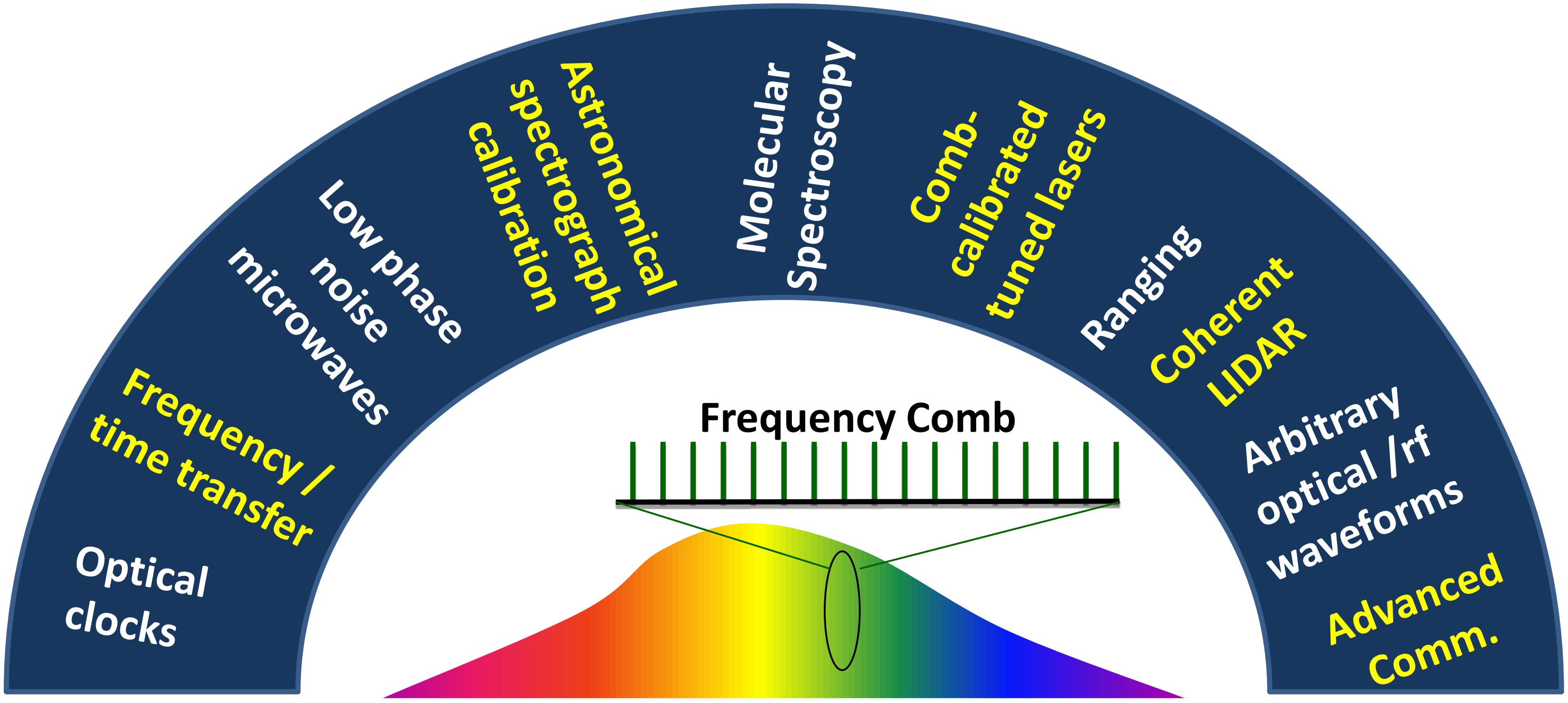
Applications of Frequency Combs

Optical Frequency Combs for Space Applications
November 2, 2015

Nathan R. Newbury

National Institute of Standards and Technology, Boulder, CO
nnewbury@boulder.nist.gov

Applications of Frequency Combs



- Applied to laser-based metrology/sensing systems
  - As a spectral ruler
  - As a “time” ruler

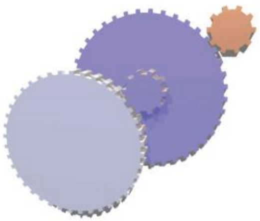
Newbury, Nat. Phot., 5, 186 (2011)
Diddams, JOSA B, 27, B51 (2010)

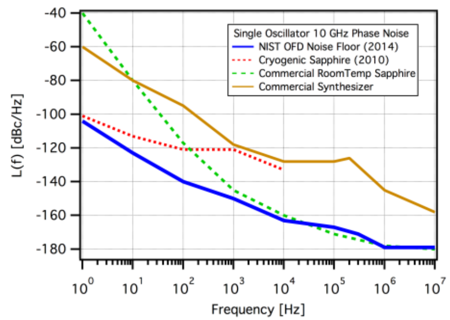
Outline

- **Introduction**
- **Overview of comb applications**
  - All terrestrial and mainly all laboratory based
  - NIST-centric view!
- **Some applications not covered**
- **Conclusion**

Example applications

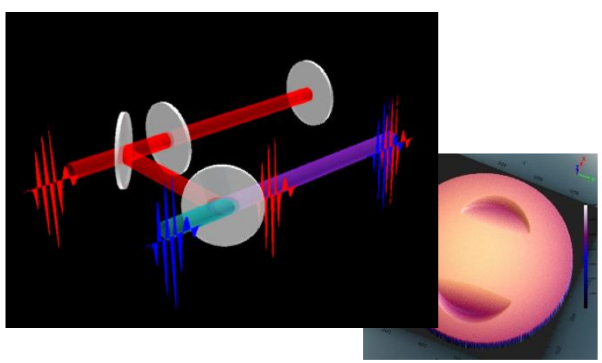
Precision microwave generation
(for RADAR)



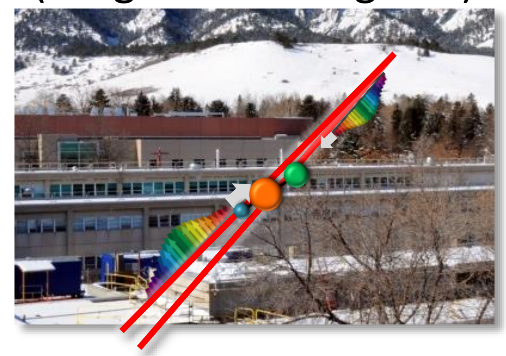


Precision spectroscopy
(for exoplanet searches)

Precision Ranging



Precision molecular spectroscopy
(for greenhouse gases)

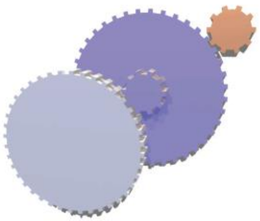


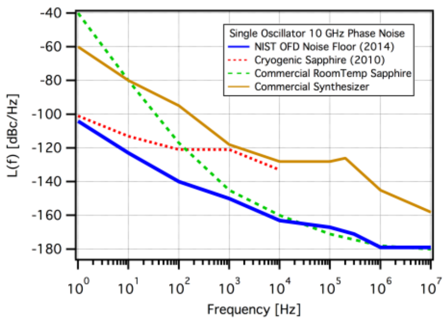
Precision timing across synchronized network

Others:
Advanced communications
Fundamental scientific tests
…

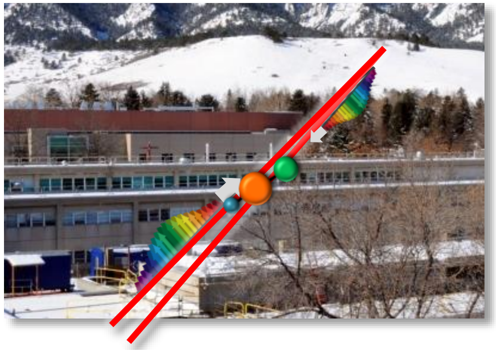
Example applications

Precision microwave generation
(for RADAR)





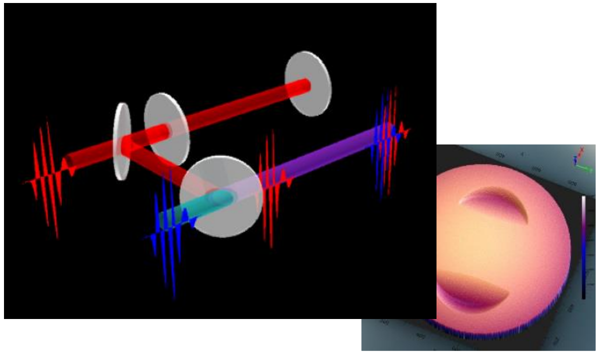
Precision molecular spectroscopy
(for greenhouse gases)



Precision spectroscopy
(for exoplanet searches)

Precision timing across synchronized network

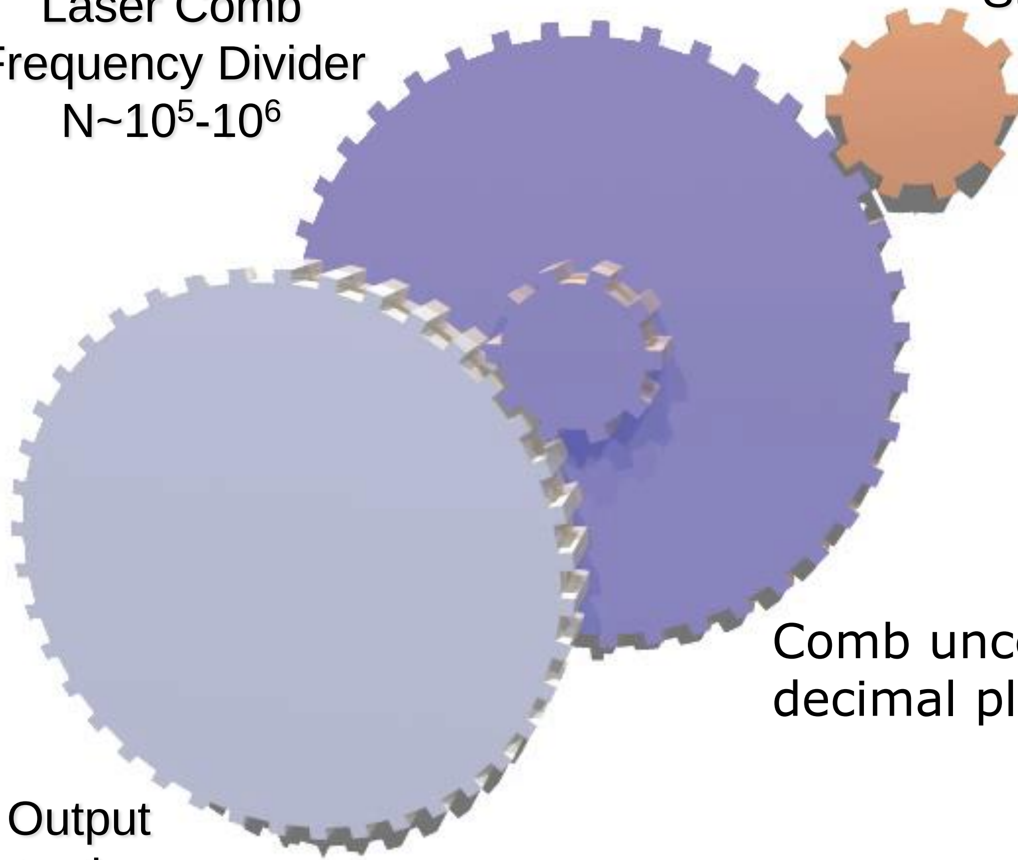
Precision Ranging



Others:
Advanced communications
Fundamental scientific tests
…

Photonic Microwave Generation

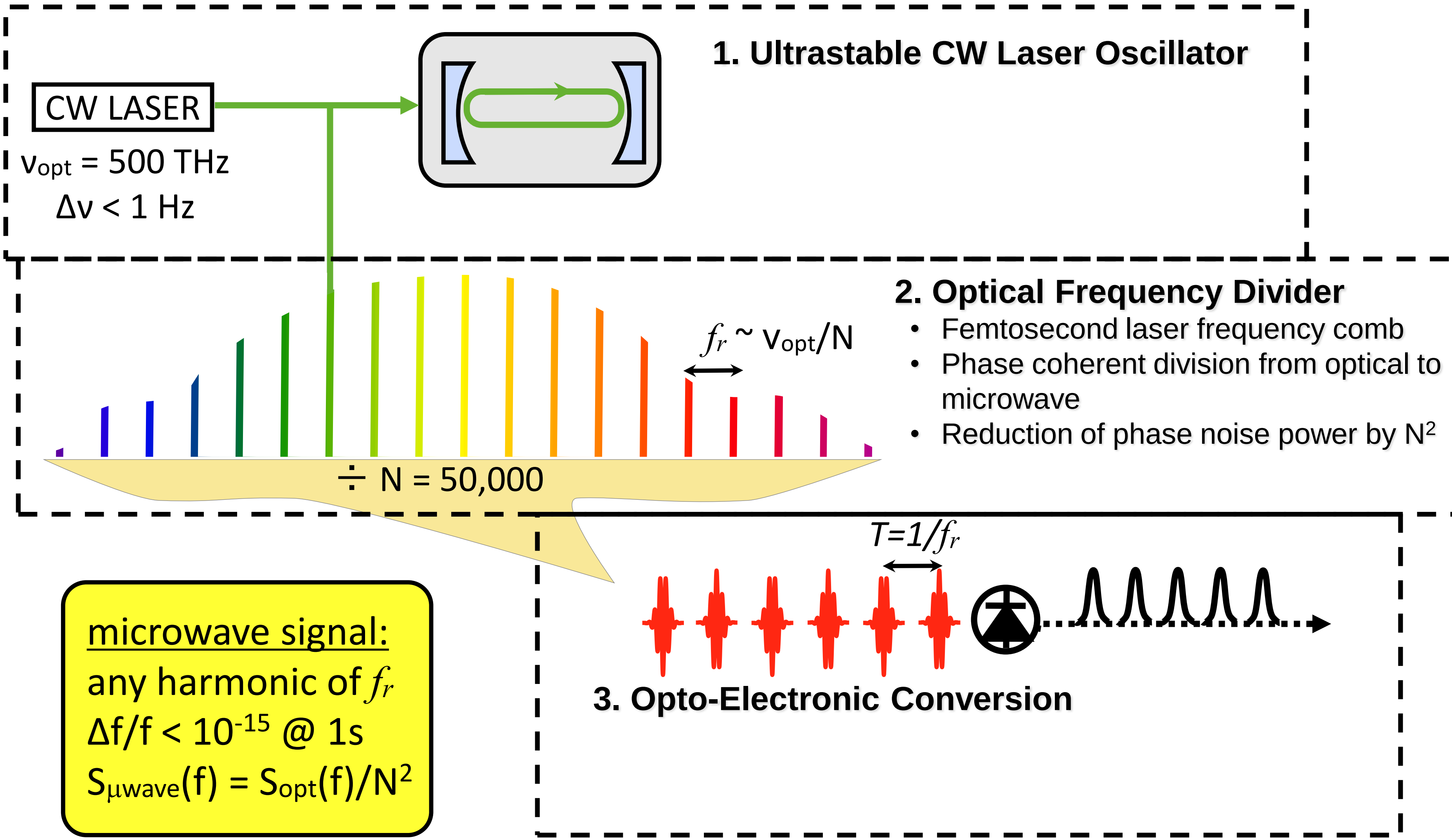
Slides courtesy of Scott Diddams, Tara Fortier, Frank Quinlan



L.-S. Ma, et al., Science, **303**, 1843 (2004)

Optical Frequency Division

NIST
National Institute of Standards and Technology

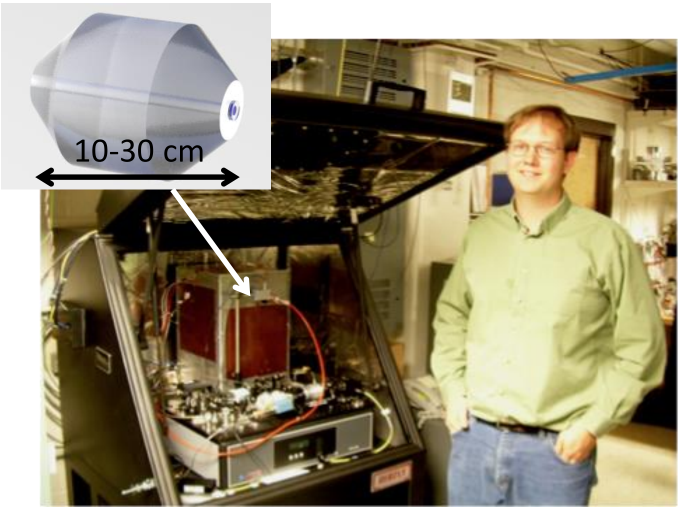


S. Diddams et al, IEEE JSTQE, **9**, 1072 (2003); A. Bartels, et al, *Opt. Lett.* **30**, 667 (2005); J. McFerran, et al. Electron. Lett. **41**, 36 (2005); T. Fortier, et al. *Nat. Photon.* **5**, 425 (2011).

Main Components of Present System

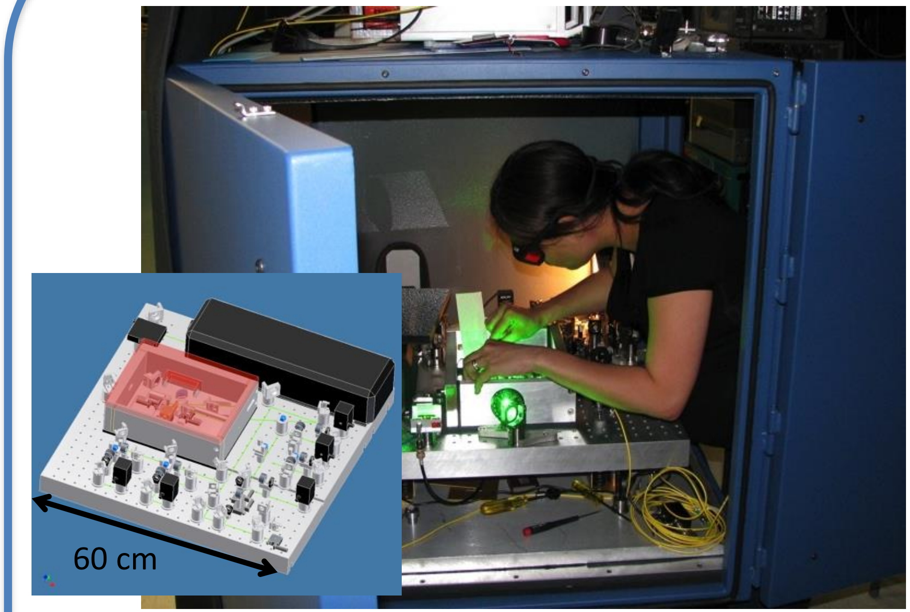
National Institute of Standards and Technology

Frequency Reference: Cavity-Stabilized Laser



- ULE fused silica Fabry-Perot etalon
- Housed in temp-controlled vacuum chamber
- Vibration (active) and acoustic isolation
- Cavity length is thermal noise limited to <1 femtometer (nuclear diameter)

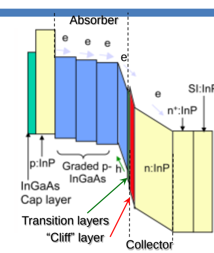
Optical Frequency Divider



- Self-referenced (octave spanning) femtosecond laser
- Demonstrated with both Ti:sapphire and Er:fiber systems
- Need very low intensity noise

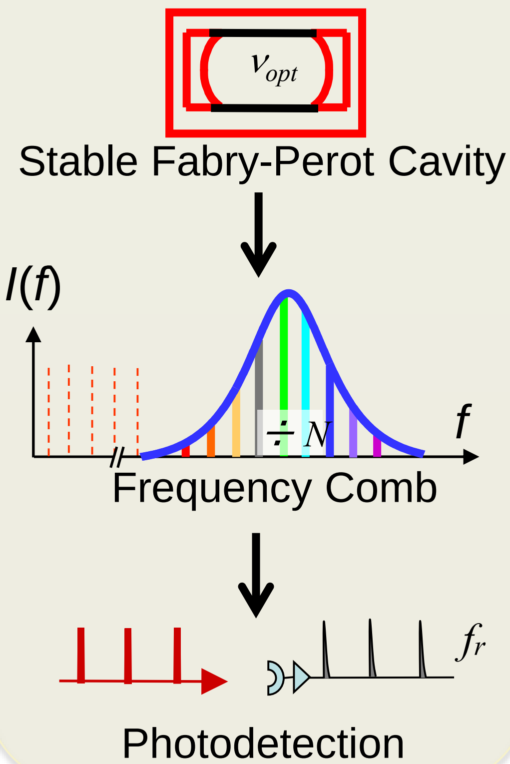
Photodiode

- 10-50 GHz bandwidth
- High linearity, high power handling



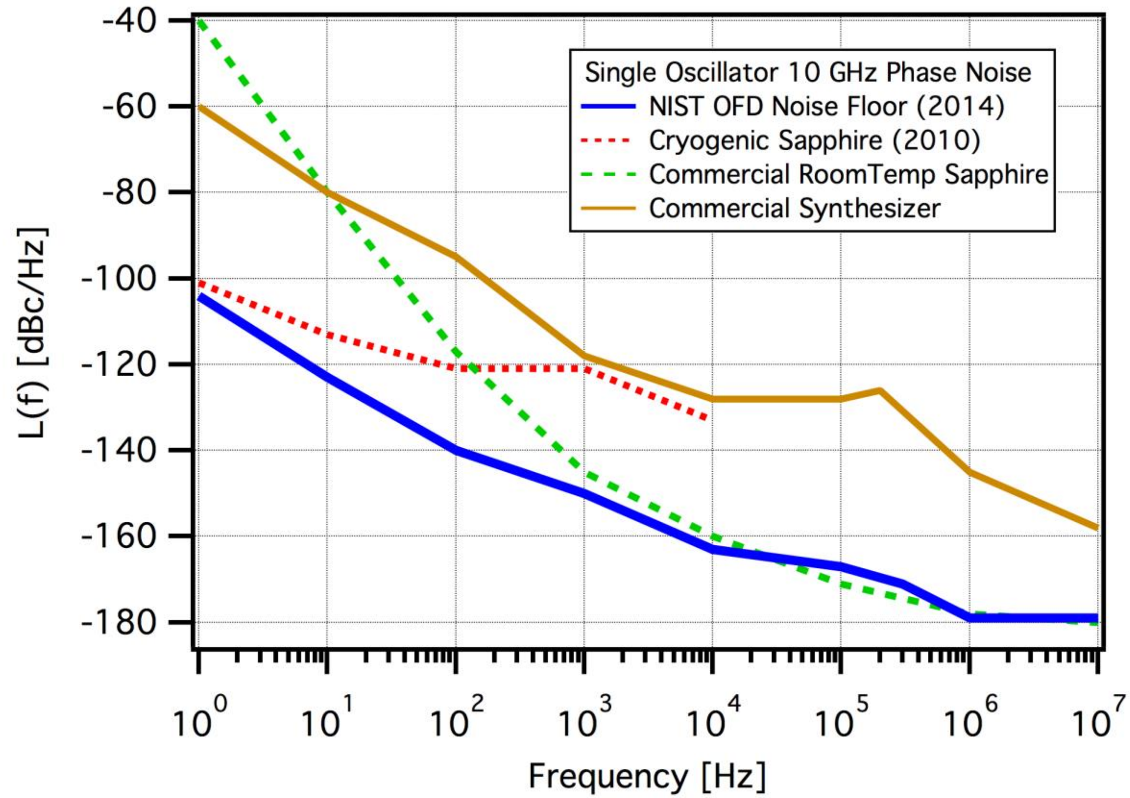
Optics beats electronics

Optical
Frequency Division



$$f_r = \nu_{opt}/N$$
$$S_{\mu wave}(f) = S_{opt}(f)/N^2$$

Integrated Jitter (1Hz – 5 GHz)	
OFD	2.6 fs
Sapphire dielectric	300 fs

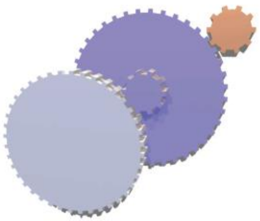


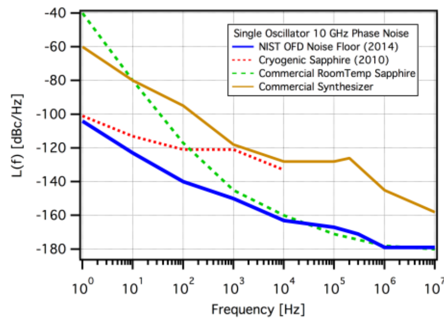
→ Have extended to frequencies from 10 MHz to 100 GHz

T. Fortier, et al. *Nat. Photon.* (2011), T. Fortier, et al. *Opt Lett* (2013), F. Quinlan, et al. *Opt. Lett* (2014)

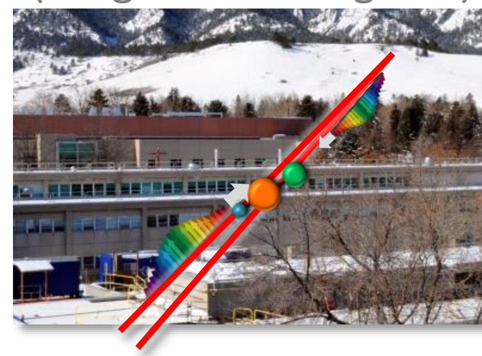
Example applications

Precision microwave generation
(for RADAR)



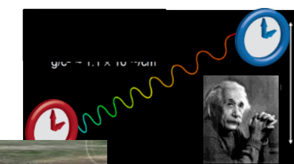


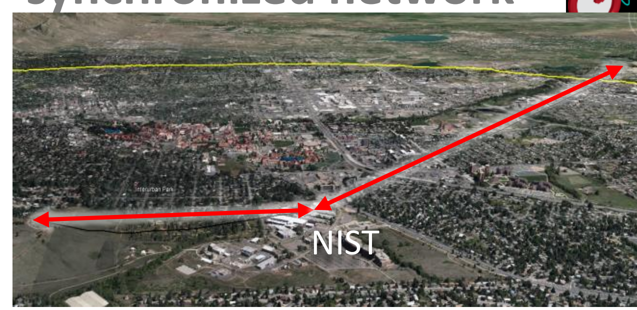
Precision molecular spectroscopy
(for greenhouse gases)



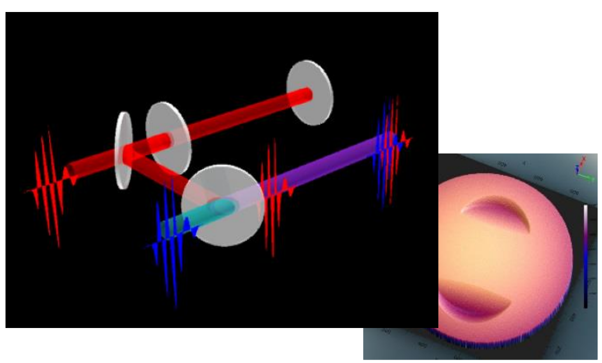
Precision spectroscopy
(for exoplanet searches)

Precision timing across synchronized network



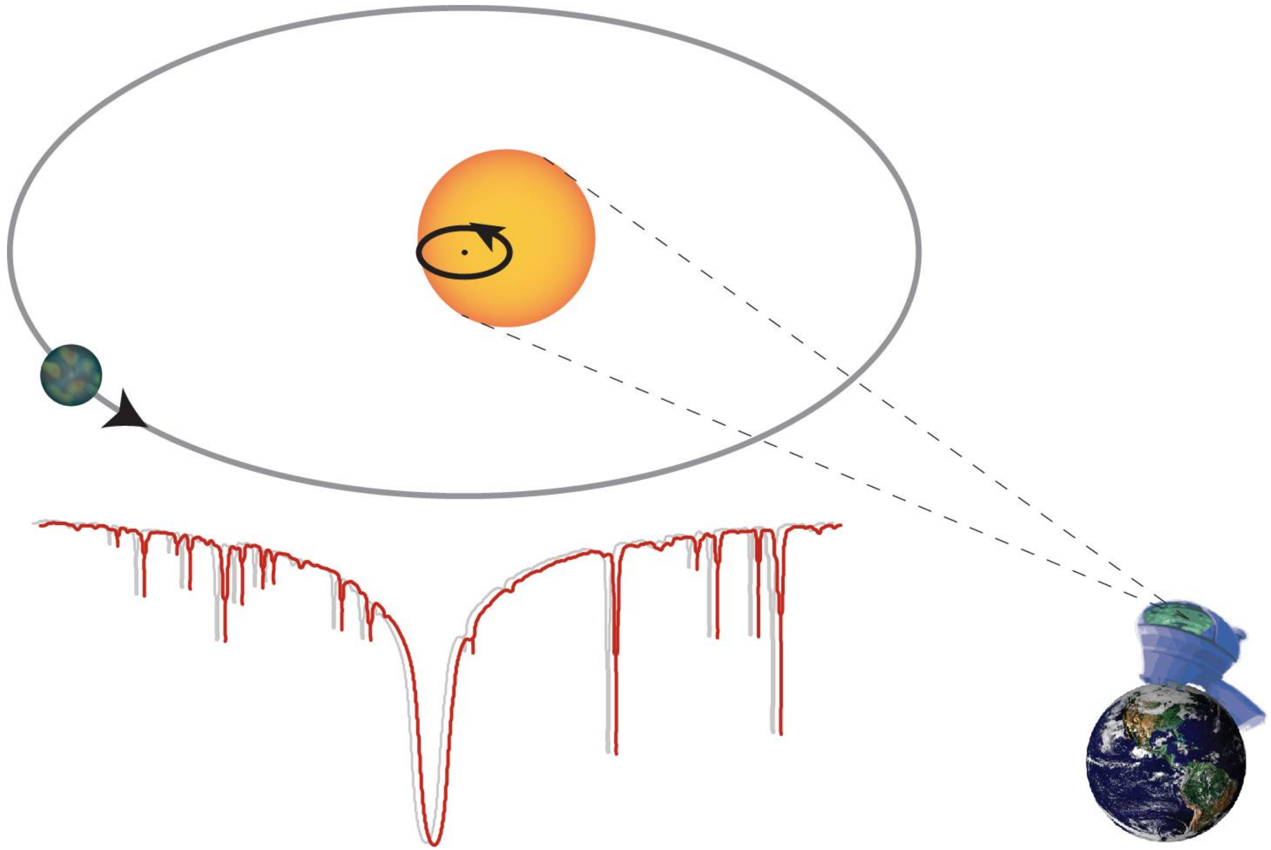


Precision Ranging



Others:
Advanced communications
Fundamental scientific tests
…

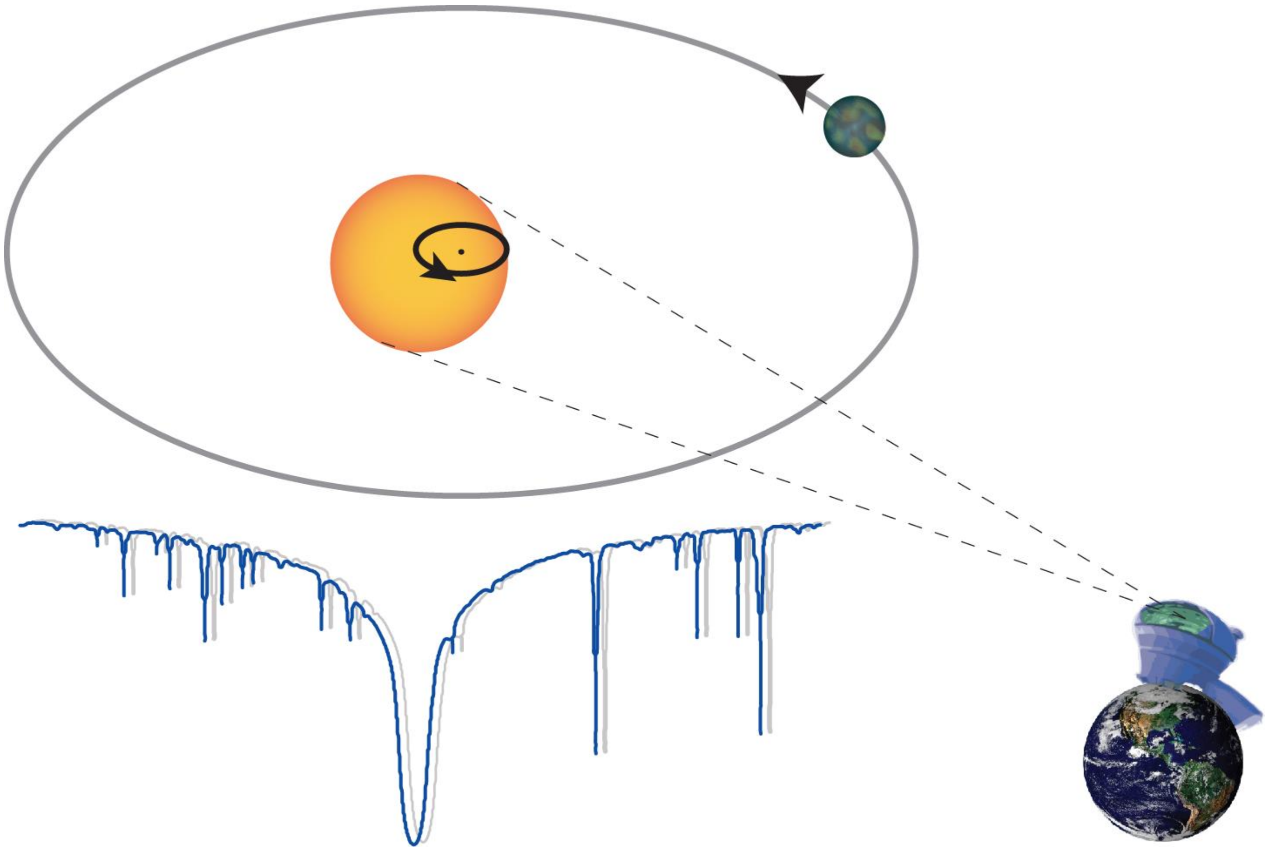
Searching for Exoplanets with the Radial Velocity Technique



Slides courtesy of Gabe Ycas & Scott Diddams

Mayor & Queloz, Nature (1995)

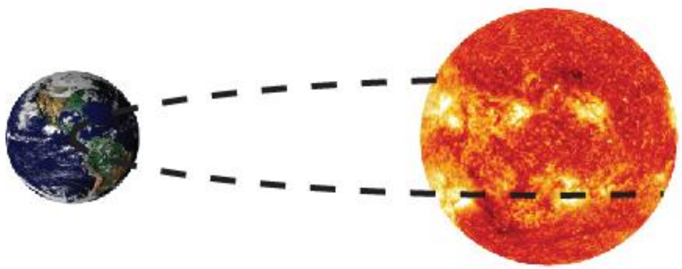
Searching for Exoplanets with the Radial Velocity Technique

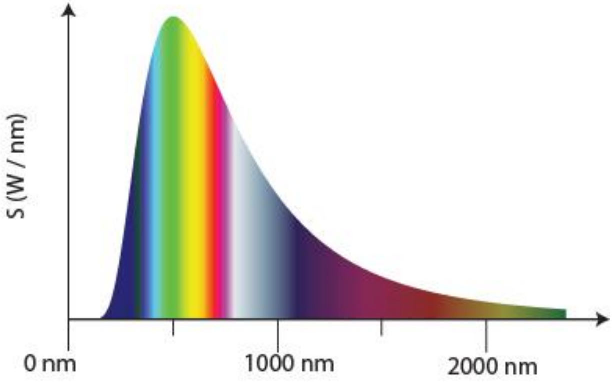


Mayor & Queloz, Nature (1995)

Searching for Exoplanets with the Radial Velocity Technique

Earth-like Planets orbiting Sun-like stars
Doppler shift 10 cm/s (~100 kHz in the visible)



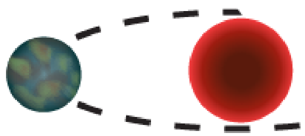


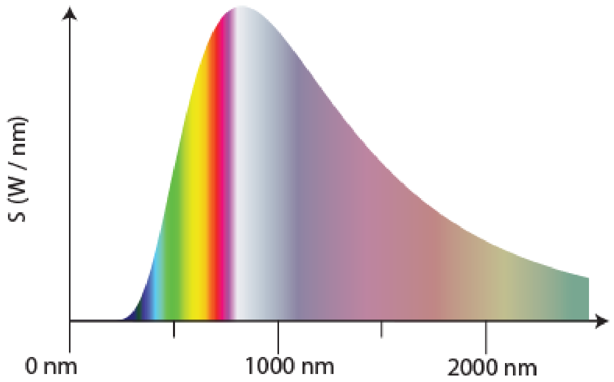
HARPS, HARPS-N(ESO)
ESPRESSO, CODEX (ESO)
Keck / HIRES (NASA)

Searching for Exoplanets with the Radial Velocity Technique

Potentially habitable planets orbiting cooler M dwarf stars

Doppler shift 100-1000 cm/s (~500 - 5000 kHz in the near IR)





Habitable-zone Planet Finder (Penn State University)

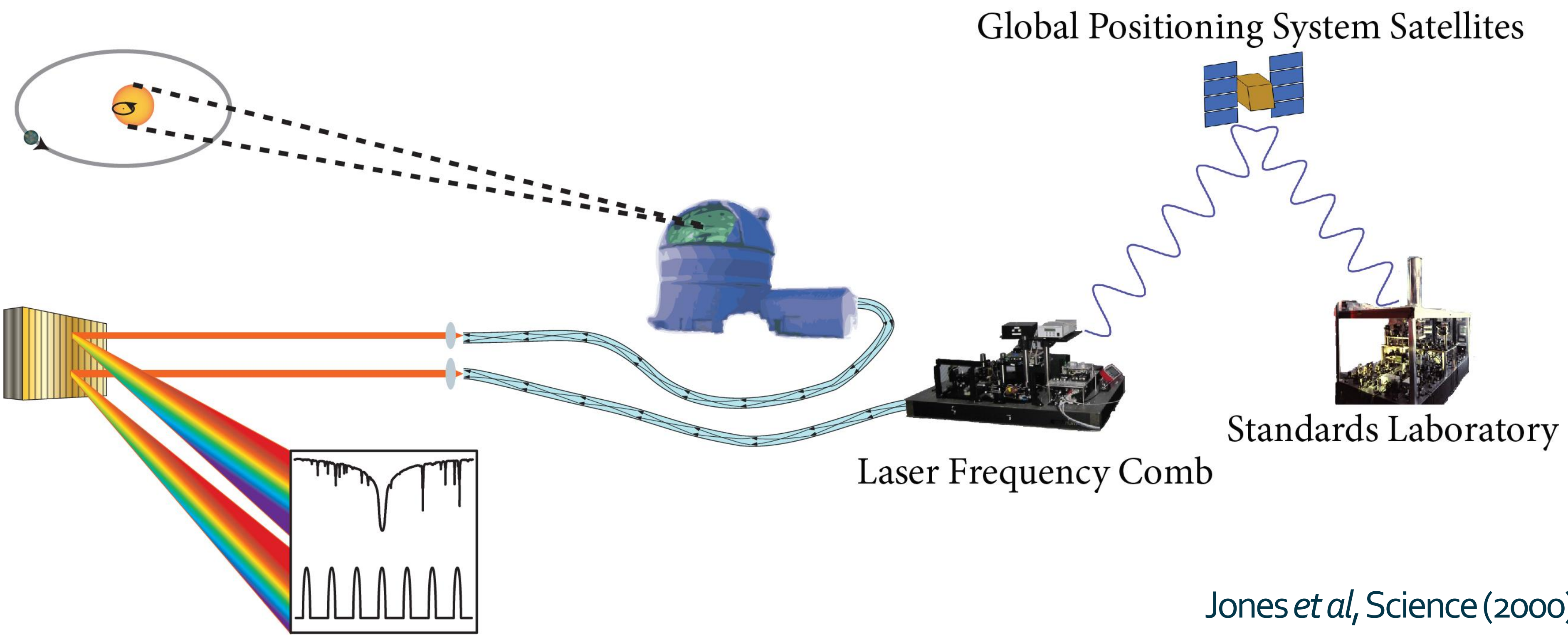
CARMENES (EU)

Astronomical Spectrograph Calibration

Frequency Comb Calibration Source:

Bright, uniformly spaced, well resolved features

Stability achieved by referencing comb to atomic clocks, $\Delta\lambda/\lambda = 10^{-9}$-$10^{-11}$

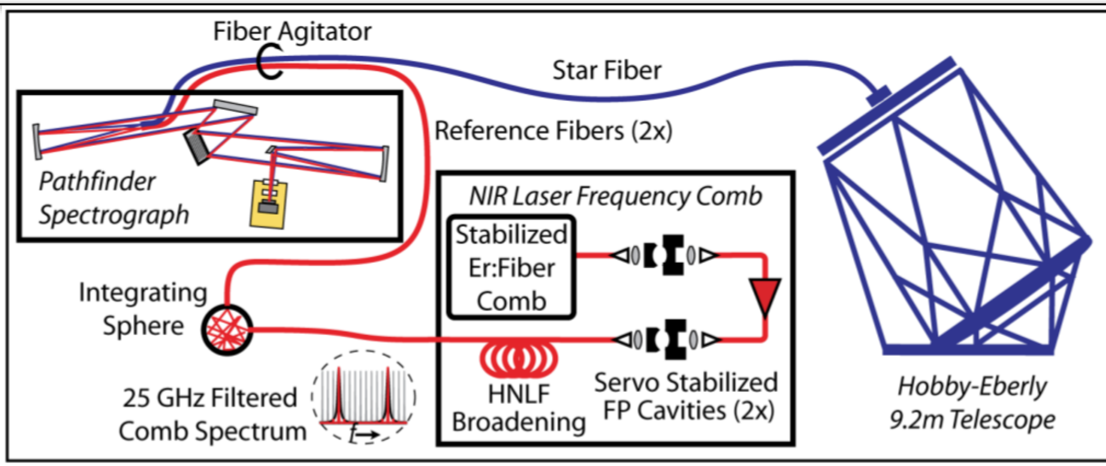


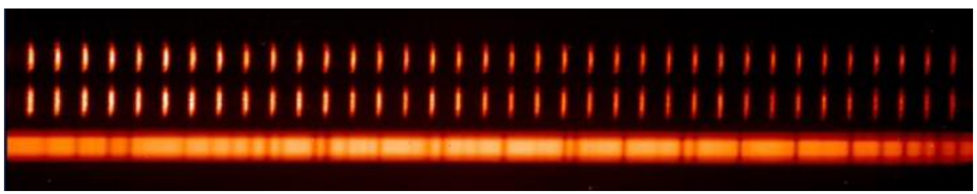
Jones *et al*, Science (2000)
Murphy *et al*, MNRAS (2007)
Wilken *et al*, MNRAS (2010)

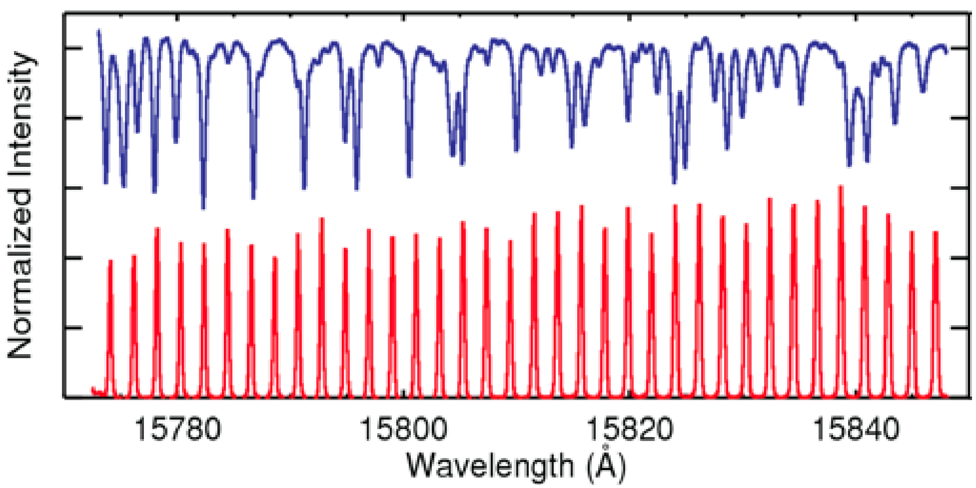
Out of the Lab and into the Field

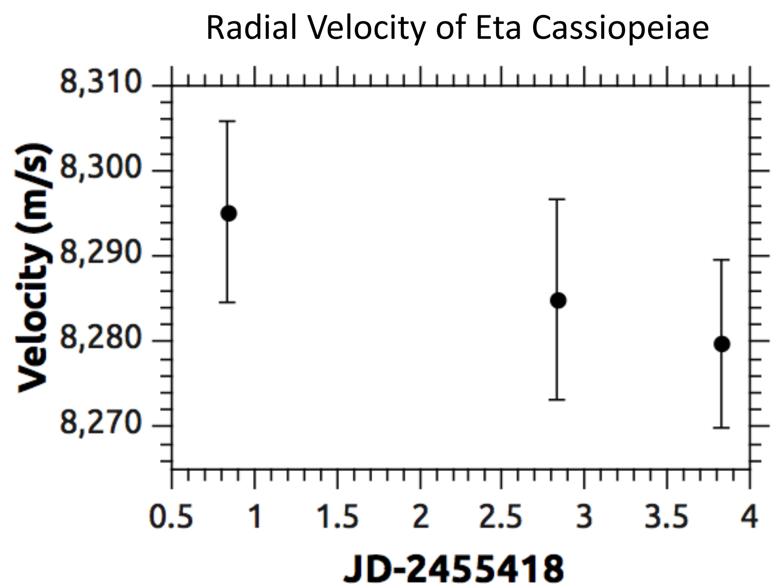
Frequency Comb Calibration of Stellar RV's

National Institute of Standards and Technology





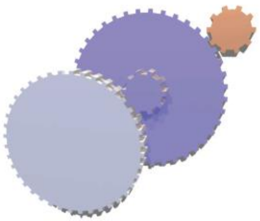


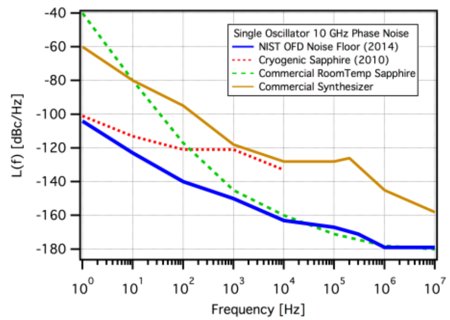


G. Ycas, et al, Optics Express **20**, 6631 (2012)

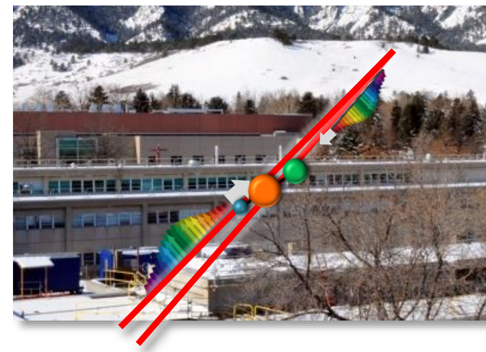
Example applications

Precision microwave generation
(for RADAR)

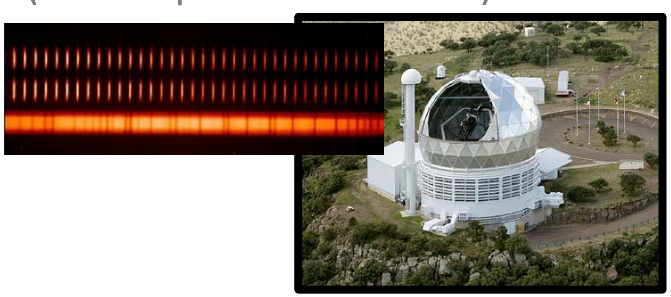




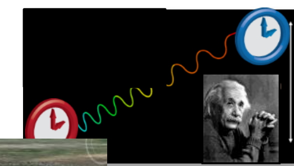
Precision molecular spectroscopy
(for greenhouse gases)



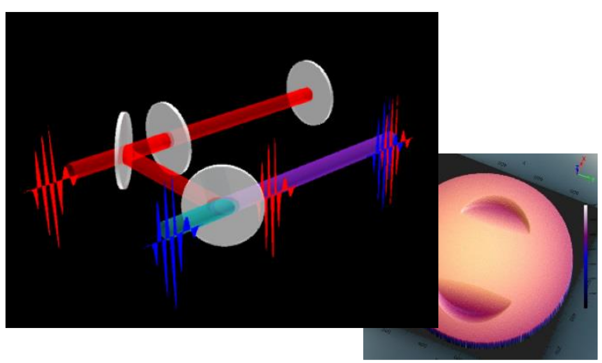
Precision spectroscopy
(for exoplanet searches)



Precision timing across synchronized network

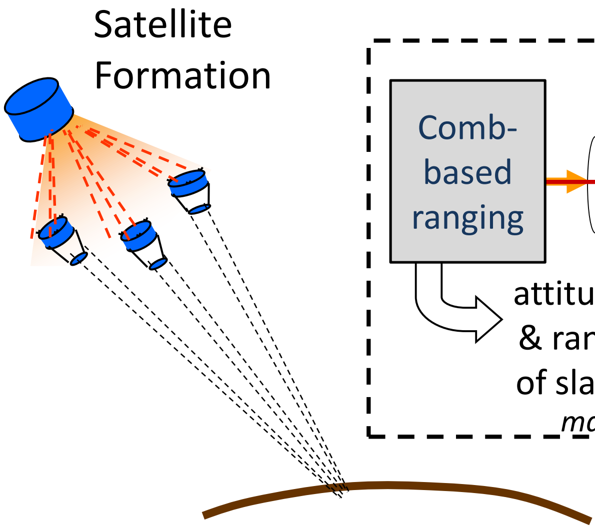


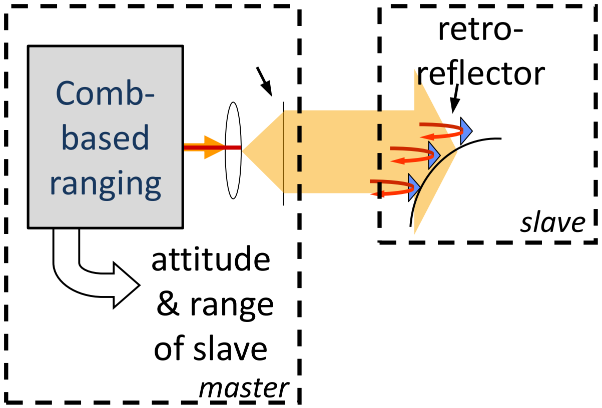
Precision Ranging



Others:
Advanced communications
Fundamental scientific tests
…

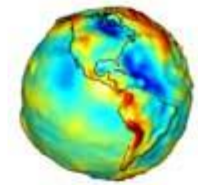
Why precision ranging?

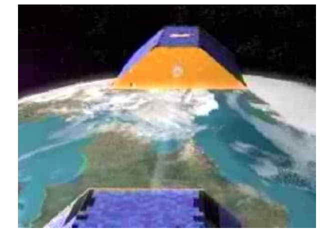




Formation flying for synthetic apertures

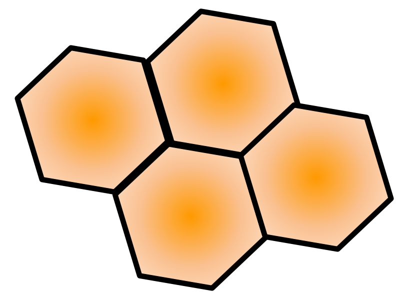
Precision Range & Attitude Control





Grace-like constellations for geodesy

Absolute ranging to multiple satellites



Large-scale optical metrology to support large aperture imaging

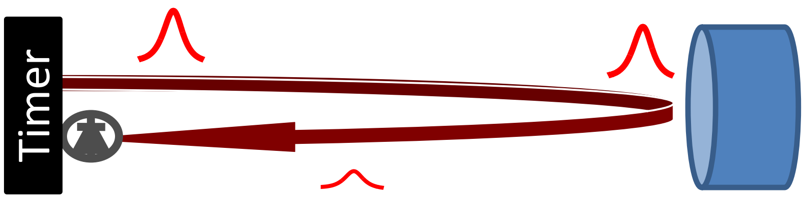
Combs have not played a role in these systems, but maybe they could…

Possible advantages of a comb-based system

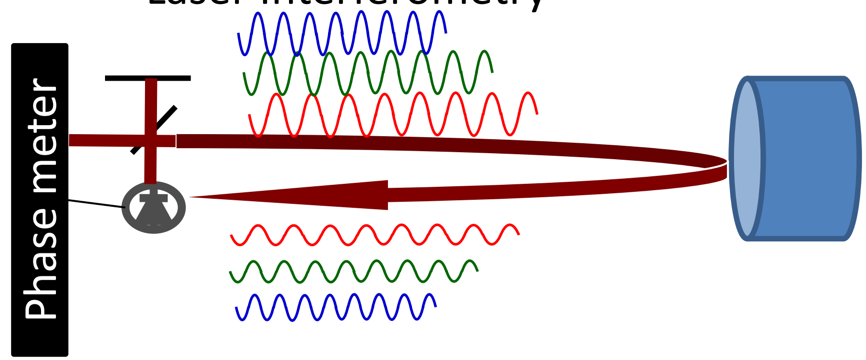
- Absolute distance with interferometric precision & fast update rates
- Absolute calibration to rf standard rather than secondary length reference (etalon)
- Low systematics from spurious reflections & cyclic errors

Laser ranging (LADAR)

Pulsed Time-of-Flight



Laser Interferometry



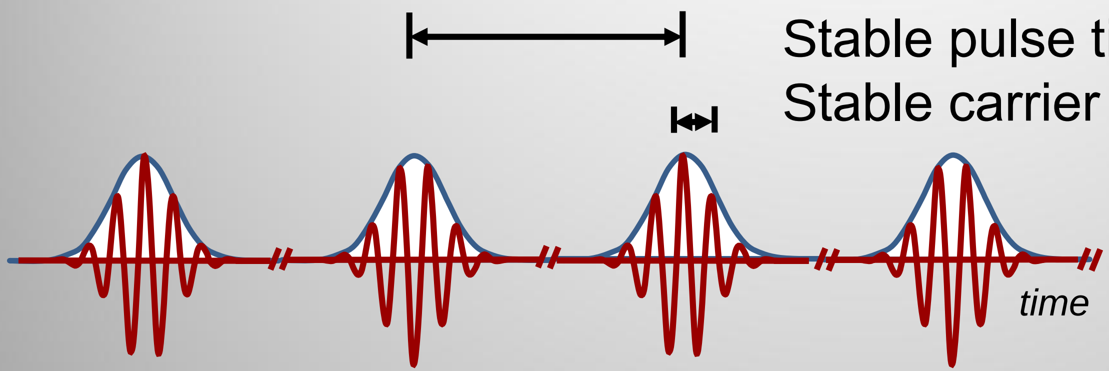
Absolute distance
Poor resolution

Sub-wavelength resolution
No absolute range (λ ambiguity)
(remove by adding more λ's)

Comb combines these!

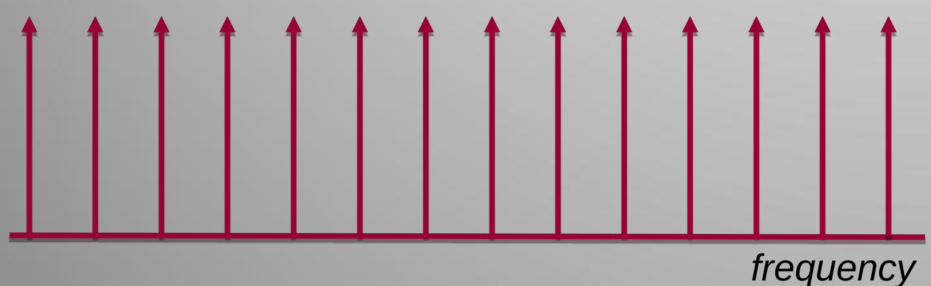
Properties of Combs For Ranging

Time-domain



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

Frequency-domain

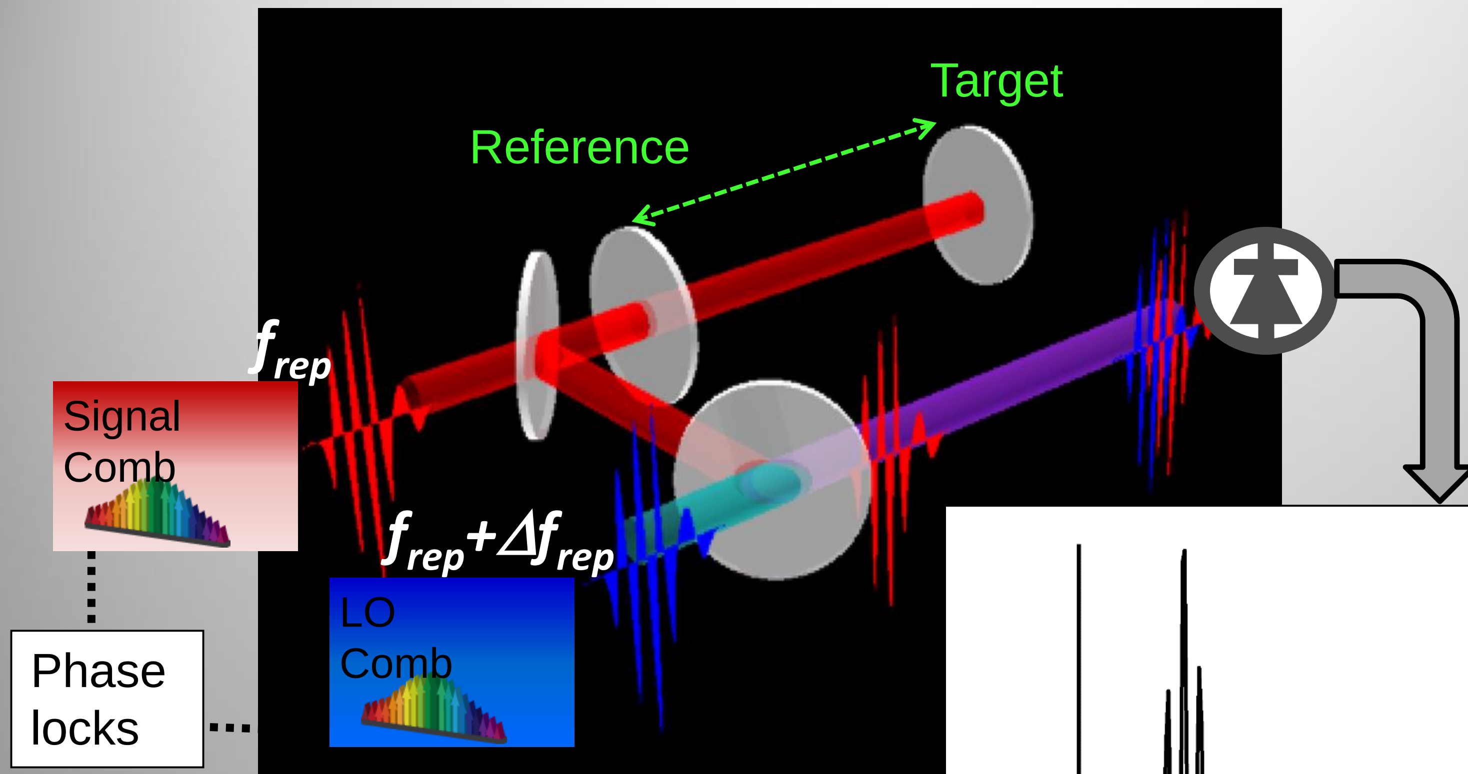


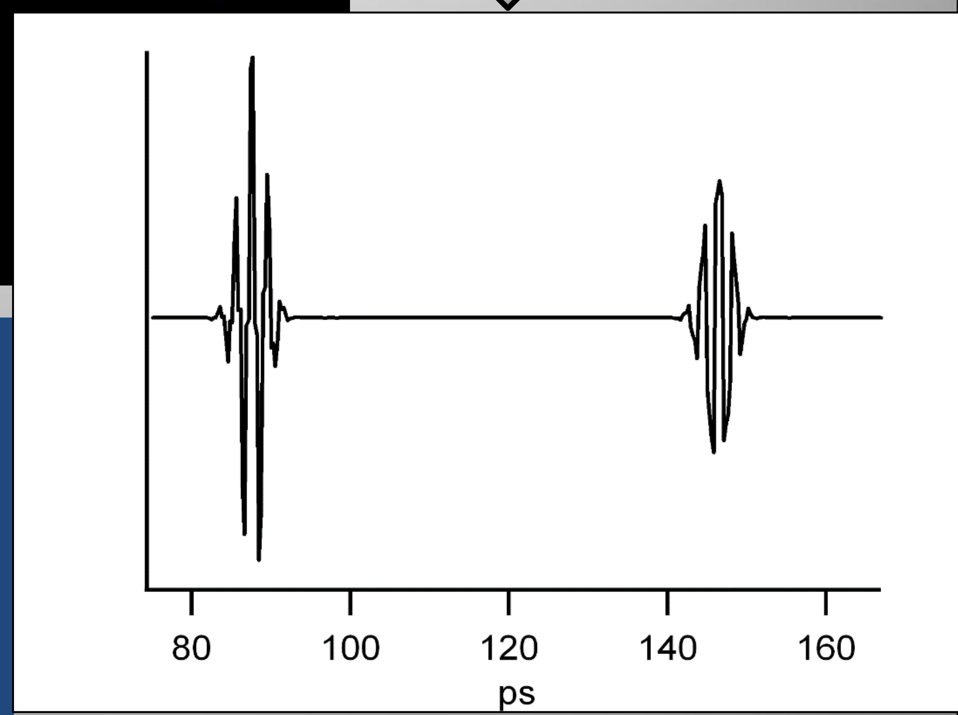
Comb = thousands to millions of "cw lasers"
→ Multi-wavelength interferometry

Many (tens) of comb-based LADARs demonstrated in labs worldwide

Joo et al, OE, 14, 5954 (2006)
Cui et al. OE 19, 6549 (2011)
Balling et al, OE 17, 9300 (2009)
Lee et al, Nat. Phot. 4, 716 (2010).
Schuhler et al, OL 31, 3101 (2006)
Salvade et al, AO, 47, 2715 (2008)
Joo et al, OE 16, 19799 (2008).
Minoshima et al, AO 39, 5512 (2000)
Yokoyama et al, OE, 17, 17324 (2009)
And many more

Dual-Comb Ranging

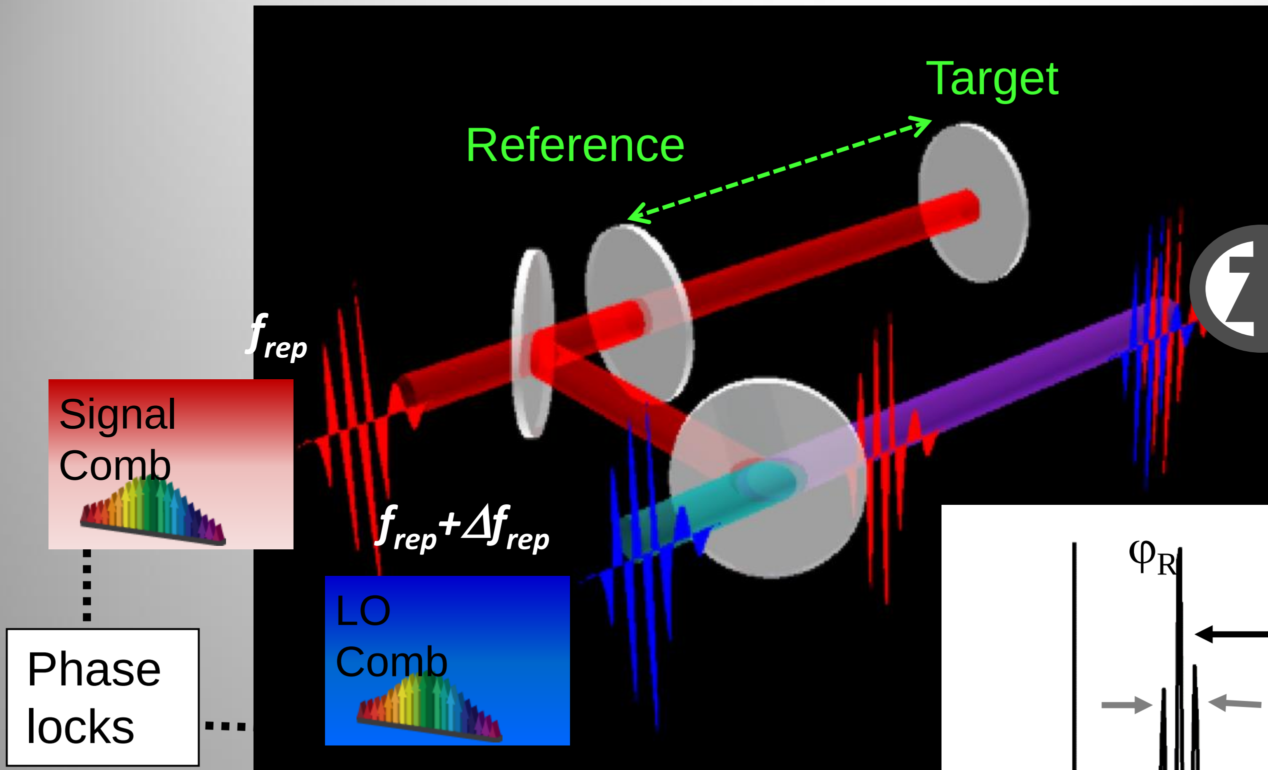


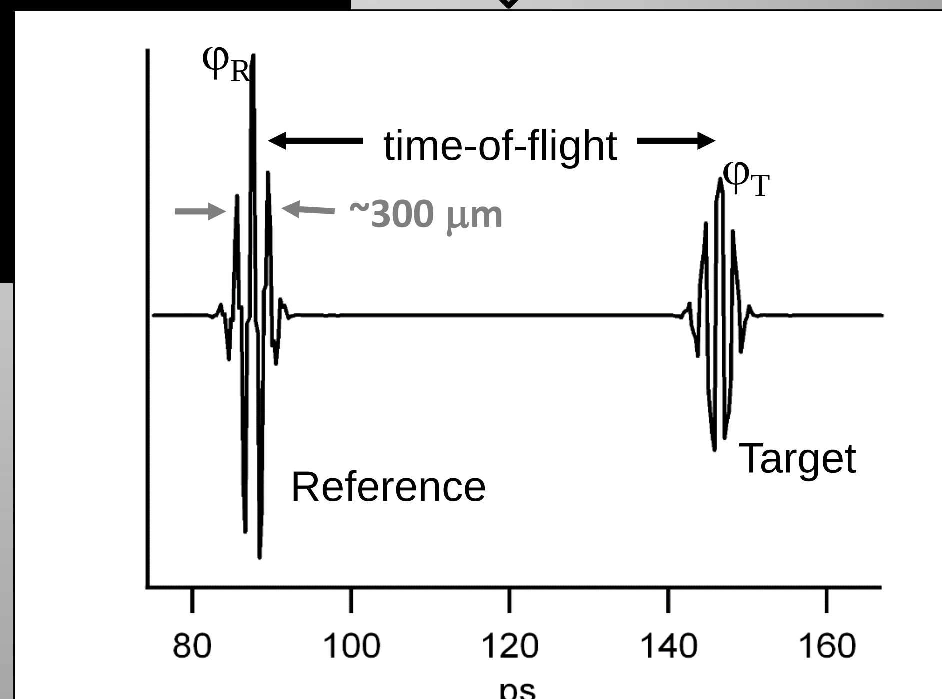


- LO comb “reads out” reflected signal pulses
  - LO comb at detuned repetition rate
  - Equivalent to a linear optical sampling scope
- Sensitivity , fast and accurate

Coddington et al, Nat. Phot. 3, 351 (2009).

Dual-Comb Ranging





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

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

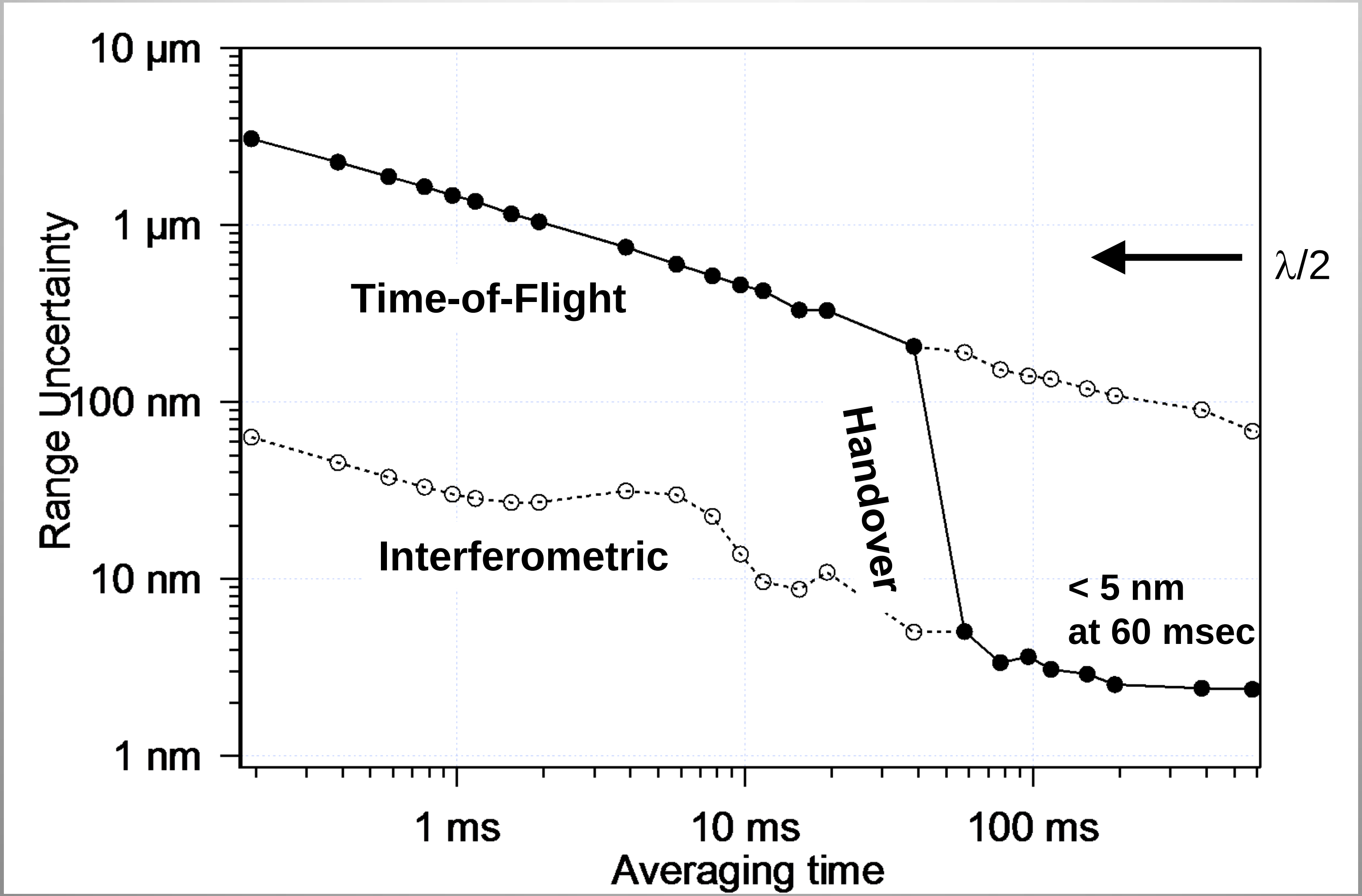
ambiguity

Handover of time-of-flight to interferometric range…

Coddington et al, Nat. Phot. 3, 351 (2009).

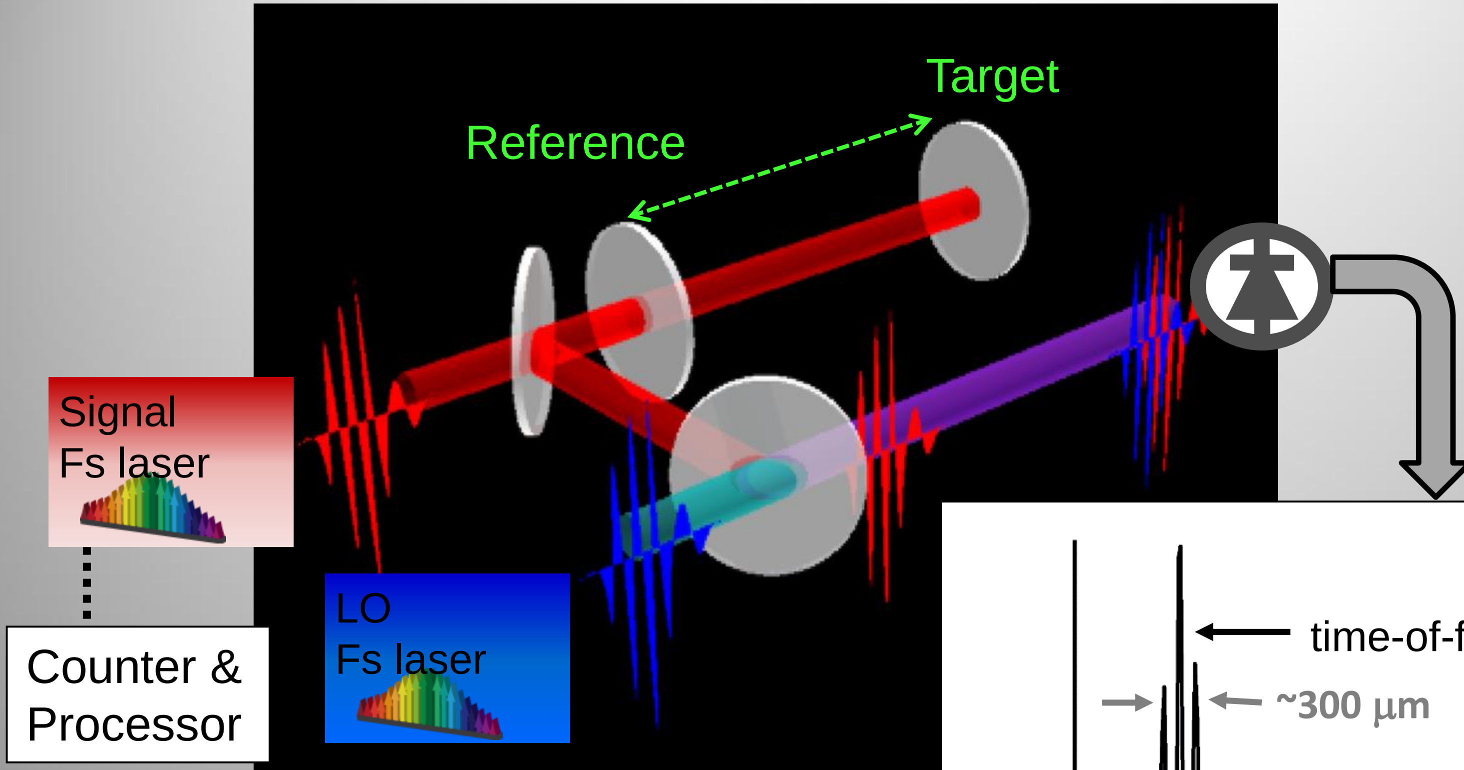
Range Uncertainty versus Observation Time

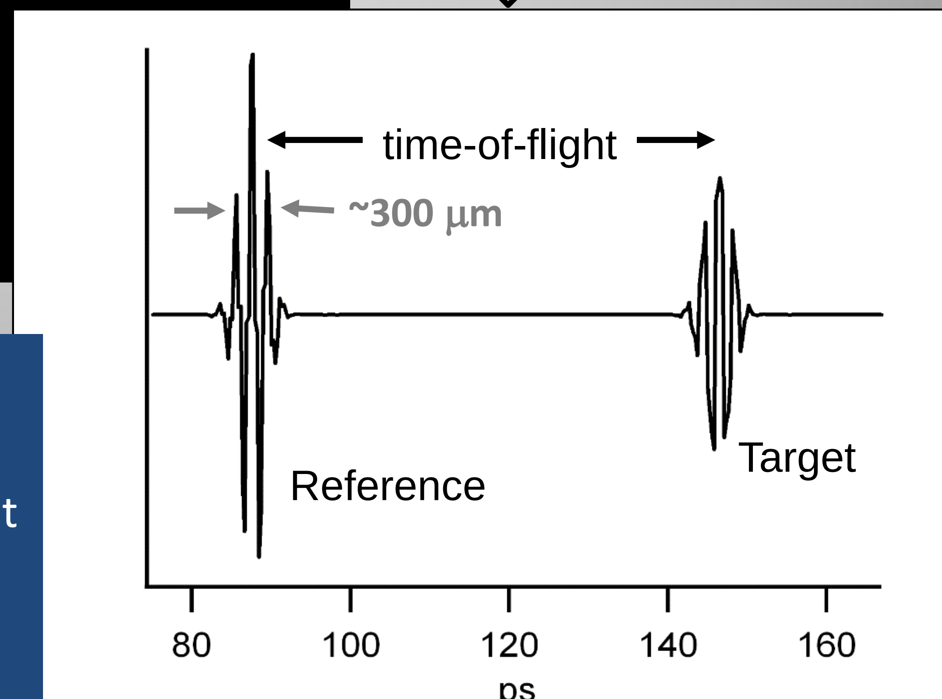
(Also verified Time-of-Flight and Interferometric *Agree*)



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

Dual-Comb Ranging with “free running” fs lasers



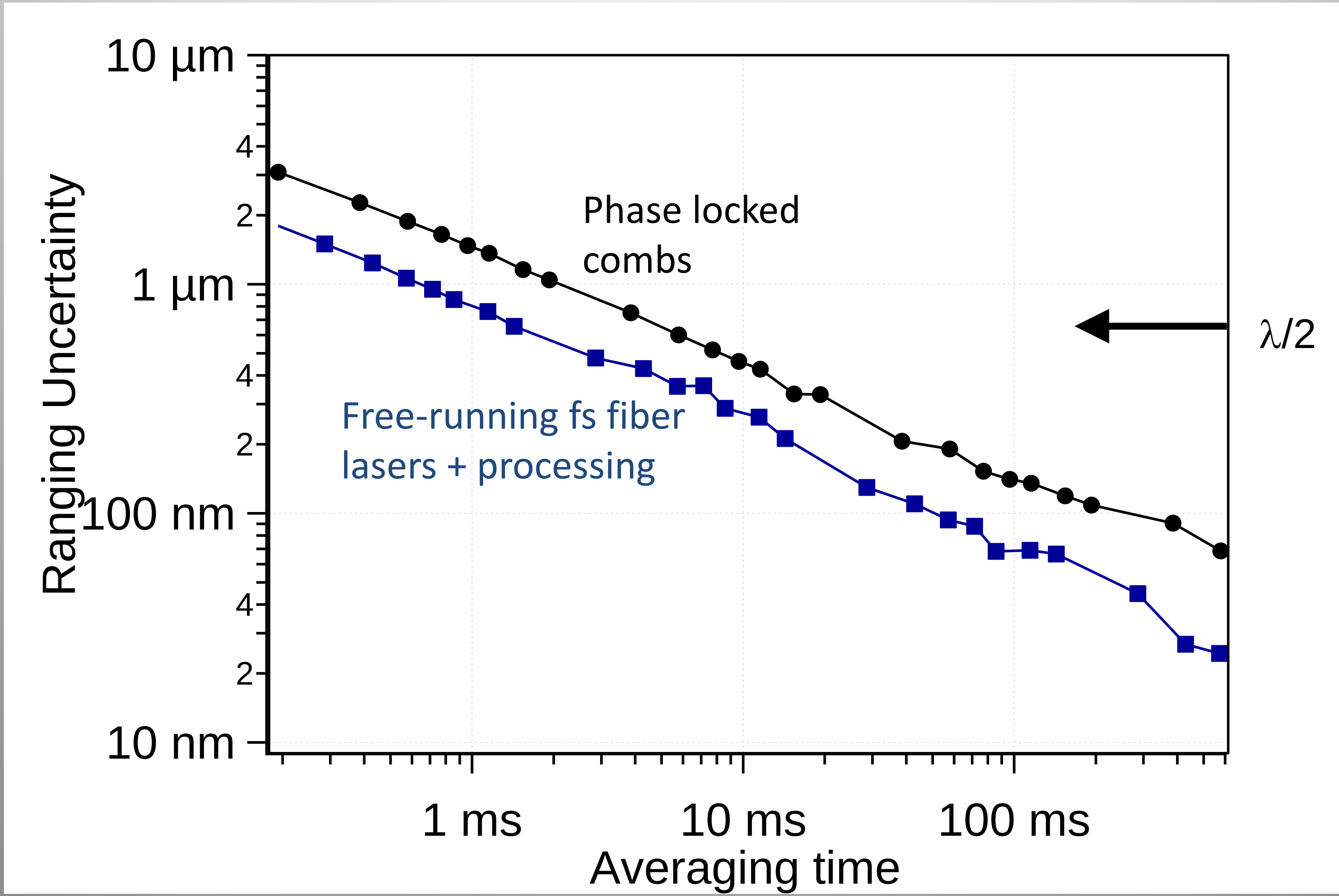


- No phase locking of combs
- Simple linear fs Er laser cavity
- Roughly tune to desired repetition rate offset
- Count repetition rate & process signals
- Range still traceable to rf reference clock
- Lose interferometric ranging

Liu et al, Opt. Express, 19, 18501 (2011)

Dual-comb ranging with free-running fs fiber lasers

No penalty except loss of interferometric range



Dual-Comb Ranging

- **Advantages**
  - Rapid, absolute, high precision ranging (sub-micron in sub-ms)
  - Immune to spurious reflections with no significant dead zones
- **Disadvantage**
  - Two combs
  - Linear sampling -> inefficient use of photons -> nWatts needed

- Conventional swept laser interferometry (FMCW LADAR) is more photon efficient

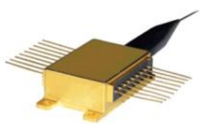
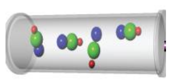
Can we combine combs and swept laser interferometry?

Combing Swept Cw Lasers & Combs

Goal: Track a swept laser's phase with a comb
- ❖ With high accuracy
- ❖ At high speeds
- ❖ Over arbitrary waveforms

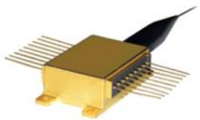
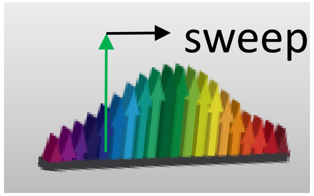
Why?
- ❖ Swept laser ranging
- ❖ Swept laser spectroscopy

Conventional etalon-calibrated swept laser

 +  + 

Swept laser | Gas cell | Etalon

Comb-calibrated swept laser

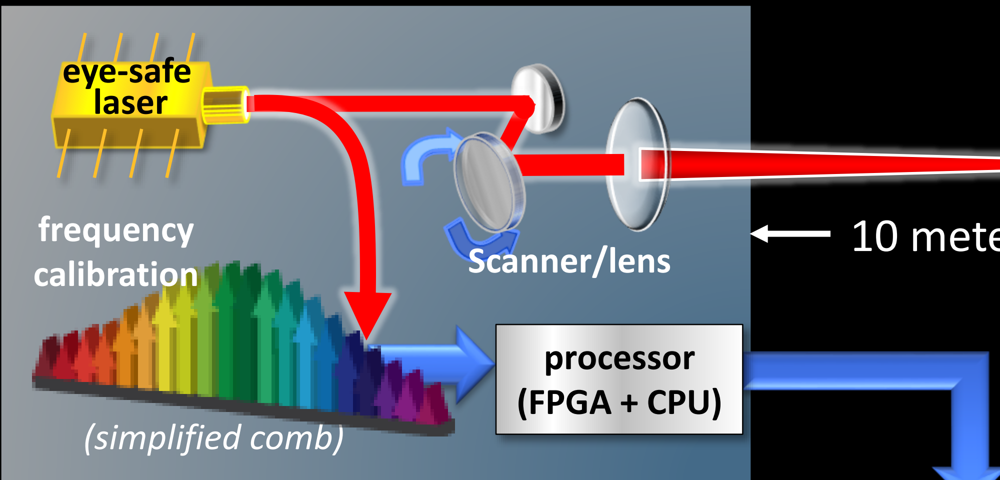
 + 

Swept laser | Comb = Fs fiber laser + f_{rep} counter

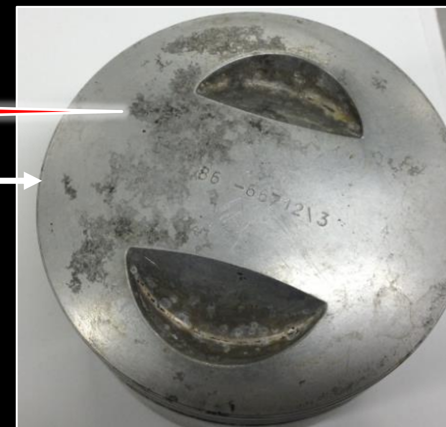
Disadvantage:
- **Greater complexity – needs a comb!**

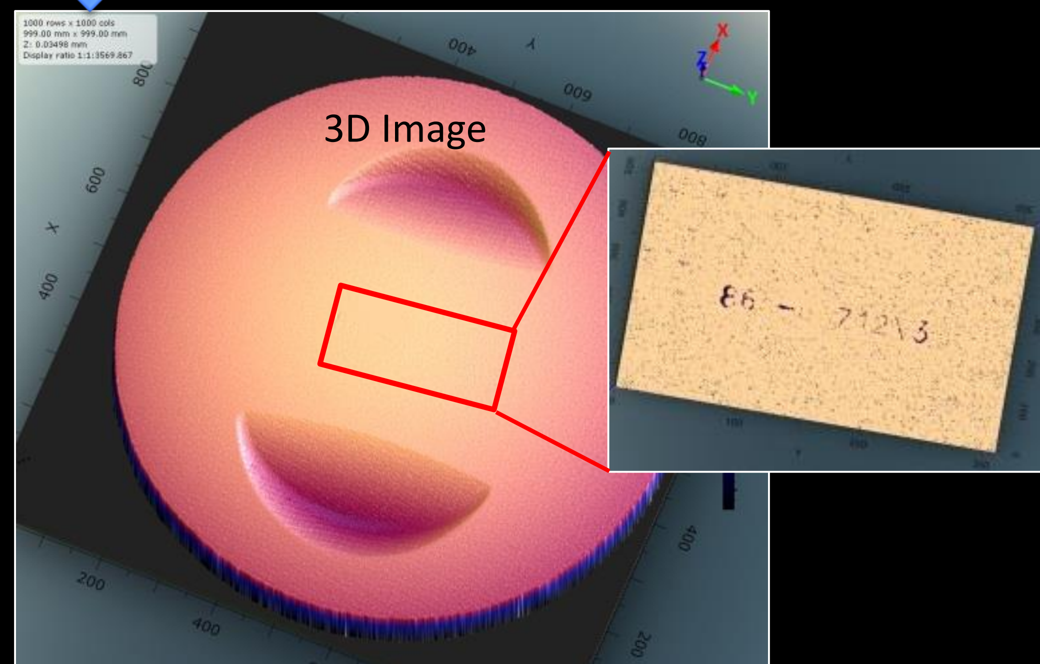
Advantages:
- **Absolute calibration based on f_{rep} vs. physical etalon**
- **Phase continuous measurements**
- ***Compatible with future chip-scale systems***

Comb-calibrated Laser Ranging



Engine Piston (1975 Ducati 860 GT)



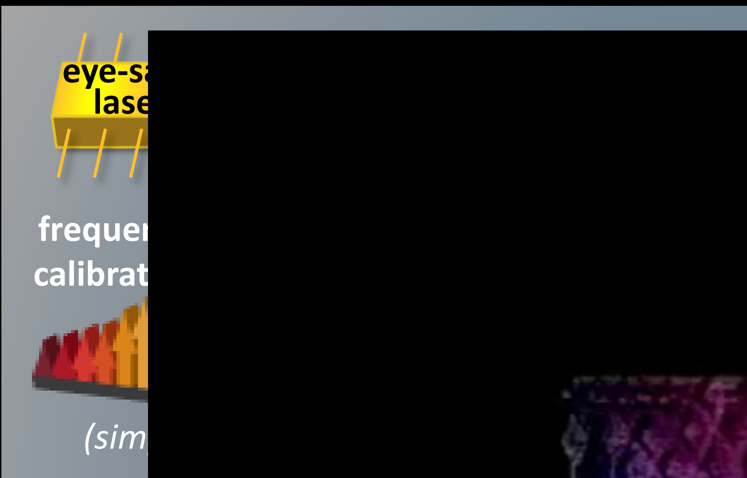


FMCW LADAR (= Swept Source LIDAR)

- 1 THz bandwidth
- 100 nm accuracy traceable to rf clock (limited by air index)
- Speckle phase noise limited
- 2000 points/sec
- 8 min for a megapixel image

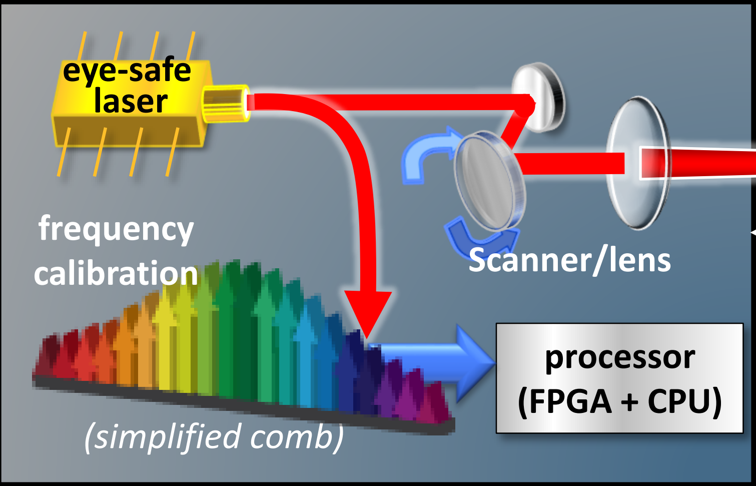
Baumann et al, Opt. Lett. 38, 2026 (2013)
Baumann et al., Opt. Exp., 22, 24914 (2014)

Comb-calibrated Laser Ranging



Repl
lov
im

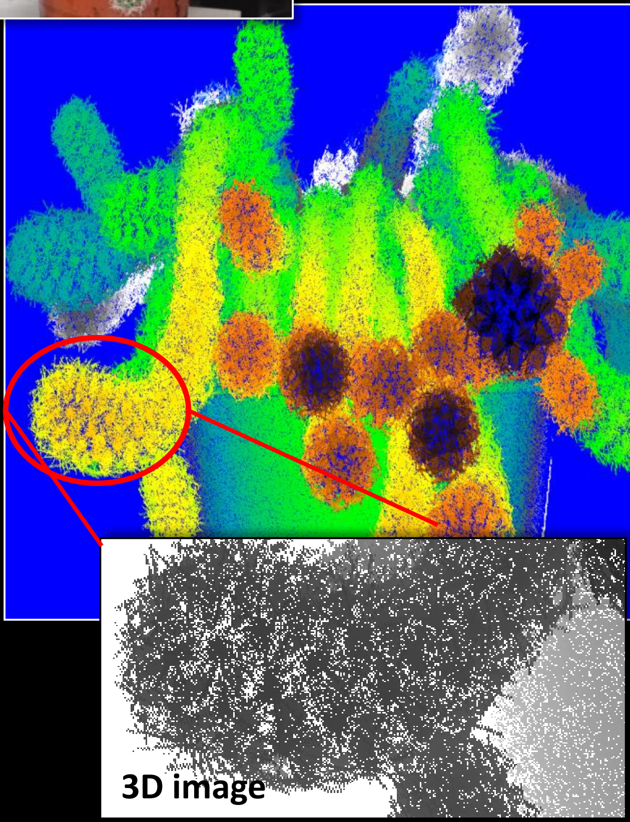
Measuring Complex, Soft Surfaces



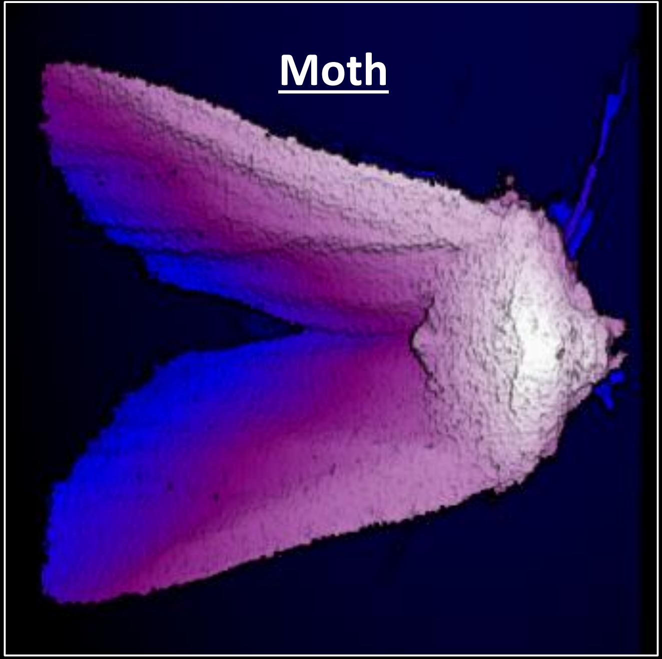
← 2 - 10 meter →

(100 m should be possible)

Cactus

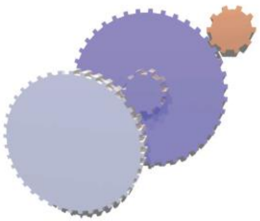


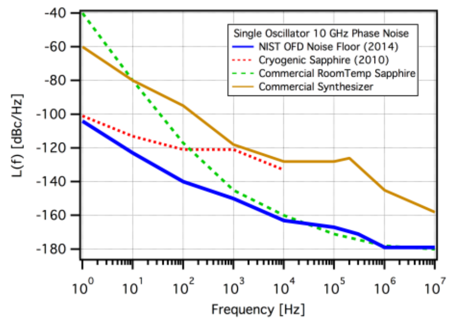
Non-metallic surface with enormous range variation



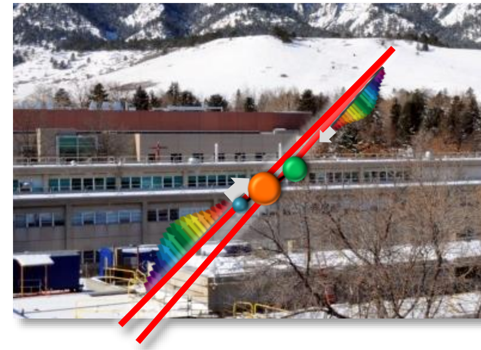
Example applications

Precision microwave generation
(for RADAR)



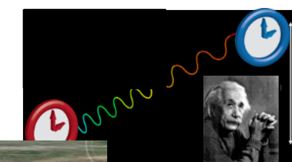


Precision molecular spectroscopy
(for greenhouse gases)

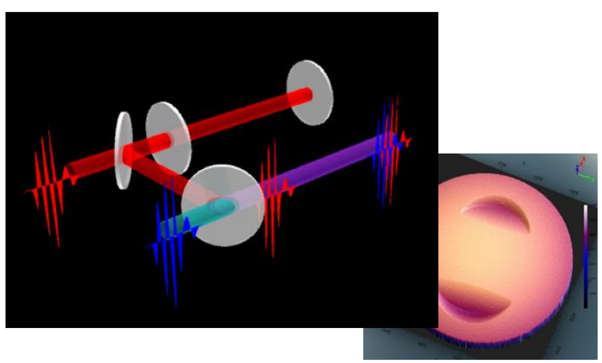


Precision spectroscopy
(for exoplanet searches)

Precision timing across synchronized network



Precision Ranging

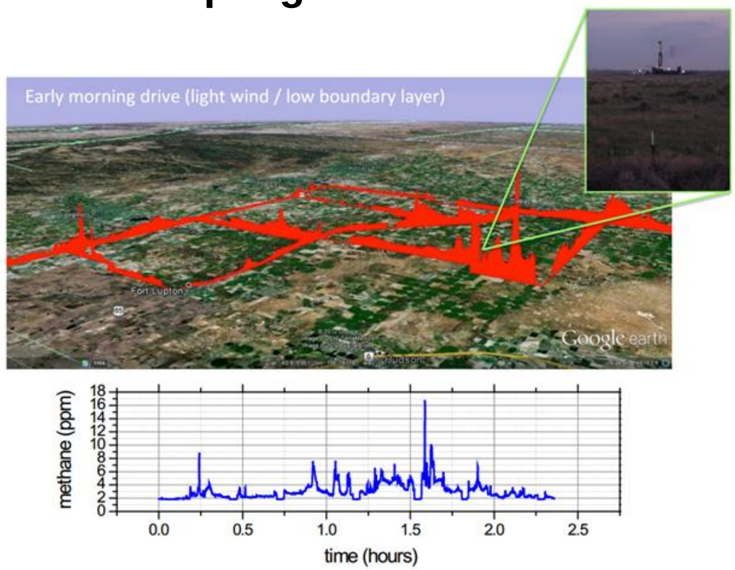


Others:
Advanced communications
Fundamental scientific tests
…

Climate Change And Greenhouse Gases

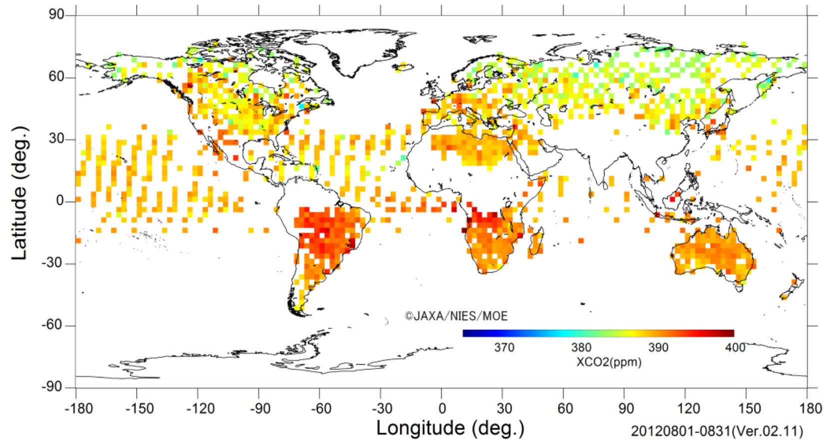
Goal: Accurately measure Greenhouse gases [CO_2, CH_4, H_2O, isotopes]
Identify sources and sinks (cities, wells, landfills) etc.

Point-sampling in a Vehicle



CW Rella, Global Monitoring Annual Conference, 2013

GOSAT (GHG-observing satellite) Monthly Column-averaged CO_2 Concentration

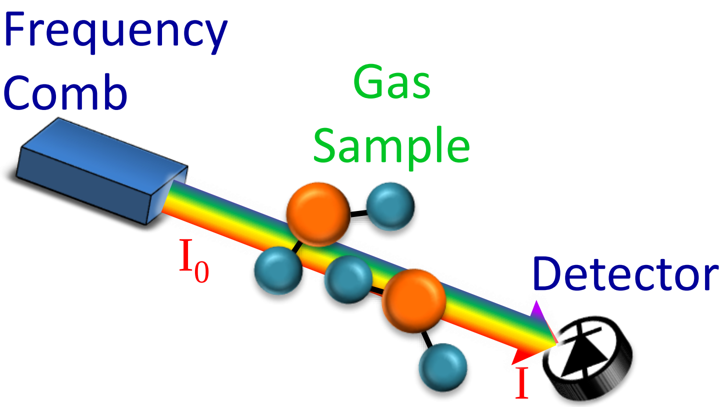


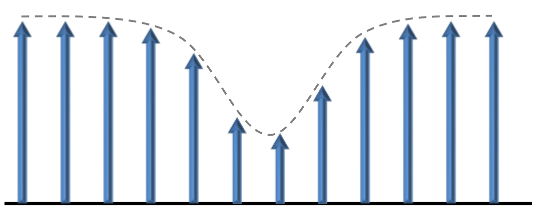
GOSAT Public Data, August 2012 (Ver. 02.11)

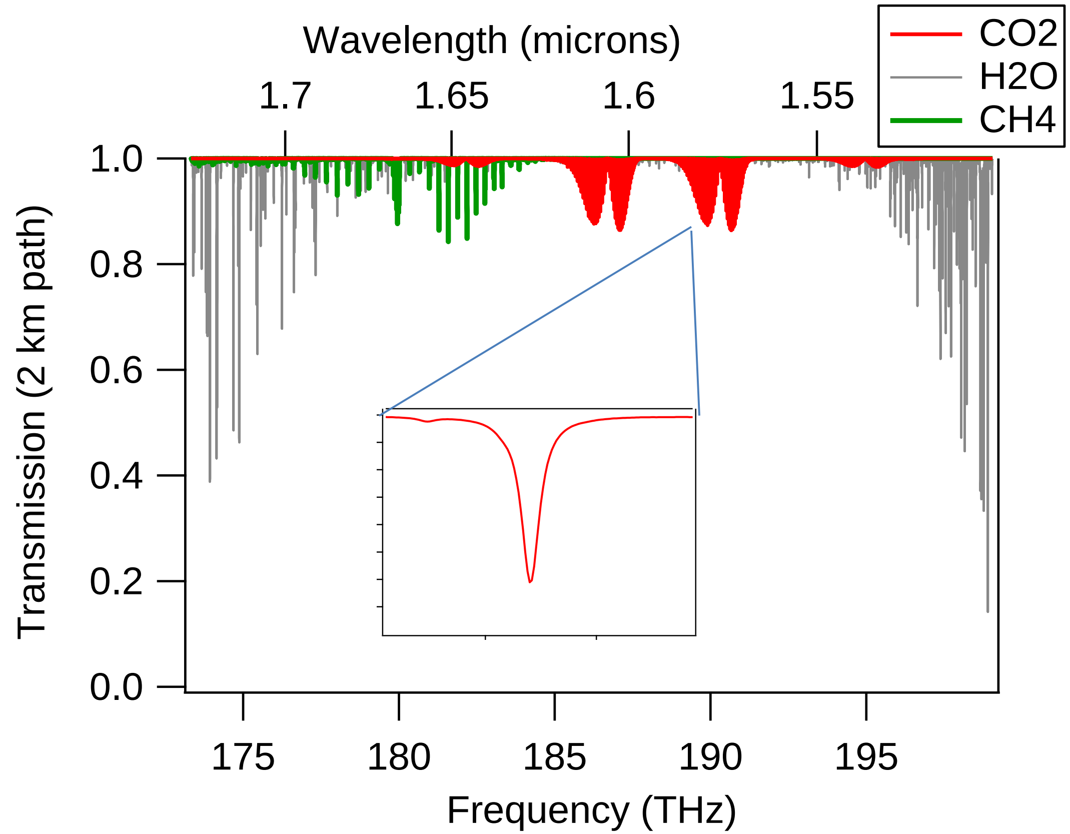
Comb spectroscopy over a km-scale open air path can provide:

- **1-10 km length scales (between point & satellite sensors)**
- **Eye safe, accurate, continuous, automated measurements….**

Absorption Spectroscopy





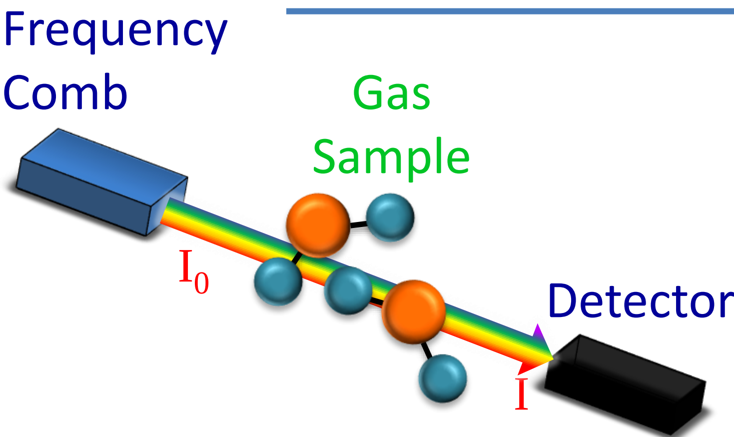


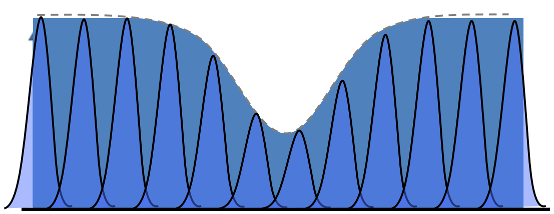
Comb as the ideal source

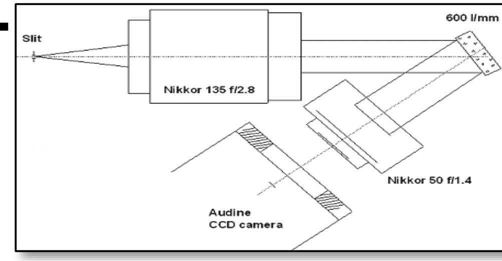
- **Collimated, single-mode light for long interactionl lengths**
- **Broadband spectral coverage across vis/ir/uv spectrum**
- **Narrow "delta-function" frequency sampling**
- **Built-in frequency calibration**

But how to detect?

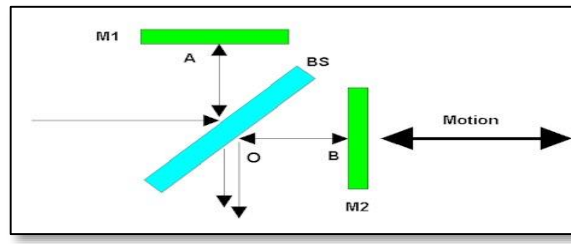
Spectral dispersers



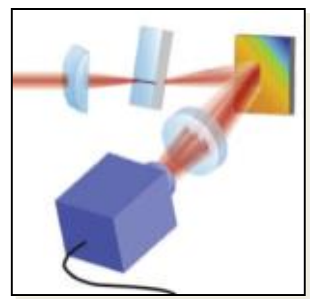




Grating Spectrograph



Fourier Transform Spectrometer

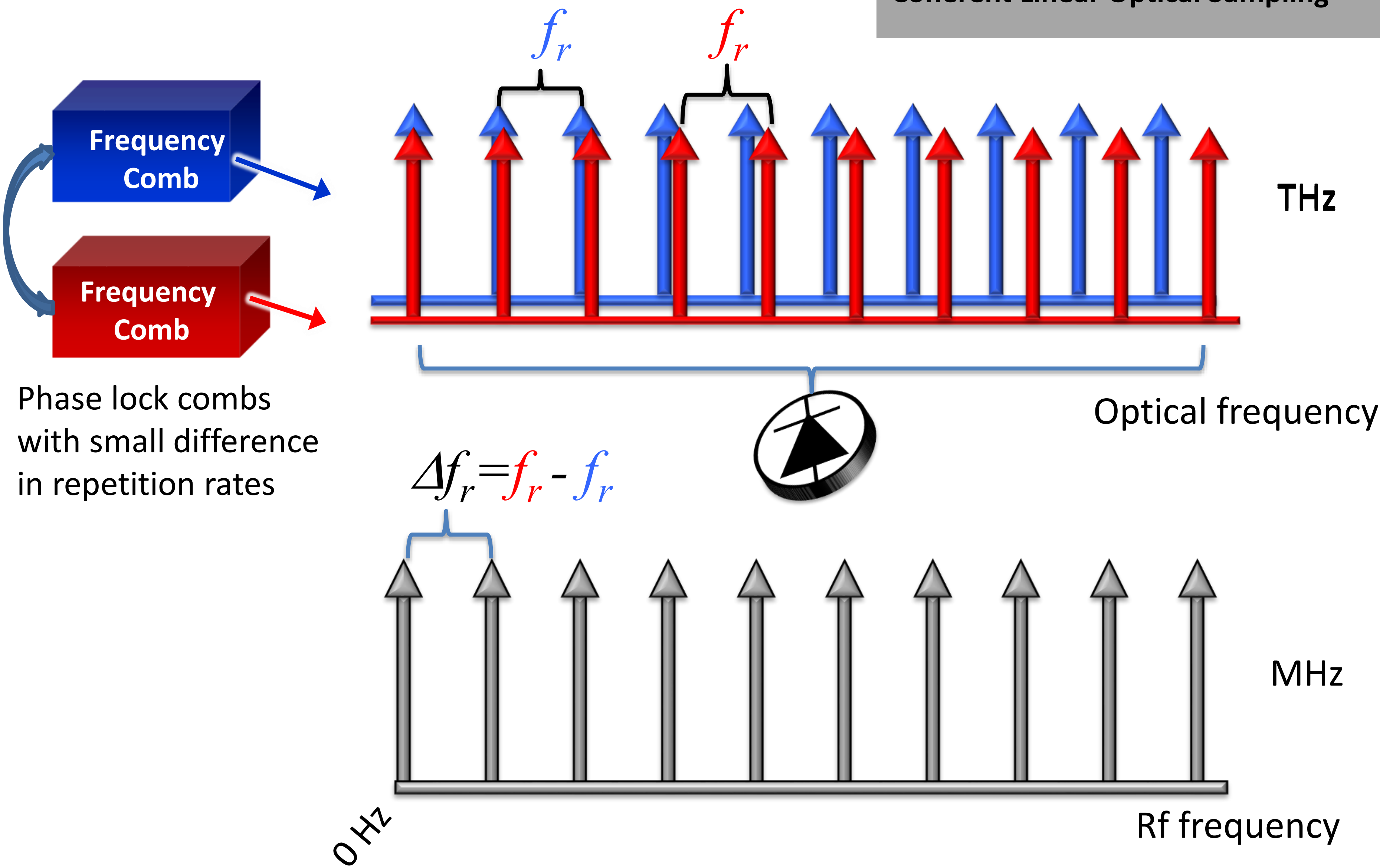


Grating/VIPA (high res) Spectrograph

Dual-Comb Spectroscopy

Dual-Comb Spectroscopy

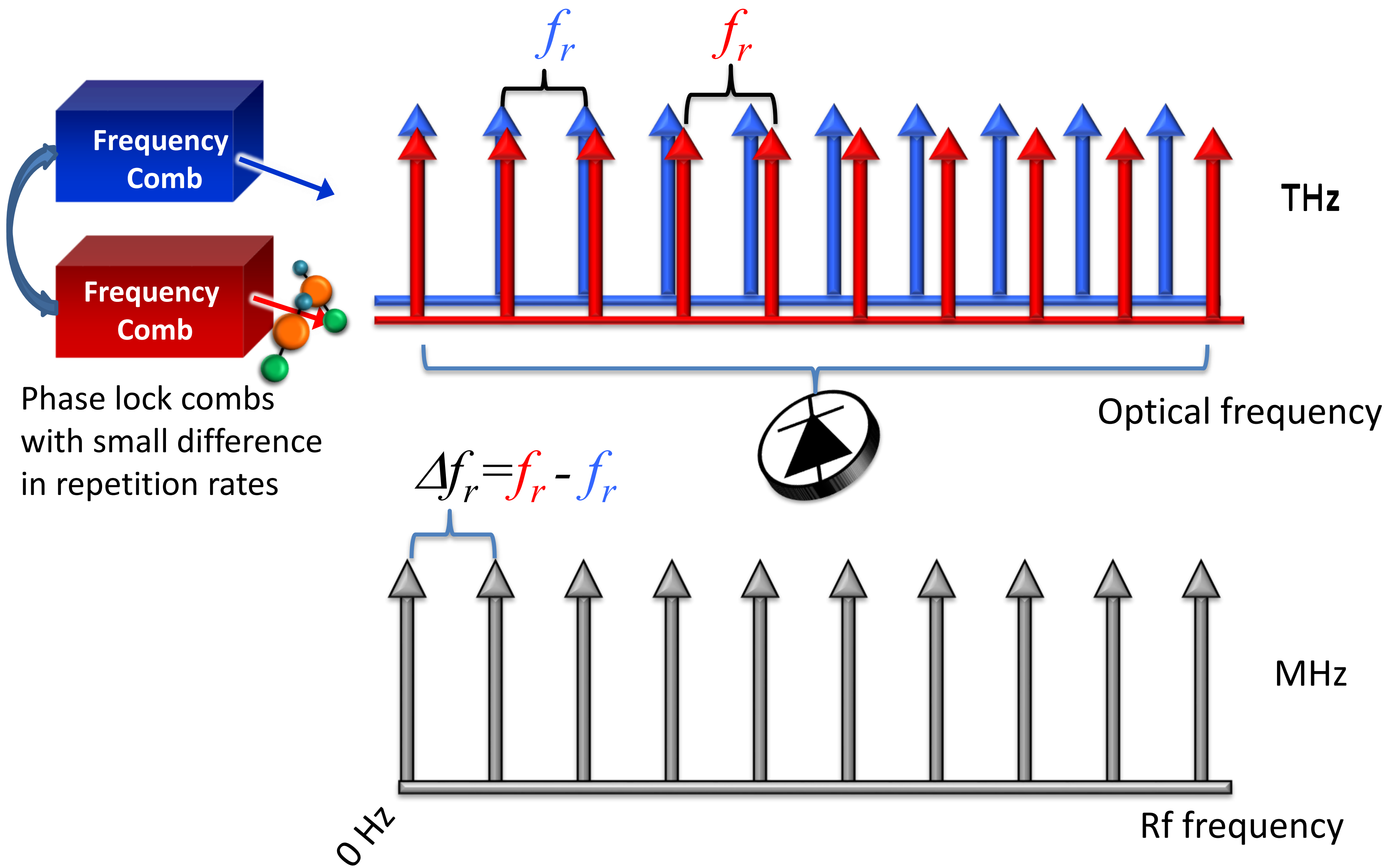
Otherwise known as: Multi-heterodyne spectroscopy, THz TDS, Coherent Linear Optical Sampling



Phase lock combs with small difference in repetition rates

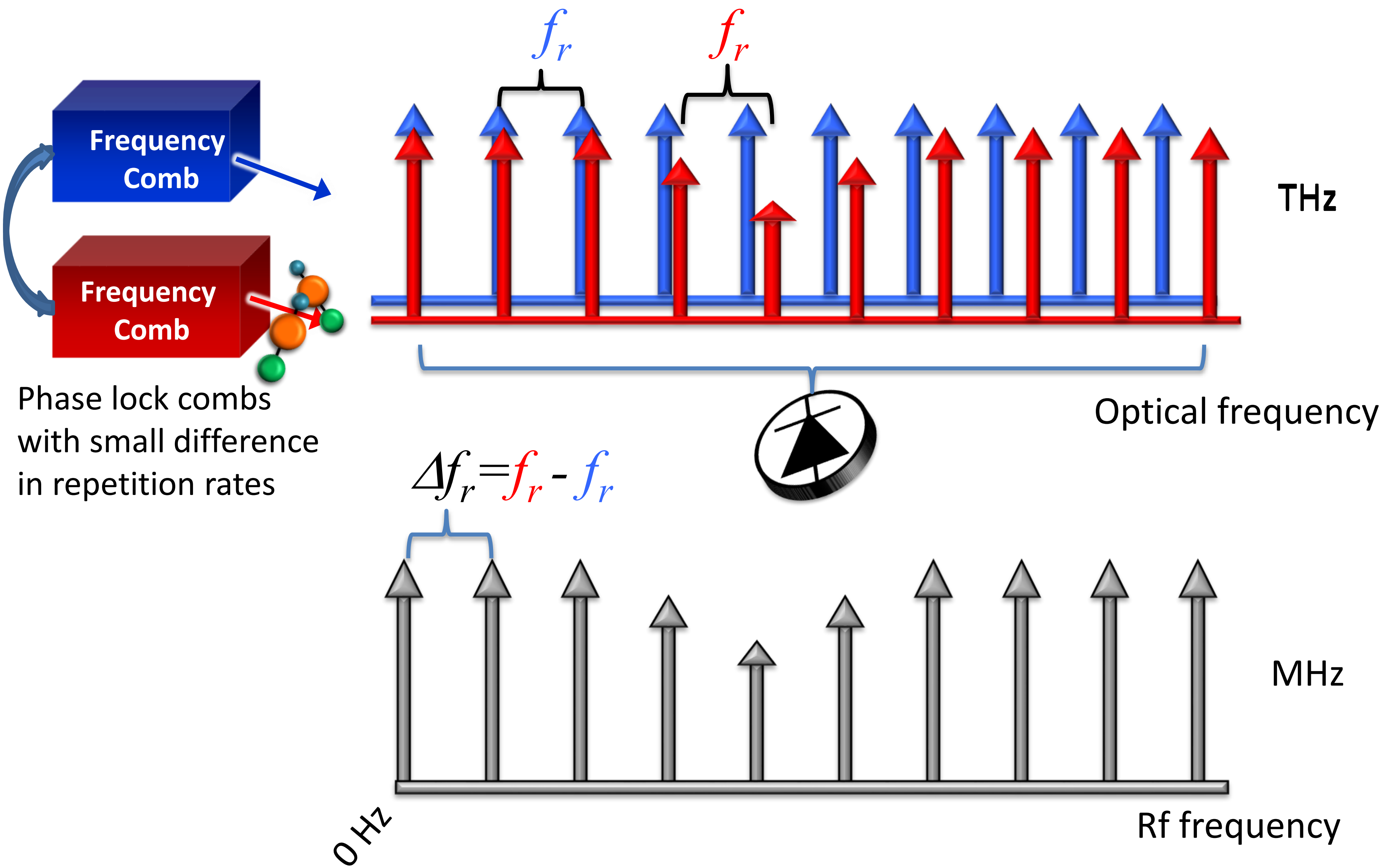
EXACT one-to-one correspondence between optical & rf frequencies

Dual Comb Detection



EXACT one-to-one correspondence between optical & rf frequencies

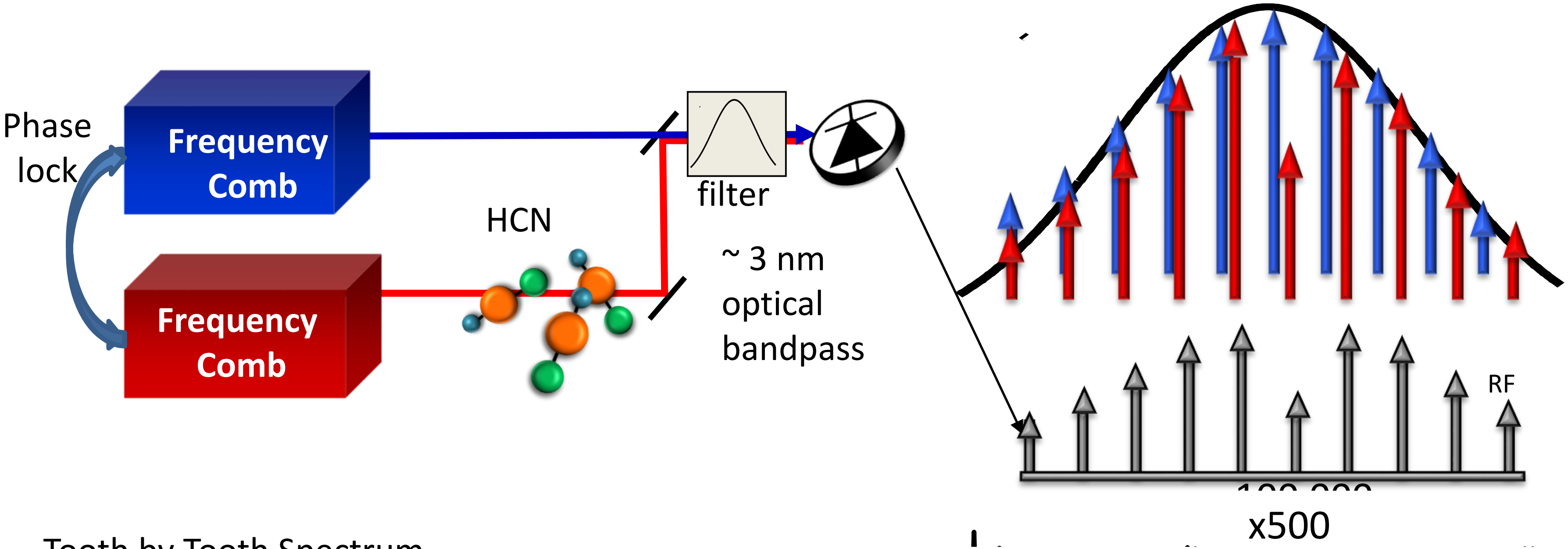
Dual Comb Detection

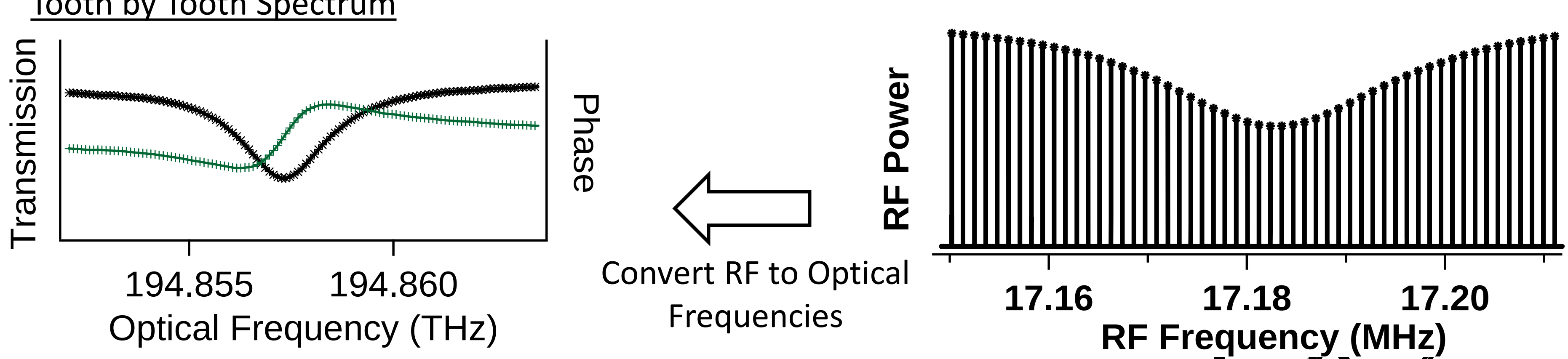


Phase lock combs with small difference in repetition rates

EXACT one-to-one correspondence between optical & rf frequencies

Dual Comb Spectroscopy: real data

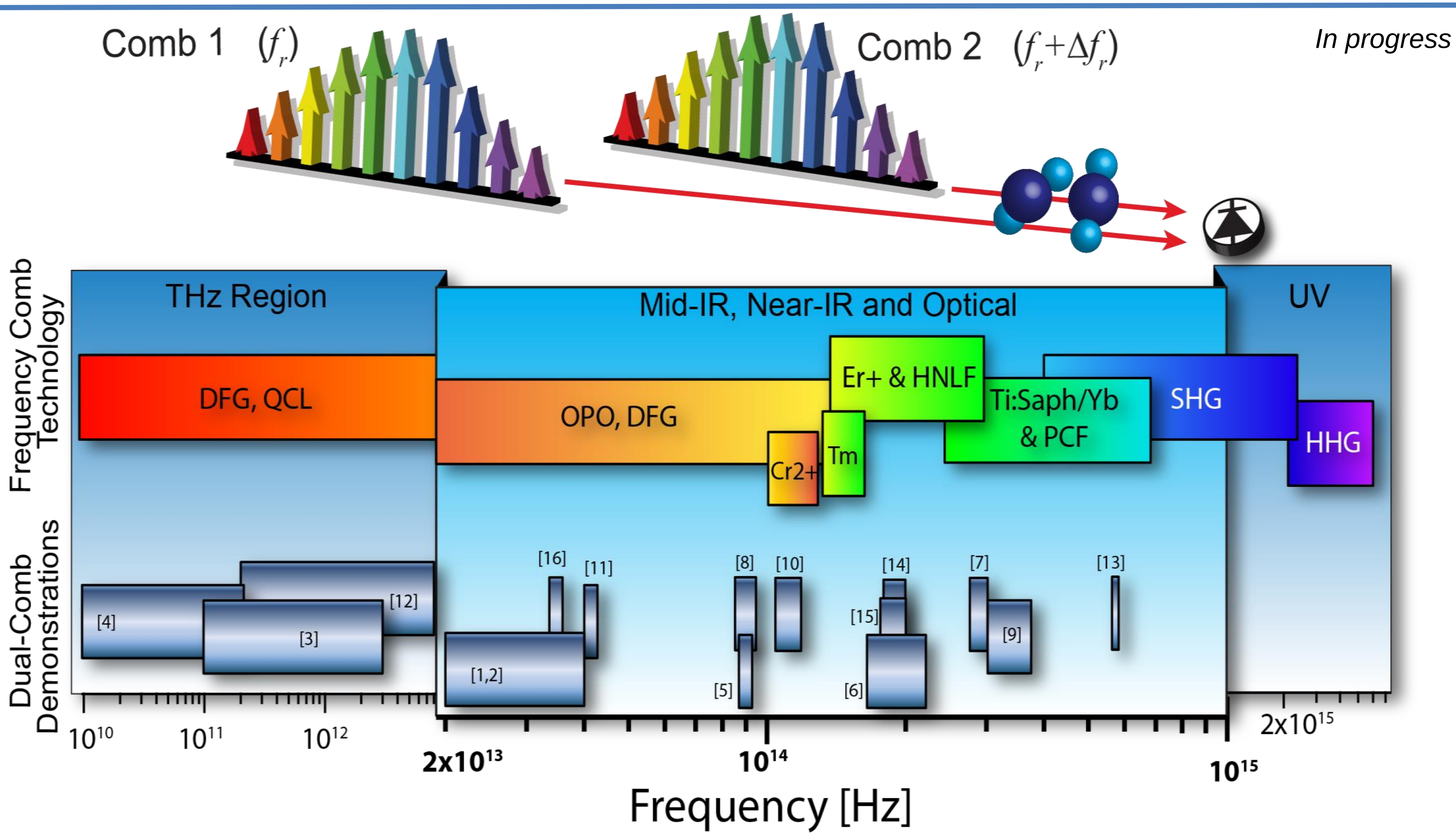




Measure gas absorption (and phase shift) on a comb tooth by comb tooth basis

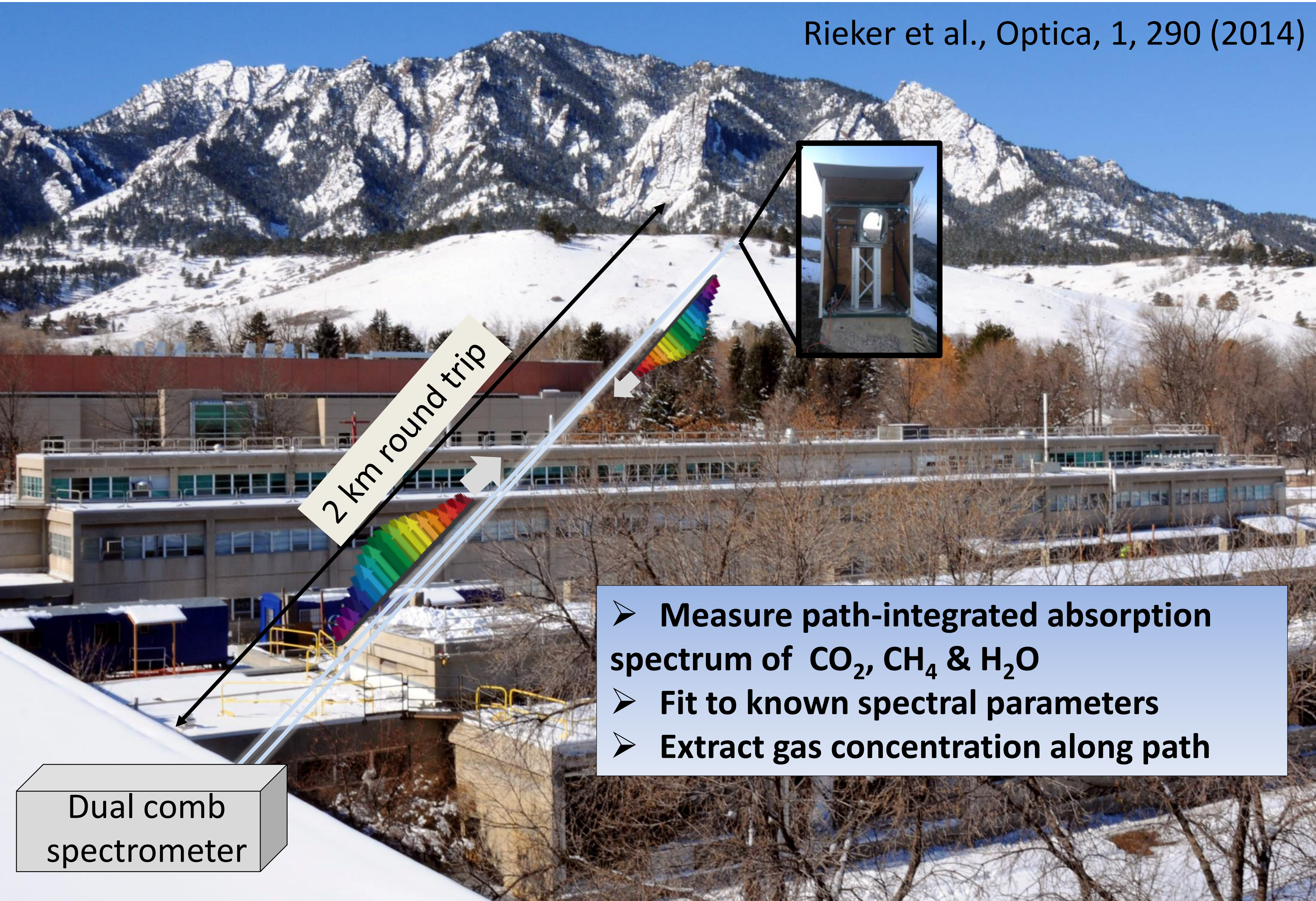
Ian Coddington, Bill Swann, PRL **100**, 013902 (2008)

Frequency Comb and Dual-Comb Spectroscopy: Demonstrations



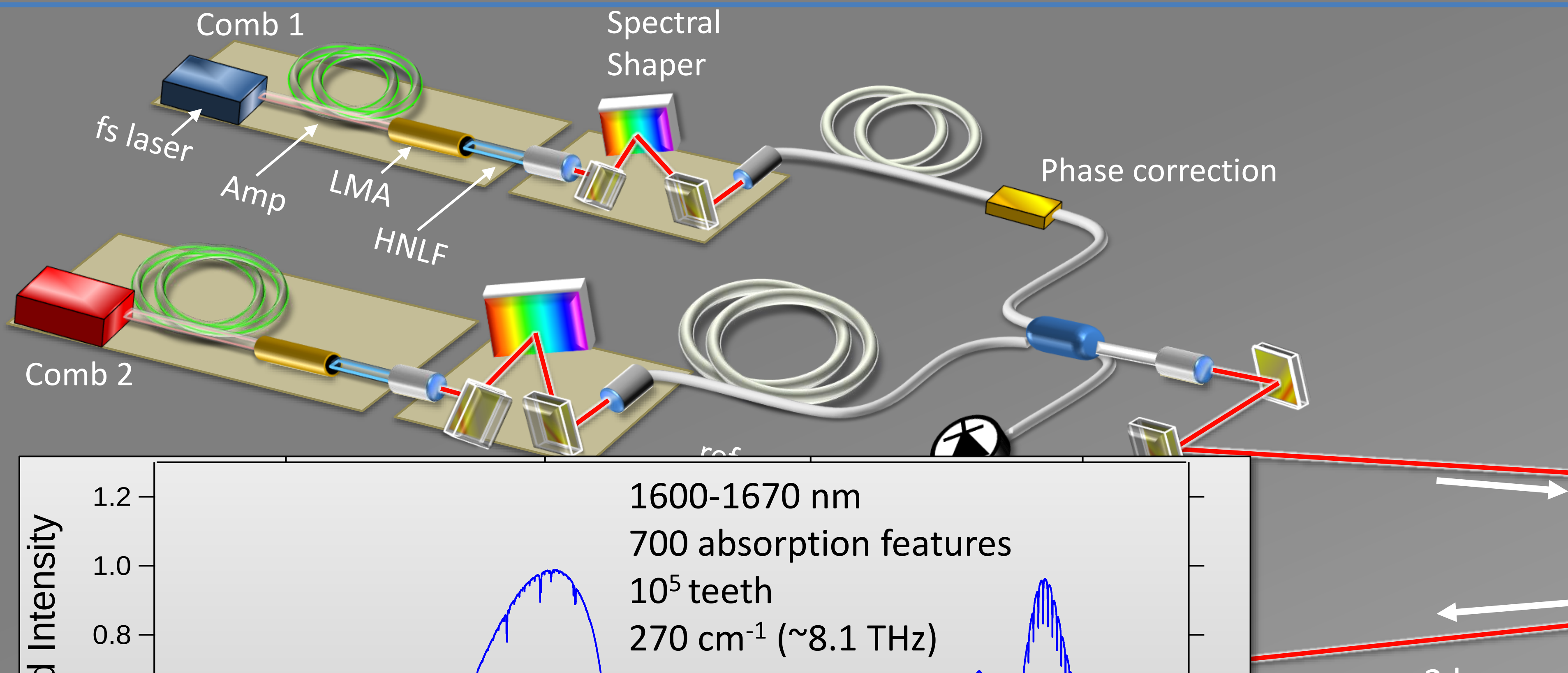
1. Schliesser, et al. , D. Opt. Express 13, 9029–9038 (2005).
2. Keilmann, F., Gohle, C. & Holzwarth, R. Opt. Lett. 29, 1542–1544 (2004).
3. Von Ribbeck, H.-G. et al. Opt. Express 16, 3430–3438 (2008).
4. Yasui, T., et al. , T. Appl. Phys. Lett. 88, 241104 (2006).
5. Baumann, E. et al. Phys. Rev. A 84, 062513 (2011).
6. Zolot, A. M. et al. Opt. Lett. 37, 638–640 (2012).
7. Bernhardt, B. et al. Nat. Photonics 4, 55–57 (2010).
8. Zhang, Z. et al. Opt. Lett. 38, 3148–3150 (2013).
9. Potvin, S. & Genest, J. Opt. Express 21, 30707–30715 (2013).
10. Bernhardt, B. et al. Appl. Phys. B 100, 3–8 (2010).
11. Villares, G. et al. Nature Comm. 5, 5192 (2014)
12. Klatt, G., et al. IEEE JSTQE 17, 159–158 (2011).
13. Ideguchi, T., et al. Opt. Lett. 37, 4847–4849 (2012).
14. Coddington, I., Swann, W. C. & Newbury, N. R. Phys. Rev. Lett. 100, 013902 (2008).
15. Roy, J., Deschênes, J.-D., Potvin, S. & Genest, J. Opt. Express 20, 21932–21939 (2012).
16. Wang Y., et al., Appl. Phys. Lett. 104, 031114 (2014)

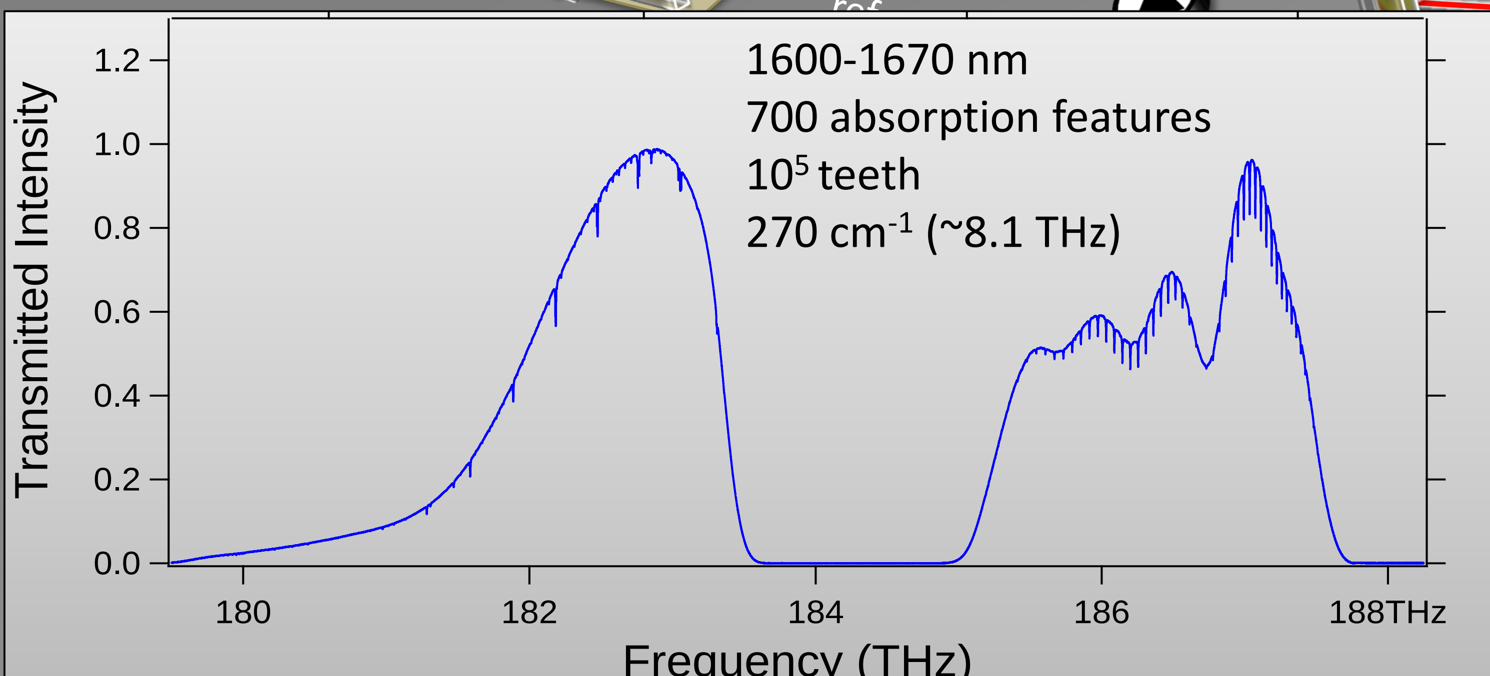
Dual Frequency Comb Spectroscopy over Open Air Path



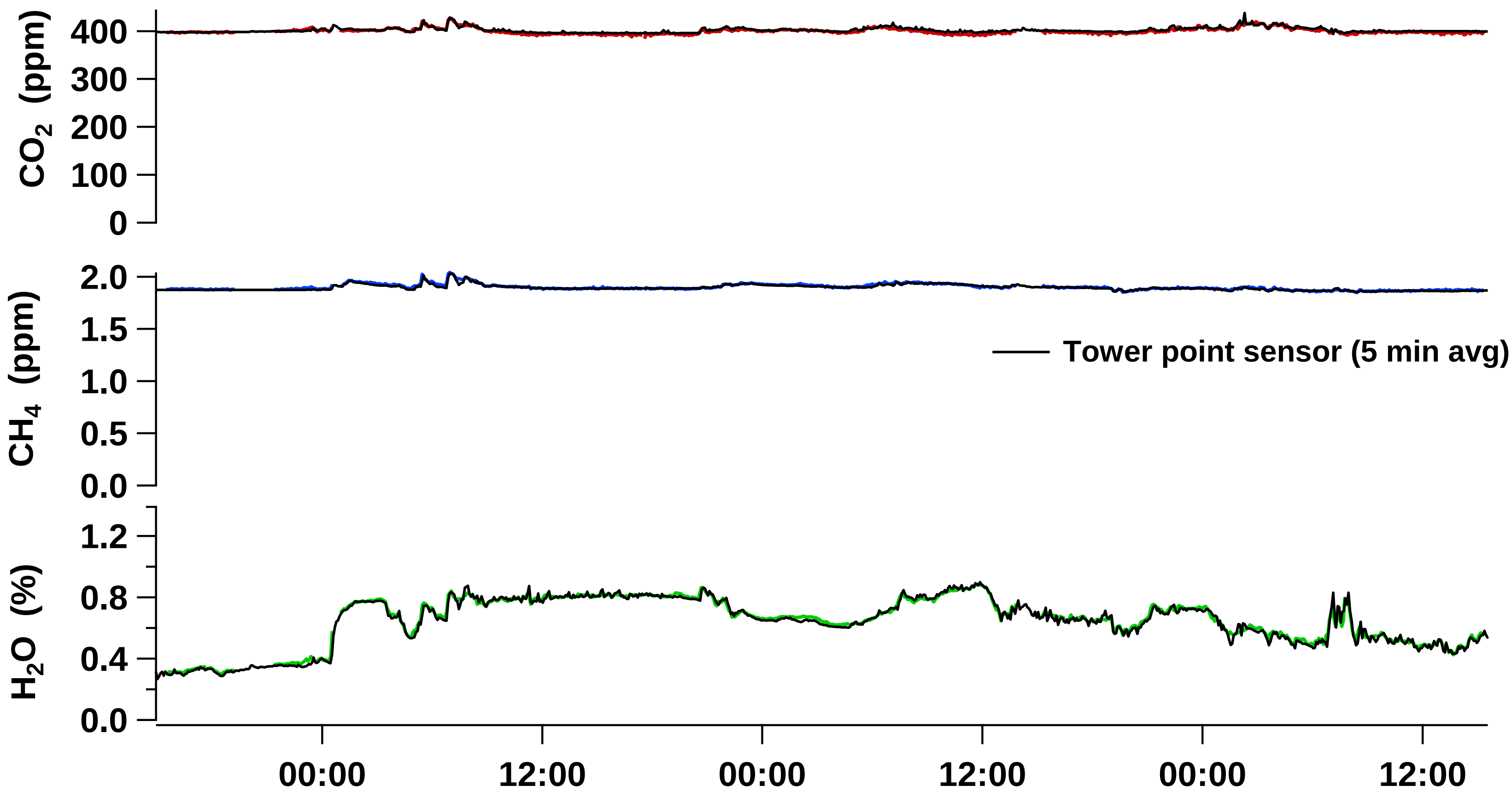
- Measure path-integrated absorption spectrum of CO_2, CH_4 & H_2O
- Fit to known spectral parameters
- Extract gas concentration along path

Dual-Comb spectrometer





Time-Dependence of Greenhouse Gas Concentrations
Three days in June, 5 minute averages

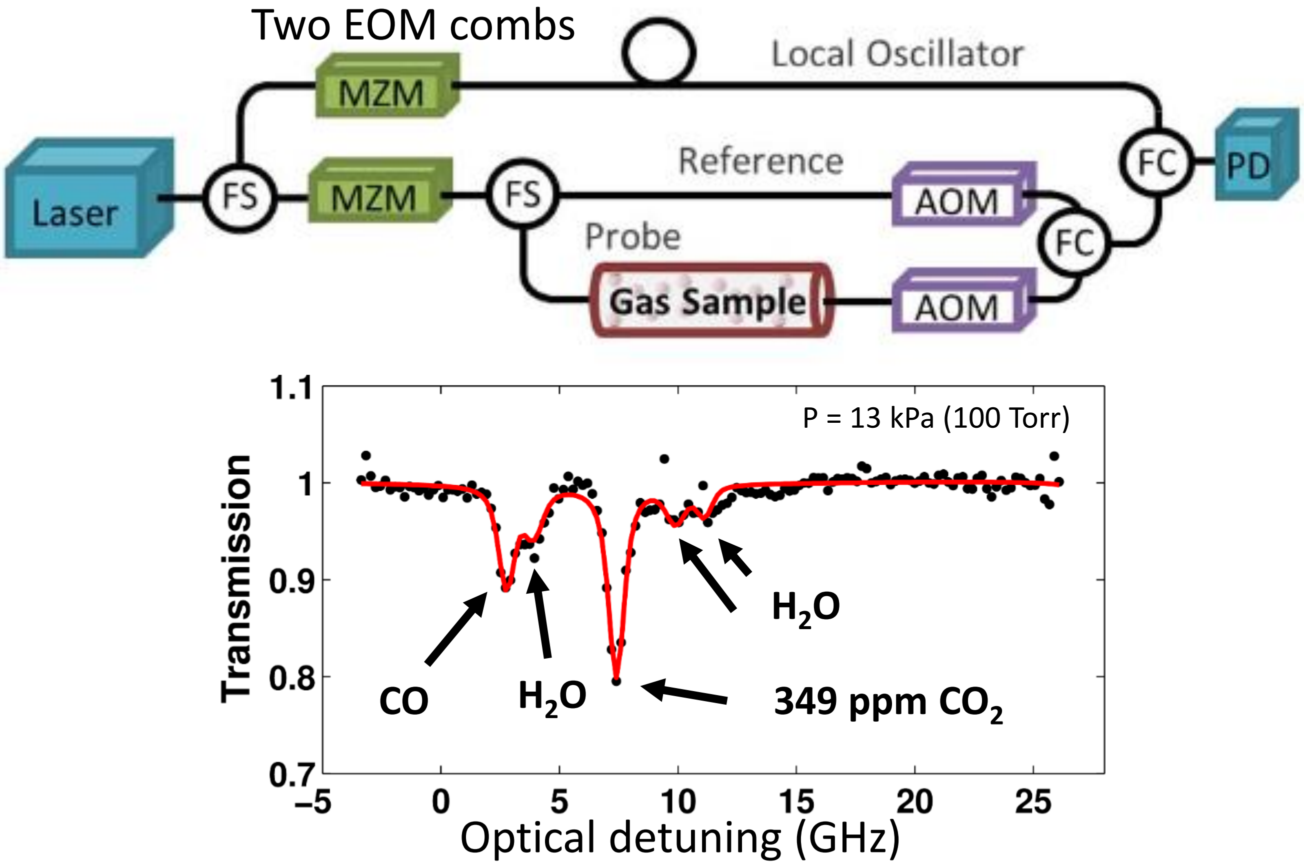


- CO2 & CH4 reported as true dry mixing ratios
- CO2 adjusted by 1.76% bias vs WMO-calibrated sensor
- HDO and air temperature not shown

Retrieved Concentrations are Model Dependent without spectrometer bias

Dual-comb spectroscopy & space platform

- **Broadband dual-comb spectroscopy likely too photon inefficient**
- **More modest bandwidth EOM-based dual-comb spectroscopy?**
  - Still many spectral points across a few lines for low systematics
  - Compatible with ASCENDS-type system

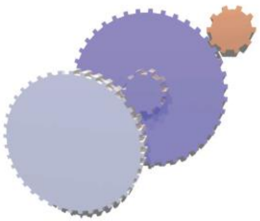


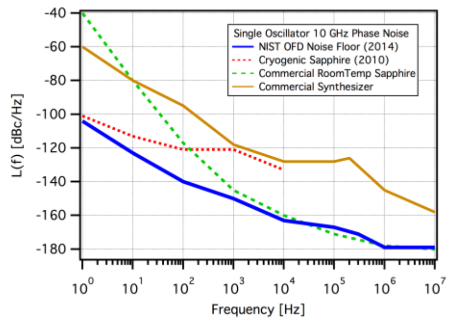
D.A. Long et al., *Opt. Lett.* **39**, 2688 (2014)

A.J. Fleisher et al. unpublished (2015)

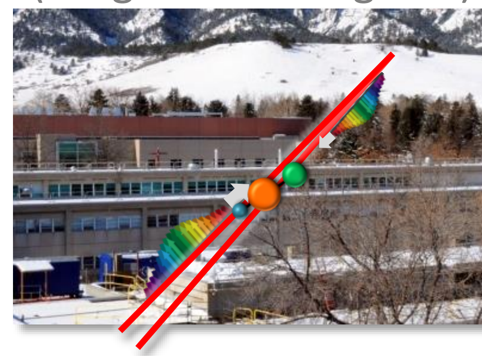
Example applications

Precision microwave generation
(for RADAR)



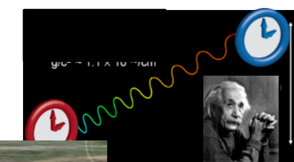


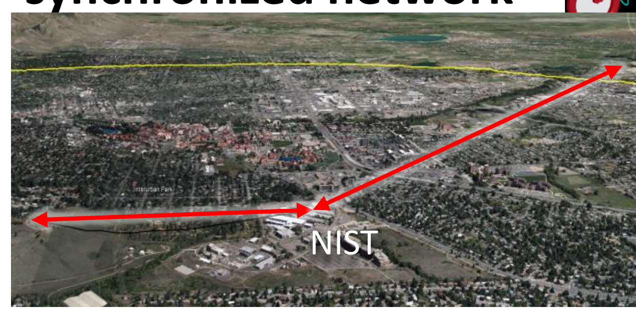
Precision molecular spectroscopy
(for greenhouse gases)



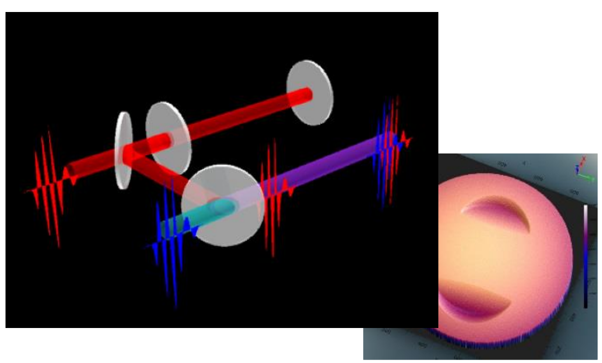
Precision spectroscopy
(for exoplanet searches)

Precision timing across synchronized network



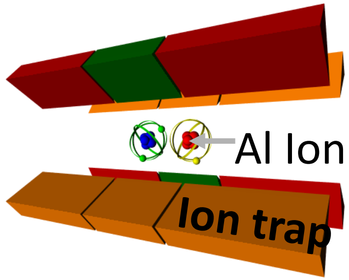


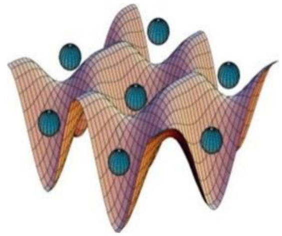
Precision Ranging

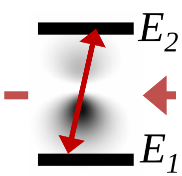


Others:
Advanced communications
Fundamental scientific tests
…

Optical Clocks / Oscillators: femtosecond timing & <10^{-17} Accuracy



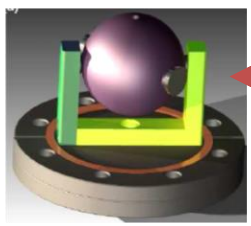




Optical transition

slow loop

Cavity-stabilized Laser (300 THz)



fast loop (PDH)

Highly stable optical cavity

<u>Optical Clock Output</u>
Laser light with a 300 THz
Stable to >15 digits @ 1sec

frequency accurate to >17 digits

How small is 10^{-17} ?

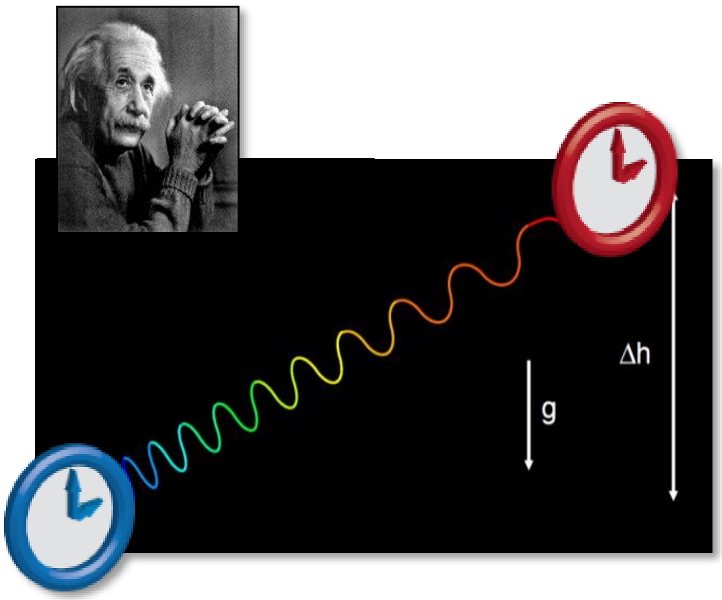
- Requires extended precision
- <u>Diameter of human hair</u>
  Distance to Pluto
- Doppler shift of 3 nm/sec
- Gravitational redshift for 10 cm

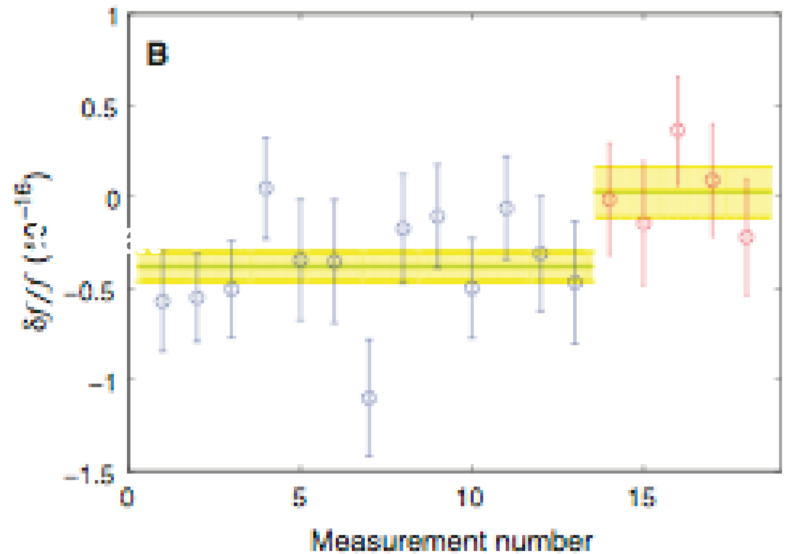
PRL **104**, 070802 (2010)
Science **319**, 1808 (2008)
PRL **98**, 220801 (2007)
Bloom et al. *Nature*, **506**, 71, 2014
Hinkley et al. 2013
Ushijima et al. arXiv, 2014

Optical Clocks and Relativity

C. W. Chou,* D. B. Hume, T. Rosenband, D. J. Wineland

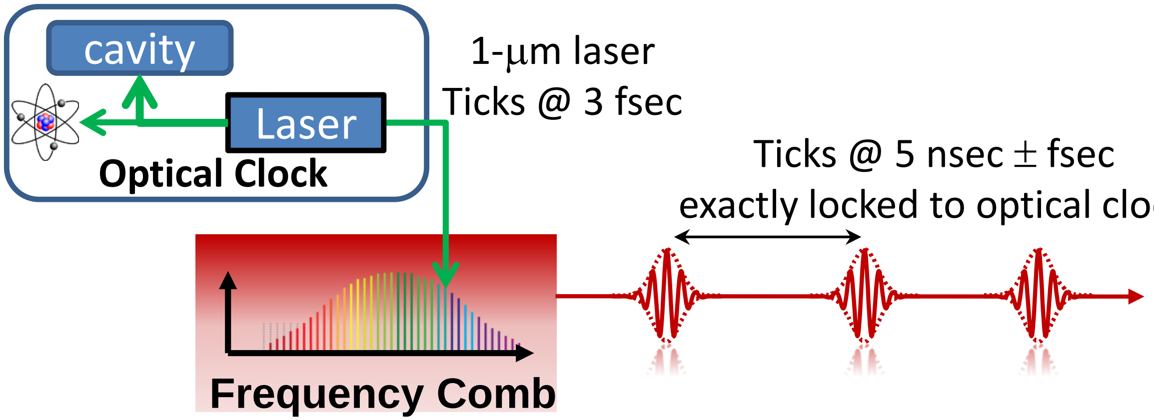
24 SEPTEMBER 2010 VOL 329 SCIENCE





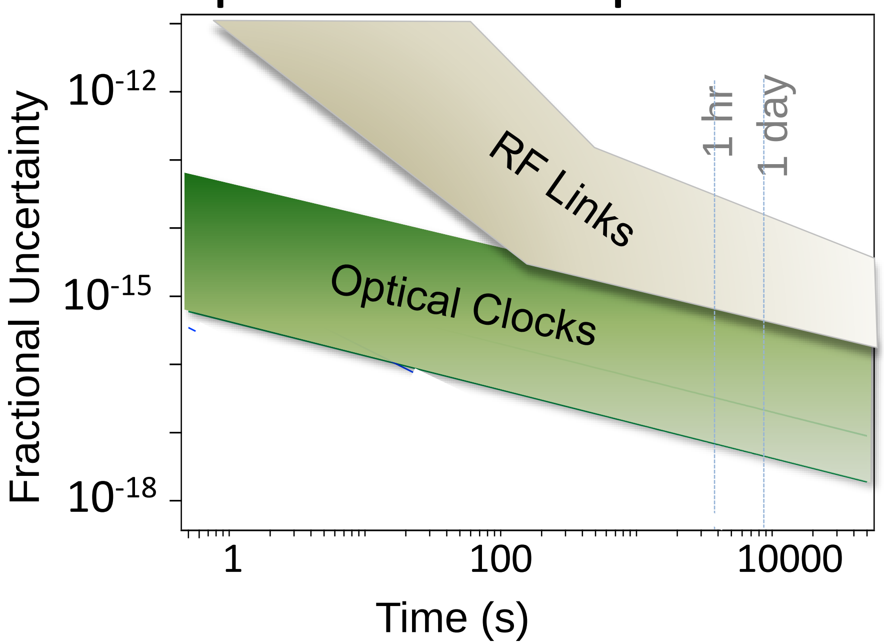
1 part in 10^{18} corresponds to 1 cm displacement

Combs and Clocks

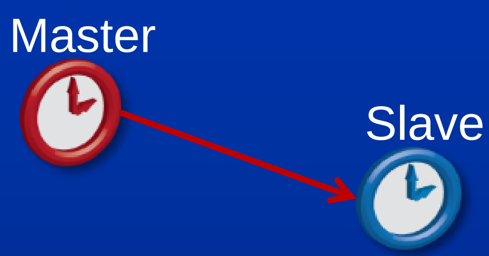


- Comb translates clock signal to other optical signals
- Combination is the ultimate measurement tool for
  - Length, time, frequency, SI constants
  - Gravitational potential (from redshift)
- If we can get the signals out of the lab!

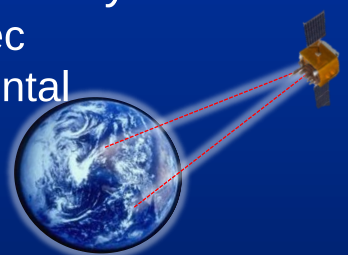
Optical Clocks need Optical Links



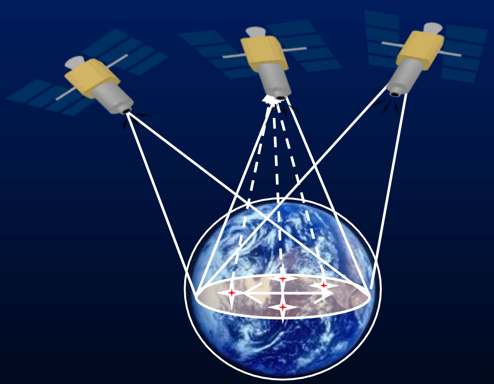
Comparing Optical Clocks Across Distance



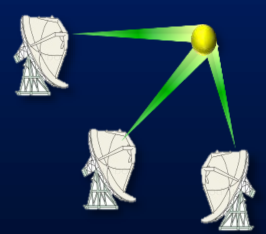
1. Time and Frequency Dissemination
- Redefinition of sec
- Support fundamental measurements



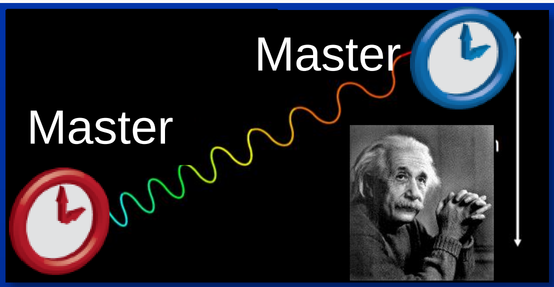
2. Sensing/Defense:
Position, Navigation &Timing



synthetic aperture

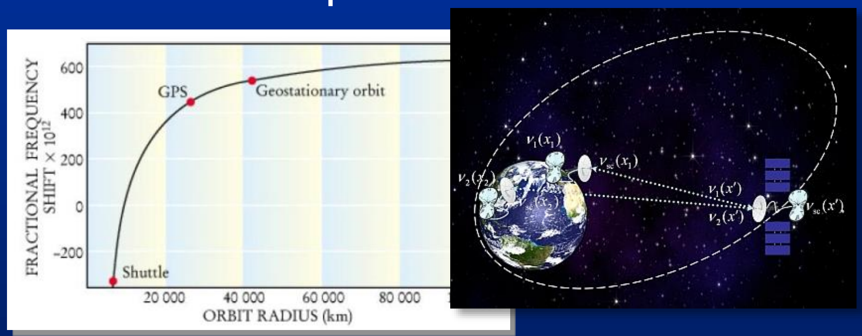


coherent beam forming

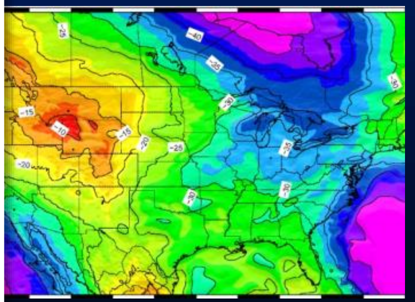


1 cm = 10^{-18} at 1g

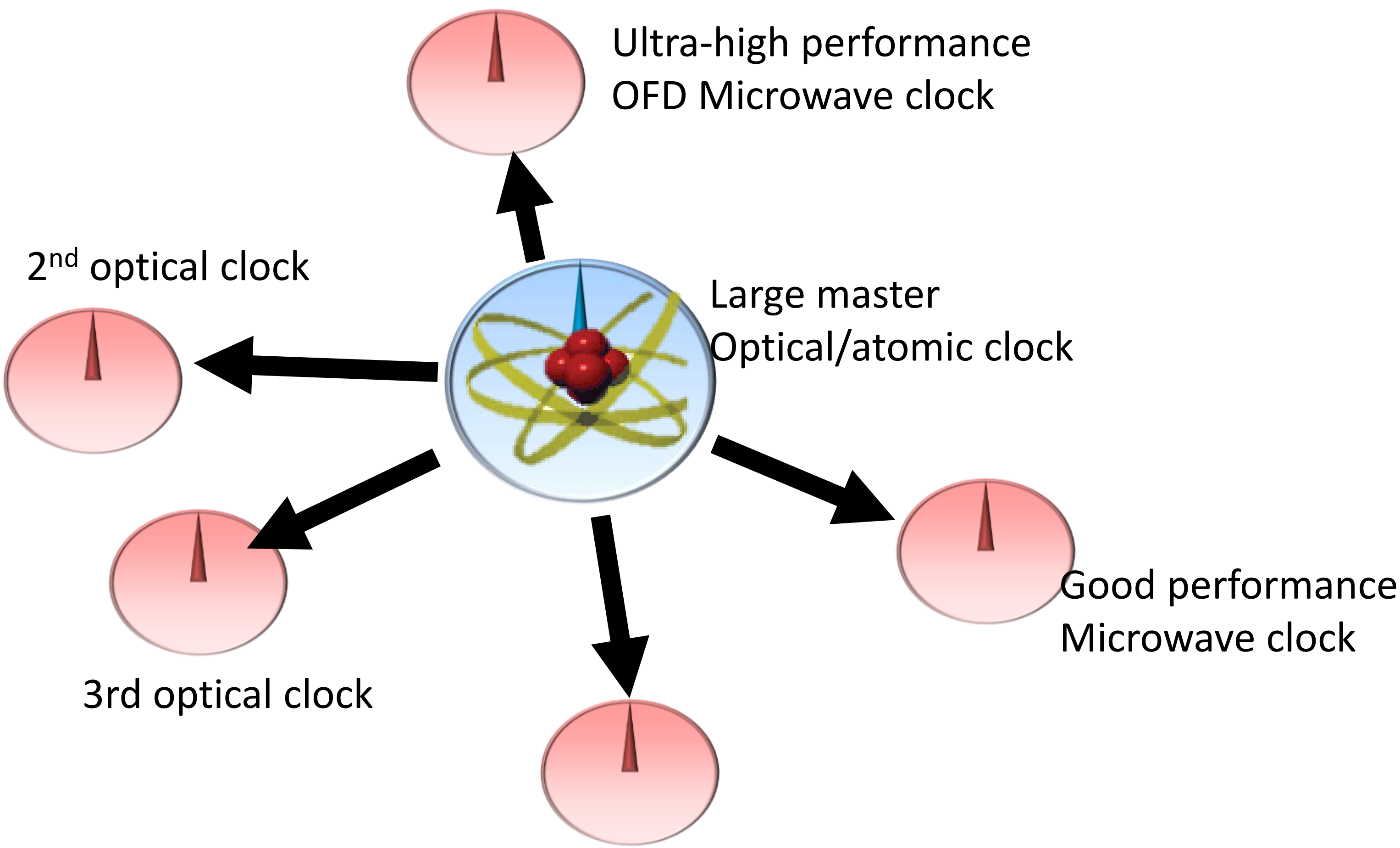
1. Tests of Special & General Relativity



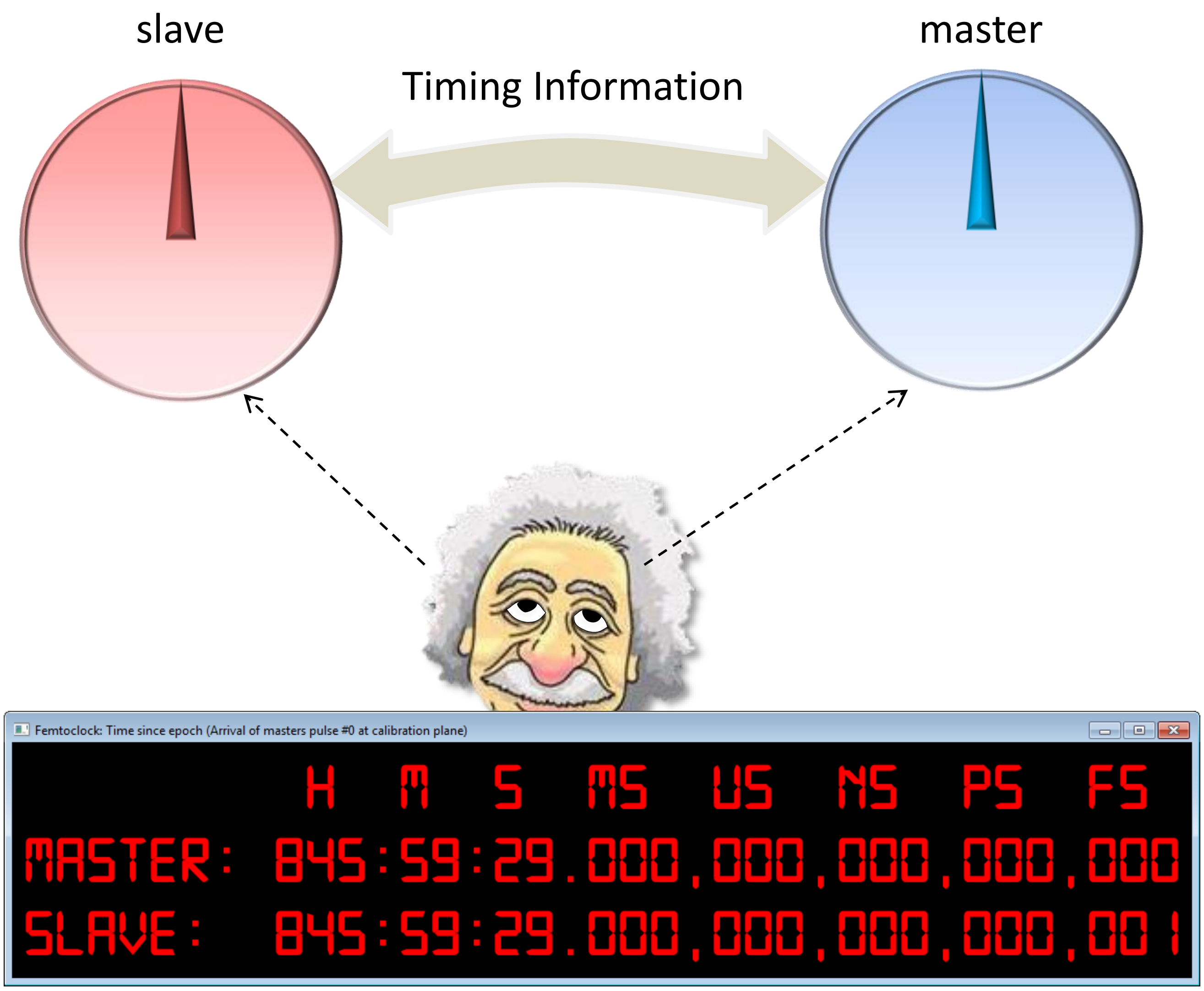
2. Geodesy (vertical maps):
Flooding & Earth Science



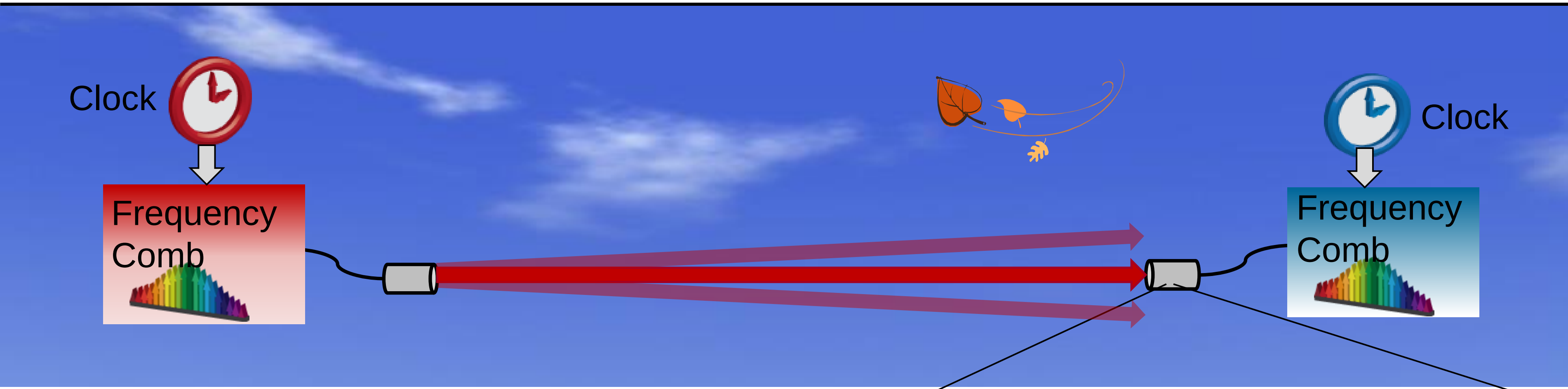
Combining optical and microwave clocks: Future clock networks?



Two Clocks: Synchronized



Why is this hard? *Turbulence, platform motion…*

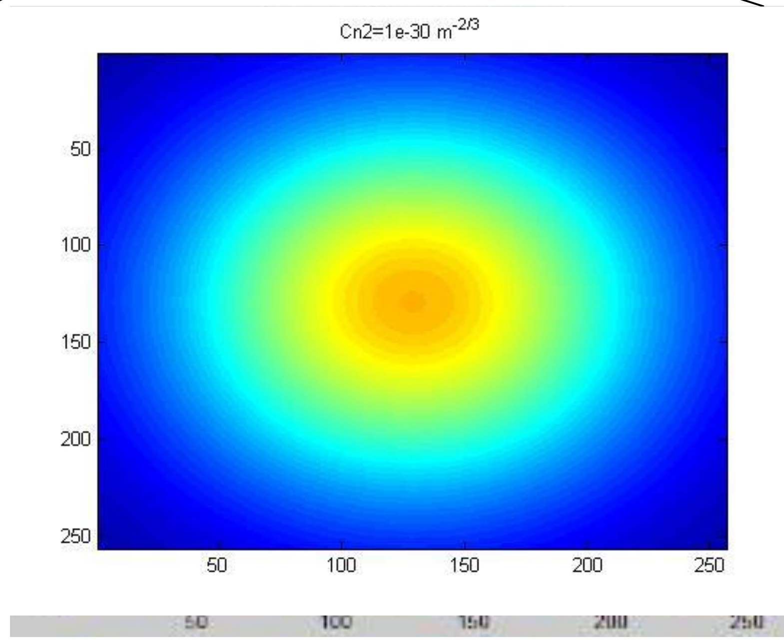


1) Amplitude noise & signal loss

- From turbulence (scintillation & beam wander
- From obstructions & platform motion
- Well-known from free-space optical communications

2) Phase noise (time-of-flight variations)

- From turbulence ("piston effect")
- From platform motion



1st order Doppler shifts -> Need less than 3 nm/sec to reach $v/c < 10^{-17}$

Solution to Phase Noise: Two-Way Link

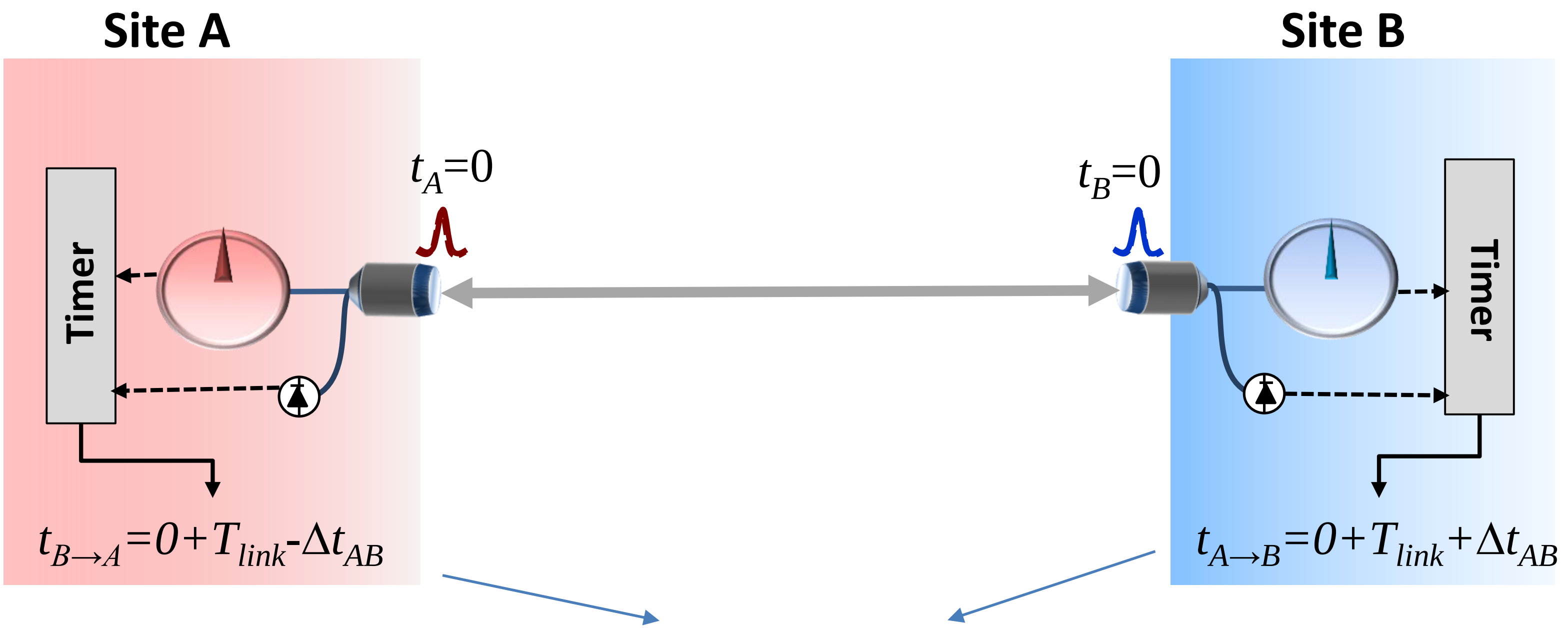
Turbulent Atmosphere is reciprocal*

For ***two-way single-mode*** link, time-of-flight variations are common mode

(not true for a multi-mode link)

* J. Shapiro *J. Opt. Soc. Am.* **61** 492 (1971); J. Shapiro & A. Puryear, *J. Opt. Commun. Netw.* **4** 947 (2012); R. R. Parenti et al., *Opt. Exp.* **20** 21635 (2012)

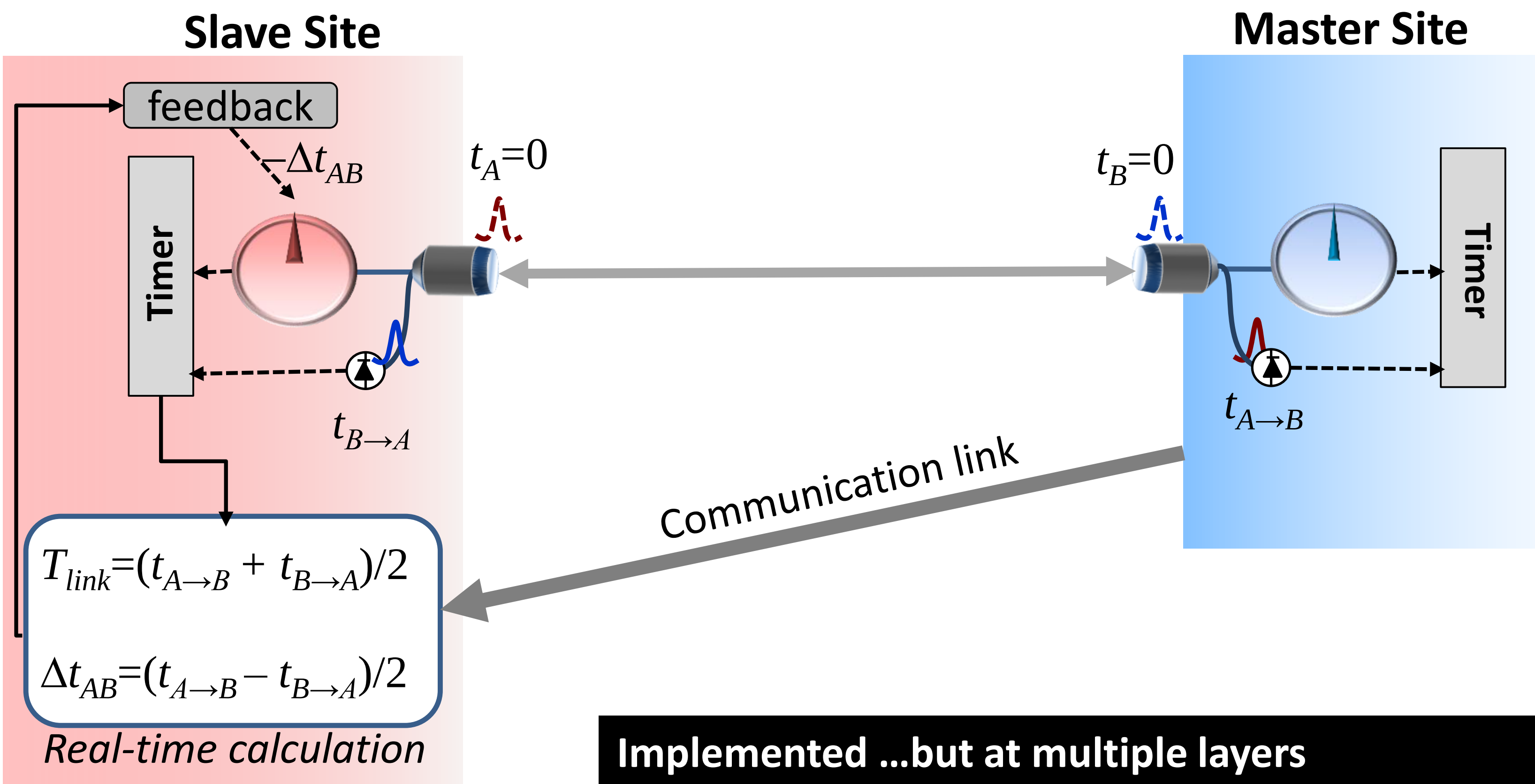
Two-Way Time Transfer: Basic Concept



$T_{link}=(t_{A\rightarrow B} + t_{B\rightarrow A})/2$ Time-of-flight between clocks

$\Delta t_{AB}=(t_{A\rightarrow B} - t_{B\rightarrow A})/2$ Time Offset between clocks

Two-Way Time Transfer + Feedback Synchronization



Implemented …but at multiple layers

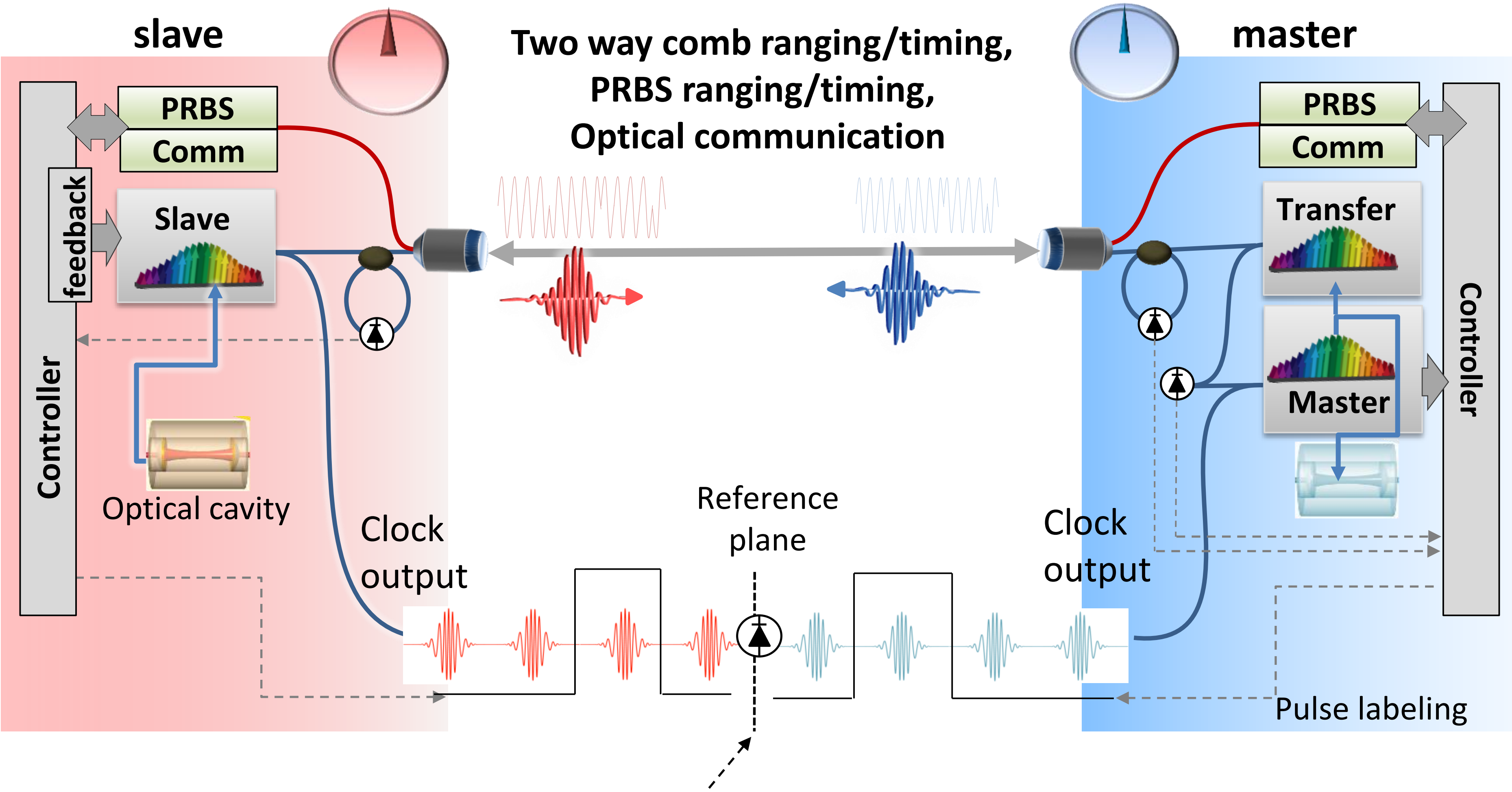
- **Psuedo-random Binary Sequence (PRBS) phase modulated light for "coarse" time transfer**
- **Comb-based transfer for "fine" time transfer**
- **Coherent comm channel**

Overall Synchronization Setup

Deschenes et al, arXiv, 1509.07888

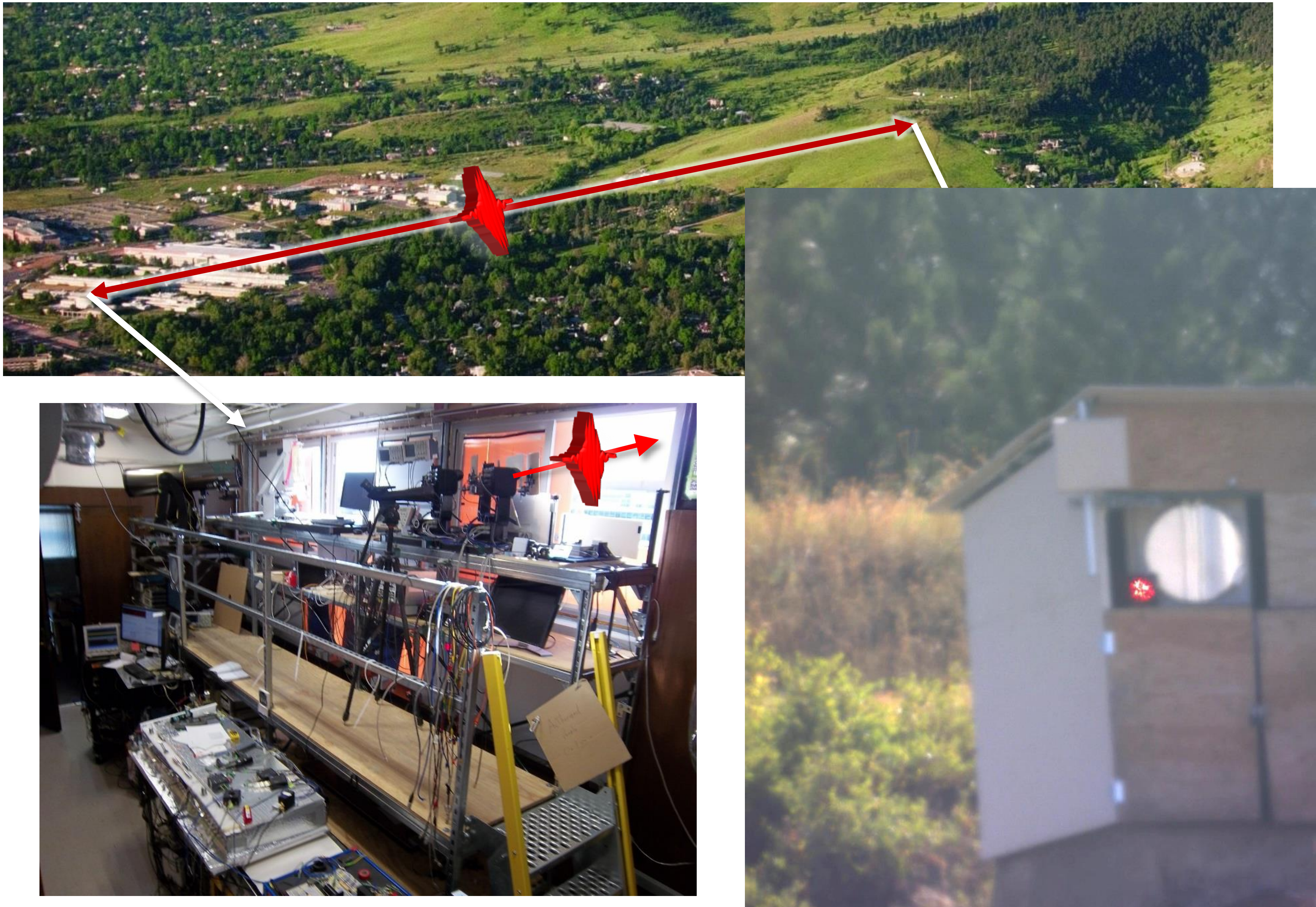
System exchanges three signals:

Two way comb ranging/timing,
PRBS ranging/timing,
Optical communication

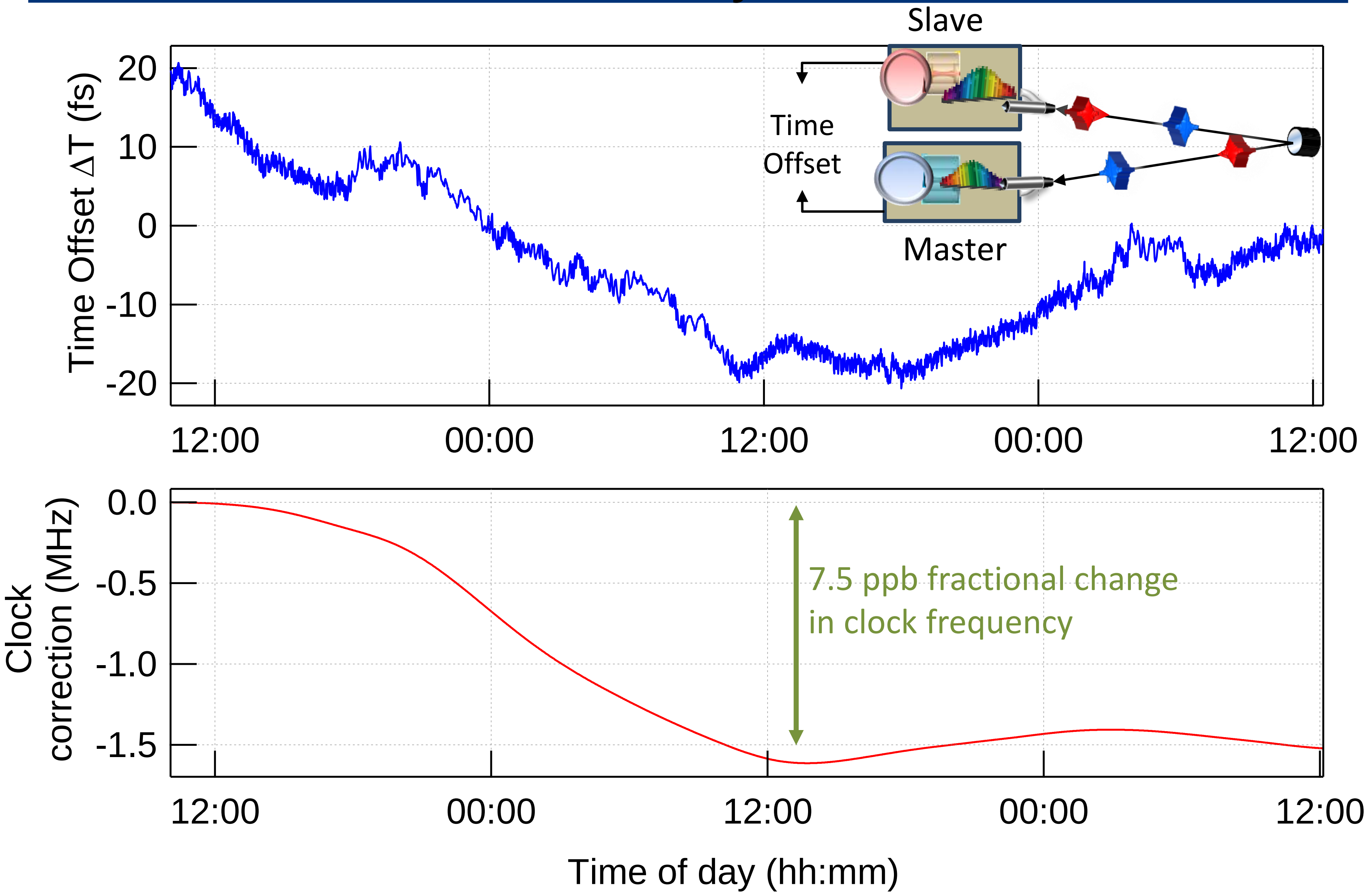


Common reference plane for truth data

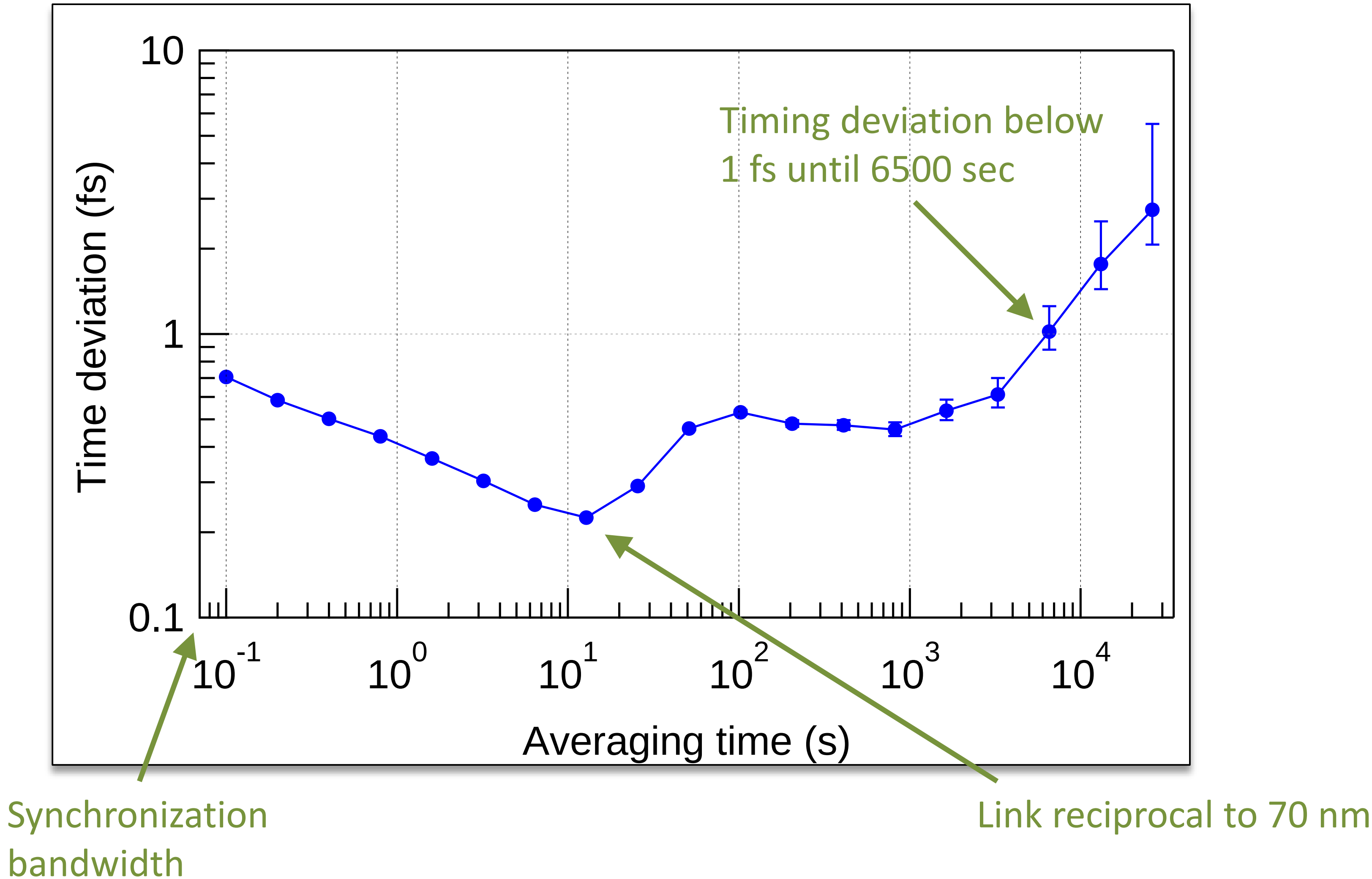
4 km Turbulent Air Path



50 Hours of Optical-to-Optical Synchronization Across 4 km with only 40 fs of wander

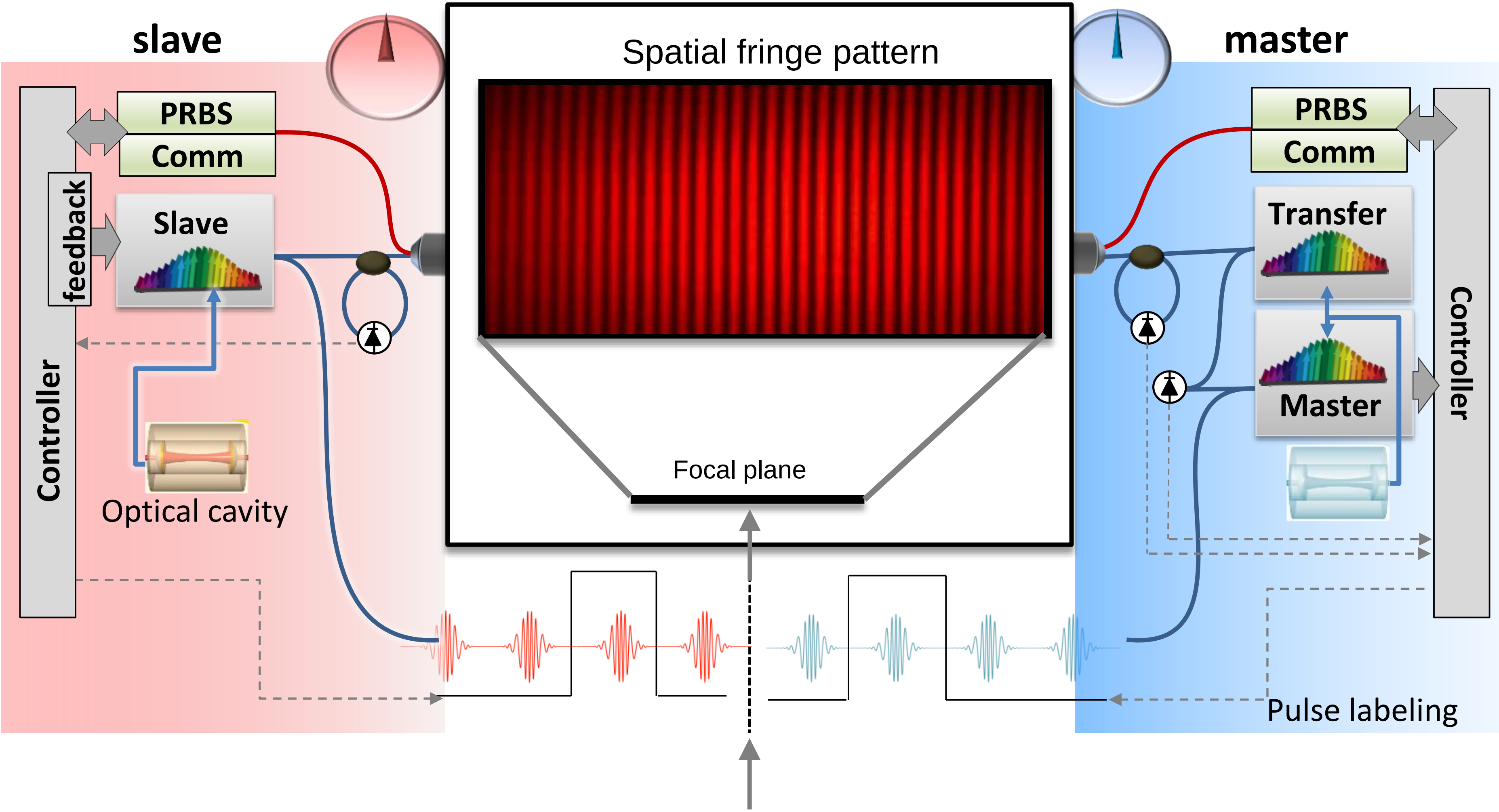


Timing Deviation for 50 Hour Measurement



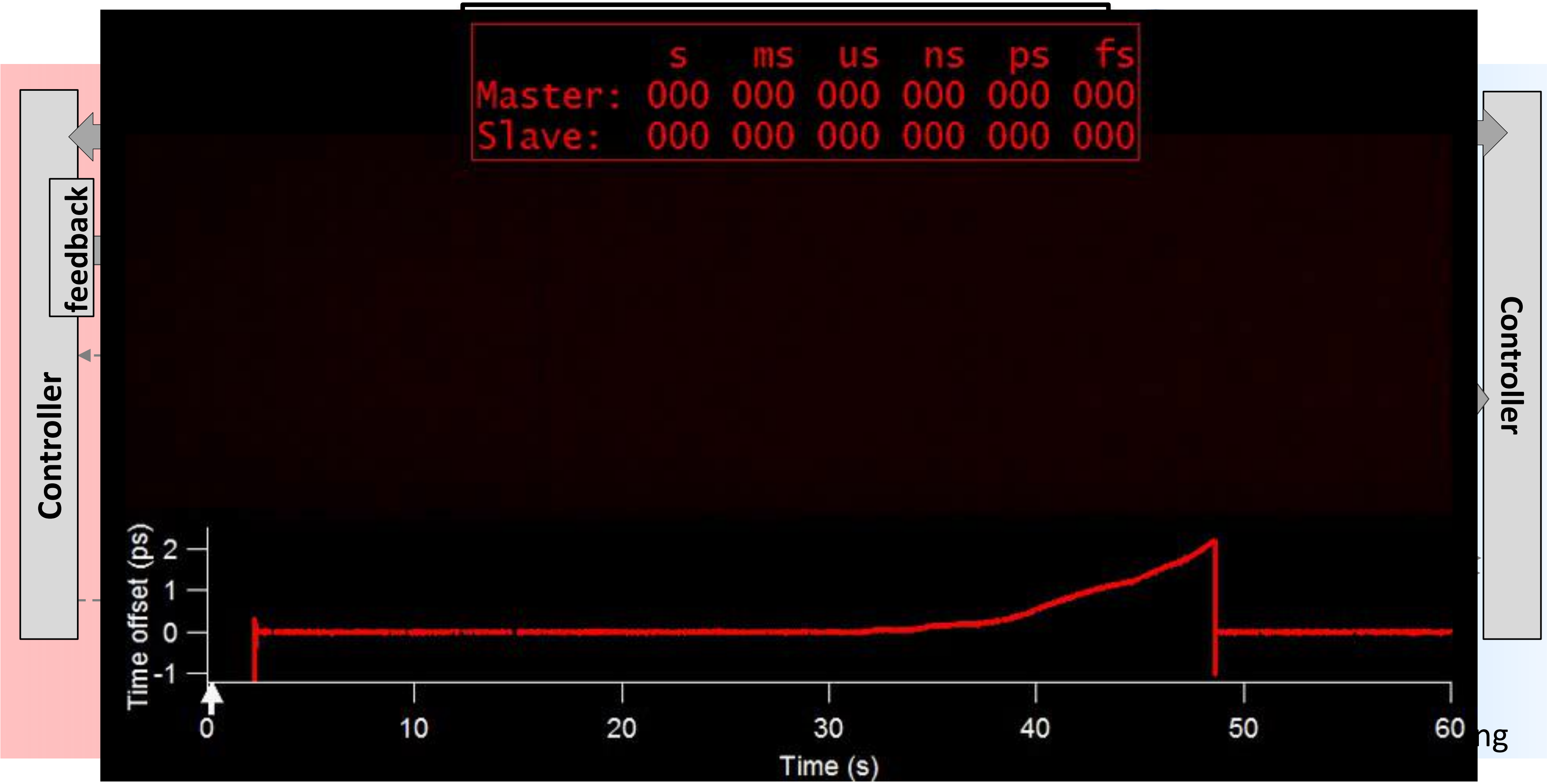
Corresponding modified Allan Deviation <10^{-18} @ 1000s

Optical Pulse Synchronization



Detect optical interference between
1 PPS signals at reference plane
with sheering interferometer

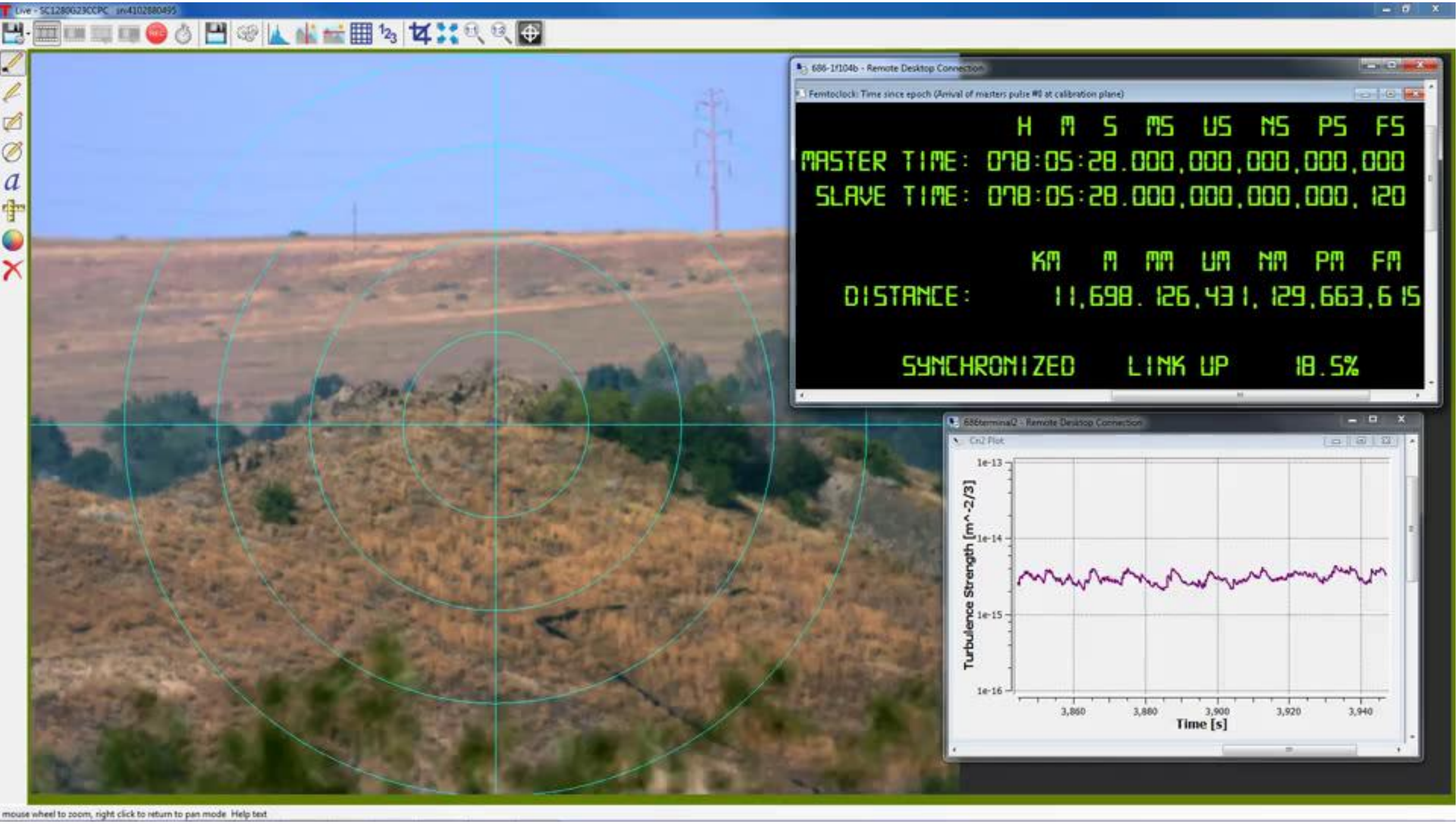
Optical Pulse Synchronization



From 4 km to 11.6 km: NIST to Valmont Butte

View from NIST

Synchronization at 11.5 km
Initial data



Only ~ 3 mW of comb light and ~ 3 mW of comm/PRBS light launched

People

Esther Baumann
Hugo Bergeron
Mick Cermak
Ian Coddington
Kevin Cossel
Stefan Droste
Fabrizio Giorgetta
Dan Herman
Isaac Khader
Nathan Newbury
Laura Sinclair
Bill Swann
Gar-Wing Truong
Eleanor Waxman
Gabe Ycas

U. Of Colorado
Greg Rieker

Kansas State
Brian Washburn

Optical Clock Transfer
Dave Leibrandt
James Chou
Till Rosenband

Comb/Spect.
Scott Diddams
Frank Quinlan
Tara Fortier
Scott Papp
….

NOAA
Jon Kofler
Colm Sweeney
Pieter Tans

U. Of Laval
Jean-Daniel Deschenes
Jerome Genest

$$: NIST, DARPA

Some applications not covered…

- **Fundamental scientific tests of**
  - General relativity
  - Local Lorentz invariance
  - Changes in fundamental constants
  - Searches for dark matter*
  - Etc.
- **Advanced communications****
  - Single coherent comb source can replace multiple transmitters
  - Lower redundancy but much lower SWAP (both from transmitter and processing)
  - Low phase noise microwaves for higher order QAM
- **THz spectroscopy**
  - Dual-comb spectroscopy = (original) Time-domain THz spectroscopy

*Derevianko et al., Nat. Phys.10 (2014)
**Pfeifle et al, Nat. Phot. 8 (2014).

Space based comb applications

- **Evolutionary vs revolutionary**
  - e.g. comb-assisted ranging vs optical clocks
  - Both of value
- **Complexity**
  - Phase locked combs are complicated but

    …phase locking not always needed (vs processing)

    …could still simplify overall system since 1 comb = many lasers
- **Photon efficiency important**
  - Intrasatellite vs Intersatellite vs Ground-to-Satellite
- **Fiber combs** vs **Solid state** vs **EOM based** vs **Microcombs?**

Conclusion

- Frequency Combs a unique new laser tool for measurement
  - As a spectral ruler
  - As a temporal ruler

- Many potential applications
  - Precision absolute ranging
  - Timing synchronized networks at femtosecond levels
  - Precision optical and microwave sources
  - Precision spectroscopy (active and passive)
  - Fundamental science
  - Future deployment of optical clocks

- What lab demonstrations can be "translated" to robust, autonomous, useful operation in space?