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)
- **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 molecular spectroscopy
(for greenhouse gases)

Precision spectroscopy
(for exoplanet searches)

Precision timing across synchronized network

Precision ranging

Others:
Advanced communications
Fundamental scientific tests
...
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  ...

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![Graph showing precision microwave generation for RADAR](image1.png)

![Image of precision molecular spectroscopy for greenhouse gases](image2.png)

![Image of precision spectroscopy for exoplanet searches](image3.png)

![Image of precision timing across synchronized network](image4.png)

![Image of precision ranging](image5.png)
Photonic Microwave Generation

Laser Comb
Frequency Divider
N ~ 10^5-10^6

Stabilized CW Laser
~ 500 THz

Microwave Output via Photodetection
1-100 GHz

Comb uncertainty at the 20th decimal place

1. Ultrastable CW Laser Oscillator

- CW Laser
  - $\nu_{opt} = 500$ THz
  - $\Delta \nu < 1$ Hz

2. Optical Frequency Divider
- Femtosecond laser frequency comb
- Phase coherent division from optical to microwave
- Reduction of phase noise power by $N^2$

3. Opto-Electronic Conversion

- Microwave signal: any harmonic of $f_r$
  - $\Delta f/f < 10^{-15}$ @ 1s
  - $S_{\mu\text{wave}}(f) = S_{opt}(f)/N^2$

Main Components of Present System

**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**

Stable Fabry-Perot Cavity

\[ f_r = \nu_{\text{opt}}/N \]

\[ S_{\mu\text{wave}}(f) = S_{\text{opt}}(f)/N^2 \]

Integrated Jitter (1Hz – 5 GHz)

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>OFD</td>
<td>2.6 fs</td>
</tr>
<tr>
<td>Sapphire dielectric</td>
<td>300 fs</td>
</tr>
</tbody>
</table>

\[ f_r \rightarrow \text{Have extended to frequencies from 10 MHz to 100 GHz} \]

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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)
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, $\Delta \lambda / \lambda = 10^{-9} - 10^{-11}$

Out of the Lab and into the Field
Frequency Comb Calibration of Stellar RV’s

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

Absolute distance
Poor resolution

Laser Interferometry

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

Dual-Comb Ranging

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

Interferometric Range = \( \frac{\varphi_T - \varphi_R}{(4\pi)\lambda + N\lambda/2} \)

Handover of time-of-flight to interferometric range...

Reference

Target

"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

Dual-comb ranging with free-running fs fiber lasers

No penalty except loss of interferometric range

Phase locked combs
Free-running fs fiber lasers + processing
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

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

Comb-calibrated Laser Ranging

Replace time-consuming, low-quality casting of impression evidence

eye-safe laser

frequency calibration

(simplified comb)

Scanner/lens processor (FPGA + CPU)

Comb-calibrated Laser Ranging
Measuring Complex, Soft Surfaces

2 - 10 meter
(100 m should be possible)

Non-metallic surface with enormous range variation

Moth

Cactus

eye-safe laser

Scanner/lens

frequency calibration

(simplified comb)

processor (FPGA + CPU)

3D image
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**Others:**
*Advanced communications*
*Fundamental scientific tests*
...

**Precision Ranging**
Climate Change And Greenhouse Gases

Goal: Accurately measure Greenhouse gases [CO$_2$, CH$_4$, H$_2$O, 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

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 interaction lengths
- Broadband spectral coverage across vis/ir/uv spectrum
- Narrow “delta-function” frequency sampling
- Built-in frequency calibration

But how to detect?
Spectral dispersers

Frequency Comb

Gas Sample

Detector

Grating Spectrograph

Fourier Transform Spectrometer

Grating/VIPA (high res) Spectrograph

Dual-Comb Spectroscopy

$I_0$

$I$

Comb 1 ($f_0$)

Comb 2 ($f_0 + \Delta f$)
Phase lock combs with small difference in repetition rates

\[ \Delta f_r = f_r - f_r \]

EXACT one-to-one correspondence between optical & rf frequencies
Phase lock combs with small difference in repetition rates

EXACT one-to-one correspondence between optical & rf frequencies
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\[ \Delta f_r = f_r - f_r \]

**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

Comb 1 \( (f_r) \)

Comb 2 \( (f_r + \Delta f_r) \)

Dual Frequency Comb Spectroscopy over Open Air Path

- Measure path-integrated absorption spectrum of CO$_2$, CH$_4$ & H$_2$O
- Fit to known spectral parameters
- Extract gas concentration along path

Rieker et al., Optica, 1, 290 (2014)
Dual-Comb spectrometer

Comb 1
- fs laser
- Amp
- LMA
- HNLF

Comb 2

Spectral Shaper

Phase correction

Fast Steering mirror

Transmitted Intensity vs Frequency (THz)

1600-1670 nm
700 absorption features
$10^5$ teeth
270 cm$^{-1}$ ($\sim$8.1 THz)

2 km Open path
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

Two EOM combs

Example applications

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Others:
Advanced communications
Fundamental scientific tests...

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

How small is 10^{-17}?
- Requires extended precision
- Diameter of human hair
- Distance to Pluto
- Doppler shift of 3 nm/sec
- Gravitational redshift for 10 cm

Optical Clock Output
Laser light with a 300 THz stable to >15 digits @ 1sec frequency accurate to >17 digits

References:
- Hinkley et al. 2013
- Ushijima et al. arXiv, 2014

PRL 104, 070802 (2010)
Science 319, 1808 (2008)
PRL 98, 220801 (2007)
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!
Comparing Optical Clocks Across Distance

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


1. Tests of Special & General Relativity

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

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

- $1 \ cm = 10^{-18}$ at 1g
Combining optical and microwave clocks: Future clock networks?

- Ultra-high performance OFD Microwave clock
- Large master Optical/atomic clock
- Good performance Microwave clock
- 2nd optical clock
- 3rd optical clock
Two Clocks: Synchronized

slave

Timing Information

master

H M S MS US NS PS PS FS
MASTER: 845:59:29.000,000,000,000,000,000
SLAVE: 845:59:29.000,000,000,000,000,000
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 $v/c < 10^{-17}$
Turbulent Atmosphere is reciprocal*

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

(not true for a multi-mode link)

Two-Way Time Transfer: Basic Concept

\[ t_A = 0 \]
\[ t_B = 0 \]
\[ t_{B \rightarrow A} = 0 + T_{\text{link}} - \Delta t_{AB} \]
\[ t_{A \rightarrow B} = 0 + T_{\text{link}} + \Delta t_{AB} \]

\[ T_{\text{link}} = \frac{(t_{A \rightarrow B} + t_{B \rightarrow A})}{2} \]

Time-of-flight between clocks

\[ \Delta t_{AB} = \frac{(t_{A \rightarrow B} - t_{B \rightarrow A})}{2} \]

Time Offset between clocks
Two-Way Time Transfer + Feedback Synchronization

Slave Site

- Timer
- Feedback
- $t_B \rightarrow A$
- $t_A = 0$
- $\Delta t_{AB}$

Master Site

- Timer
- $t_B = 0$
- $t_A \rightarrow B$

Communication link

$T_{link} = (t_A \rightarrow B + t_B \rightarrow A)/2$

$\Delta t_{AB} = (t_A \rightarrow B - t_B \rightarrow A)/2$

Real-time calculation

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

Clock correction (MHz)

Time Offset DT (fs)

7.5 ppb fractional change in clock frequency
Timing Deviation for 50 Hour Measurement

![Graph showing timing deviation vs. averaging time. The graph indicates that the timing deviation is below 1 fs until 6500 sec.](image)

- **Timing deviation below 1 fs until 6500 sec**
- **Synchronization bandwidth**
- **Link reciprocal to 70 nm**
- **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 $\sim 3$ mW of comb light and $\sim 3$ mW of comm/PRBS light launched
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?