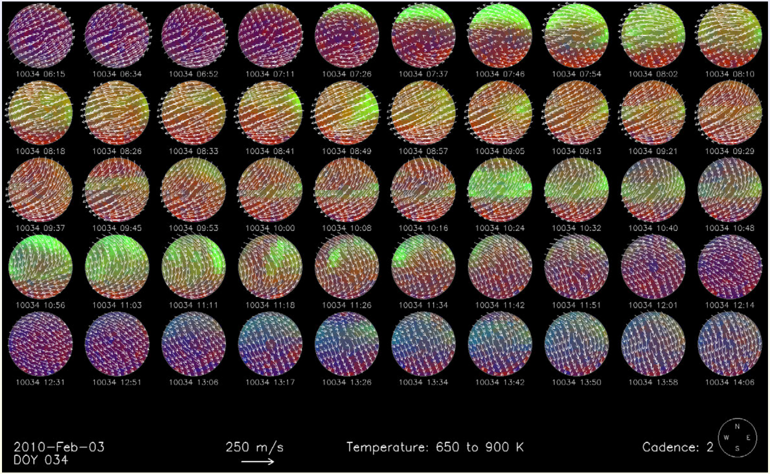
Fabry-Perot Measurement of Aeronomic Winds and Temperatures

Mark Conde – University of Alaska Fairbanks



This talk is a tutorial on the technique of using Fabry-Perot spectrometers to measure *neutral winds* and *neutral temperatures* in Earth's uppper atmosphere.

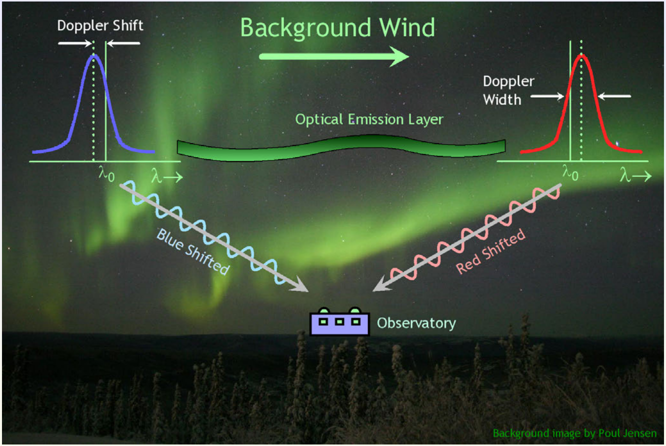
CEDAR Workshop: Calibration and Analysis Techniques for Passive Optical and Lidar Observations

Thurs. June 26th, 1:30-3:30 PM

Accurate calibration is important for inter-comparison of observations, data/model comparisons, and long-term investigations. We invite discussion on a broad range of topics relating to passive optical and lidar observations and their analysis. Possible topics include absolute and relative intensity calibration, wavelength calibration, spatial scale determination, error analysis, correction for scattering within the lower atmosphere, isolation of atmospheric lines of interest, flat field techniques, and spectral fitting approaches. In addition to reporting progress on calibration and analysis techniques, this workshop provides an opportunity to discuss challenges and questions to gain feedback from other workshop participants. In addition, we welcome modelers to discuss use of observations for model-data comparisons, and associated questions and challenges for model validation. *We encourage hands-on demonstrations and presentations by students.*

Please email Susan Nossal (nossal@physics.wisc.edu) and Don Hampton (dhampton@gi.alaska.edu) if you are interested in giving a short presentation.

Passive Doppler Wind & Temperature Measurement



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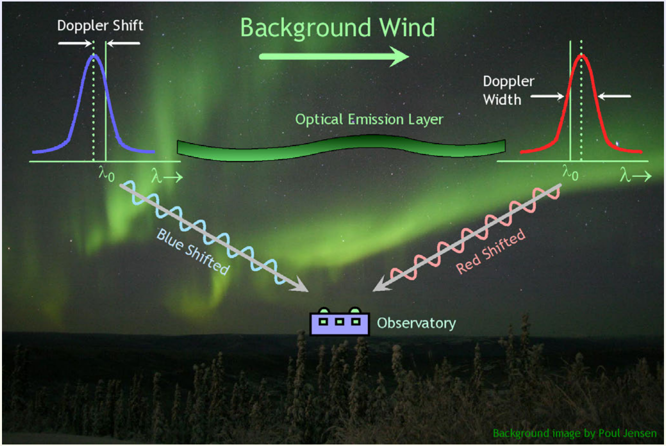

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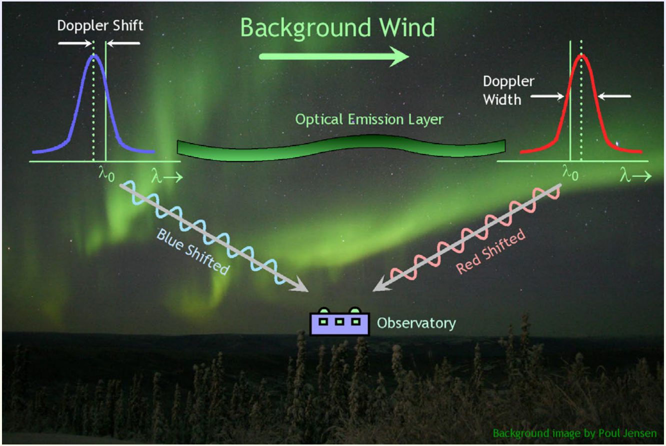

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- While the Doppler shift only measures the line-of-sight wind component, the complete wind vector can be estimated by viewing in several directions.[1]
- Further, temperatures may be inferred from the width of the Doppler spectrum.

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Required Resolution

The $\frac{1}{e}$ half-width of an unstructured spectral line's Doppler broadening function is related to kinetic temperature by

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To resolve such a width, we'd like a spectrometer with a comparable bandwidth, which corresponds to a resolving power of

$$R = \frac{\lambda}{\Delta\lambda} = \frac{630\,\mathrm{nm}}{3.2\,\mathrm{pm}} \simeq 200{,}000$$

Required Stability

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Thus, Doppler spectral measurement of thermospheric wind and temperature requires an instrument with a resolving power of $R \simeq 200,000$ and a wavelength stability of around *5 femtometers*!

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Suitable Emission Lines

Useful emissions for Fabry-Perot measurements of wind and temperature include:

Oxygen Red Line: From atomic oxygen at a wavelength $630.0\,\mathrm{nm}$. Volume emission rate maximizes at a height of around $240\,\mathrm{km}$ for airglow, or as low as $\sim 180\,\mathrm{km}$ for aurora. Layer thickness spans many tens of kilometers.

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Oxygen Green Line: This emission is from atomic oxygen at a wavelength 557.7 nm. Volume emission rate maximizes at a height of around 97 km for airglow, or anywhere in the range 95 km to about 150 km for aurora. Height variation in aurora is due to variable characteristc energy of the precipitating electrons, and can be a problem for wind & temperature retrieval.

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732 nm O^+: This emission from O^+ comes from the F-region and above. It is very weak, but potentially useful for measuring ion velocities, among other things.

OH emissions: Various OH emission lines occur at around 840 nm and are useful for measuring winds at around 87 km. The emissions are relatively weak, and doublet spectral structure complicates wind & temperature retrievals.

Twilight Sodium: Resonant scattering of sunlight from the mesospheric sodium layer at ~ 90 km altitude produces bright "D" doublet emission at 589.0 nm and 589.6 nm The layer must be sunlit, so the best data are obtained during twilight. Again, hyperfine doublet structure complicates wind & temperature retrievals.

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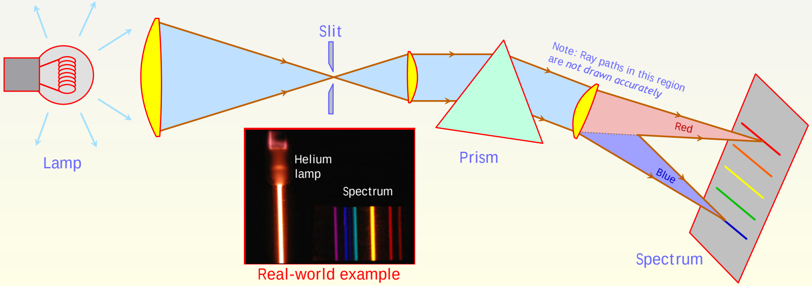
The tuning can either be done by varying a single pass band over time, or by having multiple sensors spread out across a region where the pass band is dispersed spatially. The cartoon diagram below shows a prism spectrometer using the latter strategy.



Example – Recording a Solar Spectrum

- This is an conceptual example of scanning a single pass band over time to record a spectrum.
- In this case I am using the solar spectrum near 630 nm as an example of the source or input spectrum.
- Although it not obvious with the very narrow passband used here, *the recorded spectrum is not the same as the source*. The recorded spectrum is the *convolution* of the source spectrum with the instrumental pass band function.

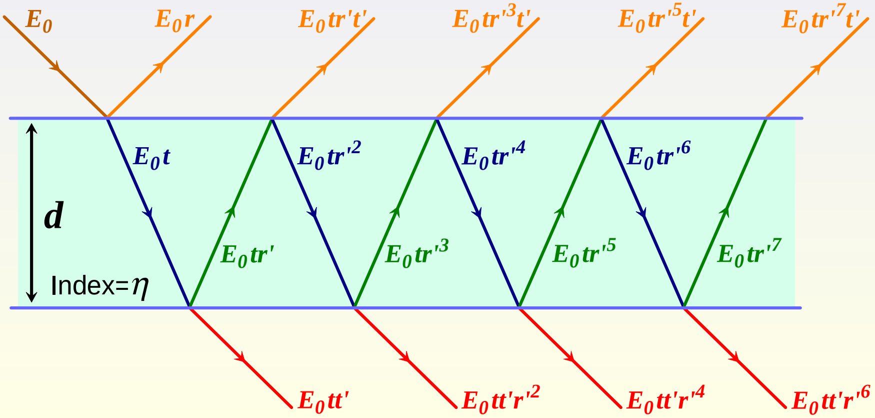
Effect of Pass Band Width

- This is the same as the previos example, except *the instrumental pass and is now much wider* in wavelength.
- Note how the narrow spectral features now appear broader and less deep in the recorded spectrum.
- It is not possible to build a spectrometer with a pass band of zero width. (It would have zero transmission.) *Instrumental broadening is inevitable*.
- To calculate atmospheric temperature from recorded spectral widths, our *analysis procedures must account for this broadening* (Using either deconvolution or forward modeling.)

Fabry-Perot Etalon

A Fabry-Perot etalon is comprised of two glass plates that are flat and parallel to $\sim\lambda/30$ or better, whose inner surfaces are coated to achieve a reflectance roughly in the range 0.75 to 0.95.

The plate coatings cause multiple reflections, which interfere so that only certain wavelengths are transmitted. (All others are reflected). The etalon acts as a *highly selective spectral filter*.



The Airy Function

Definition (**Airy Function**)

Neglecting losses, the transmitted relative intensity is given by the Airy Function

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The parameter δ is the phase difference between successively reflected beams. It depends on the wavelength λ of the incident light, the spacing d between the etalon plates, the refractive index η of the spacer material, and the incidence angle θ of the incoming light.

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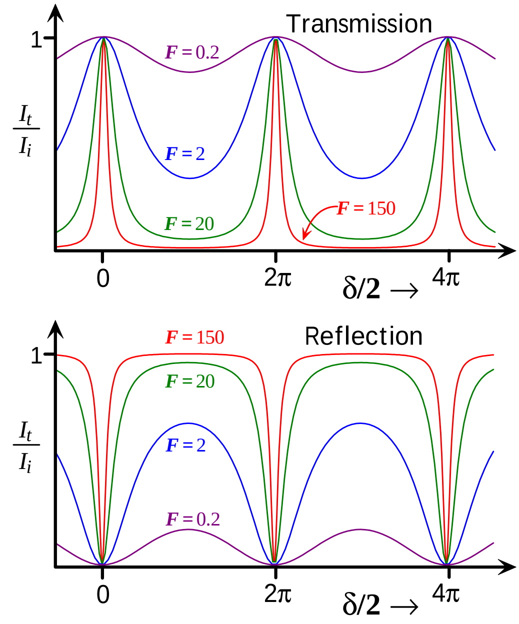
The quantity F is known at the *coefficient of finesse*. It is determined by the amplitude reflection coefficient r of the plate coatings

$$F = \left(\frac{2r}{1 - r^2}\right)^2 \tag{5}$$

(Note that we usually specify the plate coating reflectance R rather than the reflection coefficient, with $R = r^2$.)

Spectral Profile of the Transmission and Reflections



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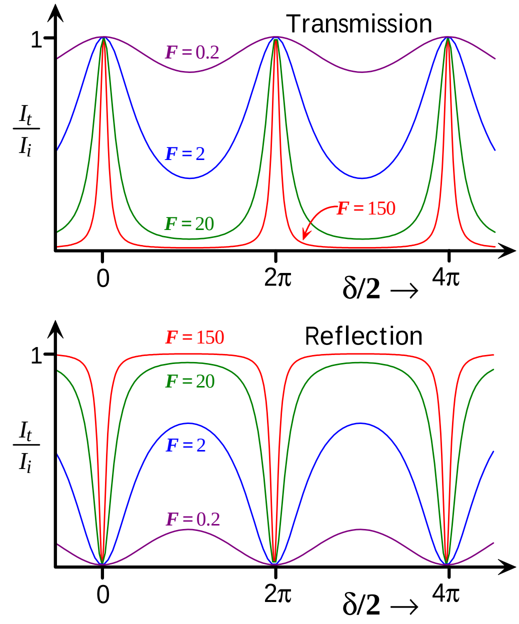

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- *The coefficient of finesse determines the "sharpness" of the fringes, and how deeply modulated they are*.
- The bottom panel shows one minus the Airy function, and describes the reflected intensity.

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Answer: The expression for m is derived the same way as one does for thin film interference. The derivation is straightforward, though care must be taken to account for all contributions to phase lag. The result is that

$$m = \frac{2\eta d \cos\theta}{\lambda}$$

where
$$\begin{cases} \eta = & \text{refractive index between the plates} \\ d = & \text{plate separation thickness} \\ \theta = & \text{optical incidence angle} \\ \lambda = & \text{wavelength} \end{cases}$$

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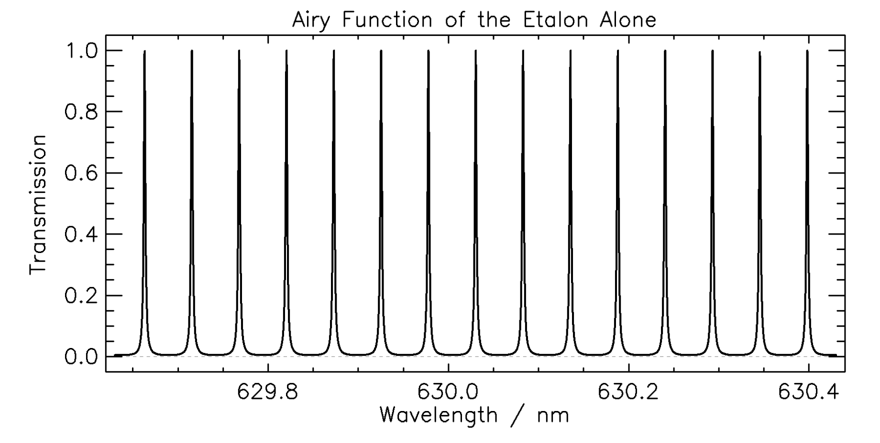
- *So the etalon transmission is actually a function of everything that m depends on: d, θ, λ, and η.*
- If we keep any three of these constant, the transmission is a periodic function of the remaining parameter.
- In particular, if we hold d, η, and θ constant, then the etalon transmission is solely a function of wavelength.

Typical Airy Function



- This figure shows the transmission of a perfect air-spaced etalon with a gap of $d = 3.78\,\mathrm{mm}$ and a plate coating reflectance of $R = 0.88$.[2]

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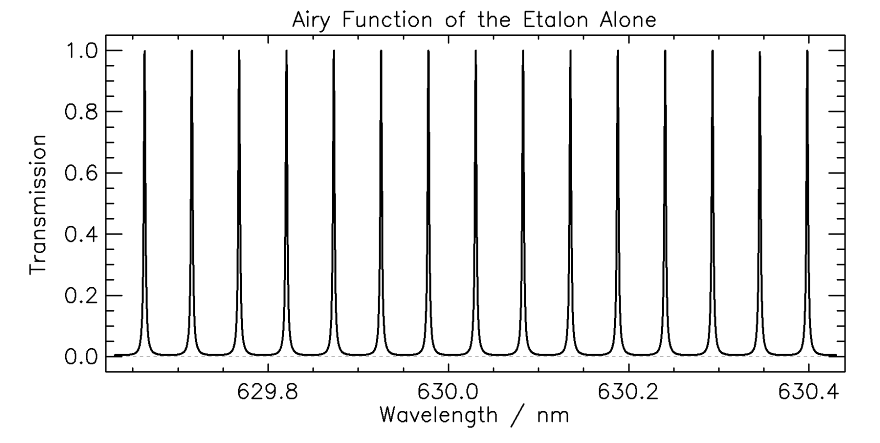

- This figure shows the transmission of a perfect air-spaced etalon with a gap of $d = 3.78\,\mathrm{mm}$ and a plate coating reflectance of $R = 0.88$.[2]
- Note how narrow the pass bands are – the FWHM is about $2\,\mathrm{pm}$.

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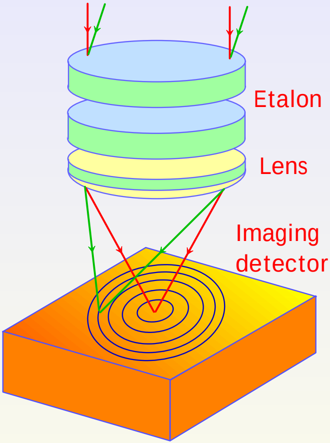
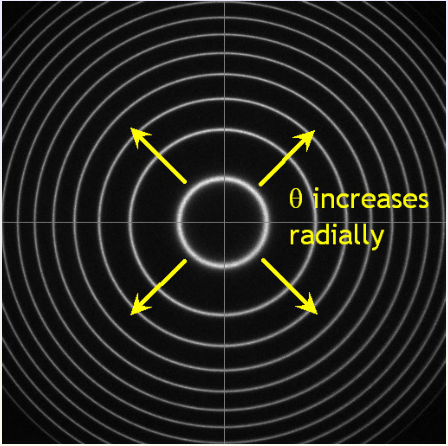
Imaging the Fringes





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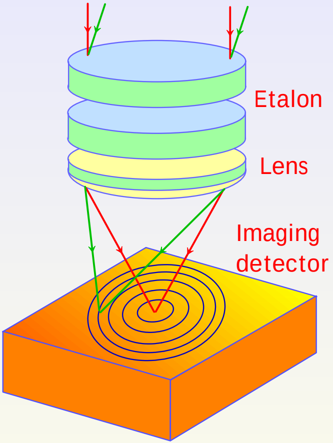

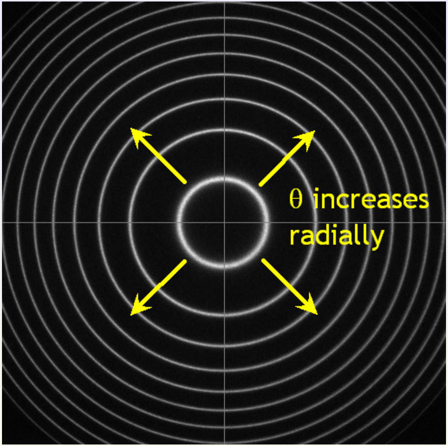

- Imaging detectors record simultaneously the transmitted brightness as a function of θ, over a range of incidence angles.
- *If we illuminate the etalon monochromatically*, the result is a series of concentric circular Fabry-Perot fringes.

Angular Field of View

The interference order is given by

$$m = \frac{2\mu d \cos\theta}{\lambda}.$$

The condition for j interference orders in the pattern is thus

$$\begin{aligned} j &= \frac{2\mu d \cos 0}{\lambda} - \frac{2\mu d \cos\theta_j}{\lambda} \\ &\simeq \frac{\mu d \theta_j^2}{\lambda}, \\ \text{So for the } j\text{-th fringe,} \quad \theta_j &= \sqrt{\frac{j\lambda}{\mu d}} \end{aligned}$$

- Therefore, to image 8 fringes at $630\,\mathrm{nm}$ with an etalon of spacing $d = 3.78\,\mathrm{mm}$, $\theta_8 \simeq 2^\circ$, whereas for $d = 20\,\mathrm{mm}$ we have $\theta_8 \simeq 0.9^\circ$.
- Conversely, for a "pinhole" passing only (say) $\frac{1}{20}$th of an order, $\theta_{0.05} \simeq 4$ arc minutes.
- Fringe imaging instruments obviously accept far more light, which is why most modern instruments work in this mode.

Using a Fabry-Perot Etalon to Record Spectra

- It is possible to make etalons with large aperture – plate diameters up to $150\,\mathrm{mm}$ are common in aeronomy applications. By using coating reflectances greater than ~ 0.8 and gaps greater than $\sim 3\,\mathrm{mm}$, it is possible to achieve spectral passbands narrower than the $\sim 3\mathrm{pm}$ required for aeronomic Doppler sectroscopy.
- Thus, Fabry-Perot etalons have been used since the 1960's to measure Doppler spectra of the airglow and aurora, for the purpose of estimating the large scale "background" wind and temperature fields in the thermosphere [*Wark*, 1960; *Jarrett and Hoey*, 1966; *Roble et al.*, 1968.]

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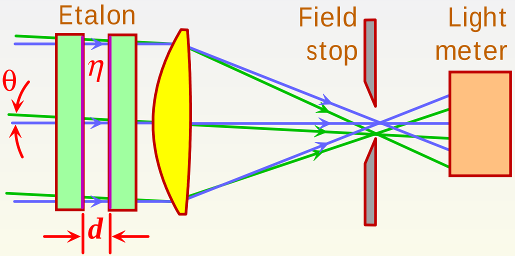

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Using a Fabry-Perot Etalon to Record Spectra

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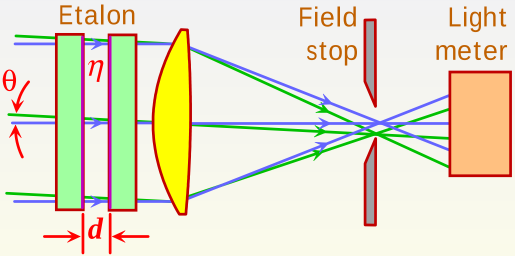

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Answer: By varying one of the etalon's operating parameters θ, η, or d.

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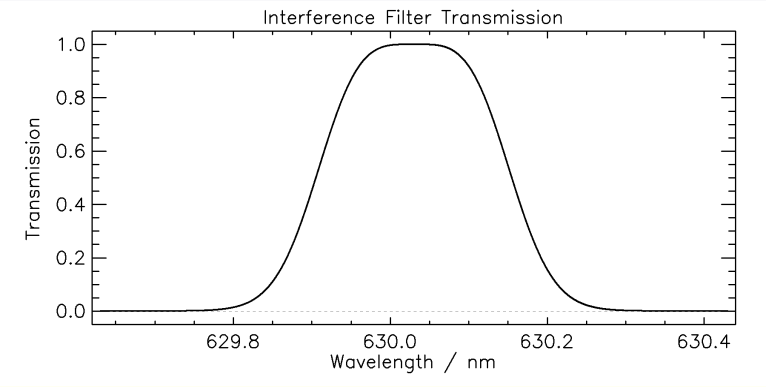
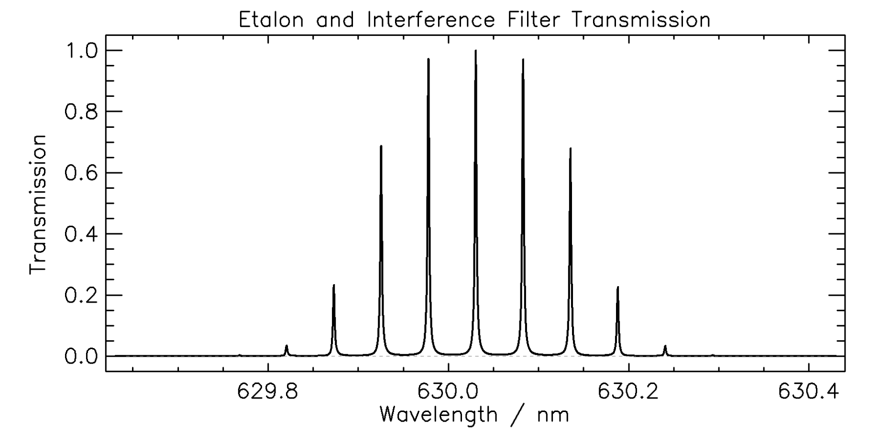
Answer: Part of the answer is that we use a narrow band interference filter to block most of the pass bands. A typical narrow band-pass filter profile is shown below. .



Pass Bands of the Etalon-and-Filter Combnation



- This figure shows the pass bands of an etalon and filter in series.[3]
- Now although we can usually tune the etalon pass bands in wavelength, the filter is not (normally) tuned. So, as the instrument scans in wavelength, the narrow pass bands move "through" the filter envelope.

[3] Here I have used an etalon gap of $d = 3.78\,\text{mm}$ for clarity; it results in relatively few pass bands within the filter envelope. While this configuration works fine, other practical considerations mean that most modern instruments use larger gaps (10 to 20 mm.) This results in the pass bands being closer spaced in wavelength, so that many more would occur inside the filter envelope.

A Truly Stupid Spectrometer

- But even after adding a filter, we still haven't reduced the transmission down to one isolated narrow passband.
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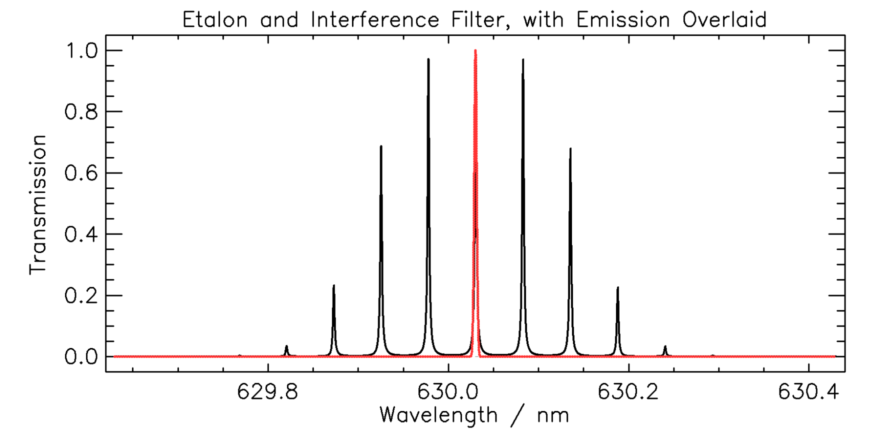
Question: So can it possibly be useful? .

Answer: Multple pass bands aren't a problem provided there is *only one narrow spectral line within the filter envelope*.

Nightglow Spectroscopy



The aeronomic application in which a single etalon spectrometer works well is nightglow spectroscopy – in which we can usually ensure that *the dark sky illumination contains only one spectral emission line* (shown here in red) within the system of instrumental pass bands (shown here in black.)

What We Get from Fabry-Perot Nightglow Spectral Measurements

- Using a single etalon spectrometer (with filter) to observe a single nightglow produces the output shown here.
- As each pass band "sweeps over" the emisison line, a new peak appears in the recorded spectrum. Each new peak actually corresponds to transmission by the etalon at a different interference order.
- Since we only want to define the shape of the emission line itself, we can use any one of these recorded peaks for that. Actually, there is no need to scan over more than one order, although we can of course do so if we wish.

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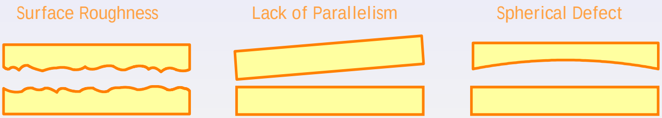

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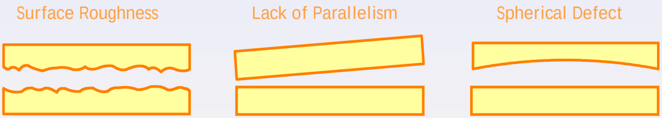

The effect of such defects is that the overall etalon behaves like a "montage" of a large number of small "elemental etalons", each with a slightly different gap. When expressed in terms of wavelength, the Airy functions of these elemental etalons are all shifted slightly relative to each other.

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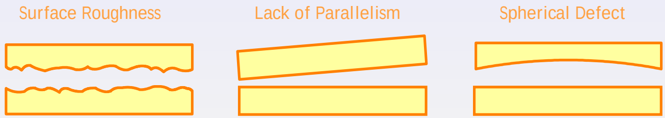

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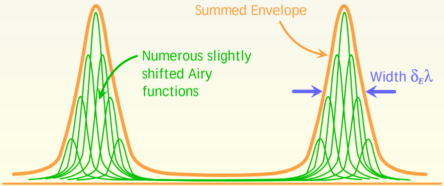
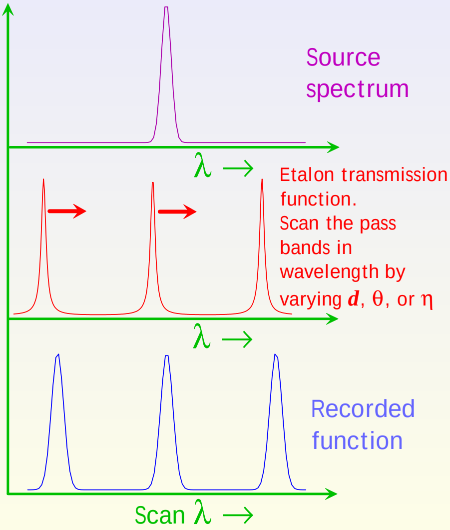
Thus, there is a distribution of shifts, peaked around the mean. *The net result is to broaden the wavelength transmission function of the overall etalon*, as shown. It is the width $\delta_E\lambda$ of this summed transmission that actually limits the wavelength resolution.



Recording Spectra



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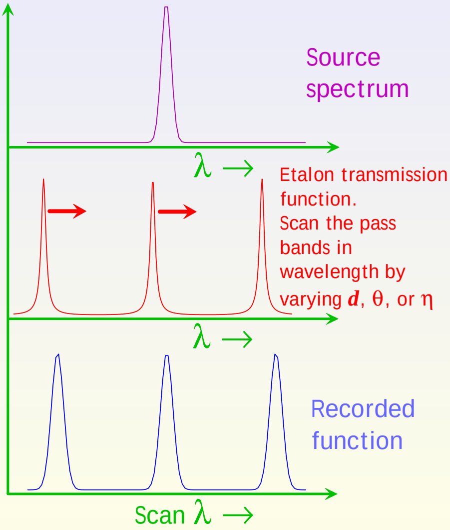

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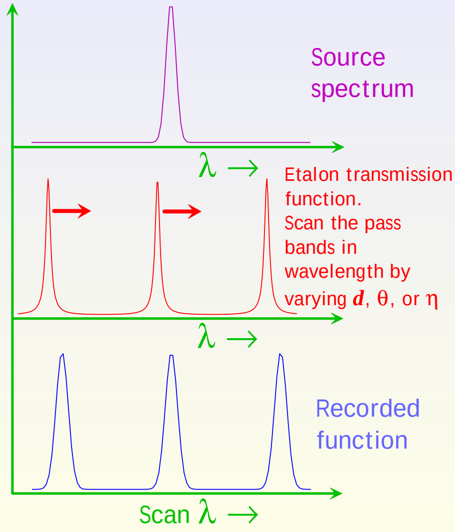

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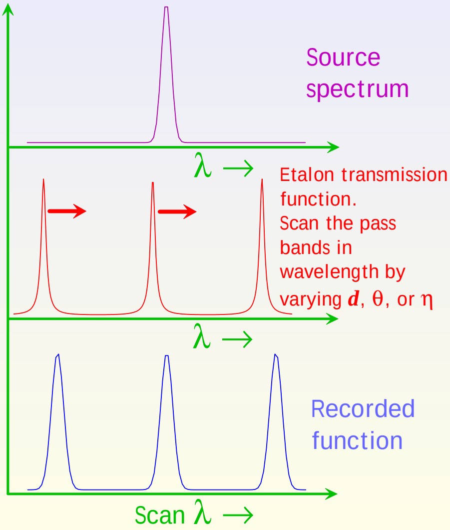

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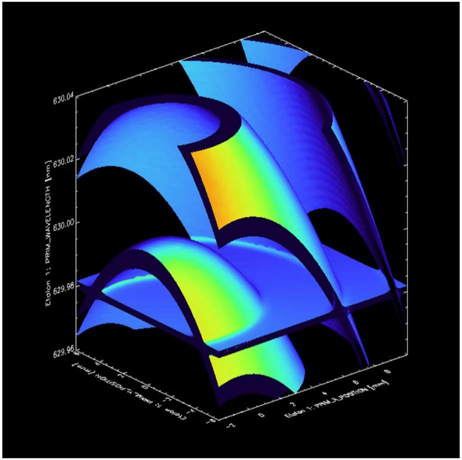
- θ : This is known as *angular scanning* or sometimes as *spatial scanning*. Today, it is easily achieved without having to scan over time, by simply recording a 2D image of the fringes.

Circular Interference Fringes



- Fabry-Perot fringes are formed when *monochromatic* light illuminates the etalon's pass bands, which are paraboloids[a] when plotted as functions of wavelength and 2-dimensional incidence angle.
- Each successive "shell" corresponds to an integer increment of one in interference order.
- The figure shows why a static etalon with an imaging detector can function as a spectrometer: *the center wavelength of each pass band decreases with increasing incidence angle.* Effectively, the pass band is "scanned" by radial distance on the detector.

[a] The paraboloidal shape arises from the $\cos\theta$ term in the expression for intrference order.

Recovering Spectra from Static Fringes

- Provided that neither the brightness nor the spectral distribution $B(\lambda)$ of the illumination varies across the etalon's angular field of view, then the two-dimensional fringe shapes are determined solely[4] by the Airy function $A(d, \eta, \theta, \lambda)$ of the etalon at each pixel, spectrally convolved with $B(\lambda)$.

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- The video below illustrates one possible procedure for doing this.

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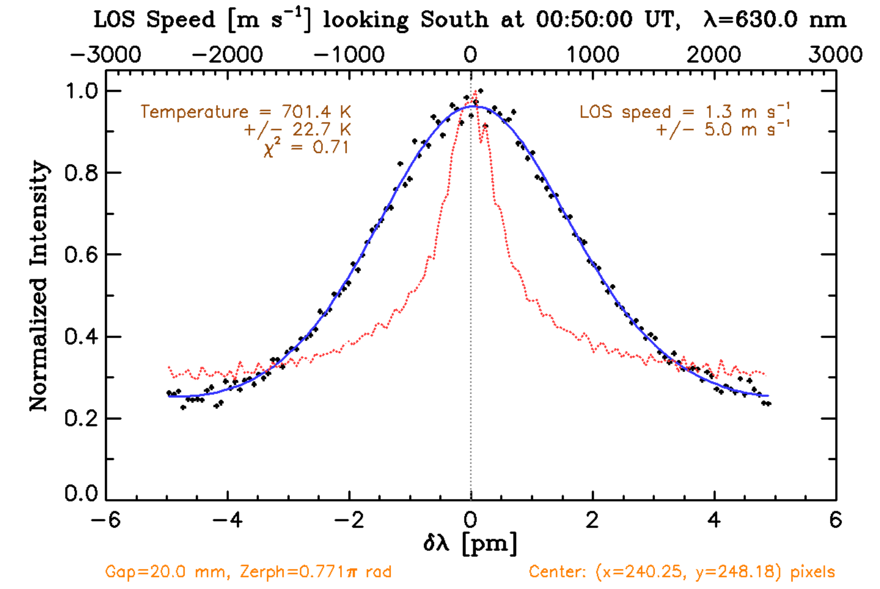
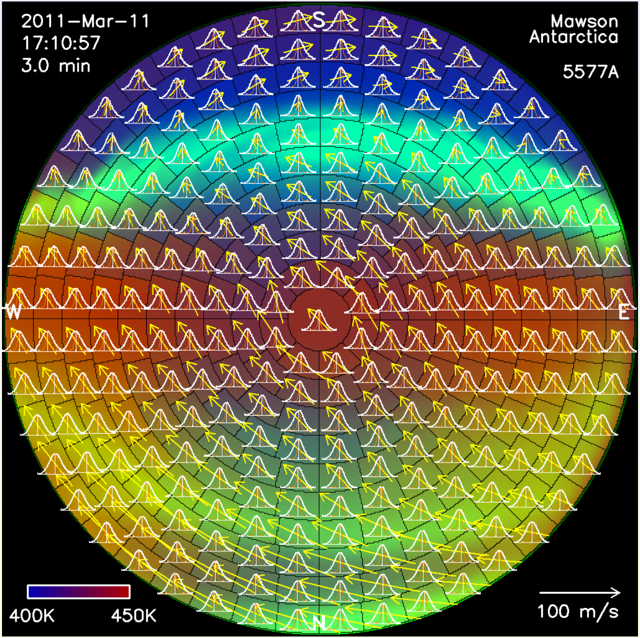
Example Data – Clemson University Fabry-Perot at Fort Yukon



All-Sky Doppler Imaging



- The SDI views multiple interference orders and scans its etalon gap over time, producing many independent spectra mapped across the sky.
- This image shows $\lambda 558\,\mathrm{nm}$ spectra from 261 "zones" across the sky (white) and the measured instrumental passbands (orange).
- Green hues show $558\,\mathrm{nm}$ brightness, blue through red hues show Doppler temperature, and yellow arrows show the fitted horizontal

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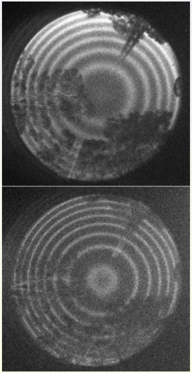
- As seen opposite, the result is then *a sky image that is modulated by the fringe pattern*.
- This shows some of the first night-sky images taken with the new Mawson FPS, from a site with lots of trees in the field of view. Fringes in the upper image are from mid-latitude 630 nm airglow, whereas the lower panel show 558 nm fringes.



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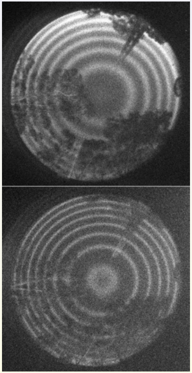
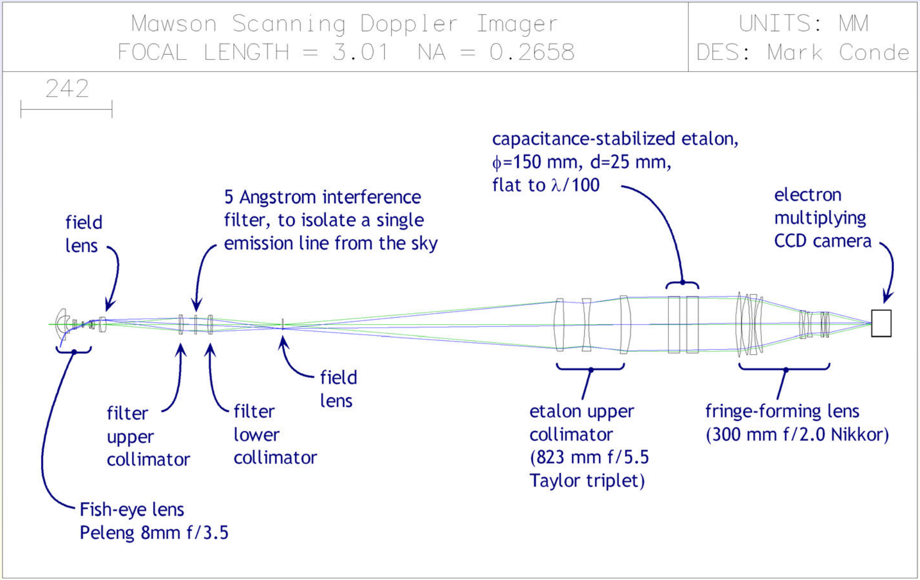


But now the spectral distribution can no longer be recovered unambiguously, because *the fringe shapes also depend on the angular distribution of source brightness*.

Optical Layout



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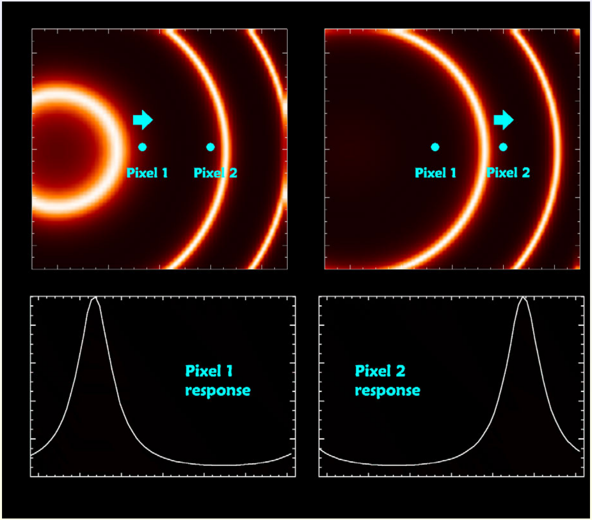

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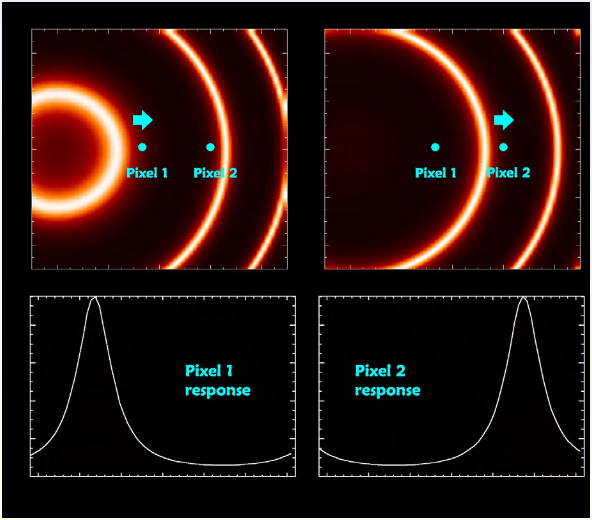

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- To co-add or even to compare spectra from different pixels requires *correction for this phase shift*.

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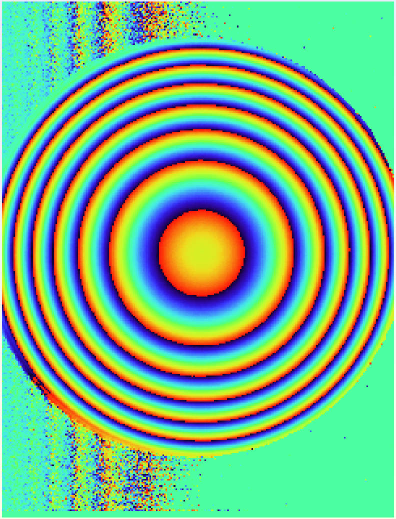
The result is a *map* of the phase difference between successively reflected beams, across the field of view.



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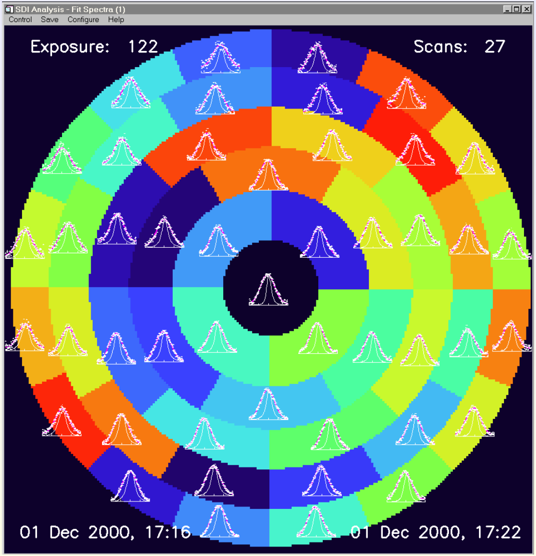

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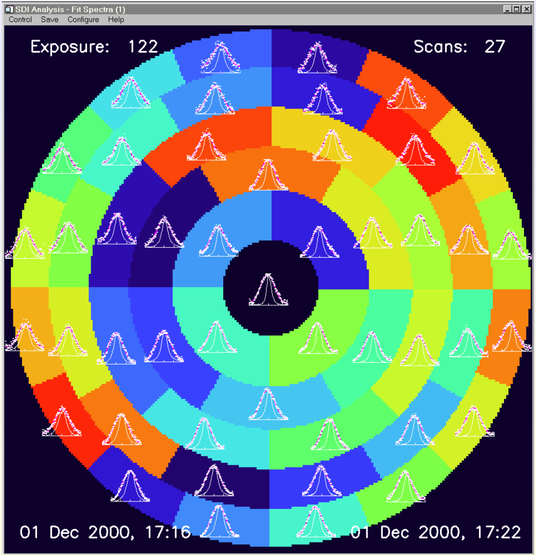

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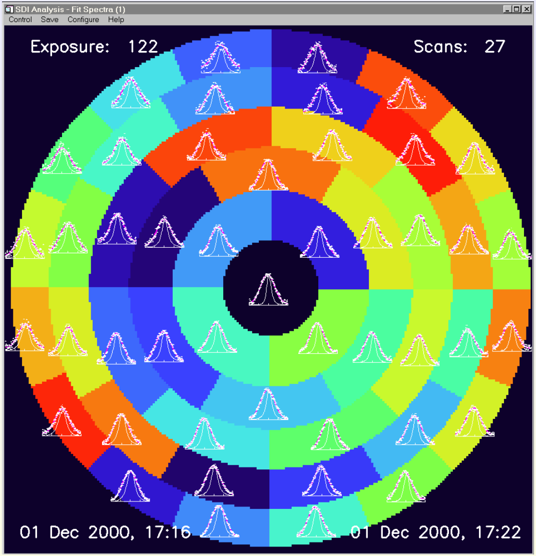

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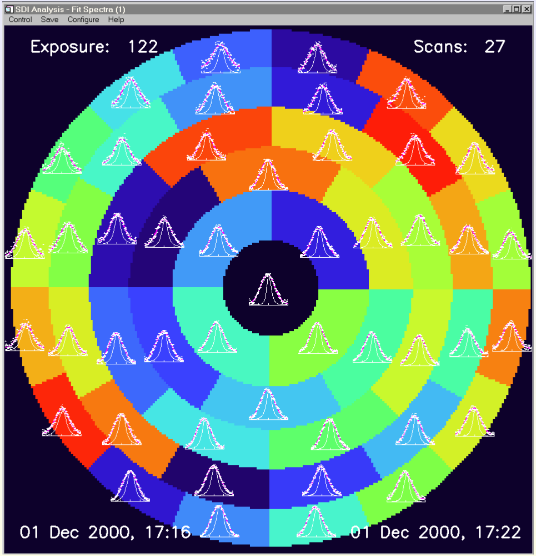

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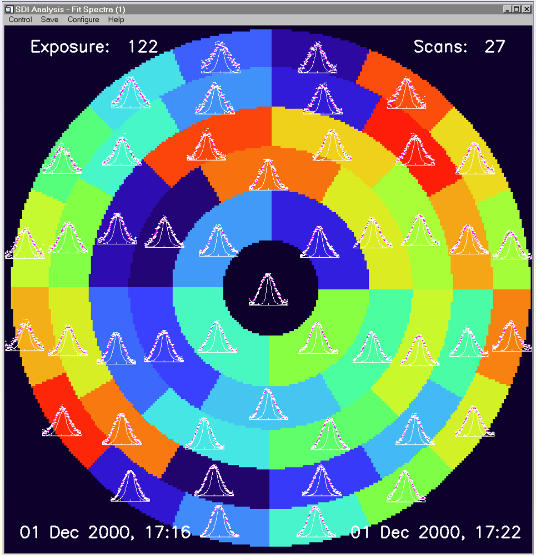

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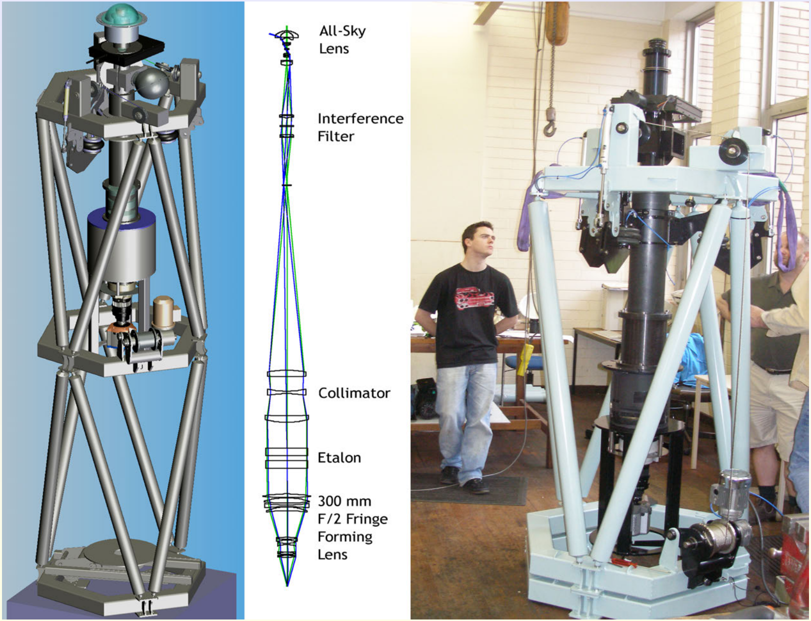
47 zones are allocated here. We have in the past used between 25 and 119 zones.

A Scaning Doppler Imager for Studying the Aurora



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Consider the transmission of two such etalons, with gaps related as $d_2 = 0.88 d_1$: