Frequency Combs and Hyperspectral Sources for Absorption Spectroscopy

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University of Wisconsin, Department of Mechanical Engineering


Outline:
- Overview of hyperspectral design space
- Continuous-spectral sources
  - FDML laser in piston engine at Honda
  - frequency combs
- Discrete-spectral sources
  - TDM in Ramgen combustor at AFRL
- Future work
Usual goal: gas thermometry in dynamic (~30 kHz) systems

- **piston engines**
- **shock tubes**
- **gas turbine burners**
- **pulse detonation tubes**

* denotes possibility of a steady pre-test: slow (e.g. < 100 Hz) sensors are useful prior to (or after) dynamic event. such cases are < 100% dynamic
Monitoring gas properties with hyperspectral sources

**Beer-Lambert Law:**

\[ T_\lambda = \frac{I}{I_0} = \exp(-k_\lambda L) \]

\[ k_\lambda = f(T,P,X) \]

- Infer **temperature** from rotational distribution (band shape)
- Infer **mole fraction** from heights of features
- Often need ~ 30 nm spectral coverage for best performance
- Absorption spectroscopy: final results are generally path-integrated
Swept-wavelength sources

- Straightforward spectral encoding in time
- “Continuous-spectral” (source delivers complete spectra without gaps)
- Fast sweeps (e.g., every 10 μs) are needed for dynamic test articles
- We work mostly in the infrared; however, throughout this talk, my charts and language may use visible colors
Fourier-domain source: a “continuous-spectral” alternative

Swept-wavelength:

Light Source  Sample  Detector

Fourier domain:

Light Source  Sample  Detector
Sample continuous-spectral data

- emission spectra
- Fourier-domain approach
Continuous (swept) vs. discrete (TDM)

- Spend more ‘integration time’ on most important wavelengths
Sample “discrete-spectral” data
Home-built light sources can compete

- Tunable diode lasers (TDLs) are no longer the only option for high-quality ‘sensor light’
- Traditionally: Based on available TDLs, design a sensor

\[ \lambda_{\text{FR1}} = 1290 \text{ nm (soot)} \]
\[ \lambda_1 = 1343.299 \text{ nm (H}_2\text{O)} \]
\[ \lambda_2 = 1391.672 \text{ nm (H}_2\text{O)} \]
\[ \lambda_3 = 1799.179 \text{ nm (H}_2\text{O)} \]
\[ \lambda_{\text{FR2}} = 1643 \text{ nm (soot)} \]

- Now: Starting from sensor requirements, design the source

Time-division multiplexed (TDM) source

Rapid wavelength-swept (FDML) source


Kranendonk et. al., *Optics Express* 15(23) 2007

Select “continuous-spectral” sources

<table>
<thead>
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<th>source</th>
<th>advantage</th>
<th>disadvantage</th>
<th>features of ideal application</th>
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* denotes commercially available

Each of these sources can be ‘best’
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Each of these sources can be ‘best’
FDML = Fourier-domain mode-locked (laser) 
{collaboration with MIT}
- laser cavity is 2 km long (storage of scans)
- scans 1333-1377 nm in 5 μs, repeats every 10 μs (50% duty cycle for split-pulse referencing)
Measured engine spectrum compared to BT2 simulation

- 3x shot noise limit, MDA = 5x10^{-8} Hz^{-1/2}
- Peak residual < 10% across entire spectrum (as of Feb 2008)
Results: 100 kHz thermometry in Honda engine, Japan

- Each spectrum (one every 10 µs) compared to precomputed library of BT2 spectra to infer temperature vs. time
- RMS temperature precision 5-10 K (from ~50K in 2004)
- Absolute accuracy not yet known, but low residual and agreement with simulation are encouraging
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fs comb (comb Fourier transform spectroscopy: c-FTS)

- Developed by Fritz Keilmann, Max Planck Institut, and Daniel van der Weide, U. of Wisconsin
- Expensive, but likely to be used in practical dynamic environment soon

A. Schliesser, F. Keilmann, D. W. van der Weide
Optics Express (2005)
Inexpensive CW version of comb-FTS


- Inexpensive, but difficulties associated with noise, spectral coverage

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<th>Continuous</th>
<th>Discrete</th>
<th>Future</th>
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Example discrete-spectral wavelength selection: 10-λ

- R = ‘reference’;
- TSF = ‘temperature-sensitive feature’;
- B = ‘broadening’

5 moles H₂O / m³
T = 1670 K

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spectral absorption coefficient \( k \) [cm⁻¹]

wavenumber [cm⁻¹]

7300  7350  7400  7450  7500
Why choose discrete over continuous?

- Less data to acquire: cheaper DAQ and computation → on-board sensing and control
- Lower-noise: all else equal, get 7x better temperature precision by spending a longer time measuring the most important parts of the spectrum

However:
- Susceptible to error, especially in 100% dynamic or ‘quick trial’ applications
Select “discrete-spectral” sources

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**Overview | Continuous | Discrete | Future**
Schematic of 10-wavelength TDM source

see CThL7, Thursday at noon


- physical length of fiber laser cavity ~ 3.5 km
- repetition rate ~ 29 kHz
Photos of 10-wavelength TDM source
Photos of 10-wavelength TDM source

- 10 temperature-controlled FBGs
- temperature of gratings controlled within 0.1 K ( = 0.0015 nm = 0.008 cm⁻¹ = 200 MHz)
Results: 10-wavelength time-division-multiplexed (TDM) output

- A sequence of pulses, each at a unique wavelength

- This pulse pattern repeats every 35 μs (25% duty cycle)
- Noise in pulse pattern is irrelevant: cancelled by split-pulse referencing down to near shot noise limit (MDA ~ 1x10^{-4})
A separate, 4-wavelength TDM source for fuel & T measurements

- The pulse pattern repeats every 35 μs, just like the H₂O TDM system, so it is easily time-multiplexed with the 25% duty cycle H₂O TDM output
Combined use of H$_2$O/fuel TDM laser in Ramgen rig at AFRL

- In total: monitor 4 parameters using 14 wavelengths at 30 kHz
Fiber installation in Ramgen rig at AFRL January 10, 2008

- All-fiber access design successful: just bolt in place and begin testing
Results from upstream station (CH$_4$ temperature & mole fraction)

Timing of fuel arrival, other dynamics all useful to Ramgen
Results from downstream station (H₂O temperature & mole fraction)

- Known noise sources in these datasets will be reduced in next tests.
Future work: still more near-IR hyperspectral sources

- ~WMS hyperspectral source for sensitive measurements, e.g., source with constant power but with a wavelength that does this:

- Feel free to ask me about spectroscopic sources that ‘you wish you had’

![Graph showing wavelength changes over time](image-url)
Future work: Extension of hyperspectral systems to mid-IR and UV

- There are obstacles, such as component availability and fiber delay limits:

  FBG availability

  total round-trip fiber loss = 20 dB

- But opportunities such as wavelength-conversion of hyperspectral sources, e.g., in PPLN, also exist.
Future work: Hyperspectral Tomography

- Images courtesy Hugh McCann, University of Manchester:

- Each laser beam (projection) through the test article is expensive (e.g., $3000) whereas each wavelength can be inexpensive (e.g., $300)
- Collaborating with Prof. Lin Ma, Clemson University and Dr. Sukesh Roy, ISSI. Prof. Ma’s simulations show promising performance, e.g., for continuous low-spatial-resolution temperature imaging at 30 kHz using ~ 20 beams and ~ 20 wavelengths
Acknowledgements

- Collaborators:
  - Honda: Yasuhiro Urata, Yasuhiro Okura, Toshiyuki Suga
  - MIT: Prof. James Fujimoto, Dr. Robert Huber (now at U. of Munich)
  - WPAFB/AFRL: Dr. James Gord, Dale Shouse, Craig Neuroth
  - ISSI: Dr. Sukesh Roy
  - Ramgen: Ryan Edmonds
  - Clemson: Prof. Lin Ma
  - UW Engine Research Center: Prof. Rolf Reitz, Yu Shi
- Special thanks to senior students: Thilo Krätschmer, Andrew W. Caswell