Chapter 2. Airglow Imaging of Plasma Depletions

This chapter describes the methodology followed in the study. First an introduction is given to the ionospheric processes those results in major airglow lines. While there are several airglow lines, only certain emission could be used for ionospheric research. Thus, it is important that the intensities of the selected airglow lines are related to the plasma density. The detailed emission mechanisms of the important spectral emissions that are used in the current study are provided, elaborating how the observed intensities are related with electron density. Next, the concept of all sky optical imaging is introduced, and the details of the imaging system are described. A brief description of the all sky imager developed at the Physical Research Laboratory, Ahmedabad, INDIA, which is used to collect the data used in the current study is provided, followed by some of the procedures used for image analysis.

2.1 Airglow Emissions

The earth’s ionosphere is sometimes called a chemical laboratory, where a number of chemical reactions take place. These reactions involve neutrals as well as ionised species. Some of the products of these reactions may be in the excited states and as they transfer to lower energy state, spectral lines are emitted. The emissions may be in the ultraviolet, visible or infrared regions of the electromagnetic spectrum, depending up on the particular reaction responsible for it, and are generally termed as airglow. It is continuous throughout the globe. The main source of airglow emissions is the photochemical reactions involving solar radiation and various atmospheric species. At higher latitudes, the energetic particles from the solar wind give rise to the fascinating phenomenon called aurora. The main emission mechanism is the excitation of atmospheric species into higher states. The excited species returns to ground state in one or more steps, emitting radiation characteristic of that species. The excitation mechanisms involve (a) fluorescence and resonance scattering, (b) excitation by energetic particles, (c) chemical excitation and (d) energy transfer through collisions.

The important airglow emissions that are used in optical aeronomy, are the emission lines of atomic oxygen, atomic sodium and hydroxyl radicals. These emissions are present at all altitudes, but bulk of the emission comes from a certain
altitude range where the constituents responsible for the emission have a maximum concentration. The altitude profile of the important species in the upper atmosphere is given in Figure 2.1. Nitrogen (N\textsubscript{2}), and Oxygen (O\textsubscript{2}) molecules are the dominant neutral species in the lower heights, while above about 220 km, atomic oxygen becomes important. As a result of the small mean free path at the low altitudes (F-region bottom side), N\textsubscript{2}, and O\textsubscript{2} plays an important role in loss processes. At higher heights the neutrals do not have any significant role in the interactions.

![Figure 2.1](image)

**Figure 2.1** The distribution of neutral particles above 100 km. Also shown are the distributions of charged particles.

The important emission lines of atomic oxygen are 630.0 nm, 777.4 nm and 557.7 nm (Figure 2.2). The bulk emission of 630.0 nm line comes from an altitude region centered at about 250 km. This height region corresponds to the bottom side of the F region. The 7774. nm bulk emission is from the F-peak, which is at about 350 km. The 557.7 nm OI green line has two emission peaks, one is at about 100 km altitude region (mesospheric contribution) and the second peak it at about 250 km (F region contribution). So this emission can be used to study different altitude regions, depending on which altitude region contributes more to the total emission. The sodium doublet is originating from an altitude region of 90 km to 95 km. The source of this
metallic ion at these altitude regions is attributed to the meteoritic activity. Another important emission is the IR emission of OH radical at 839.4 nm. It comes from about 90 km. This emission is responsible for the cooling of this atmospheric region.

![Figure 2.2](image)

**Figure 2.2** Altitudes of the important spectral emissions from atomic oxygen (777.4 nm, 630.0 nm, and 557.7 nm) used in the current study. The electron density profile from the IRI model and atomic oxygen density from MSISE model for 2002 March are also shown.

### 2.2 Airglow and Ionospheric Irregularities

The recombination processes in the coupled ionospheric-thermospheric system results in the excitation of neutral particles, especially the atomic oxygen, and the subsequent transition to the ground state results in airglow emissions in the ultraviolet (UV), visible, and near infrared (IR) regions. The intensity of these emissions is a function of the plasma density. Thus, by monitoring the airglow using a ground based instrument, one can study the plasma density at the altitude of their bulk emission. A time series of such observations can be used to investigate the plasma density variations. Though there are numerous spectral emissions from the upper atmosphere, but only those lines produced as a result of recombination processes, and, whose intensity is a function of the plasma density can be used for ionospheric research. The emissions from the excited states of atomic oxygen such as 630.0, 557.7, and 777.4 nm
are related to the plasma density, and are used as tracers of ionospheric properties in ground based observations.

The study of airglow intensities gives important information regarding the source of the emission. From the measured intensity of the emitted lines and knowing the excitation cross-section, the column density of the emitting species can be calculated. The line of sight velocities and temperatures can be calculated from the Doppler profiles and line shifts of radiation. The airglow intensity gets modulated as a result of interaction between neutrals and plasma. Hence, by studying the airglow intensity variations, dynamics of the neutrals and plasma can be understood. Also, this enables the study of coupling mechanism of different atmospheric regions. If the intensity of the airglow emission is some known function of the electron density, then from the variations in the intensity of that particular emission one can study the electron density variation at the altitude of bulk emission. The irregularities in the electron density distribution will appear as airglow intensity variations.

Plasma depletions are regions of large-scale reduction in electron density. When they are generated at the equator in the ionosphere, the low density regions distribute along the magnetic field lines to reach low-latitudes. Thus, along a very large area, the plasma density drops by orders of magnitudes. Such, irregularities move with velocities of the order of 100-150 m/s, which gradually decreases with time. Thus, over such regions, the intensity of any airglow emission that is related to electron density will also be less. The intensity of airglow emission depends on the intensity of the source of emission and the corresponding excitation cross-sections. If one could monitor the time variation of the airglow intensity over the area, it is possible to study the ionospheric irregularities producing the intensity variations. So, any variation in the observed intensity can be attributed to a corresponding variation in the density of the emitting source, under normal conditions.

The present study is conducted using the All Sky Imaging System developed at P.R.L., Ahmedabad. The atomic oxygen emissions at 630.0, 557.7 and 777.4 nm are used to image the plasma depletions. These airglow lines are chosen since their intensity is a known function of electron density at the altitude where they are produced. In the case of 630.0 and 557.7 nm line, intensity is proportional to the electron density where as in the case of 777.4 nm line; intensity is proportional to
square of the electron density. Hence, any variation in the electron density at the corresponding altitudes can be inferred from the intensity variation of the airglow lines. Hence the depletion images obtained using these two emission lines can be used to study the formation, growth and propagation of ionospheric irregularities. The important mechanisms involved in the emission of these lines are described below.

2.3 Airglow Chemistry

Atomic oxygen is the source of major airglow emissions in the ionosphere. As a result of the various photochemical reactions involving neutral and charged particles, the oxygen atoms are populated in higher energy states. Figure 2.3 gives the energy level diagram of atomic oxygen. The oxygen in the excited states transfers to the lower energy states, emitting the difference in the energy as radiation. Figure 2.3 also gives the wavelength of the possible emissions from atomic oxygen. Though, there are several such emission lines, as described above, the 630.0, 557.7, and 777.4 nm wavelengths are used here.

![Figure 2.3 The energy level diagram of atomic oxygen, showing the various spectral transitions (Rees, M. H., Cambridge Uni. Press, 1989).](image-url)
2.3.1 Dissociative Recombination: 630.0 and 557.7 nm Emission

The 630.0 nm, known as the ‘red line’, is the most extensively observed airglow emission of the night sky. In a review, Chakrabarti [1998] describes the first observation of 630.0 nm by Garrigue as early as in 1936. The 557.7 nm green line is known several years before, and its association with atomic oxygen was suggested in 1923. The green emission comprises of two components, a weaker emission from the lower thermosphere, and a much stronger emission from the upper mesosphere. The main source of the 630.0 nm, as well as the thermospheric component of the 557.7 nm, is the dissociative recombination of O$_2^+$ [Peterson et al., 1966; Peterson and VanZandt, 1969; Link and Cogger, 1988; Sheeshan and St.-Maurice, 2004, Vlasov et al., 2005].

The transitions from the metastable states O($^1$D), and, O($^1$S), of the atomic oxygen to the ground state O($^3$P), result in the red and green emissions, respectively. The main source of these metastable states in the nighttime thermosphere is the dissociative recombination of O$_2^+$ given by the reaction,

$$O_2^+ + e \xrightarrow{\alpha_i} 2O(^3P, ^1D, ^1S)$$

(2.1)

where, $\alpha_i$ (cm$^3$/s) is the rate coefficient, which depends on electron temperature (see Table 2.1). The fraction of the atomic oxygen resulting in either of the O($^1$D) or O($^1$S) states as a result of equation (2.1) is given by the quantum yields ($\mu_D$ and $\mu_S$, respectively) of these states. The production rates of O($^1$D) and O($^1$S) states can be written as,

$$\mu_D \alpha_i [O_2^+][e] \text{, and}$$

(2.2a)

$$\mu_S \alpha_i [O_2^+][e]$$

(2.2b)

The O$_2^+$ ions are produced through the charge exchange reaction,
Table 2.1 Reaction coefficients for dissociative recombination process

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Coefficient</th>
<th>Value (cm$^3$s$^{-1}$, s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>O($^1$D)+N$_2$ → O+N$_2$</td>
<td>$k_1$</td>
<td>$2 \times 10^{11}\exp(107.8/T_n)$</td>
</tr>
<tr>
<td>O($^1$D)+O$_2$ → O+O$_2$</td>
<td>$k_2$</td>
<td>$2.9 \times 10^{11}\exp(67.5/T_n)$</td>
</tr>
<tr>
<td>O($^1$D)+O → O+O</td>
<td>$k_3$</td>
<td>$(3.730+1.1965 \times 10^{-1}T_n^{-0.5}-6.5898 \times 10^{-1}) \times 10^{12}$</td>
</tr>
<tr>
<td>O($^1$D)+O → hv(630.0nm)</td>
<td>$A_{1D}$</td>
<td>$7.1 \times 10^{-3}$</td>
</tr>
<tr>
<td>O($^1$D)+O → hv(636.4nm)</td>
<td>$A_{2D}$</td>
<td>$2.2 \times 10^{-3}$</td>
</tr>
<tr>
<td>O($^1$S)+O → hv(557.7nm)</td>
<td>$A_{1S}$</td>
<td>$1.215$</td>
</tr>
<tr>
<td>O($^1$S)+O → hv(297.2nm)</td>
<td>$A_{2S}$</td>
<td>$1.95 \times 10^{-7}(T_e/300)^{-0.7}$</td>
</tr>
<tr>
<td></td>
<td>$\gamma_1$</td>
<td>$0.076$</td>
</tr>
<tr>
<td></td>
<td>$\mu_D$</td>
<td>$1.1$</td>
</tr>
<tr>
<td></td>
<td>$\mu_S$</td>
<td>$0.08$</td>
</tr>
</tbody>
</table>

\[ O_2 + O^+ \xrightarrow{\gamma} O_2^+ + O \tag{2.3} \]

where, $\gamma_1$ is the rate of the charge exchange process. The main loss process of O$_2^+$ thus formed is the dissociative recombination given by equation (2.1). Combining the equations (2.1) and (2.3), the O$_2^+$ concentration can be written as,

\[ [O_2^+] = \frac{\gamma_1[O_2][O^+]}{\alpha_1[e]} \tag{2.4} \]

Using equation (2.4) in (2.2) gives the production rates of O($^1$D) and O($^1$S) as,

\[ \mu_{i,0} \alpha_i [O_2][O^+] \text{, and} \tag{2.5a} \]

\[ \mu_{i,2} \alpha_i [O_2][O^+] \tag{2.5b} \]

There is another contribution to the O($^1$D) state due to the dissociative recombination of NO$^+$, but the quantum yield of the production is very small [Link, 1992], and have been shown to minor compared to the above reactions [Sobral et al., 1993]. The O($^1$D) state can be deactivated through collisions with neutrals as well as
electrons, in addition to the emission of 630.0 nm photon, where as the O\(^{(1S)}\) deactivation by collisions with neutral constituents is negligible. The collisional quenching of O\(^{(1D)}\) state are given by,

\[
\begin{align*}
O^{(1D)} + N_2 &\xrightarrow{k_1} O^{(3P)} + N_2 \\
O^{(1D)} + O_2 &\xrightarrow{k_2} O^{(3P)} + O_2 \\
O^{(1D)} + O &\xrightarrow{k_3} O^{(3P)} + O
\end{align*}
\]

The radiative deactivation of O\(^{(1D)}\) state can be realized either by the emission of a 630.0 nm photon or by the emission of a 636.4 nm photon, as illustrated in Figure 2.3. The transition probability (Einstein coefficient) of the 630.0 nm is represented by \(A_{1D}\), while that of the 636.4 nm is \(A_{2D}\) (Table 2.1). It can be seen from Figure 2.3 that the

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Coefficient</th>
<th>Value (cm(^3)s(^{-1}), s(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>O(^{+}) + e \rightarrow O(^{+}) + N(_2)</td>
<td>(\alpha_{1})</td>
<td>7.8\times10(^{13})</td>
</tr>
<tr>
<td>O + e \rightarrow O(^{-}) + O(_2)</td>
<td>(k_{1})</td>
<td>1.3\times10(^{15})</td>
</tr>
<tr>
<td>O(^{-}) + O(^{+}) \rightarrow O(^{+}) + O(^{-})</td>
<td>(k_{2})</td>
<td>1.5\times10(^{7})</td>
</tr>
<tr>
<td>O(^{-}) + O \rightarrow O(_2) + e</td>
<td>(k_{3})</td>
<td>1.4 \times10(^{10})</td>
</tr>
<tr>
<td>(\beta_{777.4})</td>
<td>0.42</td>
<td></td>
</tr>
<tr>
<td>(\beta_{135.6})</td>
<td>0.54</td>
<td></td>
</tr>
</tbody>
</table>

O\(^{(1S)}\) state too has two transition probabilities, \(A_{1S}\) for the emission of 557.7 nm photon, and \(A_{2S}\) for the transition to the ground state O\(^{(3P)}\) emitting a 297.2 nm photon.

Combining the production and loss processes and the reaction probabilities, and since \([O^+] = [e]\) in the F2 region, the volume emission rate for the 630.0 nm can be written as,
\[ V_{630.0} = \frac{A_{1D} \mu_D \gamma_1 [O_2] [e]}{k_1 [N_2] + k_2 [O_2] + k_3 [O] + A_{1D} + A_{2D}} \] (2.9)

and, that for the 557.7 nm,

\[ V_{557.7} = \frac{A_{1S} \mu_S \gamma_1 [O_2] [e]}{A_{1S} + A_{2S}} \] (2.10)

It can be seen from equations (2.9), and, (2.10), that the volume emission rate is directly proportional to the electron density. Also, when the F-layer altitude decreases, the numerator in the equations decreases more rapidly than the denominator (the quenching efficiency is very low), and hence the emission intensity decreases.

### 2.3.2 Radiative recombination: 777.4 and 135.6 nm Emission

The 777.4 nm and 135.6 nm lines are also used for ionospheric studies, where the latter is a favorite choice in satellite experiments [Ogo 4, IMAGE/FUV, TIMED/GUVI, COSMIC/TIP]. The earlier measurements of 135.6 nm are done from Ogo 4 [Hicks and Chubb, 1970; Barth and Schaffner, 1970], while ground based instruments are used to observe the 777.4 nm [Tinsley, 1966; 1972]. These allowed transitions of atomic oxygen are due to the radiative recombination of O\(^+\) [Hanson, 1969; Tinsley et al., 1973]. The reaction can be written as,

\[ O^+ + e \rightarrow \alpha_1 O^- + h\nu \] (2.11)

where \(\alpha_1\) is the rate of the radiative recombination (see Table 2.2). The excited oxygen atom (O\(^\ast\)) gives rise to a 135.6 nm or 777.4 nm photon, depending on its particular energy level and the level to which the transition occurs. As illustrated in Figure 2.3, the 777.4 nm emission would occur if the excited oxygen is in the O\((\Sigma^P)\) state and undergoes transition to the O\((\Sigma^S)\) state, and the 135.6 nm is emitted when the oxygen atom transfers from O\((\Sigma^S)\) state to the ground (O\((\Sigma^P)\)) state.

In addition to the radiative recombination process, the ion-ion recombination between O\(^+\) and O\(^-\) is also found to excite oxygen atom to the corresponding energy levels [Knudsen, 1970; Tinsley, 1973]. The O\(^-\) ions are produced through radiative attachment. The reactions are,

\[ O + e \rightarrow k_1 O^- + h\nu \] (2.12)

\[ O^- + O^+ \rightarrow k_2 O^+ + O^+ \] (2.13)
The loss of $O^-$ ions are given by,

$$O^− + O \xrightarrow{k} O_2 + e$$  \hspace{1cm} (2.14)

The volume emission rate for the 777.4 nm can be written as,

$$V_{777.4} = \alpha_e [O^+] [e] + \frac{\beta_{777.4} k_1 k_2 [O][O^+] [e]}{k_2 [O^+] + k_1 [O]} , \text{ and,}$$  \hspace{1cm} (2.15)

the volume emission rate for 135.6 nm,

$$V_{135.6} = \alpha_e [O^+] [e] + \frac{\beta_{135.6} k_1 k_2 [O][O^+] [e]}{k_2 [O^+] + k_1 [O]} ,$$  \hspace{1cm} (2.16)

where, $\beta_{777.4}$, and $\beta_{135.6}$ are the fractions of the ion-ion recombination that result in the emissions of 777.4, and 135.6 nm, respectively.

It can be seen from equations (2.15) and (2.16), that the 777.4 and 135.6 nm lines also depend on the electron density. The contribution through ion-ion recombination in the nighttime is smaller compared to the radiative recombination [Hanson, 1970; DeMajistre et al., 2004]. Since $[O^+] = [e]$ in the F2 region, the emission has a quadratic relationship with the electron density. Also, the radiative recombination process is independent of height, and hence the intensities do not vary significantly with the F-layer movements.

### 2.3.3 Barth mechanism: Emission of 557.7 nm

In the case of 557.7 nm, in addition to the dissociative recombination, there is an additional process of emission described as Barth mechanism (Barth, 1961, 1964). This process is responsible for the mesospheric component of this emission. In this method, two oxygen atoms, in presence of other neutral species, combine together to form an oxygen molecule, which undergoes collisions with other oxygen atoms to dissociate back to oxygen atoms. These oxygen atoms, if in the $^1S$ state, will result in 557.7 nm photons upon transition to the ground state. The reactions are given below.

$$O + O + M \xrightarrow{k} O_2 (c^3Σ_u^+, b^1Σ_g^+) + M$$  \hspace{1cm} (2.17)

$$O_2 (c^3Σ_u^+) + O \longrightarrow O_3 (X^3Σ_g^-) + O(^1S)$$  \hspace{1cm} (2.18)

$$O(^1S) \longrightarrow O(^1D) + 557.7nm$$  \hspace{1cm} (2.19)

where M represents a neutral species, and could be N$_2$, O$_2$, or atomic oxygen. In these reactions, the exact precursor state responsible for the production of O($^1S$) is not
known. Laboratory studies have shown that there are about six possible precursor states [Bates, 1988], and hence there is an uncertainty in the estimation of volume emission rate.

McDade et al. [1986], using simultaneous measurements of atomic oxygen density and the airglow intensity, derived a set of empirical parameters that can be used to describe the emission, without having any prior knowledge of the precursor state. The volume emission rate according to McDade et al. [1986] is given by,

\[
V_{557.7} = \frac{A_3 k_1 [O] (\frac{N_2}{O_2})}{(A_6 + k_5 [O_2])(C_{O2}^{O}[O_2] + C_{O}^{O} [O])},
\]

where, \(A_3\) is the 557.7 nm line (\(O^1D-O^1S\)) transition probability, \(k_1\) is the rate coefficient for the three body recombination of atomic oxygen, \(A_6\) is the inverse radiative life time of \(O^1S\) state, \(k_5\) is the quenching coefficient of \(O^1S\) state by \(O_2\). \(C_{O2}^{O}\) and \(C_{O}^{O}\) are the empirical parameters provided by McDade et al. [1986].

It can be seen from equation (2.20) that the mesospheric 557.7 nm, unlike the other emission, is independent of electron density, and hence cannot be used for ionospheric studies. This emission, much stronger compared to the thermospheric component, contaminates the ground based measurements of the latter, and thus makes the 557.7 nm not very useful for ionospheric research. Nevertheless, this line is widely used to the dynamics and wave activities in the mesospheric region.

2.4 All Sky Imaging

The ESF irregularities are considered to be generated in the bottom side F region at the geomagnetic equator in the post-sunset period, and the regions of depleted plasma density grow non-linearly to the stable topside [Scannapieco and Ossakow, 1976]. In this process, the low-density plasma diffuses down along the geomagnetic field lines to low and mid-latitude regions, affecting the recombination reactions, and hence the airglow. The locations where the foot prints of these depleted flux tubes encounter the airglow emitting regions corresponds to a drastic reduction in the intensity, provided the emission is a function of the plasma density. The basic principle of all sky imaging is to take snapshots of the night sky using selected airglow lines that are related to ionospheric plasma density. When large scale irregularities associated with ESF are generated, the regions of reduced airglow would appear in these images as dark bands.
extending along the geomagnetic N-S direction. The name plasma depletion is related to this manifestation as dark bands of depleted airglow intensity.

Mende and Eather [1976] came up with a wide-angle instrument to study auroral emissions. Weber et al., [1978, 1980] developed a similar system to study the equatorial airglow emissions. They conducted observations carrying the instrument on an aircraft, and reported depletion bands at 630.0 nm. Mendillo and Baumgardner [1982] described a ground base photographic method to image the airglow depletions. They used a 180° field of view (FOV) lens to achieve large spatial coverage required for the plasma depletion studies. The work reported here is carried out using an imaging system, which is developed based on the system described by Mendillo and Baumgardner [1982], at Physical Research Laboratory (PRL), Ahmedabad, India [Raizada, 1998; Sinha and Raizada, 2000; Sinha et al., 2001].

The basic setup of an all sky imager consists of 180° FOV front end lens, a collimating arrangement, interference filters of desired wavelengths to isolate the emission from background, and an imaging optics to focus the beam to a detector, which is normally a CCD camera. The 180° FOV provides a large spatial coverage that helps the study of evolution and dynamics of large scale irregularities. At an altitude of about 250 km, this FOV is estimated to cover a hemispherical area of about 1800 km radius. The mapping of such a wide area into a circular image results in large compression at the edges of the images. Thus, any attempt to determine depletion parameters from such regions in the image could result in large errors. To avoid such situations, for all practical calculations, the imager FOV is restricted to 150°.

Narrow band interference filters are used to select the airglow emissions. Interference filter works on the principle of interference of light. The filter, a multi-layer thin-film device, consists of a set of thin films of high and low refractive indices with spacers or absentee layers between these sets. When the light beam is incident on the film, reflection and transmission occurs and the transmitted beam undergoes multiple reflections, and, interferes in the region between the film boundaries. The thickness of the film ($\lambda/4$) and the spacing between them ($\lambda/2$) are fixed such that only the wavelength $\lambda$ satisfies the condition for constructive interference given by,

$$2\mu \cos \theta = n\lambda,$$

(2.21)
where $\lambda$ is the refractive index of the spacer, $t$ is the thickness of spacer and $n$ is the order of interference fringe. From equation (2.21), it can be seen that the wavelength transmitted by the filter will change with a change in the angle $\theta$. The collimating lens is to make sure that the light collected by the system is parallel to the optical axis, so that near normal incidence with the surface of the filter is possible. Note that $\lambda$ and $t$ depends on temperature. Hence, in the environments where large fluctuations in temperature are expected, it is desired to use some mechanism to maintain uniform filter temperature.

The airglow emissions to be imaged are very weak, and hence the choice of the CCD camera is very important. The camera should have high quantum efficiency in the spectral region of interest, and should be capable for integrating the signal for a longer period of time. Thus the thermal noise of the CCD should be as low as possible, and the dynamic range should be high.

All sky imagers can be developed with relatively lower costs than that required for setting up radar, ionosonde, or lidar facilities, or conducting a rocket or satellite experiment. The imager offers a wide spatial coverage and provides two dimensional information about the evolution and dynamics of large scale irregularities that no other technique is capable of doing. Moreover, an imager system can be easily transported from one location to other location. One of the major drawbacks of the method is that uninterrupted monitoring of the ionosphere is not possible, and the observations are limited to dark, clear sky nights (free of moon, clouds, and any other light pollution) only.
2.4.1 PRL All Sky Imager

The optical arrangement of PRL all sky imager is shown in Figure 2.4. A Nikkor 8mm, f/2.8, 180° FOV, fish eye lens is used to collect the airglow photons. The fish eye lens creates a circular image of 23 mm diameter at the film plane. The light beam from the fish eye is diverging in nature. A field lens is used to reduce the divergence of the beam so that all the rays pass through the interference filter. A 50 mm, f/1.2 plano-convex lens is used as field lens. The collimating lens is a 280 mm, f/2.8 lens of 100 mm diameter. The interference filters used are of 100 mm in diameter, and have a bandwidth of 1 nm. A filter wheel that can accommodate four filters is used to select the desired emissions. The 630.0, 557.7, and 777.4 nm wavelengths are used for the present study.

Since the emissions are very weak, the imager system uses an image intensifier to amplify the signal. An imaging lens, identical to the collimating lens, is used to focus the parallel beam from the filter to the input photocathode window of the intensifier,
which converts the incident photons to electrons, forming an electrical image corresponding to the optical signal. These electrons are accelerated through a micro channel plate (MCP), wherein each electron gets multiplied several times by the production of secondary electrons at the walls of the MCP channels. The micro channel plate is in the form of a small disc of 0.48 mm in thickness and 25 mm in diameter, formed by fused glass fibers numbering in millions, each of which having a diameter of about 12 µm. The end surface of the intensifier is a phosphor screen, which re-converts the amplified electrical image to optical image. The intensifier output is transferred to the CCD camera using a combination of Nikkor 105 mm, f/1.2, and 24 mm, f/1.2 lenses. A 16 bit CCD camera from Starlight Express, which employs a thermo electric cooling, is used for recording the images.

2.4.2 Optical design details of the All sky Imager

The front end of All sky imager is a commercially available fish-eye lens (f/2.8, 8mm), used to image the sky, which makes an image of 23mm diameter at the image plane.

Four interference filters are used to select different emissions. Filter requires that the beam is parallel to the optical axis. Hence we need a collimating lens. In order to get best results, the maximum incident angle should be less than 3 degrees.

\[
(\Delta \lambda_{\text{max}} = \frac{\lambda \theta_{\text{max}}^2}{2 \mu^2} ; \text{ for } \theta = 3^\circ \Rightarrow \Delta \lambda_{\text{max}} = 3 \mu^2)
\]

This requires that we must use a collimating lens of a large focal length to minimize the angle

\[
[\tan(\text{angle}) = \frac{23 \text{ mm}}{2 \times \text{focal length}}]
\]

If we consider angle to be 3 degrees, then the focal length of collimating lens should be at least 220 mm (or more for angle less than 3 degrees). Since we need to keep the angle well below 3 degrees, 280 mm is used. For f/2.8 optics, the diameter should be 100 mm. Hence we need to use 100 mm filters.

The 180 degree FOV of the fish-eye lens produces an image with beams of large divergence. Some of the diverging beams from the image plane of the fish eye lens could miss the collimating lens kept at about 280 mm. To minimize this, a field lens is
used. A field lens reduces the divergence of the beam from the focus without losing flux.

The field lens should have the f-number as that of fish-eye lens, and its diameter should be at least as that of the image size produced by the fish-eye. Now, we use an f/2.8 optics and the image size by the fish-eye is 23 mm. Thus, if we consider 23 mm as the diameter of the field lens, then its focal length should be,

\[ f = 2.8 \times 23 \text{ mm} = 64.4 \text{ mm.} \]

The field lens is kept at the image plane of the fish eye. Since the focal length of field lens is about 64 mm, and the collimating lens is kept at about 280 mm from it, the image magnification is about a factor of ~4 (280/64), which also comes to about 100 mm (for an image size of 23 mm). The angle of the rays after field lens is calculated using the diameter and focal length of field lens as:

\[ \tan(\text{angle}) = \frac{\text{diameter of field lens (23 mm)}}{2 \times \text{focal length (64 mm)}}. \]

Therefore the reduced divergence with Field lens = 10°

Thus, the field lens reduces the 180 FOV of the fish-eye lens to a maximum divergence angle from the above calculation.

2.5 Image Geometry

It is often required to calculate the widths as well as velocity of plasma depletions from airglow images. For such calculations it is necessary to convert the pixel locations of depletions into distances in standard units from a reference point in the sky at the corresponding altitude of the emission. This can be done with the help of Figure 2.5, which shows the response curve of the fisheye lens provided by the manufacturer. The curve gives the relationship of the distance \( y \) in millimeters of any point in the image from the center, with the zenith angle \( \theta \) of that point. Figures 2.6a and 2.6b illustrates the definitions of \( y \) and \( \theta \). The task at hand now is to determine \( y \) of any given pixel in the image, and then convert the corresponding \( \theta \) from Figure 2.5 into distance in km or any other convenient unit. The first part (determining \( y \)), is straightforward and can be easily done knowing the physical size of an individual pixel, and, that the fisheye lens produces a circular image of 23 mm diameter.
Figure 2.5 The response curve of the fisheye lens, provided by the manufacturer showing the relationship between distance from the center of the image and zenith angle.

The second part, i.e. of converting $\theta$ into distance can be done by considering the geometry shown in Figure 2.7. $I$ is the location of the imager, $D$ is the depletion, $O$ is the center of the earth, and $d$ is the distance to be determined. From the geometry, it can be seen that the arc length $d$ can be calculated if the angle $\phi$ is known. Applying the law of sine’s to $\Delta OID$,

$$\frac{R_E + h}{\sin(180 - \theta)} = \frac{R_E}{\sin(\theta - \phi)} \quad (2.22)$$

The equation (2.22) can be used to calculate $\phi$, and hence the distance $d$. The only assumption required in this calculation is the value of $h$, which is the mean altitude of the emission layer.
Figure 2.6 (a) Distance of a point from the image center. (b) The corresponding zenith angle.

Figure 2.7. Converting $\theta$ into distance can be done by considering the above geometry shown.
As mentioned above, the all sky imager uses three airglow emissions, 630.0, 557.7, and 777.4 nm, to take the images of the night sky. However, these emissions are not from the same altitude region. While 630.0 nm has its peak altitude around 250 km altitude, the 777.4 nm is mainly from the F-peak altitude of about 350 km. The spatial coverage of the instrument at the two altitudes regions is thus slightly different. Figure 2.8 gives a sketch of the observing geometry of the all sky imager for the 630.0 nm airglow. The geometry is drawn for the observation site at Kavalur. The 180° degree FOV covers approximates 17° S to 28° N latitudes for the 630.0 nm layer centered at 250 km altitude. The figure also gives the magnetic field-lines over the observing site, showing their corresponding apex altitudes. It can be seen from the figure that the low density flux tubes that produce depletions at the north most edge of the image corresponds to an altitude of about 1800 km over the magnetic equator. Note that the wide FOV of the fish eye lens results in large compression at the edges of the images. Hence in the calculations, the usable FOV is restricted to only 150°. The spatial coverage of the imager at 100, 250, and 350 km altitudes are given in Table 2.3.

![Figure 2.8 Viewing geometry of the all sky imager at Kavalur. The vertical arrows denote the center, as well as the north and south edges of the FOV, for a 180° observing geometry. The thick dark curve is the 630.0 nm airglow layer centered at 250 km and the thin curves are the magnetic field lines.](image)
Table 2.3 The spatial coverage of the all sky imager for 100, 250, and 350 km altitudes.

<table>
<thead>
<tr>
<th>Emission lines</th>
<th>Altitude of bulk emission</th>
<th>Spatial extent of the instrument</th>
</tr>
</thead>
<tbody>
<tr>
<td>557.7 nm</td>
<td>100 km</td>
<td>2275 km</td>
</tr>
<tr>
<td>630.0 nm</td>
<td>250 km</td>
<td>3640 km</td>
</tr>
<tr>
<td>777.4 nm</td>
<td>350 km</td>
<td>4340 km</td>
</tr>
</tbody>
</table>

Based on the observation geometry explained above, the spatial resolutions of the imager at the center as well as for a zenith angle of 75° are calculated. For an airglow layer at 250 km altitude, one pixel of the CCD camera used for the observations in 2002 can resolve structures with horizontal scale of about 2 km or less at the center of the image and about 10-12 km at 75°. At an altitude of 350 km, the corresponding resolutions are about 2 km and 16 km, respectively.

2.6 Image Analysis

The data analysis is mainly done using the softwares Image Reduction and Analysis Facility, IRAF developed by Smithsonian Astrophysical Observatory (SAO) and also using Interactive Data Language (IDL) by Visual Information Solutions. In a CCD, the response of different pixels for a uniform light is not similar. That is, there will be always a pixel to pixel variation in the value of the signal recorded for a uniform input. This arises due to the inherent error associated with each pixel. Hence flat fielding was done to correct this pixel defect. For this, a frame was generated, by exposing the CCD using a uniform light. An image having same pixel value throughout was divided by this image, and a flat fielding frame was thus generated. This value was selected by taking the average of the maximum and minimum pixel values in the frame generated using the uniform input. All images were multiplied using this flat fielding frame.

These images were then corrected for the image intensifier noise and dark current of the CCD. For this a frame with same exposure time as the data frame was taken, keeping the fish eye lens covered, which is with cover on. This frame was subtracted
form each data frame to remove the system noise. The next step was to remove the
constant background noise. This was done by averaging all data frames and subtracting
each frame from this averaged frame. By this process, constant features in the image
such as building lights etc. gets subsided, thus enhancing the depletions. This also
compensates for the Van Rhijn and vignetting effects. (Ref. Mendillo and

The 16 bit digitiser is capable of detecting an intensity variation of about 0.02%. To
utilise the full intensity levels provided by the digitiser, the frames were subjected to
histogram equalisation. The geographical N-S and E-W of these images were
disoriented by about 20° from the perpendicular axes that pass through the center of the
image. Hence, to rectify this, the images were rotated by 20°. These images were then
further analysed to calculate various parameters, such as degree of depletion, drift
velocity, orientation and tilt of depletions, their E-W and N-S extent, width of
delepitions and spacing between depletions etc.