Rocket-borne Instrument Design to Observe Peak OH Meinel Band Vibrational Emission Profiles

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Rocket-borne Instrument Design to Observe Peak OH Meinel Band Vibrational Emission Profiles

By
Joshua T. Bryson

A Thesis Submitted to the
Physical Science Department
In Partial Fulfillment of the Requirements for the Degree of
Master of Science in Space Science

Embry-Riddle Aeronautical University
Daytona Beach, Florida
Spring 2005
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Rocket-borne Instrument Design to Observe Peak OH Meinel Band Vibrational Emission Profiles

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Joshua T. Bryson

This thesis was prepared under the direction of the candidate's thesis committee chair, Dr. Peter Erdman, Department of Physical Science, and has been approved by the members of his thesis committee. It was submitted to the Department of Physical Science and was accepted in partial fulfillment of the requirements for the Degree of Master of Science in Space Science

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Abstract

The effects of density-dependent molecular quenching produce a unique, altitude
dependant emission profile of the vibrational emission band for each OH \( v' \) value in the
mesosphere. Previous rocket flights using broad band sensors have been able to detect a
1-2 km altitude gap between the peak emissions of \( \Delta v \leq 6 \) and \( \Delta v > 6 \). An instrument
design is presented which will directly measure the individual peak OH vibrational
emission altitudes for the \( v' = 2, 3, 4, 6, 7, \) and 8 transitions radiating from the
mesosphere. This high altitude resolution altitude profile information will enhance the
ability to observe vertical propagation of atmospheric gravity waves and other large-scale
atmospheric disturbances with high altitude resolution using ground-based observations
of the OH emission spectrum.
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Introduction

The brightest components of the NIR terrestrial nightglow are the vibration-rotation spectra of the excited OH molecule radiating from the mesosphere. These emissions originate from the vibrationally excited electronic ground state of the OH molecule and are known as the airglow Meinel Bands. The Meinel Bands are widely observed by the scientific community because of their relative brightness and the unique emission properties of the OH molecule. The radiative lifetime of the vibrationally excited OH molecule is very long, which means it makes many thermal collisions with the surrounding gas before emitting a photon. These collisions redistribute the rotational energy of the OH molecule to follow a Boltzmann temperature distribution. When the emissions of atmospheric OH is observed, the temperature of the mesosphere can be inferred from the brightness distribution of the individual rotational lines within a vibrational transition band.

Due to the collisional quenching and chemical destruction of the excited OH molecules, there is a non-uniform altitude distribution of the emissions from the set of possible vibrational transitions. The transitions with longer radiative lifetimes will be quenched more at lower altitudes due to the higher gas density and so will have a peak radiation at higher altitudes compared to the transitions with shorter radiative lifetimes.
Chapter 1. Reason for Project

The rotational lines of the excited OH molecule would provide information about the vertical propagation of atmospheric gravity waves and other large scale atmospheric disturbances if the altitude of the various OH transition emission peaks could be accurately determined. Once the location of the various OH transition emission peaks are determined experimentally, atmospheric perturbations such as gravity waves can be quantitatively observed from the ground as they propagate through the various emission regions by observing the spectra originating from different heights and studying the temporal dependence on fluctuations in the signal. These OH emission intensity perturbations have been widely observed for over 40 years. Krassovsky first discussed the idea that these intensity variations could signify the compression of air due to the passing of acoustic gravity waves in his paper published in 1972 [Krassovsky, 1972].

The goal of this project is to design a multi-sensor sounding rocket payload to make a high-resolution measurement of the altitude distribution of the individual OH vibrational-rotational band emission peaks. The altitude profiles of the various OH emission bands can be determined from measurements of a sample of OH emission bands radiating from different v’ values taken while traveling through the mesosphere. By measuring the altitude distribution of a representative sample of v’ values, the location of the peaks of the remaining profiles can be estimated.

Previous rocket measurements have been conducted which show a 1 to 2 km altitude separation between the OH (v’<6) and the OH (v’>6) emission peaks [Rogers et al, 1973; Baker, 1978; Lopez-Moreno et al, 1987; McDade et al, 1987; Baker and Stair, 1988]. These previous rocket flights have all employed wide-band sensors which provide minimal information on the altitude location of any single v’ emission line. This project is designed to expand on these previous rocket flights and determine the location of the individual v’ value emission peaks.
Chapter 2. OH Spectrum Background

2.1 Remote Atmospheric Temperature Measurements

The temperature of the mesosphere can be derived from the relative strength of rotational lines within various vibrational transition bands of the OH molecule. The transition of a molecule from an excited vibrational state to a lower vibrational state takes orders of magnitude longer than a dipole allowed transition from an excited electronic state to a lower electronic state. The OH Meinel Bands are emissions from the vibrationally excited hydroxyl molecule in its electronic ground state. The OH molecule will usually spend a significant amount of time in its vibrationally excited state before it emits a photon and decays down to a lower state unless it is quenched [Sivjee and Hamwey, 1987].

With each collision there is a probability that the excited OH molecule will be quenched. The quenching process and its effects are discussed in section 2.3.1 of the current paper. Each collision that does not result in quenching transfers small amounts of thermal energy between the participating molecules, populating the rotational energy levels within the given OH vibrational level but not affecting the vibrational level itself. After several collisions have taken place, the OH molecule contains some amount of rotational energy in addition to its vibrational energy. When the OH molecule finally emits a photon, the photon energy will be slightly different due to the additional energy from this rotation. By observing large quantities of OH molecules together in the atmosphere, the average temperature of the air can be inferred from the relative strength of the rotational lines within the vibrational emission bands. As temperature increases, more energy is transferred to the OH molecule on average, so higher energy level rotational lines are populated and radiate. By observing the brightness of the range of rotation lines, the temperature of the mesosphere can be determined [Sivjee and Hamwey, 1987].
2.2 **OH Excitation Mechanism**

The formation of OH in the atmosphere is mostly due to the combination of ozone and hydrogen through the following reaction

\[ H + O_3 \rightarrow O_2 + OH^* \]  

Equation 2.1

This is an exothermic reaction that releases 3.34 eV of energy [Bates, Nicolet, 1950; Baker, 1978; Sivjee, 1992]. The excess energy is usually contained in the form of vibrational energy of the OH molecule. Several eV of energy is required to excite OH to the first excited electronic energy level, while only tenths of eV of energy is required to excite OH to the first vibrational energy level. The amount of energy released during the reaction (3.34 eV) is insufficient to excite the OH molecule to the first electronic ground state (~ 4.05 eV) [Baker, 1978]. So the end result of this chemical reaction is that the mesosphere contains a relatively high concentration of OH molecules that are vibrationally excited.

2.3 **OH Emission Properties**

2.3.1 **Atmospheric Quenching**

The amount of time it takes for any excited molecule in a particular energy state to emit a photon and drop to a lower energy state (its radiative lifetime) varies according to the various electric properties of the energy state of the individual molecule. Since the radiative lifetime of the vibrationally excited OH molecule is long, the OH molecule will make several collisions with the surrounding atmospheric species while in its excited state. The exact number of collisions will vary depending on the translational energy of the OH molecule and the density of the surrounding medium. Each time a collision
occurs, there is a chance that the excited OH molecule will be “quenched” by chemically combining with another molecule or simply losing its energy through a collision with O₂, N₂, O, etc. The most common reaction that occurs to quench OH is given by the reaction [Llewellyn et al, 1977].

\[
OH^* + O \rightarrow O_2 + H
\]

Equation 2.2

This means that the extra energy of the excited OH molecule is converted to kinetic energy of O₂ or H after the collision, and so is contained as translational, rotational or vibrational energy, not emitted as a photon. Obviously, the more collisions the excited OH molecule makes, the greater the chance of quenching and thus not releasing a photon.

The result of this quenching phenomenon is that excited OH molecules in different energy states with different radiative lifetimes should radiate at different rates depending on the surrounding air density and therefore the altitude. At lower altitudes, more collisions occur because of the greater air density, and so the quenching becomes more probable. The OH energy transitions with shorter decay times are able to radiate at lower altitudes, but the transition states with longer decay times make so many collisions that they become quenched at lower altitudes. As the air density drops at higher altitudes the transition states with longer decay times are able to radiate because there are fewer opportunities for the molecule to be quenched because of the fewer number of collisions that are occurring.
2.3.2 Altitude Emission Heterogeneity

The quenching phenomenon sets up an interesting scenario in the mesosphere: the various OH vibrational energy levels emit different intensities at different altitudes depending, in part, on their respective decay times. The peak emission altitude for one $v'$ level will not be the same for other $v'$ levels because of the differences radiated lifetime of each excited state (Figure 2.1) [Lopez-Moreno, et al., 1987].

Figure 2.1 Altitude Distribution of Volume Emission Rate of Several Broad OH Channels
[From Lopez-Moreno, et al., 1987]

Figure 2.1 shows a graph of the volume emission rate for several wide-band channels of an instrument flown on a sounding rocket through the OH emission layer. The specific OH bands observed by each channel are given in Table 2.1 [Lopez-Moreno, et al., 1987].
Table 2.1 OH transitions observed in each channel

<table>
<thead>
<tr>
<th>Channel</th>
<th>Transition Observed</th>
<th>Fractional Transition (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.55</td>
<td>(2,0)</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>(3,1)</td>
<td>69</td>
</tr>
<tr>
<td></td>
<td>(4,2)</td>
<td>55</td>
</tr>
<tr>
<td></td>
<td>(5,3)</td>
<td>2</td>
</tr>
<tr>
<td>1.63</td>
<td>(3,1)</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>(4,2)</td>
<td>61</td>
</tr>
<tr>
<td></td>
<td>(5,3)</td>
<td>63</td>
</tr>
<tr>
<td></td>
<td>(6,4)</td>
<td>5</td>
</tr>
<tr>
<td>1.7</td>
<td>(4,2)</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>(5,3)</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>(6,4)</td>
<td>46</td>
</tr>
<tr>
<td></td>
<td>(7,5)</td>
<td>2</td>
</tr>
</tbody>
</table>

Although the channels contain several individual OH bands to varying degrees, there is a clear asymmetry in the peak emission altitude profile. The signal received through the 1.55 μm channel is dominated by slightly lower v’ values and it appears to have a lower peak emission rate than the other two channels which are predominantly observing slightly higher v’ value transitions.
Chapter 3. Characteristics of OH

3.1 Quantum Mechanics

The OH molecule contains 8 electrons from oxygen and 1 electron from hydrogen giving it a total of 9 electrons. The oxygen atom is in the $^{3}\text{P}$ state which means that it has angular momentum equal to 1, while the hydrogen atom is in the $^{1}\text{S}$ because it has angular momentum equal to 0. The combination of these two atoms results in a molecule with angular momentum equal to 1.

The electronic orbital angular momentum vector, $\mathbf{L}$, has a component directed along the internuclear axis represented by the vector $\Lambda$. The quantum number $\Lambda$ is associated with the vector $\Lambda$ and is equal to 1 in this case. The magnetic field generated by the non-zero component of the electronic orbital angular momentum along the internuclear axis, $\Lambda$, causes the spin vector, $\mathbf{S}$, to precess about the internuclear axis. Although the spin vector is constantly changing as it precesses, there remains a constant component of $\mathbf{S}$ along the direction of the internuclear axis given by $\Sigma$. By adding $\Lambda$ and $\Sigma$ together, the total electronic angular momentum about the internuclear axis, $\Omega$, can be determined (Equation 3.1).

$$\Omega = \Lambda + \Sigma$$

Equation 3.1

Since $\Lambda = \pm 1$ and $S = \pm 1/2$, then $\Omega = 3/2$ or $1/2$. Equation 3.2, then, can describe the total state of the OH molecule when it is in the electronic ground state.

$$\text{OH} \left( X^2\Pi_{3/2} \right)$$

Equation 3.2

This state is a doublet ($\Omega = 3/2$ or $1/2$), so the energy of each rotation level within a vibration energy level is split into two branches depending on whether $\Omega = 3/2$ or $1/2$. 

15
The electronic orbital momentum component vector, $\Lambda$, can be combined with the vector representing the total nuclear angular momentum vector, $N$, to yield the total angular momentum of the molecule without spin, represented by $K$ (Equation 3.3).

$$\hat{K} = \hat{\Lambda} + \hat{N}$$

$$K = |\Lambda + N|$$  

Equation 3.3

Because both $\Lambda$ and $N$ are integer quantum numbers, $K$ must also be an integer ($K = 1, 2, \ldots$). The $K$ vector can be combined with the $S$ vector to give the total angular momentum of the molecule, $J$ (Equation 3.4).

$$\hat{J} = \hat{K} + \hat{S}$$

$$J = |K + S|$$  

Equation 3.4

Because the $K$ values are integer and the $S$ values are half integer, the total angular momentum quantum number will be half integer values ($J = K \pm \frac{1}{2}$).

The energy of formation (Equation 2.1) limits the OH vibrational quantum number, $v$, to be less than or equal to 9. The value for $v$ must be an integer, so $v = 0, 1, 2, 3, \ldots, 9$. The vibration of the molecule can change from any initial upper vibrational level, $v'$, to any lower vibrational level, $v''$. The change in $v$ ($\Delta v$) can then be any value from 1 to $v'$ (Equation 3.5).

$$\Delta v = 1, 2, \ldots, v'$$  

Equation 3.5

The vibrationally excited OH molecule will emit a photon as it drops from one vibrational energy level to another. The energy of the emitted photon will be related to the $\gamma v$ of the drop, but it is also dependant on any change in $K$, the total angular momentum without spin. $\Delta K$ changes by integer values ($\Delta K = 0, \pm 1$), which affect the emitted photon by changing its energy. A branch consists of a selection of rotation lines within the emission spectrum that are grouped together and labeled according to the $\Delta K$ value to which they belong. The rotation lines that have $\Delta K = +1$ are grouped into the R-Branch, the rotation lines that have $\Delta K = 0$ are grouped into the Q-Branch, and the lines that have $\Delta K = -1$ are grouped into the P-Branch. In addition to this three-way split, the total electronic angular momentum, $\Omega$, bifurcates the spectral lines again, so that each branch has two sets of rotational emission lines, $Q_1, R_1, P_1$ corresponding to $\Omega = 3/2$, and $Q_2, R_2, P_2$ corresponding to $\Omega = \frac{1}{2}$. 
Figure 3.1 Illustration of the OH Spectrum

Figure 3.1 is included as an illustration of the divisions in the OH emission spectrum. The molecules are dropping from nuclear vibration level $v' = 3$ to $v'' = 1$, so $\Delta v = 2$. In addition to that vibrational energy drop there is a three-way split in the spectrum due to the possible changes in the rotation of the molecule ($\Delta K = 0, \pm 1$), which causes the R, Q, and P-Branches to separate. Each branch is split into set 1 and 2 based on the total spin ($S = \pm \frac{1}{2}$), which is used to calculate the total electronic angular momentum, $\Omega$. Set 1 belongs to molecules which have $\Omega = 3/2$, and set 2 belongs to molecules which have $\Omega = 1/2$. The Q-Branch emission lines are too compact for identification in Figure 3.1, but they follow the same pattern as the R and P-Branches.

In Figure 3.1, the number in parenthesis in each label is the $K''$ for that line. Since the P-Branch is composed of $\Delta K = -1$ and the values for $K$ begin at 1, the lowest $K''$ for the P-Branch is $K'' = 2$. This is the reason that the P-Branch starts with $K'' = 2$ while the R and Q-Branches begin with $K'' = 1$ [Baker, 1978].
3.2 Synthetic Spectrum of OH

Several computer programs were obtained which generate synthetic spectrum plots for several of the OH transitions of interest in this project. The programs were originally written in IDL and were re-written into Matlab for use in this project. The platform change was performed so that the code could be more easily customized for the specific needs of this project. Each program imports a data file containing wavelength, magnetic moment, change in rotational energy, and Einstein coefficient data for each energy transition and generates a plot of normalized signal vs. wavelength. The rotational energies were calculated using [Mies, 1974] and the Einstein coefficients were obtained from [Coxon, et al, 1982]. The plots generated by the programs are shown in Figure 3.2, Figure 3.3, Figure 3.4, Figure 3.5, and Figure 3.6. These synthetic spectrum plots will be used in section 4.3 of the current paper.

Figure 3.2 Synthetic Spectrum of OH (8,3)
Figure 3.3 Synthetic Spectrum of OH (6,2)

Figure 3.4 Synthetic Spectrum of OH (4,2)
Figure 3.5 Synthetic Spectrum of OH (3,1)

Figure 3.6 Synthetic Spectrum of OH (2,0)
3.3 **Theoretical Emission Rates of Excited OH**

The predicted emission rates of the various OH vibrational transitions are shown in Figure 3.7 [Chamberlain, 1959]. The emission values given in the graph assume a total OH brightness (all bands) of 4.5 MegaRayleighs. The total brightness varies from 3 to 5 MR depending on many factors in the atmosphere, but 4.5 MR is a reasonable approximation.

![Figure 3.7 Predicted Emission Rates of OH](image)

Figure 3.7 Predicted Emission Rates of OH [From Chamberlain, 1959]
Each point on the graph represents an OH emission band within the identified sequence. The location of the point on the graph shows the wavelength region of emission and the predicted brightness of the emission band. Previous rocket flights have mainly observed the first overtone sequence ($\Delta v = 2$) because the emissions are located mostly to the short wavelength side of the thermal emission boundary of $\sim 2 \mu m$ and have high brightness values. The observation of emissions beyond the thermal emission boundary is not trivial because the rapid increase in blackbody radiation from the instrument and the lower atmosphere becomes a serious concern.
Chapter 4. Selection of Viable OH Transitions

This project calls for transitions that have isolated emission lines and relatively small background noise. A wide range of excited OH vibrational levels would allow for the most accurate and detailed analysis of the altitude distribution of the emissions. The selection process is performed mainly based on emitted brightness and contamination levels and the need to maximize the number and range of different energy levels that are sampled.

4.1 SPRL CCD Spectrometer Data

4.1.1 OH Emission Spectrum from 0.7 to 0.9 μm

The Space Physics Research Lab (SPRL) at Embry – Riddle Aeronautical University has abundant OH spectrum data taken from several ground-based instruments around the world. One instrument is a CCD spectrometer located at Sondrestromfjord, Greenland that operates at wavelengths from 0.7 to 0.9 μm (Figure 4.1). This region of the NIR spectrum contains six separate OH vibrational transitions with only minor contamination from other airglow sources. The transitions are listed along with their approximate central wavelength in Table 4.1.

<table>
<thead>
<tr>
<th>Transition</th>
<th>Approx. Wavelength</th>
</tr>
</thead>
<tbody>
<tr>
<td>OH (8,3)</td>
<td>0.73 μm</td>
</tr>
<tr>
<td>OH (4,0)</td>
<td>0.755 μm</td>
</tr>
<tr>
<td>OH (9,4)</td>
<td>0.78 μm</td>
</tr>
<tr>
<td>OH (5,1)</td>
<td>0.795 μm</td>
</tr>
<tr>
<td>OH (6,2)</td>
<td>0.84 μm</td>
</tr>
<tr>
<td>OH (7,3)</td>
<td>0.89 μm</td>
</tr>
</tbody>
</table>
The OH excitation levels represented in this table range from \( v' = 4 \) to \( v' = 9 \), forming a satisfactory representation of the various excited vibration states OH. Figure 4.1 shows the identified spectrum as measured from the CCD spectrometer at Sondrestromfjord.

![Figure 4.1 CCD Band OH Spectrum (0.7 - 0.9 \( \mu \text{m} \))](image)

The brightness of the signal in this region of the spectrum is not exceptional, but there are many important \( v' \) states in this region. A preliminary evaluation of each transition in this region will reveal which transitions might be used for this project.
4.1.2 Individual OH Emission Bands

The OH (8,3) transition emission is weak, but it has no major unidentified background emissions, and is a good candidate for further analysis (Figure 4.2). Although this transition is a popular choice for observation from the ground, it must be determined whether there is sufficient brightness from this transition for measurement from onboard a rocket where sampling time is greatly limited.

![Figure 4.2 OH (8,3) Individual Spectrum](image)
The OH (4,0) transition emission is very weak compared to the background noise (Figure 4.3). In addition, there is an O₂ atmospheric absorption feature at around 0.752 and 0.757 μm that lies within the emission range. The combination of these two large obstacles leads to the conclusion that the OH (4,0) transition cannot be used for this project.

Figure 4.3 OH (4,0) Individual Spectrum
The OH (9,4) and OH (5,1) transitions have no signal contamination from other species, but their emission lines overlap (Figure 4.4). This cross-contamination makes the emissions of these two transitions very difficult for use in this project, which requires individual transition emission measurements. The OH (9,4) and OH (5,1) emissions are too overlapped and will provide compromised signal measurements. Another \( v' = 9 \) transition must be found to complete the higher line vibrational level emission survey.

Figure 4.4 OH (9,4) and OH (5,1) Combined Spectrum
The OH (6,2) transition has acceptable signal strength and is isolated from all surrounding major emission spectra (Figure 4.5). The OH (6,2) transition is an excellent candidate for further analysis.

Figure 4.5 OH (6,2) Individual Spectrum
The OH (7,3) transition has acceptable signal strength and is isolated from all surrounding major emission spectra (Figure 4.6). The OH (7,3) transition is an excellent candidate for further analysis.

Figure 4.6 OH (7,3) Individual Spectrum

Analysis of the emission spectrum for the individual OH vibrational transitions in this region of the spectrum has shown that the OH (8,3), (6,2), and (7,3) transitions are the primary candidates for observation for this project.
4.2 SPRL Michelson Interferometer Data

4.2.1 OH Emission Spectrum from 1.1 to 1.65 μm

In addition to CCD spectrometer data, SPRL has large amounts of Michelson interferometer (MI) data taken from several locations around the globe. The interferometer data used has a range from 1.1 to 1.67 μm is also located in Sondrestromfjord, Greenland. Although simultaneous measurements of each section of the OH emission spectrum would be ideal, those measurements were not available. Instead, an informal survey of the available data from both the CCD spectrometer and the MI was conducted to find an “average” spectrum for each instrument. The location of the data collection was kept at Sondrestromfjord because this location appeared to yield the most accurate and consistent data. One example of a MI spectrum is given in Figure 4.7.

Figure 4.7 MI Band OH Spectrum (1.1 - 1.7 μm)
The NIR spectrum from 1.1 to 1.67 \( \mu \text{m} \) contains multiple OH vibrational transition states. These transition states are listed in Table 4.2.

<table>
<thead>
<tr>
<th>Transition</th>
<th>Approx. Wavelength</th>
</tr>
</thead>
<tbody>
<tr>
<td>OH (6,3)</td>
<td>1.16 ( \mu \text{m} )</td>
</tr>
<tr>
<td>OH (7,4)</td>
<td>1.22 ( \mu \text{m} )</td>
</tr>
<tr>
<td>OH (8,5)</td>
<td>1.29 ( \mu \text{m} )</td>
</tr>
<tr>
<td>OH (9,6)</td>
<td>1.38 ( \mu \text{m} )</td>
</tr>
<tr>
<td>OH (2,0)</td>
<td>1.44 ( \mu \text{m} )</td>
</tr>
<tr>
<td>OH (3,1)</td>
<td>1.52 ( \mu \text{m} )</td>
</tr>
<tr>
<td>OH (4,2)</td>
<td>1.6 ( \mu \text{m} )</td>
</tr>
</tbody>
</table>

There are several transition states in this region that belong to the higher vibrational levels as well as a few that come from extremely low vibrational levels – a good cross section. Again, this region of the spectrum contains a multitude of possible transition states to study that would be useful in extending the range and variety of the \( v' \) levels of OH.

This region of the spectrum is more complicated to accurately analyze because of the existence of a water vapor absorption feature at around 1.42 \( \mu \text{m} \) that attenuates the signals from the OH (2,0) and OH (9,6) emission bands. Although this absorption complicates the spectral analysis of ground-based observations, one of the benefits of a rocket flight is that the measurements are taken above the majority of the atmospheric water vapor and so these two emission bands will be much brighter.
Figure 4.8 Atmospheric Transmittance Plot

Figure 4.8 shows the transmission for the average column of atmosphere from ground to space and uses the U.S. Standard model atmosphere as the basis for the calculations [Jursa, 1985]. The 1.4 μm region clearly shows a drop in atmospheric transmission to almost zero.
4.2.2 Individual OH Emission Bands

The OH (3,1) and OH (4,2) transitions are by far the brightest in this wavelength range (Figure 4.9). There is little background signal interference, but the two emission spectra have a slight overlap with each other. Hopefully, careful filter placement can minimize the cross-contamination of these two transitions. Because of the strength of their emissions, the OH (3,1) and OH (4,2) transitions are good candidates for this project provided that careful filter placement can minimize the overlapping signal while still providing accurate brightness data.

![Sondrestromfjord MI Spectrum OH (3,1) and OH (4,2)](image)

Figure 4.9 OH (3,1) and OH (4,2) Combined Spectrum

Since the atmospheric water vapor absorption has reduced the ground-based signal measurements of the OH (2,0) and OH (9,6) emission bands to almost nothing, it will be difficult to estimate the radiated brightness of each. A different approach is required since the available ground-based data cannot be used to approximate signal levels. The method for estimating the brightness of the two bands in this region is presented in section 4.2.3 of the current paper.
The remaining transition emissions are not bright enough to be easily observed as individual vibrational bands at these wavelengths. OH (8,5) and OH (7,4) could possibly be useable should the need arise, but the OH (8,3) and OH (7,3) transitions are much better candidates to represent those v' values.

4.2.3 OH (2,0) and OH (9,6) Brightness Estimation

Due to the absorption features of atmospheric water vapor, the ground-based data available on the OH (2,0) and OH (9,6) emission band brightness is not an accurate representation of the signal levels that will be measured with a rocket-borne instrument.

Ground-based data measured using a Michelson interferometer located near the South Pole was obtained from SPRL to illustrate the water absorption of the 1.42 μm region. Since the atmosphere above Antarctica is colder than the atmosphere above Greenland, there is less water vapor contained in the Antarctic atmosphere so the absorption is slightly less severe. Figure 4.10 shows the relative brightness of the spectrum detected at Sondestromfjord, Greenland, while Figure 4.11 shows the relative brightness of the same region of the spectrum detected at a scientific research post near the South Pole. The two plots have been normalized to correct for large-scale emission intensity variations detected between the two locations. While the relative brightness at wavelengths longer than 1.5 μm appears to be identical between the two plots, the relative brightness differs noticeably between the two plots at wavelengths shorter than 1.5 μm. The data from the South Pole site contains noticeably stronger signals in the water absorption region of the spectrum.
Figure 4.10 Sondestromfjord Spectrum

Figure 4.11 South Pole Spectrum
Figure 4.12 was created by plotting both the Sondestromfjord data and the South Pole data on the same wavelength axis and magnifying the 1.4 to 1.5 μm area of interest. The Sondestromfjord signal line is shown in bold and is noticeably lower than the South Pole observation signal especially towards the shorter wavelengths.

![Water Vapor Absorption Illustration Close-up](image)

Figure 4.12 Water Vapor Absorption Close-up
Although these figures illustrate the water vapor absorption, they do not present a solution to the problem of determining the brightness of the OH (2,0) and OH (9,6) emission bands when observed with a rocket-borne instrument. Figure 4.13 is a close-up of the predicted emission rate graph (Figure 3.7) presented earlier in section 3.3. The OH emission bands are represented by circles, which are connected with lines identifying the various sequences. The predicted brightness of each emission band can be determined by circle’s position on the y-axis.

![Figure 4.13 Close-up of Predicted Emission Rate Figure](image)

The predicted brightness for OH (3,1), (2,0), and (9,6) are shown on the graph as 70 kR, 40 kR, and 13 kR, respectively. According to these numbers, the brightness of the OH (2,0) emission band is 57% of the brightness of the OH (3,1) emission band; likewise, the brightness of the OH (9,6) band is 19% of the brightness of the OH (3,1)
These percentages allow an estimation of the brightness of the OH (2,0) and OH (9,6) emission bands based on the brightness of the OH (3,1) band.

Using the graph of OH (3,1) emission brightness that has already been presented in the form of Figure 4.9, a simple integration of the brightness signal over the appropriate wavelengths will provide an acceptable estimate of the total brightness of the OH (3,1) band (Figure 3.5).

![Integration of Brightness for OH (3,1)](image)

**Figure 4.14 Integration of OH (3,1) Spectrum**

The integration of the outlined section of Figure 4.14 gives a brightness of 64.2 kR as an estimation for the measured brightness of the OH (3,1) emission. Using the ratios determined from Figure 4.13, the OH (2,0) transition should have a brightness of about 36.6 kR, and the OH (9,6) transition should have a brightness of about 12.2 kR. These numbers are estimates, but are sufficiently accurate to estimate instrument performance for this feasibility study.
4.3 Data Correlation with Synthetic Spectrum plots

The synthetic spectrum generated by the Matlab programs was superimposed onto the data signals from the SPRL lab to verify their accuracy and reliability as instrument design tools. The synthetic spectrum plots had to be multiplied by an arbitrary conversion factor to scale them to the SPRL data, so the individual emission line brightness correlation is artificial. The overall brightness distribution and location of the emission lines is very similar between the synthetic spectrum and the SPRL data. This correlation allows for an acceptable level of confidence in the validity and accuracy of the SPRL data so that it can be used to drive the design of an instrument.

There were only two OH transitions available in a synthetic spectrum that fell within the wavelength range of the CCD spectrometer to verify its measured spectrum (Figure 4.15 and Figure 4.16). However, the degree to which the OH (8,3) and OH (6,2) measured emission spectra corresponds to their synthetic spectra implies a general trend of accuracy across the wavelength range of the CCD spectrometer. Based on this implication, it is assumed that since the OH (8,3) and OH (6,2) measured spectra correspond well to their synthetically generated spectra the measured spectra for OH (4,0), OH (9,4), OH (5,1), and OH (7,3) would also correspond to their synthetically generated spectra if it were available.
Figure 4.15 Correlation of OH (8,3) Data to the Synthetic Spectrum

Figure 4.16 Correlation of OH (6,2) Data to the Synthetic Spectrum
As with the CCD spectrometer, the Michelson interferometer measured spectrum was compared with the two synthetic spectra. The major concern in the analysis of these plots is that the emission peaks are present in the correct proportions and to ensure the absence of major unidentified background emission signals.

Upon inspection of Figure 4.17 and Figure 4.18 it is apparent that the R-Branch emissions of OH (4,2) and the extreme upper rotation emissions of the P-Branches of OH (3,1) overlap. It appears that the overlap is minor enough to be dealt with using proper filter placement and design.
Figure 4.17 Correlation of OH (4,2) Data to the Synthetic Spectrum

Figure 4.18 Correlation of OH (3,1) Data to the Synthetic Spectrum
Although the majority of the signal of the OH (2,0) spectrum has been attenuated by the atmosphere, there are remnants that are still visible which correlate with the generated synthetic spectrum for the transition (Figure 4.19).

Figure 4.19 Correlation of OH (2,0) Data to the Synthetic Spectrum
Chapter 5. Instrument Design Constraints

5.1 Detector Characteristics

The wavelength region in which this instrument will operate lies within a detector transition region of the NIR spectrum. Photomultiplier tubes (PMT's) are capable of counting individual photons, which is useful for low signal levels. There is a trade-off, however, because the PMT quantum efficiency is very low in this region and a better signal may possibly be obtained using a Solid state detector (SSD) with a higher sensitivity. PMT's operate effectively only to about 0.9 μm before the low detector quantum efficiency becomes prohibitive. SSD's can cover the entire spectrum of interest with good quantum efficiency, but may have problems with noise as the signal levels may be low.

5.2 Vehicle Characteristics

The instrument is designed to fly on a sounding rocket. In particular, the Terrier-Orion rocket is representative of the class of vehicle that was kept in mind during the design of this instrument as it is low cost and often flown, which increases the possibility of piggy-back flight.
5.3 Altitude Resolution

Radar Telemetry data from a previous Terrier-Orion rocket flight conducted by Dr. Erdman and the Atmospheric Physics Research Lab at Embry-Riddle was obtained to learn the general characteristics of this vehicle (Figure 5.1).

![Terrier-Orion Velocity Graph](image)

Figure 5.1 Terrier-Orion Rocket Velocity Graph

In order for this instrument to yield conclusive results, the altitude resolution of the data should be as high as possible to accentuate the differences in the peak emission locations of the various \( v' \) values. Altitude resolution is based on velocity and instrument sample rate, and judging from Figure 5.1, the rocket was traveling about 1 km/s at 80km altitude. Thus to achieve 500m altitude resolution, the data would need to be sampled every 0.5 seconds. The limiting factor on reducing the sampling time and achieving greater altitude resolution is the statistical error.
For any set of random, uncorrelated events such as photon counts in a PMT, as smaller sampling times are taken (thus reducing the number of counts detected), the statistical error or "shot noise" increases according to the following equation.

\[
\sigma = \frac{1}{\sqrt{n}}
\]

Equation 5.1

where \( n \) is the number of counts within the sampling time. Table 5.1 shows the statistical error for various sampling times. A PMT signal of 10,000 photons per second and a rocket velocity of 1 km/sec are assumed for this example.

<table>
<thead>
<tr>
<th>delta T (s)</th>
<th>counts/interval</th>
<th>sigma (%)</th>
<th>altitude resolution (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10000</td>
<td>1.00</td>
<td>1000</td>
</tr>
<tr>
<td>0.8</td>
<td>8000</td>
<td>1.12</td>
<td>800</td>
</tr>
<tr>
<td>0.6</td>
<td>6000</td>
<td>1.29</td>
<td>600</td>
</tr>
<tr>
<td>0.5</td>
<td>5000</td>
<td>1.41</td>
<td>500</td>
</tr>
<tr>
<td>0.4</td>
<td>4000</td>
<td>1.58</td>
<td>400</td>
</tr>
<tr>
<td>0.3</td>
<td>3000</td>
<td>1.83</td>
<td>300</td>
</tr>
<tr>
<td>0.2</td>
<td>2000</td>
<td>2.24</td>
<td>200</td>
</tr>
<tr>
<td>0.1</td>
<td>1000</td>
<td>3.16</td>
<td>100</td>
</tr>
</tbody>
</table>

The statistical error for this signal level is acceptable down to a time step of about 0.25 seconds corresponding to an ideal altitude resolution of 250 m. However, if the instrument is observing in the ram direction of the rocket, the detected signal will decrease as the rocket flies through the radiating layer. Figure 5.2 plots atmospheric brightness data from a 1.53 \( \mu m \) instrument flown on a previous mission by the Atmospheric Physics Research Lab at Embry-Riddle Aeronautical University. The brightness falls off linearly with respect to altitude across the 10 km emission range, so the signal at the top will have a greater statistical error than the signal at the bottom.
One solution to this problem is to record samples very quickly throughout the rocket flight, then during the data analysis, variably combine individual samples to make the sampling time and counts fluctuate to maintain an acceptable statistical error while maximizing the altitude resolution of the data. A sampling time of 20 ms (50 Hz) is a reasonable sampling rate based on previous experience, which is limited by the electronics of the instrument. The samples can then be dynamically combined after the rocket flight to ensure the total counts per interval yields the largest acceptable statistical error and thus the smallest altitude resolution.

Figure 5.2 Brightness Data from Previous Rocket Flight
Fortunately, as it is the peak emission altitude that is being investigated, the most critical measurements of the flight will be where the brightness for each particular emission band is the highest, thus yielding the highest altitude resolution. Once the peak transmission altitude is passed and the brightness begins to diminish, the most useful data will already have been gathered.
Chapter 6. Instrument Design

Due to the variety and variability available in each component of the instrument to be designed in this project, several iterations of the instrument were considered in order to explore all the possibilities for the instrument. Since many of the components for this instrument have a level of customizability, it was necessary to make preliminary designs for several variations and evaluate them in order to ensure the best possible instrument would result.

6.1 Filter Design

The initial design called for a band pass filter with an 80% or more peak transmission and a relatively steep drop-off on either side of the desired pass-band. These characteristics describe modern interference filters almost exactly, so interference filters were chosen for this project. By studying generic filter transmission curves for several interference filter manufacturers, a generic equation was developed that yielded a customizable filter transmission curve for use in this project. A single cavity interference filter transmission curve is basically Gaussian in shape and multiple cavities are often combined for a more flat-peaked filter shape. With this in mind, several combinations of Gaussian curves were multiplied together in the attempt to create a customizable equation that would model the transmission of a commercially available filter to a reasonable approximation. In the end, Equation 6.1.1 was used as the model.

\[
T = T_{\text{max}} e^{-\frac{(\lambda - \phi)^4}{2\sigma^2}}
\]

Equation 6.1.1

where \( T \) is the transmission of the filter and \( \lambda \) is the wavelength. \( T_{\text{max}} \) is the maximum transmission of the filter and \( \phi \) is the center wavelength of the filter. The \( \sigma \) variable
does not represent the FWHM directly but is related to it with some unknown scale factor; as $\sigma$ is increased, the FWHM of the curve produced also increases.

Using this equation, filter curves were designed for each OH vibrational transition that had the potential to be used for this project. A conservative value of 80% was used for $T_{\text{max}}$. Using the filter curve for each transition, a reasonable estimate of transmitted brightness for each transition can be calculated by multiplying the filter curve and the spectrum graph together and then integrating the result.

### 6.1.1 Filter Curve Design Using Experimental Data

The filter designed for the OH (8,3) transition is centered at 0.731 $\mu$m with a 0.022 $\mu$m FWHM (Figure 6.1). This transition does not have major unidentified background emission signals close by, so the filter is designed to simply maximize the signal received. The filter curve multiplied through the signal graph yields a brightness of 529 Rayleighs.

![Figure 6.1 Filter Curve and Transmitted Signal for OH (8,3)](image-url)
The filter designed for the OH (6,2) transition is centered at 0.839 μm with a 0.030 μm FWHM (Figure 6.2). This transition does not have major unidentified background emission signals close by, so the filter is designed to simply maximize the signal received. The filter curve multiplied through the signal graph yields a brightness of 1664 Rayleighs.

Figure 6.2 Filter Curve and Transmitted Signal for OH (6,2)
The filter designed for the OH (7,3) transition is centered at 0.891 \( \mu \text{m} \) with a 0.038 \( \mu \text{m} \) FWHM (Figure 6.3). This transition does not have major unidentified background emission signals close by, so the filter is designed to simply maximize the signal received. The filter curve multiplied through the signal graph yields a brightness of 3112 Rayleighs.

![Figure 6.3 Filter Curve and Transmitted Signal for OH (7,3)](image_url)
The filter designed for the OH (9,4) transition was centered at 0.778 \( \mu \text{m} \) with a 0.029 \( \mu \text{m} \) FWHM (Figure 6.4). The filter is designed to minimize contamination with the overlapping OH (5,1) transition emission while still maximizing the transmitted signal. The filter curve multiplied through the signal graph yields a brightness of 878 Rayleighs.

![Figure 6.4 Filter Curve and Transmitted Signal for OH (9,4)](image-url)

**Figure 6.4 Filter Curve and Transmitted Signal for OH (9,4)**
The filter designed for the OH (5,1) transition is centered at $0.798 \, \mu m$ with a $0.023 \, \mu m$ FWHM (Figure 6.5). The filter is designed to minimize contamination with the overlapping OH (9,4) transition emission while still maximizing the transmitted signal. The filter curve multiplied through the signal graph yields a brightness of 813 Rayleighs.

Figure 6.5 Filter Curve and Transmitted Signal for OH (5,1)
The filter designed for the OH (4,2) transition was centered at 1.602 \( \mu m \) with a 0.073 \( \mu m \) FWHM (Figure 6.6). The filter is designed to minimize contamination with the overlapping OH (3,1) transition emission. The filter curve multiplied through the signal graph yields a brightness of 64.7 kiloRayleighs.

Figure 6.6 Filter Curve and Transmitted Signal for OH (4,2)
The filter designed for the OH (3,1) transition was centered at 1.519 \( \mu \text{m} \) with a 0.069 \( \mu \text{m} \) FWHM (Figure 6.7). The filter is designed to minimize contamination with the overlapping OH (4,2) transition emission. The filter curve multiplied through the signal graph yields a brightness of 53.8 kiloRayleighs.

![Figure 6.7 Filter Curve and Transmitted Signal for OH (3,1)](image_url)

Figure 6.7 Filter Curve and Transmitted Signal for OH (3,1)
6.1.2 Filter Design for OH (2,0) and OH (9,6)

The lack of ground-based experimental data on the brightness of the OH (2,0) and OH (9,6) means that alternative methods of determining the brightness must be used. It was determined in section 4.2.3 that the OH (2,0) and the OH (9,6) bands have 57% and 19%, respectively, of the brightness of the OH (3,1) band. In section 4.2.3 the total brightness of the OH (3,1), (2,0), and (9,6) bands were estimated as 64.2 kR, 36.6 kR, and 12.2 kR, respectively. These values will be used to calculate the transmitted brightness through a filter.

The optimal design and placement of the OH (2,0) and OH (9,6) filters is made less trivial than for previously discussed transition bands by the lack of signal data available to analyze the emission structure and exact location. Figure 6.8 shows the identified spectrum for OH (2,0) and its overlap of the OH (3,1) and OH (9,6) spectrum.

![South Pole Signal for OH (2,0) and OH (9,6)](image)

Figure 6.8 Identified Spectrum for OH (2,0)

The emissions from the OH (2,0) R-Branches are completely overlapped by the emissions from the OH (9,6) P-Branches. The OH (2,0) P-Branches overlap slightly with the OH (3,1) R-Branches. The OH (2,0) spectrum is a marginal candidate for this project.
because of the overlapping and the added obstacle of the atmospheric absorption reducing the available research data.

The filter for the OH (2,0) will not include the R-Branches and will cut off the long wavelengths of the P-Branches to minimize the contamination of the signal from the neighboring OH emissions. Because the available data is not indicative of the actual strength of each spectral line at higher altitudes, the filter for OH (2,0) is designed using the synthetic spectrum plot (Figure 6.9).

![Synthetic Spectrum of OH (2,0)](image)

\[ \lambda_{\text{center}} = 1.447 \, \mu m \]
\[ \text{FWHM} = 0.042 \, \mu m \]

![Transmission Signal for (2,0)](image)

Transmission = 49.6% of Total Brightness

**Figure 6.9 Filter Curve and Transmitted Signal for OH (2,0)**

The filter designed for OH (2,0) is centered at 1.447 \( \mu m \) and has a FWHM of 0.042 \( \mu m \). The filter is designed to minimize signal contamination from the OH (9,6) and OH (3,1) emissions. Since there is no measured data available to estimate the brightness of the emission, the transmitted brightness through the filter cannot be determined. Integrating the original synthetic spectrum plot and integrating the transmission plot can determine a brightness ratio. The filter for the OH (2,0) transition passes 49.6% of the total signal predicted by the synthetic spectrum. Using the 36.6 kR estimated brightness for the total OH (2,0) transition, the transmitted brightness is approximated as 18.2 kR.
The OH (9,6) spectrum is too overlapped to be used in this project because any filter designed to isolate the OH (9,6) spectrum from the surrounding emissions would have to exclude the majority of the OH (9,6) emissions to do so, and yield a transmitted brightness that is to faint for this project.

6.2 Optics Setup

The f/# is one of the main factors driving the size of the instrument. To boost signal levels, lower f/#'s are used but these call for wide instruments that would crowd already cramped payload areas. Low f/#'s also increase the effect of spherical aberration and degrade interference filter performance because of the increased incidence angles of the incoming light. A tradeoff is needed: an f/# low enough to provide adequate signal, yet high enough to remain a physical possibility for the system. The design of this detector began with f/10 as a reasonable starting point.

The most critical part of the optics setup is getting a reasonable aperture area focused down as small as possible. The larger aperture lets more light through to the detector, but the noise on SSD’s is proportional to the detector area. Thus a large aperture focused down onto a tiny detector would be ideal, however spherical aberration and lens material limits the design.

A table-driven ray trace program called Beam 4® was used to test a variety of different lens designs in an f/10 system. The goal was to find the lens that would focus a 1 cm² aperture down as small as possible while taking into account all the possible ray angles for the system. Several biconvex and planoconvex lenses listed in the Melles Griot® optics catalogue were tested with the ray trace program. Biconvex lenses tended to have shorter focal lengths, which lead to a more compact instrument design, but planoconvex lenses were not as affected by spherical aberration and so yielded a smaller focus point.

The system was modeled using BK7 glass because of its availability and low cost. Index of refraction information was obtained from the Melles Griot optics catalogue for BK7 glass for each wavelength region to be observed. The focal length of the lens
changes for different wavelengths of light due to the wavelength dependence of the index of refraction. A flat 5mm thick glass disk was used to represent the interference filter and a flat 0.5 mm thick glass disk was used to represent the detector window for the optical testing (Figure 6.10). Since, as a general rule, no more than about 80% of the lens diameter should be used, the lenses tested were all above 1.4 cm in diameter.

Figure 6.10 General Optics Setup of Instrument
The position of sharpest focus on the detector comes when the detector is slightly farther away from the lens than the focal point (Figure 6.11). This position minimizes the spread of the extreme angle rays that come through the system and thus minimizes the focus area of the light.

![Figure 6.11 Location of Minimum Focus Area](image)

Table 6.1 gives the index of refraction of BK7 glass at each wavelength region and the subsequent detector positions that reflect the slightly different focal lengths. Although the index of refraction changes slightly for each transition band location, the actual placement of the detector plane does not change by much.

<table>
<thead>
<tr>
<th>OH Transition</th>
<th>8.3</th>
<th>9.4</th>
<th>5.1</th>
<th>6.2</th>
<th>7.3</th>
<th>2.0</th>
<th>3.1</th>
<th>4.2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Center Wavelength</strong></td>
<td>0.731</td>
<td>0.778</td>
<td>0.798</td>
<td>0.839</td>
<td>0.891</td>
<td>1.43</td>
<td>1.520</td>
<td>1.602</td>
</tr>
<tr>
<td><strong>Index of R. for Lens</strong></td>
<td>1.512</td>
<td>1.511</td>
<td>1.511</td>
<td>1.510</td>
<td>1.509</td>
<td>1.502</td>
<td>1.501</td>
<td>1.500</td>
</tr>
<tr>
<td><strong>Lens to Detector Distance</strong></td>
<td>2.35</td>
<td>2.36</td>
<td>2.36</td>
<td>2.36</td>
<td>2.37</td>
<td>2.40</td>
<td>2.40</td>
<td>2.41</td>
</tr>
</tbody>
</table>
Beam 4® is able to generate random rays and pass them through the optical system to explore every possible path that light can take to the detector. By using this feature and plotting the rays as they intersect the plane of the detector, the focus area can be experimentally determined (Figure 6.12). Both types of lenses have small enough focal lengths for this project, but the planoconvex lenses tested performed slightly better than the biconvex lenses at minimizing focus area. The lens that performed the best was a 1.5 cm diameter planoconvex lens with focal length of 1.5 cm at 1 um. The focus area from this lens is a circle about 3 mm in diameter.

![Randomly Generated Rays at the Plane of the Detector](image)

Since SSD noise is proportional to detector area, another test was performed to determine what percentage of the signal would be lost if a 2 mm diameter detector were used instead of a 3 mm. The outer ring of the focus area may contain a relatively smaller proportion of rays; the rays might mostly be focused to the center of the focus area. If this were the case, then a smaller detector would not miss much signal and might wind up with a better signal to noise ratio (SNR) than a larger one.

When the random ray generation test was conducted with a 3 mm diameter detector, 99.7% of the rays that made it through the aperture hit the detector surface. When a 2 mm diameter detector was used, only 43% of the rays that made it through the aperture hit the detector. This ratio scales with detector area and is an unacceptable
signal loss. A detector of at least 3 mm diameter should be used to yield the highest signal and best SNR.

### 6.3 Detector Selection

#### 6.3.1 Detector for 0.75 to 0.9 \( \mu m \) region of OH spectrum

The 0.75 to 0.9 \( \mu m \) region of the OH spectrum can be observed by either PMT’s or SSD’s. Several variations of each detector were compared qualitatively with each other to determine a handful of possible detector designs for this region. Some basic characteristics for each detector are listed in Table 6.2 and Table 6.3.

**Table 6.2 Basic Characteristics of Possible PMT’s**

<table>
<thead>
<tr>
<th>Model</th>
<th>Cathode</th>
<th>Q. E.</th>
<th>Detector Area</th>
<th>Appx. Dimensions</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>R2658P</td>
<td>InGaAs(Cs)</td>
<td>2 - 0.8%</td>
<td>3x12 mm</td>
<td>8 cm x 2.8 cm dia.</td>
<td>PMT</td>
</tr>
<tr>
<td>R316</td>
<td>AgOCs</td>
<td>0.3 - 0.2%</td>
<td>25 mm dia.</td>
<td>11.2 cm x 2.8 cm dia.</td>
<td>PMT</td>
</tr>
<tr>
<td>R3310-02</td>
<td>InGaAs(Cs)</td>
<td>2 - 1%</td>
<td>10x10 mm</td>
<td>8.8 cm x 5.1 cm dia.</td>
<td>PMT</td>
</tr>
<tr>
<td>R943-02</td>
<td>GaAs(Cs)</td>
<td>12 - 1%</td>
<td>10x10 mm</td>
<td>8.8 cm x 5.1 cm dia.</td>
<td>PMT</td>
</tr>
</tbody>
</table>

**Table 6.3 Basic Characteristics of Possible SSD’s**

<table>
<thead>
<tr>
<th>Model</th>
<th>Cathode</th>
<th>Photosensitivity</th>
<th>Detector Area</th>
<th>Appx. Dimensions</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1133-01</td>
<td>Si</td>
<td>0.45 - 0.55 A/W</td>
<td>2.4 x 2.8 mm</td>
<td>8 x 6.1 x 1.5 mm</td>
<td>SSD</td>
</tr>
<tr>
<td>S1337-33BR</td>
<td>Si</td>
<td>0.46 - 0.59 A/W</td>
<td>2.4 x 2.4 mm</td>
<td>6 x 7.6 x 2 mm</td>
<td>SSD</td>
</tr>
<tr>
<td>S1787-08</td>
<td>Si</td>
<td>0.41 - 0.55 A/W</td>
<td>2.4 x 2.8 mm</td>
<td>8 x 6 x 2.2 mm</td>
<td>SSD</td>
</tr>
</tbody>
</table>

The R316 detector simply has too low of a quantum efficiency to work with the low signals expected in this region. The R934-02 detector has a quartz window that may result in the failure of the detector during the rocket flight. This is poor choice for use in an instrument flying onboard a rocket due to the fragility of the quartz-glass boundary.
with thermal stresses and vibration. The R2658P and R3310-02 detectors are adequate possibilities, however, the R3310-02 is a little large physically and the R2658 is a side-on detector, both of which will complicate the physical setup of the total rocket payload. The R2658P and R3310-02 detectors have different packaging and design, but both have InGaAs(Cs) photocathodes, and their spectral responses are practically identical.

Signal calculations with the remaining detector possibilities were performed using the f/10 setup and the transmitted source brightness of the various potential OH emission bands (Table 6.4). This was done to compare performance by both SSD and PMT detector possibilities for this region in order to decide which was the best detector to use.

Table 6.4 Calculated Signals for Possible Detectors

<table>
<thead>
<tr>
<th>OH Transition</th>
<th>Trans. Brightness</th>
<th>Appx. Wavelength</th>
<th>InGaAs (Cs) Q.E.</th>
<th>Si Sensitivity</th>
<th>PMT Signal</th>
<th>SSD Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>8.3</td>
<td>9.4</td>
<td>5.1</td>
<td>6.2</td>
<td>7.3</td>
<td>R</td>
</tr>
<tr>
<td>Trans. Brightness</td>
<td>529</td>
<td>878</td>
<td>813</td>
<td>1664</td>
<td>3112</td>
<td>R</td>
</tr>
<tr>
<td>Appx. Wavelength</td>
<td>0.073</td>
<td>0.78</td>
<td>0.8</td>
<td>0.84</td>
<td>0.89</td>
<td>μm</td>
</tr>
<tr>
<td>InGaAs (Cs) Q.E.</td>
<td>2.2</td>
<td>1.8</td>
<td>1.3</td>
<td>1.1</td>
<td>0.9</td>
<td>%</td>
</tr>
<tr>
<td>Si Sensitivity</td>
<td>0.45</td>
<td>0.47</td>
<td>0.47</td>
<td>0.50</td>
<td>0.54</td>
<td>A/W</td>
</tr>
<tr>
<td>PMT Signal</td>
<td>7,274</td>
<td>9,878</td>
<td>6,606</td>
<td>11,440</td>
<td>17,505</td>
<td>phot/sec/cm²</td>
</tr>
<tr>
<td>SSD Signal</td>
<td>4.05E-14</td>
<td>6.59E-14</td>
<td>5.95E-14</td>
<td>1.23E-13</td>
<td>2.34E-13</td>
<td>amps/cm²</td>
</tr>
</tbody>
</table>

Table 6.4 shows that the PMT’s will detect a signal on the order of 10k photons per second if a 1 cm² aperture is used. This signal is large enough to be used in this project. The photocurrent detected by the photodiodes is only about 0.1 pA for a 1 cm² aperture, which is too small for this project if a system noise of 10⁻¹⁴ A is assumed. Either the R2658P and R3310-02 detectors could be used. Of the two, the R2658P detector was selected for use in this project because of its smaller size and more robust design.
6.3.2 Detector for 1.45 to 1.65 μm region of OH spectrum

SSD’s with InGaAs photocathodes will work the best this region of the spectrum. One new PMT, designated R5509-73, with a InP/InGaAs photocathode was found that could operate out to 1.7 μm with 0.9% quantum efficiency. The relatively new and untried nature of this detector and photocathode made it too much of a risk to use for this project, but it may be considered for future missions.

Several designs of InGaAs SSD’s were compared as possibilities for this project (Table 6.5). The main concern was to have a detector with an area large enough to cover the focus area of the optics design, but at the same time have as low of a dark current as possible.

<table>
<thead>
<tr>
<th>Model</th>
<th>Cathode</th>
<th>Photosensitivity</th>
<th>Detector Area</th>
<th>Appx. Dimensions</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>G8370-03</td>
<td>InGaAs</td>
<td>0.95 A/W</td>
<td>3 mm dia.</td>
<td>4.9 x 9.2 dia.</td>
<td>SSD</td>
</tr>
<tr>
<td>G5851-13</td>
<td>InGaAs</td>
<td>1.07 A/W</td>
<td>3 mm dia.</td>
<td>6.4 x 15.3 mm dia.</td>
<td>SSD</td>
</tr>
<tr>
<td>G8370-10</td>
<td>InGaAs</td>
<td>0.95 A/W</td>
<td>10 mm dia.</td>
<td>16.5 x 15 x 2.2 mm</td>
<td>SSD</td>
</tr>
</tbody>
</table>

Using the focus area of 3 mm diameter as determined by the ray trace program, the large detector area of the G8370-10 is not necessary. The increased area adds noise to the signal, and although the aperture size could be increased to compensate, the G8370-10 is not the best choice if a detector of smaller area will work. The G5851-13 has a built in thermoelectric cooler, which is an attractive feature as it simplifies and miniaturizes the individual instrument design, however since PMT’s will be flown in the same payload, it is simpler for this project to use one refrigeration mechanism for all the detectors at once. The G8370-03 detector has the correct detector area and is the detector selected to observe the bands in the 1.45 to 1.65 μm region of the spectrum. An additional advantage brought about by using a circular, rather than rectangular, detector to measure a circular focus area is that the corners, which are not required and would only contribute noise to the system, are absent. This makes the circular detector a more efficient choice.
Table 6.6 gives the calculated signals for G8370-03 for the two OH bands to be observed.

Table 6.6  Calculated Signals for InGaAs Detectors

<table>
<thead>
<tr>
<th>OH Transition</th>
<th>2.0</th>
<th>3.1</th>
<th>4.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trans. Brightness</td>
<td>18,200</td>
<td>53,800</td>
<td>64,700</td>
</tr>
<tr>
<td>Appx. Wavelength</td>
<td>1.44</td>
<td>1.52</td>
<td>1.602</td>
</tr>
<tr>
<td>InGaAs Sensitivity</td>
<td>0.92</td>
<td>0.95</td>
<td>0.95</td>
</tr>
<tr>
<td>SSD Signal</td>
<td>1.43E-12</td>
<td>4.18E-12</td>
<td>4.77E-12</td>
</tr>
</tbody>
</table>
6.4 Final Instrument Analysis and Design

Now that the optical design has been established and detectors have been selected for each band, the effectiveness of each instrument as a whole can be determined. The signal levels for each band have been calculated but the noise levels experienced by each detector have not yet been taken into consideration. The R2658P detector has an average dark count of 50 counts per second at 25 degrees Celsius. The detector will be cooled on the rocket, but using 50 counts will provide worst-case numbers for the calculated SNR. Equation 6.1 gives the signal, in counts per second, for a pulse-counting PMT.

\[ S = \frac{B_s \cdot \Delta \lambda \cdot \tau_e \cdot A \cdot \Omega \cdot QE \cdot C_e}{E_p \cdot e} \quad \text{Equation 6.1} \]

where:
- \( B_s \) = Source Brightness \( \left[ \frac{\text{Watts}}{\text{cm}^2 \cdot \text{ster} \cdot \mu} \right] \)
- \( \Delta \lambda \) = Filter Bandwidth [\( \mu \)]
- \( \tau_e \) = Transmission efficiency of the optical system
- \( A \) = Area of limiting aperture [cm\(^2\)]
- \( \Omega \) = Solid angle of limiting aperture [ster]
- \( QE \) = Detector Quantum Efficiency
- \( C_e \) = Counting Efficiency
- \( E_p \) = Energy of each photon [eV]
- \( e \) = conversion [Joules / eV]
This signal divided by the dark count gives the signal to noise ratio (SNR) for the system. The calculated SNR’s for the PMT observed bands are listed in Table 6.7. The dark count of 50 counts per second listed in the data sheets assumes the detector is operating at 25° C. Since the detector will be cooled, this dark count will decrease in the actual instrument. The SNR results listed in table could be underestimations, but they at least provide an approximation.

<table>
<thead>
<tr>
<th>OH Transition</th>
<th>Appx. Wavelength</th>
<th>PMT Signal</th>
<th>Dark Count</th>
<th>SNR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>8.3</td>
<td>0.73</td>
<td>7,274</td>
<td>50</td>
</tr>
<tr>
<td>9.4</td>
<td>0.78</td>
<td>9,878</td>
<td>50</td>
<td>198</td>
</tr>
<tr>
<td>5.1</td>
<td>0.8</td>
<td>6,606</td>
<td>50</td>
<td>132</td>
</tr>
<tr>
<td>6.2</td>
<td>0.84</td>
<td>11,440</td>
<td>50</td>
<td>229</td>
</tr>
<tr>
<td>7.3</td>
<td>0.89</td>
<td>17,505</td>
<td>50</td>
<td>350</td>
</tr>
</tbody>
</table>
The G8370-03 SSD has a dark current of 15 nA listed in the data page, however this value assumes the detector is operated at 25° C and with a reverse voltage of 1 volt. To reduce this dark current, the detectors for this project will be flown with almost no reverse voltage and will be cooled, so this number does not accurately describe the noise which the detector will experience. A more accurate estimate of the SNR for the G8370-03 detector can be calculated using Equation 6.2.

$$SNR = \frac{L_s(\lambda) \cdot \Delta \lambda \cdot \tau_\varepsilon \cdot A \cdot \Omega \cdot D'(\lambda)}{\sqrt{A_d \cdot f_\beta}}$$  \hspace{1cm} \text{Equation 6.2}

where:

- $L_s(\lambda)$ = Source Radiance \[ \text{Watts} \, \text{cm}^{-2} \cdot \text{ster} \cdot \mu \]
- $\Delta \lambda$ = Filter Bandwidth \[ \mu \]
- $\tau_\varepsilon$ = Transmission efficiency of the optical system
- $A$ = Area of limiting aperture \[ cm^2 \]
- $\Omega$ = Solid angle of limiting aperture \[ ster \]
- $D'(\lambda)$ = "D-star" = Detectivity \[ cm \cdot \sqrt{Hz/W} \]
- $A_d$ = Detector area \[ cm^2 \]
- $f_\beta$ = Bandwidth \[ Hz \]
The SNR’s for the SSD observed bands are listed in Table 6.8. These SNR’s are an estimate of the best case for the SSD detectors. Based on previous experience, there will be system noise on the order of $10^{14}$ amps from the electronics as well as other factors.

Table 6.8 SSD Signal to Noise Ratio

<table>
<thead>
<tr>
<th>OH Transition</th>
<th>2,0</th>
<th>3,1</th>
<th>4,2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Appx Wavelength</td>
<td>1.44</td>
<td>1.52</td>
<td>1.602</td>
</tr>
<tr>
<td>Trans. Brightness</td>
<td>18,200</td>
<td>53,800</td>
<td>64,700</td>
</tr>
<tr>
<td>SSD Signal</td>
<td>1.44E-12</td>
<td>4.18E-12</td>
<td>4.77E-12</td>
</tr>
<tr>
<td>SNR</td>
<td>384.2</td>
<td>1,111.1</td>
<td>1,267.8</td>
</tr>
</tbody>
</table>

This project is designed to be a collection of stand-alone instruments (Figure 6.13). Each detector will have its own optics and electronics. If budget constraints of size restrictions limit the implementation of this project, individual instruments can be removed without changing the total system. However, this versatility comes at a cost; for each instrument that is removed from the design, one less OH ν’ level is directly observed and the project loses a degree of its uniqueness and novelty.

![Figure 6.13 Basic Instrument Layout](image)

Figure 6.13 Basic Instrument Layout
Chapter 7. Conclusion

An instrument design has been presented which will directly measure the peak OH vibrational emission altitudes for the \( v' = 2, 3, 4, 6, 7, \text{ and } 8 \), providing an excellent survey of the various \( v' \) values radiating from the mesosphere (Table 7.1).

The sample of \( v' \) values examined by this instrument could be more complete if \( v' = 1, 5, \text{ or } 9 \) could be included. Unfortunately, due to the location of the \( v' = 1 \) and the examined \( v' = 9 \) transition emissions, the inclusion of \( v' = 1 \) or 9 would require a major escalation in instrument design. The \( v' = 9 \) upper vibrational level is too overlapped in the regions studied in this project to provide a unique signal of sufficient strength to be measured with a rocket-borne instrument. The only \( v' = 1 \) upper vibrational level transition belongs to the \( \Delta v = 1 \) sequence whose emissions are at wavelengths longer than 2.5 \( \mu \text{m} \). These upper vibrational levels cannot be observed without extensive complications to the instrument design. The absence of \( v' = 5 \) in the survey is not a primary concern as its upper vibrational level does not represent either extreme and its peak emission altitude profile can be extrapolated from the data that will be gathered on the other upper vibrational levels.

The altitude profile information provided by this instrument will enhance the ability to detect and observe atmospheric gravity waves and other large-scale atmospheric disturbances with ground-based observations of the OH emission spectrum. By determining the altitude where the emission peak of each \( v' \) level is located, atmospheric disturbances can be tracked from the ground by observing what altitude region is being affected. This will be accomplished through long-term observations of the emissions from several \( v' \) levels. Once the altitude of peak emission has been determined for each \( v' \) level, simply observing the collective spectrum and noting which \( v' \) level emissions fluctuate will provide an illustration of the disturbance passing through the mesosphere.
Table 7.1 Summary Table of the Instrument Design

<table>
<thead>
<tr>
<th></th>
<th>OH Transition</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>8.3</td>
<td>9.4</td>
<td>5.1</td>
<td>6.2</td>
<td>7.3</td>
<td>2.0</td>
<td>3.1</td>
</tr>
<tr>
<td>Center Wavelength</td>
<td>0.731</td>
<td>0.778</td>
<td>0.798</td>
<td>0.839</td>
<td>0.891</td>
<td>1.43</td>
<td>1.520</td>
</tr>
<tr>
<td>Center Filter Wavelength</td>
<td>0.731</td>
<td>0.778</td>
<td>0.798</td>
<td>0.839</td>
<td>0.891</td>
<td>1.43</td>
<td>1.519</td>
</tr>
<tr>
<td>Filter FWHM</td>
<td>0.022</td>
<td>0.029</td>
<td>0.023</td>
<td>0.03</td>
<td>0.038</td>
<td>0.069</td>
<td>0.069</td>
</tr>
<tr>
<td>Transmitted Brightness</td>
<td>529</td>
<td>878</td>
<td>813</td>
<td>1664</td>
<td>3112</td>
<td>18,200</td>
<td>53,800</td>
</tr>
<tr>
<td>Lens to Detector Distance</td>
<td>2.35</td>
<td>2.36</td>
<td>2.36</td>
<td>2.36</td>
<td>2.37</td>
<td>2.40</td>
<td>2.40</td>
</tr>
<tr>
<td>PMT signal</td>
<td>7,274</td>
<td>9,878</td>
<td>6,606</td>
<td>11,440</td>
<td>17,505</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SSD Current</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.45E-12</td>
<td>4.18E-12</td>
</tr>
<tr>
<td>SNR</td>
<td>145</td>
<td>198</td>
<td>132</td>
<td>229</td>
<td>350</td>
<td>386.9</td>
<td>1111.1</td>
</tr>
</tbody>
</table>

Detector Model: R2658P, R2658P, G8370-02, G8370-03, G8370-04

Note: All values are in micrometers (μm) except for SNR which is in cm²/phot/sec.
Chapter 8. Future Work

There are many individual OH vibration bands (Figure 3.7) and some might be more suited for observation that the ones selected for this project. The transitions selected in this project were based largely on the availability of first-hand data and the lack of background emissions surrounding the OH transition emissions. Although there are other useable transitions in the \( \Delta v = 2 \) or \( \Delta v = 1 \) sequences, the longer wavelengths of the emissions complicates the instrument design. The transitions selected for this project were chosen because they have acceptable brightness and no background contamination, but there may be a few transitions that are even better.

The addition of a \( v' = 1 \) and a \( v' = 9 \) emission to the set already observed would make the investigation much more complete. The OH (1,0) emission is long of the 2 \( \mu m \) thermal emission boundary, so its observation would require a more complicated instrument to minimize the effects of the thermal emission noise. The \( v' = 9 \) upper vibrational level radiates from 9 different transitions spread across the spectrum from about 0.4 to 4.5 \( \mu m \). Only 2 of these transitions were examined in this project and there could be one that can be observed more easily.
Chapter 9. Bibliography and Works Cited

Krassovsky, V.I.; Infrasonic variations of OH emissions in the upper atmosphere.


