Frequency-Comb Based Approaches to Precision Ranging Laser Radar

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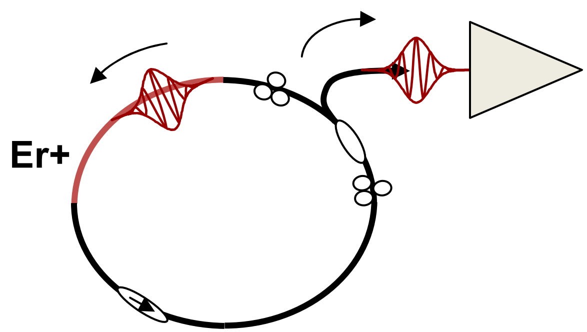
Outline

- **Introduction: Combs**
- **Combs for ranging**
- **Dual Comb ranging**
  - **Initial phase-locked system: nm-level precision**
  - **Simplified free-running system: sub-μm precision in < 1 ms**
- **Comb-assisted coherent FMCW ranging Ladar**
  - **Tracking a fast swept laser**
  - **Preliminary results**
- **Conclusion**

Frequency Comb

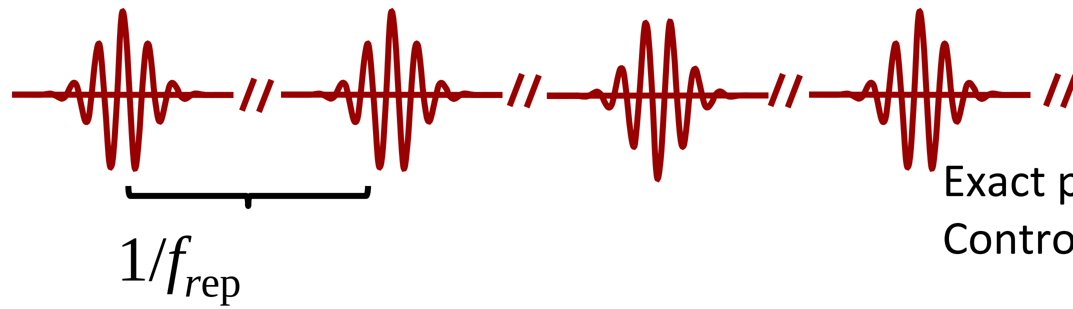
Coherent, stabilized femtosecond, mode-locked lasers

2005 Nobel prize to J. Hall & T. Hänsch



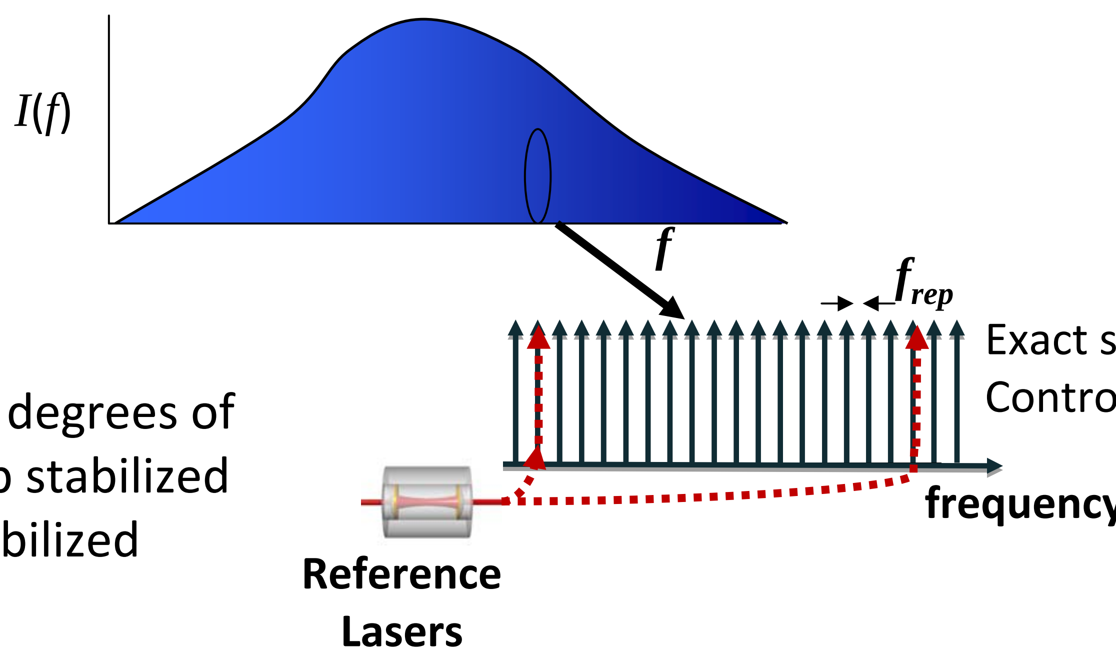
Femtosecond Passively modelocked Laser

Pulse Train



Exact period
Controlled phase

Frequency Comb (Spectrum)

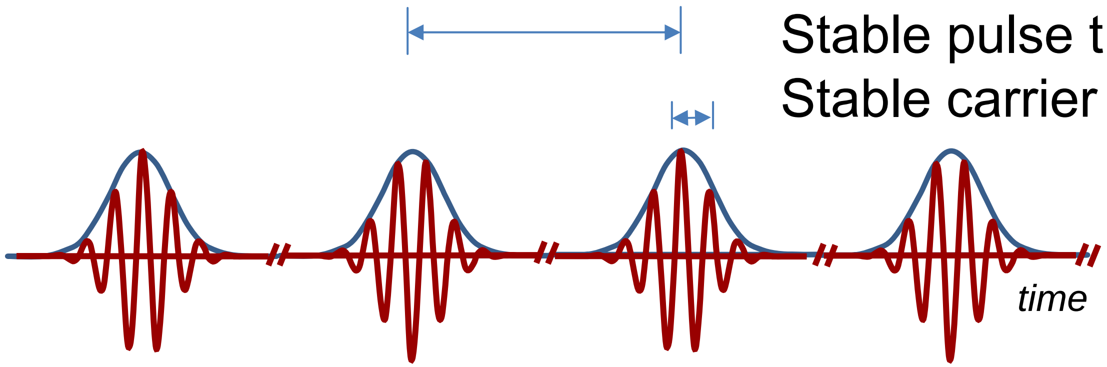


Exact spacing
Controlled offset

Stabilization of any two degrees of freedom → Entire comb stabilized → Entire pulse train stabilized

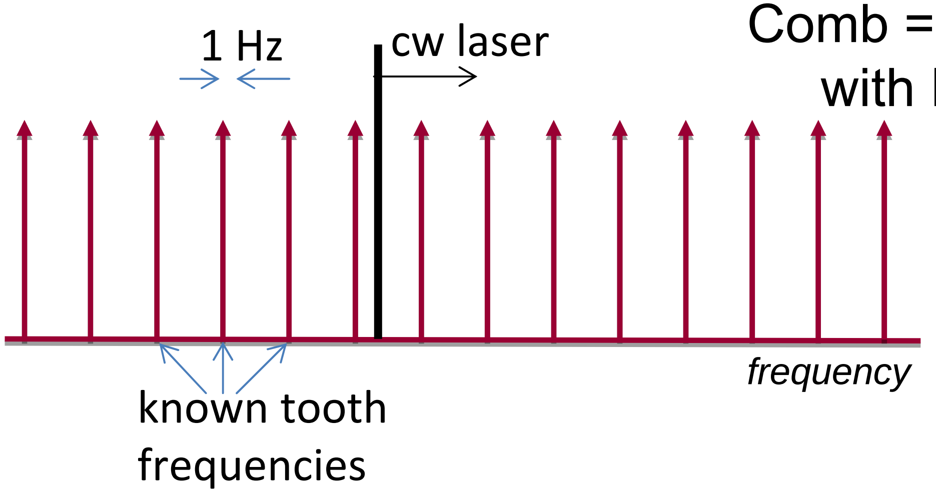
Properties of Combs For Ranging

Time-domain



Stable pulse timing → time-of-flight
Stable carrier frequency→ interferometry

Frequency-domain



Comb = thousands to millions of "cw lasers" with Hz-linewidths and known frequencies

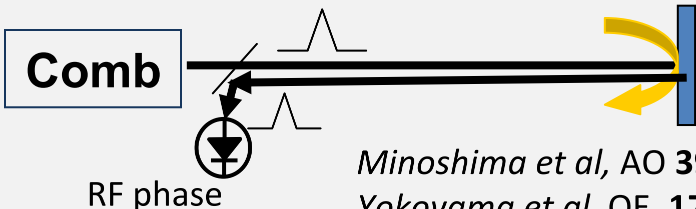
→ Multi-wavelength interferometry

→ Calibration of fixed/swept lasers

Different Comb-Based Ranging Systems

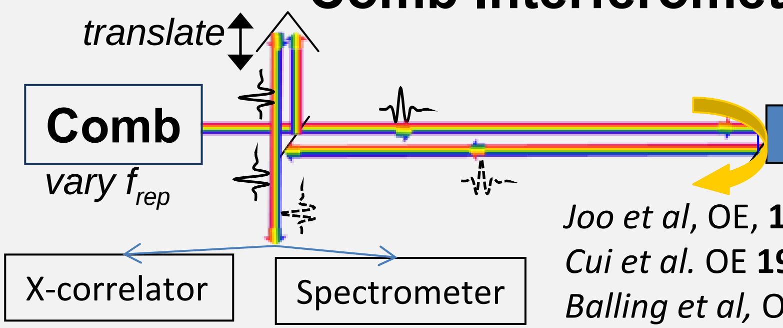
"Direct" Comb Ranging

Modulated waveform



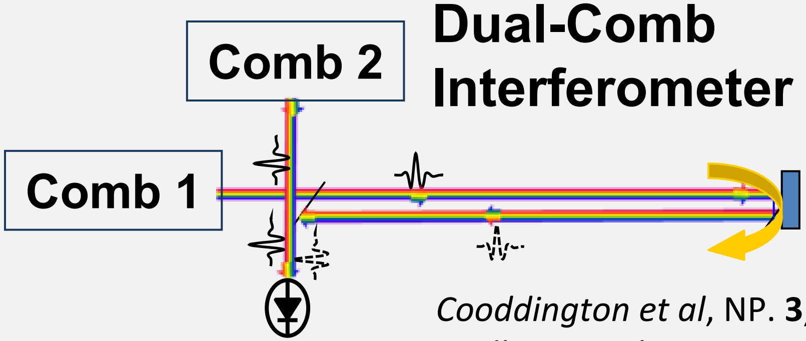
Minoshima et al, AO **39**, 5512 (2000)
Yokoyama et al, OE, **17**, 17324 (2009).

Comb Interferometer



Joo et al, OE, **14**, 5954 (2006)
Cui et al. OE **19**, 6549 (2011)
Balling et al, OE **17**, 9300 (2009)
Lee et al, NP **4**, 716 (2010).

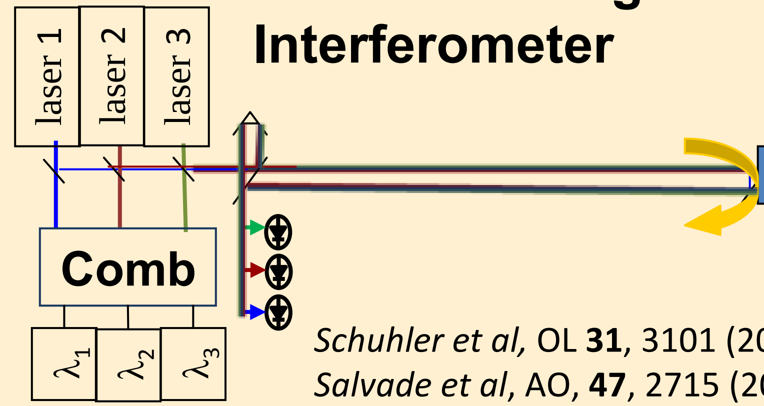
Dual-Comb Interferometer



Cooddington et al, NP. **3**, 351 (2009).
Godbout et al, OE **18**, 15981 (2010).

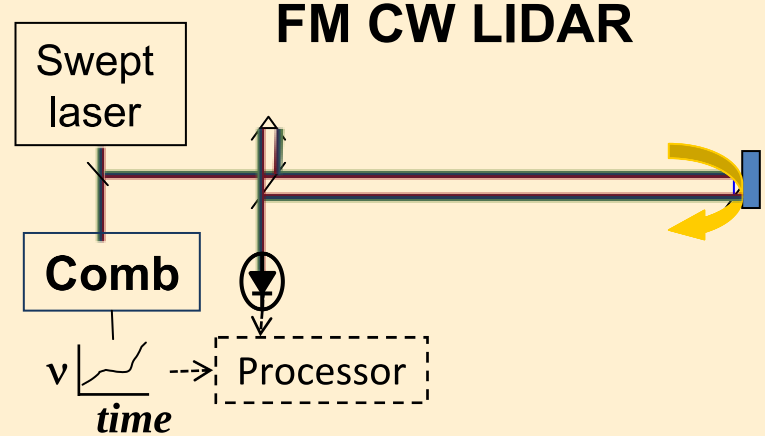
Comb-Assisted Ranging

Multi-Wavelength Interferometer



Schuhler et al, OL **31**, 3101 (2006)
Salvade et al, AO, **47**, 2715 (2008)
Joo et al, OE **16**, 19799 (2008).

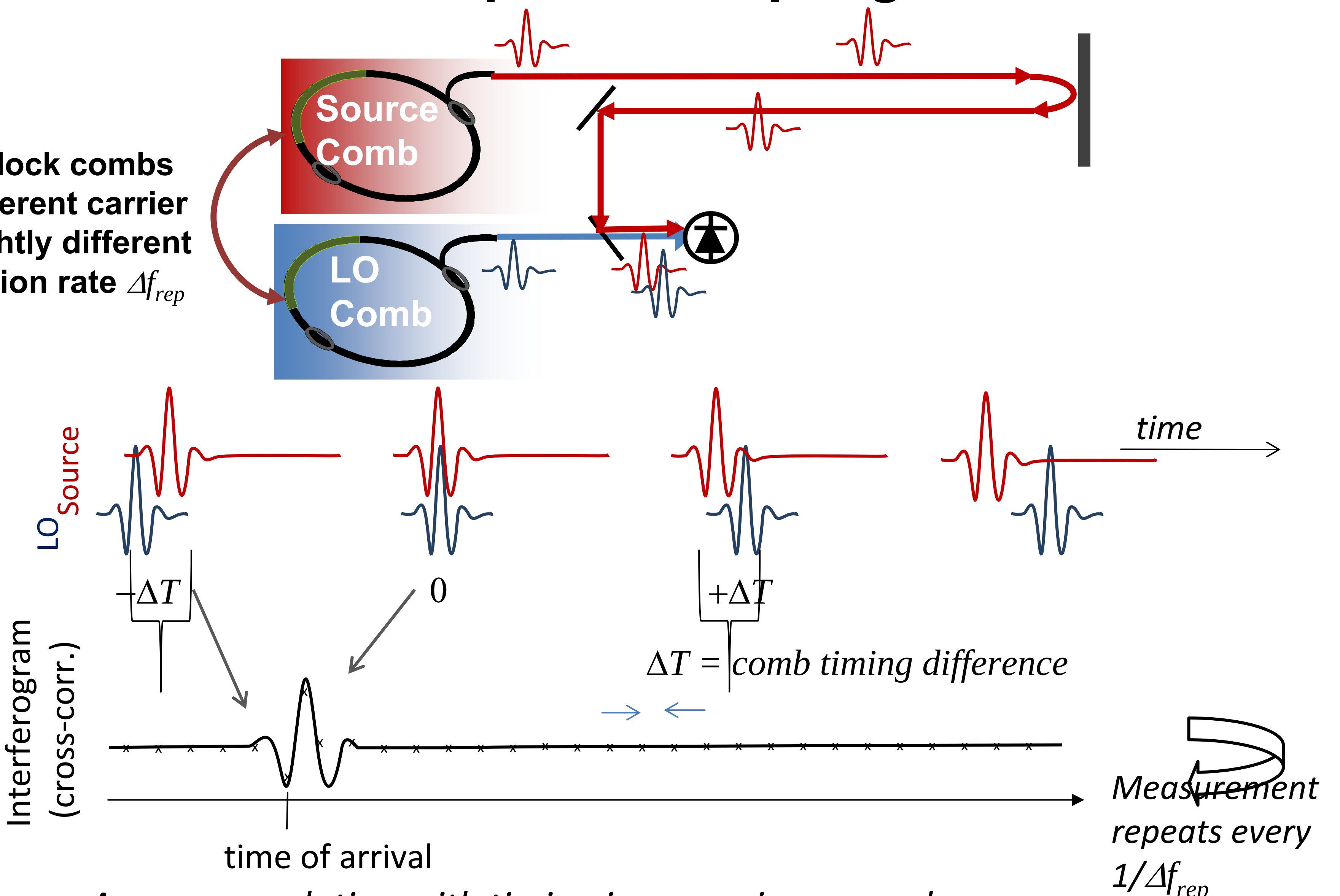
FM CW LIDAR



Barber et al, OL **36**, 1152 (2011).)
This work

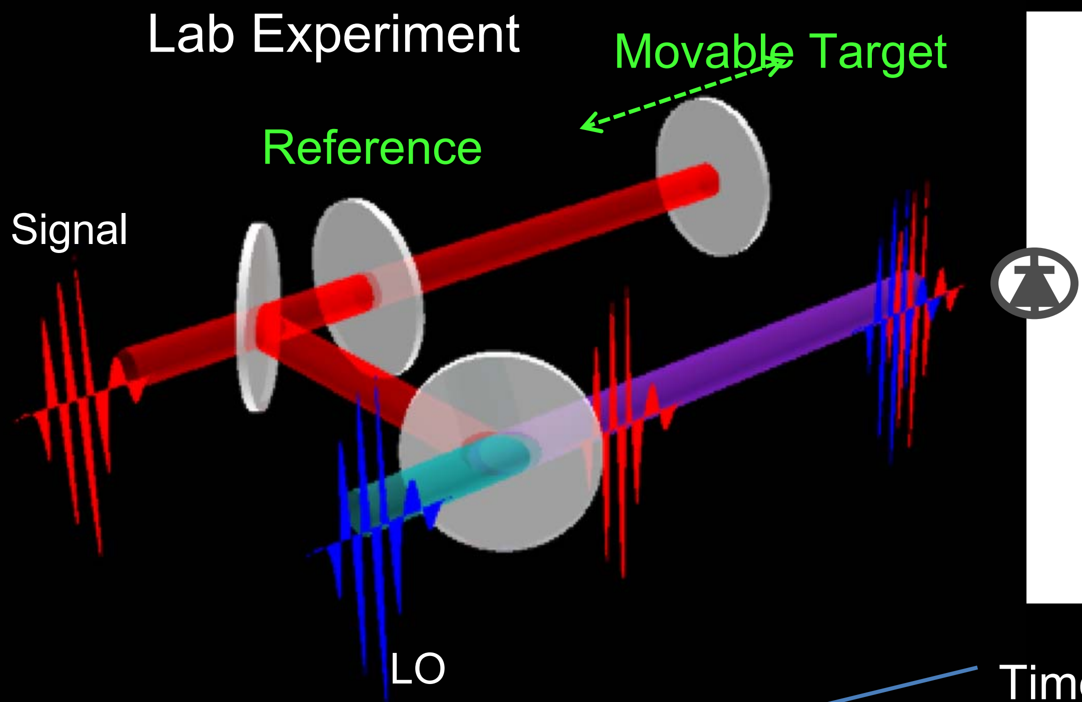
Dual Comb System in Time Domain: Linear Optical Sampling

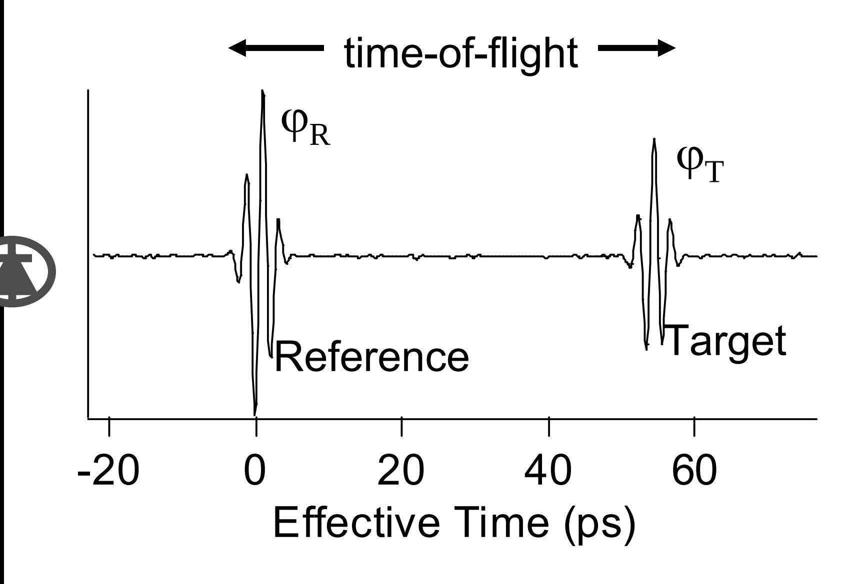
Phaselock combs
- **Coherent carrier**
- **Slightly different repetition rate** Δf_{rep}



A cross-correlation with timing is as precise as combs

Dual-Comb Ranging: Lab Demo





Combs phase-locked together
- Coherent carrier
- Precisely offset repetition rate

Time-of-Flight Range $= (v_{group}/2) \times$ time-of-flight

Absolute Range

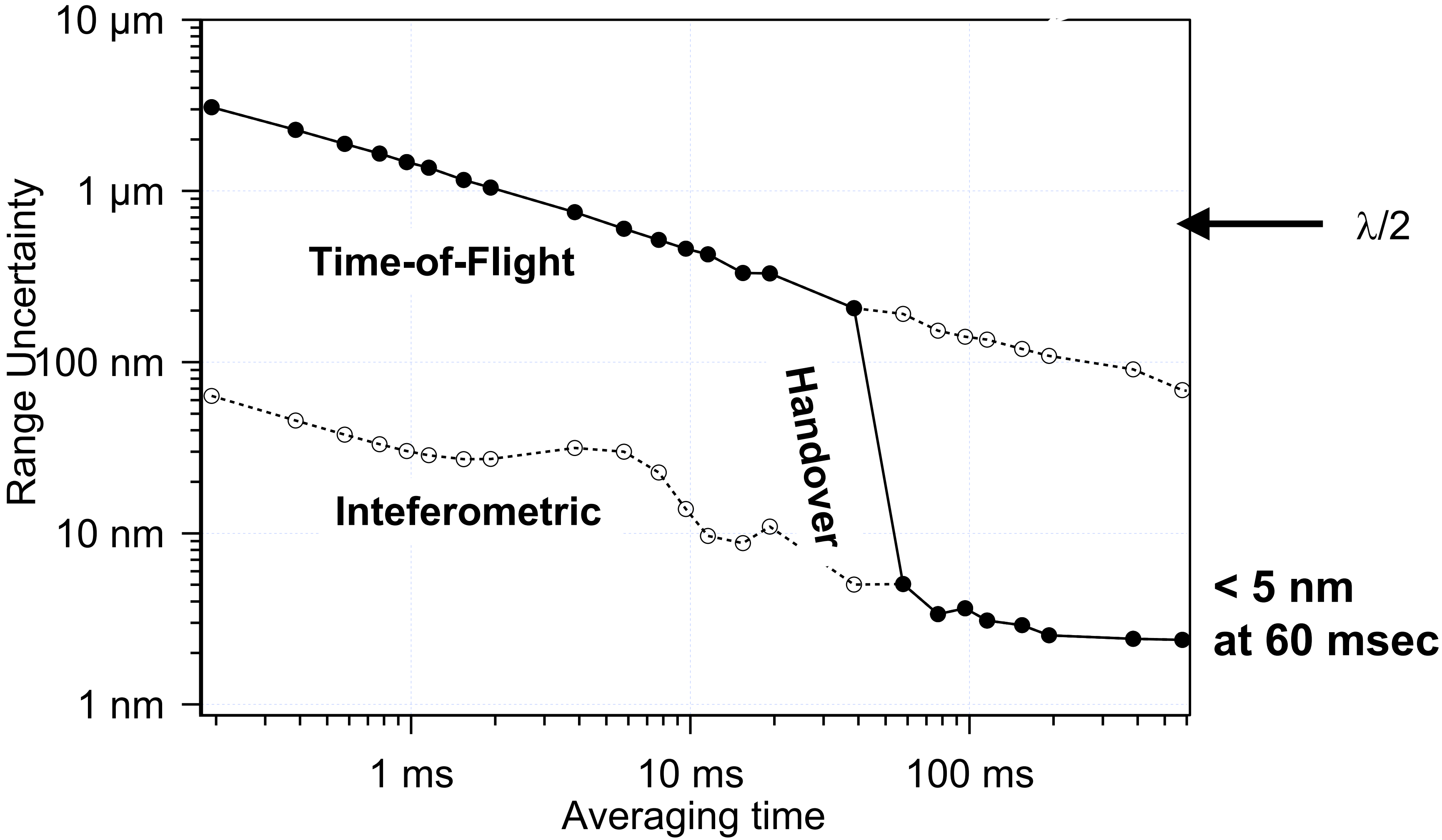
Interferometric Range $= (\varphi_T - \varphi_R)/(4\pi)\,\lambda + N\,\lambda/2$

High-precision Range

ambiguity

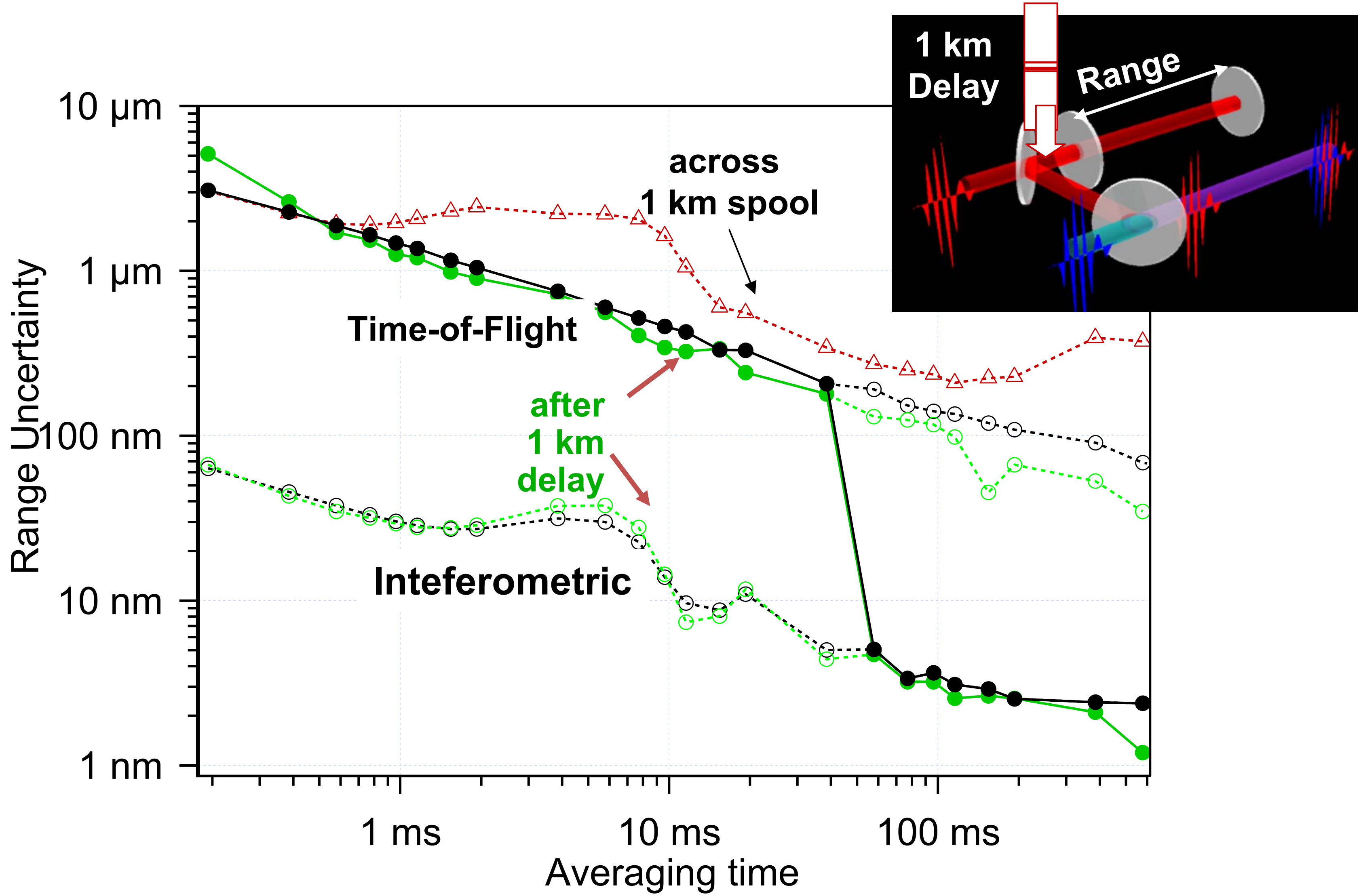
Range Uncertainty versus Observation Time
nm-level absolute distance measurements

(Also verified Time-of-Flight and Interferometric *Agree*)



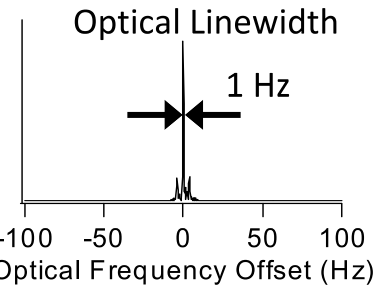
“Range Window” or Ambiguity is 1.5 meters (but can extend to > 30 km)

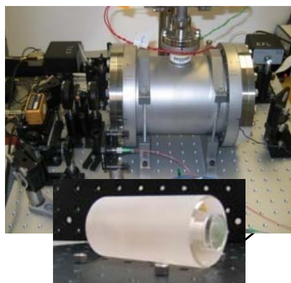
Range Uncertainty versus Observation Time
nm-level absolute distance measurements

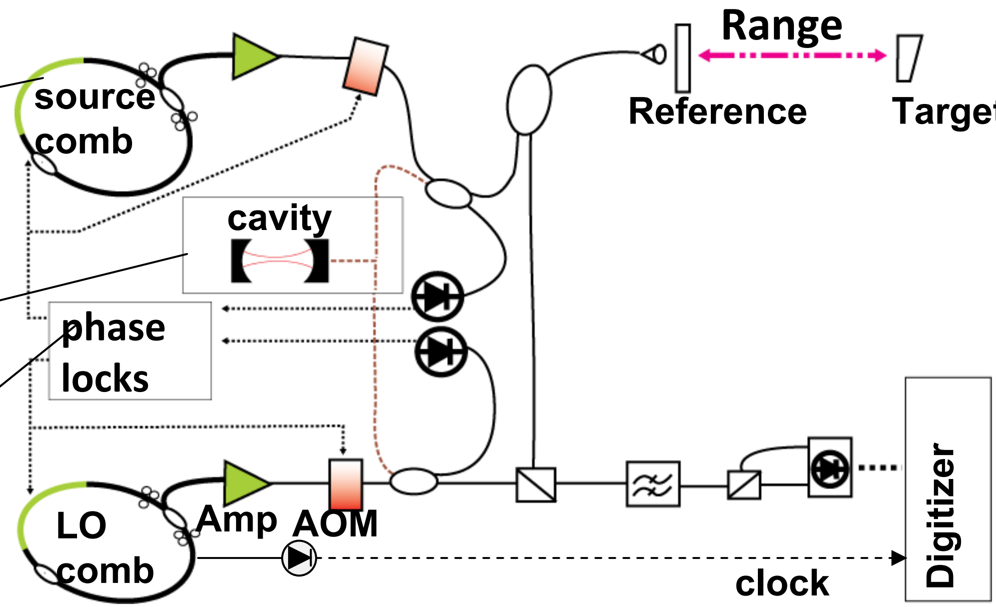


“Range Window” or Ambiguity is 1.5 meters (but can extend to > 30 km)

Fully Phase-Locked Dual Comb System





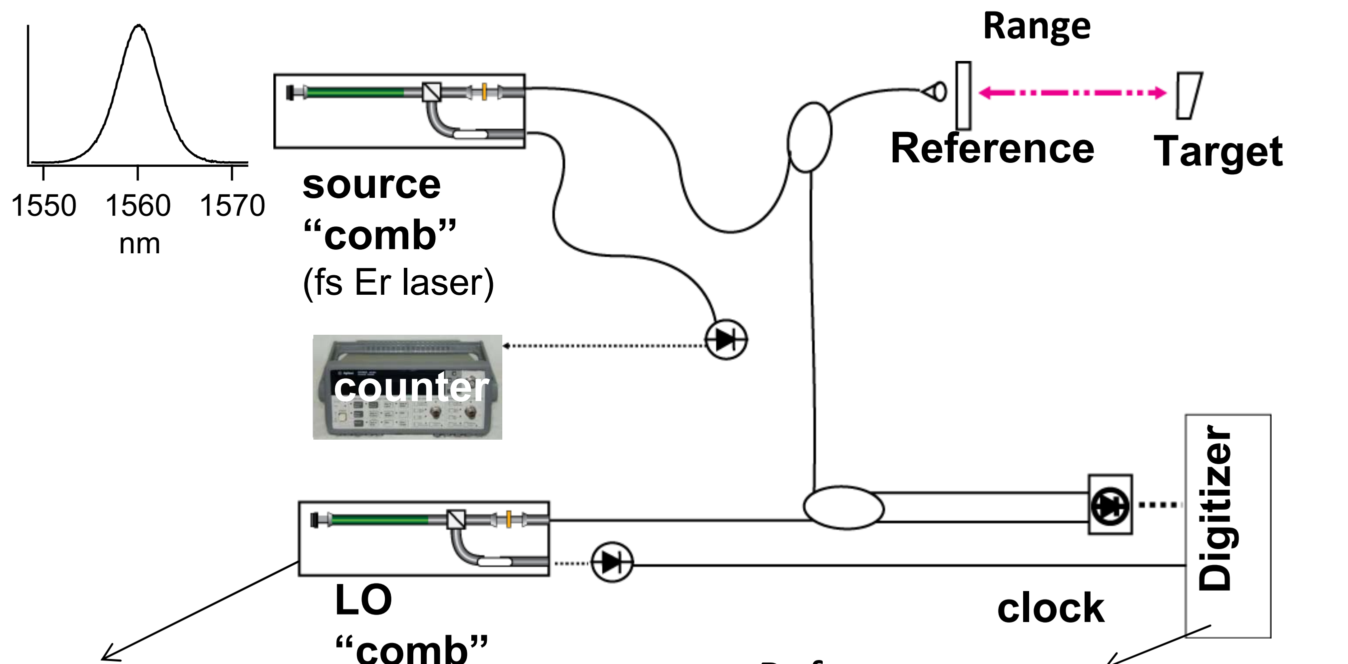


- Four phase locks to two cavity-stabilized laser
- Can we trade off precision for simplicity?
  - Nanometer precision excessive for typical terrestrial ranging of ~ 10^{-7} to 10^{-8} precision

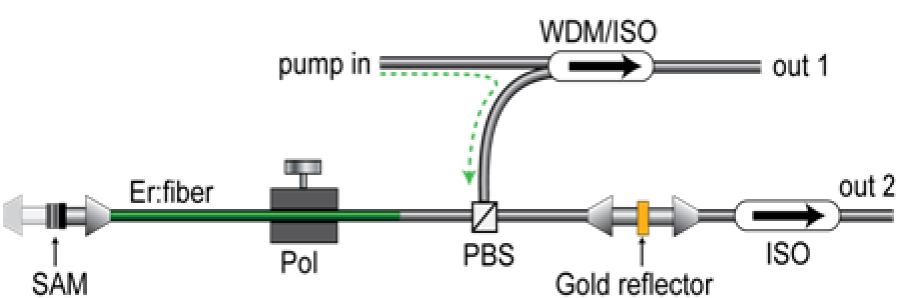
Try a free-running system with no phase locks…

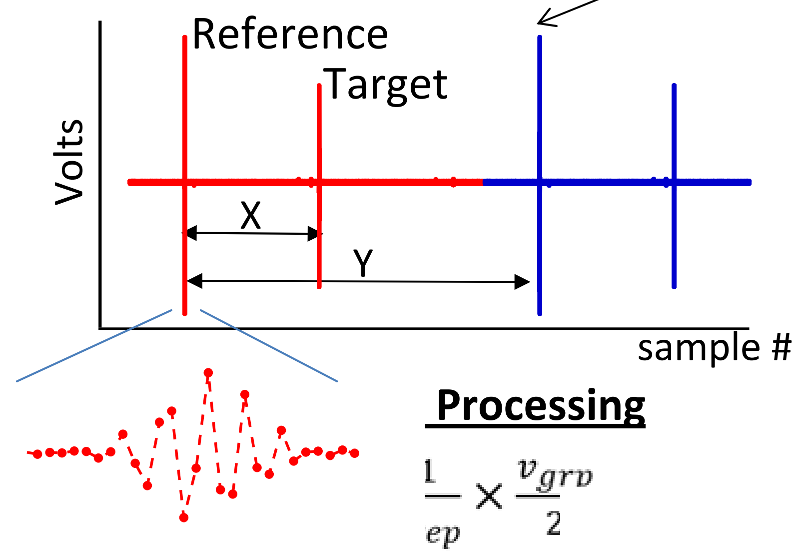
- ***Interferometric ranging lost***
- ***Time-of-flight ranging still possible?***

Free-running Dual Comb System
Time-of-Flight Ranging Without Phase Locks



Simplified 200 MHZ Er fs laser

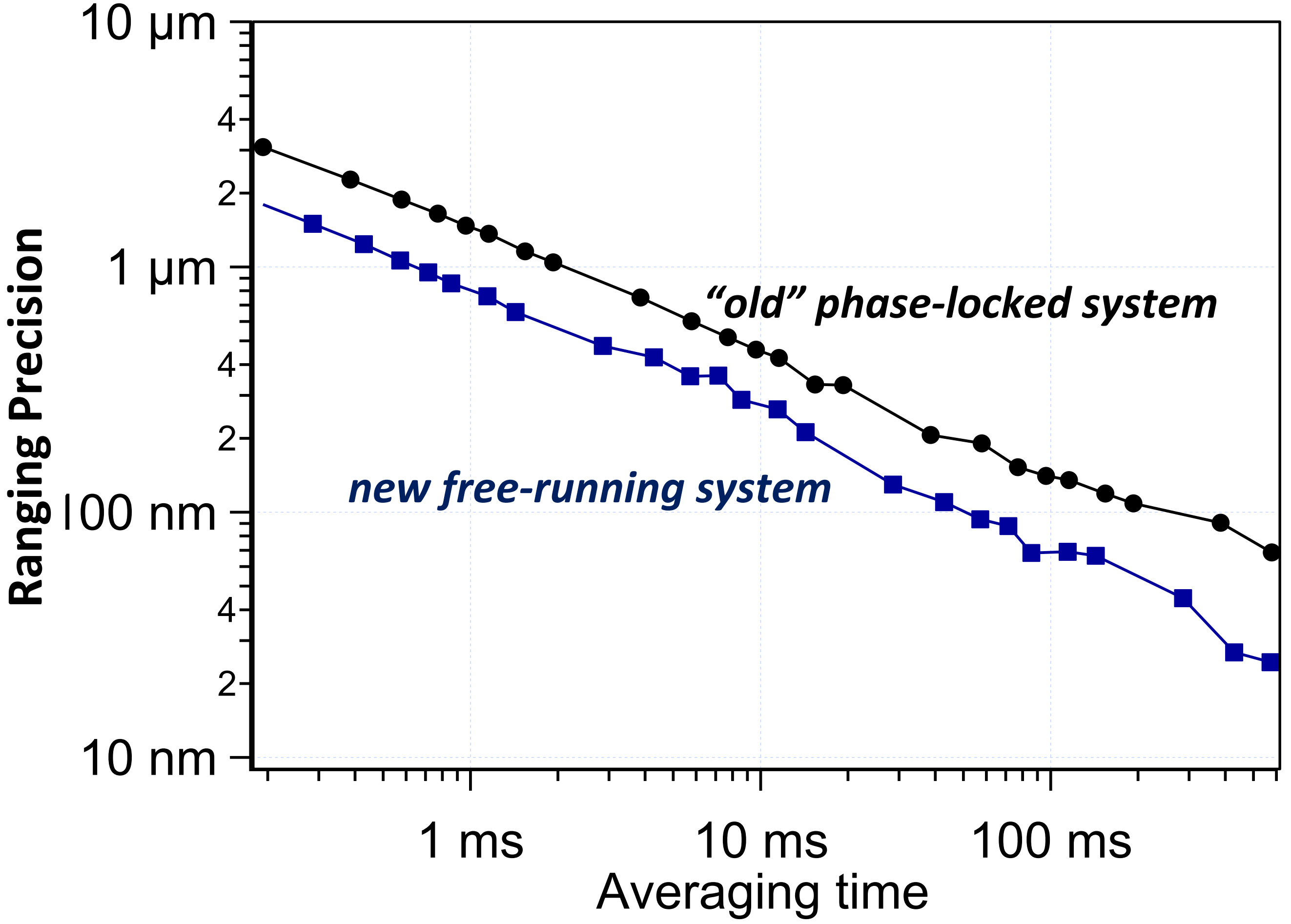




Free-running rep rate stable to 10^{-8} @ 1 sec
Adjust for Δf_{rep} = 7 kHz between combs
Free-running carrier stable to ~ MHz

Time-of-Flight Ranging with Simpler System

Sub-micron in Sub-milliseconds with 0.75 m range window



- Superior performance (due to higher repetition rate sources)
- Also verified 200 nm linearity across 1 meter

Dual-Comb Ranging

- **Advantages**
  - **Rapid, absolute, high precision ranging (sub-micron in sub-millisecond)**
  - **Immunity to spurious reflections**
  - **No significant dead zones**
- **Disadvantage**
  - **Inefficient use of photons: Multiplexed disadvantage of $\sqrt{N}$**

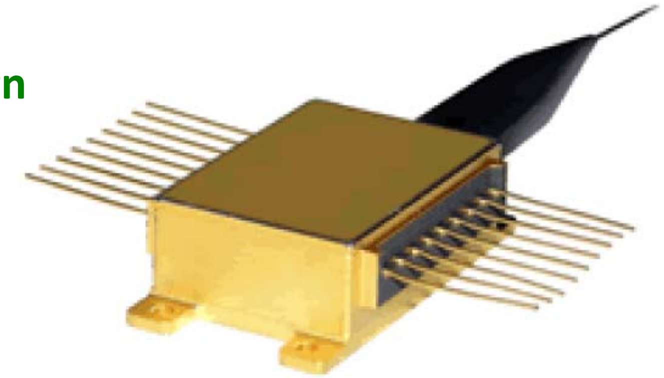
    10's of nW to μW return powers (100's of photons per pulse)
- **Suitable for ranging to "cooperative" target with retroreflector**
  - **Not suitable for diffuse target**
  - **(True of all direct comb ranging systems….)**

Can we combine accuracy of combs with efficiency of FM CW LIDAR?

Combing Swept Cw Lasers & Combs

Tunable diode lasers offer

- ~100 nm tuning ranges
- Rapid scan rates >1000 THz/s in MEMS or Y-branch design
- >10 mW - many Watts and single mode operation.
- Much higher SNR than direct-comb illumination



But

- Optical frequency is poorly defined during sweeps
  (orders of magnitude worse than linewidth)
- Also fastest sweeps will not be linear (but quasi-sinusoidal)

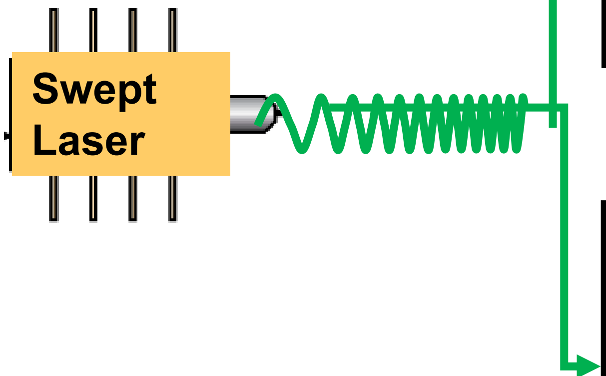
Goal:

- ➢ Use frequency combs to track the phase of a swept laser
- ❖ With high accuracy
- ❖ At high speeds
- ❖ Over arbitrary waveforms

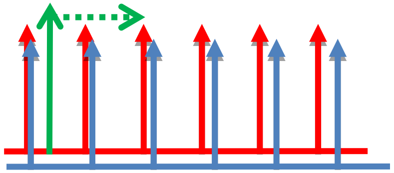
Metrology of a Swept CW laser using Frequency Combs

Basic Approach: Heterodyne laser against comb & digitize (fast)

T.-A. Liu, et al. , *Opt. Exp.*, 16, 10728, (2008).
P. Del'Haye *et.al.*, *Nat. Photon.*, **3**, 529, (2009).
F. R. Giorgetta, *et.al.*, *Nat. Photon.*, **4**, 853, (2010)
Z. W. Barber, *et. al.*, *Opt. Lett.*, **36**, 7, 1152, (2011).
I. Coddington, *et. al.*, *JSTQE* (Invited), IEEE Early Access, (2011)

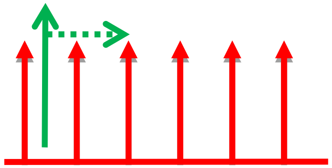


Dual Comb Spectrometer



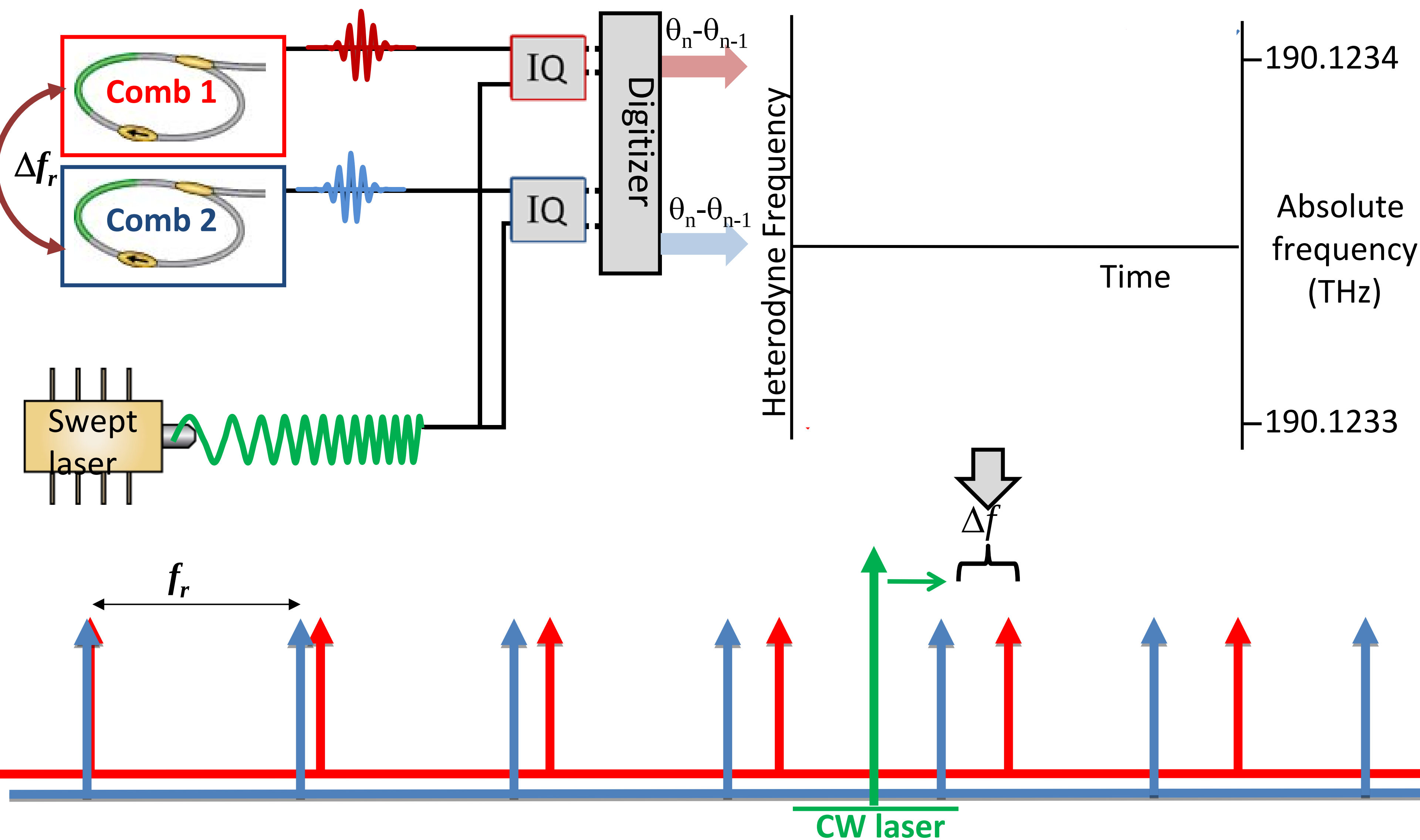
- *Absolute* optical frequency vs time
- Requires dual phase-locked combs
- >1000x faster than wavemeter
- Unique tool for metrology of fast swept lasers

Single Comb Spectrometer



- *Relative* optical frequency vs time
- Single, free-running comb
- ~20 nanosecond time resolution
- Much higher linearity, speed, flexibility than etalon approaches

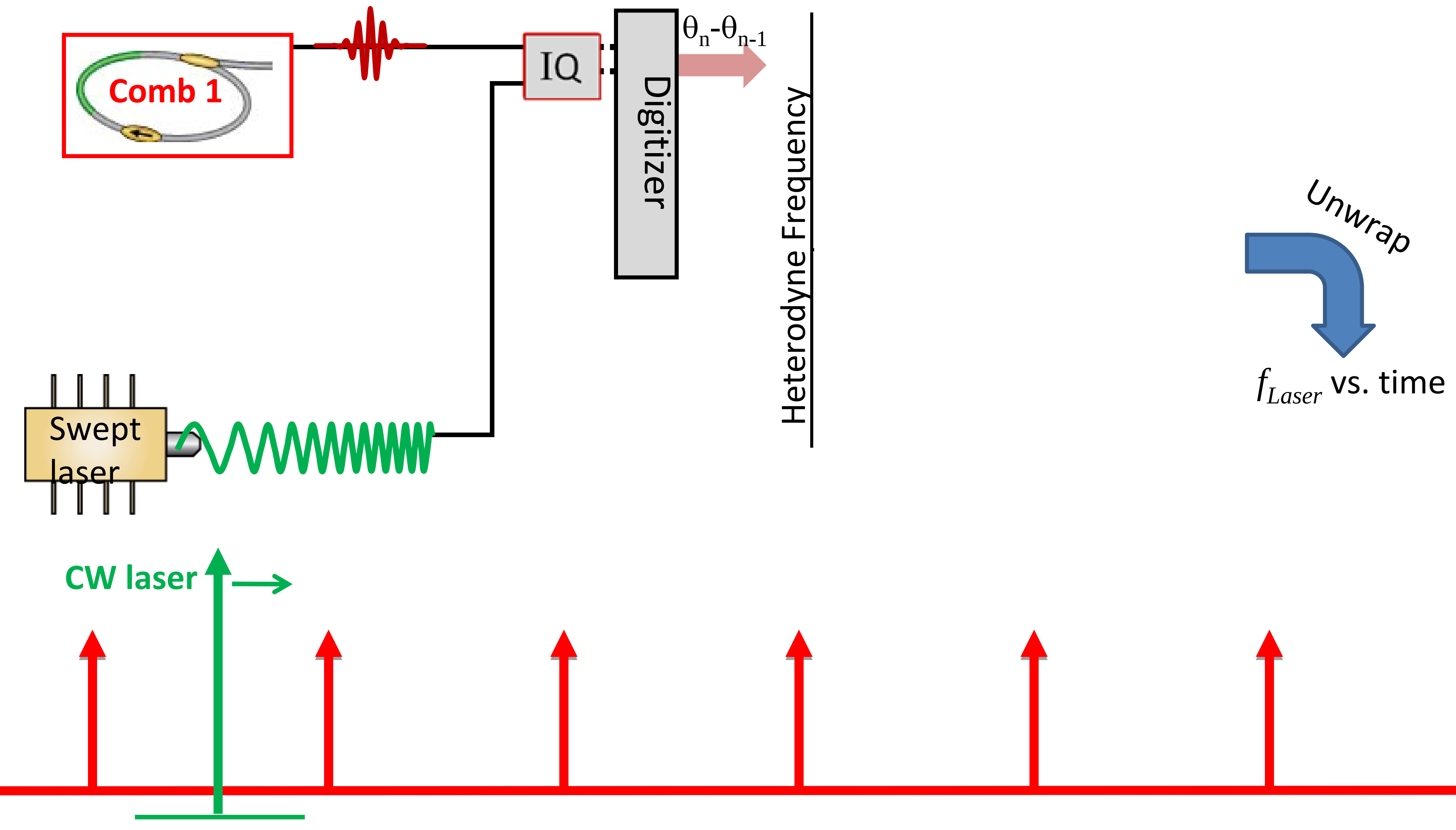
Swept CW laser + Dual Comb Spectrometer
Absolute Frequency Determination



Maximum sweep rate (chirp) $< f_r \, \Delta f_r$ = 0.1-1 THz/s (0.8-8 nm/s)

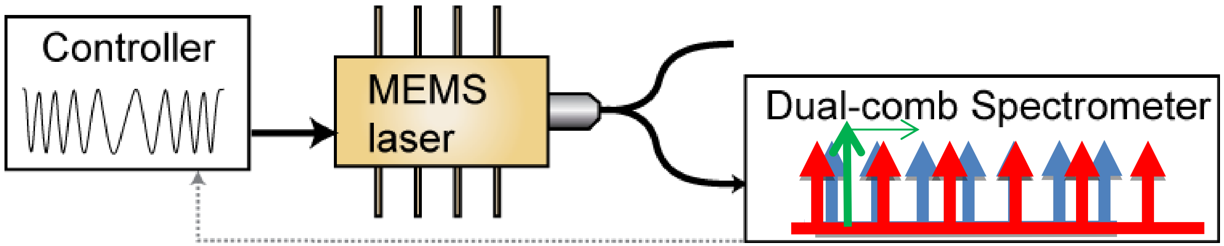
Swept CW laser + Single Comb Spectrometer

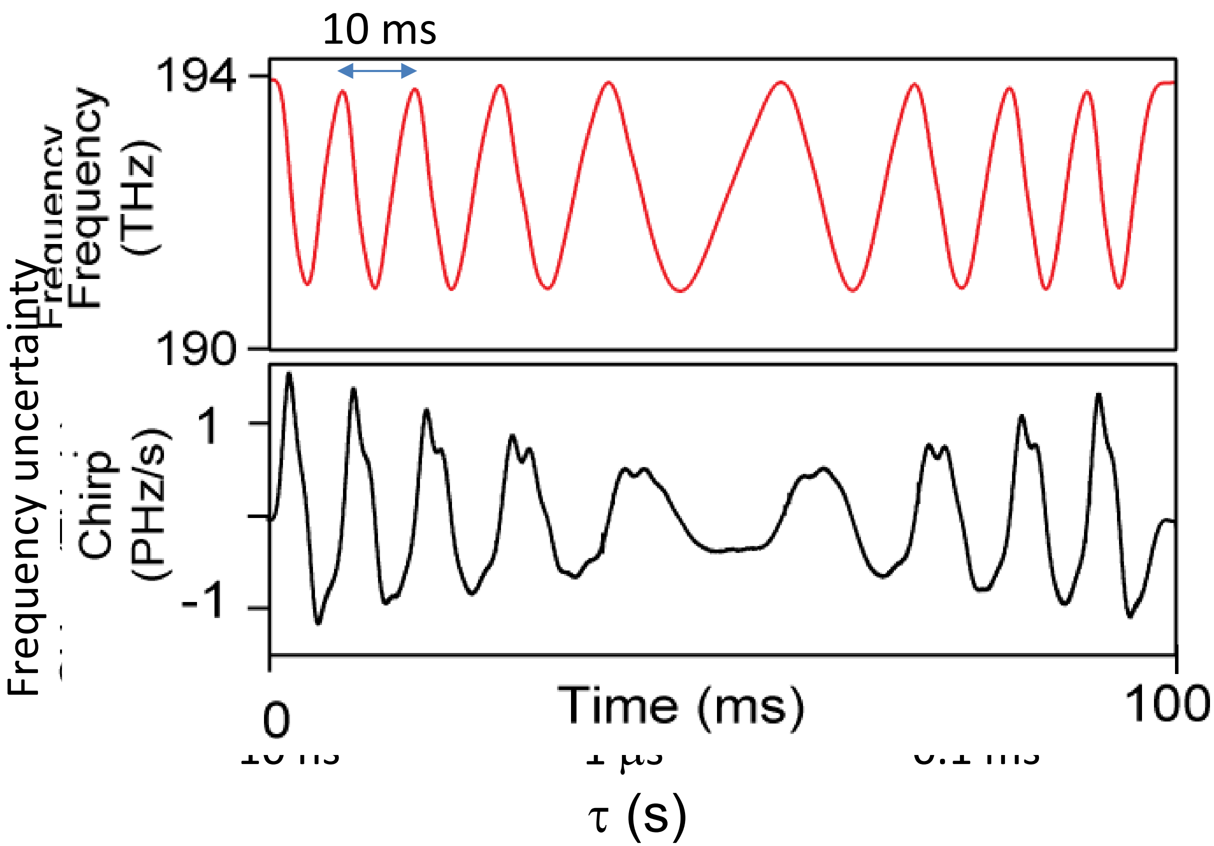
Fast Relative Frequency Determination



Maximum sweep rate (chirp) $< f_r f_r / 2 =$ **5,000 THz/s (40,000 nm/s)**

Example Measurement of a Fast Swept Laser MEMS-based ECL



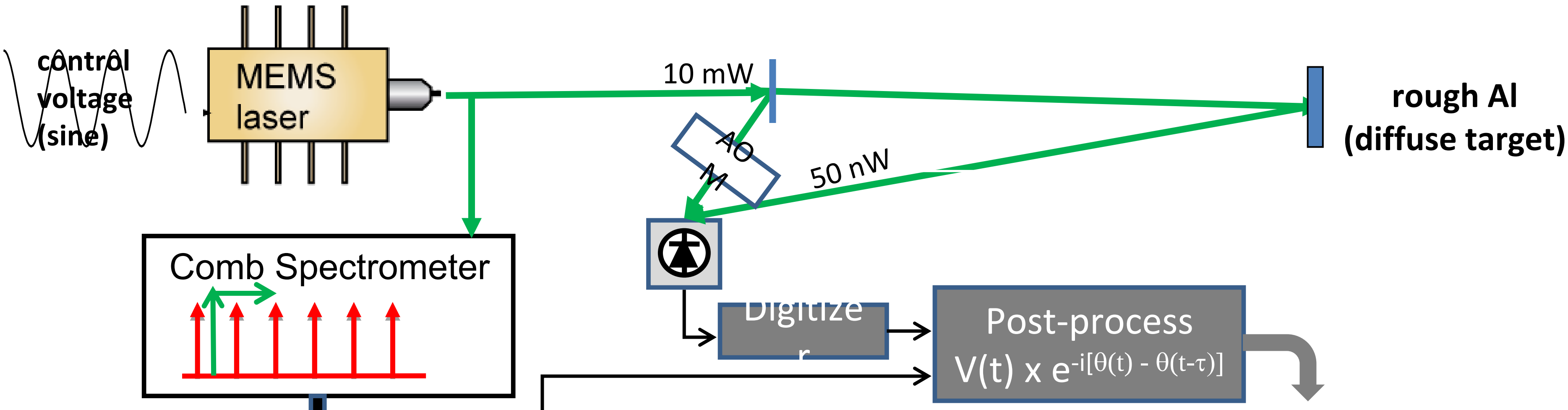


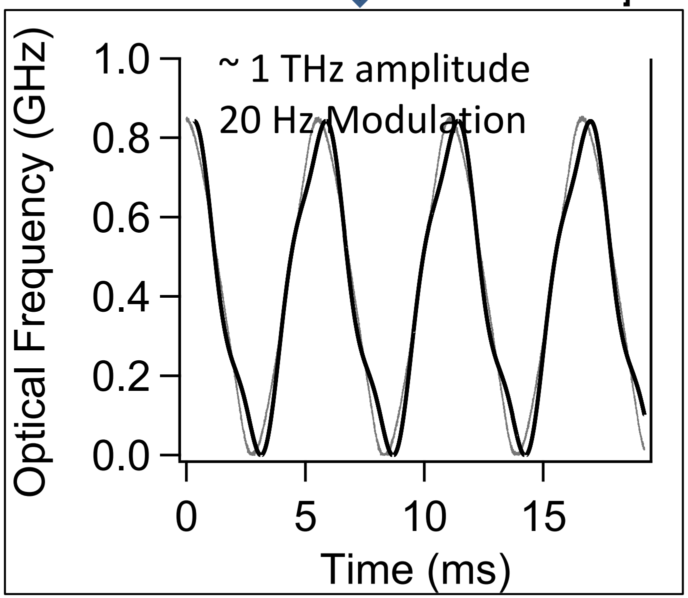
Chirp rates > 10^{15}/sec (10,000 nm/sec)

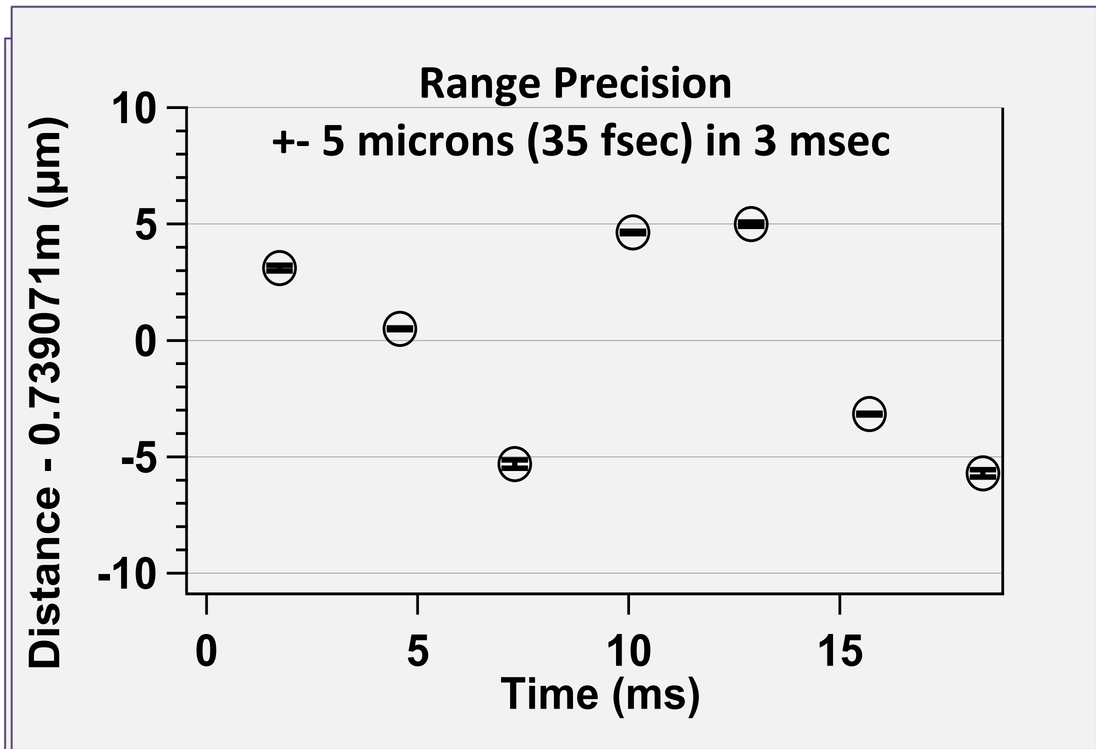
Accuracy ~ 30 kHz/μs (1.5 MHz @ 20 ns)

I. Coddington, *et. al., JSTQE* (Invited), IEEE Early Access, (2011)

FM CW Ranging Lab Demonstration
Preliminary Results







>10x faster should be possible

Conclusion

- Combs used in many ways for ranging
- Direct Dual Comb Ranging system
  - Phase-locked system: nanometer absolute ranging at a distance
  - Free-running system: sub-micron ranging in < 1 msec at distance
  - Multiplexed penalty compared to cw coherent laser radar
- Comb-based metrology of swept lasers can track “arbitrary” cw laser waveforms
  - Follow waveforms with chirps of few thousand THz/sec
  - Absolute or relative frequency measurments
- Preliminary comb-assisted FMCW
  - Processing intensive
  - Range resolution ~ 1/Bandwidth~ 1 psec ~ 150 microns in 3 msec
  - Range precision of 5 microns in 3 msec
  - Potential 10x improvement in speed possible….