Lidar Sensing and Coherent Imaging Research in Montana

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Montana State University

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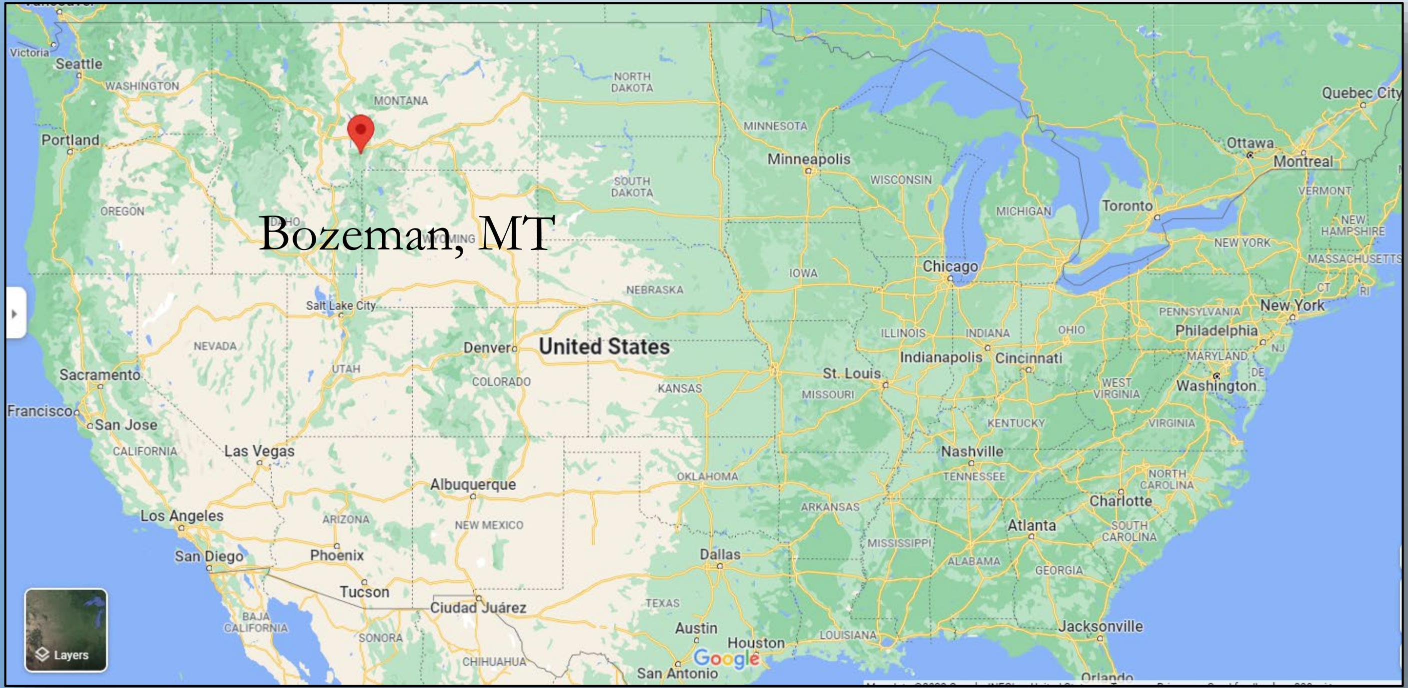
MONTANA STATE UNIVERSITY

Montana Photonics Industry Alliance

Spectrum LAB Montana State University

SPECTRUM LAB OVERVIEW



Montana State University

History

- Spectrum Lab is a Research Center at Montana State University established in 1999
- Controlled unclassified (CUI) research facility

- Research Expenditures/Assets
  - >$1M per year in research expenditures
  - >>$3M of accumulated equipment for optics and photonics research

SPECTRUM LAB OVERVIEW

Spectrum Lab's Mission

- Develop and help commercialize Montana grown photonic technologies.
- Transfer developed technologies to Montana companies.
- Provide enhanced educational and employment opportunities for Montana undergraduate and graduate students.

Expertise

- Applied Research and Development: Spatial-Spectral Holography, Microwave photonics, Precision Lidar, Coherent Imaging, Laser Development
- Interdisciplinary Research: Students/Collaborators in Optics and Photonics, Physics, Material Science, Electrical and Computer Engineering, and Mechanical Engineering
- IP generation and protection => Fostering research spin-offs
- Educating students for careers in optics and photonics industry.

Research Spin-offs

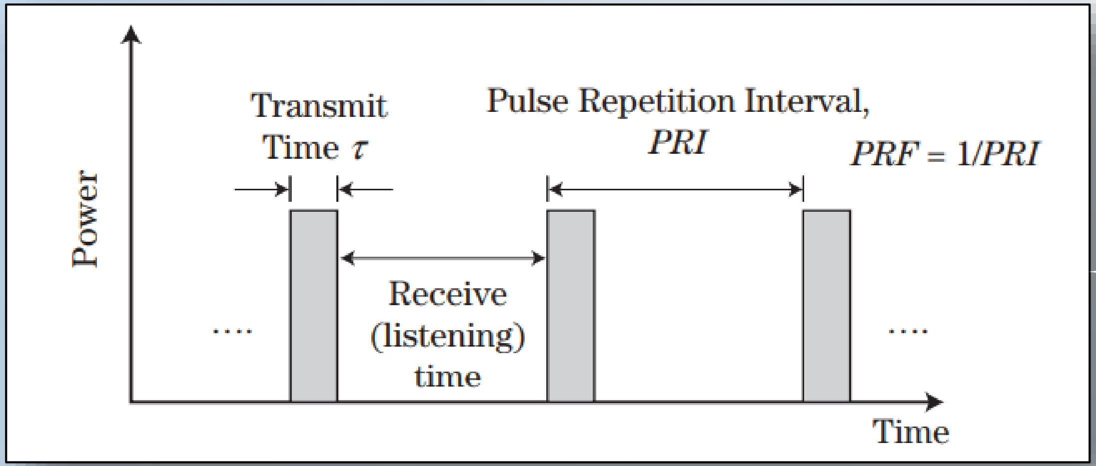
- Four successful (25-75 employees, >>$1M annual revenue) direct and indirect "research spin off" companies
- S2 Corporation, Bridger Photonics, Blackmore Sensors/Aurora, Montana Instruments

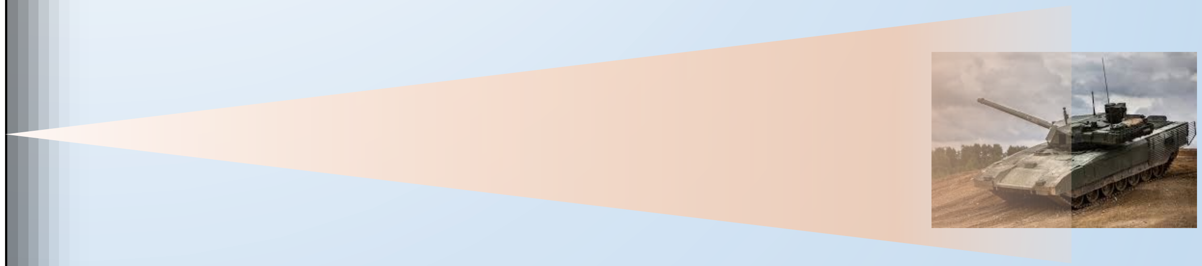
OUTLINE

1. Introduction
2. Coherent Lidar Research
3. Applications of Coherent Lidar
4. Pulsed Lidar Research
5. Coherent Digital Holography

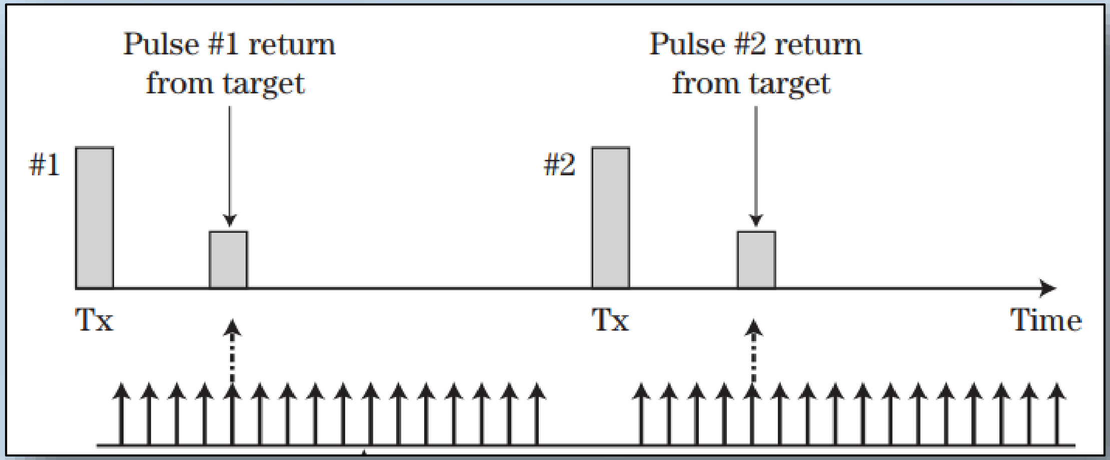
PULSED RADAR

Pulsed radar waveform





Pulsed radar waveform echoes timed by clock pulses



Round-trip time for the radar pulse $DT = 2R/c$

To prevent range ambiguities $PRI \geq DT_{max} = 2R_{max}/c$

$$R_{max} \leq c\, PRI/2$$

Unambiguous Range Measurement

$$R_{max} = c\, PRI/2$$

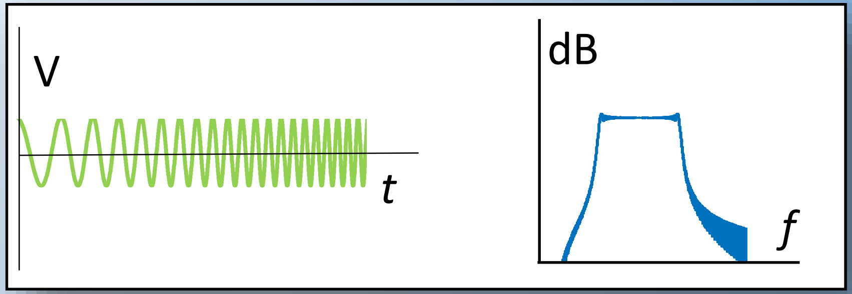
- ❑ Velocity can be measured by tagging multiple pulses in one direction

FMCW RADAR/LADAR PRINCIPLE

- Frequency modulation of the carrier is one of the most common techniques used to broaden the spectrum. Radars employing this technique are called **frequency modulated continuous wave** (FMCW) radars

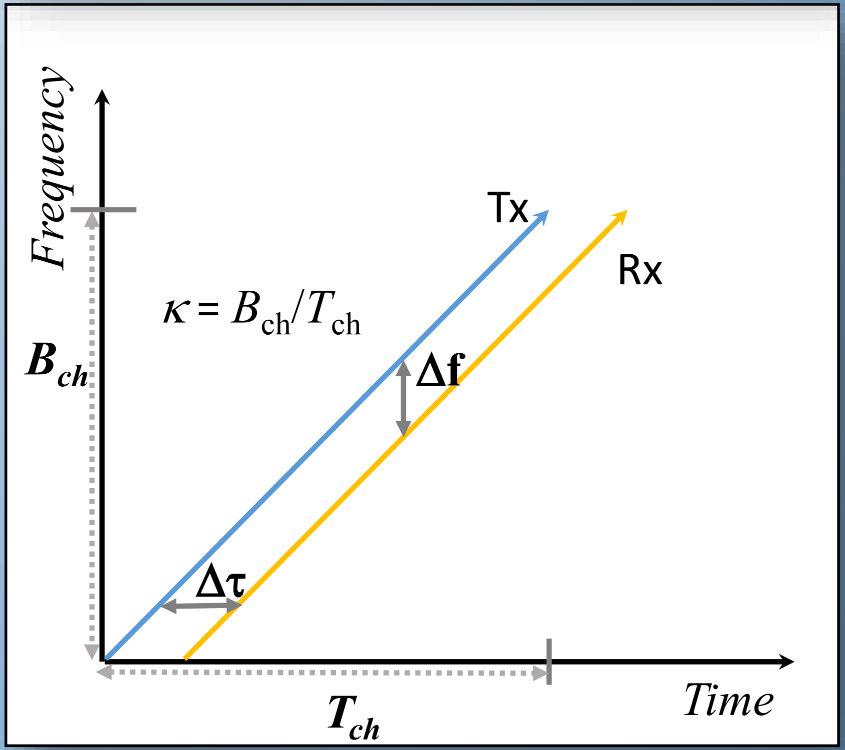
- **Linear Frequency Modulation** (LFM), where frequency changes *linearly* with time is a popular one. This is also called a Chirp (linear)

    - The frequency modulation spreads the transmitted energy over a large modulation bandwidth (helps with resolution)
    - The power spectrum is nearly rectangular over the modulation bandwidth (makes interception difficult)

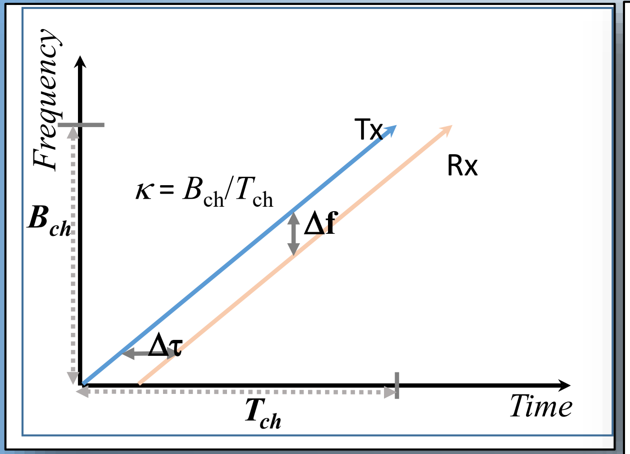


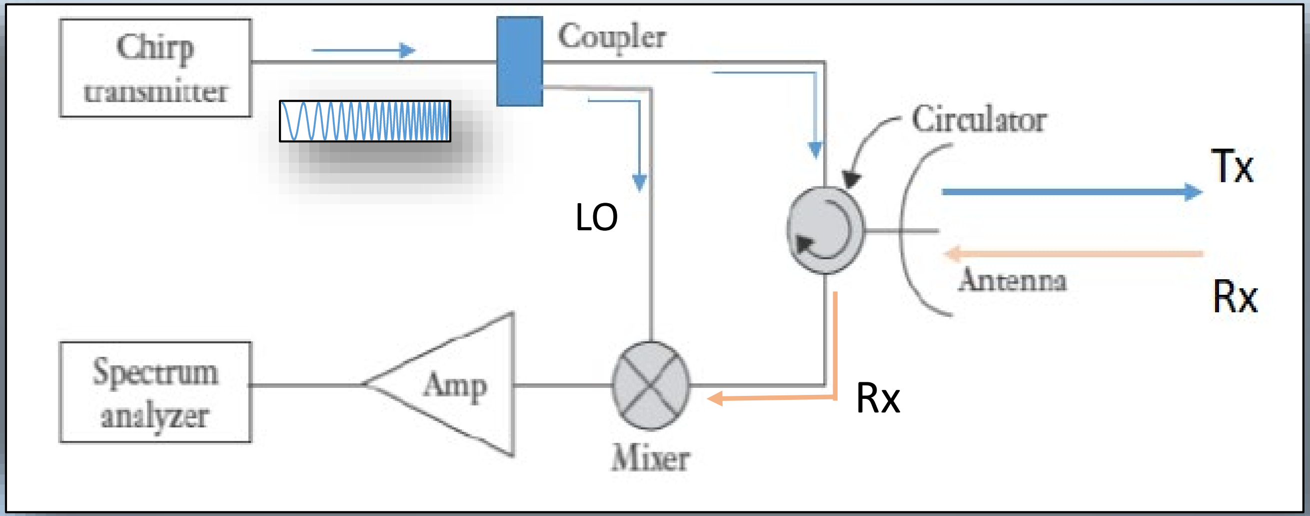
LFM Radar

- A chirp signal (**Tx**) is transmitted at a chirp rate of $\boldsymbol{k = B_{ch}/T_{ch}}$, where $\boldsymbol{B_{ch}}$ is the maximum sweep bandwidth and $\boldsymbol{T_{ch}}$ is the sweep time.
- The return signal is received (**Rx**) after a time $\boldsymbol{\Delta t}$, ($= 2R/c$), where R is the target range and c is the velocity of light.
- If the Rx is mixed with a copy of the Tx a difference frequency ($\boldsymbol{\Delta f}$) beat signal can be observed. ***The frequency of the beat is proportional to the range.***

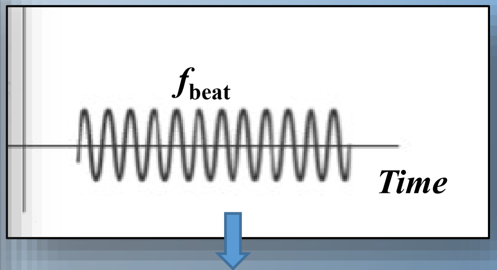


FMCW LIDAR- DESIGN AND PRINCIPLE

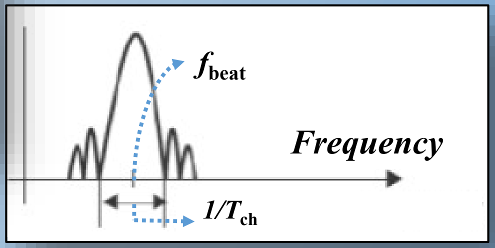




Receiver output amplitude



Receiver output power



→ ***The frequency of the beat is proportional to the range*** $f_{beat} = \kappa\,\Delta\tau$

Setup some math

$$T_x(t) = \cos\left(2\pi\left(f_0 t + \frac{\kappa}{2}t^2\right)\right)$$

$0 \le t \le T$, T is the chirp width, $\kappa = B/T$, and B is the bandwidth.

$$R_x(t) = A(t)\cos\left[2\pi\left(f_0(t-\Delta\tau) + \frac{\kappa}{2}(t-\Delta\tau)^2\right)\right]$$

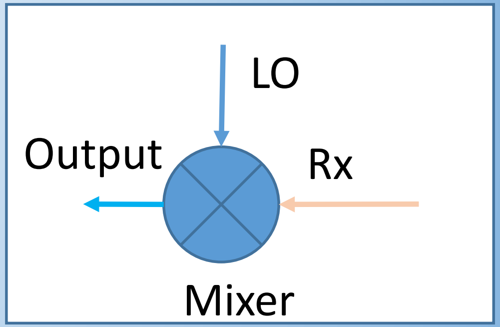
$\Delta\tau = 2R/c$, is the round trip time to the target at Range R. $A(t)$ has the details about target, attenuation, pulse, antenna

$$LO(t) = \cos\left(2\pi\left(f_{LO} t + \frac{\kappa}{2}t^2\right)\right)$$

This is the reference field that acts as a local oscillator. Assume that $f_{LO} = f_o$

FREQUENCY MODULATED CONTINUOUS WAVE RADAR

→The output of the mixer is the product of the received and LO signals. **Both are cosines that have f_o terms**



→ Use the cosine product rule ***2 cosA cosB = (cos(A+B) + cos(A-B))***

→ The resultant signal will have two terms, one of which is at *cos(2f_ot. ...)*. This is at a high frequency. So let us low pass filter the signal

Coherent Detection

→The resultant output signal is $S(t) = A(t)\cos(2\pi f_o \Delta\tau + 2\pi\kappa\Delta\tau\, t - \pi\kappa(\Delta\tau)^2)$

→The phase of the resultant signal $\phi(t) = 2\pi f_o \Delta\tau + 2\pi\kappa\Delta\tau\, t - \pi\kappa(\Delta\tau)^2$

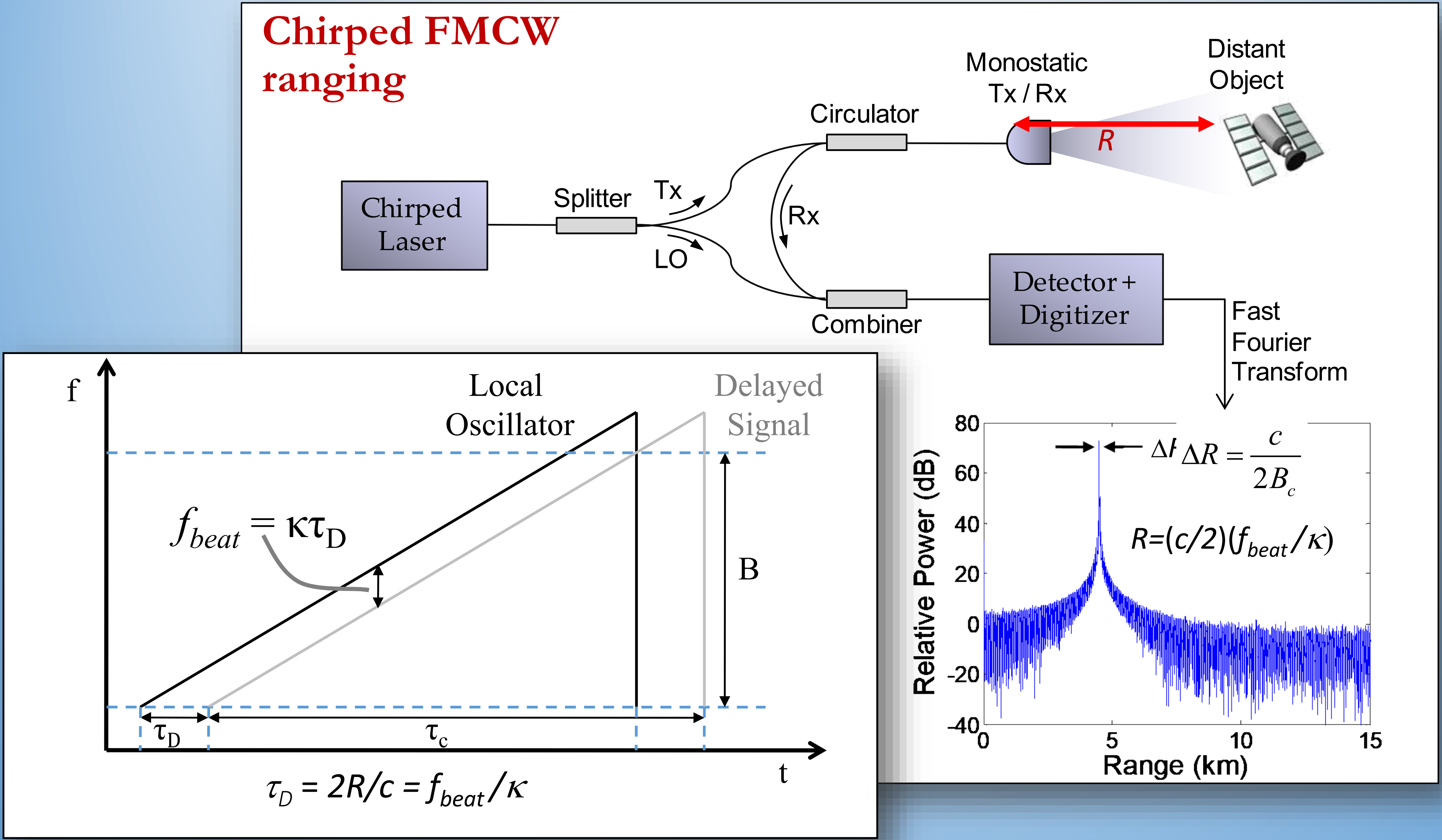
→The instantaneous frequency is $f_b = \frac{1}{2\pi}\frac{d\varphi(t)}{dt} = \kappa\Delta\tau$

Range is given by $R = \frac{c\, f_b\, T_{ch}}{2B_{ch}}$

If the target is moving, the beat frequency will be $f_{Range} \pm f_{Doppler}$

Range resolution is given by $\Delta R = \frac{c}{2B_{ch}}$

FREQUENCY MODULATED CONTINUOUS WAVE LIDAR/LADAR



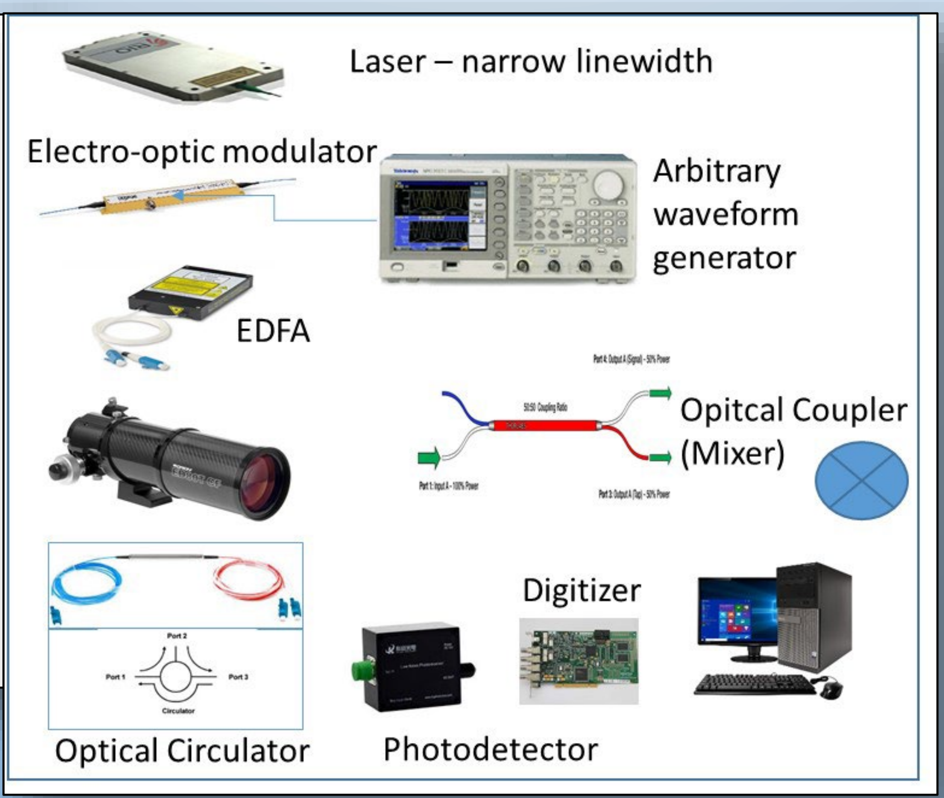
FMCW LIDAR/LADAR COMPONENTS

- The same measuring principles can often be used in both radar and lidar systems
- The source is at optical frequencies (~200 THz) instead of microwave frequencies (~100 GHz)
- Development of stable laser sources, fiber transport, modulators, amplifiers, receivers (thanks to Optical communications industry)
- Better range, less prone to interference, lot more applications in remote sensing.
- Better fractional bandwidth enables higher range resolution

- Coherent optical carrier
- Modulator/modulation scheme
- Optical amplifier
- Transmit channel T_x
- Receive channel R_x
- Channel separator
- Optical coupler
- Detection scheme
- A/D converter, DAQ
- Post-processor

Options

- Monostatic or Bistatic configuration
- Balanced detection, IQ etc



Advantages of FMCW Lidar

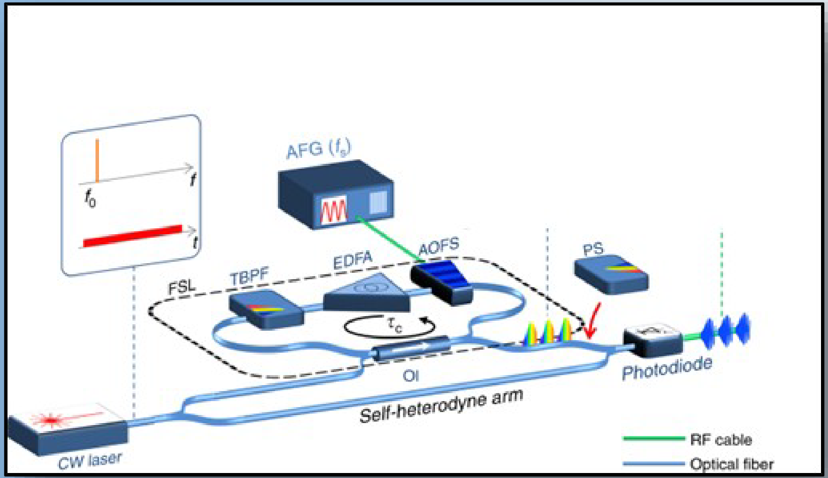
- More energy, with much less peak power
  - Higher energy => better SNR
  - Less chance of optical damage
  - More eye safe
  - Requires much lower bandwidth detectors and digitizers
  - Can be well characterized to reduce distortion or jitter

.

COHERENT LIDAR RESEARCH

- ❑ Generation of modulated waveforms
- ❑ Coherent lidar modalities
- ❑ Applications of Coherent lidar

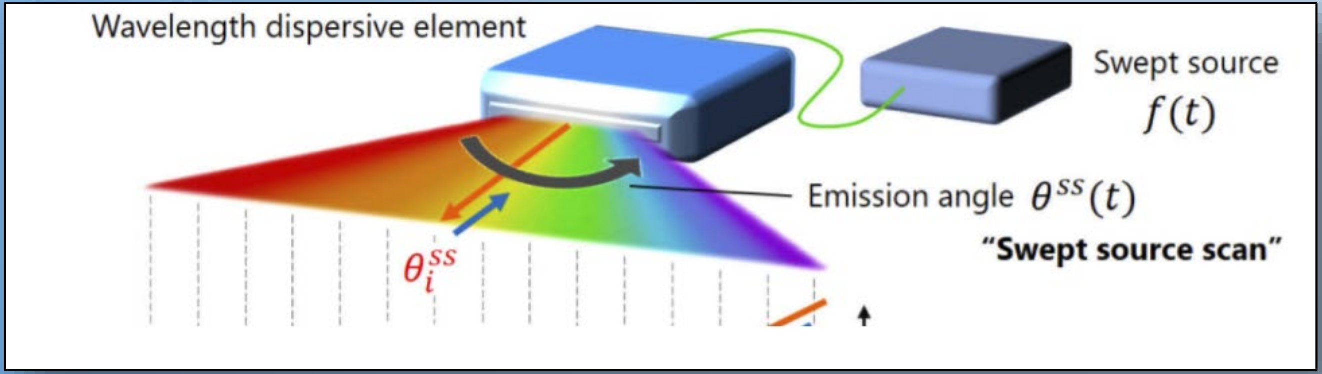
GENERATING AN OPTICAL CHIRP



Acousto-Optic frequency shifter– RING CHIRPER *

OEWAVES – High Q Whispering Gallery Mode (WGM) micro-resonator.

BRIDGER PHOTONICS SLM-IM Length Metrology System - Stabilized frequency tunable source *



SANTEC- swept VECSEL source scan

STABLE OPTICAL CARRIER + ELECTRO-OPTIC MODULATOR

S2 CORPORATION – RF Chirp modulated onto an optical carrier*

These were demonstrated at Spectrum Lab and subsequently commercialized

SINGLE SIDEBAND SUPPRESSED CARRIER (SSBSC)

US PATENT 9020360:

Techniques for single sideband suppressed carrier (SSBSC) optical signals that scale to bandwidths over 20 gigahertz

Inventors:

S2 Corporation

Colton Richard Stiffler, Scott Henry Bekker, Kristian D. Merkel,

MSU Spectrum Lab

Randy R. Reibel, William R. Babbitt, Krishna Mohan Rupavatharam

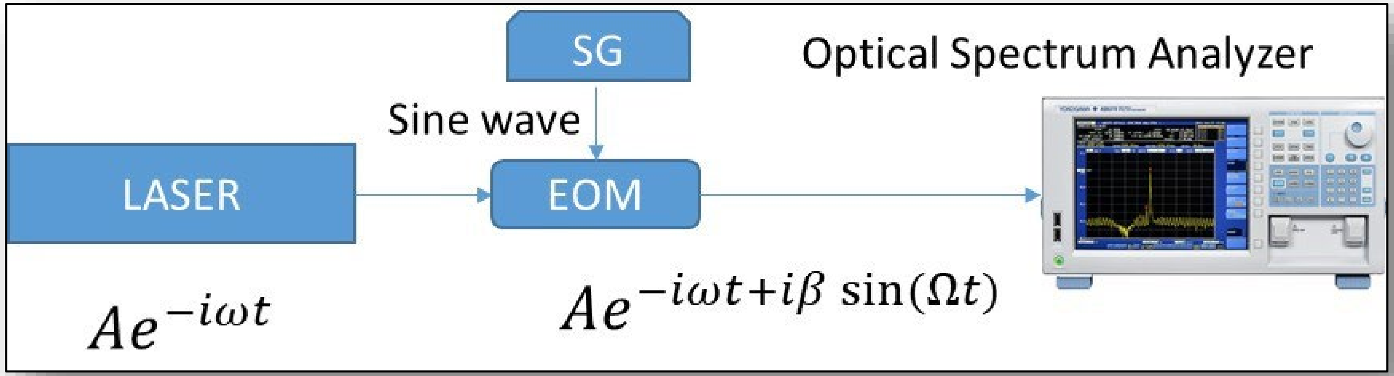


FIG. 8A

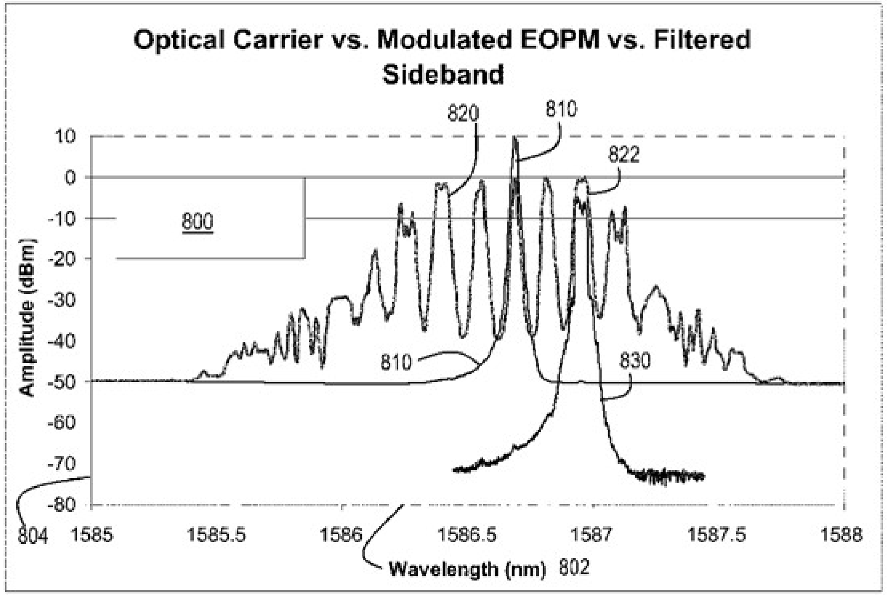
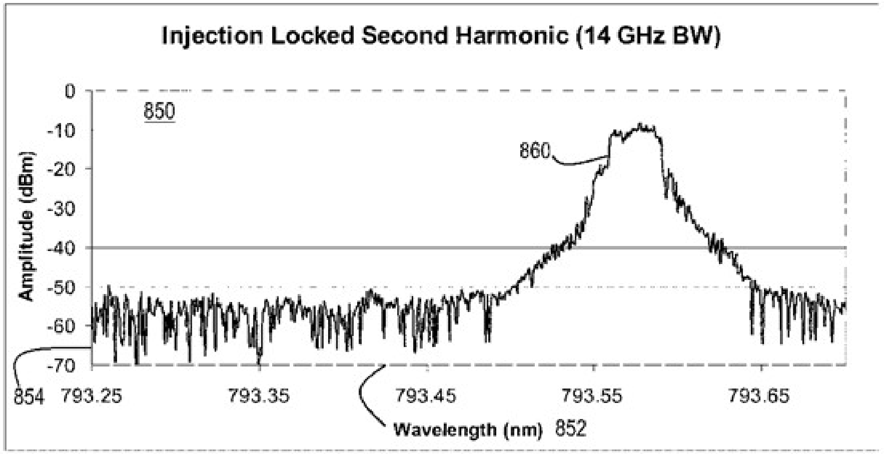
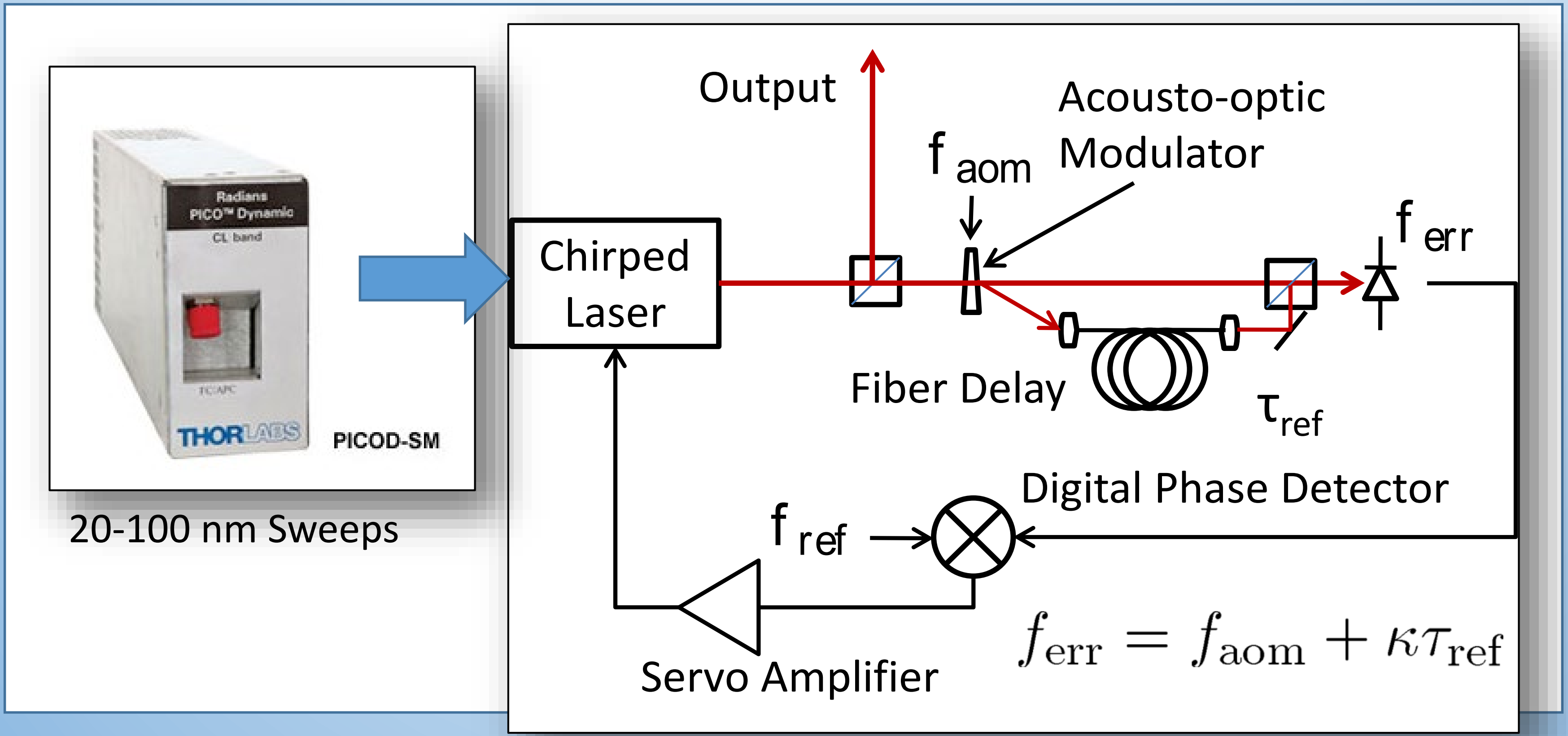


FIG. 8B



S2 Corporation commercialized the chirp generator

ACTIVELY LINEARIZED CHIRP LASERS



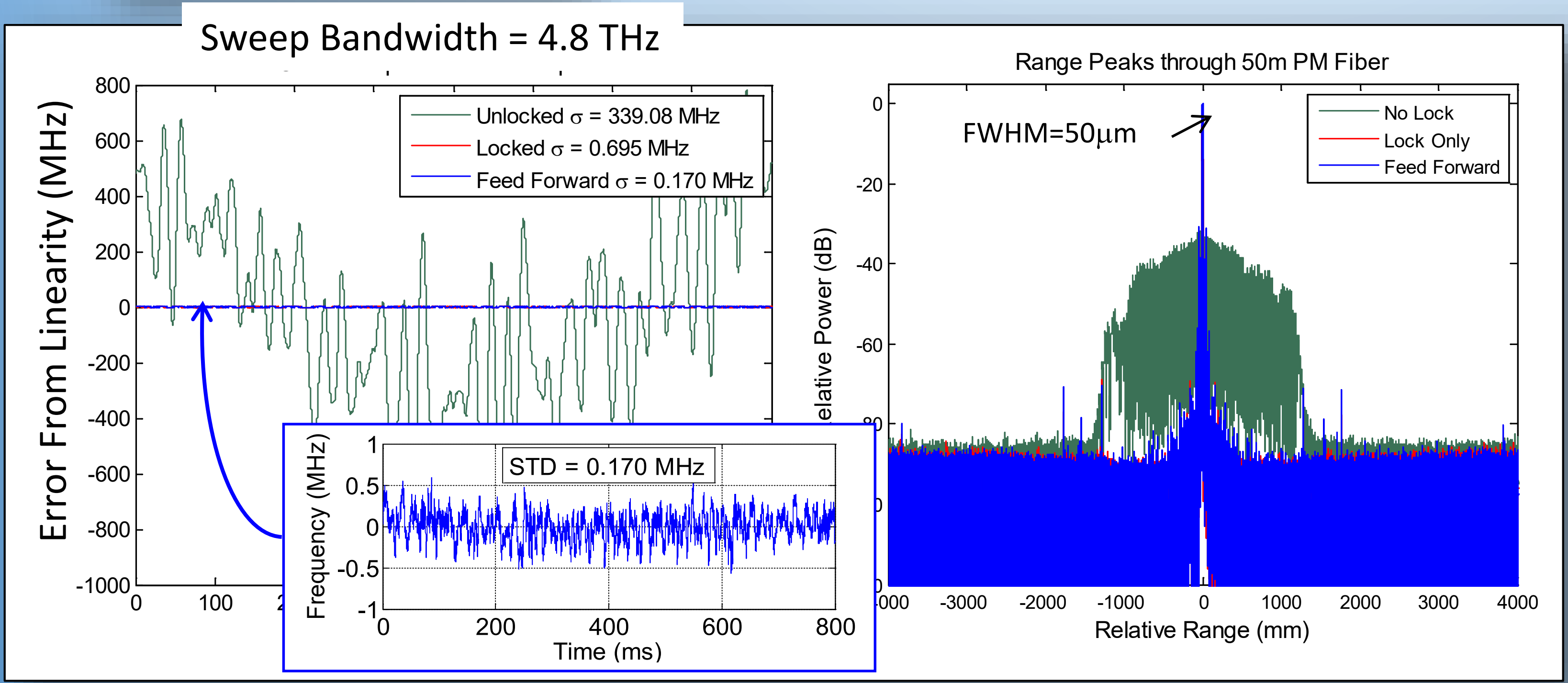
1. P. A. Roos, R. R. Reibel, T. Berg, B. Kaylor, Z. Barber, W. R. Babbitt, "Ultra-broadband optical chirp linearization for precision metrology applications," Opt. Let. 34, 3692 (2009).
2. Zeb W. Barber, Wm. Randall Babbitt, Brant Kaylor, Randy R. Reibel, and Peter A. Roos, "Accuracy of active chirp 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).

ULTRA-BROADBAND CHIRP LINEARIZATION

Bridger Photonics commercialized the chirp generator

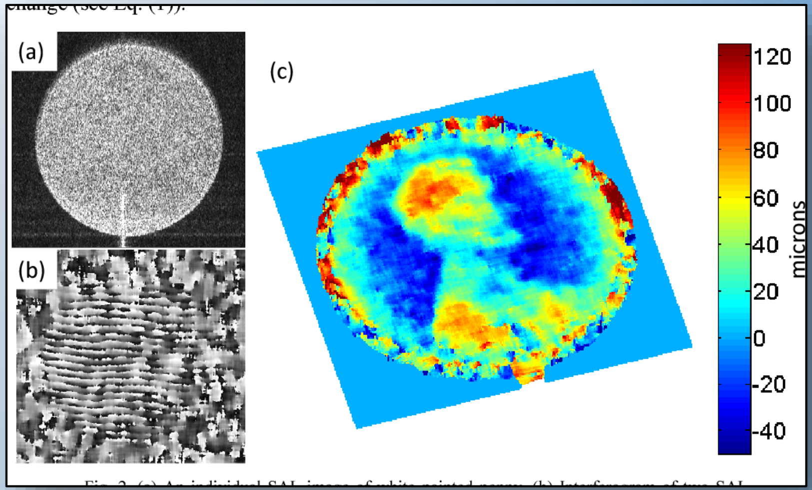
BRIDGER PHOTONICS

- **Precise broadband frequency modulated laser, Patent number:** 9559486, 2017
- **Length metrology apparatus and methods for suppressing phase noise-induced distance measurement errors, Patent number:** 20170343333, 2017

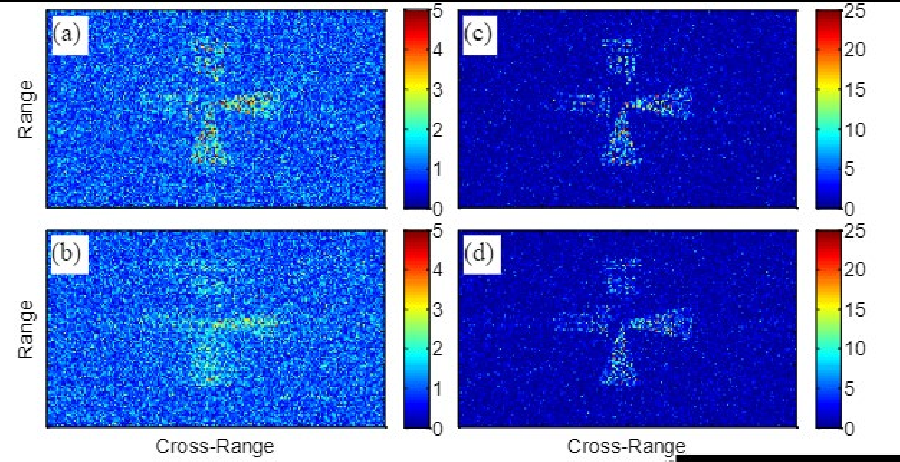


DEMONSTRATIONS WITH FMCW LADAR AT SPECTRUM LAB

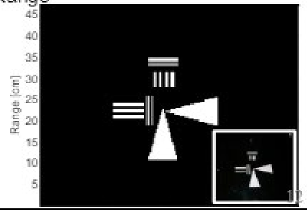
- *Extremely High-Resolution LADAR System for Precision Length Metrology and Imaging*
  Imaging and Applied Optics Congress, OSA Technical Digest (CD) (Optica Publishing Group, 2010), paper AMA3
  P. A. Roos, R. R. Reibel, T. J. Berg, B. M. Kaylor, Z. W. Barber, and W. Randall Babbitt,
- *Laboratory demonstrations of interferometric and spotlight synthetic aperture ladar techniques.*
  Optics express 20 22 (2012): 24237-46
  Stephen Crouch, Z. Barber
- *High Resolution FMCW Ladar for Imaging and Metrology,*
  Imaging and Applied Optics 2015, OSA Technical Digest (online) (Optica Publishing Group, 2015), paper LM4F.2
  Z. W. Barber, J. R. Dahl, A. B. Mateo, S. C. Crouch, and R. R. Reibel,
- *Precision and accuracy testing of FMCW ladar-based length metrology.*
  Appl Opt. 2015 Jul 1;54(19):6019-24. doi: 10.1364/AO.54.006019. PMID: 26193146. Mateo AB, Barber ZW.
- *FMCW Differential Synthetic Aperture Ladar for Turbulence Mitigation*
  18th Coherent Laser Radar Conference, CLRC 2016,
  Z. Barber, J. Dahl, Christophe Blaszczyk



Extremely Low Return Levels

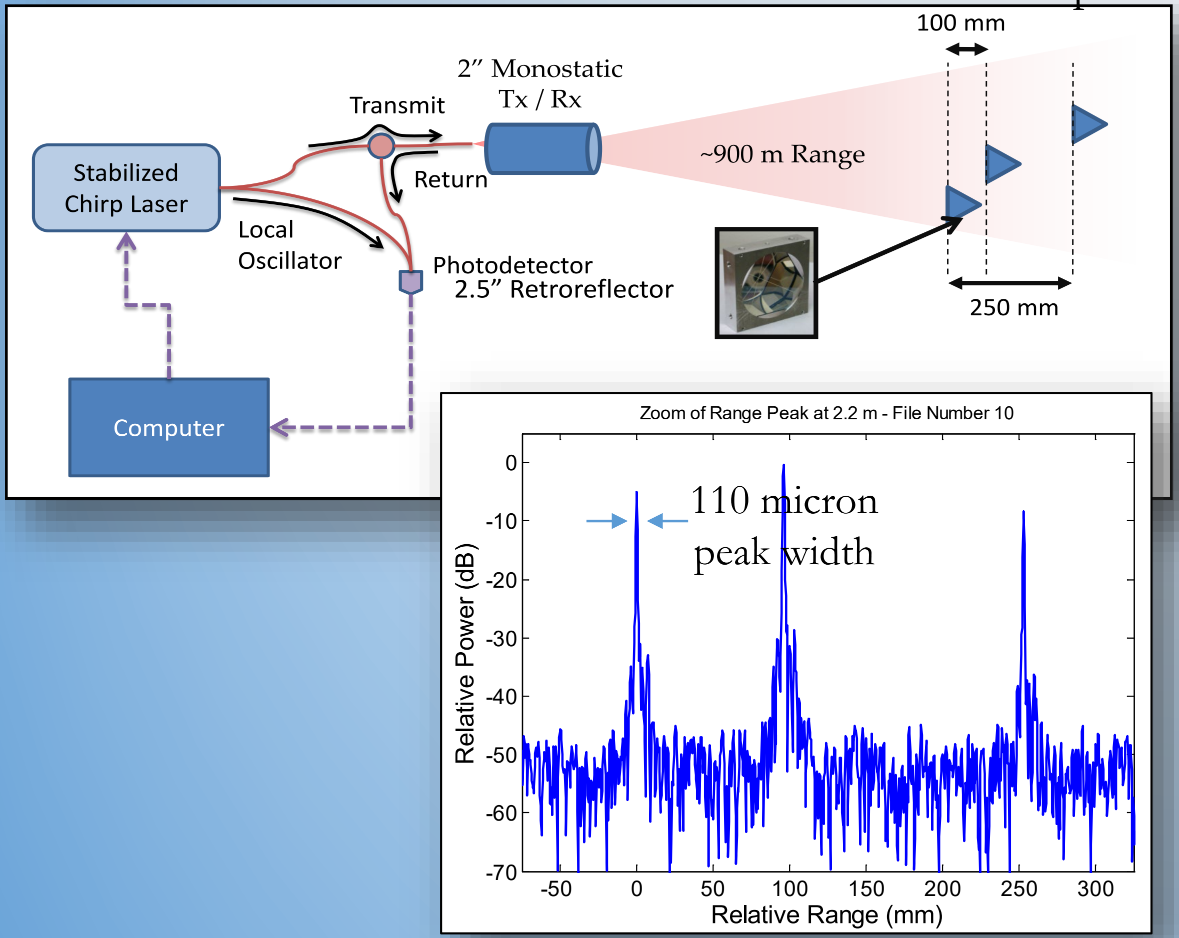


- 5 photons per "on" pixel
  - Top: Retro phased; Bottom: PGA phased
  - Left: ~ 1 photon per pixel averaged 5 times
  - Right: ~5 photons per pixel no averaging
  - 200 cross-range samples

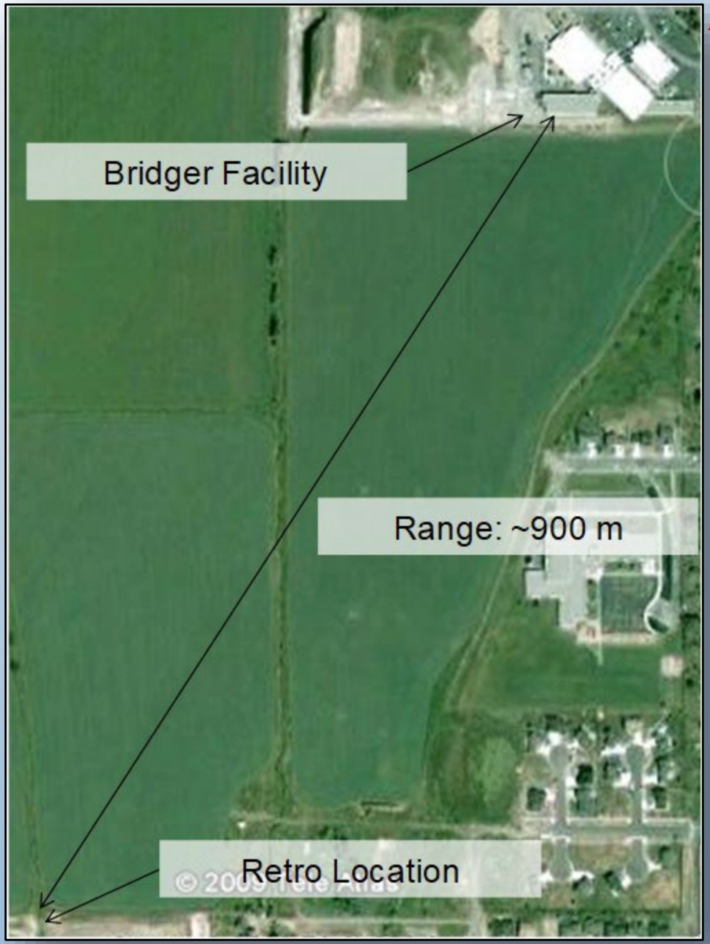


Some of the research was performed in collaboration with Bridger Photonics and Blackmore Inc, Bozeman, MT

LONG RANGE MEASUREMENTS



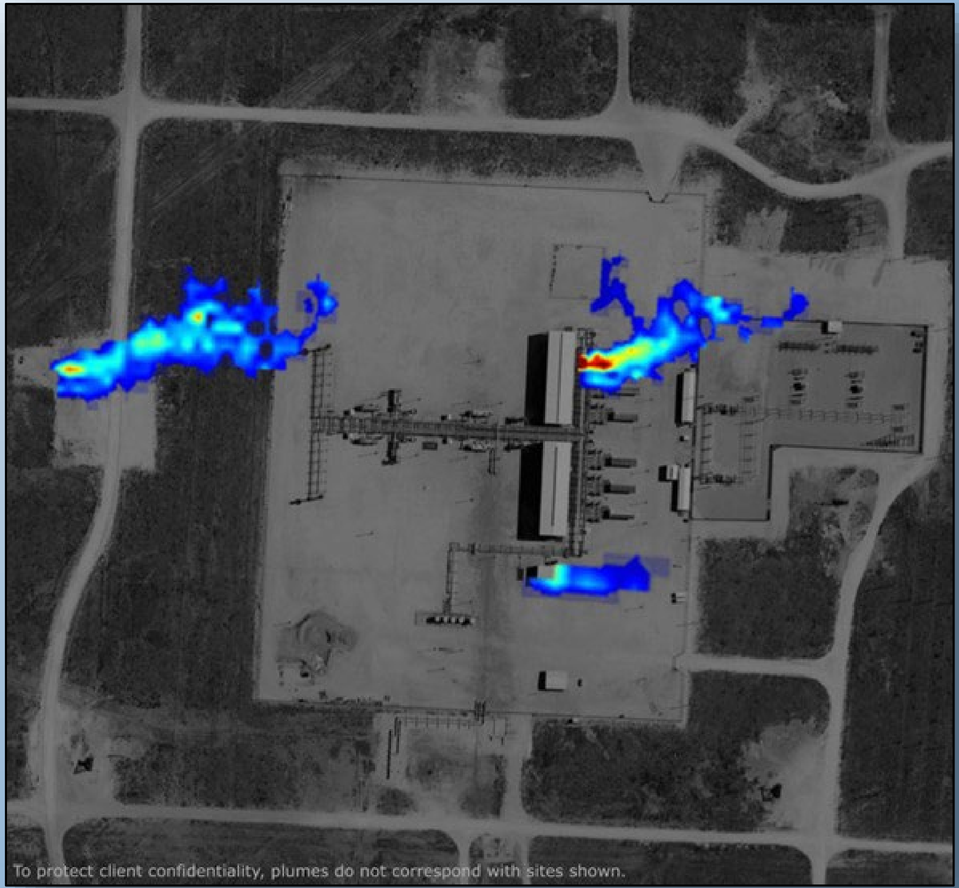
Spectrum Lab in collaboration with Bridger Photonics



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

Ultra-Compact LADAR Systems for Next Generation Space Missions
https://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=1192&context=smallsat

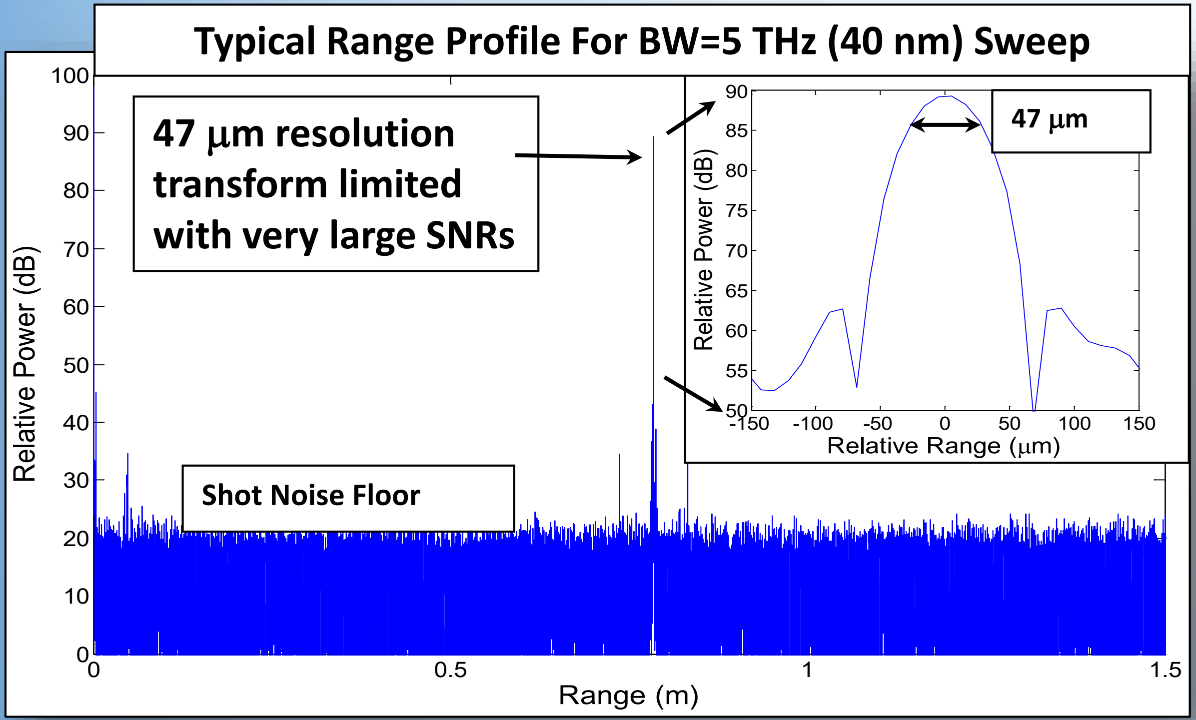
GAS MAPPING LIDAR

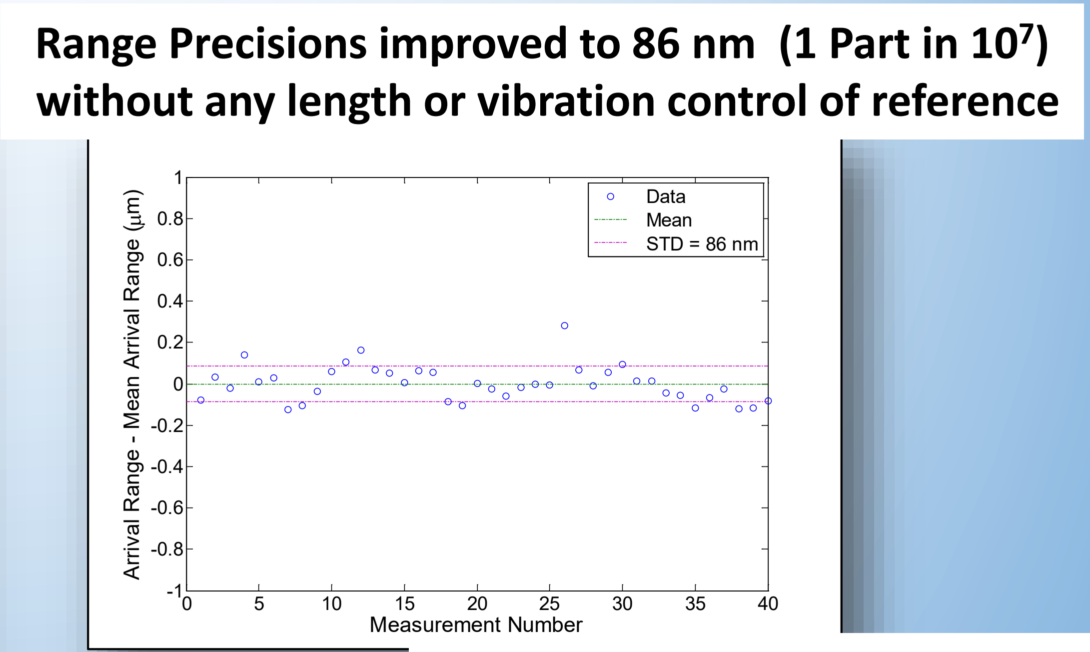


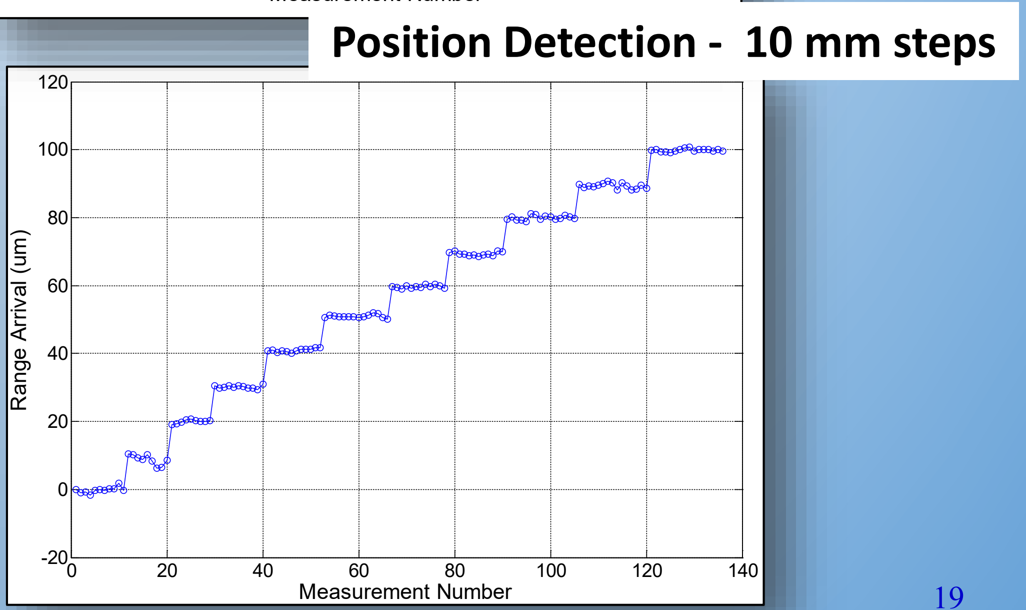
Unparalleled Methane Emissions Detection

- Gas Mapping LiDAR sensitively detects, precisely locates, and accurately quantifies methane emissions across the entire natural gas value chain.
- Dual lidar head with ranging and spectroscopic capability

FMCW PRECISION METROLOGY

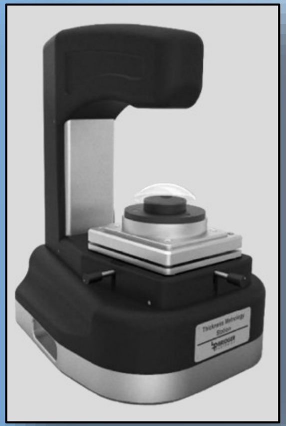


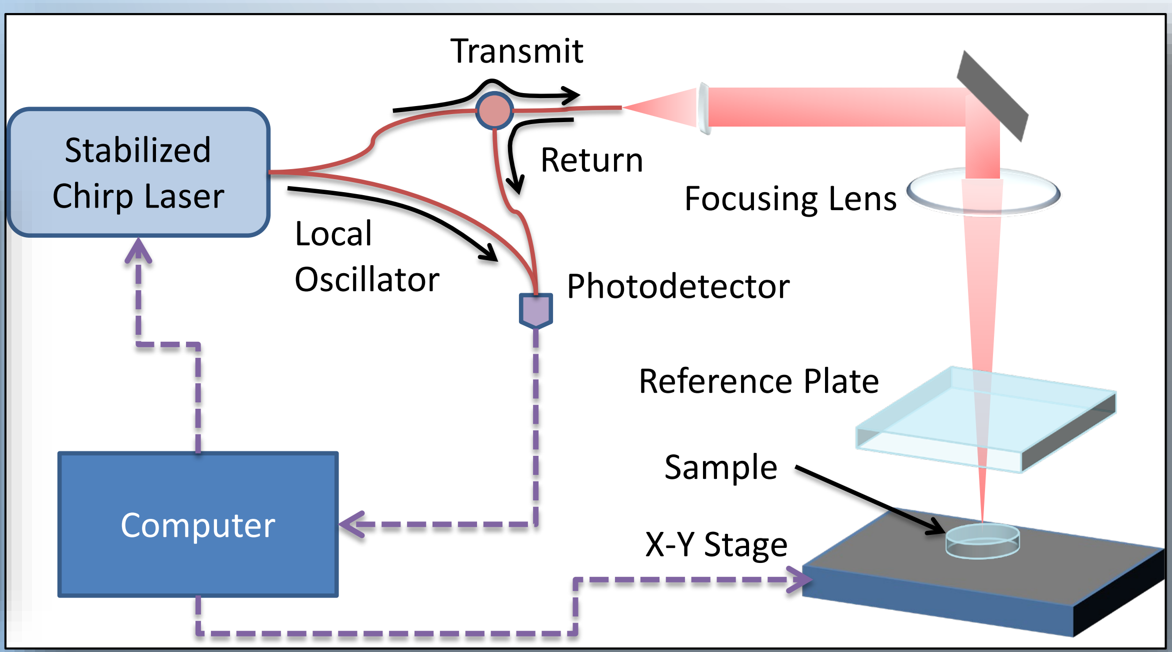


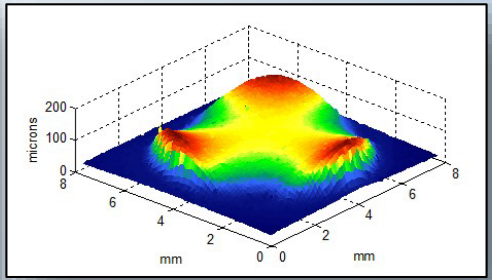


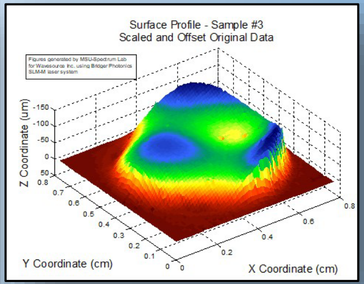
- Results Summary:
  - 47 micron resolution
  - 86 nm precision best from non-interferometric technique

PRECISION METROLOGY









INDUSTRIAL METROLOGY

Non-contact physical thickness metrology

Refractive index measurements

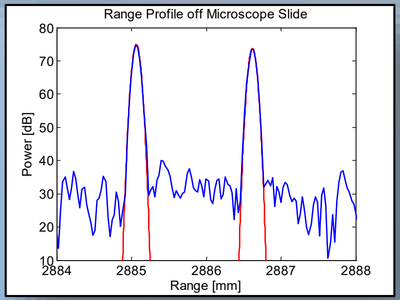
Max part diameter: 150 mm

Max part optical thickness: 75 mm

Fractional uncertainty (thickness): 1:10^6

Repeatability: <1 µm typical, specular surface

- Specular reflections and large off normal surface angles require high NA objectives.
- Multiple surfaces can be measured simultaneously



USE APPLICATIONS

- Multiple retro-reflector position measurements
- Precise surface separation measurements
- Surface error measurements
- Thickness measurements
- Large volume optical metrology
- In-situ metrology for laser materials processing

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

SCANNED FMCW LIDAR

blackmore

Precision Point Clouds

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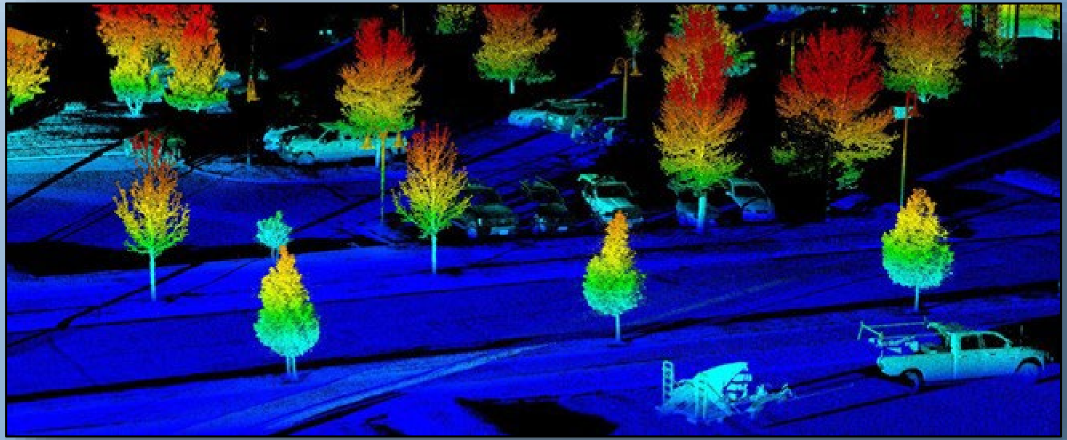
University Communications / MSU News / Local photonics company practices at MSU stadium

At MSU's stadium, local photonics company practices for the big time

Marshall Swearingen, MSU News Service

APRIL 18, 2018

Blackmore High Resolution Scanning FMCW Lidar



SCANNED FMCW LIDAR

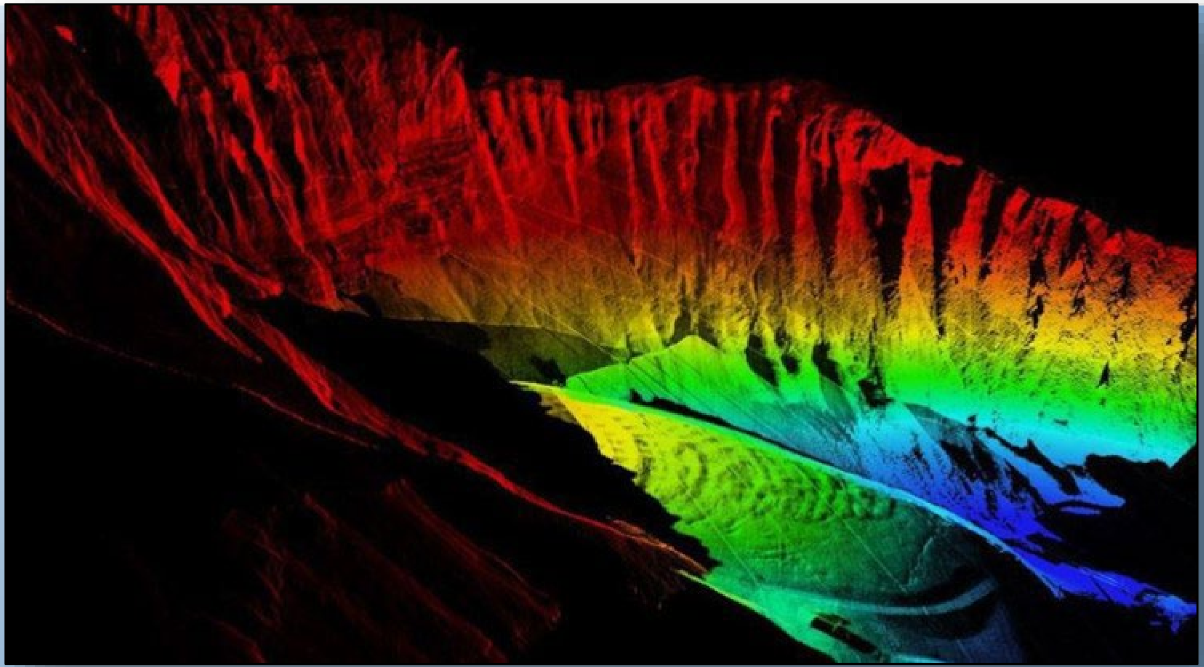
blackmore

Blackmore personnel worked with Montana State University to use its portable lidar to measure the surface of the 200-foot-deep glacier in Big Couloir to see how it's moving.

BOZEMAN DAILY CHRONICLE NEWS OPINIONS SPORTS BUSINESS OUTDOORS EVENTS POLICE REPORTS OBITUARIES MAGAZINES

High-speed lasers measure glacial movement at Big Sky Resort

By BRETT FRENCH Billings Gazette Nov 29, 2018

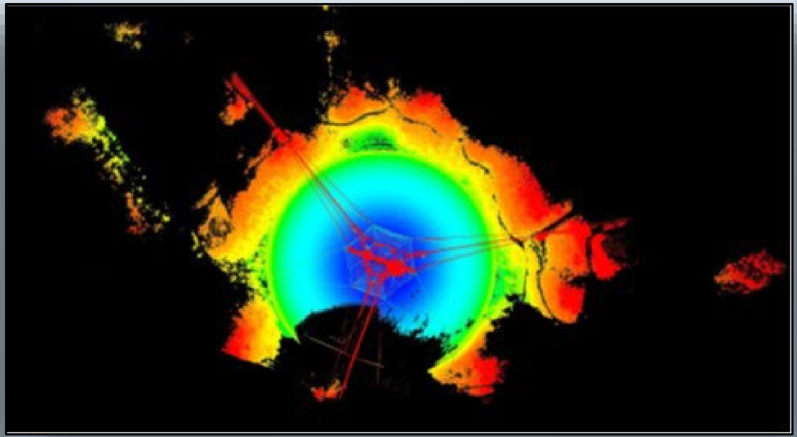


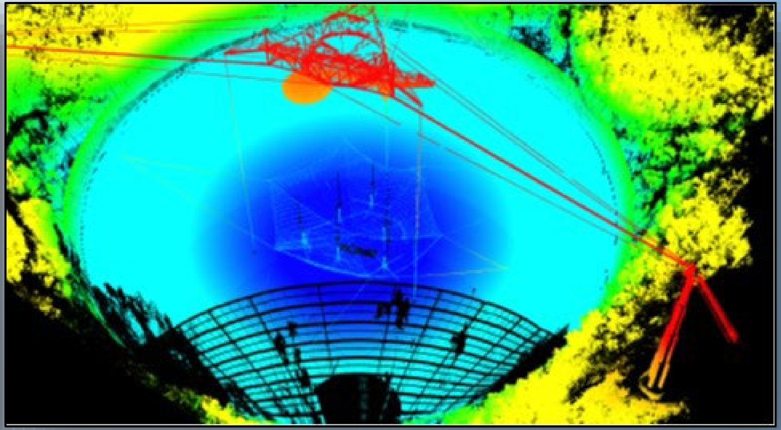
Blackmore's lidar captured millions of points across the glacier's surface to quickly create a high-definition 3D map. *Image courtesy of Blackmore via Billings Gazette*

SCANNED FMCW LIDAR

blackmore

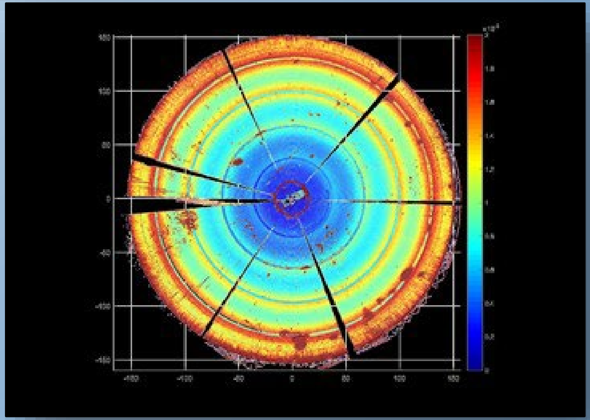
Arecibo Radio Telescope Surface scan



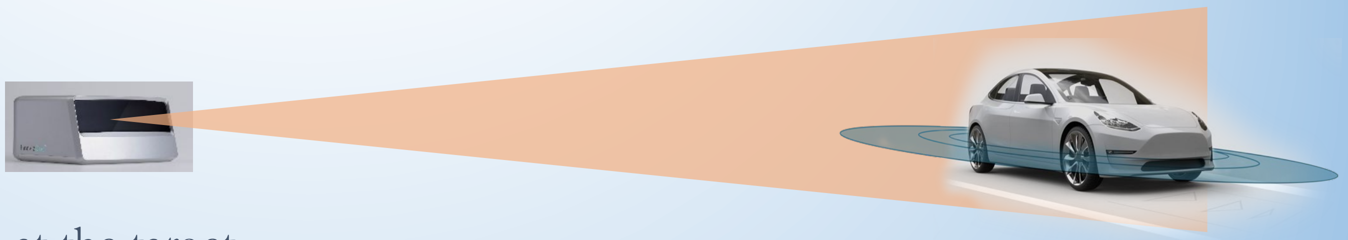


Arecibo radio telescope has a huge "dish", 305 m (1000 feet) in diameter, 167 feet deep, and covers an area of about twenty acres. The surface is made of almost 40,000 perforated aluminum panels, each measuring about 3 feet by 6 feet, supported by a network of steel cables strung across the underlying karst sinkhole. It is a spherical (not parabolic) reflector .

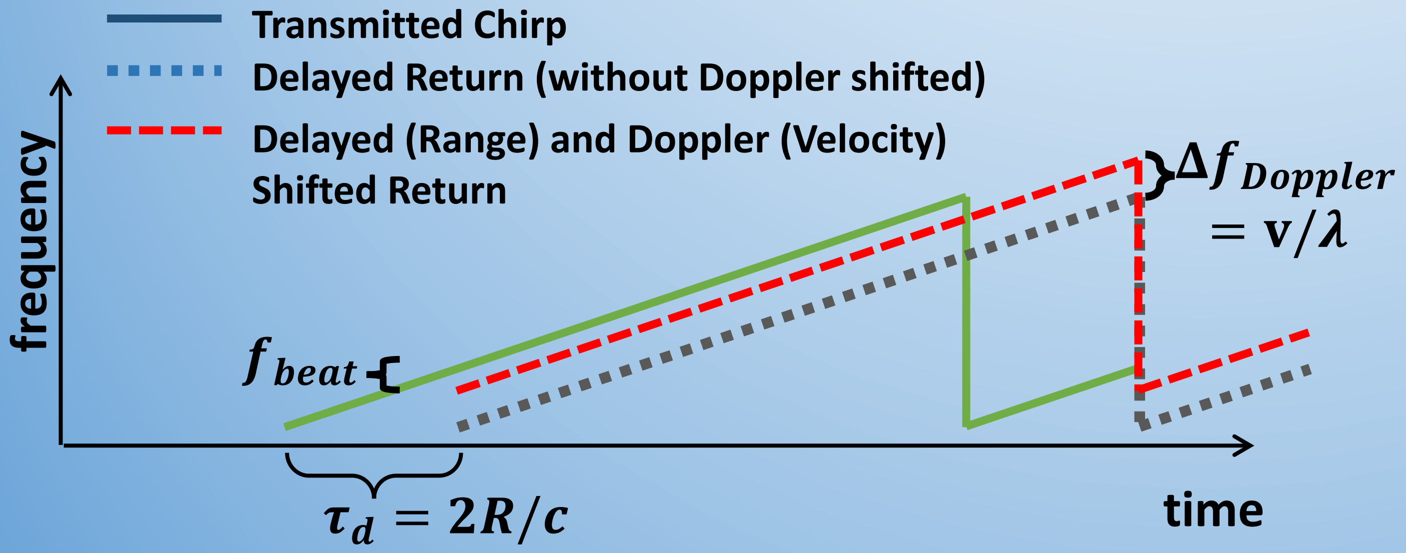
Polar heatmap of Uncertainity ~± 1cm



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 frequency shifts



Blackmore Patents

METHOD AND SYSTEM FOR DOPPLER DETECTION AND DOPPLER CORRECTION OF OPTICAL PHASE-ENCODED RANGE DETECTION

Publication/Patent Number: WO2018144853A1
Publication Date: 2018-08-09
Inventor： Reibel, Randy R. Crouch, Stephen C. Curry, James Rupavatharam, Krishna Milvich, Michelle
Assignee: Blackmore Sensors & Analytics, LLC

METHOD AND SYSTEM FOR TIME SEPARATED QUADRATURE DETECTION OF DOPPLER EFFECTS IN OPTICAL RANGE MEASUREMENTS

Publication/Patent Number: WO2019014177
Publication Date: 17.01.2019
Inventor： Crouch, Stephen C. Rupavatharam, Krishna
Assignee: Blackmore Sensors & Analytics, LLC

SCANNED FMCW LIDAR WITH VELOCITY

blackmore

Aurora

https://aurora.tech/

https://www.businesswire.com/news/home/20180905005322/en/Blackmore-Unveils-First-Doppler-Lidar-On-the-Road-Demonstrates-How-its-Current-Sensor-Can-Make-Autonomous-Vehicles-Safer

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

https://youtu.be/Cd48BiiPgLA

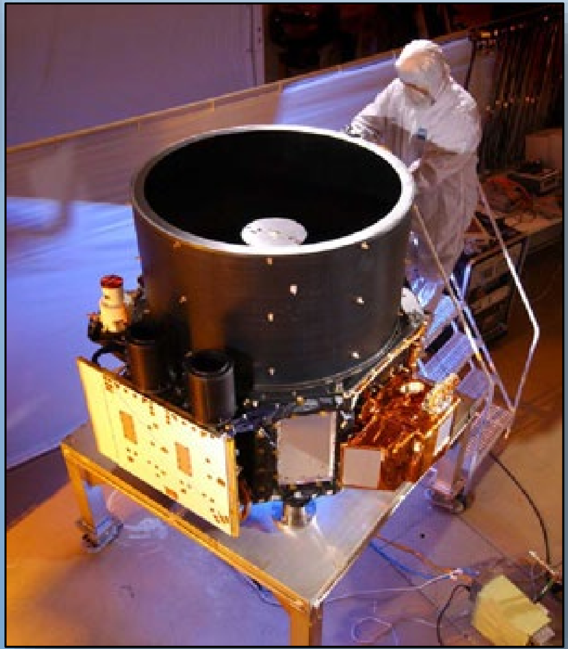
PULSED LIDAR RESEARCH

Atmospheric Lidar

Fish and Insect Lidar

ATMOSPHERIC LIDAR

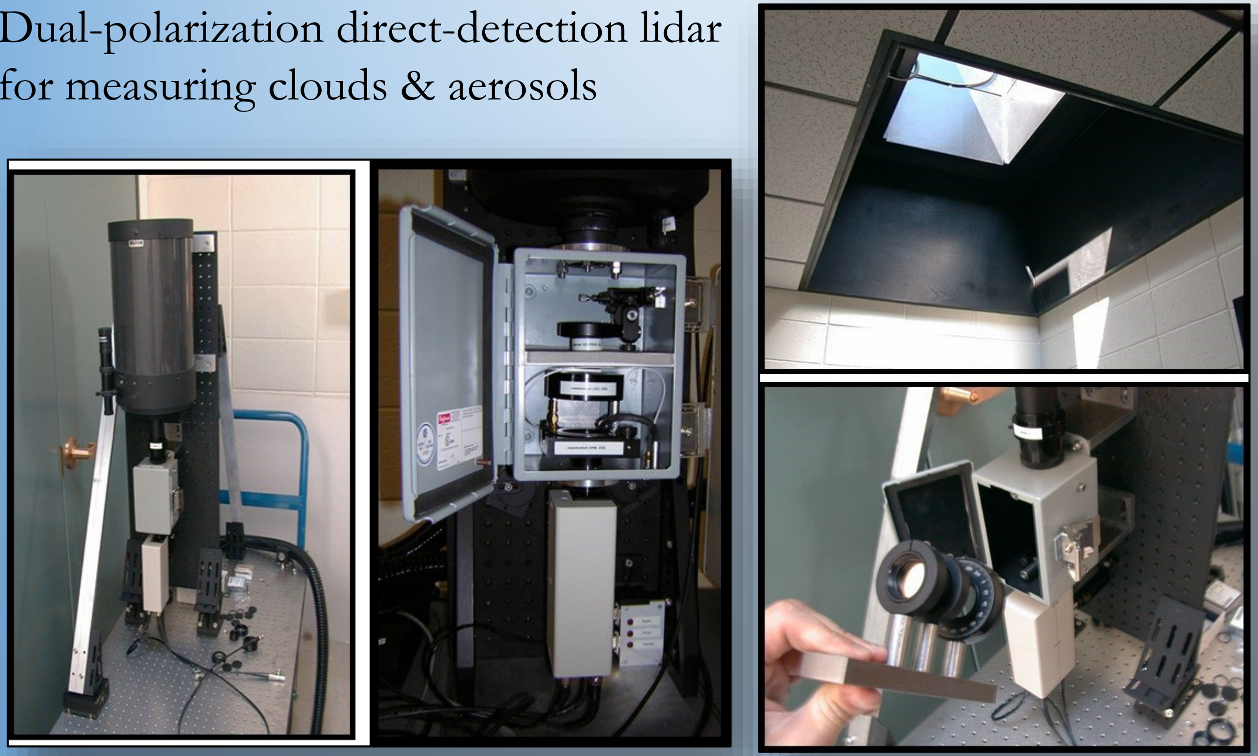
Dr. Joseph A. Shaw
Distinguished Professor
Montana State University
Bozeman, Montana USA



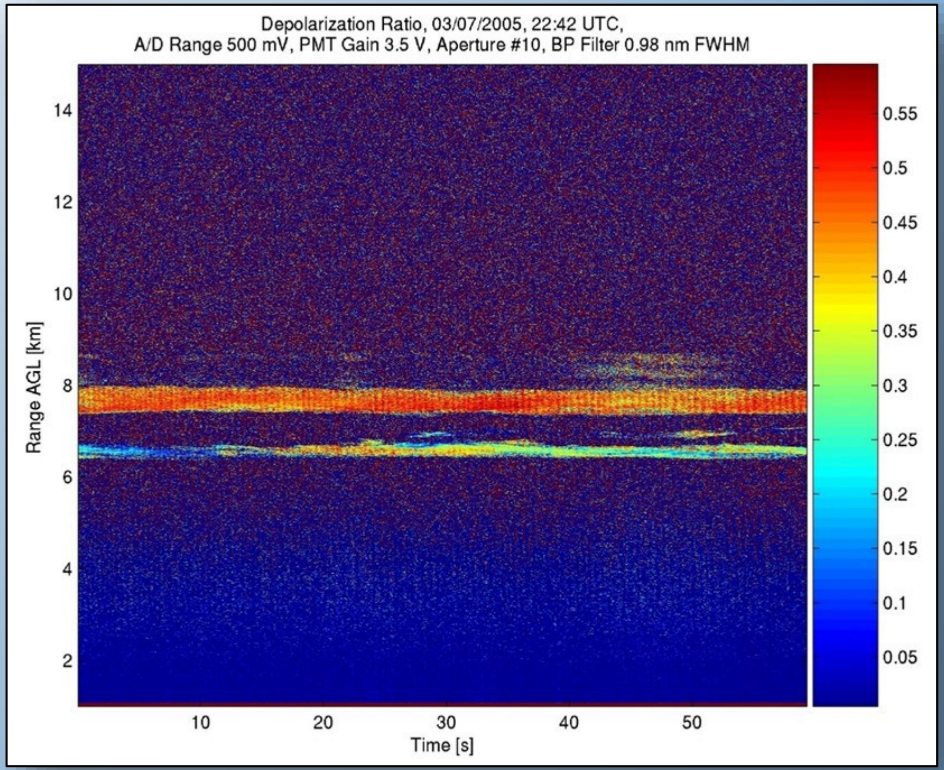
Director, Optical Technology
Center (OpTeC)

MONTANA STATE UNIVERSITY (BISTATIC) DUAL-POLARIZATION AEROSOL & CLOUD LIDAR

Dual-polarization direct-detection lidar for measuring clouds & aerosols

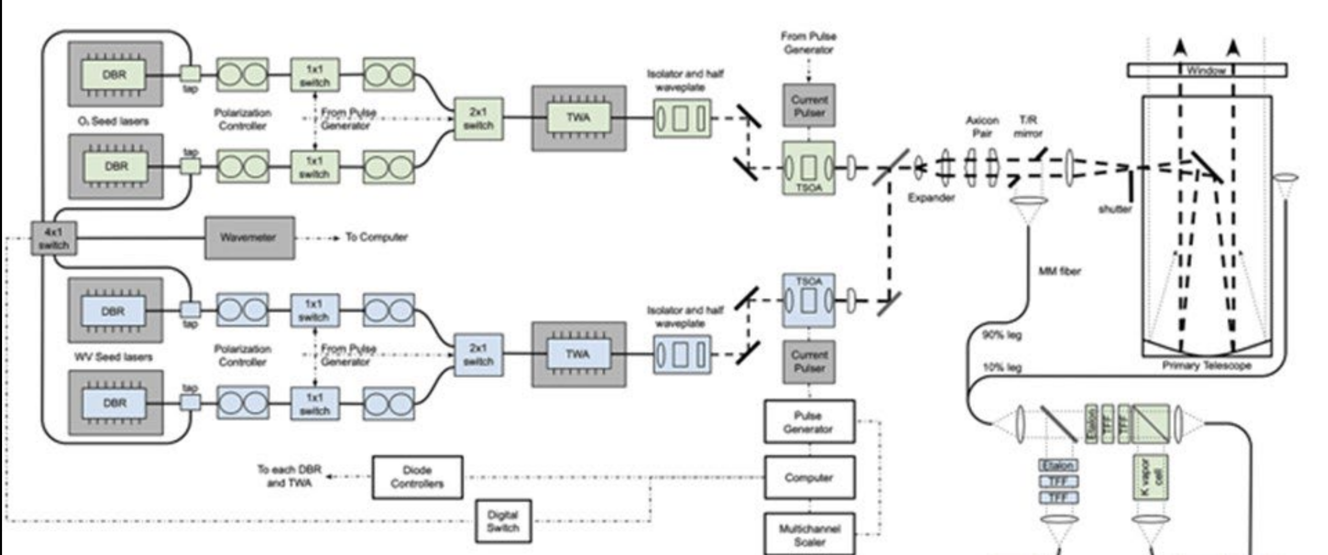


Cross-polarization ratio shows that both cloud layers contain ice



N. L. Seldomridge, J. A. Shaw, and K. S. Repasky, "Dual-polarization lidar using a liquid crystal variable retarder," Opt. Eng. 45(10), 106202–1-10 (2006).

MICRO-PULSE DIAL HIGH SPECTRAL RESOLUTION LIDAR



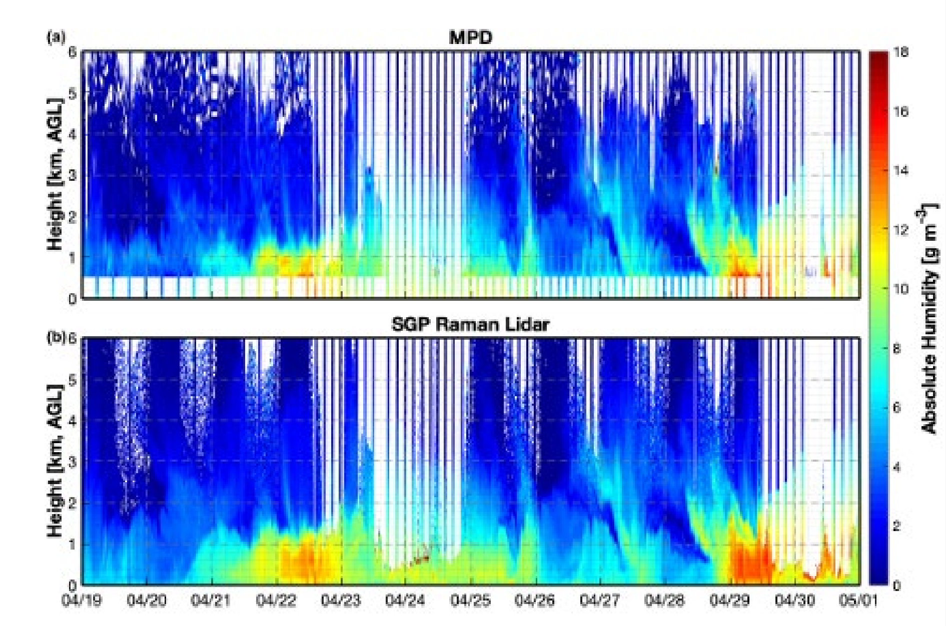
Gen5 MPD

Micropulse differential absorption lidar
Inventors: Scott M Spuler, Kevin S Repasky, Amin R Nehrir
Patent : US10605900B2 - 2020
NASA Langley Research Center, Montana State University, University Corp for Atmospheric Research UCAR

- Spuler, S., Hayman, M., Stillwell, R., Carnes, R., Bernasky, J., **Repasky, K.** (2021) MicroPulse DIAL (MPD)–a diode-laser-based lidar architecture for quantitative atmospheric profiling. *Atmopsheric Measurement Techniques*: v. 14 i. 6 p. 4593-4616
- Stillwell, R., Spuler, S., Haymann, M., **Repasky, K.**, Bunn, C. (2020) Demonstration of a combined differential absorption and high spectral resolution lidar for profiling atmospheric temperature. *Optics Express*: v. 6 i. 28 p. 71-93

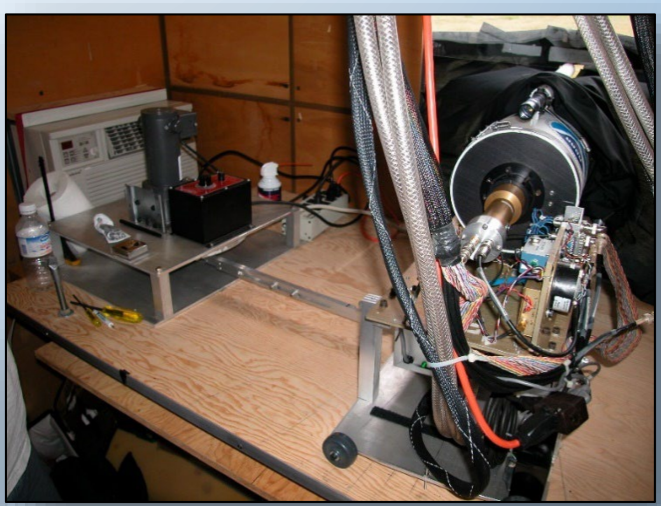
Dr. Kevin Repasky
Professor
Optical Remote Sensing,
Laser Development,
Nonlinear Optics

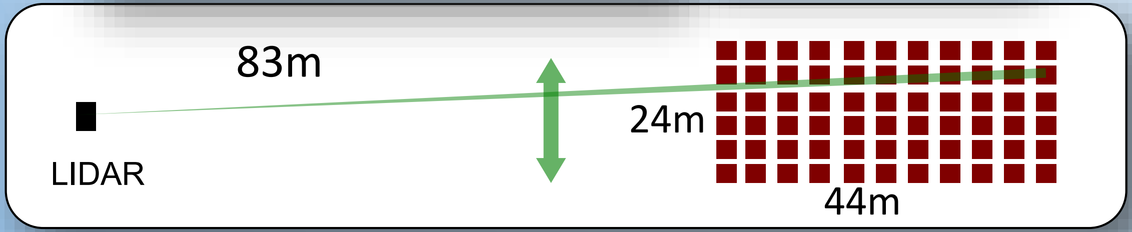
Micro-Pulse DIAL & Raman lidar water vapor data



LIDAR DETECTION OF HONEYBEES TO MAP LANDMINES

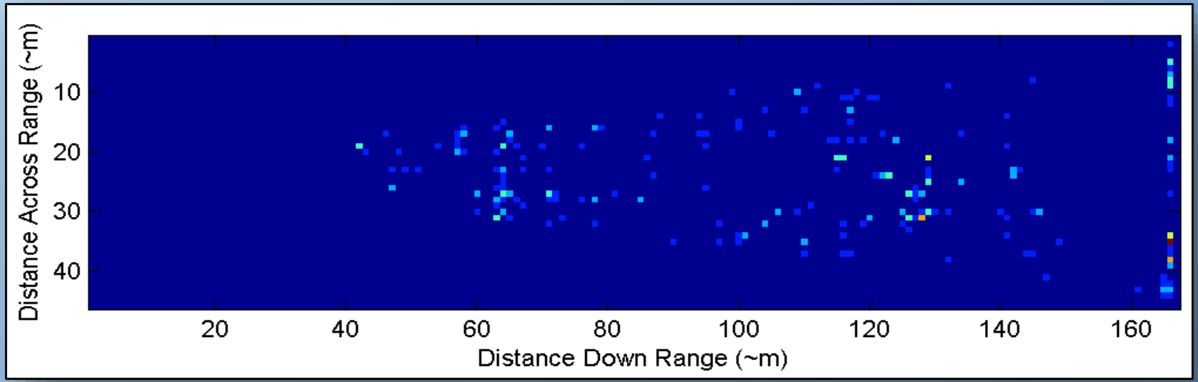
In a collaboration between Montana State University and the University of Montana, a scanning polarized lidar was used to measure the density of bees conditioned to locate explosives through smell. The resulting bee-density map indicated the location of buried land mines. The field test was conducted at Fort Leonard Wood, Missouri.





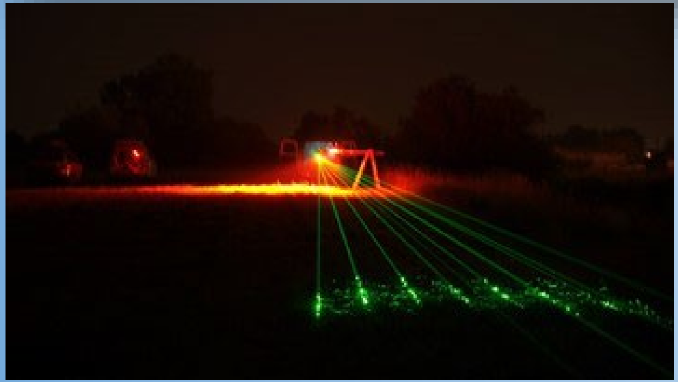
Layout of lidar scanning across minefield

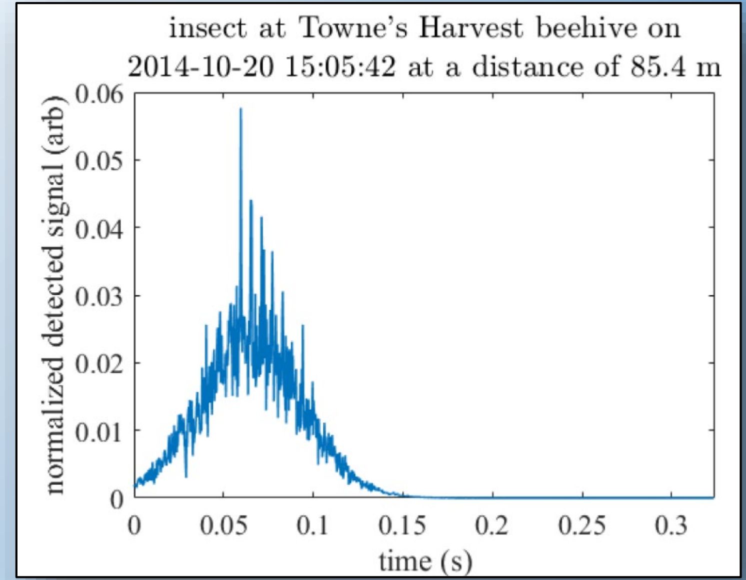
Bee density measured by lidar…



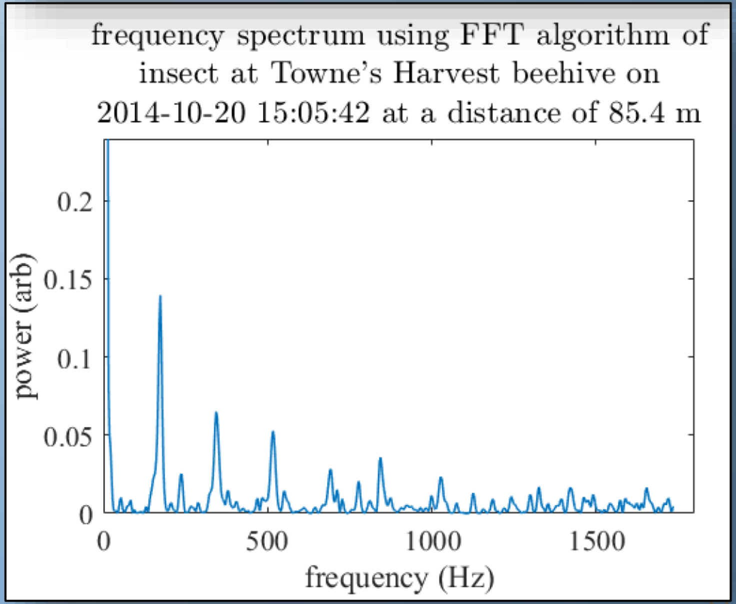
J. A. Shaw et al., "Polarization lidar measurements of honey bees in flight for locating land mines," Optics Express 13(15), 5853-5863 (2005).

WINGBEAT-MODULATION LIDAR SIGNAL FROM HONEYBEE AT 85 M





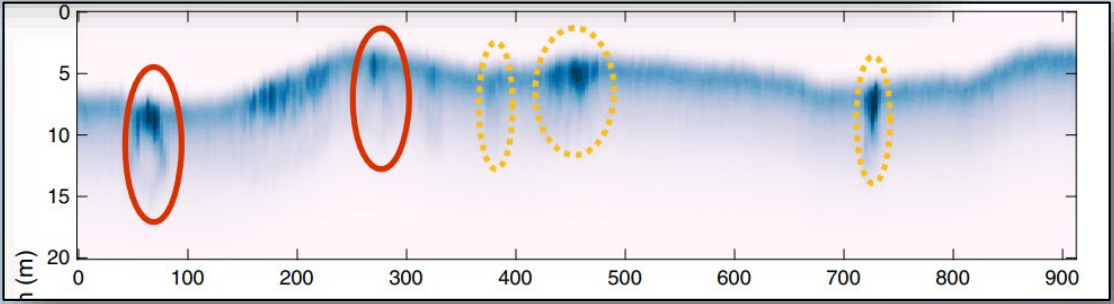
M. J. Tauc, K. M. Fristrup, K. S. Repasky, and J. A. Shaw, "Field demonstration of a wing-beat modulation lidar for 3D mapping of flying insects," OSA Continuum 2(2), 332-348 (2019).

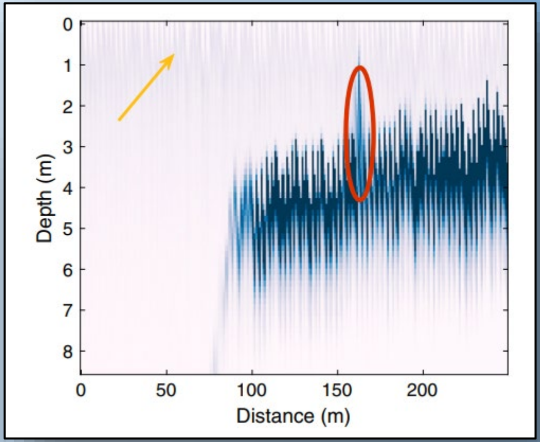


Optical detection of oscillating targets using modulation of scattered laser light
Inventors: Joseph Shaw, Kevin Repasky, John Carlsten, Lee Spangler
Patent : 7,511,624 B2 (2009)
Montana State University

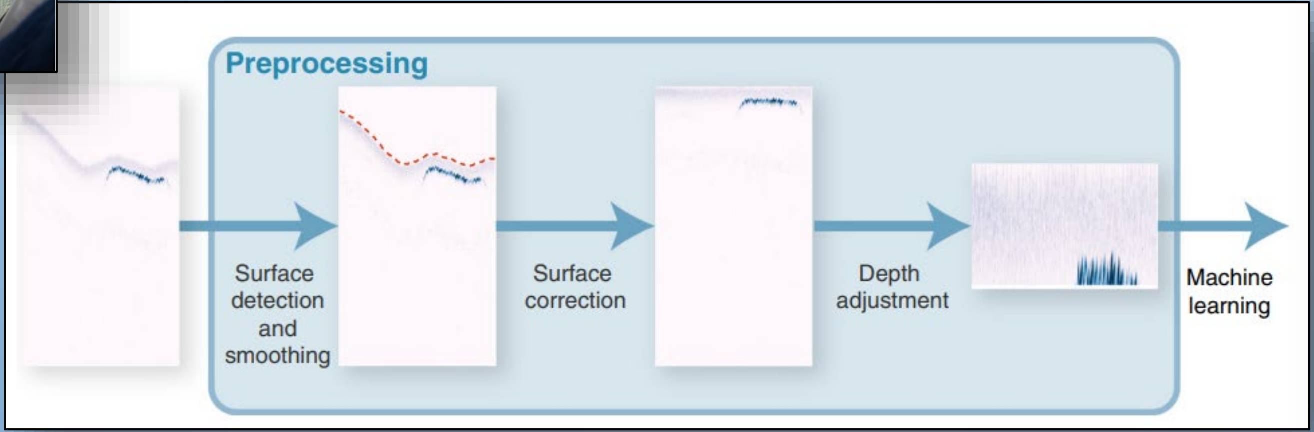
MACHINE LEARNING ALGORITHMS FOR FISH LIDAR

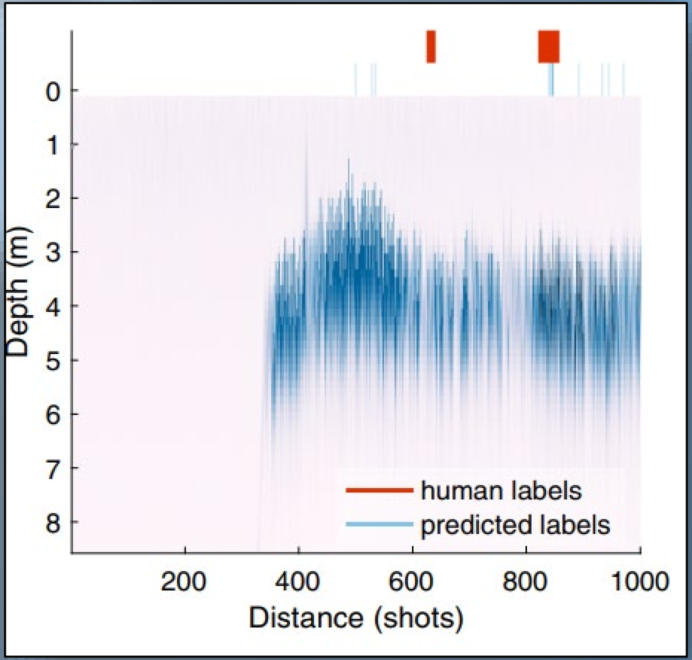
MSU laser technology could help Yellowstone battle invasive trout





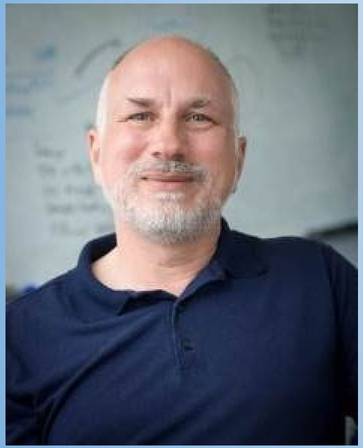
MSU's device was able to identify clusters of two or more lake trout to a depth of at least 26 feet



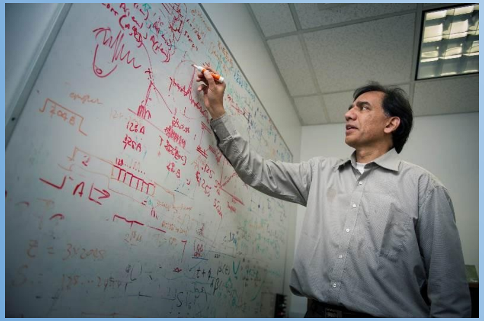


T. C. Vannoy, J. Belford, J. N. Aist, K. R. Rust, M. R. Roddewig, J. H. Churnside, J. A. Shaw, B. M. Whitaker, "Machine learning-based region of interest detection in airborne lidar fisheries surveys," J. Appl. Rem. Sens. 15(3), 038503 (2021).

COHERENT DIGITAL HOLOGRAPHY AND RANGE RESOLVED IMAGING



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



Dr. Krishna Rupavatharam
Associate Director, Spectrum Lab
Montana State University

Recent Spectrum Lab Projects

- **Coherent Lidar/Ladar and Imaging**
  - Stable, Linearized Optical Chirps
  - Range-Resolved Digital Holographic Imaging
  - Polarimetric Digital Holography
  - Imaging through Turbulence and Fog

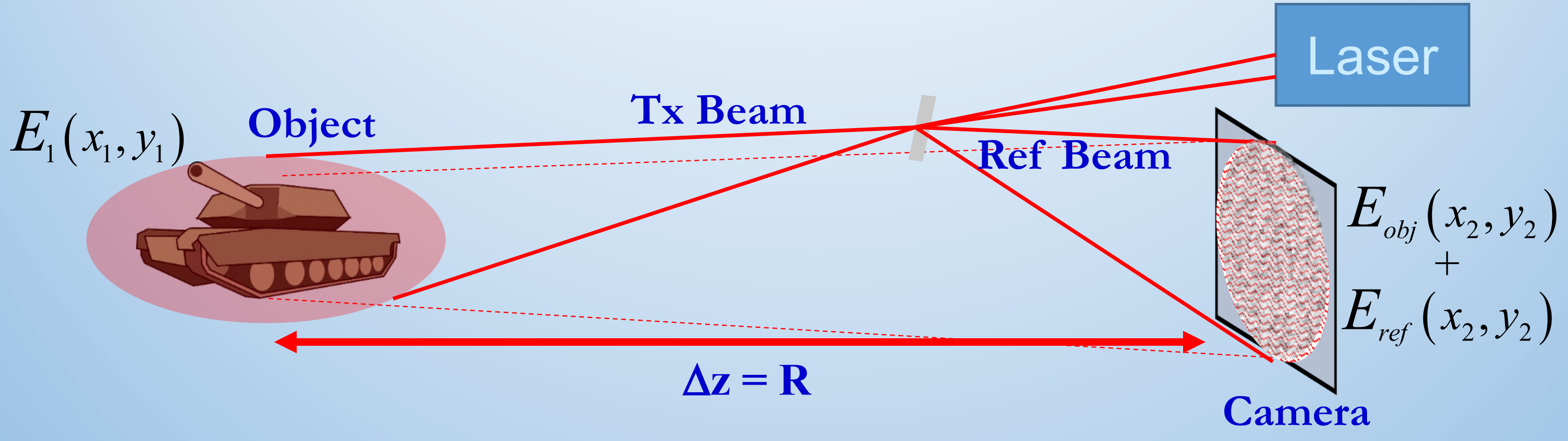
- **Quantum Networks**
  - Quantum information transfer in free space and fiber networks
  - Materials for quantum memories and sources

- **Spatial-Spectral Holographic Microwave Signal Processors**
  - ➢ Microwave Photonics
    - Extremely broadband, high resolution spectrum monitoring and geolocation
      - 0-110 GHZ, 40 GHz IBW, sub-MHz resolution, >1 KHz frame rates, >60 dB SFDR
    - Broadband, high SFDR analog photonics links
  - Real-Time High Bandwidth Correlator
    - Broadband “noise” radar and geolocation

DIGITAL HOLOGRAPHY: PUPIL PLANE RECORDING (LENLESS)

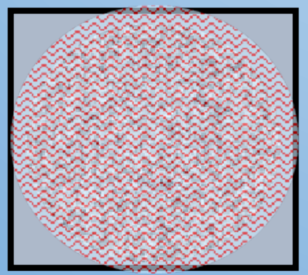
Object field after propagation from Object plane to Camera plane without lens

$$E_{obj}(x_2,y_2)=\frac{ke^{ikR}}{i2\pi R}\exp\left(\frac{ik(x_2^2+y_2^2)}{2R}\right)\iint dx_1dy_1\left(E_1(x_1,y_1)\exp\left(\frac{ik(x_1^2+y_1^2)}{2R}\right)\right)\exp(ik_xx_1+ik_yy_1)$$

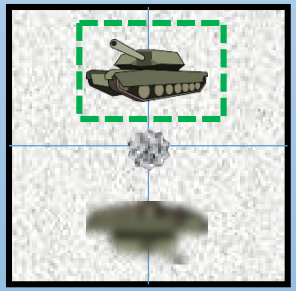


$$I(x_2,y_2)\ \propto\ E_{obj}(x_2,y_2)\,E_{ref}^{*}\,e^{i\vec{k}_r\cdot\vec{r}_2}+\text{c.c.}+I_{obj}(x_2,y_2)+I_{ref}(x_2,y_2)$$

Captured Intensity Pattern



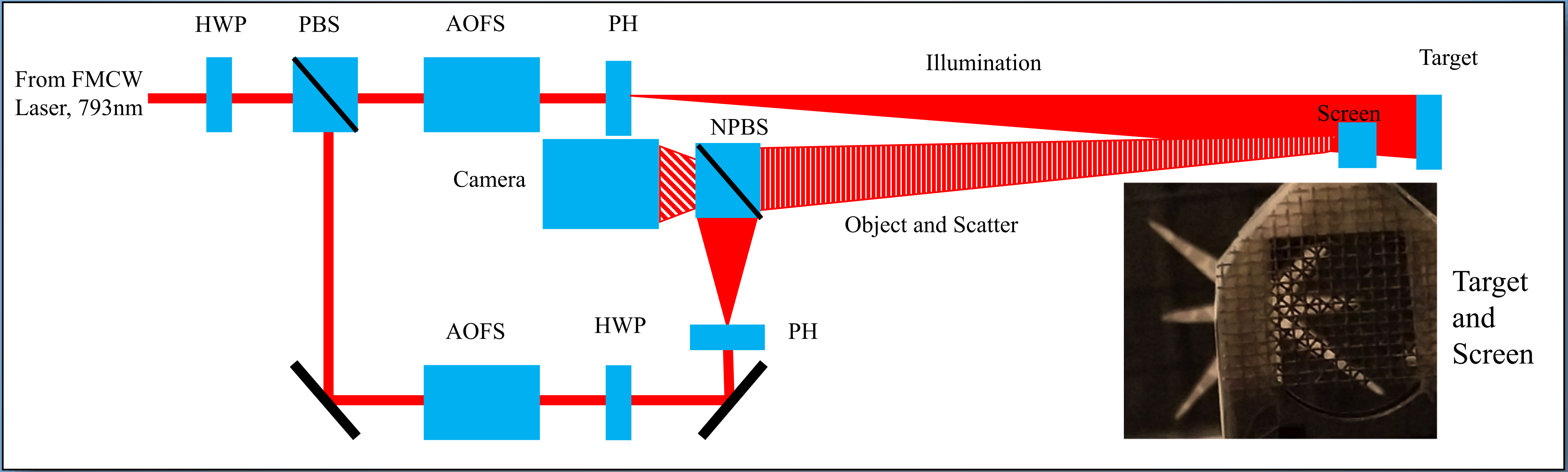
Multiply by inverse phase factor (x_2,y_2) and FFT



{Mask} and {multiply by inverse phase factor (x_1,y_1) }

Complex valued E_{obj}(x’,y’)

RANGE SELECTIVE FMCW DIGITAL HOLOGRAPHY



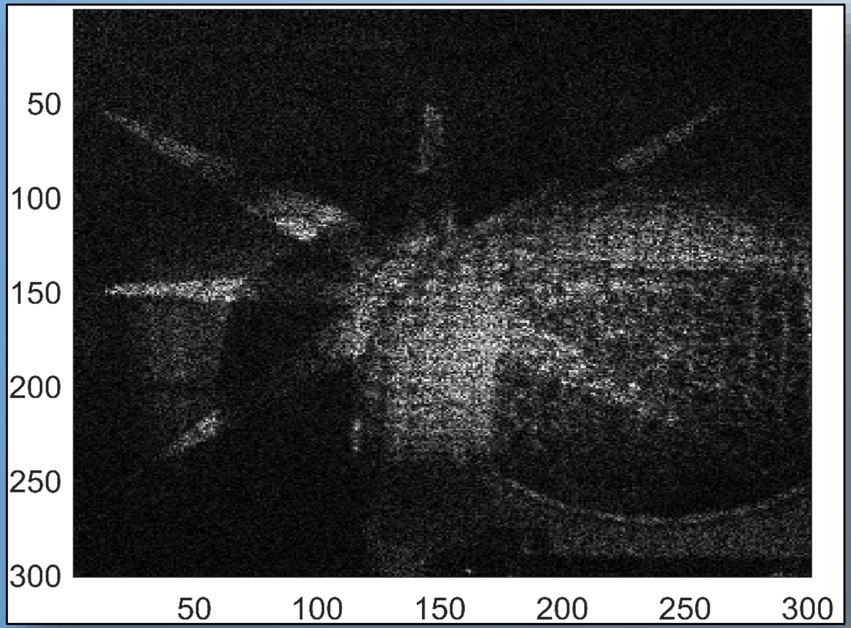
Acousto-optic frequency shifters(AOFS) in both transmit and reference paths create frequency shifted LO to cancel out range frequency shift of selected target produces a spatial hologram on camera

- AOFS in transmit path was fixed at 200MHz
- AOFS in reference path driven by frequency synthesizer capable of 0.01Hz precision
- Sensor array integration time (12ms)
- Reference clocks between frequency synthesizers were locked

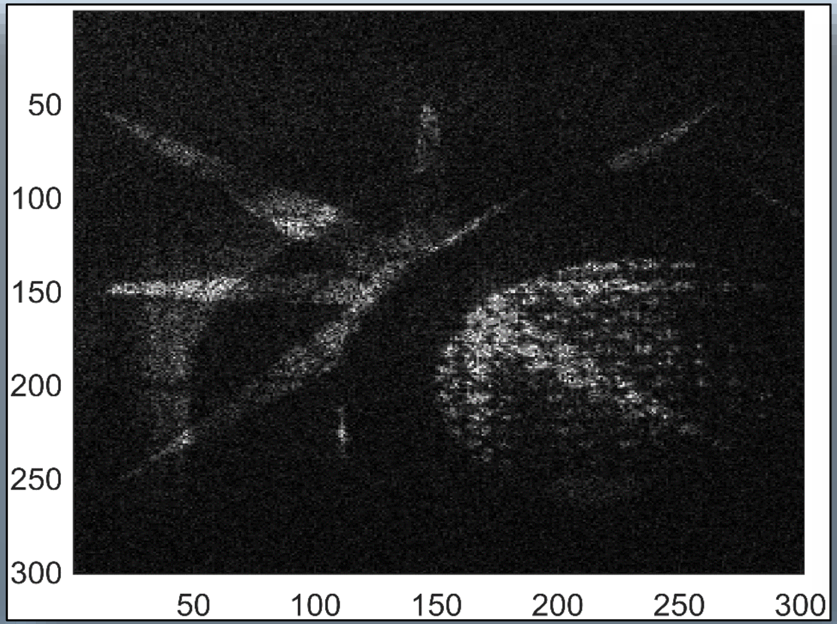
Matthew A. Goodman, R. Krishna Mohan, and Wm. Randall Babbitt, "Range selective digital holographic imaging using FMCW lidar," Appl. Opt. 61, B255-B261 (2022)

RANGE SELECTIVE FMCW DIGITAL HOLOGRAPHY

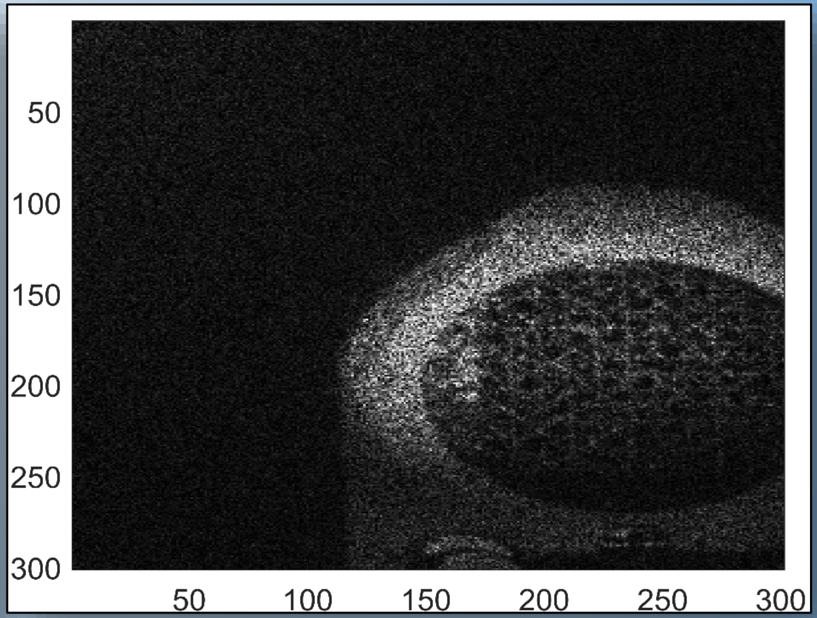
- FMCW range resolution of 2.1cm allows for system to be tuned to selectively reconstruct image from target or obstructor, which are 12.5cm apart.
  - Mesh screen on empty lens mount
  - 12.5cm in front of target



Reconstructed image using conventional CW DH



Reconstructed image using FMCW DH tuned to location of target

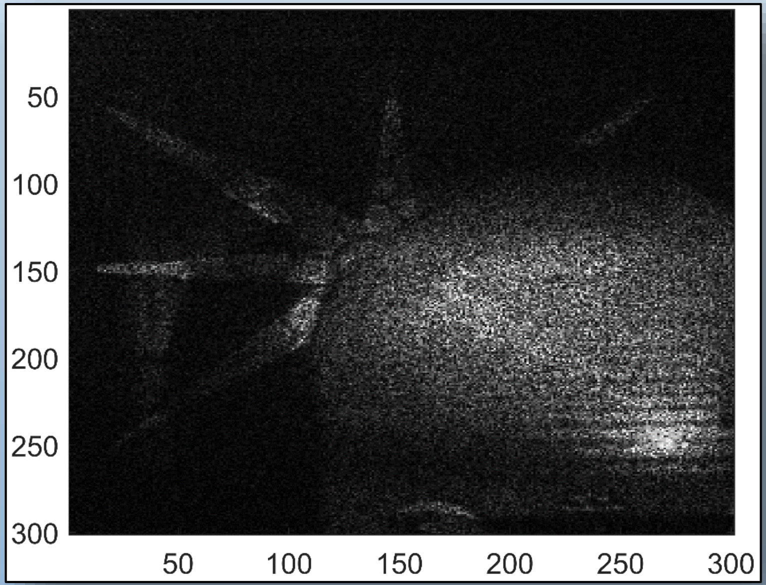


Reconstructed image using FMCW DH tuned to location of mesh screen

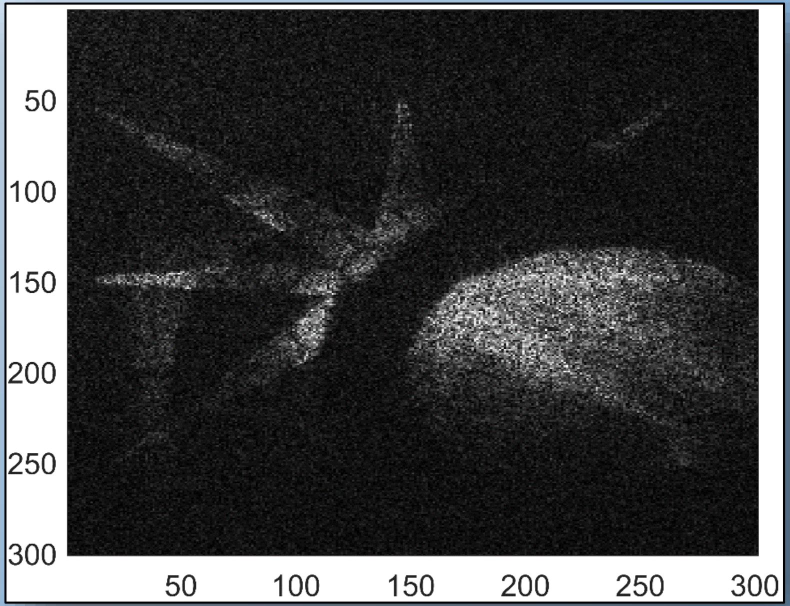
FREQUENCY SELECTIVITY TO ENHANCE IMAGING THROUGH SCATTERERS

- FMCW range resolution enables system to see through scatters
- Scatterer
  - Microscope slide sprayed with white spray paint
  - Placed 12.5cm in front of target

Picture of target and scatterer



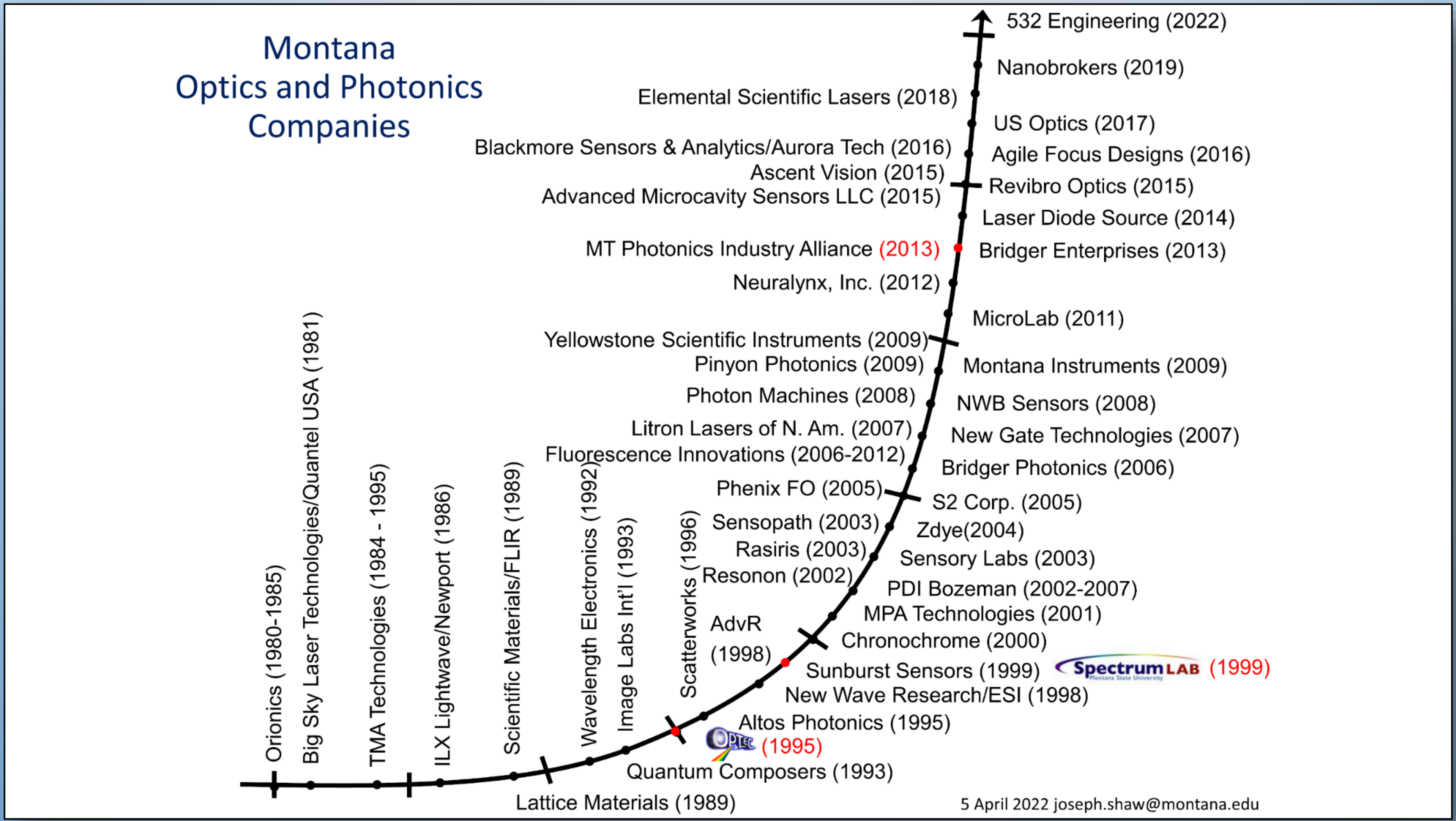
Reconstructed image using conventional CW DH



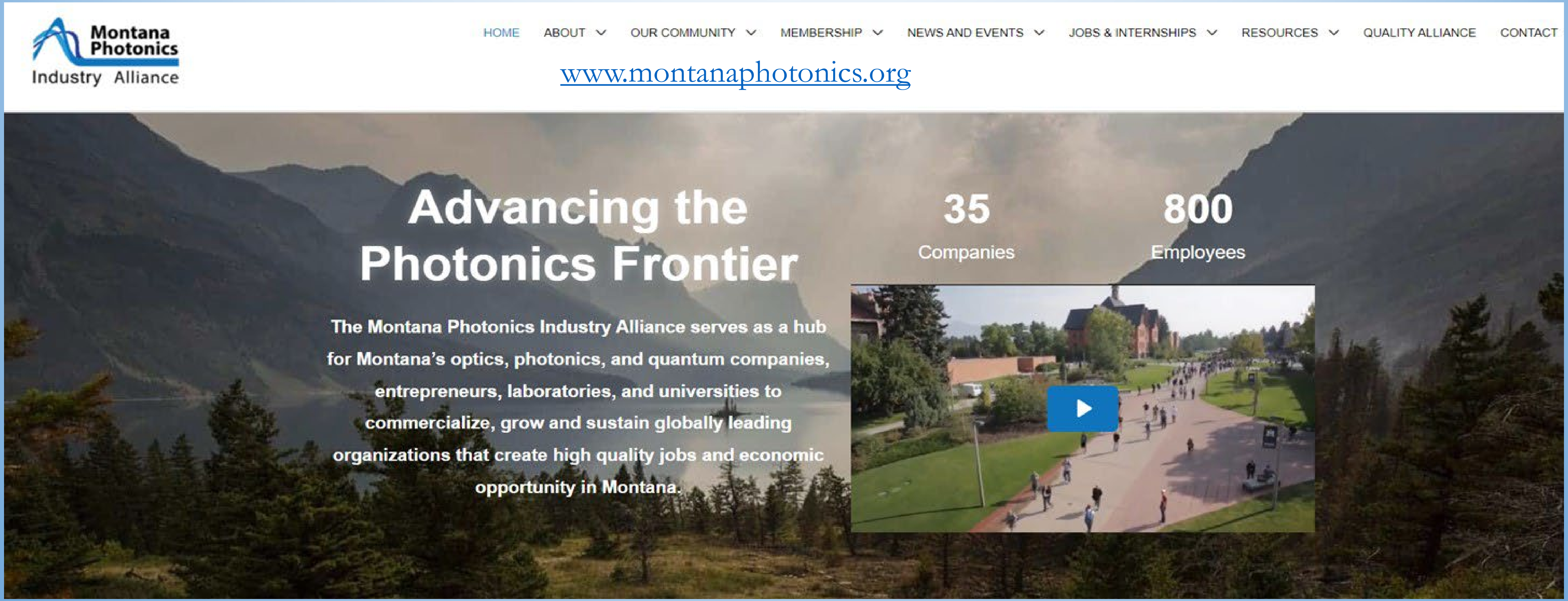
Reconstructed image using FMCW DH

Growth of Optics and Photonics Companies in Montana

Montana Optics and Photonics Companies



MONTANA PHOTONICS INDUSTRY ALLIANCE (MPIA)



- MSU helped found the MPIA
- MSU faculty and staff serve on the MPIA Board of Directors
- MSU and MPIA collaborate continuously to grow and sustain relationships in Montana and world-wide