1991 CEDAR Workshop
NIST Auditorium, Boulder, CO
2-5PM Tuesday, June 18, 1991

Optics Short Course

Roger Smith et al.
University of Alaska at Fairbanks
Optics Tutorial
(Featuring Hernandez, Romick and Smith)

Tuesday Afternoon
NIST Auditorium 2.00pm - 5.00pm
4 Sessions starting at:-
2.00pm: Optics in Aeronomy
3.00pm: Imaging the atmosphere
3.45pm: Observing lines and bands
4.30pm: Doing dynamics optically.
The View of a Ground Based Instrument

The van-Rhijn Effect
Meridian Scan Mode

Alt-Azimuth Scan

Horizon Zenith Horizon
Uniform Airglow Layer

Isophote map
Multiple Auroral Arcs

Airglow Layer

Ground-based view of Auroral Green Line

Equatorial F-region 6300 plumes

Complex F-Region View
Imaging the airglow layer

Signal seen = \( \frac{A \Omega}{4\pi} R \times 10^6 \) Photons per second

Small pixels receive a weak signal, require more time.
Possible Interpretations of Varying Intensity

Airglow patch

Patch moving?
Patch changing
Intensity?

Intensity

Time
Observations with a Medium Resolution Spectrometer

OH airglow Layer

Graphs showing data for OH(6-2) and OH(16-21) transitions.
Observing Geometry

[Diagram showing observing geometry with w, z, and e labels and a 6300A airglow layer]

Observed Spectra from a Fabry-Perot Spectrometer

[Dynamics Data (for each direction of view)]

Line of Sight Wind

- Eastwards
- Westwards

Kinetic Temperature

Time
Observing Geometry

Observed Spectra for a Michelson Interferometer similar to a WAMDII

Dynamics Data for each pixel in fringe image

Line of Sight Wind
- Eastwards
- Westwards

Kinetic Temperature

Path Difference

Time
Wave length Resolved Emissions can be used to identify the particular radiating atom or molecule. Other conditions lead to information about the excitation process.
Identification of the Emitter Through

ATMOSPHERIC RADIATION PROCESSES

Resonant Scattering
\( \lambda_1 = \lambda_2 \)

Fluorescent Scattering
\( \lambda_1 < \lambda_2, E_1 > E_2 \)

Radiative Recombination

Dissociative Recombination

Chemiluminescence

Electron Impact Excitation
<table>
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<tr>
<th>Excitation Conditions</th>
<th>Basic Process</th>
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<tr>
<td>Dayglow</td>
<td>Solar EUV and Photoelectrons</td>
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<tr>
<td>Twilight</td>
<td>Mixture - decay processes and Chemistry - Conjugate photoelectrons</td>
</tr>
<tr>
<td>Nightglow</td>
<td>Chemistry and conjugate photoelectrons</td>
</tr>
<tr>
<td>Aurora</td>
<td>All types of energetic particles</td>
</tr>
</tbody>
</table>
$N_2 \ C^3\Pi_u - B^3\Pi_g$

$NO \ A^2\Sigma^+ - \chi^2\Pi_g$

$N_2^+ \ B^2\Sigma_u^+ - \chi^2\Pi_g^+$

$N_2 \ A^3\Sigma_u^+ - \chi^1\Sigma_g^+$

KILORADIANTS/20 $\AA$

WAVELENGTH, $\AA$

2000 3000 4000

0 10 20 30 40
<table>
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<th>Objective</th>
<th>Observable</th>
<th>Approach</th>
<th>Mode</th>
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<tbody>
<tr>
<td>Neutral Composition</td>
<td></td>
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<tr>
<td>-Day atomic O</td>
<td>OI 130.4, 164.1 nm</td>
<td>Line ratios</td>
<td>E,L</td>
</tr>
<tr>
<td>-Day N2</td>
<td>OI 130.4, 135.6 nm</td>
<td>Line ratios</td>
<td>E,L</td>
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<td>-Day O2</td>
<td>N2 VK bands</td>
<td>Quenching</td>
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<td>N2 LBH, 2PG bands</td>
<td>Emission peak</td>
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<tr>
<td>-Global dynamics</td>
<td>O2 Herzberg I</td>
<td>Absorption O2, SR</td>
<td>E,L</td>
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<tr>
<td>-Air density</td>
<td>He 58.4 nm</td>
<td>He density</td>
<td>L,E</td>
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<tr>
<td></td>
<td>Rayleigh scattering</td>
<td>Limb scans</td>
<td>L,E</td>
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<tr>
<td>Ionization rates</td>
<td></td>
<td></td>
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<tr>
<td>-O+hv,e</td>
<td>OII 83.4, 61.7 nm</td>
<td>Rate from intensity</td>
<td>E,L</td>
</tr>
<tr>
<td>-N2+hv,e</td>
<td>NII 108.5, 91.6 nm</td>
<td>Rate from intensity</td>
<td>L,L</td>
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<td>Photoelectron fluxes</td>
<td>N2 LBH, 2PG</td>
<td>Combine with model</td>
<td>E,L</td>
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<td>Minor species</td>
<td></td>
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<tr>
<td>-Day NO</td>
<td>NO γ 215 nm</td>
<td>Fluorescent scattering</td>
<td>E,L</td>
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<tr>
<td>-Day N</td>
<td>NI 149.3, 174.3 nm</td>
<td>Electron impact</td>
<td>L,E</td>
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<td>-Day Mg</td>
<td>MgI,II 285.2, 279.8 nm</td>
<td>Resonant scattering</td>
<td>L,E</td>
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<td>-Day/night H</td>
<td>HI 121.6, 102.6, 656.3 nm</td>
<td>Resonant scattering</td>
<td>L,E</td>
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<tr>
<td>-Day He</td>
<td>HeI 58.4 nm</td>
<td>Resonant scattering</td>
<td>L,E</td>
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<tr>
<td>-Night N</td>
<td>NO 6 bands</td>
<td>N+O</td>
<td>E,L</td>
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<tr>
<td>-Night NO</td>
<td>NO2 continuum</td>
<td>N+O</td>
<td>E,L</td>
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E= Earth-viewing spectroscopic imager makes measurement
L= Limb-viewing imaging spectrograph makes measurement
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<tr>
<td><strong>Electron density</strong></td>
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<tr>
<td>-Day</td>
<td>OII 83.4 nm</td>
<td>multiple scattering</td>
<td>L</td>
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<td>-Day</td>
<td>OII 61.7, 54.0 nm</td>
<td>line ratios</td>
<td>L</td>
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<tr>
<td>-Day/Storm</td>
<td>OI 135.6 nm, N₂ LBH</td>
<td>N₂ from O/N₂ ratio</td>
<td>L</td>
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<tr>
<td>-Night</td>
<td>OI 91.1, 130.4, 135.6 nm</td>
<td>O⁺⁺e</td>
<td>E, L</td>
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<td>-Night</td>
<td>OI 630 nm</td>
<td>O₂⁺⁺e</td>
<td>E, L</td>
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<td>-F layer height</td>
<td>OI 130.4, 135.6, 630 nm</td>
<td>Hgt from line ratios</td>
<td>E, L</td>
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<td>OH (6.2) 825–860 nm</td>
<td>line ratio and spatial variations</td>
<td>E, L</td>
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<td>OH Meinel</td>
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<td>O₂ ATM</td>
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<td>E, L</td>
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<td>OI 557.7 nm</td>
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<td>E</td>
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<td>Observable</td>
<td>Approach</td>
<td>Mode</td>
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<td>Polar mesosph clouds</td>
<td>ice</td>
<td>Mie scattering</td>
<td>E.L</td>
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<tr>
<td>Auroras</td>
<td>all bands</td>
<td>Particle precipitation</td>
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<td>Energy deposition</td>
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<td>- Electrons</td>
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<td>- Protons</td>
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<td>- Solar EUV</td>
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<td>Neutral temperatures</td>
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<tr>
<td>- Day</td>
<td>O₂ ATM</td>
<td>Band profile</td>
<td>E.L</td>
</tr>
<tr>
<td></td>
<td>OI 135.6 nm, N₂ LBH, 2PG</td>
<td>Scale height</td>
<td>E.L</td>
</tr>
<tr>
<td>- Night</td>
<td>OH Meinel, O₂ ATM</td>
<td>Band profile</td>
<td>E.L</td>
</tr>
</tbody>
</table>

- N₂ 2PG, LBH; N₂⁺ 1NC
- OI 297.2, 557.7, 630 nm
- OI 844.6 nm
- HI 121.6, 496.1 nm
- Dayglow
There are very few cases where there is a simple direct relationship between a particular emission and the density of the emitter. Thus models enter as necessary linkages between observed emissions and derived parameters.
There are some studies that do not need quantitative intensity measurements or derived constituent densities. Morphological studies from images have contributed a great deal towards our understanding of the auroral oval.
To cover all of the quantitative studies using optical observations is beyond the scope of this short course. As examples I will concentrate on some DAYGlow observations and derived quantities.
Satellite limb scan
(Analysis from CPI and JHU/APL)
Figure 17 - Conversion of a reduced earth limb dayglow observation of the NO intensity into a NO density profile.

(Analysis from CPI and JHU/APL)
(Analysis from CPI and JHU/APL)
The MUV dayglow observed from a low earth orbiting satellite at 2.8 nm resolution have been analyzed. Theoretical radiances were calculated utilizing a dayglow energy deposition and radiance model. Comparison of theory and data below a tangent altitude of 80 km shows that the emission is dominated by Rayleigh scattering. As the tangent altitude rises spectral signatures of NO, N₂, O⁺ and O appear. Analysis of these emissions shows that the observed emission is consistent with currently accepted ion-neutral chemistry in the mesosphere and lower thermosphere.

The NO density deduced compares well with SME results and shows an apparent scan-to-scan variation which implies very short time scale variations in the radiation field and/or NO density. The theory consistently overestimates the data near 205 nm where both NO and N₂ LBH emit radiation. The good fit to the remaining N₂ LBH data provides a measure of magnitude of the solar EUV energy deposited in the thermosphere. The deduced NO density above 110 km is used as input to the ion-neutral chemistry model which calculates the O(¹S) and O(³D) excitation rates. The neutral density background atmosphere was calculated with MSIS86 for the solar and geomagnetic conditions appropriate to the measurements. No scaling of the MSIS86 densities were required.

(Analysis from CPI and JHU/APL)
General Guidelines

1) OPTICAL Observations provide a method for remotely determining atmospheric parameters.

2) The accuracy of these determinations depends on our knowledge of specific excitation and loss mechanisms cross sections and perhaps neutral and ion dynamics.

3) Characteristics of the geometry of the measurement impact the resolution of the derived parameter.

4) Simultaneous observations of different emissions are necessary to evaluate models which link emissions to atmospheric parameters.
Coordination with Rockets

Auroral Arc
Rocket Trajectory

Launch site camera
Tomographic Meridian Scanning Photometer Group at A, B and C
Downrange camera
Coordinated Experiments with Incoherent Scatter Radars

Auroral Arc under investigation

Incoherent Scatter Radar

Photometers measuring spectral ratios

Video imager looking at lower border
THE PHOTOMETRIC MATRIX

$I_\lambda(x, y, t)$

* Imaging data fills in the values in this 3-D matrix. The instrument is truly multiplex, ie all dimensions in the matrix are filled at once.

* Data studies are usually shown in 2-D extracts. For any given position in the imaged field, "post-hoc" photometry can be performed giving

$I_{x,y,\lambda}(t)$.

* Alternatively we can study spatial variations at an instant:

$I_{\lambda,x}(x)$ or $I_{\lambda,y}(y)$

* Studies in any of these spatial or temporal series must be done in the awareness that layer height and geometry can change without any direct knowledge from the measurement.

* Calibrations in intensity, flatfielding, optical distortion, and photometric linearity are required before that data have a scientific value. Also error bars must be determined.
Photometric Imager

\[ I = \frac{A \Omega}{4\pi} \times 10^6 \tau_L \tau_F Q \]

- \( A \) = the aperture of the optical component
- \( \Omega \) = the solid angle of acceptance of the component
- \( \tau_F \) = the transmission of a prefilter
- \( \tau_L \) = the transmission of the lens or other component
- \( Q \) = the quantum efficiency of the detector
Flying Spot Imager

Data quality depends upon the sensitivity and noise performance of the single channel photometer, and the brightness of the light source in the atmosphere.
The Imaging Photon Detector

Incoming single photon

Expanding stream of secondary electrons

Photocathods

Triple deck microchannel plate mounted chevron style

Resistive plate or wedge/strip electrodes

Charge on anode spreads uniformly to electrodes

Uniform resistive plate

\[ x = \frac{(A+B) - (C+D)}{A+B+C+D} \]

\[ y = \frac{(B+C) - (A+D)}{A+B+C+D} \]
Figure 2-2. Cross-Section of a Simple Photodetector

Figure 2-3. Charge Transfer in a 3-Phase CCD
Image Intensifiers

Devices which convert an optical image to electronic form, amplify the signal and convert back to optical.

Conversion to electronic form is by a photocathode. Amplification may involve secondary electrons. Conversion back to an optical image is by phosphor.

Focussing can be magnetic or electrostatic. (proximity). Here is an electrostatic type.
# TABLE OF COMPARISON

<table>
<thead>
<tr>
<th>Criterion</th>
<th>CCD</th>
<th>IPD</th>
<th>Flying Spot</th>
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<tbody>
<tr>
<td>Wavelength sensitivity</td>
<td>&lt;4000 Å - 10000 Å</td>
<td>525 – 3000 – 7500 Å GaAs &lt;4000 – 9000 Å</td>
<td>&gt;25 GaAs Bi-Alk UV.</td>
</tr>
<tr>
<td>Read noise</td>
<td>2-10e/pix at 50MHz (increases with A/D speed)</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Thermal noise</td>
<td>0.5e/s at -50°C using MP bias</td>
<td>15x10^-3 e/s at 0°C for 525</td>
<td>1-25°C dependent on cooling and photocathode</td>
</tr>
<tr>
<td>Spatial non-linearity</td>
<td>&lt;0.2%</td>
<td>~1%</td>
<td></td>
</tr>
<tr>
<td>Photometric non-linearity</td>
<td>Y.small up to full well.</td>
<td>depend on dead time in processing and on any MCP overload.</td>
<td>Linear over 3.4 cm.</td>
</tr>
<tr>
<td>Image brightness limitation</td>
<td>Full well ~250k electrons</td>
<td>MCP* overload dependent on limit on pixel storage except in computer.</td>
<td>Dead time limited</td>
</tr>
</tbody>
</table>

*Multi-pinned phase

* MCP = microchannel plate
Effect of diffraction on the image of a point source
Vignetting

Some off-axis rays are obstructed by camera structure
Aberrations

Spherical

Astigmatism

Coma
CONSTANCY OF $A \Omega$

\[ I = \frac{A \Omega}{4 \pi} \times 10^6 \tau_L \tau_F Q \]

- $A$ = the aperture of the optical component
- $\Omega$ = the solid angle of acceptance of the component
- $\tau_F$ = the transmission of a prefilter
- $\tau_L$ = the transmission of the lens or other component
- $Q$ = the quantum efficiency of the detector
Data Storage

- Camera
  - 512 x 512
  - Analog signal

- 512 x 512 x 2 bytes
  - 500 kbytes
  - Controller

- Display

- PC CPU

- Optical Disk
Imaging Speed

- Depends on shot, dark and read noise.

- Limited by speed of data handling and transfer to disk.

- For IPD also limited by the serial processing time.
THE SPECTROPHOTOMETRIC MATRIX

\[ I(\lambda,x,t) \]

* Data matrix in 3 dimensions:
  1 spectral, 1 spatial (along the slit), 1 time.

* Data studies (often 2-dimensional):
  - Spectral type:
    Spatial variations \( I_x(\lambda,x) \)
    Temporal variations \( I_t(\lambda,t) \)
  - Photometric study of one feature:
    Spatial variations \( I_x(x,t) \)
    Temporal variations \( I_t(\lambda,t) \)

* Geometrical factors, such as the van Rhijn effect need to be considered in any spatial studies.
Spectral Information in lines and bands

Line and band intensities
Most information can be obtained with between 1 and 5Å resolution.

Peak shift
47.6 m/s /mA at 6300Å

Spectral line shapes

FWHH = k x SQRT(T/M)
= 23.3 mA for 5577Å OI at 200K
= 59.4 mA for 6300Å OI at 1000K
GENERALIZED SPECTROMETER
Spectral Properties:

a) Color (Wavelength).
b) Shape.
c) Area.
d) Time behavior.

Wavelength:

\( \lambda \), expressed at 1 atmosphere, 15 °C.
\( \sigma = \lambda_0^{-1} \), expressed in wavenumbers (cm\(^{-1}\)). \( \lambda_0 \): vacuum wavelength.

Resolving limit:

\( \delta \lambda \): smallest resolvable spectral element, in wavelength. \( \delta \sigma \): smallest resolvable spectral element, in wavenumbers.

Resolving power:

\[ R = \frac{\delta \lambda}{\lambda} = \frac{\delta \sigma}{\sigma} . \]

Flux delivered to the detector:

\[ F = I \ A \ \Omega \ \tau . \]

Luminosity:

\[ L = \frac{F}{I} = A \ \Omega \ \tau . \]

Angular dispersion:

\[ D = \frac{d\beta}{d\lambda} = \frac{d\beta}{d\sigma} . \]

Spectral width:

\[ \omega = \frac{\Theta}{D} . \]
A spectrometer has a slit (or aperture) with angular width $\Theta$ and angular height $\Phi$. The transmission properties for this aperture are given by $\tau(\Theta, \Phi)$. The associated solid angle is:

$$\Omega = \int_0^{2\pi} \int_0^{\Theta^2} \tau(\Theta, \Phi) \sin \Theta \, d\Theta \, d\Phi .$$

$$\Omega = 2\pi \left[ 1 - \cos(\Theta/2) \right] = \Theta^2$$  \(\text{ (circular aperture)}\).

$$\Omega = \Theta \Phi$$  \(\text{ (otherwise)}\).

$$L = A \tau \Theta \Phi \text{ or } A \tau \Theta^2 .$$

For one-dimensional dispersion devices, such as a grating or prism spectrometer:

$$\Theta = \omega D .$$

$$L_{sp} = A \tau \Phi \omega D = A \tau \Phi D \lambda R^{-1} .$$

For two-dimensional dispersion devices, such as Michelson and Fabry-Perot spectrometers:

$$\omega = \sigma \Theta^2 8^{-1} ,$$

$$L_{FP} = A \tau 8 \omega \sigma^{-1} = A \tau 8 R^{-1} .$$

For the specific case of a grating spectrometer at near-normal incidence with a grating with a blaze angle $\gamma$:

$$D = N n (\cos \beta)^{-1} ; \quad \sin \alpha + \sin \beta = N n \lambda ,$$

$$D = A (\sin \alpha + \sin \beta) (A \cos \beta \lambda)^{-1} .$$
\[ A \cos \beta = A_0, \] where \( A_0 \) is the area normal to the beam. In addition, \( \sin \alpha + \sin \beta = \sin(2\gamma) \).

\[ A_0 D = A \sin 2\gamma \lambda^{-1}, \]
\[ L_g = \tau \Phi A \sin 2\gamma R^{-1}. \]

The comparison of the luminosity between these two types of dispersing spectrometers, at equal resolving power, assuming equal area grating and interference spectrometer pupils, is:

\[ [L_{FP} (L_g)^{-1}]_{A_{FP}} = A_g = 8 \left( \Phi \sin 2\gamma \right)^{-1}. \]

For a typical grating with a blaze angle near 15° and a spectrometer with an angular height of 0.2 radians:

\[ [L_{FP} (L_g)^{-1}]_{A_{FP}} = A_g = 8 \left( 0.2 \times 0.5 \right)^{-1} = 80. \]

This comparison shows that, for the same resolving power, a 0.5 inch by 0.5 inch interference filter (a special case of a Fabry-Perot device) is as luminous as a grating spectrometer with a 4 inch by 5 inch grating.

Because of the larger luminosity of the two-dimensional dispersing devices, their use is preferentially directed to high-resolution studies where spectral line shapes and width measurements are desired.

The simple, instruments described above have a Luminosity \( \times \) Resolving-Power product that is constant. However, there exist another class of instruments that are inherently compensated or can be compensated. A compensated device has the
property of a Luminosity $\times$ Resolving-Power product that increases with increasing Resolving Power. They will not be discussed here.

Purposely, the above discussion has been limited to the flux delivered to the detector, and this detector is considered to be large enough to accept the flux for one resolvable element. A single detector requires that the spectrum be scanned across this detector, while a multiple detector device can observe many spectral elements simultaneously (multiplexing). For intrinsically-noisy detectors, it is possible to detect multiple wavelengths simultaneously and still have a net gain (Fellgett advantage). This technique is employed with Michelson devices in the infrared region.

Finally, there is the topic of selectivity, that is the ability of a given spectrometer to observe an arbitrary region of the spectrum without instrumentally-caused contamination from other regions. In general, grating instruments have greater selectivity, although interference devices can be made to approach this selectivity.

**Selected References**


USE AN ORDER-SORTER FILTER WHICH ABSORBS THE HIGHER ORDERS AT SHORTER WAVELLENGTHS.
STRAY LIGHT
Dynamic Range of the Detector

Example: structure at the base of the 5577 line molecular oxygen first negative bands.
Michelson Interferometer

\[ B(1 + \cos(6.28sd)) \]

- \( s \) = wavenumber
- \( d \) = path difference

Visibility = \( \exp(-QTd^2) \)
Fabry Perot Etalon

Instrument Function

Sensitive to pressure (gas refractive index), temperature, vibration
Field Widening for Michelson Interferometer

Maintains the quasi-zero path condition when the path difference is non-zero and the rays are off-axis utilizing a glass block whose thickness is specific to the geometrical paths.
Field-Widening a Fabry-Perot Spectrometer

The Dual Etalon Modulator Approach

Fig. 1. Schematic representation of the beam expander used to couple the two etalons ($E_1$ and $E_2$) in this experiment.
FPI SCANNING

\[ 2nd \cos \theta = p\lambda \]

*For pinhole scanning*, \( \theta \) may be considered close to zero
and \( \cos \theta = 1 \)

Hence \( 2nd = p\lambda \)

Pressure scanning: \( p,d \) constant, vary \( n \) to scan \( \lambda \)
this is refractive index scanning

Piezo scanning: \( n,p \) constant, vary \( d \) to scan \( \lambda \)
this is scanning in plate separation

*For spatial scanning*, we may assume that \( \theta \) is small so that
\[ \cos \theta = 1 - \theta^2/2 \]

Hence \( \theta^2 = (p - p_0)/p_0 \)

where \( p_0 \) is the order at the center of the pattern.

Since \( \theta \) is proportional to fringe radius, \( p \propto \text{radius}^2 \)
Finding the peak wavelength of a profile

* Use a fit function
  or
* Use the phase of FT
  or
* Other suitable technique

For emissions not available in laboratory discharges
  * get zero wavelength by averaging zenith

Scale velocities using standard Doppler theory.
Getting the Temperature from the spectrum

* Analyze using one FSR
* Remove instrument function
* Find best fit to Gaussian curve for $T$ at given $M$.
* Check for Gaussian shape.

Temperature is found from the slope.

For noiseless data.

For data with noise.