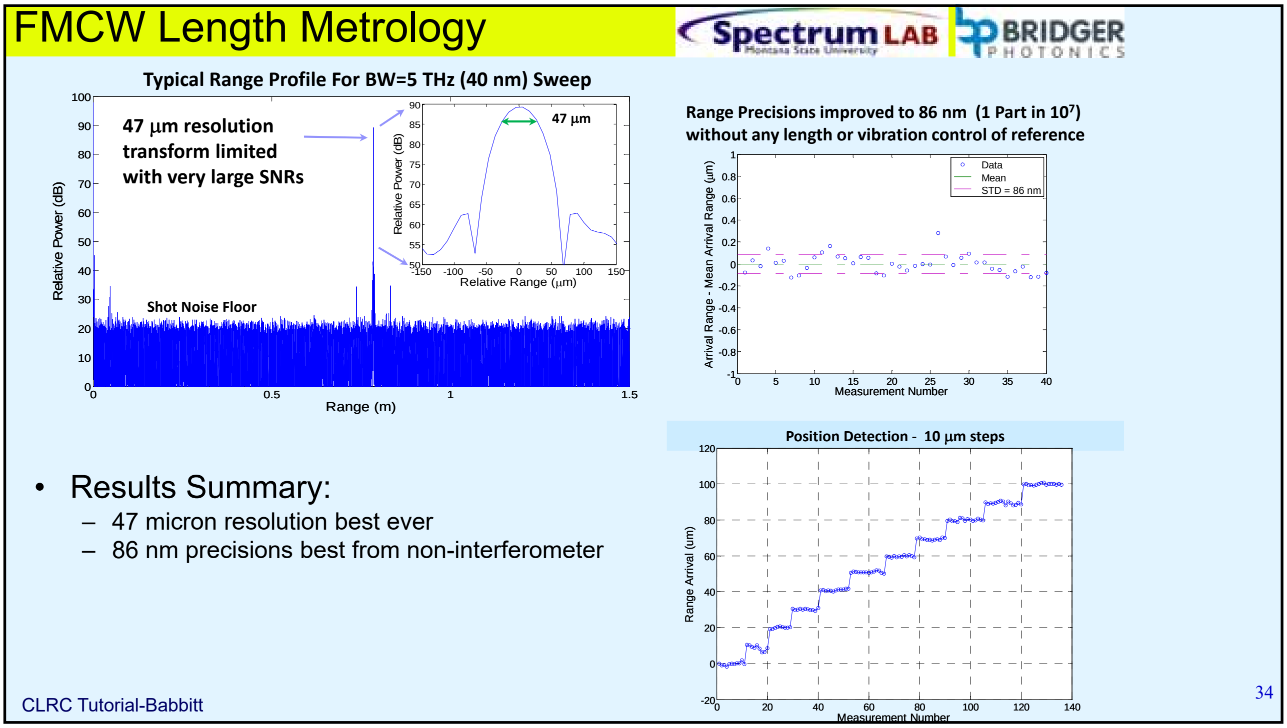

# FMCW Length Metrology

Typical Range Profile For BW=5 THz (40 nm) Sweep

**47 μm resolution transform limited with very large SNRs**

Range Precisions improved to 86 nm (1 Part in $10^7$) without any length or vibration control of reference

Position Detection - 10 μm steps

- Results Summary:
  - 47 micron resolution best ever
  - 86 nm precisions best from non-interferometer

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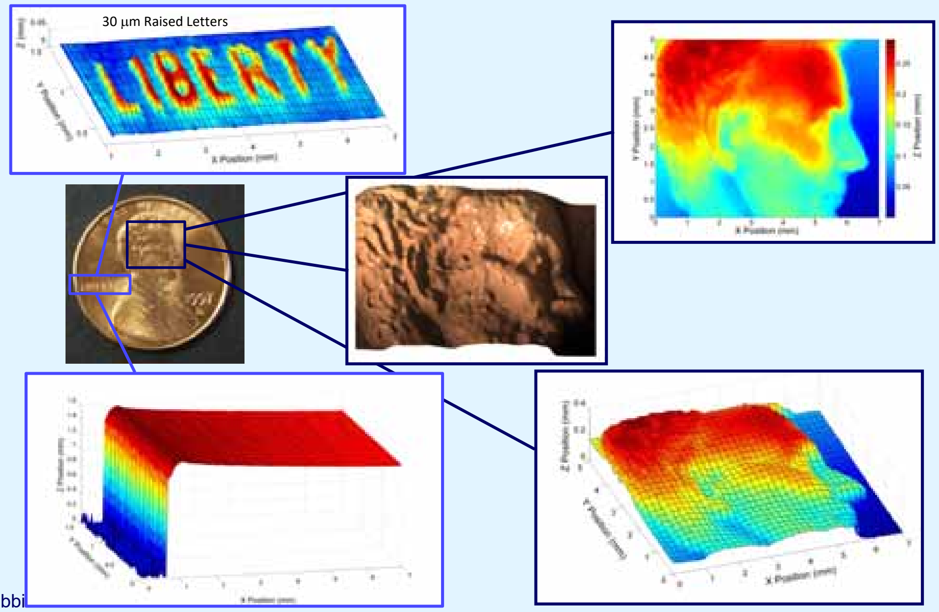
## Surface Profiling

Spectrum LAB Montana State University | BRIDGER PHOTONICS



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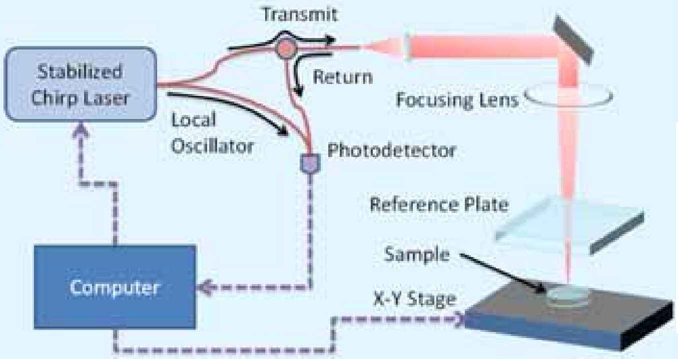
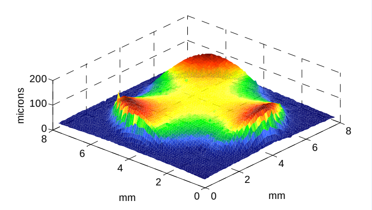
## Optical Metrology

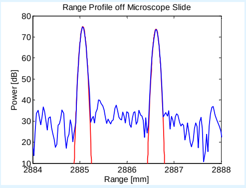
Spectrum LAB Montana State University | BRIDGER PHOTONICS

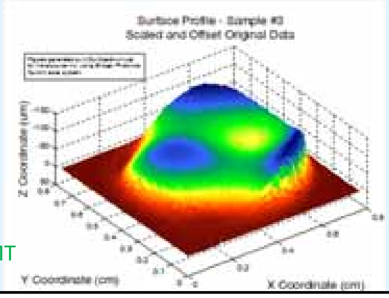




Specular reflections and large off normal surface angles require high NA objectives.

Multiple surfaces can be measured simultaneously





Samples provided by WaveSource Inc.
an innovative custom contact lens manufacturer in Whitefish, MT

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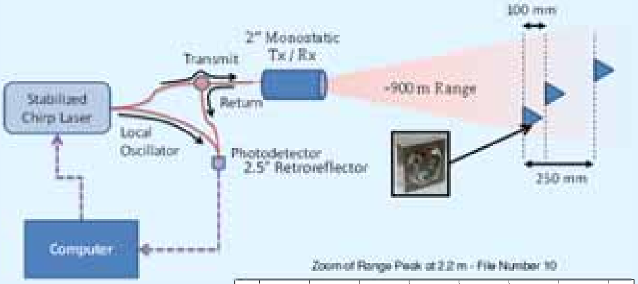
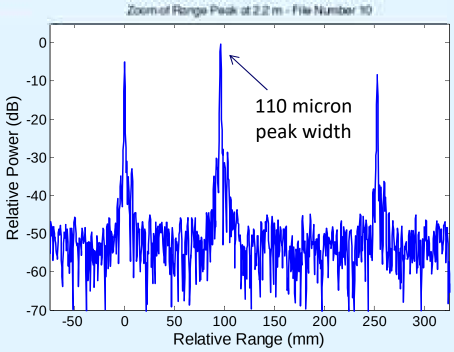
# Long Range Measurements

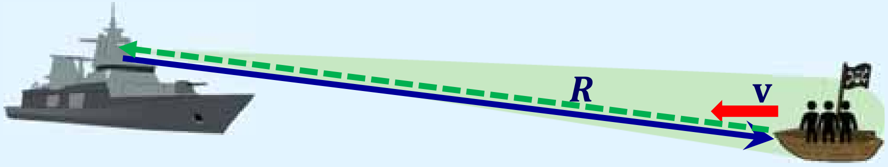
Spectrum Lab in collaboration with Bridger Photonics



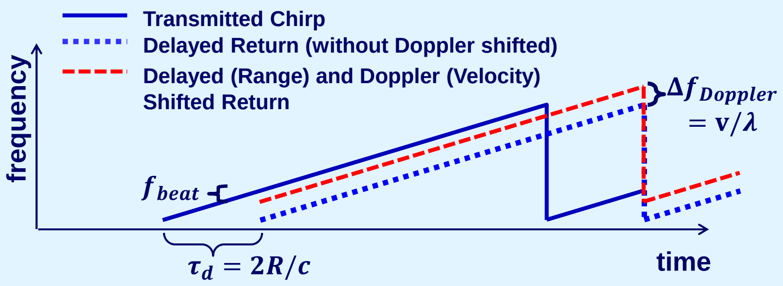


Also ranged out to 14km with 3 mW
and sub-mm range resolution (turbulence limited)

# Effect of Target Velocity

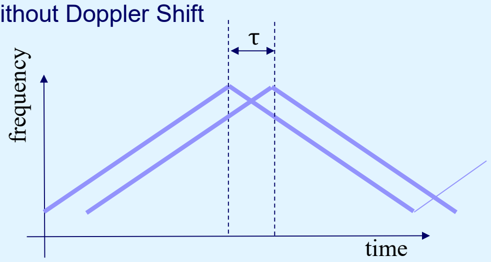


- *A frequency chirped light beam is transmitted at the target.*
- *Return is delayed (by round-trip range) and Doppler shifted (by target velocity)*
- *The LO is mixed with return light.*
- *Beat frequency contains range and Doppler shifts*

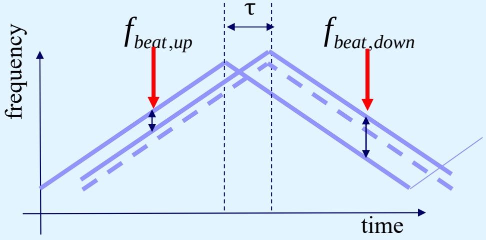


# Up-Down Chirps to Resolve Range-Doppler Ambiguity

Without Doppler Shift



With Doppler Shift



$$\text{Assuming } \Delta f_D < \kappa\tau$$

$$f_{beat,up} = \kappa\tau - \Delta f_D$$

$$f_{beat,down} = \kappa\tau + \Delta f_D$$

$$f_{range} = (f_{beat,up} + f_{beat,down})/2$$

$$f_{speed} = \left| f_{beat,up} - f_{beat,down} \right| / 2$$

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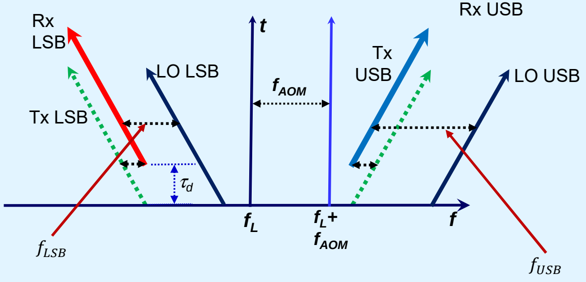
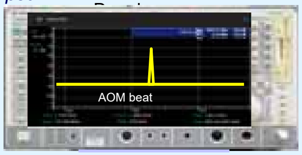
# Double Sideband FMCW Lidar

*Crouch, S. C. & Reibel, R. R. & Curry, J., Berg, T. (2018). Method and System For Doppler Detection And Doppler Correction Of Optical Chirped Range Detection. Intl. Patent, aWO2018160240A2 (Sept. 7, 2018).*

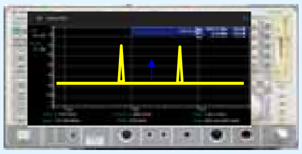
Heterodyne detection with AOM shifted LO



Zero Range



Range – Stationary



$$\text{Assuming } f_{AOM} > \kappa\tau$$

$$f_{USB} = f_{AOM} + \kappa\tau$$

$$f_{LSB} = f_{AOM} - \kappa\tau$$

$$f_R = \frac{f_{USB} - f_{LSB}}{2}$$

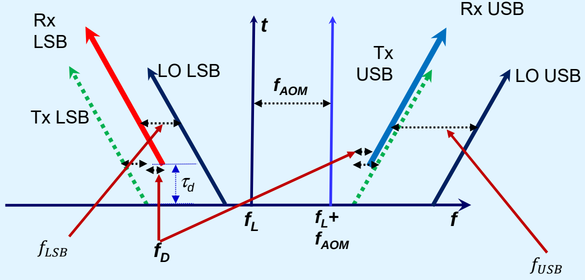
➔ $R = f_R \tau_c / (2B_c)$

# Double Sideband FMCW Lidar

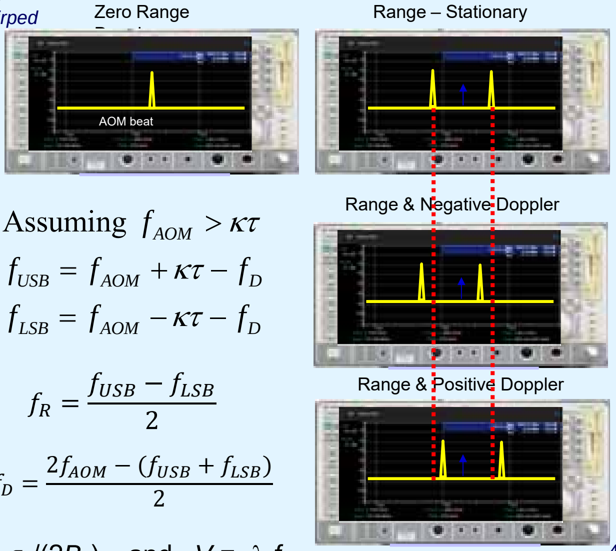
blackmore

*Crouch, S. C. & Reibel, R. R. & Curry, J., Berg, T. (2018). Method and System For Doppler Detection And Doppler Correction Of Optical Chirped Range Detection. Intl. Patent, aWO2018160240A2 (Sept. 7, 2018).*

Heterodyne detection with AOM shifted LO



Spectrum LAB
Montana State University



Assuming $f_{AOM} > \kappa\tau$

$$f_{USB} = f_{AOM} + \kappa\tau - f_D$$

$$f_{LSB} = f_{AOM} - \kappa\tau - f_D$$

$$f_R = \frac{f_{USB} - f_{LSB}}{2}$$

$$f_D = \frac{2f_{AOM} - (f_{USB} + f_{LSB})}{2}$$

$R = f_R \tau_c /(2B_c)$ and $V = -\lambda f_D$

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# Scanned FMCW Lidar

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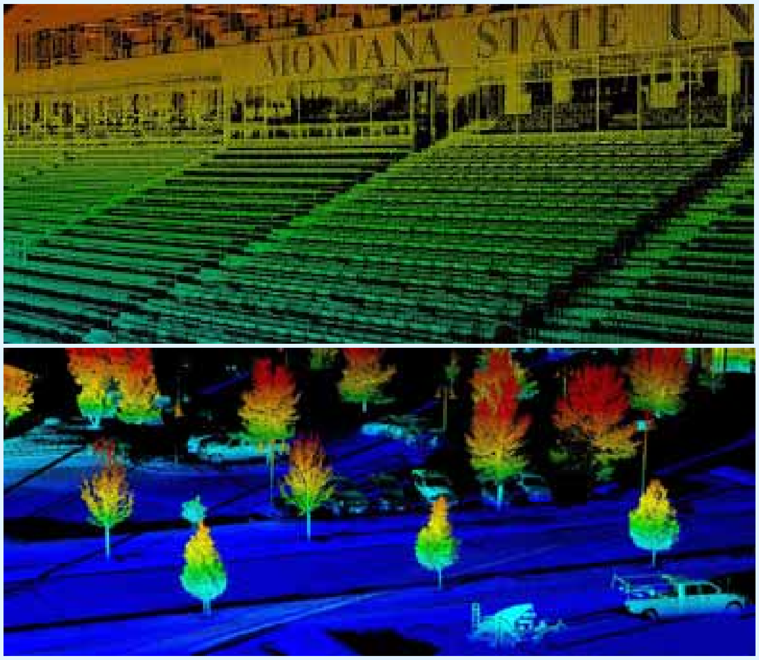
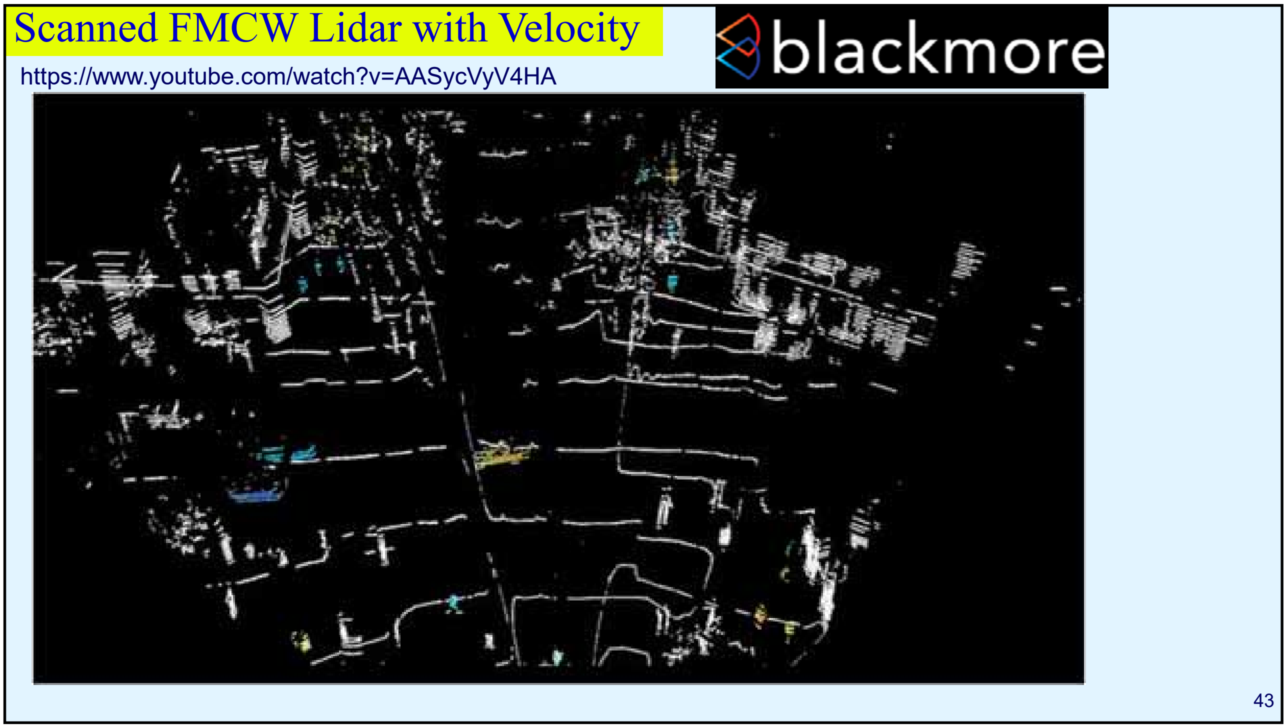
Precision Point Clouds





# Scanned FMCW Lidar with Velocity

blackmore

https://www.youtube.com/watch?v=AASycVyV4HA