1. Introduction

The use of the Fabry-Pérot interferometer (FPI), consisting essentially of two parallel, flat, semi-transparent mirrors separated a known distance (i.e., an etalon), for spectroscopic measurements has been discussed in numerous writings since its inception in the late 1890’s by Charles Fabry and Alfred Pérot. The usefulness of the instrument is made apparent when one understands that the FPI is the most luminous instrument for a given resolving power. As such, the FPI has made its appearance in a large number of disciplines; from basic spectroscopy, to laser cavity development, to optical computing, to the telecommunications industry. An excellent review of the FPI is given by Hernandez [1986] and is considered to be a “classic text” on the instrument.

The first application of the FPI to thermospheric/ionospheric measurements was by Babcock [1923] with measurements of the upper mesospheric green line at 557.7345 nm, now known to be the 1D2-1S0 transition of atomic oxygen (OI). This particular line is generated in a narrow altitude region centered around ~96 km altitude, and spectroscopic measurements of the emission line result in a measured Doppler shift and Doppler broadening when compared to a reference line. These Doppler shifts and Doppler widths can therefore be converted to absolute wind measurements via

\[
\frac{v_r}{c} = \frac{\lambda_m - \lambda_o}{\lambda_o} \quad \text{(A1)}
\]

where \(v_r\) is the radial component of the wind velocity (and thus requires multiple measurements to obtain the full wind vector), \(\lambda_m\) is the measured wavelength at the peak of the emission line, \(\lambda_o\) is the corresponding Doppler reference wavelength, and \(c\) is the speed of light, and temperature measurements via

\[
T = \frac{m \cdot c^2 \left( \frac{\Delta \lambda_m}{\lambda_m} \right)^2}{2 \cdot k_B} - T_{\text{instr}} \quad \text{(A2)}
\]

where \(\Delta \lambda_m\) is the measured 1/e half-width of the [assumed] Gaussian emission profile, \(T_{\text{instr}}\) is the equivalent instrument temperature due to the FPI instrument function (i.e., the spectral response of the FPI to a monochromatic source), \(k_B\) is Boltzmann’s constant, and \(m\) is the mass of the constituent [other variables defined above]. Such measurements thus
serve as one of the few remote sensing techniques available for probing the upper mesosphere.

FPI observations of other atmospheric lines originating from different altitudes (e.g., those listed in Table A1) can therefore yield important base-state dynamical parameters necessary for understanding the upper atmosphere. An excellent review of remote sensing of the middle and upper atmosphere via passive optical instrumentation and the science obtained from such data can be found in Meriwether et al. [2004].

2. Particulars of the FPI

Discussions of how a FPI works can be found in numerous texts, from the undergraduate (e.g., Klein and Furtak [1986], Hecht [1998]) to the graduate (e.g. Saleh and Teich [1991], Born and Wolf [1999]) to the professional (e.g., a series of HRDI optical engineering papers by P. Hays and W. Skinner, e.g. Skinner et al. [1987]). Such analyses fundamentally focus on the optical arrangement depicted in Figure A1, where a Fabry-Pérot etalon (denoted FP) of gap distance, d, is placed in front of a lens of focal length, f. The etalon is composed of a highly transmissive material (e.g., glass) whose interior surfaces are coated with a highly reflective material (e.g., silver), characterized with a reflectivity, R. The outer surfaces of the glass are often beveled so as to reduce back reflections from those surfaces and other components in the optical path, known as “etaloning.” Light is introduced from the right of the figure, passes through the etalon, and is then focused onto the screen.

Because of the multiple reflections occurring within the etalon, multiple “images” of the source are formed which differ by a set phase difference. This is similar to the multiple images formed by double-paned glass windows. These images are combined by use of the focusing lens which forces the multiple rays to interfere at some spot on the screen. Hence the interference takes place because of the lens, not the etalon (whose role is to create the multiple images, each with a set phase difference).

The general formula for the transmission through a FPI for a single wavelength can be expressed as

\[ T(A,R,n,d,\lambda,\theta) = \left(1 - \frac{A}{1 - R}\right)^2 \cdot \frac{1 - R}{1 + R} \cdot \left[1 + 2 \cdot \sum_{m=1}^{\infty} R^m \cdot \cos\left(\frac{m \cdot 4 \cdot \pi \cdot n \cdot d}{\lambda} \cdot \cos(\theta)\right)\right] \] (A3)

where A is the absorption of the etalon, n is the index of refraction of the material between the plates (e.g., air), \( \lambda \) is the wavelength, and \( \theta \) is the incident angle of the ray (R and d are explained above). This particular formulation omits etalon plate defects, which can be included as per Hernández [1986]. Generally, A and R are set by the nature of the measurement and cannot be varied and \( \lambda \) and \( \theta \) depend on the source to be studied. Adjusting n and d can be accomplished by changing the pressure [and hence the n] or the plate separation, respectively.

The nature of the source is fundamentally important in the experimental configuration. At one extreme, a non-diffuse source, like that from a star, is only comprised of \( \theta=0 \) rays. In this case, the light is often collected by a photon-counting device, like a PMT. A spectrum is then obtained by scanning the FP etalon by varying n
or d. At the other extreme, a diffuse source, consisting of many different input \( \theta \)'s will create the traditional bull’s-eye ring pattern on the screen, with each annular ring representative of a different input theta. Such a pattern is then “imaged” by using photographic plate or, most commonly today, a CCD.

A wide array of experiments operate in between these 2 extremes and care must be taken in discussing the particulars of FPI experiments. For example, solar physicists working in the visible and near infrared often image solar photospheric structures such as sunspots. Though using a traditionally considered diffuse source, the input angles are so small that the FPI is essentially only imaging the central region of the bull’s-eye pattern. Hence, solar imaging work requires scanning the FP to collect a series of images, each corresponding to a different wavelength.

A typical pattern created by a diffuse source is depicted on the screen in Figure A1. A radial slice of this bull’s-eye pattern would yield a cross-section similar to that in Figure A2. This later figure illustrates the nature of the FPI fringe pattern under different conditions. We note that this cross-section is in “pixel space” (i.e., the x-axis is represented in CCD pixels) and would need to be converted to “wavelength space” before equations A1 and A2 are utilized. This conversion can be done a number of ways, most all stemming from the phase relation used in the derivation of equation A3,

\[
m \cdot \lambda = 2 \cdot n \cdot d \cdot \cos(\theta),
\]

where \( m \) is the order corresponding to a particular fringe peak and \( \theta \) is calculated by measuring the pixel value of the peak along with the dimensions of each pixel and the focal length of the lens. For example, one approach is to use equation A4 to give

\[
\lambda_i = \frac{2 \cdot n \cdot d}{M_0} \left( 1 - \left( \frac{i \cdot \Delta x}{\sqrt{2 \cdot f}} \right)^2 \right)
\]

where \( \lambda_i \) is the wavelength of the \( i \)-th pixel, \( i \) is the \( i \)-th pixel, \( \Delta x \) is the lateral size of a pixel, and \( M_0 \) is the order corresponding to the nearest fringe peak.

3. Important FPI Considerations and Terminology

As with all fields, the FPI/optical engineering community often invoke terminology that at first may seem foreign to the outsider. Generally, however, such terms are simple and require only a mere translation. Examples include:

Etendue (often spelled étendue): A measure of the light gathering ability of an optical system, often expressed as \( E = A \cdot \Omega \), where \( A \) is the collection area of the optic and \( \Omega \) is the optical field-of-view (i.e., solid angle) of the optic. We note that the etendue for an optical system should be conserved for each component.

Free Spectral Range (FSR): Denoted herein as \( \Delta \lambda_{\text{FSR}} \), the FSR is the wavelength separation between adjacent fringe peaks. FPI measurements of features separated by a spectral distance greater than the FSR will be aliased into subsequent fringes.
\[ \Delta \lambda_{\text{fsr}} \approx \frac{\lambda^2}{2 \cdot n \cdot d} \]  \hspace{1cm} (A6)

Finesse ($\mathcal{F}$): the ratio of the separation of adjacent fringe maxima to their half-width.

\[ \mathcal{F} = \frac{\pi \cdot 2 \cdot \sqrt{R}}{2 \cdot (1 - R)} = \frac{\Delta \lambda_{\text{fsr}}}{\Delta \lambda_{\text{min}}} \]  \hspace{1cm} (A7)

Least resolvable wavelength ($\Delta \lambda_{\text{min}}$): The best spectral resolution of the optical system.

Resolving Power ($\mathcal{R}$): the ratio of the central wavelength of interest to the least resolvable wavelength difference

\[ \mathcal{R} = \frac{\lambda}{\Delta \lambda_{\text{min}}} \]  \hspace{1cm} (A8)

Illumination Pattern: The spatial distribution of the light collected on the screen. Variations in the source, dimming of the outer bull’s-eye pattern due to absorption along the optical path, etc. all cause the intensity of the collected signal to fluctuate across the surface of the screen. These variations need to be “normalized” out of the fringe pattern if independent sources are to be compared; e.g., when comparing a data fringe to a reference fringe.

Contrast: A term with many different definitions which depend on the application of the FPI. For example, when used in the description of a FPI with multiple FP etalons, the contrast refers to the ratio of the peak fringe intensity to the nearest adjacent fringe intensity.

Reference Line: Ideally, a laser line matching the wavelength of interest is used to obtain the FPI instrument function (and thus provide $T_{\text{instr}}$) and provide a Doppler reference. Rarely is this the case in practice, however, as laser lines at the wavelength of emission are often lacking. As such, some other Doppler reference is often used to determine the line-of-sight radial Doppler shift. For example, many FPI’s measuring winds in the thermosphere/ionosphere use the vertical line-of-sight spectra as a Doppler reference, working under the assumption that the vertical winds are very small compared to the horizontal winds. This assumption is often questioned, particularly at high latitudes where there is significant vertical motion of the thermosphere.

An Example of a Contemporary FPI

In this final section we present a contemporary FPI, the Second-generation, Optimized, Fabry-Pérot Doppler Imager (SOFDI, Figure A4, [Gerrard and Meriwether [2007], Gerrard et. al. [2007a,b,c]]). At its core, SOFDI is a triple etalon Fabry-Pérot interferometer capable of making wind and temperature measurements from the spectra
obtained from various middle and upper atmospheric emission lines. Table A1 happens to give a list of the various emission lines measurable by SOFDI.

As previously discussed in the Introduction, the design and application of FPI instrumentation consisting of a single etalon to make middle and upper atmospheric wind and temperature measurements can be found in the literature extending back over ~90 years. Most of these past airglow measurements were obtained during nighttime conditions when the emission can be 1) more easily discerned from the low background noise continuum and 2) when surrounding continuum emission is relatively weak. However, driven by a large number of scientific needs, notably data collection for initialization and constraint of upcoming space weather models, the aeronomy community is attempting to extend such measurements into daytime conditions when the overwhelming solar background signal masks the much fainter airglow emission.

This extension of a traditionally nighttime technique/measurement into the daytime regime comes with a considerable increase in instrumental complexity. Specifically, additional etalons, serving to both decrease the transmission width of the overall instrument function/response and to block adjacent transmission windows which are located at integer values of the free spectral range from the primary order of interest, need to be included into the optical system. The end effect is to approximate a Delta function instrument response which is centered on the emission line of interest (i.e., herein, we use the term “signal” to represent the light collected from the desired emission). These additional etalons ultimately reduce the solar “noise” continuum, thus increasing the signal-to-noise ratio of the measurement. Such a triple-etalon configuration is depicted in Figure A5, with parameters of the 3 etalons (i.e., the low-resolution etalon (LRE), medium resolution etalon (MRE), and the High Resolution Etalon (HRE)) within SOFDI listed in Table A2.

The SOFDI FPI instrument is housed within a relocateable trailer, sized to fit inside a standard shipping container and equipped with combined light/sound alarm system. The trailer requires an electrical hookup providing 10 kW peak power, with which internal transformers condition input power as needed and offer protection against electrical surge, brownouts, etc., and a network connection, with which the entire SOFDI instrument can be started, operated, rebooted, and shutdown remotely. These two relatively available commodities makes operation of the trailer in remote locales much less costly, especially in regard to personnel costs (e.g., in summer 2007 SOFDI is scheduled to travel to Huancayo, Peru to undertake remote operations under the magnetic equator in collaboration with the Air Force Communications/Navigation Outage Forecasting System (C/NOFS) satellite). Heating and air conditioning units keep the internal trailer temperature at 26.5 °C ± 0.5 °C.

Five domes are visible atop the SOFDI trailer in Figure A1. The tallest dome houses the Cornell all-sky imager which makes 2-D, relative intensity maps of mesospheric and thermospheric OI emissions that are used in conjunction with SOFDI wind-temperature measurements. This imager can also be operated remotely and is controlled on a computer system separate from the SOFDI operations computer. The other four domes contain 5.08 cm (2") diameter telescopes which collect light from SkyScanner pointing heads developed by KeoScientific. The collected light from all four telescopes is eventually fed into the SOFDI instrument simultaneously via fiber optic cables. Normally, the mirrors are set so that there is a field-of-view (fov) directly to the
east, north, and vertical, with a redundant telescope that usually points to the west during nighttime measurements and at the sun for daytime measurements. This four telescope design allows simultaneous wind and temperature measurements in all fovs without the traditional delay associated with other FPI instruments, in which a single fov points to the same four cardinal directions sequentially, allowing perhaps 30 minutes to pass between a particular look direction. In addition, the four telescopes allow for the simultaneous observation of the solar spectrum during the day that is required to account for the Doppler shifting of the solar spectrum introduced by the rotation of the earth. Past daytime FPI experiments have had to account for the delay between airglow measurement and solar reference measurement. Furthermore, during limited campaigns where a specific scientific objective is to be studied, the four mirrors can be rotated during operations so as to cover different parts of the sky.

As mentioned above, the light from each telescope is coupled into a fiber optic bundle. The bundle from each telescope consists of 118 fibers, each with a measured transmission of 0.92, a NA of 0.22, and 220 \( \mu \text{m} \) [clad] diameter (bare fiber diameter of 200 \( \mu \text{m} \), for an overall packing fraction of 0.55), and is combined into one cable, hereafter called a super bundle, and configured into four independent 63.89° (full angle) wedge-shaped fovs. Thus, each wedge corresponds to a particular telescope, and the fibers within the cable are incoherently arranged. It is this 4-wedge pattern, designed such that the fiber pattern is smoothed by optical aberrations within each wedge bundle, that is eventually imaged onto a CCD camera (hence the “I” in the SOFDI acronym is for Imager).

The super bundle is then passed through a hermetic fiber chuck into the SOFDI casing. Electrical connections and water lines (to cool the CCD camera) also pass through the chamber and have airtight seals. All of the optics of the SOFDI instrument lay within a large 2.54 cm (1”) thick aluminum chamber that, in normal operation, is pressurized to \( \sim99974 \) Pa (\( \sim14.5 \) psi) and thermalized to 28.00 °C. The aluminum chamber, depicted in Figure A4 with the \( \sim61.2 \) kg (\( \sim135 \) lbs) lid open, is mounted on a steel support frame consisting of five shock and spring combinations (four in each corner, one in the center, each with heating pads to suppress thermal conduction) to reduce vibration and keep the entire optical system aligned.

Within the chamber, the light from the fibers is collimated and passed through an interference filter. The interference filters are mounted into a filter wheel assembly which is rotated to select the various emission line of interest. Pico-motors control mechanical shutters along the optical path, allowing one to diagnose various problems that can occur in aligning the system, to block incoming light, and to move a diffusive screen into and out of the optical path, if needed. A calibration lamp assembly, currently consisting of Hf (Ne fill gas) and Ce (Xe fill gas) hollow cathode lamps along with frequency stabilized HeNe laser, emit light into a single fiber that passes out of the chamber and is combined with the super bundle that passes back into the chamber so as to introduce calibration light along the same optical path as the four fovs.

For nighttime operations, like those corresponding to the thermospheric OI data shown in Figure A2, only the high-resolution etalon (HRE) is placed in the optical path to image approximately 11 orders onto the CCD. Each of the 11 orders represents an independent measurement of the wind and temperature in that particular fov. For daytime operations, all three etalons are placed in the optical path so as to reduce solar
contamination of the weak airglow line. Effectively, the LRE and MRE block 10 of the 11 orders of the HRE, allowing only 1 order to pass, as shown in Figure A5. Daytime measurements are currently work in progress and are beyond the scope of the FPI summary.
References


Figure A1. Schematic of a Fabry-Pérot Interferometer. The screen can be considered a CCD detector.
Figure A2. Typical nighttime wind and temperature data obtained from 630 nm OI emission observed with the SOFDI instrument (described in the last section) located in Oneida, NY over the night of September 9-10, 2005. Local Solar Time (LST) is denoted with 0 representing local midnight. Thin lines represent climatological winds.
Figure A3. Idealized FPI instrument functions for a monochromatic 630 nm line with a ~2.3 mm etalon gap (d) and 23.7 cm focal length (f) for various reflection (R) and absorption (A) terms. No plate defects parameters are included. X-axis is in CCD pixels, measured from the center of the screen outward. Black Line: R=90%, A=0. Red Line: R=80%, A=0. Green Line: R=80%, A=5%. Plate defect terms tend to further lower transmission and broaden the fringes.
Figure A4. (top) Outside view of the SOFDI trailer, currently located in Oneida, NY. (bottom) Inside view of the SOFDI trailer, showing the optical chamber with the 3 etalons along the back wall [the LRE is out of the optical path in this figure] and the CCD against the far wall. Four fiber optics cables, each coming from a separate telescope, are seen entering the front of the optical chamber. This chamber is closed, pressurized, and thermalized during normal operation.
Figure A5. Idealized LRE, MRE, and HRE fringe patterns. When all three etalons are placed in the optical path, the result instrument function is denoted by the red line. The contrast for this triple-etalon configuration is ~15.
<table>
<thead>
<tr>
<th>Vacuum Wavelength (Å)</th>
<th>Wavelength in Air* (Å)</th>
<th>Emitter</th>
<th>Science Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>5578.887</td>
<td>5577.339</td>
<td>OI</td>
<td>Nighttime mesospheric winds and temperatures</td>
</tr>
<tr>
<td>6302.046</td>
<td>6300.304</td>
<td>OI</td>
<td>Nighttime and Daytime thermospheric winds and temperatures</td>
</tr>
<tr>
<td>7322.01</td>
<td>7319.99</td>
<td>O+</td>
<td>Nighttime and Daytime thermospheric ion drifts and temperatures</td>
</tr>
<tr>
<td>8401.429/8401.527</td>
<td>8399.121/8399.219</td>
<td>OH</td>
<td>Nighttime mesospheric winds and temperature</td>
</tr>
<tr>
<td>8467.534/8467.835</td>
<td>8465.208/8465.509</td>
<td>OH</td>
<td>Daytime mesospheric temperatures from analysis of intensity ratios with 8400 Å</td>
</tr>
</tbody>
</table>

* Air is defined here as 15 °C and 101325 Pa, with 0.033% CO₂

Table A1: Commonly Observed Upper Atmospheric Emission Lines
<table>
<thead>
<tr>
<th>Parameter</th>
<th>HRE</th>
<th>MRE</th>
<th>LRE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gap</td>
<td>1.0007 cm</td>
<td>0.186 cm</td>
<td>0.024 cm</td>
</tr>
<tr>
<td>Coated Diameter</td>
<td>8.8 cm</td>
<td>8.8 cm</td>
<td>8.8 cm</td>
</tr>
<tr>
<td>Reflectivity</td>
<td>0.86</td>
<td>0.86</td>
<td>0.86</td>
</tr>
<tr>
<td>Coating Materials</td>
<td>ZnS-ThF4</td>
<td>ZnS-ThF4</td>
<td>ZnS-ThF4</td>
</tr>
<tr>
<td>Etalon Material</td>
<td>Fused Silica</td>
<td>Fused Silica</td>
<td>Fused Silica</td>
</tr>
<tr>
<td>Type</td>
<td>Fixed spacer</td>
<td>Piezoelectric</td>
<td>Piezoelectric</td>
</tr>
<tr>
<td>Post Material</td>
<td>Zerodur</td>
<td>PZT-5H</td>
<td>PZT-5H</td>
</tr>
<tr>
<td>Num Orders @630 nm</td>
<td>12.5</td>
<td>~2.3</td>
<td>~0.3</td>
</tr>
<tr>
<td>FOV (full angle)</td>
<td>3.2°</td>
<td>3.2°</td>
<td>3.2°</td>
</tr>
</tbody>
</table>

**Table A2: Specifications of the SOFDI etalons**