Spectral Calibration of Ultra-High Resolution Volume Holographic Spectrometer

Jeff Bourne
Majid Badiei (Advisor)
What is a spectrometer?

- Any device that converts different input wavelengths into different output positions.
- Visible NIR Spectrometers
  - 350-1000 nm
- UV Spectrometers
  - 200-350 nm
- Most spectrometers report
  - Wavelengths
  - Intensities of light
A Typical Vis-NIR Spectrometer

- A wavelength source
  - Usually an incandescent bulb or LED (Visible and NIR)
  - Deuterium lamp (UV)
- A diffraction grating to split the light into individual wavelengths
  - Typically a reflection grating
- A sample the light passes through
  - Often a liquid
- A detector
  - Photodiode
  - CCD (charge coupled device)
Single Beam Spectrometer

http://www.chemistry.nmsu.edu/instrumentation
Double Beam Spectrometer

http://www.cem.msu.edu/~reusch/virttxtJml/Spectrpy/UV-Vis/uvspec.htm
The need…

- Typical spectrometers
  - Expensive $1000+
    - High schools can’t afford more than one
  - Sensitive to light alignment
  - Large (Spectronic 20)
  - Must be treated very carefully
    - Too many moving parts
The Solution…

- A spectrometer that uses holograms instead of reflection grating (much cheaper)
- Small (fit in palm of your hand)
- Less expensive (3-4X)
- Rugged (no moving parts)
- Source of light can be diffuse
- Good resolution
My job…

- To learn basic theories of
  - waves
  - interference/diffraction
  - transfer functions
- To reproduce the calibration process of the new spectrometer
Process of Calibration

- Determine transfer function of the spectrometer
  - A transfer function calculates the wavelength associated with a particular position or pixel.

<table>
<thead>
<tr>
<th>Input</th>
<th>Transfer Function</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_i(\lambda)$</td>
<td>$H(r, \lambda)$</td>
<td>$S_o(r)$</td>
</tr>
</tbody>
</table>
Calibration of Hologram

- Calibrating the Cylindrical beam volume hologram
- Basic Set-up:
Calibration of Hologram

- Using monochromator, measure pixel position between 500 and 600 nm at 5 nm intervals.
- Determine x position with greatest intensity using Matlab.
- A graph of the pixel positions versus the wavelengths is generated.
Formula to calculate the wavelength from the pixel position:

\[(\text{pixel} + 608.7)/1.574\]
Calibration of Hologram

- Line of best fit found
- This is transfer function
- Unknowns were tested with transfer function
- Errors typically between 1 to 4 nm.
  - Resolution of hologram is 2 nm
Fabry-Perot Interferometer

Fabry-Perot optical resonator and the Fabry-Perot interferometer (schematic)

© 1999 S. O. Kasap, *Optoelectronics* (Prentice Hall)
Fabry-Perot Interferometer

- An interference pattern is established at the detector.
- The pattern is a series of concentric circles.
- Notice how thin the lines are. The resolution of the FP interferometer is very good.
  - Less than .2 nm resolution.
Fabry-Perot Interferometer

- By picking a common radial line through all the orders, a graph of order position vs. light intensity is created.
  - The 553 nm wavelength occupies the same position as the 550 nm wavelength!
  - The difference in wavelength when this occurs is called the Free Spectral Range (FSR)
  - The FSR of this particular FP interferometer is about 3 nm
    - The FSR is wavelength dependent: $FSR \approx \lambda^2/2d$
Summary (So far)

- The cylindrical beam volume hologram can be used instead of a reflecting diffraction grating.
  - Plus: wide range of wavelengths
  - Minus: resolution is fair (about 2 nm)

- The FP interferometer
  - Plus: excellent resolution (about .2 nm)
  - Minus: very limited range of wavelengths
Solution: combine the two spectrometers into one: Ultra-High Resolution Volume Holographic Spectrometer

1st lens focuses light from FB to a point on CCD

2nd lens focuses light from hologram to a point on CCD

Since both light sources add together at the same point to create one interference pattern, this is an example of Fourier Transformation.
How the tandem spectrometer works

- The output from the holographic material is added to the output of the Fabry-Perot interferometer to create bands of overlap.

```
      +  =  
```

Only the top portion is read, so one small band for each order appears for a particular wavelength.

2 orders
How the tandem spectrometer works

The good...

535 nm

535.5 nm

Resolution at .5 nm

The bad...

535 nm

538 nm

Free Spectral range
How the tandem spectrometer works

- 2 waves pass through the spectrometer. One wave is 540 nm, while the other is 540.3 nm.
  - 540 nm: Can’t tell difference
  - 540.3 nm: Can tell difference
A 2D spectral analysis

546 nm

577 nm

579 nm

546 nm

20 40 60 80 100

200 180 160 140 120 100 80 60 40 20

Courtesy of Majid Badiei
Calibrating the tandem spectrometer

- Measured between 555 to 570 nm in .2 nm increments.
- Chose random wavelengths inside and outside the calibration range.
- Graphed the results.
Calibration data for tandem spectrometer

\[ \Delta \lambda = 3 \text{ nm} \]
Calibration data for tandem spectrometer

- Excel spreadsheet was used to determine wavelengths for random pixels.
- Strategy: the x pixel indicates the FSR interval, and the y pixel indicates the actual wavelength within the interval.
- A linear function was assumed for the y pixels
- Required creating multiple spreadsheets to handle each range.
## Calibration data for tandem spectrometer

- **Results:**

<table>
<thead>
<tr>
<th>x-pixel range= 90-94</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>x pixel</td>
<td>y-pixel</td>
<td>λ Calc.</td>
<td>λ Actual</td>
<td>delta λ</td>
<td>% error</td>
</tr>
<tr>
<td>92</td>
<td>218</td>
<td>556.1</td>
<td>556.3</td>
<td>0.17</td>
<td>-0.031</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>x-pixel range= 104-109</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>x pixel</td>
<td>y-pixel</td>
<td>λ Calc.</td>
<td>λ Actual</td>
<td>delta λ</td>
<td>% error</td>
</tr>
<tr>
<td>105</td>
<td>144</td>
<td>565.8</td>
<td>566.1</td>
<td>0.29</td>
<td>-0.052</td>
</tr>
</tbody>
</table>
Calibration data for tandem spectrometer

- The relative error < resolution limit
- Conclusion: Within small range, transfer function successful!
  - But not convenient
  - Multiple spreadsheets
- Better method: matrix comparison using least squares estimation.
Calibration data for tandem spectrometer

- Establish normalized matrix for each wavelength at .1 nm
  - 0 → no light; 1 → light reached pixel

Source matrix:

<table>
<thead>
<tr>
<th></th>
<th></th>
<th>1</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>B</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>C</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>D</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

A · S = 0
B · S = 0
C · S = 0
D · S = 1

Therefore: The source is 535.3 nm
The prototype…

Courtesy of Prospect Photonics Inc.
The End

- Thanks to Majid Badiei for being an excellent mentor during the project