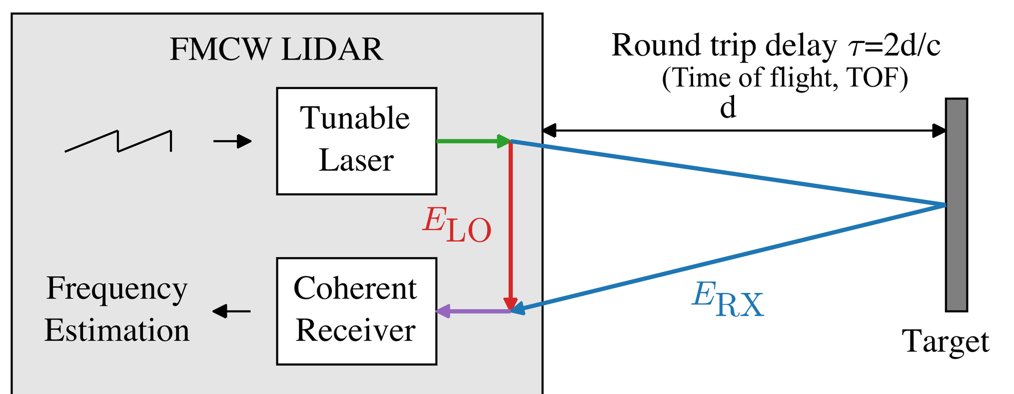
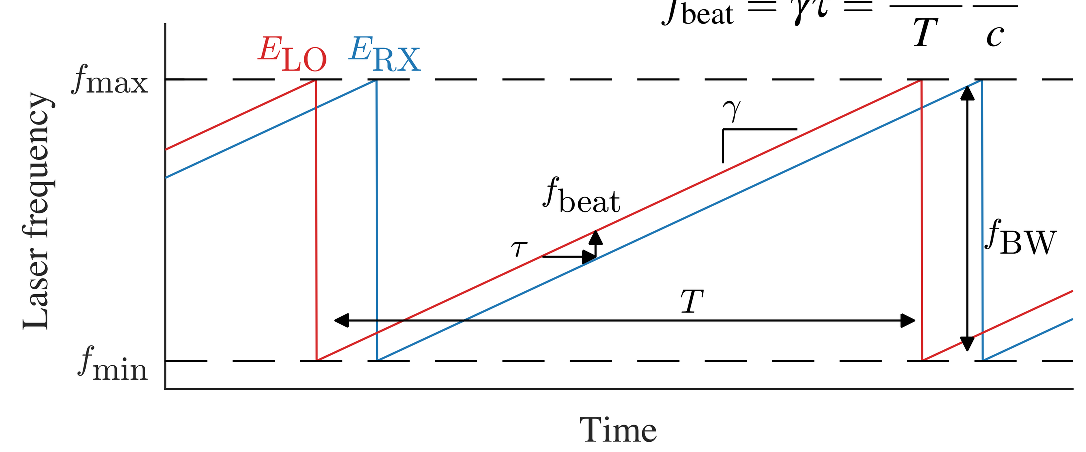
Optimal Spectrum Estimation and System Trade-Off in Long-Distance Frequency-Modulated Continuous-Wave LIDAR

Taehwan Kim, Pavan Bhargava, Vladimir Stojanović, University of California, Berkeley

FMCW LIDAR CONCEPT



$$f_{\text{beat}} = \gamma\tau = \frac{f_{\text{BW}}}{T}\frac{2d}{c}$$



- Modulate laser wavelength with certain pattern (e.g. sawtooth) and measure the beating tone frequency (proportional to TOF)
- For given receiver bandwidth, much higher ranging precision compared to pulsed LIDAR
- Coherent RX achieves shot-noise limited detection without avalanche photodiodes
- Interference (ambient & other sensors) rejection

COHERENT DISTANCE BARRIER IN LONG-DISTANCE FMCW LIDAR

- Since FMCW LIDAR encodes distance information in the phase domain, spectral purity of the laser (i.e. phase noise) affects the ranging precision, and *it gets worse for larger target distance*
- Linewidth: metric for laser phase noise
  - For given linewidth Δv, PSD of the spontaneous-emission dominated laser frequency noise:

$$S_{\dot{\phi}_n}(\omega) = \Delta\omega = 2\pi\Delta v$$

- Phase noise in the photocurrent signal at the coherent receiver (whose frequency is f_{beat})

$$\phi_{n,\text{photocurrent}}(t) = \phi_{n,\text{LO}}(t) - \phi_{n,\text{RX}}(t) = \phi_n(t) - \phi_n(t-\tau)$$

- Corresponding PSD of the photocurrent signal

$$S_i(\omega) = S_i^{\circ}(\omega - 2\pi f_{\text{beat}}) + S_i^{\circ}(\omega + 2\pi f_{\text{beat}}) + qP_{\text{LO}}R_{\text{PD}}$$

$$S_i^{\circ}(\omega) = R_{\text{PD}}^2 P_{\text{RX}} P_{\text{LO}} \left[T\,\text{sinc}^2\left(\frac{T\omega}{2}\right) e^{-\Delta\omega\tau} + \frac{2/\Delta\omega}{1+\left(\frac{\omega}{\Delta\omega}\right)^2}\cdot\left\{1 - e^{-\Delta\omega\tau}\left[\cos(\omega\tau) + \frac{\Delta\omega}{\omega}\sin(\omega\tau)\right]\right\}\right]$$

Beating tone

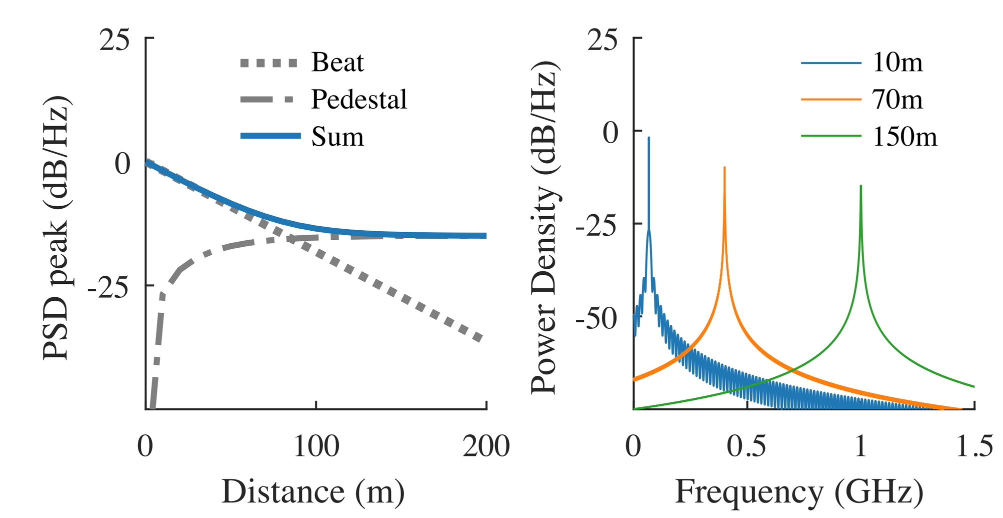
Noise pedestal from phase noise

- Coherent distance: crossing point between first and second term

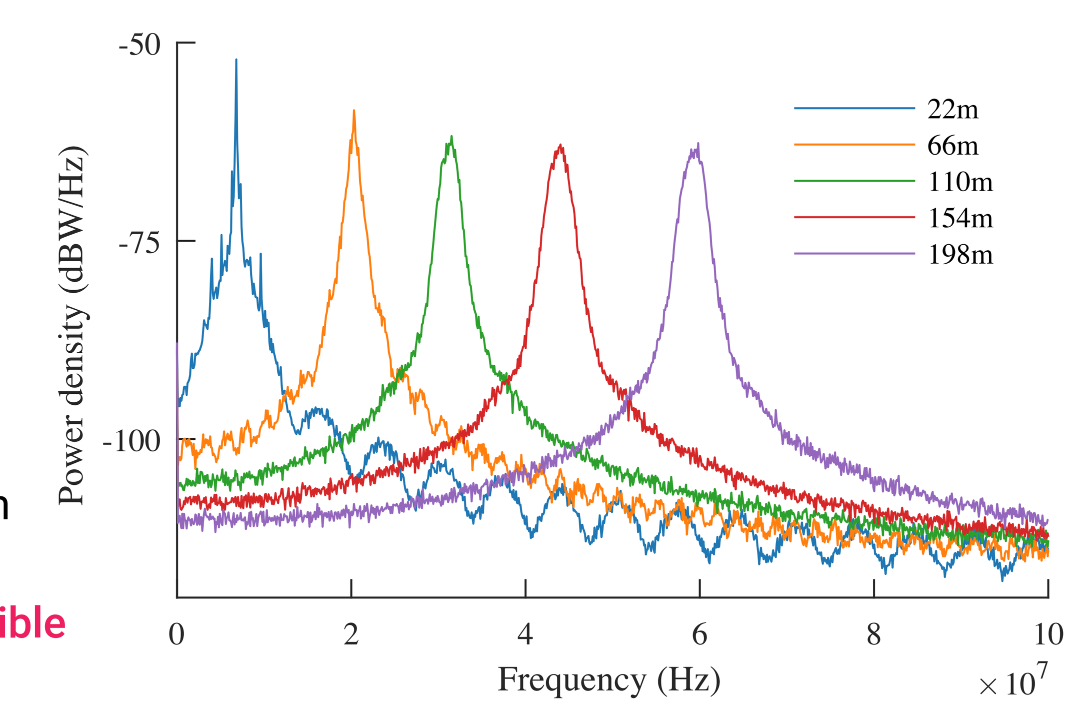
$$d_c = \frac{c}{2\Delta\omega}\ln\left(\frac{\Delta\omega T}{2}\right)$$

Has been thought detection is impossible beyond d_c

Analytical PSD (T=10μs, Δv=1MHz)

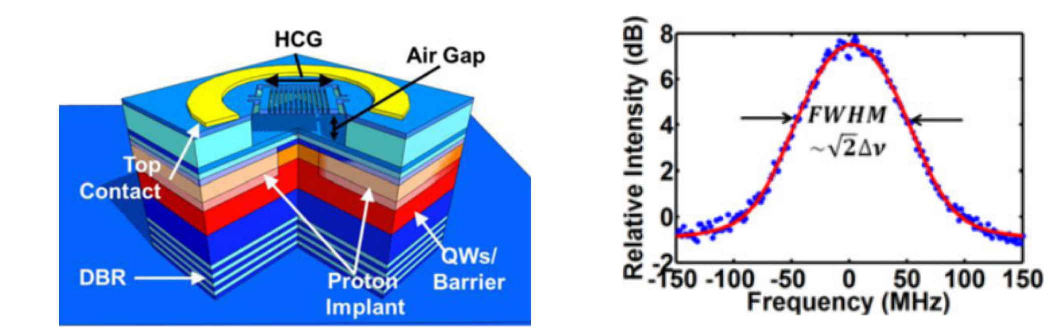


Experimental PSD Using Commercial DFB Laser

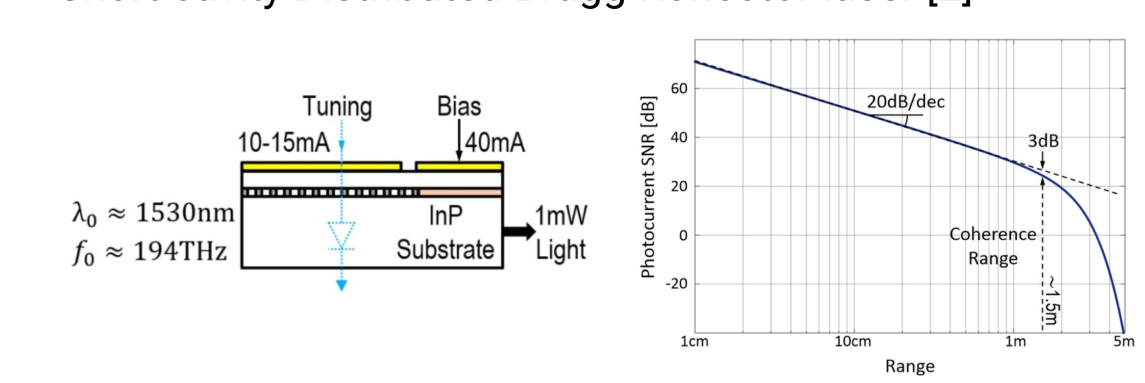


TUNABLE LASERS FOR FMCW LIDAR

- Desired features
  - Wide, fast, continuous wavelength tuning
  - Compact, cost-efficient implementation
  - Emission power decoupled from wavelength
- Existing solutions
  - MEMS mirror + VCSEL [1]



  - Short-cavity Distributed Bragg Reflector laser [2]



- Common issue: poor phase noise performance ($\Delta v \gg$1MHz)

[1] Rao et al., JSTQE 2013 [2] Aritomo et al., JLT 2006

PROPOSED ALGORITHM

- FMCW LIDAR detection in incoherent regime = line spectral estimation with random phase offset

$$y(t) = \sum_{i=1}^{N} a_i \sin(2\pi f_i t + \phi_n(t)) + n(t),\ \text{estimate } f_i$$

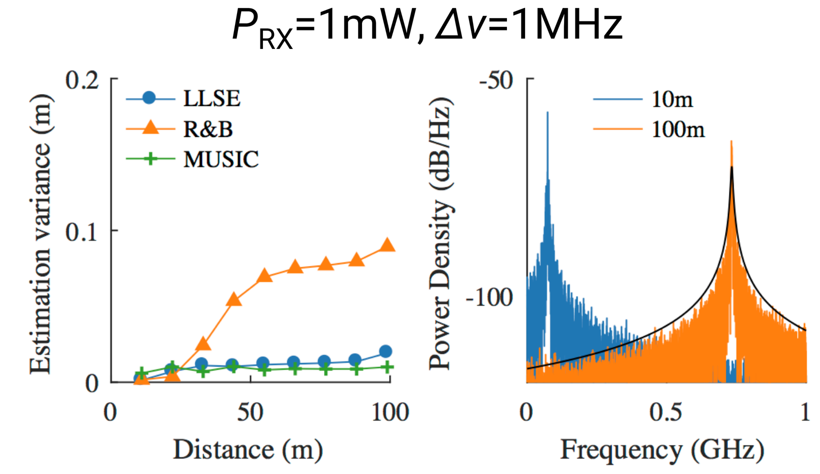
  - Traditional parametric/non-parametric spectral estimation algorithms (e.g. periodogram, MUSIC) become sub-optimal in presence of significant phase noise
- Key idea
  - The signal is highly sparse in the spectral domain, as the reflection is mostly coming from the surface of the target
  - Spectral line shape can be pre-characterized (e.g. Lorentzian)
  - Flat noise floor from the shot-noise can also be characterized
  - Then, we can do Bayesian spectral estimation using experimental line shape & noise floor level as our prior!
- Algorithm
  - Signal model for SSB PSD of incoherent FMCW measurement with Lorentzian line shape

$$\tilde{S}(\omega;\alpha,\omega_{\text{beat}}) = \sum_{i=1}^{n}\frac{\alpha_i\Delta\omega}{(\omega-\omega_{\text{beat},i})^2+\Delta\omega^2} + 2qR_{\text{PD}}P_{\text{LO}}$$

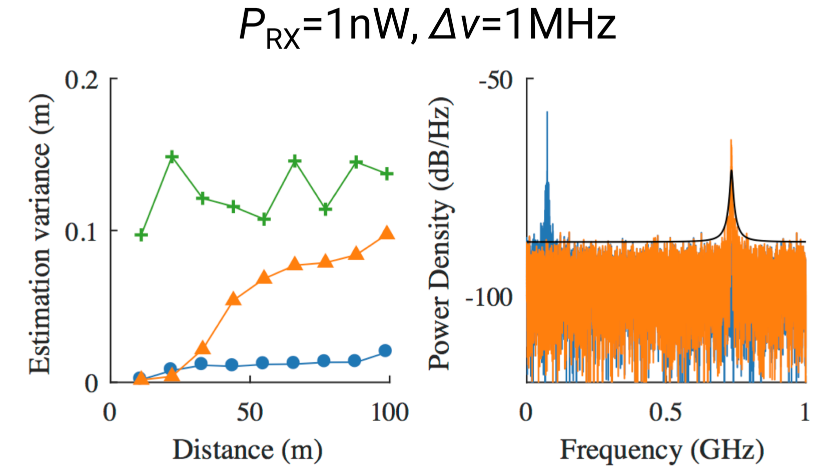
  - Simple least squares to estimate the beating frequency

$$\alpha^*, \omega_{\text{beat}}{}^* = \underset{\alpha,\omega_{\text{beat}}}{\arg\min}\left|S(\omega) - \tilde{S}(\omega;\alpha,\omega_{\text{beat}})\right|^2$$

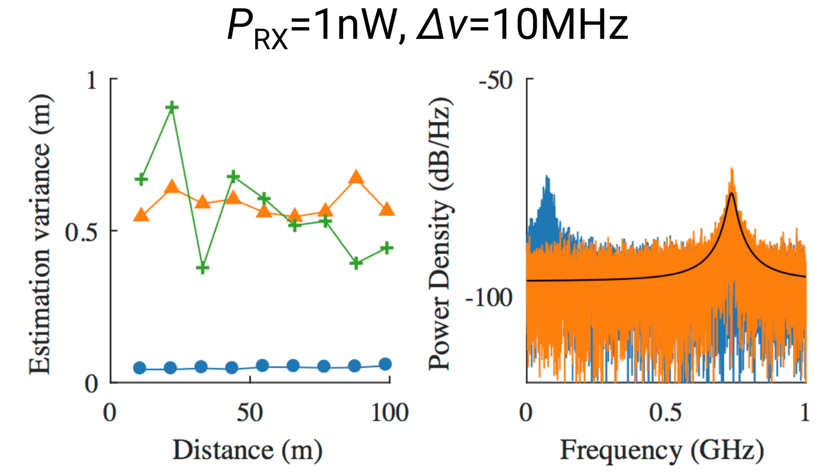
P_{RX}=1mW, Δv=1MHz



P_{RX}=1nW, Δv=1MHz



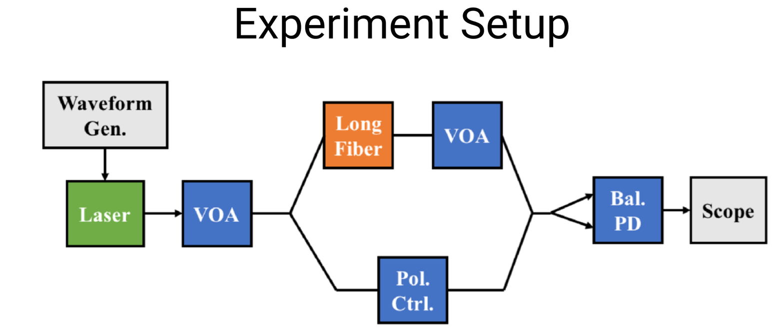
P_{RX}=1nW, Δv=10MHz



Lineshape can be experimentally characterized!
(might differ from Lorentzian)
Better performance possible using more flexible model (e.g. c-spline)

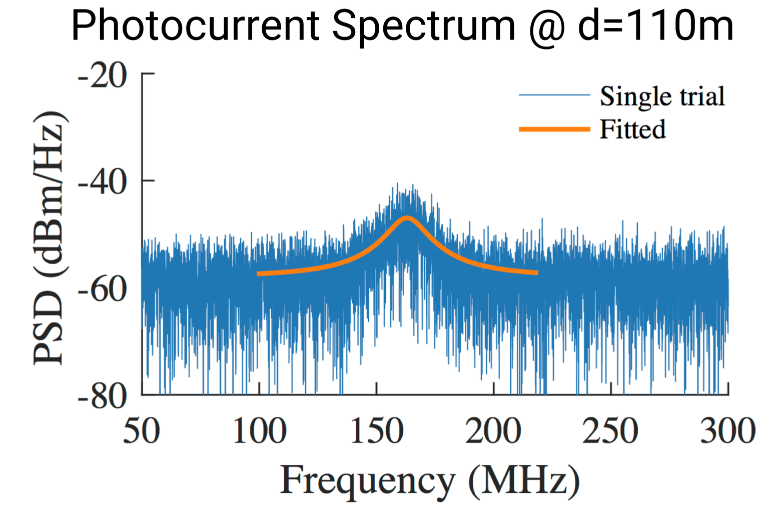
EXPERIMENTAL RESULTS

Experiment Setup

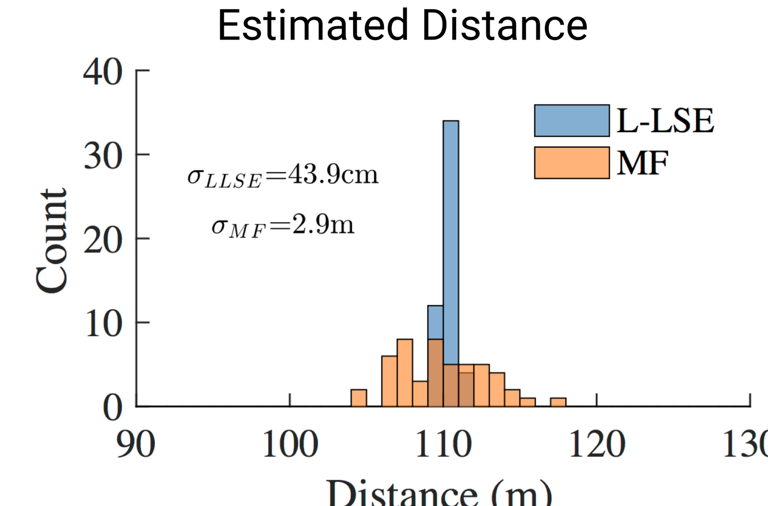


Fiber length = 2×(target distance)/(fiber group index)

Photocurrent Spectrum @ d=110m



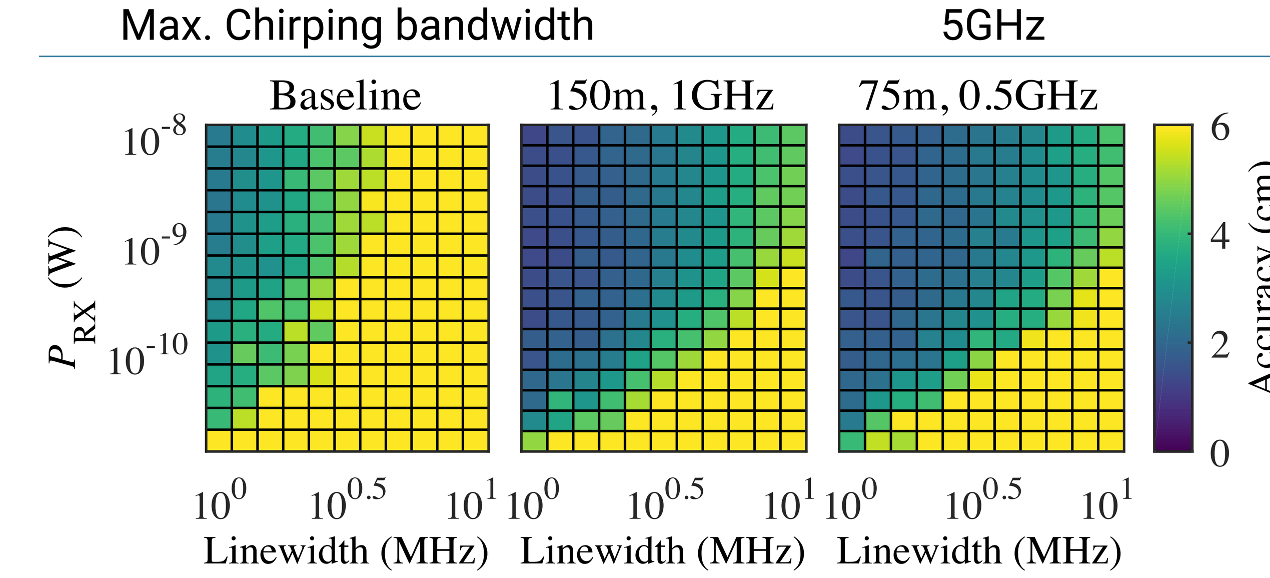
Estimated Distance



SYSTEM LEVEL IMPLICATION

Baseline System Specification

Ranging accuracy	<5cm
Scanning time	10μs
Frequency estimation	Lorentzian LSE
Photodetector responsivity	1A/W
Receiver bandwidth	500MHz
Detection range	150m
Max. Chirping bandwidth	5GHz



- Example: P_{RX} =8mW, aperture=60mm, 80% isotropic reflector @ 150m → P_{RX} =0.5nW
- For Δv~1MHz, detection is impossible regardless of P_{RX}
- The range can be extended by increasing receiver bandwidth
- Spectral estimation algorithm should also be included for system level study

ICASSP 2018, April 18