Chapter 2

Instrumentation and data analysis

2.1 Basic requirements

The importance of airglow emission spectroscopy in monitoring the upper atmospheric parameters has been well recognized, since the early work of Babcock [1923]. The various emission lines and their relative intensities are well documented in the literature [Chamberlain, 1961]. The spectroscopic temperatures determined from line profile analysis are being used as measures of the kinetic temperature and its variations and as indicators of excitation mechanisms leading to airglow emissions. A knowledge of the rotational structure of molecules leads to determination of rotational temperatures. Several naturally occurring lines such as O₂ Atmospheric 0–1 band at 8645 Å, O₂ Herzberg bands and OH Meinel bands are being routinely studied to obtain rotational temperatures of the upper atmosphere. At heights where the atomic species dominates, the profile of an emission line is usually governed only by the motions of the atoms, and by the associated Doppler effect. This line-broadening serves well to define a Doppler temperature representing the region of emission. In the presence of neutral air motions, the whole profile gets shifted in wavelength due to Doppler
effect and the magnitude of this shift yields the value of line-of-sight wind. Measurements of Doppler parameters have been made on the atomic oxygen green (5577 Å) and red (6300 Å) lines by several workers [Babcock, 1923; Armstrong, 1953; Bens et al., 1965; Biondi and Feibelman, 1968; Shepherd, 1969; Hernandez, 1977; Sipler and Biondi, 1978; Hernandez and Roble, 1979; Burnside et al., 1981; Meriwether et al., 1983; Yagi and Dyson, 1985; Cogger et al., 1985; Sridharan et al., 1991].

Following Babcock [1923] who demonstrated the use of interferometric techniques to detect the night airglow emissions, several studies have been made to evaluate the spectrometers used for such purpose [Chabbal, 1953; Jacquinot, 1954; Connes, 1956; Meaburn, 1976; Desai, 1984; Hernandez, 1986]. After making a comparative study of different instruments, namely, prism, grating and an interferometer like Fabry Perot etalon, Jacquinot [1954] concluded that for a given spectral resolution, the Fabry Perot interferometer has the highest luminosity of all these dispersing devices. The arguments forwarded by him in comparing the Fabry Perot with prism and grating spectrometers are discussed in detail by Hernandez [1986]. It is recognized now that the high resolution Fabry Perot Spectrometer is an ideal choice for line profile measurements of natural airglow emissions.

In the present study in which neutral temperatures and winds at $F$ region heights are desired, a central aperture-scanned high resolution Fabry Perot Spectrometer is most suited for measurements of O I 6300 Å red line emissions emanating from an altitude of above about 250 km during nighttime. The Fabry Perot system is required to operate from Mt. Abu (24.6°N, 72.7°E geographic; 20°N dip latitude), a station located under the crest of equatorial ionization anomaly. As catalogued in the book on aurora and airglow by Chamberlain [1961], the red line is expected to have a pronounced post-twilight decrease and on some occasions a pre-dawn rise, the
intensity in the middle of the night averaging around 50 to 100 Rayleighs (1 Rayleigh = 10^6 photons/cm²/s). The low intensities of O I 6300 Å red line at a low latitude station like Mt. Abu, pose stringent requirements on the stability and the flux gathering power of the instrument. During solar maximum period, due to the passage of crests of equatorial plasma fountain, the red line exhibits significant variations in its intensity calling for careful analysis of line profiles.

The basic design of the Fabry Perot Spectrometer selected for the present study is described following a brief discussion on the theory pertaining to such devices. The choice of various instrument parameters is argued upon, in the next section. The optimum operating conditions for its use are discussed next. A new data analysis procedure to recover Doppler parameters from the observed fringes is described in one of the sections to follow. The errors induced upon the retrieved parameters due to various reasons are elaborately examined and a criterion is set to select line profiles for analysis. Finally, the use of such a Fabry Perot in its applications to upper atmospheric studies is critically studied.

2.2 Theory of Fabry Perot Spectrometer

A complete mathematical treatment of Fabry Perot interferometers is described by Hernandez [1986]. In this section, only the important points are highlighted.

A Fabry Perot etalon is made up of a two high quality fused silica plates arranged perfectly parallel with a spacing t between them. On incidence at an angle θ to the normal, the light of wavelength λ undergoes multiple reflections and the transmitted and reflected rays interfere to form circular fringes. Constructive interference takes place for the transmitted light beam, when the path difference between rays is
an integral multiple of wavelength satisfying the following relation:

\[ 2\mu t \cos \theta = n\lambda \]  

(2.1)

where \( n \) is the order and \( \mu \) is the refractive index. The resultant reflected and transmitted beams can be collected by two separate lenses. It is seen that for a fixed wavelength \( \lambda \), a change in optical spacing \( \mu t \), forces \( \lambda \) to appear at any arbitrary angle \( \theta \), actually a set of \( \theta \)'s. This change can be accomplished by either changing the value of \( t \) or \( \mu \). If both \( \mu \) and \( t \) are fixed, the necessary change in wavelength to vary the order by one unit is called the free spectral range (FSR) and is given by

\[ \Delta \lambda = \frac{\lambda^2}{2\mu t} \]  

(2.2)

The name, free spectral range, arises due to the fact that the separation between two lines is free of ambiguity over the wavelength interval defined by one order.

The behaviour of an ideal etalon of reflectivity and absorption coefficients being \( R \) and \( A \) respectively, is expressed as follows:

\[
Y_t(\delta) = \left[1 - A(1 - R)^{-1}\right]^2 (1 - R)(1 + R)^{-1} \left[1 + 2 \sum_{m=1}^{\infty} R^m \cos(m\delta)\right]
\]

(2.3)

[Hernandez, 1986]

where \( Y_t \) is the intensity of the transmitted beam and \( \delta \) is the phase. Thus a strictly monochromatic beam undergoes broadening on passage through a Fabry Perot (FP) etalon. The spread of the resultant profile defines the instrument function of the FP etalon. The full width at half maximum (FWHM) (\( \delta \lambda \)) of the output profile is related to FSR through the instrument finesse \( N_R \):

\[ N_R = \frac{\Delta \lambda}{\delta \lambda} = \frac{\pi \sqrt{R}}{1 - R} \]  

(2.4)

This is called the reflective finesse. Since two lines cannot be resolved unless their wavelengths differ by \( \delta \lambda \), the FP should have a limit of resolution of at least \( \delta \lambda \). This
implies that the resolving power of the instrument is proportional to $N_R$. The finesse can be interpreted as the effective number of interfering beams which increases rapidly with $R$. With the advent of multi-layer dielectric coatings which eventually replaced metallic coatings, a value of $N_R$ upto 300 can be achieved. Though such high values of reflectivity can be achieved, the finesse, in practice, is limited by plate defects of the etalon. Since the Fabry Perot plates are neither flat nor perfectly parallel, small deviations in both these quantities will broaden the output profile.

The effect of defects may be quantified by attributing a defect finesse to the interferometer [Atherton et al., 1981]:

1. Spherical defect: When the plates are spherically bowed with a maximum deviation $\delta t_s$ from the plane surface, then the associated finesse is given by

$$N_{DS} = \frac{\lambda}{2\delta t_s} = \frac{k_s}{2} \quad (\delta t_s = \lambda/k_s)$$

2. Roughness defect: If the plate is not perfectly smooth and the root mean square deviation of surface irregularities appearing in the plate is given by $\sqrt{\delta t_G^2}$, then

$$N_{DG} = \frac{K_G}{4.7}$$

3. Parallelism: The finesse associated with the departure from parallelism of the plates is given by

$$N_{DP} = \frac{K_p}{\sqrt{3}}$$

An overall instrument finesse is then written as

$$\frac{1}{N^2} = \frac{1}{N_R^2} + \frac{1}{N_D^2} \quad \left( \frac{1}{N_D^2} = \frac{1}{N_{DS}^2} + \frac{1}{N_{DG}^2} + \frac{1}{N_{DP}^2} \right)$$

(2.5)

Thus as the reflectivity of the coating is increased, the half width of the output profile reaches a lower limit determined by the overall defect finesse $N_D$.  

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An aperture is used normally to collect the flux over a solid angle. Since the signal transmitted by the etalon is integrated over this finite angular spread, further broadening of the resultant profile is effected by this process. The finesse due to the aperture-broadening is given by

$$N_{AP} = \frac{\Delta \lambda}{\delta \lambda_{AP}} = \Delta \lambda \left[ \frac{\lambda d^2}{8 f_{L}^2} \right]^{-1}$$

where $d$ is the diameter of the aperture, and $f_L$ is the focal length of the lens used to focus the transmitted beams on to the aperture. For a fixed $f_L$, more and more flux can be collected by increasing the aperture size $d$ as the finesse goes down.

Taking all the broadening factors into account, it is seen that the output profile of a Fabry Perot Spectrometer is a distortion of the original source profile. The broadening depends on the reflectivity, the quality and the surface defects of the etalon plates, the parallelism maintained between them and the aperture used.

### 2.3 Selection of instrument parameters

The foremost requirement of any high resolution optical instrument meant for the detection of faint line emission, is the aperture of the spectral device to be as large as possible. For nightglow measurements when detection of low emission rates ($< 100$ R) is desired, the Fabry Perot etalon is required to have an aperture of at least 125 mm [Hernandez and Mills, 1973] with good stability. Owing to limitations imposed by cost and other factors, an etalon of 100 mm usable aperture has been selected for the present study. The resolution of the instrument is determined by the order of interference selected, which can be made high by choosing a high value of the etalon spacing. A gap of 1 cm between the etalon plates with reflectivity of 85 %, yields a resolving power of $6 \times 10^5$ which is most suited for high resolution measurements. An air-gap etalon with optically contacted plates has been purchased from IC Opticals,
UK. The substrates that support the etalon plates are made of Spectrosil B of 30 mm thickness. The spacers use Zerodur as basic material because of its extremely low thermal coefficient of expansion. The flatness and the parallelism at wavelengths close to red region of the electromagnetic spectrum, have been specified to be \(\lambda/100\) and \(\lambda/20\) respectively. To measure a line profile, a change in the refractive index is effected by changing the pressure of the air between the etalon plates.

Following the description of the spectrometer described by Jacquinot and Du-four [1948], we use an annulus of zero inside diameter, i.e., a circular aperture, following the etalon. This aperture will receive radiation which passes through the etalon between angles \(0\) and \(\theta\), i.e., a cone of angle \(2\theta\) is subtended at the position of the aperture. Thus the field of view of the instrument becomes \(2\theta\). If the size of the aperture \(f\) is expressed in orders, say, then

\[
\cos \theta = 1 - f/n_0
\]

(2.6)

where \(n_0\) is the central order [Hernandez, 1986]. Using the definition of half width \((\delta\lambda_{AP})\) of the profile due to aperture broadening given in the last section, the relation between \(f\) and \(\delta\lambda_{AP}\) is

\[
f = \frac{\delta\lambda_{AP}}{\Delta\lambda}
\]

\(f\) being a fraction of the free spectral range.

For an ideal etalon with high reflectivity, the resolving power \(R_0 = n_0/f\) and hence the solid angle \(\Omega = 2\pi f/n_0\) becomes \(\Omega = 2\pi/R_0\) which is the result arrived at by Jacquinot [1954]. Thus the product of the solid angle of acceptance and resolving power is fixed and is equal to \(2\pi\). The resolving power \(R\) of the instrument examining a line source of finite width, however, is less than \(R_0\), since the resultant width becomes greater than \(f\) [Hernandez, 1986].

In the literature, two methods of selecting the optimum aperture size have
been discussed \cite{Chabbal, 1953; Hernandez, 1979}. Chabbal \cite{1953} made use of the requirement that the product of flux received by the optical device and the resolving power is greatest, what is called later an LRP criterion. This was found to occur when the ratio of the FWHM of the aperture $f$ to the FWHM of the etalon-source combination is near unity. He plotted the ratio of the ideal etalon width to the resultant width and the ratio of the flux transmitted by the aperture to that flux transmitted over one free spectral range, as a function of the ratio of aperture width to etalon width ($f/a$). When the product of the former two ratios is plotted against $f/a$, there exists a maximum value of intensity for which $f/a$ is 1.15. In practice, there exists a range of values of $f/a$ ($0.9 < f/a < 1.5$) when the intensity for a given resolution is constant and maximum (Fig. 2.1). Thus using the LRP criterion, a compromise between instrumental broadening and luminous flux can be made.

Hernandez \cite{1979} has discussed the limitations of this method for the optimum choice of resolution of the instrument. The LRP criterion is strictly applicable only when the recorded line is well separated from other wavelengths prominently placed in the spectrum. This may not hold when the emission line is contaminated by a continuous background and when noise inherent in the signal reduces the precision with which the Doppler parameters are retrieved using this criterion. Hernandez \cite{1979, 1986} has derived the optimum conditions for operating a Fabry Perot Spectrometer taking into account all these factors. For minimum uncertainty in the retrieved parameters, he has obtained a set of values for $a$, $f$ and $dg$, the widths corresponding to an ideal etalon, the aperture and the Gaussian line source. Near the optimum points of operation, the effects due to surface and curvature defects of the etalon are negligible \cite{Hernandez, 1982a}. Least minimum uncertainty in the Doppler temperature occurs when $a$, $f$ and $dg$ take values of 0.07, 0.13 and 0.22, normalized with respect to free spectral range. Similarly, for the wind determination, he has obtained values of 0.14, 0.256 and 0.28. He has suggested that when simultaneous wind and
Fig. 2.1. Optimum range of operation of a Fabry Perot Spectrometer. The curves plotted are (1) the ratio of ideal etalon width to resultant width (convolution of ideal etalon function with the aperture broadening function), \( \frac{a}{a \ast f} \), versus ratio of aperture width to etalon width \( f/a \) and (2) the ratio of flux transmitted by the aperture to that flux transmitted over one free spectral range, \( \frac{Y_f}{Y_{\Delta \sigma}} \), versus \( f/a \). The product \( \frac{a}{a \ast f} \) and \( \frac{Y_f}{Y_{\Delta \sigma}} \) is shown as the unlabeled curve. The optimum range of operation corresponds to the broad maximum. (after Hernandez, 1986)
temperature measurements are desired, it is necessary to use the parameters obtained from minimum uncertainty in temperature. Since the response of a Fabry Perot Spectrometer can be expressed in terms of a Fourier series, the minimum number of coefficients necessary to unambiguously describe a measurement becomes equal to 7, and the minimum number of samples to be taken is twice this number, for these conditions. Though the LRP criterion does not demand any preference for the above parameters, only that the ratio of the scanning aperture to the etalon-source width combination should be nearly unity. However, the results by Hernandez [1979] show that there exists a set of parameters for the least uncertainty in temperature and winds and for other values, the uncertainties are more. Thus use of these different methods to optimize the instrument, yields different results for the set of parameters that should be used.

In the present study, since $a$, the normalized FWHM of the etalon (without defects) has already been fixed ($=0.0519$, for a reflectivity of 0.85), it is desirable to use an optimum value for the scanning aperture. The relation between the normalized full width at half maximum of an emission line of central wavelength $\lambda$ and the Doppler temperature ($T_n$) is given by

$$dg = 7.16 \times 10^{-7}\lambda(T_n/M)^{1/2}/\Delta \lambda$$

where $M$ is the molecular weight of the emitting atom. For a temperature of 1000 K and when the emitting atom is oxygen, $dg = 0.1797$ at $\lambda = 6300$ Å. This width varies from a value of 0.127 for $T_n = 500$ K to a value of 0.22 for $T_n = 1500$ K. We have adopted the LRP criterion of Chabbal [1953] to determine the resolution of the instrument for maximum luminosity. It is seen later that as the selected parameters are not too far from the best set of parameters arrived at by Hernandez [1979], the increase in standard deviation of Doppler parameters for the selected set is small.

The following calculations were made to arrive at the optimum value of $f$, ...
given all the etalon parameters. We shall consider an emission profile of Gaussian shape with a Doppler temperature of 800 K. This yields the source width \( s = 0.1607 \) (normalized with respect to free spectral range).

With the given etalon parameters, the contribution of the etalon to the broadening of a monochromatic line is given by \( e = 0.1162 \) (corresponding to an etalon finesse of 8.6). A source of width \( s \) will get broadened by the etalon and the resultant width is a convoluted product of \( e \) and \( s \). This turns out be 0.1983 for the above selected value of \( s \). Use of the LRP criterion that \( f/e\times s \) should vary between 0.9 and 1.5 implies a value of aperture diameter in the range 3.3 mm to 4.3 mm, using the basic definitions presented in last section. We have chosen a value of 3 mm for the size of the aperture for which the luminosity should be very close to its maximum. An aperture of 3 mm diameter leads to a width \( f = 0.1428 \). Using equation (2.6), this corresponds to a field of view of 0.34° for the instrument.

It is interesting to compare the set of parameters arrived at with that recommended by Hernandez [1986] for least uncertainty in the retrieved Doppler parameters. The above value of \( f \) is different only by 9 %. For the extreme conditions of \( T_a = 700 \) K and \( T_a = 1500 \) K, the selected value of \( s \) deviates by 30 % for the lower limit and approaches that obtained by the least uncertainty criterion of Hernandez as the temperature reaches its upper limit of 1500 K. However, the present value of the ideal etalon width is 70 % of that using the least uncertainty criterion. Since the derived and the available parameters, \( f, a \) and \( s \), are close to their optimum values determined by least uncertainty criterion, the minimum uncertainties of determination are expected to be only slightly larger than what have been arrived at by Hernandez [1979].
2.4 Experimental details of the Fabry Perot Spectrometer

The optical lay-out of the high resolution Fabry Perot Spectrometer used in the present investigation for upper atmospheric studies is depicted in Fig. 2.2. This FPS system is being operated from Mt. Abu since the winter months of 1985. The position of the instrument within the observatory is such that detection of light from only two, namely, south and east, out of the four cardinal directions is possible. The lowest elevation chosen for the measurements of the horizontal component of neutral wind, has been 20°. Because of the increased emission column, the apparent emission rate of the natural airglow increases by a factor of almost 2 relative to that for the overhead sky (Van Rhijn advantage). It becomes necessary to gather light from a low elevation sky, especially during solar minimum period, when the 6300 Å line intensity decreases continuously throughout the night, with occasional recovery around midnight. Since the large scale geophysical processes of interest like equatorial ionization anomaly and equatorial spread F depend on the configuration of the magnetic field and originate over the dip equator, observations are confined to emissions originating from magnetic south. For wind measurements to be discussed later, the reference wavelength is obtained from the measurements made overhead (zenith), with the assumption that the Doppler shifts in the vertical direction are negligible.

Front silvered mirrors are used to direct light from the sky to the FPS. The optically contacted etalon is sealed inside a housing with an optical window in the front end and a lens (L₁) in the rear end. The beam of light after multiple reflections is projected onto the scanning aperture by means of the lens L₁ of focal length 50 cm. The beam is collimated before getting directed into a narrow band (3 Å) interference filter which selects the wavelength of interest and the resultant beam is focused onto the photocathode of an EMI 9863 A photomultiplier tube with a cathode sensitivity
Fig. 2.2. Schematic diagram of the high resolution Fabry Perot Spectrometer (central-aperture pressure-scanned).
of ~ 200 μA/lumen. The data acquisition system employed for counting the photons collected by the etalon and integrated over the area of the aperture, is described later.

The air between the plates of the etalon acts as a medium whose refractive index μ needs to be changed to get the spectral distribution of incident radiation. This can be achieved by changing the pressure of the air. A stepper motor controlled piston drive unit serves this purpose. The limitations of using pressure scanning are in maintaining the linearity of the change in μ with pressure, and the temperature dependence of μ. With air as the medium, a pressure change of about 90 torr (1 torr ≡ 1 mm Hg) results in one order change (FSR = 0.1985 Å) for a 1 cm gap etalon. The change in μ for this pressure change is non-linear to only about 1 part per thousand [Hernandez, 1986] and hence can be assumed to be negligible for the work presented here.

An absolute temperature-controlled pressure transducer (type 590, Datametrics Inc.) is used to monitor the pressure. This has a Barocel pressure sensing element which acts as a high precision stable capacitive potentiometer in which the variable element is a thin highly prestressed metal diaphragm. Positioned between fixed capacitor plates, the diaphragm forms the separation between the two gas-tight enclosures. A difference in total pressure within enclosures produces a force which deflects the diaphragm and varies the relative capacitance of the diaphragm and the fixed capacitor plates. The capacitance variations are converted into voltage whose amplitude is proportional to applied pressure. The prescribed accuracy of pressure reading is ± 0.05 %. The etalon housing has two external ports, one connected by a rubber tube to the piston drive unit for changing the pressure and the other for monitoring the pressure through the pressure transducer.

Since the refractive index μ also depends on the temperature, the thermal stability of the etalon is important, especially when the measurements of neutral
winds are desired. It is necessary to maintain the temperature of the etalon to better than 0.1°C (corresponding to a shift of 0.0002 Å which is equal to a wind of 10 m/s). Typically the winds in the upper atmosphere are of the order of 50 to 100 m/s. The thermal stability is achieved by means of a dual heating enclosure. The gap between the etalon chamber and the outside jacket kept close to each other, is maintained at a constant temperature by an on-off type temperature controller. The resistive heating element wound on the etalon chamber is used as a part of a linear-proportional temperature controller. This dual heating system is found necessary in order to encounter the variation in room temperature at Mt. Abu, which becomes pronounced during winter.

Coming to the separation of the selected wavelength $\lambda$, the lens $L_2$ is used to collimate the beam for normal incidence to fall on the narrow band interference filter (3 Å bandwidth; 35% peak transmission at 6300 Å). The interference filter makes use of the same principle as that of Fabry Perot etalon but with a spacing of a few thousand angstroms thickness. The reflectivity of the filter is greatly increased by the use of a multi-layer dielectric coating. Each layer has a thickness of $\lambda/4$ with a refractive index either higher or lower than the layer adjacent to it.

The filter is tuned to the wavelength $\lambda$ of interest (i.e., 6300 Å) by changing $\mu$ of the coatings. In this case, the temperature is varied till the peak transmission of the filter reaches $\lambda$. The characteristics of the filter have been studied and calibration curves for different temperatures obtained for the actual experimental set-up. This method is adopted to circumvent the shift in the peak transmission towards lower wavelength side due to the filter getting tilted unwantedly at the time of integration. The temperature control of the filter is maintained to better than 0.5°C, and is achieved by using Peltier elements and a bipolar temperature controller. Since the ambient temperature condition over Mt. Abu has a wide fluctuation seasonally, Peltier
elements are used in heat/cool mode. The filter along with the collimating and the camera lenses is sealed in an assembly and is attached to the earlier optics.

The filtered beam collected by a focusing lens $L_3$ is then projected onto the photocathode of 9 mm effective diameter, of an EMI 9863 A photomultiplier tube. The photocathode material is of S-20 type (Na$_2$KCsSb material) with a quantum efficiency of 6 % at red wavelengths. The gain of the PMT is about $3 \times 10^7$ and the rise time of the output pulse is typically 2.5 ns. A thermoelectrically cooled housing is made use of, for cooling the PMT to less than about $-15^\circ$ C, to bring down the thermal noise. The PMT is operated at a high optimum voltage of 1650 V. The voltage level is such that the mean signal pulse height is well above the pulse height of the noise which results from thermionic emission from the photocathode as well as other sources such as preamplifier noise and electromagnetic interference pickup. An EMI pulse amplifier/discriminator is being used to amplify the signal and to select signal pulses by setting the discriminator at a proper level. The resulting pulses are transferred to counter ‘A’ of SR400 gated photon counter (Stanford Research Systems Inc.). The latter measures the intensity of the signal by counting the number of photons which are detected by the PMT in a given time interval decided by the stepper motor piston drive (operator selectable). The pressure information which is available in analogue form from the pressure transducer is passed through a precision voltage-to-frequency converter and fed as input to counter ‘B’ of SR400 gated photon counter.

The schematic of the complete data acquisition system for the Fabry Perot Spectrometer is shown in Fig. 2.3. The two channels available within the gated photon counter are made use of for the pressure and intensity information which at each step of the spectral scan, is transferred to an IBM PC for on-line plotting and to be stored in floppy diskettes after the completion of the scan. The movement of
Fig. 2.3. Block diagram of the complete data acquisition system for the Fabry Perot Spectrometer.
the piston by the stepper motor is synchronized to the data acquisition. After every movement of the piston which changes the pressure by \( \sim 1 \) torr, the pressure inside the etalon chamber is allowed to stabilize. The respective counters for photon and pressure counts are enabled, the counts accumulated for a preset integration time, the piston moved and the cycle repeated. At each pressure step, the airglow photons are counted for 8 seconds and a spectral scan covering 1 order lasts for about 18 minutes.

A single mode helium-neon laser operating at 6328 Å is used to obtain the instrument profile at the beginning of observations on each night. The representative instrument parameters observed on 13 February, 1991 are as follows:

\[
\text{FWHM} = 12.46 \text{ torr}; \quad \text{FSR} = 91.061 \text{ torr}; \quad \text{Contrast} = 15
\]

These parameters yield an overall instrument finesse of 7.3 which is considered adequate for wind and temperature measurements.

As discussed in the next section, the measured instrument profile is used for the retrieval of Doppler width. For the pressure-scanned Fabry Perot Spectrometer, it is being assumed that the variation in the refractive index \( \mu \) with respect to changes in temperature between the etalon plates, is either negligible or small. If the changes are significant upto, say 0.1°C, then the magnitude of the drifts in the peak position of the line profile due to changes in temperature, need to be known beforehand for the line-of-sight wind measurements. An AD-590 precision temperature sensor has been attached to the body of the etalon to continuously monitor the temperature of the etalon chamber. Making use of the convenience of setting the temperature of the heating system used for the thermal stability of the etalon to our choice, the peak positions of the highly stable, single mode, 6328 Å He-Ne laser profile were determined for various chamber temperature settings after allowing sufficient time to lapse for the etalon chamber to get stabilized. Fig. 2.4 is a result of such an exercise.
Fig. 2.4. Drifts (measured in pressure units, i.e., torr) in peak position of Fabry Perot fringes obtained using a highly stable He-Ne laser with respect to changes in temperature between the etalon plates. The slope of the best fit curve has a value of 2.77 torr/K.
The instrument profiles obtained on each of the nights during the February, 1991 campaign were made use of, for this purpose. The linear increase in pressure corresponding to the peak position, with chamber temperature, when the latter varies by 4 K, is to be noted. The best fit line yielded a slope of 2.77 torr/K, which has been incorporated as a correction for determining Doppler shifts.

2.5 A method to retrieve Doppler parameters from observed fringes

The output profile of the Fabry Perot Spectrometer is essentially a distortion of the source profile due to the various broadening factors discussed in section (2.2). The instrument acts as a window over which each spectral element of the source function is integrated. In other words, the expected output profile $\phi(x)$ is a resultant of the convolution of the source function $S(x)$ and the instrument broadening function $I(x)$ and can be expressed as

$$\phi(x) = \int I(x - x') S(x') \, dx'$$

In practice, the observed profile is contaminated by noise inherent in the detected signal, the background continuum and the contribution due to neighbouring sources, if present. If $O(x)$ represents the observed profile, $\epsilon(x)$ the noise and other extraneous factors and $B$ the background continuum, then

$$O(x) = \phi(x) + \epsilon(x) + B$$

The problem is to solve for $S(x)$, the source function under consideration given $O(x)$ and $I(x)$ and then retrieve the Doppler parameters of interest from $S(x)$. There are two ways of doing this.

(1) Assuming that the noise and the background are insignificant, express each of the functions in (2.7) in terms of their Fourier transforms. In the Fourier domain,
the convolution becomes simple multiplication of the Fourier transforms of the two
functions. The deconvolution then can be easily performed since the problem reduces
to a simple division. The solution is obtained by taking the inverse Fourier transform
of the resultant function. However, this method becomes useless when the noise
inherent in $\phi(x)$ and to a lesser extent in $I(x)$ gets amplified in the deconvolution
process [Anandarao and Suhasini, 1986]. Cooper [1977] expresses this important fact
in the following way:

'All too often deconvolution procedures are applied blindly to ailing data with the
expectation of a miraculous recovery of information. However, the hallucinatory side
effects of this particular course of treatment can be more damaging than the original
illness!'

(2) The second approach is to take into consideration the noise $\epsilon(x)$ in the observed
profile $O(x)$, which can be effectively filtered out by applying one of the smoothening
procedures to the acquired data before the Doppler parameters are determined.
The noise-free data can then be subjected to an appropriate statistical optimization
method to arrive at the solution, i.e., to retrieve the source profile $S(x)$ under considera-
tion. Several workers have followed the general non-linear least-squares approach
to estimate the best solution for the Doppler parameters of $S(x)$ [Hays and Roble,
1971; Hernandez, 1986; Meriwether et al., 1986; Okano and Kim, 1986; Sahai et al.,
1992b].

We have developed a new method entirely suited to the quality and the amount
of data that are being collected. Though the approach is based on the general non-
linear minimization principle, the method at each step takes care of the practical
problems we faced during observations and enables us to examine and overcome the
limitations imposed by various factors in retrieving the Doppler parameters. The
method of line profile analysis is as follows.
It can be assumed that the line source associated with the optical observation of this kind is described by a function $S(x)$ that is of Gaussian shape.

$$S(\lambda) = \frac{S_0}{d\lambda} \exp \left[ -\frac{(\lambda - \lambda_0)^2}{(d\lambda)^2} \right]$$  \hspace{1cm} (2.8)

$S_0$ is the intensity of the line whose center wavelength is $\lambda_0$ and $d\lambda$ is the Doppler width of the emission profile and is related to the full width at half maximum ($\delta\lambda$) by $\delta\lambda = 2 (\ln 2)^{1/2} d\lambda$ and to the kinetic temperature $(T_u)$ by

$$\delta\lambda = 7.16 \times 10^{-7} \lambda_0 (T_u/M)^{1/2}$$

where $M$ is the molecular weight of the emitting species in amu.

In its discrete form, the convolution integral can be written as

$$\phi(x_i; p_j) = \sum_{k=1}^{n} I(x_i; x_k) S(x_k; p_j)$$  \hspace{1cm} (2.9)

Here $p_j$'s ($j = 1, 2, 3$) represent the parameters of the Doppler profile to be determined. $n$ is the number of data points. In terms of $p_j$'s, $S(x)$ becomes

$$S(x_k; p_j) = \frac{p_1}{p_3} \exp \left[ -\frac{(x_k - p_2)^2}{p_3^2} \right]$$

$p_1$ being the peak line intensity, $p_2$ the line centre and $p_3$ the line width. $x_i$ is a variable that describes the scan of the device. In our experiment, it represents the value of the pressure at a particular step $i$. The summation of (2.9) is over one free spectral range, and if there are $n$ steps to cover this, then we have $n$ equations for $\phi(x_i; p_j)$.

The criterion for estimating $p_j$'s is minimization of the sum of squares of deviation $([\chi(p_j)]^2)$ between the observed and the expected profiles at each step $i$ which would then lead to a best set of estimates of $p_j$'s.

$$[\chi(p_j)]^2 = \sum_{i=1}^{n} [O(x_i) - \phi(x_i; p_j)] = \sum_{i=1}^{n} [e(x_i)]^2$$  \hspace{1cm} (2.10)
then minimization of \( \chi(p_j)^2 \) implies

\[
\frac{\partial}{\partial p_j} \chi(p_j)^2 = \frac{\partial}{\partial p_j} \sum_{i=1}^{n} [w_i (O(x_i) - \phi(x_i; p_j))^2] = 0
\]

that can be solved for \( p_j \)'s.

There are several methods available for searching parameter space for a minimum of \( \chi(p_j)^2 \) [Bevington, 1969]. An alternative to such methods and a simpler approach would be to linearize the fitting function \( \phi(x_i; p_j) \) in the neighbourhood of optimum values of \( p_j \)'s [Guest, 1961; Draper and Smith, 1966; Bevington, 1969]. Since the form of the expected profile \( \phi(x_i; p_j) \) is known (equation 2.9) (a convolution of the instrument and source profiles), this method is adopted for the determination of \( p_j \)'s.

Hays and Roble [1971] have adopted an analytical expression for the behaviour of the instrument by expressing its response in terms of a Fourier series. The overall instrument function is expressed as a convolution of all known broadening functions described in section (2.2). For the instrument employed in the present work, difficulties were experienced in describing analytically the behaviour of the instrument with the available etalon parameters. This could be due to our limited knowledge on the possible errors present in the optical system. Though the observed contrast is in the range 10–15, the contrast deduced from an analytical expression representing the instrument function is as high as 50. However, the widths do not differ much. Further, it is not possible to incorporate any asymmetry in the observed instrument profile if present, in the analytical expression. Thus since the theoretical profile evaluated from Fourier series analysis of etalon parameters does not represent the actual instrument performance, the observed instrument profile measured on each night is made use of for deconvolution, in the present analysis.

The detector attached to the Fabry Perot Spectrometer yields photon counts
per unit time interval. The properties of the photon field are that it is fluctuating and is discontinuous, and follows a Poisson distribution [Bevington, 1969; Hernandez, 1986]. If the detector yields \( N \) photons for a given time, then the variance is \( N \) for the same time. Hernandez, in a series of papers [1978, 1979, 1982a, 1985], has highlighted and quantified the uncertainties caused by inherently noisy measurements. Hays and Roble [1971] have shown that the high frequency components associated with the fluctuating photon field can be effectively filtered by considering only the first five Fourier coefficients when the observed profile is expressed in terms of a Fourier series. The other approach would be to employ cubic smooth spline functions with appropriate weighing factors in order to minimize the random errors present in the data [Sridharan et al., 1991]. We have used both the methods and the results agreed well within the statistical uncertainties in the retrieved parameters. However, we adopt the Fourier decomposition method described below to minimize the random errors associated with the photon noise, since this is computationally faster.

If \( Y(p_i) \) represents the observed count at a pressure \( p_i \) of the medium between the etalon plates and \( \Delta p \) is the free spectral range expressed in pressure units, then the cosine and sine transforms are written as

\[
\tilde{Y}_{cm} = \frac{1}{\pi m} \sum_{i=1}^{n} Y(p_i) \left[ 2 \sin \left( \frac{2\pi m p_i}{\Delta p} \right) \sin^2 \left( \pi m \frac{\delta p_i}{\Delta p} \right) \right. \\
+ \cos \left( \frac{2\pi m p_i}{\Delta p} \right) \sin \left( \pi m \frac{\delta p_i}{\Delta p} \right) \right]
\tag{2.11}
\]

and

\[
\tilde{Y}_{sm} = -\frac{1}{\pi m} \sum_{i=1}^{n} Y(p_i) \left[ 2 \cos \left( \frac{2\pi m p_i}{\Delta p} \right) \sin^2 \left( \pi m \frac{\delta p_i}{\Delta p} \right) \right. \\
- \sin \left( \frac{2\pi m p_i}{\Delta p} \right) \sin \left( \pi m \frac{\delta p_i}{\Delta p} \right) \right]
\tag{2.12}
\]
Theoretically, the fringe profile can then be expressed in terms of the Fourier series:

\[ Y_s(x) = \frac{Y_{co}^2}{2} + \sum_{m=1}^{\infty} \hat{Y}_m \cos(mx + \alpha) \]  

(2.13)

where \( \hat{Y}_m = (\hat{Y}_{cm}^2 + \hat{Y}_{sm}^2)^{1/2} \) and \( \alpha = \tan^{-1}(\hat{Y}_{sm}/\hat{Y}_{cm}) \). \( \hat{Y}_{co} \) is the zero order transform of the data. Using the above equations and with \( m = 4 \) (first four coefficients), the random noise in the observed data appearing as higher order coefficients in (2.13), is filtered out leaving the data free of fluctuations associated with these components.

Hays and Roble [1971] have solved equation (2.10) in terms of Fourier transforms and the coefficients. They have used a parabolic least squares technique to determine the minimum values of the sum squares of deviations between the observed data and the analytical profile calculated using the instrument coefficients and a Gaussian profile of a given temperature \( T_n \). Three arbitrary temperatures are assumed to begin with, and a search is made for a minimum in deviations. The constants which are made use of to fit a parabola to the deviations, are solved to yield \( T_n \). However, this method is computationally intensive and the solution will not converge, if the selected initial values are too far from the minimum and if the curvature of the deviations calculated happen to be of wrong sign such that the minimum is never approached [Bevington, 1969; Killeen and Hays, 1984].

We adopt the linearization method mentioned earlier to retrieve the Doppler parameters in our data reduction procedure in which the first step would be to assume that the background is zero. In order to estimate the best set of estimates \( p_j \)'s, the generalized Newton-Raphson method is used which is an iterative procedure based on a Taylor series expansion about the current approximation to the required solution.

The linearization method uses the results of linear least squares in a succession of stages. The function, \( \phi(x_i; p_j) \) is first expanded in a Taylor series about \( p_j^0 \)'s (a set
of initial values):

\[ \phi(x_i; p_j) = \phi(x_i; p_j^0) + \sum_{j=1}^{3} \left( \frac{\partial \phi^0}{\partial p_j} \right)_i p_j' \]  \hspace{1cm} (2.14)

where \( p_j' = p_j - p_j^0 \) and \( \phi^0 = \phi(x_i; p_j^0) \), \( p_j^0 \) being an approximation to \( p_j \). Higher order terms in \( p_j' \) are neglected. The parameters corresponding to the observed profile \( O(x_i) \), are taken to be the initial values \( p_j^0 \)'s assuming that \( O(x_i) \) follows a Gaussian distribution. If

\[ v_i' = O(x_i) - \phi(x_i; p_j^0) \quad \text{and} \quad x_{ji}' = \left( \frac{\partial \phi^0}{\partial p_j} \right)_i \]

then \( \chi^2 \), the sum of squares of deviation is given by

\[ \chi^2 = \sum_{i=1}^{n} w_i v_i'^2 = \sum_{i=1}^{n} w_i \left[ v_i' - \sum_{j=1}^{3} p_j' x_{ji}' \right]^2 \]

Minimization of \( \chi^2 \) leads to the normal equations

\[ \sum_{i=1}^{n} w_i \left( v_i' - \sum_{j=1}^{3} p_j' x_{ji}' \right) x_{ni} = 0 \]  \hspace{1cm} (2.15)

which can be solved for \( p_j' \) and hence the estimates of the parameters will be \( p_j = p_j^0 + p_j' \).

Writing out the functional form of \( \phi(x_i; p_j) \), in the case of a Doppler-broadened profile,

\[ \phi(x_i; p_j) = \sum_{k=1}^{n} \frac{p_1}{p_3} \exp \left[ \frac{-(x_k - p_2)^2}{p_3^2} \right] I(x_i - x_k) \]

The derivatives are

\[ \frac{\partial \phi}{\partial p_1} = \frac{\phi}{p_1} \]

\[ \frac{\partial \phi}{\partial p_2} = \frac{2(x_k - p_2)}{p_3^2} \phi \]
\[
\frac{\partial \phi}{\partial p_3} = \left[ \frac{2(x_k - p_3)}{p_3^2} - \frac{1}{p_3} \right] \phi
\]

Since the derivatives of the sum squares of deviations with respect of \( p^i \) are zero,

\[
\frac{\partial}{\partial p_m} \left[ \sum_{i=1}^{n} w_i \left[ O(x_i) - \phi(x_i; p^0) - \sum_{j=1}^{3} \left( \frac{\partial \phi^0}{\partial p_j} \right) p^j \right]^2 \right] = 0
\]

which becomes

\[
2 \sum_{i=1}^{n} w_i \left[ O(x_i) - \phi(x_i; p^0) - \sum_{j=1}^{3} \left( \frac{\partial \phi^0}{\partial p_j} \right) p^j \right] \left( \sum_{j=1}^{3} \frac{\partial \phi^0}{\partial p_j} \right) = 0
\]

neglecting the second derivative terms.

The normal equations are therefore

\[
\sum_{i=1}^{n} w_i O(x_i) \left( \frac{\partial \phi^0}{\partial p_m} \right)_i - \sum_{i=1}^{n} w_i \phi^0 \left( \frac{\partial \phi^0}{\partial p_m} \right)_i
\]

\[
- \sum_{i=1}^{n} w_i \sum_{j=1}^{3} \left( \frac{\partial \phi^0}{\partial p_j} \right)_i \left( \frac{\partial \phi^0}{\partial p_m} \right)_i p^j = 0
\]

\[(m = 1, 2, 3)\]

Let \( O(x_i) - \phi^0 = R_i \) and \( B_m = \sum_{i=1}^{n} w_i R_i \left( \frac{\partial \phi^0}{\partial p_m} \right)_i \). Then (2.16) reduces to

\[
B_m - \sum_{i=1}^{n} w_i \left[ \sum_{j=1}^{3} \left( \frac{\partial \phi^0}{\partial p_j} \right)_i \left( \frac{\partial \phi^0}{\partial p_m} \right)_i p^j \right] = 0
\]

Writing in matrix form

\[
B = A \mathbf{P}' \quad \text{or} \quad \mathbf{P}' = A^{-1} B
\]

\[(2.18)\]

\( \mathbf{P}' \) are obtained by solving (2.18) by one of the standard elimination methods and retaining the elements of \( A^{-1} \) also at every step.

Since \( p^j_0 \)'s have been the rough estimates of the original parameters, they can be improved upon by successive iteration. \( p^j_0 \)'s will then play the same role as \( p^j \)'s and...
the whole procedure is repeated till the solution converges. The rate of convergence of this method varies with the quality of the data and the initial values selected. The second step of the data reduction procedure would be to estimate the background count for these estimated values of \( p_j \)’s.

**Evaluation of background for the estimated \( p_j \)’s**

The response of a Fabry Perot etalon to a broadened source profile has been considered by Chabbal [1953]. The transmission of the instrument is a product of the contributions due to (i) absorption by reflecting layers of the etalon (these are extremely small in the case of the dielectric coatings), (ii) surface defects of the etalon, (iii) the scanning function \( f \), and (iv) the source not being monochromatic. Except the source itself having a finite width, all the other factors are inherent in the measured instrument profile. Thus the former needs to be estimated for an accurate determination of the source width. The actual contrast of the airglow profile is always less than the instrument contrast as determined using a laser due to the finite width of the source function and is related to the product of the instrument contrast and the transmission of the etalon for the Doppler-broadened source. Due to the presence of unwanted background radiation in the signal, the observed contrast \( (I_{\text{max}}/I_{\text{min}}) \) is slightly less than the actual contrast \( C_{\text{act}} \). Hence the contribution due to the background needs to be subtracted from the observed profile. The actual contrast is then

\[
C_{\text{act}} = \frac{I_{\text{max}} - BG}{I_{\text{min}} - BG}
\]  

(2.19)

where \( I_{\text{max}}, I_{\text{min}} \) and \( BG \) represent the maximum and minimum intensities and the background level respectively. Chabbal [1953] has studied the variation of the transmission factor of the instrument in response to various source-instrument width combination.
In order to evaluate the performance of our instrument in response to a Doppler-broadened source, a method was developed which also yields the background level. The instrument coefficients \(a_n\) are first evaluated using the Fourier decomposition technique described earlier. The expected airglow profile for a temperature \(T_n\) is then given by

\[
A(x) = I_{\text{max}} \left[ a_0 + \sum_{m=1}^{M} a_m e^{-m^2 \gamma T_n / \Delta x} \cos \left( \frac{2\pi x \mu}{\Delta x} \right) \right]
\]  

(2.20)

where \(\gamma\) is a constant \((= 0.000458)\), \(\Delta x\) is the free spectral range and \(I_{\text{max}}\) is the intensity at the peak position \([\text{Hays and Roble, 1971}]\). \(a_0\) is the zero order coefficient \((= 1/2\pi)\). If \(C\) is the resultant contrast for a zero width source, i.e., a monochromatic line, the transmission in response to a finite width source is written as

\[
\tau_B = \frac{C_{\text{act}}}{C}
\]

where \(C_{\text{act}}\) is the contrast for the assumed source width \((= C\) if the line width is zero for which \(\tau_B = 1\)). The ratio of the source width \(s\) to the etalon width \(e\) is increased in discrete steps and the transmission is evaluated using the above expression. Fig. 2.5 shows the response curve of the instrument which is compared with the theoretical curve given by \(\text{Chabbal [1953]}\). The deviation of the actual response curve from that obtained by Chabbal is due to the fact that the instrument broadening has a functional form between a Gaussian and an Airy type whereas the theoretical curve \((G\otimes F)\) has a functional form when the etalon function \(E\) is of a rectangular type. Similar result with regard to the spectrometer behaviour has also been obtained earlier by \(\text{Rajaraman [1982]}\).

Using the transmission curve and the formulation given above, the background can be evaluated for any value of source width under consideration. The background thus determined is then subtracted from the observed profile. The first step of the method is once again applied to this new profile for the determination of a new set
Fig. 2.5. The response of the instrument to various source widths. The dashed curve represents the result of theoretical calculation done by Chabbal [1953] and the continuous curve represents the result based on observed data from the instrument.
of $p_j$ values and the whole process is repeated until the difference in the estimated temperatures between two successive iterations is less than 10 K.

Estimation of errors

The standard deviation $\sigma_{n_i}$ for the uncertainty of determination of any parameter $p_j$ is the root sum square of the products of the standard deviation of each data point $\sigma_i$ multiplied by the effect that data point has on the determination of the parameter $p_j$ [Bevington, 1969].

\[
\sigma_{n_i}^2 = \sum_{i=1}^{n} \left( \sigma_i \left( \frac{\partial p_j}{\partial O(x_i)} \right)^2 \right)
\]  

(2.21)

Since the fluctuations in our measurements are statistical, the standard deviation corresponding to each observation can be estimated analytically. It is known that the observed counts follow a Poisson distribution. With the usual assumptions and approximations owing to the difficulties in solving equations associated with a Poisson distribution, the uncertainties $\sigma_i$ are reasonably approximated by $\sigma_i^2 = O(x_i)$ which is the observation corresponding to the independent variable $x_i$ [Hernandez, 1978].

From the normal equations,

\[
p_j = \sum_{m=1}^{3} \epsilon_{jm} \left[ \sum_{i=1}^{n} w_i \left(O(x_i) - \phi^0\right) X_m(x_i) \right]
\]

(2.22)

where $\epsilon_{jm}$ are the elements of the inverse matrix $A^{-1}$ and

\[
\left( \frac{\partial \phi^0}{\partial p_j} \right) = X_j(x_i)
\]

The remaining factor on the right hand side of (2.22) is the same as the matrix $B$ defined earlier.

For determining the uncertainty in each parameter $p_j$, the derivative of $p_j$ with respect to the observation $O(x_i)$ is to be calculated.

\[
\frac{\partial p_j}{\partial O(x_i)} = \frac{\partial}{\partial O(x_i)} \left[ \sum_{m=1}^{3} \epsilon_{jm} \left[ \sum_{i=1}^{n} w_i \left(O(x_i) - \phi^0\right) X_m(x_i) \right] \right]
\]
Therefore
\[
\left[ \frac{\partial p_j}{\partial \theta(x_i)} \right]^2 = \left[ \sum_{i=1}^{n} w_i \epsilon_{jm} X_m(x_i) \right]^2
\]
(2.21) becomes
\[
\sigma_{p_j}^2 = \sum_{m=1}^{3} \sum_{l=1}^{3} \epsilon_{jm} \epsilon_{jl} \sum_{i=1}^{n} \left[ w_i X_m(x_i) X_l(x_i) \right]
\]
\[
= \sum_{m=1}^{3} \sum_{l=1}^{3} (\epsilon_{jm} \epsilon_{jl} \epsilon_{ml}) = \epsilon_{jj} \quad (j = 1, 2, 3)
\]
(2.23)

The result of this calculation is that the diagonal elements of the error matrix \( \epsilon \) which is the inverse of the matrix \( \Lambda \) defined earlier, are the uncertainties of the parameters \( p_j \)'s.

To have a check on the temperature determined using this method, a fringe profile is constructed using equation (2.20) with this temperature and the available instrument coefficients and is compared with the observed profile. An example is depicted in Fig. 2.6 and the agreement is indeed very good. Using this powerful technique to determine Doppler parameters, useful results have been obtained on the dynamics of the thermosphere-ionosphere system [Sridharan et al., 1991; Gurubaran and Sridharan, 1993].

### 2.6 Line profile measurements of O I 6300 Å emissions

Though the method developed for the deconvolution of a source profile can be applied to any optical observation, its application to airglow O I 6300 Å emission is critically examined in this section. This follows from our basic necessity of obtaining thermospheric parameters for which the present investigation was initiated. The properties
Fig. 2.6. An observed airglow fringe (— ) after filtering out the random noise present in the data by applying Fourier decomposition and after due correction for the background, and the theoretical fringe (- - -) determined for the measured temperature from the former.
of the $^1$D to $^3$P transition of excited atomic oxygen giving rise to 6300 Å emission are well known [Chamberlain, 1961]. The emission line strictly follows the shape of a Doppler-broadened profile and can be expressed by a Gaussian function [Biondi and Feibelman, 1968]. The factors which limit the precision of the parameters of the line profile retrieved using the method described in the last section, are as follows: (1) Tilt and/or smear in the aperture used, (2) Thermal stability of the etalon, (3) Low intensity level of the emission, (4) Fast intensity variations, (5) Shears present in the wind systems of the emitting region and (6) Contamination of 6300 Å due to OH molecular band. These aspects and the methods adopted to overcome/minimize the effects are briefly discussed below.

(1) One of the effects which causes an asymmetry in the measured profile is due to the tilt of the aperture plate with respect to the normal to the optical axis and possible smear in the aperture (due to improper machining). A careful examination of the fringe pattern as the spectral scan is made, will show that as the pressure of the air between the etalon plates is increased, a bright spot first appears at the centre of the aperture which subsequently evolves into a fringe. At a particular value of pressure, it completely fills the aperture and then moves away from the centre, leading to the original 'darkening' of the aperture. Similarly, the reverse happens if the pressure is varied in the opposite direction, i.e., when it is decreased. The left half of the scanned profile gets developed during the period when the bright spot first appears at the centre, evolves and completely fills the aperture (during forward scan). The right half corresponds to the fringe 'leaving' the centre. A simple reasoning suggests that, in the absence of other factors, any asymmetry in the measured profile arises either due to the aperture not being exactly circular or it is not concentrically aligned and/or the aperture plate has a tilt with respect to the optical axis. Under such circumstances, once the fringe maximum is reached, the light will not be uniformly cut as the scan progresses, and hence would lead to an asymmetry. Due to the
reasons mentioned above, the left half of the airglow profile is reflected to the right thus eliminating the asymmetry and broadening, and the resultant profile is analysed using the method described in the previous section.

(2) If the etalon chamber temperature and hence the temperature of the air enclosed changes during a scan, the profile is likely to get distorted. This is mainly due to the refractive index being dependent on temperature. This effect becomes significant for wind determination and not so much for temperature estimates. However, since the thermal stability of the etalon is maintained to better than 0.1°C by a dual heating enclosure and by housing it in a chamber having large thermal capacity (section (2.4)), the instrument profile is not expected to drift in wavelength due to the variations in \( \mu \) arising purely out of changes in etalon temperature. This eliminates the possibility of the distortion of the observed profile due to changes in \( \mu \) associated with temperature alone, during a spectral scan.

(3) Earlier workers have stressed the need for an adequate signal to noise ratio to obtain accurate Doppler temperatures [Hays and Roble, 1971; Hernandez and Roble, 1976; Hernandez, 1978; Hernandez et al., 1984].

The emission profiles and the corresponding retrieved temperatures obtained during the coordinated campaign in the month of February, 1991, are scrutinized and a plot of the peak intensity (in counts) versus the standard deviation in retrieved temperature (the third diagonal element of the error matrix \( \epsilon \); see last section) is shown in Fig. 2.7. The peak intensity level measured is in the range of 100–1400 counts. The precision with which the temperature is determined, is seen to fall sharply as the count level reaches below 200. Owing to a large error present (> 200 K), profiles with peak intensity below 100 counts, which is rather frequent at our
Fig. 2.7. Standard deviation in the temperature determination versus peak intensity (in counts) of airglow fringe profiles for February 1991. The best fit curve using polynomial approximation is also plotted.
latitudes, are not considered for analysis. This sets a criterion for the rejection of line profiles.

(4) Fast variations in line intensity distort the profile shape and width, and lead to uncertainties in the retrieved parameters [Hernandez et al., 1975; Hays and Roble, 1971; Rajaraman, 1982]. It was suggested by Hernandez et al. [1975] that an intensity variation of more than about 20% leads to a greater uncertainty and such profiles need to be rejected. This suggestion is seriously considered in the present work and profiles with large variation in intensity (peak to peak of sequentially observed fringes) are carefully analysed. As the intensity of the line increases, during a forward scan, the left half of the profile is expected to have a larger contrast (maximum to minimum ratio) than that of the right half and the reverse holds when the scan is made in the opposite direction. Similar effects would be seen when the intensity decreases. Such distortions in the profile are expected to affect the temperature measurements often manifesting as higher temperatures. In spite of these expectations, on many occasions, when the intensity changes were by more than 25%, the temperatures obtained are not very different and the profiles are still neat and clean. However, variations on a much larger scale do contribute to significant changes in temperatures, and profiles with such variations are duly rejected.

(5) Biondi and Feibelman [1968] pointed out the possibility of a line profile distortion due to gross motions of the thermosphere. Within the emitting layer of thickness in the range of 50 km, a shear or velocity gradient in the neutral atmospheric motion is expected to lead to a slightly non-Gaussian line with a skew about the line centre. During their observations from Laurel Mountain, Pennsylvania, Biondi and Feibelman [1968] have observed a few profiles of marked asymmetry and attributed them to a sharp gradient in wind velocity within the emitting region. However, in the Indian zone, in situ measurements by means of release of vapour clouds by rockets, revealed
that there were no shear or changes in the wind velocity in the altitude region of emission [Sridharan et al., 1989] thus suggesting that such occurrences may not be common. Hence their possible effect is not considered in the line profile analysis.

(6) The presence of emission lines of the OH molecule (6287.5 Å, 6297.9 Å and 6307 Å) near the O I 6300 Å emission line has been well recognized for more than three decades [Chamberlain, 1961; Hernandez, 1974]. Hernandez [1974], in an important work, has investigated the effects of OH contamination of the 6300 Å line and found them to be significant at certain times. As the emission rate of atomic oxygen line decreased below 20 R, the OH contribution has been observed to be significant. In the present work, a narrow band interference filter (3 Å bandwidth) tuned to 6301 Å is expected to filter out all the other lines of the OH emission band except 6297.9 Å. Though the 6297.9 Å component of the OH band is close to 6300 Å, it lies at the rapidly falling edge of the filter transmission curve and secondly the gap between the Fabry-Perot etalon plates (1 cm gap) is so chosen as to make this emission feature appear in the middle of two 6300 Å profiles corresponding to adjacent orders. Hence it is not expected to contaminate the observations even when the emission rate of 6300 Å falls low, except on occasions when the molecular emission intensity is unusually high.

The results obtained on temperatures and winds from the low latitude station are presented and discussed in the chapters to follow.