REMOTE SENSING OF MESOSPHERIC OZONE

by

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Chairman, Departmental Committee on Graduate Students

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Submitted to the Department of Electrical Engineering on 29 January 1971 in partial fulfillment of the requirements for the Degree of Doctor of Philosophy.

ABSTRACT

The photochemistry of ozone in the upper stratosphere and mesosphere is reviewed. Numerical calculations in the literature predict a change in ozone concentration at 70 km altitude from $10^9$ cm$^{-3}$ during the day to $10^{11}$ cm$^{-3}$ at night. The few ozone measurements in the 50 to 80 km region are not consistent, and no valid measurement of the diurnal variation has been made.

Atmospheric ozone should produce an emission line $8^0$K high with a half-height width of 80 MHz, as viewed from the ground. The line is the $4_0^0-4_1^1$ molecular transition at 101.74 GHz and its intensity and width are due primarily to the stratospheric ozone maximum at 25 km. If the mesospheric ozone concentration increases to $3\times10^{10}$ at 70 km as predicted by Hunt (J.G.R., 71, 5, 1385, 1966), then a line $20^0$K high and 300 kHz wide at half-height should appear on top of the broader line.

A radiometer was designed and built to observe the mesospheric ozone line. It was a double-conversion, Dicke switched receiver with a system temperature between 4,000 and 5,000$^0$K. When connected to the Haystack Observatory spectral line processor, a resolution of 100 kHz in a 4 MHz bandwidth was possible. When connected to the MIT 20 channel digital synchronous detector, the bandwidth was 48 MHz with 1 MHz resolution.

In a subsidiary effort to develop low loss mixers, diodes were packaged with cutoff frequencies exceeding 10,000 GHz. A 60 GHz balanced mixer was built with a 6 dB conversion loss.

Observations were made from August through October, 1970, about three times a week, at various times during the day and night. The broadband emission line from the stratospheric ozone was detected. Its line strength and shape agree with the predicted values. The narrow mesospheric line was never detected.

On the basis of these measurements, an upper limit can be placed on the nighttime mesospheric ozone concentration. The limit, represented by an exponential distribution between a number density of $5\times10^{10}$ cm$^{-3}$ at 50 km and $10^9$ cm$^{-3}$ at 80 km, would have been detected with this instrument.

The diurnal concentrations predicted by the photochemical theory are believed to be in error because the reaction rates are incorrect, dynamic processes are not included, and the water vapor concentration may be slightly higher than calculated.

THESIS SUPERVISOR: David H. Staelin
TITLE: Associate Professor of Electrical Engineering
ACKNOWLEDGEMENTS

Kazał pan, musiaż sam. Polish, Anon.

This thesis could not have been accomplished without the loving help of my wife, Nancy, and the moral support of my four children, John, Jeanne, Thomas, and Michael, who stood by like staunch warriors while their father was lost to the academic world.

I would like to thank my thesis committee, especially Professor D. H. Staelin for supervising the research. Professors A. H. Barrett, R. E. Newell, and D. H. Steinbrecher were most kind to serve as readers.

Many people helped in the experimental portion of this work. Dr. J. W. Waters was most helpful during the course of the investigation. C. Papa and J. Barrett were always ready to help solve the many engineering problems that arose. J. Keefe and his able machinists were remarkable in transforming my ideas into working blocks of copper, and the patience of L. Ryan in drawing the quartz diode sleeves was appreciated.

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1. INTRODUCTION

Ozone is a trace constituent of the atmosphere with concentrations of a few parts per million. It is a strong absorber of ultraviolet radiation, and it is very active chemically. It plays an important part in the earth's radiation budget as it absorbs solar ultraviolet radiation, and absorbs and reradiates the infrared radiation from the earth. A measure of its importance is the fact that it is believed to be responsible for the increase with altitude of the temperature of the stratosphere.

Few ozone concentration measurements have been made above 35 km. Photochemical theories describe some of the gross features of the ozone concentration profile satisfactorily. One key point of the theory is that the concentration of mesospheric ozone should vary diurnally, increasing at night and decreasing during the day. This has never been verified experimentally. A major objective of this thesis is to measure with microwave techniques, the extent to which mesospheric ozone does vary diurnally.

A review of the photochemical theories predicting the diurnal increase of mesospheric ozone and a summary of mesospheric ozone measurements reported in the literature are found in Chapter 2. These theories and the data are compared to show the wide discrepancies between the predicted and observed concentrations of ozone in the mesosphere.

Chapter 3 is devoted to microwave measurement of mesospheric and
stratospheric ozone. The possibility of observing the diurnal variation using a microwave radiometer is discussed after the microwave spectrum of the ozone molecule is computed. The specifications of a radiometer necessary to perform the experiment are then outlined.

The development of the radiometer is described in Chapter 4. Eight versions of the radiometer were built with the final one, Version VIII, meeting the design specifications outlined in Chapter 3. Paralleling the radiometer development was an effort to build a substitute mixer in the event the Caton instrument could not be made sensitive enough. Low loss mixer development is covered and the experimental results at 5 mm are described. Guidance for further improvements in low loss mixers is given.

The radiometer used in the final part of the experiment is described in detail in Chapter 5. The tests made to establish confidence in the radiometer data are also described.

The results obtained from several months of observation are discussed in Chapter 6. The experimental spectra are compared with the predicted spectra. The effects of water vapor on microwave observations at 101 GHz are also covered.

The conclusions reached concerning the diurnal variation of ozone are presented in Chapter 7. The spectra obtained support the measurements of Johnson, et. al., during the daytime, and establish an upper limit to the possible increase in ozone during the night as observed at a latitude of 42 degrees, 30 minutes north. Possible reasons for the discrepancy between our observations and the photochemical theory
predictions are discussed.

Microwave sensing is a relatively new technique for studying the atmosphere. Suggestions for further work are outlined in Chapter 9. The development of a multipurpose system is outlined which, with the new low loss microwave mixers to be available in the next year or so, should improve the effective system temperatures of present radiometers approximately an order of magnitude. Experiments which are possible with the existing instrument and improved instruments are long term studies of the effect of water vapor at 3 mm, more accurate microwave spectroscopy, and ozone profile inversion studies.
2. PHOTOCHEMICAL THEORIES OF THE DIURNAL VARIATION OF OZONE: DEVELOPMENT, PREDICTED VALUES, AND COMPARISON WITH MEASURED DATA.

In the early 1900's observations of stellar spectra, including that of the sun, were cut off sharply in the vicinity of 3000 Å. As this coincided with the absorption bands of ozone measured in the laboratory, the presence of ozone in the atmosphere was suspected. Fabry and Buisson (1913) studied the absorption of the solar spectrum between 3000 and 3340 Å at different zenith angles and showed conclusively that absorption spectra coincided with the absorption bands of ozone.

Dobson (1930) concluded a long and extensive series of absorption measurements of the total amount of ozone in the atmosphere and showed the extent of the seasonal and latitudinal variations of the total amount of ozone above the observation stations. Concurrently, Götz and Dobson (1928) began their attempts to determine the mean height of the ozone. Their tentative conclusion at that time was that the main part of the ozone was to be found at a height of about 50 km. Götz then developed the Ümkehr method of determining the height with much greater precision, and Götz, Meetham, and Dobson (1934) showed that the ozone concentration reached a maximum around 25 to 30 km, with a rapid decrease above it, and a less rapid decrease below it. This finding was then confirmed by balloon flights by Regener and Regener (1934), and by many measurements afterwards.

The first attempt to explain the presence of ozone in the atmosphere was made by Chapman (1930c), using photochemical reactions. In this chapter, the development of the photochemical theory will be traced. The
discussion will begin with the work of Chapman and then trace through the works of Bates and Nicolet, Paetzold, Leovy, Hunt, Maeda, Dütsch, and finally the later work of Leovy. Emphasis will be placed upon the diurnal variation theories, since the ozone concentration up to an altitude of 30 km is measured routinely. It is true that the fine structure of the concentration around the ozone maximum is still not completely accounted for. But, the central thrust of this experiment was to study the diurnal variation, and this will be emphasized.

An attempt will also be made to organize the theory somewhat, for, as Dütsch (1968) points out, "The current system whereby reaction rates are numbered according to their sequence in a paper results in an un-systematic notation for these indices varying from paper to paper, rendering a discussion among workers in the field rather difficult." So the reactions will be organized upon the foundation laid by Dütsch, and hopefully, the table of reactions and rates will tie the theories together and allow intercomparison.

Table 1, Reactions and Rates, is a compilation of all the photo-chemical reactions and rate coefficients pertaining to ozone that are found in the literature. They are organized by the scheme suggested by Dütsch where the reaction rates are grouped by classes of reaction. But the numbering scheme used by Dütsch was found to be inadequate. He proposed identifying the reaction rates by $k_{ij}$, where the $i$ identified the group, the $j$ represented an arbitrary listing within the group. As there are more than nine reactions in some of the groups, a new scheme is proposed, labeling the reaction rates as $K_{i-i}$. The groups are
identified by Roman numerals and the 1 represents an arbitrary listing of reactions within a group. The group organization is:

I  Reactions by which odd oxygen particles \((O_3\) and \(O)\) are transformed into one another. The reaction rates are identified by \(K\) I-i.

II Reactions which produce or destroy odd oxygen particles. The reaction rates are identified by \(K\) II-i.

III Reactions by which odd oxygen particles are destroyed or produced by active hydrogen particles. The reaction rates are identified by \(K\) III-i.

IV Reactions by which active hydrogen particles are created or destroyed. Reaction rates are identified by \(K\) IV-i.

V Reactions by which active hydrogen particles are produced from hydrogen peroxide. The reaction rates are identified by \(K\) V-i.

VI Reactions by which odd oxygen particles are produced or destroyed by nitrogen compounds. Reaction rates are identified by \(K\) VI-i.

VII Schemes by which excited particles are deactivated. The reaction rates are given by \(K\) VII-i.

2.1 The Chapman Photochemical Theory.

About the time that Dobson and Gotz were conducting their ozone
### Table 1. Reactions and Rates

**Organization of Groups:**

1. Odd oxygen particles into odd oxygen particles.
2. Odd oxygen particles produced or destroyed.
3. Odd oxygen particles destroyed by active H particles.
4. Active hydrogen particles produced or destroyed.
5. Active hydrogen particles produced by $H_2O_2$.
7. Deactivation schemes.

**Abbreviations:**

- $5(-35) = 5 \times 10^{-35}$
- $X = \text{Reaction considered, no rate given.}$
- $* = \text{Vibrationally excited state.}$
- $B. \& N. = \text{Bates and Nicolet}$
- Units are $\text{cm}^3 \text{sec}^{-1}$ or $\text{cm}^6 \text{sec}^{-1}$

**Rate Coefficients Used By:**

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<tbody>
<tr>
<td>1.</td>
<td>$O_2(3\Sigma_g^-) + O(3P) + M \rightarrow O_3(1\Sigma_g^+) + M$</td>
<td>6(-19)</td>
<td>5(-34) $T_\Sigma^*$</td>
<td>5(-35)</td>
<td>1.2(-14)</td>
<td>5(35)</td>
<td>8(35) $T_\Sigma^*$</td>
<td>5(-34)</td>
<td>8(35) $T_\Sigma^*$</td>
<td>(-35)</td>
<td></td>
</tr>
<tr>
<td>2.</td>
<td>$O_3 + h\nu \rightarrow O_2 + O(3P), 3100 &lt; \lambda &lt; 11,800 \AA$</td>
<td>5(9)</td>
<td>X</td>
<td>7.4(-3)</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>(-3.4)</td>
</tr>
<tr>
<td>3.</td>
<td>$O_2 + h\nu \rightarrow O_2(3\Pi_g) + O(1S)$</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>4.</td>
<td>$O_3 + h\nu \rightarrow O_2(3\Sigma_g^+) + O(3D), \lambda &gt; 3100 \AA$</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>(-3.2)</td>
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<td>5.</td>
<td>$O(3D) + N_2(3\Pi_g) \rightarrow O(3P) + N_2(4\Pi_g^+)$</td>
<td>5(-15)</td>
<td>(-12)</td>
<td>(-12)</td>
<td>(-12)</td>
<td></td>
<td></td>
<td></td>
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<td>6.</td>
<td>$O(3D) + O_2(3\Sigma_g^-) \rightarrow O(3P) + O_2(4\Pi_g^+)$</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>(-3.4)</td>
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<tr>
<td>1.</td>
<td>$O_2 + h\nu \rightarrow O(3P) + O(3P)$ $\lambda &lt; 1750 \leq 2424$ Å</td>
<td>2(4)</td>
<td>X</td>
<td>4.3(-10)</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>(-7.9)</td>
<td></td>
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<td>2.</td>
<td>$O_2 + h\nu \rightarrow O(4D) + O(3P)$ $\lambda &lt; 1750$</td>
<td>X</td>
<td>4.3(-10)</td>
<td>X</td>
<td>X</td>
<td>3(-11)</td>
<td>X</td>
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<td>3.</td>
<td>$O(4D) + O_3(4A_1) \rightarrow O_2(3\Sigma_g^+) + O_2(3\Sigma_g^+)$</td>
<td>8(-20)</td>
<td>11(-18)</td>
<td>7(-18)</td>
<td>6.5(10)</td>
<td>6.1(2)</td>
<td>2.3(-15)</td>
<td>(-)</td>
<td>(-)</td>
<td>(-)</td>
<td>(-15.3)</td>
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<td>4.</td>
<td>$O(3P) + O_3(4A_1) \rightarrow O_2(3\Sigma_g^+) + O_2(3\Delta_g)$</td>
<td>8(-20)</td>
<td>74(-21)</td>
<td>2(-13)</td>
<td>13(10)</td>
<td>5.4(2)</td>
<td>2.3(-15)</td>
<td>(-)</td>
<td>(-)</td>
<td>(-)</td>
<td>(-15.3)</td>
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<td>5.</td>
<td>$O_3 + O_3 \rightarrow 3O_2$</td>
<td>2(-25)</td>
<td>X</td>
<td></td>
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<tr>
<td>6.</td>
<td>$O(3P) + O(3P) + N_2 \rightarrow O_2 + N_2$</td>
<td>8(-10)</td>
<td>5(9) T expt</td>
<td>(-32)</td>
<td>3.7(-33)</td>
<td>3.7(-33)</td>
<td>3.7(-33)</td>
<td>3.7(-33)</td>
<td>3.7(-33)</td>
<td>(-32.4)</td>
<td></td>
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<tr>
<td>7.</td>
<td>$O(3P) + O(3P) + O_2 \rightarrow O_2 + O_2$</td>
<td>8(-10)</td>
<td>5(9) T expt</td>
<td>(-34)</td>
<td>2.7(-33)</td>
<td>2.7(-33)</td>
<td>2.7(-33)</td>
<td>2.7(-33)</td>
<td>2.7(-33)</td>
<td>(-32.4)</td>
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<td>8.</td>
<td>$O_2(3\Sigma_g^+) + O_3(4A_1) \rightarrow 2O_2(3\Sigma_g^+) + O(3P)$</td>
<td>(-14)</td>
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<td>9.</td>
<td>$O_2(3\Delta_g) + O_3(4A_1) \rightarrow 2O_2(3\Sigma_g^+) + O(3P)$</td>
<td>(-14)</td>
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<td>10.</td>
<td>$O(4D) + H_2 \rightarrow OH + H$</td>
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<tr>
<td>1.</td>
<td>$O_3 + H \rightarrow OH + O_2$</td>
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<td>2.</td>
<td>$O_3 + H \rightarrow HO_2 + O$</td>
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<tr>
<td>3. $O_3 + OH \rightarrow HO_2 + O_2$</td>
<td>$1.5(\pm 0.1) \times 10^{12}$</td>
<td>$1.5(\pm 0.1) \times 10^{12}$</td>
<td>$1.5(\pm 0.1) \times 10^{12}$</td>
<td>$5(-13)$</td>
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<tr>
<td>4. $O(^3 P) + H_2 O_2 \rightarrow OH + HO_2$</td>
<td>$5(\pm 0.5)$</td>
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<tr>
<td>5. $O_3 + HO_2 \rightarrow OH + 2 O_2$</td>
<td>$(-14)(est)$</td>
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<tr>
<td>6. $O(^3 P) + OH \rightarrow H + O_2$</td>
<td>$4(\pm 0.5) \times 10^{12}$</td>
<td>$4(\pm 0.5) \times 10^{12}$</td>
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<tr>
<td>7. $H + OH \rightarrow H_2 + O$</td>
<td>$6.5(\pm 0.5) \times 10^{12}$</td>
<td>$6.5(\pm 0.5) \times 10^{12}$</td>
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<tr>
<td>8. $O(^3 P) + HO_2 \rightarrow OH + O_2$</td>
<td>$4.5(\pm 0.5) \times 10^{12}$</td>
<td>$4.5(\pm 0.5) \times 10^{12}$</td>
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<tr>
<td>9. $H + O + M \rightarrow OH + M$</td>
<td>$6(\pm 0.5) \times 10^{12}$</td>
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<tr>
<td>10. $O_3 + OH \rightarrow 2 O_2 + H$</td>
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<tr>
<td>11. $H + H_2 O_2 \rightarrow H_2 + HO_2$</td>
<td>$5(\pm 0.5)$</td>
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**Group IV. Reactions:**

1. $H_2 O + h\nu \rightarrow OH(^2 \Pi) + H(^2 S) \lambda < 2390 \AA$ | $(-23)(-14)$ | $X$ | $X$ | $X$ | $(-10.4)$ |
2. $HO_2 + h\nu \rightarrow OH + O$ | $(-4)$ | $(-4)$ | $(-4)$ | $(-4)$ | $(-4)$ |
3. $O(^4 D) + H_2 O \rightarrow 2 OH$ | $(-11)(est)$ | $(-11)(est)$ | $(-11)(est)$ | $(-11)(est)$ | $(-11)(est)$ | $(-11)(est)$ | $(-11)(est)$ | $(-11)(est)$ | $(-11)(est)$ | $(-11)(est)$ |
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<tr>
<td>4. OH + OH → H₂O + O(3 P)</td>
<td>$k_{(H₂O)}$ $k_{(H₂O)}$</td>
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<td>5. OH + HO₂ → H₂O + O₂</td>
<td>$k_{(H₂O)}$ $k_{(H₂O)}$</td>
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<td>6. OH + H₂O₂ → H₂O + HO₂</td>
<td>$k_{(H₂O)}$ $k_{(H₂O)}$</td>
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<td>7. H+HO₂ → H₂ + O₂</td>
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<td>8. H + OH + M → H₂O + M</td>
<td>$k_{(H₂O)}$ $k_{(H₂O)}$</td>
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<td>9. H + H + M → H₂ + M</td>
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<tr>
<td>10. HO₂ + HO₂ → H₂O₂ + O₂</td>
<td>$k_{(H₂O)}$ $k_{(H₂O)}$</td>
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<td>11. H₂ + OH → H₂O + H</td>
<td>$k_{(H₂O)}$ $k_{(H₂O)}$</td>
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<td>12. H + HO₂ → 2 OH</td>
<td>$k_{(H₂O)}$ $k_{(H₂O)}$</td>
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<td>13. H + O₂ + M → HO₂ + M</td>
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Group V. Reactions:

1. H₂O₂ + hv → 2 OH(3P), λ < 5650 $(-4)$ sec⁻¹ | $(-4)$ sec⁻¹ | X | X

Group VI. Reaction:

1. O₃ + NO → NO₂ + O₂ | X

2. O + NO₂ → NO + O₂ | X
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<tr>
<td>3. NO₂ + hν → NO + O λ &lt; 3800 Å</td>
<td>X</td>
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<td>4. O₃ + N₂ → N₂O + O₂</td>
<td>X</td>
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<td>5. O + N₂ + M → N₂O + M</td>
<td>X</td>
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<tr>
<td>6. N₂O + hν → NO + O λ = 1900 Å</td>
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**Group VII, Reaction:**

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<tbody>
<tr>
<td>1. O₂(¹Δ₂) → O₂(³Σ⁻) + hν</td>
<td>1.5(-4)</td>
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<tr>
<td>2. O₂(¹Σ⁺) → O₂(¹Δ₂) + hν</td>
<td>2.5(-4)</td>
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<tr>
<td>3. O₂(¹Σ⁺) → O₂(¹Σ⁻) + hν</td>
<td>1.4(-1)</td>
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<td>4. O₂(¹Σ⁺) + M → O₂(³Σ⁻) + M</td>
<td>(-18)</td>
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<tr>
<td>5. O₂(¹Δ₂) + M → O₂(³Σ⁻) + M</td>
<td>(-19)</td>
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measurement program, Chapman (1930a, b, c) proposed several photochemical reactions to explain why the ozone concentration above the ozone maximum should vary diurnally. He assumed that the ozone layer was about 10 km thick at an altitude of 45 km. The green line in the spectrum of the aurora was evidence that atomic oxygen existed in the upper atmosphere. So, he reasoned, the molecular oxygen must be dissociated into atomic oxygen, the atomic oxygen then combines with molecular oxygen to form ozone or with itself to form molecular oxygen again, and the ozone had to disappear by combining with itself or atomic oxygen to form molecular oxygen, or by dissociating to produce molecular and atomic oxygen.

These reactions are summarized below:

\[
\begin{align*}
O_2 + \nu (\lambda < 2423 \text{Å}) & \rightarrow O + O & 2.1.1 \\
O + O_2 + M & \rightarrow O_3 + M, M = O_2, N_2 & 2.1.2 \\
O + O + M & \rightarrow O_2 + M & 2.1.3 \\
O_3 + O & \rightarrow 2 O_2 & 2.1.4 \\
O_3 + O_3 & \rightarrow 3 O_2 & 2.1.5 \\
O_3 + \nu & \rightarrow 0 + O_2, \lambda < 3100 \text{Å}, 3100 \text{Å} \leq \lambda < 11,800 \text{Å} & 2.1.6
\end{align*}
\]

The presence of ozone was definitely established by observation. If atomic oxygen were produced only by ozone, the ozone would slowly disappear. So, the formation of atomic oxygen from \(O_2\) had to be the more fundamental.

During the night, the two dissociating reactions, 2.1.1 and 2.1.6, producing \(O\) stopped, but the combination reactions, 2.1.2 and 2.1.4, continued. Therefore, the \(O\) concentration had to decrease, but the ozone concentration could either increase or decrease. Chapman assumed that
the concentrations of O and O₃ were unaffected by convection or diffusion. He also estimated the reaction rates and dissociation rates as shown in Table 1. On the basis of a cosinusoidal dissociation function during the day, he estimated that the O₃ concentration just above the ozone maximum would increase as all the O was combined. Progressively higher, less and less of the O would combine to form O₂, until at around 80 km, there would not be much change in the atomic oxygen at all, and ozone concentration would remain about 10⁵ cm⁻³.

2.2 Photochemistry Using Water Vapor.

The discovery by Meinel (1950a, b) that the vibrational-rotational bands of the hydroxyl radical OH appear in the emission spectra of the night sky led to the work of Bates and Nicolet (1950). While their work was primarily concerned with atmospheric water vapor, the concentration of ozone had to be taken into account. The mechanism proposed was two body collisions between hydrogen atoms and ozone molecules to produce OH and oxygen molecules.

Once the existence of hydrogen was assumed in the mesosphere, then the number and complexity of the reactions possible increased considerably. Referring to Table 1, while Chapman considered six reactions in an oxygen-only atmosphere, Bates and Nicolet identified 32 reactions that could occur in the mesosphere. While they ignored six as being too slow or requiring too high an energy, the time integration of the remaining 26 was a formidable task. Even more important, the rate coefficients of many of the equations were known either not at all or only approximately. So, estimates of many of them had to be made as is
Figure 2.2-1 Oxygen and Ozone Concentrations from Bates and Nicolet (1950).
indicated in Table 1.

Bates and Nicolet considered both an oxygen-only and a hydrogen-oxygen atmosphere. They calculated the equilibrium concentration of ozone, \([O_3]\), and atomic oxygen, \([O]\), by means of:

\[
[O_3] = [O] \left( \frac{J_1 \cdot [O_3][M]}{J_3} \right); \quad [O] = \left( \frac{J_3 [O_3]}{k_{II-6}[M] \left( 1 + \frac{k_{II-1} \cdot k_{II-3} [O_3]}{k_{II-4} \cdot J_3} \right)} \right)^{1/2}
\]

where \(J_2\) and \(J_3\) are the rates of photon dissociation of ozone and molecular oxygen, respectively, and the \(K\) 1-1 are the reaction rates. The values of \(J_2\) and \(J_3\) used by Bates and Nicolet are given as:

\[
J_2 = 4.3 \times 10^{-10} \text{ sec}^{-1} \quad \text{(Herszberg continuum)}
\]

\[
J_3 = 7.6 \times 10^{-3} \text{ sec}^{-1} \quad \text{(Chappuis and Hartley continua)}
\]

At night the dissociation ceases, \([O]\) decreases and \([O_3]\) increases with a concentration limit given by:

\[
[O_3] \rightarrow \frac{k_{II-1} [O_3][M]}{k_{II-3}}
\]

The value of these concentrations is given in Figure 2.2-1. The profile labelled Mid-Latitude \([O_3]\) is derived from the 1966 U.S. Standard Atmosphere Supplements U.S. Government Printing Office (1966). It is the profile assumed for all the daytime calculations.

In the hydrogen-oxygen atmosphere, the hydrogen acts as a catalyst for the destruction of odd oxygen atoms below about 70 km. At night it causes the \([O]\) to diminish rapidly, and it causes the concentration of \([O_3]\) to seek a value given by:

\[
[O_3] = \frac{k_{II-1} [O_3][M]}{k_{II-3} + \left( k_{II-1}[M] + k_{II-2}[M] + k_{II-3}[O_3] \right) / [O]}
\]
Figure 2.3-1  Nighttime Ozone Profiles, Effect of Varying K I-1 and K II-6, from Paetzold (1961)
The denominator in equation 2.2.3 is larger than in equation 2.2.2. So, the total increase in \([O_3]\) would not be expected to be as large as in an oxygen-only atmosphere. This result is also shown in Figure 2.2-1.

2.3 Other Factors Influencing the Photochemistry.

The complexity of the photochemical problem continued to increase as Paetzold (1961) introduced the effect of the nitrogen compounds into the reactions. The reactions considered by him are indicated in Table 1. Unfortunately, he did not say what reaction rates he used for the various reactions, so a comparison with other works is not possible. He did consider the effects of two different rates of reactions, \(K_{I-1}\) and \(K_{II-6}\). The predicted night ozone profiles using these two different reactions is shown in Figure 2.3-1. These results demonstrate the great sensitivity of the predicted composition to reasonable uncertainties in the reaction rates.

Another complicating factor that was not considered by any of the investigators was the transport effects of circulations in the atmosphere. Newell (1963) showed that parcels of air move northward from the tropics carrying ozone to the middle latitudes. The seasonal changes in the ozone maximum, particularly the spring maximum, could be explained in this way. While the results of Newell's investigations were more applicable to the lower atmosphere, they do suggest that circulations in the mesosphere may be important. It should be noted that very little is known about the winds in the mesosphere.

2.4 Numerical Integration of the Photochemical Equations.

Leovy (1964) pointed out the interrelationship between the photo-
chemical, radiative, and dynamical processes that must exist in the atmosphere. The dynamics of global motions are determined by the effects of radiative heating. The heating, in turn, is modified by the changes in temperature brought about by the motions of the atmosphere. The motions also change the concentration of gases at different altitudes, thus changing the rate of heating.

Previous investigators assumed a stationary temperature distribution. They also assumed the concentrations to be in equilibrium or nearly so. Leovy considered the photochemical and radiative aspects of the problem simultaneously, using numerical methods to carry out the time dependent integrations. He used the two photodissociation equations and three combination reactions indicated in Table 1. The results of his calculations after twelve simulated days are shown in Figure 2.5-1.

About this time, Hunt began a series of calculations using numerical techniques. In his first, (1965), he used the same five reactions as did Leovy, but the only rate reaction noted in his paper was that for the combination of O and O₃ to form O₂. The value used was $6.45 \times 10^{-12} \exp(-3200/RT) \text{cm}^{-3}\text{molecule/sec}$, in contrast to the value used by Leovy of $1.5 \times 10^{-10} \exp(-3025/T)$.

Hunt (1966a) used sixteen reactions as indicated in Table 1, including many of the excited forms of molecular and atomic oxygen in his calculations. In order to arrive at reasonable values for the ozone concentrations, he had to compromise on the value of the reaction rate for the deactivation of the singlet D oxygen by neutral molecules. The values he used differed from the ones believed to describe the air-glow intensity.
observed by Dalgarno and Walker (1964) by four orders of magnitude.

Hunt (1966b) used thirty reactions as listed in Table 1, giving all of the reaction rates that he used in the machine computations. A comparison of the ozone concentrations predicted by the three Hunt calculations is given in Figure 2.5-1.

The effect of auroral electrons on the ozone and oxygen concentrations was considered by Maeda (1968). He considered an oxygen-only atmosphere, using the dissociation equations and combination equations that are now considered to be the "classical" approach. The effects of soft electrons were found to be negligible, but the large diurnal change in the ozone concentration in the mesosphere was still predicted.

After successive researchers expanded the list of reactions, Dütsch (1968) presented a set of calculations which he termed a "simplified" set. It was in this paper that he proposed organizing the equations in a way that would allow comparison of the reaction rates. But, both he and Leovy (1969) restricted their calculations to the stratosphere and did not consider the changes that might occur in the mesosphere.

2.5 Comparison of Theoretical Ozone Concentrations.

The results of the various calculations are shown in Figure 2.5-1. Included are the water-vapor atmosphere of Bates and Nicolet, the effects of nitrogen as computed by Paetzzold, the variable temperature model of Leovy, and finally the three models used by Hunt. All of the models predict a substantial change in the mesospheric ozone concentration during the night.
1. Leovy (1964)  
2. Hunt (1965)  
3. Hunt (1966a)  
4. Hunt (1966b)  
7. Paetzold (1961) $K = 5 \times 10^{-36}$  
(Circled Numbers Indicate Night Profiles)

Figure 2.5-1 Comparison of Predicted Ozone Concentration Profiles.
2.6 Observations of the Ozone Profile.

A representative selection of ozone profile measurements are presented below and in Figures 2.6-1 and 2.6-2. The observations are listed in the order of publication. Following the date of publication and author(s) are listed the date of observation, the approximate time, the location, and a description of the method used. The number is keyed to the profile in Figure 2.6-1.

Ultraviolet spectrograph in an Aerobee rocket observed sun at sunset at 2550-3400 A. (1)

1961 Venkateswaran, et. al.
Aug-Sep 1960; 35 N, 117 W; Sunset.
The Echo satellite observed as it entered the earth's shadow, 5295-5900 A. (2)

1964 L'Vova, et. al. 15 Feb 1961; Unknown; Solar eclipse.
Ultraviolet photometer in capsule ejected into moon's shadow measured sky brightness, 2200-3200 A. (3)

Ultraviolet radiometer in earth satellite observed sunrise and sunset, 2500-2600 A. (4)


1966 Carver, et. al. 9 Dec 1965; 31 S, 137 E; 2235 Local Time. Ultraviolet photometers mounted in HAD rockets observed the moon in bands around 2400 A, 2740 A, and 2910 A. (7)

1968 Reed 27 May 1960; 38 N, 75 W; 0030 Local Time. Ultraviolet photometers in Aerobee-Hi rocket measured night airglow at 100 km. in 2600 A and 2700 A. (8)

1968 Weeks and Smith 14 June 1966; 38 N, 75 W; Sunset. Ultraviolet photometer in Nike Apache rocket observed the sun at 2590 A. (9)

1970 Hilsenrath 6-7 Mar 1970; 38 N, 75 W; Diurnal (0430 and 1100 Local Time). Chemiluminescent parachute sonde measured the ozone mixing ratio in situ. (10)


The results of the observations of Randhawa and Hilsenrath are plotted separately in Figure 2.6-2, both to relieve the congestion of Figure 2.6-1, and because they represent the only known attempts to measure the diurnal variation in a reasonable time interval. Randhawa's measurements were made over a 24 hour period, but did not reach above 50 km. Because of a rocket failure, Hilsenrath's measurements were more than a day apart. The profiles predicted by Hunt in a moist atmosphere are shown for comparison.
Figure 2.6-2  Ozone Concentration Profiles Measured Diurnally
3. MICROWAVE MEASUREMENT OF MESOSPHERIC OZONE.

In Chapter 2, the development of the photochemical theory of the atmosphere was outlined. The ozone concentration profiles predicted by the theories were compared with the limited observations. It is evident that the diurnal variation of ozone concentration was neither verified nor disproved. The objective of this experiment was to determine if the diurnal variation existed using a microwave sensor.

3.1 Microwave Spectroscopy of Ozone.

Microwave spectroscopy is a well established technique to study the physics of molecular structures. Townes and Schawlow (1955) and Gordy, et. al. (1953) are representative texts on the subject. Under carefully controlled conditions in the laboratory, well defined spectra are obtained. Microwave spectroscopy of gases in the atmosphere is much more difficult, and there are only a few successful observations. Among the reported observations of the ozone molecule are 1.) Mouw and Silver (1960) at 36.025 GHz in absorption against the sun, 2.) Caton, et. al. (1967) at 37.836 GHz in absorption and 30.056 GHz in emission, 3.) Barrett, et. al. (1967) at 23.861 GHz in emission, and 4.) Caton, et. al. (1968) at 101.737 GHz in absorption.

The Mouw and Silver instrument was a chopper wheel Dicke system with a 2 MHz pre-detection bandwidth. The post-detection integrator had a time constant of about 1 minute and a $\Delta T_{\text{rms}} = 3^0 K$. The antenna was a 1° beam width parabola. The line observed in absorption against the sun was the 36.025 GHz, $^{23\_3}_3 \rightarrow ^{23\_2}_{19}$, $^{22\_3}_2$. The radiometer was scanned in frequency by taking data at one frequency for one day, then shifting
frequency and taking another day's data.

Caton reported detecting the $17\,\{15\}^{18}\,\{12\}^{16}$, $37.836$ GHz line in absorption and the $16\,\{14\}^{15}\,\{13\}^{12}$, $30.056$ GHz line in emission. The instrument was configured to be either frequency switched with $\Delta f = 50$ MHz or a chopper wheel Dicke switched radiometer. The pre-detection bandwidth was $10$ MHz and the integrator had a $\tau = 10$ seconds. Observations were made by shifting the center frequency in steps across a $250$ MHz band. It took $50$ minutes to get a single frequency data point, and a day to complete one scan.

The instrument used by Barrett, et. al., was a $20$ channel Dicke switched radiometer centered on the $19\,\{18\}^{17}\,\{15\}^{13}$ line at $23.860$ GHz. The bandwidth covered was $80$ MHz wide with $4$ MHz resolution. The $\Delta T_{\text{rms}}$ was $1-2^0\text{K}$ for a $\tau = 10$ sec. The line was observed in emission with an amplitude of $0.3^0\text{K}$ at a zenith angle of $78^0$.

Caton reported observing the $4_0\,\{4\}^{4}\,\{4\}^{1}$ line at $101.736$ GHz in absorption against the sun and also in emission. The instrument is described in detail in Chapter 4. His technique of using free-running klystrons raises doubts about the validity of the line shape observed.

Gora (1959) has compiled an extensive listing of the molecular resonances of ozone and compared them with the observed frequencies. The frequency of the $4_0\,\{4\}^{4}\,\{4\}^{1}$ line was listed by Gora to be $100.7367$ GHz, but it may have been a typographical error. Trambarulo, et. al. (1953) reported the measured frequency to be $101736.83\pm14$ MHz. This resonance was selected for the experiment because the equipment used by Caton was available, the frequency was
measured accurately, and it was a moderately strong line.

3.2 Theory.

The spectra, both absorption and emission, are caused by the interaction of microwave energy with the ozone molecule. Following Townes and Schawlow, molecules can be broadly categorized as diatomic, linear polyatomic, symmetric tops, or asymmetric tops. Ozone is closely approximated by a symmetric top. That is, of the three principal moments of inertia, two are nearly equal.

The rotational quantum numbers J and K are used to describe the energy levels of the molecule. Since ozone is slightly asymmetric, its energy levels are given by:

$$\frac{E}{\hbar} = \left[ \frac{B+C}{2} \right] J(J+1) + \left( A - \frac{B+C}{2} \right) \omega; \quad \omega = a \text{ constant}$$

$$A = \frac{\hbar^2}{8\pi^2 I_a} \quad B = \frac{\hbar^2}{8\pi^2 I_b} \quad C = \frac{\hbar^2}{8\pi^2 I_c}$$

and since $B \neq C$, $\omega \approx K^2$, where $K$ is an integer. In the symmetric molecule, $K$ is a "good" quantum number; in the slightly asymmetric molecule, the degenerate energy levels of the symmetric top are split. So, the energy levels are designated by giving $J$, then $K_{-1}$ for the limiting prolate level, and $K_{+1}$ for the limiting oblate level. The measure of symmetry is given either by Ray's asymmetry parameter

$$\kappa = \frac{2B - A - C}{A - C}$$

or by Gora's

$$\varepsilon = \frac{A - C}{2B - A - C} = \frac{1}{\kappa} = 0.00806155$$
The absorption line of interest, in Gora's notation is \( Q_{L}(\nu_o) \), \( \Delta J_k(J_k) \) where \( P = -1 \), \( Q = 0 \) and \( R = 1 \). It has the frequency of 101,736.8 MHz. The maximum absorption coefficient, \( \alpha_{\text{max}} \), is given by Gora as \( 185 \times 10^5 \text{ cm}^{-1} \).

The Van Vleck-Weisskopf (1945) equation is used to compute the absorption coefficient near the resonant frequency. It is given by:

\[
\alpha = \left( \frac{8\pi^3 \nu N}{3h c} \right) \frac{\varepsilon_i \varepsilon_j |\mu_{ij}|^2 f(\nu_{ij}, \nu) e^{-\varepsilon_j/kT}}{\varepsilon_j e^{-\nu_i/kT}}
\]

where \( N = \# \) of molecules/unit volume.

\( c \) = speed of light.

\( k \) = Boltzmann's constant

\( T \) = kinetic temperature of molecules.

\( \mu_{ij} \) = dipole matrix element of states \( i \), \( j \).

\( \nu \) = the frequency of interest

\( \nu_{ij} \) = resonance frequency of the transition \( i \rightarrow j \).

\( = (E_j - E_i)/h \)

The line-shape factor is given by:

\[
f(\nu_{ij}, \nu) = \frac{1}{\pi} \left[ \frac{\Delta\nu}{(\nu_{ij} - \nu)^2 + \Delta\nu^2} - \frac{\Delta\nu}{(\nu_{ij} + \nu)^2 + \Delta\nu^2} \right]
\]

The evaluation of equation 3.2.4 was done in the following form:

\[
\alpha_{i \rightarrow j} = \frac{8\pi^3}{3c \alpha T} \frac{N}{\varepsilon_j e^{-\nu_i/kT}} \mu^2 \varepsilon_i \varepsilon_j e^{-\varepsilon_j/kT} \nu \nu_{ij} f(\nu, \nu_{ij}, \Delta\nu)
\]
Where $\phi_{ij}^2$ is the intensity matrix element of the transition

\[ E_i = \text{energy level of lower state calculated from equation 3.2.1} \]

\[ T = \text{excitation temperature describing the energy level population} \]

The $\phi_{ij}^2$ were calculated from the intensity factor of Gora (1959),

\[ Y = \phi^2 \exp\left(-\frac{E_i}{kT}\right). \]

It is assumed that the excitation temperature is the atmospheric kinetic temperature and that the energy levels are populated by collisions even though the ozone molecules are in an ultraviolet radiation environment. From the properties of the U.S. Standard Atmosphere, 1962, the collision frequency at 70 km altitude is $4 \times 10^5 \text{sec}^{-1}$, corresponding to a lifetime measured in microseconds. The lifetime of an ultraviolet excited level, $a$, is given by:

\[ \frac{1}{\tau_a} = \sum_i A_{ai} \]

where $A_{ai}$ is the Einstein coefficient of spontaneous emission.

The summation is performed over all states below level $a$. This lifetime is on the order of milliseconds*, so the assumption is believed valid.

The values of the rotational constants used are given by Trambarulo, et. al. (1953) as:

\[ A = 106530.0 \pm 1.1 \text{ MHz} \]

\[ B = 13349.06 \pm 0.06 \text{ MHz} \]

\[ C = 11834.3 \pm 1.1 \text{ MHz} \]

\[ \mu = 0.53 \pm 0.02 \text{ debye} \]

* A. Barrett, personal communication.
The partition function \( Z = e^{-\frac{E_i}{kT}} \) was then computed to be:

\[
Q = 2120 \left( \frac{T}{220} \right)^{3/2}
\]

The line-width parameter \( \Delta \nu \) is given by:

\[
\Delta \nu = \left[ (\Delta \nu_{\text{collision}})^2 + (\Delta \nu_{\text{doppler}})^2 \right]^{1/2}
\]

where \( \Delta \nu_{\text{doppler}} = 5.17 \times 10^{-8} \ T^{3/2} \)

\( \Delta \nu_{\text{collision}} = 3.96 \times 10^{-7} \ PT^{-3/2} \)

The doppler broadening does not become significant until above 80 km. The pressure-temperature dependence was assumed proportional to the number of collisions. (Waters, 1970). The constant in the line width parameter \( \Delta \nu_{\text{collision}} \) was the one inferred by Walshaw (1955) from measurements in the \( 9.6 \mu \) band for an ozone-air mixture at pressures from 10 to 760 mm Hg. He estimated the Lorentz line half-width to be \( 7.8 \times 10^{-2} \text{ cm}^{-1} \) and the Doppler half width to be \( 1.1 \times 10^{-3} \text{ cm}^{-1} \) at 293°K and 760 mm Hg.

In the microwave frequency range, the Rayleigh-Jeans approximation to the Planck black-body law applies. The intensity of electromagnetic radiation from a substance is proportional to a brightness temperature, \( T_B \). If a gas has a temperature \( T (\ell) \) and an absorption coefficient \( \alpha (\ell) \) as a function of position, \( \ell \), then the brightness temperature is given by the equation of radiative transfer.

\[
T_B (\ell) = T_{B_0} e^{-\tau (\ell)} + \int_0^L T(\ell) e^{-[\tau (\ell) - \tau (\ell')]} \ d \tau (\ell)
\]

where \( \tau (\ell) = \int_0^\ell \alpha (\ell') \ d \ell' \)

and \( L = \text{total path length} \).
The absorption coefficient, $\chi(\ell)$, is assumed to be the sum of the absorption coefficients of all nearby molecular resonances. In the atmosphere, the water vapor resonances at 22.235 GHz and 183.3 GHz, the oxygen complex around 60 GHz, the single oxygen line at 118 GHz, and the individual ozone lines all contribute to the absorption coefficient around 101.7 GHz.

The computer program used to compute the absorption coefficient and brightness temperature is a modified version of the Microwave Emission Spectrum program described by Waters (1970)*. It was independently checked for the ozone contribution by the author using a different language (MAD) and found to be correct. The 1962 U.S. Standard Atmosphere model was used for the temperature and pressure values vs. heights. Subsequently, the models described by season and latitude became available (Groves, 1970). A comparison of the temperature profiles is given in Figure 3.2-1. Computations at the zenith were made by Waters using winter-summer profiles, and the change in brightness temperature was less than a degree. So the 1962 U.S. Standard Atmosphere was used in all calculations.

The ozone lines used in the calculations are listed in Table 2. The brightness temperature was first computed using all the lines from 9-119 GHz and then compared to the spectrum calculated using only the lines from 93-119 GHz. The difference was insignificant but the com-

* I am grateful to Joe Waters, not only for allowing me to use his computer program, but also for many hours of discussion and assistance.
Figure 3.2-1 Comparison of 1962 Standard Atmosphere and Seasonal Model Temperature.
<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>$P^2$</th>
<th>Energy (erg.) (E-13 = 10^{-13})</th>
</tr>
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<tbody>
<tr>
<td>1. 9.201</td>
<td>3.0114</td>
<td>0.406 E-13</td>
</tr>
<tr>
<td>2. 10.226</td>
<td>2.0987</td>
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<tr>
<td>3. 11.073</td>
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<td>0.1623 E-14</td>
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<tr>
<td>4. 14.866</td>
<td>4.1098</td>
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<tr>
<td>5. 16.163</td>
<td>4.3914</td>
<td>0.6852 E-13</td>
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<tr>
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<td>2.9229</td>
<td>0.3413 E-13</td>
</tr>
<tr>
<td>7. 25.300</td>
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</tr>
<tr>
<td>8. 25.511</td>
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<tr>
<td>9. 25.649</td>
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<td>10. 27.862</td>
<td>7.5663</td>
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<td>11. 28.960</td>
<td>4.1840</td>
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<td>2.8131</td>
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</tr>
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</tr>
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<tr>
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<tr>
<td>33. 119.306</td>
<td>4.66</td>
<td>7.774 E-14</td>
</tr>
</tbody>
</table>
puter time saved was substantial, so all subsequent calculations used only the lines from 93-119 GHz.

The model ozone profiles used were the ones given by Hunt (1966b) and shown in Figure 3.2-2. The ozone profiles expressed in mass mixing ratios are given in Figure 3.2-3. The mass mixing ratio is defined as the ratio by mass of ozone to air in a given volume. Also shown is the assumed water vapor mixing ratio profile.

The result of the calculations for a day profile is given in Figure 3.2-4. The effect of the change in mesospheric ozone concentrations would be a sharp spike on top of the line. This is illustrated in Figure 3.2-5, where both the day and night spectrum are plotted. The change from day to night in the spectrum is very substantial, almost a 20% change in absolute temperature.

The temperature measured by the radiometer is the brightness temperature integrated over the antenna pattern which is designated the antenna temperature $T_A(f)$.

$$T_A(f) = \frac{1}{4\pi} \int_4^{4\pi} G(f, \theta, \phi) T_B(f, \theta, \phi) d\Omega$$

$G(f, \theta, \phi) =$ Antenna Gain Function; $\int_4^{4\pi} G(f, \theta, \phi) d\Omega = 4\pi$

If the antenna has a high gain and narrow beam width, then the gain can be assumed constant over the beam width. Similarly, if the brightness temperature is a slowly varying function over the beam solid angle, it too can be assumed constant. This was done in the initial calculations and refined later as discussed below. The line strength was multiplied by 0.8 to account for the efficiency of the antenna. The
Figure 3.2.2 Assumed Ozone Concentration Profiles.
Figure 3.2-3 Model Ozone and Water Vapor Mixing Ratios.
Figure 3.2-4 Computed Brightness Temperature For the Assumed Day Ozone Concentration Profile.
FREQUENCY (MHz): $v_0 = 101736.83\text{ MHz}$

Figure 3.2-5 Comparison of Day and Night Spectra.
line strength was estimated to be \( 20^\circ \) 0.8 = 16\(^\circ\) high, in a bandwidth or "window" of 4 MHz.

To investigate the possibility that the antenna beam efficiency was the reason the night temperature increase was not seen, the antenna effects were studied in more detail. Using the equations for a pyramidal horn with phase error, the gain over an isotropic radiator and the normalized power pattern were computed.* The results are shown as a logarithmic plot, Figure 3.2-6, and as a linear plot in Figure 3.2-7. From the logarithmic plot, it is seen that the H plane pattern drops to a negligible value around 20\(^\circ\) off-axis, while the E plane pattern is significant out to 90\(^\circ\) off-axis. To simplify the calculations, the effective H plane pattern was approximated as a fan shaped beam with an angle of 9.1\(^\circ\). The horn was assumed to be isotropic in the back hemisphere. Following Krauss (1966) the antenna temperature can be computed by:

\[
T_A(f) = \frac{1}{\Omega_A} \int \int \frac{T_B(f,\theta,\phi) P_n(\theta,\phi) \sin \theta \, d\theta \, d\phi}{\pi}
\]

where \( T_A \) = antenna temperature (\( ^\circ \)K)
\( \Omega_A \) = beam solid angle (rad.\(^2\))
\( T_B \) = brightness temperature (\( ^\circ \)K)
\( P_n \) = normalized power pattern

The directivity is given by:

\[
D = \frac{U(\theta,\phi)_{\text{max}}}{U(\theta,\phi)_{\text{average}}} = \frac{4\pi}{\Omega_A}
\]

where \( U(\theta,\phi) \) = radiation intensity (watts rad\(^{-2}\))

* I wish to acknowledge the assistance of B.L. Page for allowing me to use his approximations and to L. Niro for programming the equations.
$F = 101.737 \text{ GHz}$
Baytron Horn
H plane aperture : 0.995"
E plane aperture : 0.745"
H plane slant length : 3.2087"
E plane slant length : 3.185"

$\theta$ = the angle off-axis.

Figure 3.2-6 Gain Patterns, Baytron Horn.
Figure 3.2-7 Normalized Power Gain Pattern.
This was calculated to be 26 dB over isotropic. So:

\[ \hat{\Theta}_A = \frac{4\pi}{400} = \frac{\pi}{100} \text{ rad}^2. \]

Assuming the gain was constant over 9.1° in the H plane, the antenna temperature reduces to:

\[ T_A(f) = \frac{100}{\pi} \int \frac{T_B(f, \theta, \phi) P_m(\theta, \phi) d\Omega}{4\pi} = \frac{100}{\pi} \text{ rad}^{-2} \frac{\text{rad}^2}{3.282 \text{ deg}^2} \cdot 9.12 \cdot \frac{\sum T_B(\theta_i) P_m(\theta_i)}{360} \]

The majority of the observations were made from a hut located near the Haystack radome. (See Section 4.2.1) A sketch of the antenna beam relative to the hut and the assumed \( T_B \) versus zenith angle is given in Figure 3.2-8. Superimposed on the temperature model is the E plane normalized power pattern when the horn is at a 30° elevation angle.

The convolution of the pattern and temperature profile were performed by computer.* The antenna temperature versus elevation angle and frequency is given in Figure 3.2-9. The increase in antenna temperature near zenith is due to radiation from the hut. The night profile of Hunt (1966b) was used. The line strength reaches a maximum of 17°K at an elevation angle of 20°, but to avoid contamination by the surroundings, the observations were conducted primarily at an elevation angle of 30°. The antenna approximation used to specify the radiometer was justified.

3.3 Radiometer Specifications.

With the predicted line strength and shape known, the bandwidth, 

* I wish to acknowledge the assistance of S. Edmunds for programming the equation.
Figure 3.2-8 Convolution of Temperature Distribution and Antenna Pattern.
Night Ozone Concentration Profile,
5g/m³ surface Water Density,
Baytron Horn.

Figure 3.2-9 Computed Antenna Temperature Versus Zenith Angle.
resolution, sensitivity, and frequency stability of the radiometer could be specified. The line is about 300 kHz wide at half-height, so a resolution of about 100 kHz would be required over the 4 MHz bandwidth. This established the pre-detection bandwidth to be 100 kHz.

The time required for the mesospheric ozone to reach its maximum value is predicted to be on the order of minutes, and it maintains its value over several hours (Maeda and Akin, 1968; Hunt, 1966b). A post-detection bandwidth equivalent integration time of 4000 seconds would be reasonable.

The receiver sensitivity can be expressed in terms of the rms fluctuations of the noise at the output. This is given by:

$$\Delta T_{\text{rms}} = \frac{\alpha(T_A+T_R)}{\sqrt{B \tau}} = \frac{\alpha(T_{\text{sys}})}{\sqrt{B \tau}} T_k$$

where $\Delta T_{\text{rms}}$ = rms value of the output noise ($T_k$)

$T_A$ = antenna temperature ($T_k$)

$T_R$ = noise contributed by the receiver ($T_k$)

$T_{\text{sys}}$ = system temperature = $T_A + T_R$ ($T_k$)

$B$ = pre-detection bandwidth (Hz)

$\tau$ = integration time (sec)

$\alpha$ = a constant between 1 and 3

$$\approx 2$$ for the Dicke-type receiver

A $\Delta T_{\text{rms}} = 1^0K$ would give a 16:1 ratio of the line strength to the rms noise. With these parameters fixed, a $T_{\text{sys}} = 10,000^0K$ would be required. This is also expressed as a system noise figure, $F$, by:

$$T_{\text{sys}} = (F-1)290^0K$$

and $F_{dB} = 10 \log_{10} F$. The receiver noise figure would have to be less
than 15.5 dB.

The frequency stability of the receiver should be such that the signal remains within the 100 kHz channel resolution for more than one hour. Using a margin of ten, the frequency stability would have to be 10 kHz in $101 \times 10^6$ kHz, or a stability of a part in $10^7$ over a period of one hour.

The instrument required would have to operate at 101.736 GHz with at least a 4 MHz bandwidth, 100 kHz resolution, $10^{-7}$ frequency stability, and a 10,000K single side band system temperature. Spectra produced by observations made at various times during the day and night would be analyzed. The appearance of the narrow spectral feature at night as opposed to a flat spectrum expected from the day distribution would confirm the diurnal variation of mesospheric ozone. The width and height of the feature would be a measure of the altitude and concentration of the mesospheric ozone. Eight versions of a radiometer had to be built before the specifications outlined above were met. The radiometer development is discussed in Chapter 4, while the final version, Version VIII, is described in Chapter 5.
4. RADIOMETER DEVELOPMENT

In this chapter the development of the radiometer necessary to perform the experiment is described. The radiometer used by Caton, et. al., was available under a proposed grant from NASA-ERC (National Aeronautics and Space Administration - Electronics Research Center). The Ewen-Knight Corporation was to modify the existing instrument by adding a phase lock loop to the first local oscillator (L.O.), adding provisions to switch from a Dicke switched mode to a frequency switched mode, and adding a switched, third L.O. The modifications were completed at the end of February, 1970, and a series of familiarization and checkout tests began.

In March, NASA-ERC was closed. Since NASA-ERC was to furnish some financial support and the W-band (75-110 GHz) test equipment for the mixer development, it appeared that the entire experiment would have to be cancelled.

In April, NASA-Langley assumed control of the effort, and through the efforts of A. O'Brien, permission was obtained to modify the radiometer and move it to the Haystack field station of Lincoln Laboratory. The W-band test equipment could not be removed from ERC, and since ERC was moving to its new building, the equipment was not available, as it developed, until September, 1970. Even then, it could only be used at the Department of Transportation Systems Center.

The continuation of the experiment now depended upon improvement of the existing radiometer. The replacement mixer work, already underway, was continued, with emphasis on diode manufacture and prototype
design at 55 GHz. Test equipment at V-band (50-75 GHz) was available at M.I.T., and machine shop support was available through an informal arrangement with Lincoln Laboratory.

Eight versions of the radiometer were built as the performance was slowly improved. The seven prototype versions and associated preliminary ozone observations are described in some detail in this chapter, in the hope that the results will be useful to other experimenters. Similarly, the diode development and testing form the foundation for the construction of low noise mixers in the millimeter range.

4.1 **Version I.**

4.1.1 **Circuit Description.**

Version I of the radiometer is an improved version of the instrument used by Caton, et. al. (1968). It was modified to include a phase locked first L.O. and frequency switching of the third L.O. Figure 4.1-1 is a schematic of the radio frequency (R.F.) section or "front end". The entire front end up to the bias "tee" was mounted in a weatherproof enclosure at the focus of a 60-inch search-light used as an antenna. All the control circuits were in a hut located about 100 feet away.

As Caton, et. al., do not specify it, the noise figure of the radiometer was measured using a General Microwave noise tube calibrated to 15.2 ± 0.2 dB excess noise. Two techniques were used: the Y-factor method observing the change in power level at the S-band output, and a Hewlett Packard noise figure meter modified to trigger the noise tube with a 30 MHz and 60 MHz input taken from the 2nd converter stage.
output.

The noise figure of the overall system at the antenna port was 25.3 \(\pm\) 0.2 dB. Equivalently, the system temperature was about 90,000°C. At the dual directional coupler, the first mixer-I.F. amplifier noise figure was 18.8 \(\pm\) 0.2 dB, and the I.F. amplifier traveling wave tube had a noise figure of 7.23 \(\pm\) 0.5 dB. The S-band noise figure was measured with an Airborne Instruments Laboratory Hot-Cold source and with the H. F. noise figure meter.

Besides having poor sensitivity, the frequency stability was inadequate for the proposed experiment. The phase lock loops had a combined stability of better than 10^{-7}, according to the manufacturer's specifications. But, the second L.O. had a pronounced drift. The frequency drift of the 3.255 GHz (nominal) oscillator was about 150 kHz in one hour.

4.1.2 Broad band absorption measurements with the Version I radiometer.

Absorption measurements against the sun were made at the NASA facility located near the Ewen-Knight Corporation buildings in Natick, Massachusetts. The 60-inch searchlight reflector beam-width is estimated to have a 0.14° beamwidth by \(\theta_{1/2} = 70\frac{\lambda}{D}\). The sun is approximately 0.5 degrees in diameter, so the beam pattern is much smaller than the source, and side lobes are neglected. The antenna pattern was not measured.

The tracking system was an equatorial mount driven by a variable speed drive. Both the hour angle and declination drives could be overridden by remote control in the control room. Readouts with 1/2°
Figure 4.1-1  Version 1 of 101.7 GHz Radiometer.
resolution were slaved to the control panel. With the declination held fixed, the sun could be automatically tracked for about 20 minutes before the sun began to drop out of the pattern. The override controls then had to be used to center the sun in the beam.

Caton (1968) mentions that equipment difficulties prevented night emission measurements. Ewen-Knight (1969) describes the difficulty as a diurnal tilt of the base line, and an analytical study by Smith in that report reached the conclusion that internal reflections and standing waves in the antenna structure caused the base line variations. The author could not confirm Smith's conclusions, even though all the internal surfaces except the lens of the searchlight were covered with microwave absorber. The author's measurements indicate that the overall stability of the instrument as used by Caton with a free running 98,000 MHz first L.O., a drifting second L.O., and only about 6 dB dynamic range in the detectors probably contributed more base line problems than the antenna did.

In attempting to duplicate Caton's experiment, and to see the effect on the observed spectra of free running klystrons, the following test was made when the radiometer was at Haystack. According to Caton, a harmonic marker signal generated by a free running X-band klystron was placed in the center channel by adjusting the 98 GHz klystron repeller voltage. The marker was turned off and observations then were made. In the Version I radiometer, the first L.O. was phase locked to better than $10^{-7}$. Instead of the transfer oscillator used by Caton, a direct reading frequency meter was used to count the X-band klystron frequency
as its repeller voltage was adjusted.

A 60-second integration was performed with the resulting spectrum shown in Figure 4.1-2. Note that even with the 98 GHz klystron phase locked, the resulting spectrum was almost 5 MHz wide. This should be contrasted with the spectrum produced with the Version VIII radiometer using a phase locked marker signal as shown in Figure 5.2-5. As a result of this experiment all critical oscillators were either phase locked, crystal or temperature stabilized.

In preparation for observations, the instrument was allowed to stabilize for about an hour after which the klystrons were phase locked. The integration time on all the channels was set, normally to a 20-second integration time. A calibration sequence was then followed, using a 100K calibration signal produced by a noise tube followed by a remote controlled precision attenuator. On the strip chart recorders a baseline was established for each channel, the noise tube was turned on, and the gains adjusted on each channel to keep the trace on the chart. As the D.C. balance of the entire system was poor, this required several iterations.

The sun was then tracked automatically and the antenna temperature balanced with a remote controlled precision attenuator and noise tube. By switching the first waveguide switch to calibration, the solar antenna temperature could be measured by balancing the balance noise tube against the calibration tube. The calibration of the reference temperature was Caton's and was not verified.

The servo loop controlling the balance attenuator by the broadband
Figure 4.1-2 Free running marker at 101.736 GHz.
channel output was closed and a base line established on the recorders. The waveguide switch was then turned onto the sun and the channel temperatures referenced to the balance noise tube were recorded on strip chart recorders. After equilibrium was reached, the cycle was repeated.

The recorder data from the 16 channels was reduced manually. The peak-to-peak values of the baseline was termed $6\Delta T_{\text{rms}}$. The difference between mean values during the calibration established a calibration factor for each channel. The channel calibration factor times the channel deflection when on the sun gave the channel temperature difference with reference to the balance tube temperature.

Operation of the entire system was unwieldy, and the reduction of data time consuming, requiring about 5 times as long to reduce the data as to take it. Furthermore, the data obtained with this version must be used with caution. In the process of testing the channels for possible use with the Version VIII radiometer, the detectors were not found to be square law.

The detector circuit is shown in Figure 4.1-3, which was extracted from the Ewen-Knight drawings and checked against the circuit. The response of Channel A, the center channel of the radiometer, is also shown in Figure 4.1-3. As can be seen, it is not square law. Aside from possibly indicating the presence of an absorption line, the data was not used. A spectrum observed on 8 March is shown in Figure 4.1-4. Also plotted are Caton's measured and predicted data, and our predicted spectrum, reduced by a factor of 2.

Consistently shaped spectra could be obtained if a calibration was
Figure 4.1-3 Channel A Detector Circuit and Power Response.
Figure 4.1-4  Ozone Absorption Spectra, 8 March 1970.
performed prior to a sun observation. If the radiometer was simply switched from a matched load after a base line was established to the sun repeatedly, the spectra were not consistent. Figure 4.1-5 shows a series of spectra taken every 10 minutes with no calibration between the runs.

4.2 **Version II - Total Power Radiometer.**

The Version I radiometer was designed for an absorption measurement where the antenna temperature was in the order of 2500°K. It required a balance noise tube and elaborate servo systems to keep the radiometer in balance. The ozone emission experiment balance requirements were not so stringent.

By redesigning the radiometer, its performance could possibly be improved. The 6 dB insertion loss contributed by the switches could be eliminated in a total power configuration. The RG/9 cable from the antenna focus to the first T.W.T. contributed 2 dB. The first T.W.T. could be replaced with a tube having a noise figure of 5 dB instead of 7, thus gaining 2 dB. These changes were the basis of the Version II radiometer.

4.2.1 **Circuit Description.**

The Version II radiometer, Figure 4.2-1, was considered a "learning" radiometer. It was used to become familiar with 3 mm wavelength equipment and with the Haystack spectral-line processing system. A six-inch dish designed for 95 GHz was obtained from NASA-ERC.* The "front

* The help of A. O'Brien and R. Wiegand is gratefully acknowledged. Their assistance kept the experiment alive during a critical period.
Figure 4.1-5  Absorption Spectra, Consecutive Observations without Calibration.
Figure 4.2-1 Total Power Radiometer, Version II.
end" was mounted on an aluminum plate on a tripod. An attempt was made to manually track the sun and so duplicate Caton's absorption experiment, even though the sensitivity of the instrument was marginal. A ratio of line strength to $\Delta T_{\text{rms}}$ of less than 2 was expected.

The layout of the equipment arrangement is shown in Figure 4.2-2. The radiometer was located outside the Haystack radome since the radome attenuation at 101 GHz was unknown. Since the radiometer was not mounted in the antenna, observations could be made any time the U-490 computer was free. On the other hand, control of the radiometer had to be done by phone, and the calibration program, controlled by the computer console, could not be used. Only limited use was made of the Version II radiometer.

4.3 Version III - Simple Dicke Switched Radiometer.

The Dicke switched radiometer of Version III incorporated several improvements as shown in Figure 4.3-1. The second L.O. at 3.255 GHz was replaced by a temperature stabilized oscillator that had less than 500 Hz drift over a $0^\circ\text{C}$ to $60^\circ\text{C}$ temperature range and was stable to $<10^{-7}$ over one hour as measured by a frequency counter and digital recorder. The first traveling wave tube was replaced by one with a 1 dB improvement in noise figure. But the gain in noise figure was offset by the 3 dB insertion loss of the ferrite four-port switch. A free-running frequency marker was added to the 1st L.O. leg to check the frequency settings and correlator operation. The whole radiometer front end was mounted on a large equatorial telescope mount so that the sun could be tracked, and the antenna pointed to any part of the sky. Some meaningful observations
Figure 4.2-2 Layout of experiment at Haystack Observatory.
Figure 4.3-1  Version III Radiometer.
were made with this version, even though it was marginally sensitive.

4.4 Versions IV, V, VI, and VII: Frequency Switched Radiometers.

The Version III radiometer's sensitivity was within 3 dB, or a factor of 2, from meeting the sensitivity requirements for the experiment, if the ferrite switch could be eliminated. A frequency switched radiometer would not require a ferrite switch, so four frequency switched modifications were tried. The first two were unsuccessful, the third partially successful, and the fourth, Version VII, was never tested thoroughly.

It is a simple matter to frequency switch a klystron oscillator. It is a more difficult task to switch and phase lock a klystron in the frequency range up to about K-band, and still more difficult with W-band klystrons with their narrow oscillation modes. The National Radio Astronomy Observatory has a switched 90 GHz continuum receiver.* But, to duplicate the switching and lock circuits at MIT would have required about $20,000, and this funding was not available.

In Version IV, Figure 4.4-1, the X-band reference was switched by the Haystack frequency synthesizer through a Dymec synchronizer. The analysis was that if the X-band reference could be switched slowly enough, the primary phase lock loop controlling the 98 GHz klystron would track the reference. The Haystack processor uses a 200 msec. half cycle, but during the first 15 msec. no data is taken. This time is available for switching. Unfortunately, the Dymec uses a search

* S. Weinreb, personal communication.
Figure 4.4-1  Version IV - Frequency Switched First Local Oscillator Using Switched Reference Frequency.
oscillator to maintain phase lock, and the large frequency deviation produced during the switching period drove the primary lock-loop out-of-band and the first L.O. klystron off its oscillator mode.

Version V, Figure 4.4-2, incorporated the idea suggested by J. Waters.* By switching the third L.O., the front end could remain stable. A diode switch driven by another switch driver was used to connect alternately the two crystal oscillators to the third mixer stage.

The problem with this switching arrangement was that a 2 MHz change in frequency was about a 6% change in the 30 MHz I.F. stage, a significant percentage. Since the bandpass characteristic of the I.F. stages was not uniform with frequency, a poor baseline resulted.

The spectrum produced by the Version V radiometer (third L.O. switched) is shown in Figure 4.4-3. The base line was reasonably constant. Figure 4.4-4 shows the results of one spectrum with a marker subtracted from a spectrum without the marker. The base line is reasonable, but to use this technique would require $2\sqrt{2}$ times as long in real time for an equivalent integration time. Then, the difference between two emission spectra is small, and this is further reduced when the spectra are subtracted from one another. The technique was abandoned in favor of the Version VI radiometer.

A partial schematic of the Microwave Systems PLS-160 phase lock synchronizer as connected into the primary lock loop is shown in Figure 4.4-5. It is a 60 MHz synchronizer fitted with a 160 MHz mixer stage.

The loop filter, $F(s)$, is a single pole filter, but the loop transfer

* J. Waters, personal communication.
Figure 4.4-2  Version V - Third Local Oscillator Switched.
Figure 4.4-3: Base line of Version V radiometer.
Figure 4.4-5  Block Diagram of First Local Oscillator Phase Lock Loop with Search Oscillator. (Microwave Systems PLS-160)
function is second order. This type of loop is commonly used in space-track receivers where doppler changes would otherwise require wider bandwidths than necessary, reducing the system signal-to-noise ratio. Gardiner (1966) and Tausworth (1966) are good references on phase lock techniques.

Three oscillators were available for switching, the 60 MHz reference, the 100 MHz mixer oscillator, and the X-band reference. The X-band reference was unsuccessfully switched in Version IV. The 100 MHz oscillator could theoretically be switched ± 1 MHz with the loop remaining locked because as long as the lock-loop I.F. stayed within the loop bandwidth, the phase detector would pull it into lock. This was tried in Version VI, Figure 4.4-6, and the first local oscillator was successfully switched about 1.5 MHz with a stable lock. Useable data was received with this configuration, and an example of an absorption measurement is given in Figure 4.4-7. The sun was manually tracked for 5 minutes with the radiometer on an equatorial mount. The predicted spectrum has been reduced by a factor of 2 for the double sideband response. No frequency sensitive components were ahead of the mixer in this configuration. The predicted spectrum was further reduced a factor of \((\frac{5}{14})^2\) to account for the beam width ratios of the dish and the sun. The beamwidth of the T. R. G. dish was given by the manufacturer as

\[ \frac{\lambda}{D} = 1.4^\circ. \]

Night emission measurements were also made with this instrument using a horn antenna. The sky was probed in a northerly direction at 75° zenith angle \((\varphi = 1800^\circ \text{ sec})\), 55° zenith angle \((\varphi = 3600^\circ \text{ sec})\), and
Figure 4.4-6 Versions VI and VII - Frequency Switched First Local Oscillator.
Figure 4.4-7  Frequency Switched Absorption Measurement.

31 July 1970, 18:58
Elevation Angle = 10°

\( \rho_{H_2O} = 16 \, \text{g/m}^3 \)
45° zenith angle ($T = 7200^\circ$ sec, $\Delta T_{rms} = 0.5^\circ$K) before dawn. No line was detected, and the baseline was flat. (See Table 3, 31 July 1970).

The 1.5 MHz switching limit was too small for observing the mesospheric line since the line in the comparison channel is subtracted from the line in the signal channel. That the limit was caused by the PLS-160 I.F. bandwidth was confirmed by measurements, and the loop bandwidth was widened to 2.1 MHz. Two H.P. 616A oscillators were used as reference oscillators and switched with a diode switch. The stability of the oscillators is $10^{-6}$, so they were used instead of the Haystack synthesizer. The system could also be checked out in the laboratory at MIT before it was moved to the field station. Stable 8 MHz switching of the 98 GHz oscillator was achieved in the laboratory.

A search oscillator was also added to the loop. The oscillator, a simple multivibrator, Figure 4.4-8, was added to the Microwave Systems PLS-160 phase detector differential amplifier. Even though the oscillator was left running, the frequency ripple on the 98 GHz klystron was less than 2 kHz as measured by the frequency discriminator in the PLS-160.

At Haystack the system would not remain stable, and the trouble could not be located. When the equipment was moved back to the laboratory the trouble was traced to a back panel switch that was inadvertently thrown during the move. The capability of Version VII remains to be explored.

4.5 Low Loss Mixer Development.

There is no rigorous theory which adequately describes mixer operation, taking into account both the time varying junction resistance and
Figure 4.4-8 1 kHz Search Oscillator Added to Microwave Systems PLS-160 Phase Locked Oscillator Synchronizer.
capacitance and the various parasitics that exist in a diode. Saleh's work (1970) is the most comprehensive work in the literature, but even it is restricted to resistive mixers with pure exponential diodes. The series resistance and junction capacitance are considered in only a minor way.

4.5.1 Discussion.

The purpose of a mixer is to translate a band of frequencies centered around a signal frequency, \( \omega_s \), to a lower output frequency, \( \omega_o \), called the intermediate frequency (I.F.). The frequency nomenclature used here is given in Figure 4.5-1. Unfortunately, the band of frequencies centered approximately \( \omega_s - \omega_p = \omega_o \) away from the pump frequency, \( \omega_p \), on the lower side, called the image frequency, \( \omega_i \), is also translated to the output. This band can be rejected by a filter, but this is rarely done at millimeter signal frequencies with low I.F.'s because high Q filters are difficult to build and have high insertion losses.

Further, because the pump is a "large signal" in the sense that the diode appears nonlinear to it, harmonics of the pump will also be produced. These in turn will mix with the other frequencies present, producing still more frequencies. A portion of the frequency spectrum existing in the mixer is also given in Figure 4.5-1. The frequencies other than \( \omega_s \), \( \omega_p \), and \( \omega_o \) can be called the "out of band" frequencies.

4.5.2 Optimization of mixer performance.

Several conditions for optimizing conversion loss can be inferred from Saleh's ideal mixers. He proves that the optimum embedding network for a mixer is lossless, which means that the out-of-band frequen-
\[ \omega_p = 2\pi f_p = \text{ Local Oscillator} \]
\[ \omega_s = 2\pi f_s = \text{ Signal Frequency} \]
\[ \omega_o = 2\pi f_o = \omega_s - \omega_p \ll \omega_p = \text{ Intermediate Frequency (I.F.)} \]
\[ \omega_i = 2\pi f_i = \text{ Image Frequency} \]

Figure 4.5-1  Frequencies Existing in a Mixer and Nomenclature.
cies should be terminated reactively. This may seem obvious from a conservation of energy point of view since energy from the signal must go to the output, (I.F.), if all other frequencies are terminated reactively and assuming frequency conversion takes place. But, Saleh considers other factors such as stability and realizability in his proof.

Since the ideal diode is a time varying resistance driven by the pump, Saleh shows that the optimum resistance waveform is a square wave. Under strict termination of out-of-band frequencies, he shows that the optimum loss, $L_{opt}$, is given by:

$$L_{opt} \approx 1 + 4 \sqrt{\frac{R_{min}}{R_{max}}}$$  \hspace{1cm} 4.5.1

where $R_{min}$, $(R_{max})$ = minimum, (maximum) resistance of the diode resistance waveform.

This implies that the diode must be driven hard between a short circuit state and an open circuit state. Its action could be likened to the operation of a switch and is the basis of the switch mixer of Rafuse (1967).

How closely the diode resistance waveform approaches a square wave is determined by the parasitics that exist in the diode. Saleh considers the effect of the series resistance, $R_s$, and the junction capacitance, $C_j$, and shows that the optimum loss is given by:

$$L_{opt} = 1 + 2 \left( \frac{\omega_c}{\omega_s} \right)^2 \left[ 1 + \sqrt{1 + \left( \frac{\omega_c}{\omega_s} \right)^2} \right]$$  \hspace{1cm} 4.5.2

where $\omega_c = \frac{1}{R_s C_j}$

The most realistic model used by Saleh could be described as in Figure 4.5-3.
Figure 4.5-3 Saleh's most realistic mixer model.

Figure 4.5-4 Hypothetical Diode in Waveguide and Model.
In the millimeter wavelength region, Saleh's diode model can be refined. Consider a hypothetical diode in a waveguide as shown in Figure 4.5-4. The switch resistance, $R_s^r$, or junction resistance, is shown as a function of $n$ and $I_{\text{saturation}} = I_{\text{sat}}$. These quantities are a measure of the quality of the junction and are found in the equation of a Schottky barrier diode, the only type of diode considered to be suitable for high frequency mixers:

$$I = I_{\text{sat}} \left( \frac{qV}{kT} - 1 \right)$$ \hspace{1cm} 4.5.3

where $I$ is the current through the diode produced by a voltage $V$.

This equation can be expressed in terms of the semiconductor parameters by the diffusion theory of current transport (Schottky, 1938, as discussed in Sze, 1969):

$$J_n = \left( \frac{q^2 D_n N_c}{kT} \right) \left[ \frac{8 (V_{bi} - V) \Theta T N_D}{\varepsilon_s} \right]^{1/2} \exp \left( - \frac{q \Phi_{bn}}{kT} \right) \left[ \exp \left( \frac{qV}{kT} \right) - 1 \right]$$ \hspace{1cm} 4.5.4

$$= J_{\text{sat}} \left( \exp \left( \frac{qV}{kT} \right) - 1 \right)$$

where the terms are those commonly used in semiconductor theory:

$J$ = Current density (Amp/cm$^2$)

$q$ = Electronic charge (coulomb)

$D_n$ = Electron diffusion coefficient (cm$^2$/sec)

$N_c$ = Effective density of states in conduction band (cm$^{-3}$)

$k$ = Boltzmann constant (Joules/°K)

$T$ = Temperature (°K)

$V_{bi}$ = Built in potential (volts)

$V$ = Applied voltage (volts)
\[ N_d = \text{doping density (cm}^{-3}\text{)} \]
\[ \phi_{Bn} = \text{Barrier height of the metal-semiconductor barrier (0.77v: Au-GaAs)} \]
\[ \varepsilon_s = \text{Permittivity of the semiconductor (farad/cm.)} \]

The energy band diagram of the junction under different biasing conditions is given in Figure 4.5-5 together with a typical diode current-voltage plot.

This equation is still only an approximation since it does not include the effects of image forces, tunneling, surface states, minority carrier injection, and charge storage. These effects are discussed in the literature, and the measure of their effects is usually represented by a constant, \( n \approx 1 \), in the exponential, \( \exp \left( \frac{qv}{n kT} \right) \) (Sze, 1969, has the most complete bibliography on current theories of Schottky barriers).

The junction capacitance is shown to be a variable capacitance since the depletion width changes with voltage. The depletion layer capacitance, \( C_j \), is given by the well known equation:

\[ C_j = \frac{2Q_{sc}}{V} = \sqrt{\frac{\varepsilon_s N_d}{2(V_b - V - kT/q)}} \]

where \( Q_{sc} = \text{space charge (coulombs)} \)

The addition of the parasitics, the series inductance, \( L_s \), the case capacitance, \( C_c \), and the variable junction capacitance, \( C_j \), complicates the optimization problem enormously. If the semiconductor parameters are also considered, a rigorous analysis, for example, relating doping density, \( N_d \), to conversion loss, is virtually impossible.

4.5.3 **Engineering approximations.**

The alternative to a rigorous analysis is a good "engineering
a. Energy band Diagrams

b. Current Voltage plot

Figure 4.5-5 Energy Band Diagrams and Current Voltage Plot of a Metal Semiconductor Junction.
approximation". By equation 4.5.1, the ratio $R_{\text{min}}/R_{\text{max}}$ should be as small as possible. Alternately, $G_{\text{max}}/G_{\text{min}}$ should be as large as possible.

Consider:

$$I = I_{\text{sat}} e^{\frac{V}{kT}} - 1$$

$$I + I_{\text{sat}} = I_{\text{sat}} e^{\frac{V}{kT}}$$

$$\frac{2V}{kT} = G(I) = I_{\text{sat}} e^{\frac{2V}{kT}} \frac{1}{nKT} = (I + I_{\text{sat}}) \frac{1}{nKT}$$

then $G(I)_{\text{min}} = I_{\text{sat}} \frac{1}{nKT}$

So, $I_{\text{sat}}$ should be made small by making the junction area small and the doping density, $N_d$, small from equation 4.5.4. $G(I)_{\text{max}}$ can be made large by driving the diode hard into the forward region.

The cutoff frequency, $\omega_c$, should be made large according to equation 4.5.2. But,

$$\omega_c = \frac{1}{R_s C_j} \alpha \frac{N_d}{\sqrt{N_d}} = V_N$$

since $\alpha = qN_e$ in an n-type semiconductor.

$$\alpha = \text{conductivity} \ (\text{cm}^2/\text{v-sec})$$

$$\mu = \text{carrier mobility} \ (\text{cm}^2/\text{v-sec})$$

$$D_n = \frac{q}{kT} \text{D} \text{n}$$

$R_s$ represents a direct loss in the mixer and is judged to be more important than the $I_{\text{sat}}$ term which requires $N_d$ to be small, so $N_d$ should be made large. $R_s$ can also be made small by making the area of the junction large:

$$R_s = \frac{\rho A}{\ell} = \frac{\rho}{A \sigma} = \frac{\ell}{A q N_d \mu}$$

$A = \text{area (cm)}$

$\rho = \text{resistivity (ohm cm)}$

$\ell = \text{length (m)}$
But, the capacitance becomes large in the same ratio. Since the $C_j$ shunts the junction resistance, $R_j$, it is felt to be more important, so the area of the junction should be small. The carrier mobility, $\mu$, should be as large as possible. This is the principle reason for using GaAs, one of the higher mobility semiconductors. The characteristics of the GaAs used in the diodes is given in Appendix A.

Modern planar semiconductor techniques have made it possible to produce uniform Schottky barrier junctions with a junction diameter smaller than most point-contact junctions. A $2 \times 10^{-6}$ meter ($2\mu$) diameter junction is about the state of the art at this time. The honeycomb technique of Young and Irwin (1965) made it possible to utilize junctions of $5 \mu$ dia, but their technique of registering the whisker did not realize the full potential of the planar technology. A cross section of the semiconductor Schottky barrier diode is shown in Figure 4.5-4.

One major problem that had to be solved was bringing the diode contact out to the microwave structure. A long development program resulted in an integral choke diode package that was then refined to a package useable to well above 100 GHz. A summary of the diode package development and detailed construction methods are found in Appendix A.

The image termination was made reactive by terminating it in a waveguide below cutoff. To avoid putting the signal frequency too close to the guide cutoff where the attenuation was high, a high I.F. was used. In the case of the 60 GHz mixer, 3 GHz was used. In the proposed 100 GHz mixer, 7.8 GHz was to be used, the frequency determined primarily by the availability of a 100°K uncooled parametric amplifier with a
Figure 4.5-4 Planar Schottky Barrier Diode.

Diode Structure

Figure 4.5-5 Radial Line Termination.
200 MHz bandwidth.

The frequencies in the vicinity of $2\omega_p$ were terminated in the package itself. By Marcwitz (1951) pp. 29 and 89, a non-uniform radial line has a $Y_{in} = 0$ under certain ratios of inner and outer radii that are given in the form of graphs. In Figure 4.5-5, the diode structure believed to approximate the radial line is shown. This termination has not been experimentally verified except indirectly. A mount built by R. Boyden had provisions to tune the sum frequency ($\omega_s + \omega_p$). The variation of noise figure with tuning of the sum frequency was less than 1/2 dB.*

The I.F. termination was matched to 50$\Omega$ by transitions, and the signal in the wave guide was presented a high impedance by a series of low-high impedance line sections for the 60 GHz mixer. The integral chokes in the diode package were part of this filter. In the 100 GHz mixer mount, rejection cavities tuned to the signal frequency were used. DeLoach (1963) gives design curves which were then refined by Varon (1967).

The effectiveness of the rejection cavities has not been measured. The $TE_{10}$ circular mode at 100 GHz will propagate down the I.F. port because the inner radius of the coaxial line is so large. Thus, the validity of the design based upon TEM mode propagation is questionable. But, on the other hand, only the TEM mode is believed to be excited.

* R. Chick, personal communication.
To match the diode to the waveguide impedance, reduced height guide was used. The objective was to center the diode impedance locus produced by the pump (as simulated by a d.c. bias), on the center of a Smith chart. The ideal diode characteristic would resemble Figure 4.5-6. In the forward direction, the diode appears as a short circuit (closed switch), and in the reverse direction as an open circuit (open switch). How closely the locus approaches this ideal determines how low the loss will be (by equation 4.5.1). In the 60 GHz mixer the guide height was chosen arbitrarily to be 0.020" high (0.070" is standard). This dimension was determined by the minimum working distance then achievable in the diode package. This is shown in Figure 4.5-7. Another advantage to the reduced height would be to lower $L_s$ since the whisker could be made shorter.

4.5.4 Experimental results.

The highest cutoff frequency diodes built were 2 $\mu$ junctions. Only an estimate can be made of $C_j$, the junction capacitance, because it is too small to be measured by a Boonton 75C capacitance bridge at 1 MHz. But, the change in capacitance in the reverse bias region could be measured. Figure 4.5-8 is a typical plot of the C-V curve. The bridge was balanced at a 0.05 p.f. offset corresponding to zero volts bias. Beyond -4.0 volts, avalanche is believed to occur, but this is uncertain. The zero bias capacitance was determined by measuring the differential capacitance of a 5 $\mu$-diameter diode and also its zero bias capacitance. The 5 $\mu$ diode had a zero bias capacitance of 10±2 ff. The reverse biased capacitance varied in the ratio 25 to 4 compared to
Figure 4.5-7 Diode Structure Size Limitations.

Figure 4.5-8 Capacitance versus Voltage Plot, 2 micron Diameter Diode.
the 2 μ-diode, so the 2μ-diode capacitance is assumed to be in the order of 1 ff (femto farad or "fuff").

Twenty-two diodes with 2μ diameter junctions were measured. The median value of $R_s$ measured with a curve tracer was 16 Ω with a minimum value of 6 Ω and a maximum of 28 Ω. Assuming a selection process was used to segregate the diodes with a maximum value of $R_s = 10 Ω$, the cutoff frequency would be in the order of 10,000 GHz. This is more than an order of magnitude higher than the highest cutoff frequency reported in the literature (800 GHz; DeLoach, 1964).

The 60 GHz diode mount is shown in Figure 4.5-9. A typical small signal admittance plot of the 60 GHz diodes is compared with the ideal characteristic in Figure 4.5-6. This diode was one of a pair of diodes (2-J-10 and 11) which produced a single sideband conversion loss of 6 dB in a balanced mixer with an I.F. of 3.1 GHz. The admittance was measured only to 2 mA in the forward direction, but in the mixer, the rectified d.c. current was 6.9 and 7.1 mA respectively for the two diodes. The forward admittance was thus higher during operation than the locus shows.

The 100 GHz diode mount is shown in Figure 4.5-10. Full height guide was used in an attempt to establish a sequence for design. Full height guide would be used first, then the guide impedance would be lowered to match the diode. In this way the very expensive machining of matching transition sections would be avoided. The sequence was not developed due to a lack of test equipment as noted in the beginning of the chapter.
Figure 4.5-9 60 GHz Diode Mount.
Figure 4.5-10  100 GHz Mixer Mount.
4.5.5 Recommended further mixer development.

The development of low loss mixers in the millimeter wavelength range is still more "art" than engineering. Saleh's work remains to be verified experimentally and then extended to include the parasitic elements described above. The effect on conversion loss of semiconductor parameters such as doping density, mobility, dielectric constant, and barrier height should be investigated.

There are several possible effects which can be investigated fairly easily. To make contact to the $2\mu$-diameter diodes is an extremely difficult technical job. If good conversion loss is achieved with $3.5\mu$-diameter diodes, the task of registering the diode whisker is made much simpler.

On the other hand, if $2\mu$-diameter dots produce better results, then the semiconductor theories of Schottky barriers for small areas must be investigated. An elementary calculation shows that there are about $10^4$ doping centers in the depletion region of a $2\mu$-diameter dot. Are Fermi statistics still valid under these conditions?

The series resistance, $R_s$, is believed to be due to the spreading resistance of the current in the semiconductor. The effect of the spreading resistance as opposed to a "skin depth" resistance should be investigated. In either case, an attempt should be made to make the diode wafer thinner. Present diodes are about 0.006" thick, but the author believes 0.0005" (12$\mu$) thick wafers are feasible if exceptional care is taken during handling.

Part of the loss in the 60 GHz mixer is attributed to loss down the
I.F. port. The high impedance-low impedance sections can support higher order modes than TEM because of the large inner radius of the chokes. The obvious solution is to make the package smaller. A diode diameter of 0.005" is believed to be feasible.

These are some ideas the author feels should be investigated to produce low loss mixers.
5. DESCRIPTION OF RADIOMETER.

The final version of the radiometer, Version VIII, met the design specifications outlined in Chapter 3. The final version included an accurate temperature calibration circuit, a noise balance circuit, and a precise frequency calibration circuit. It was aDicke switched receiver with a system temperature between 4,000 and $5,000^\circ K$. Rough checks of the radiometer's frequency response indicated that the image band may be attenuated by approximately 20 dB by the ferrite switch, but these tests were hampered by the lack of test equipment in this frequency band. So the system temperature is assumed to be double side band, which is still within the required sensitivity specification.

5.1 Radiometer Circuit.

Figure 5.1-1 is a schematic of the Version VIII radiometer. The noise tube balance circuit also served as the frequency calibration circuit. The tenth harmonic of an independently phase-locked signal at X-band (10.173683 GHz) was fed into the signal port of the waveguide switch through a 10 dB coupler. The second port of the switch connected to the calibration leg. The ferrite switch was driven by a switch driver, Figure 5.1-2, which could produce an asymmetric current wave. The noise figure of the receiver was optimized by adjusting the current waveform. The Adtech mixer's performance was improved about 1 dB by varying the point pressure.

The first traveling wave tube amplifier had a noise figure of 5 dB measured by both a H. P. noise figure meter and an All hot-cold noise source. The second converter stage L.O. was at 3.255 GHz, temperature
Figure 5.1-1 Version VIII of Radiometer.
Figure 5.1-2  Ferrite Switch Driver 1 Hz to 10 KHz.
stabilized to less than 500 Hz drift over 0°C to 60°C. The stability of the oscillator was measured to be less than $10^{-7}$ over one hour as measured by a frequency counter and digital recorder. The first local oscillator was phase locked against a stable X-band reference generated by another phase lock loop that was stable to $10^{-8}$ in one hour.

The second I.F. could be selected by the choice of the first L.O. frequency. For use at the Haystack Observatory, the second I.F. was 30 MHz, and a 10 MHz filter was used before the second converter as an image filter. When the MIT 20 Channel synchronous detector was used, either 60 MHz or 105 MHz was used as the second I.F. An image filter covering 3065 to 3235 MHz was used before the second converter in those circumstances.

The bandwidth of the MIT 20 Channel processor was limited by the filter bank. A tuned R.F. amplifier, detector, and audio amplifier were built on one board, and to change the filter the entire unit had to be redesigned, since the frequency selectivity was determined by the amplifier frequency response. To make the processor more flexible, a modular approach was followed in redesigning the filter bank. Separate filters were built with 50-ohm input-output impedances, and separate square-law detectors using back diodes were also made. The second converter amplifier had insufficient gain to drive the A-D converters, so a broad band (10-200 MHz), 20 dB gain amplifier was added to the detector stage*. The schematic of the amplifier detector stage is

* My thanks go to R. Chick and C. Curley for their assistance in designing and building the amplifier-detector stages.
given in Figure 5.1-3, and the detector output versus C. W. input power
for the seven channels is similar to Figure 5.1-4. The amplifier-
detector stages were tested over a 10°C temperature variation, and the
change in output was too small to plot. By terminating the detector in
a 1,000 Ω resistor, the dynamic range can be increased about 10 dB
with a resulting drop in output voltage.

The filters used for the broadband emission measurement were two
pole, 10 MHz bandwidth filters centered at 25, 80, 130, and 185 MHz, and
Telonic filters at 102.7, 105, and 108.3 MHz with 3.3 MHz bandwidths.
The schematic for the 2 pole filters is given in Figure 5.1-5. Variable
capacitors were used to facilitate tuning and shifting of the center
frequency. In addition to the 7 filter channels, a broadband channel,
20-270 MHz was used to check the mean temperature.

Each detector stage was followed by an audio amplifier, Figure 5.1-6.
The bandpass characteristic of each stage terminated by a coupling
 capacitor and the analog-to-digital converter stage is similar to Figure
5.1-7. A schematic of the broadband emission filter bank is given in
Figure 5.1-8.

5.2 Radiometer Tests and Calibration.

5.2.1 Calibration of reference noise tube.

At lower frequencies, about 10 GHz and below, the National Bureau
of Standards can calibrate gas filled noise tubes as secondary standards.
In the millimeter wavelength range, this service is not offered, and the
gas tubes must be calibrated against some reliable noise power source.
One way is to use a matched load raised or cooled to a known temperature.
Power \( P_{in} \), C.W. (dBm), \( f = 10.7 \text{ MHz} \), \( R_L = 1 \text{ kΩ} \), and VTVM

Figure 5.1-4 Transfer Characteristic Channel 3.

<table>
<thead>
<tr>
<th>Freq(MHz)</th>
<th>( L_1, L_2 )</th>
<th>( C_2 )</th>
<th>Insertion Loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>6T, ( \frac{1}{2} &quot; ) Air Core</td>
<td>11-110</td>
<td>0.5 dB</td>
</tr>
<tr>
<td>80</td>
<td>6T, ( \frac{1}{4} &quot; ) Air Core</td>
<td>3-16 pf</td>
<td>0.8 dB</td>
</tr>
<tr>
<td>130</td>
<td>6T, ( \frac{1}{4} &quot; ) Air Core</td>
<td>JFDVC9GW</td>
<td>1.0 dB</td>
</tr>
<tr>
<td>185</td>
<td>2T, ( \frac{1}{4} &quot; ) Air Core</td>
<td>JFDVC9GWY</td>
<td>1.6 dB</td>
</tr>
</tbody>
</table>

Figure 5.1-5 Bandpass Filter.
Figure 5.1-6 Filter Bank Audio Amplifier.

Figure 5.1-7 Audio Amplifier Frequency Response.

Figure 5.1-8 Broadband Emission Filter Bank.
Another way is to submerge the antenna in a black body of known temperature. This method calibrates the entire antenna-radiometer system, and is the way the radiometer was calibrated.

A "black body" was made out of a stainless steel beaker lined with microwave absorber as shown in Figure 5.2-1. The absorber is a thermo setting epoxy which is mixed with a hardener (trade name: Ferroflow Type C Liquid Microwave Absorbant). In the plastic state, it could be molded to fit the beaker. After about 15 minutes the epoxy sets and it can be easily machined.

Two absorbers were made. In one, the epoxy hardened faster than expected, so the inside surface was produced during the mixing process. It was quite rough and irregular, assuring good scattering. The second was molded around a polyethylene bottle. After the epoxy set the bottle was cut away and the inside machined into a large thread. A hole was drilled in the side to accomodate a mercury thermometer, and the beaker was fitted into a lab flask heater. The whole arrangement was encased in at least 2" of styrofoam insulaton. A variable transformer controlled the temperature which would stabilize in about 5 minutes. The VSWR of the horn while in either absorber was measured to be less than 1.08.

The radiometer gain was calibrated with the calibration noise tube, Figure 5.2-2, assuming the calibration temperature was $100^\circ$K. The insertion loss of the Hitachi precision attenuator set to 0.0 dB, two bends, and the T.R.G. waveguide switch was measured using the substitution method. At 101.7 GHz, the insertion loss was $2.1 \pm 0.1$ dB. For a
Figure 5.2-1 Antenna "Black Body".
Figure 5.2-2 Calibration and Balance Circuit.

\[
\text{Tang. Measured} = \text{Tang. Eff.} \cdot 0.9 \cdot (1-e^{-0.23}) + T_{\text{line}} \cdot (0.1) \cdot e^{-0.23} + T_{\text{line}} \cdot (1-e^{-0.23})
\]

\[
= \text{Tang. Eff.} \cdot 0.71 + T_{\text{line}} \cdot 0.29
\]

or \[
\text{Tang. Effective} = 1.41 \cdot \text{Tang. Measured} - 0.41 \cdot T_{\text{line}}
\]

Figure 5.2-3 Temperature Model of Line Loss.
$100^\circ K$ calibration, then, the attenuator was increased to 17.9 dB.

After the absorber temperature stabilized and after completion of the radiometer calibration with the noise tube, the horn was placed into the absorber-filled beaker and a rough foil placed around the neck of the horn to reflect the back lobes. A 4 min. run was taken with the Haystack correlator and the temperature measured. The $\Delta T_{\text{rms}}$ was about $3^\circ K$ for all the measurements. The temperature of the absorber was raised, the radiometer recalibrated, and the process repeated.

The reference port for all temperature measurements was at the front of the four port circulator. So, the antenna temperature measurements had to be referred to the reference port. The insertion loss of the waveguide bend, the 10 dB coupler, and the TRC switch was measured to be 1 dB, assuming the loss down the side arm of the coupler was 0.1. The assumption was then made that the energy from the antenna dropped to 0.9 of its value due to the loss in the side arm. The reduced power was then attenuated by a lossy line of 1 dB insertion loss that was at the reference temperature measured by a thermometer. The radiative transfer equation was then used to compute the temperature at the reference port as shown in Figure 5.2-3.

The temperature measured by the radiometer at the reference was also corrected for the difference between $T_o = 290^\circ K$, the reference temperature of the noise tube excess noise power, and the ambient temperature of the load at the time of measurement. The results are plotted in Figure 5.2-4. The absorber temperature was measured by the thermometer embedded in the microwave absorber. $T_{\text{measured}}$ was measured
Figure 5.2-4 Comparison of Absorber Temperature versus Effective Antenna Temperature.
by the correlator and corrected for the reference temperature deviation from $290^\circ$K, and $T_{\text{line}}$ was assumed to be the ambient temperature measured by another thermometer in the proximity. Both thermometers were laboratory grade, $\pm 1\%$ calibration.

The errors in the measurement are in the model used, the heating of the line due to conduction along the waveguide, the antenna losses, and finally the $\Delta T_{\text{rms}}$ of the correlator measurement. They are estimated to total about $5\%$, so the noise tube was assumed to produce a temperature of $10,000^\circ$K $\pm 5\%$.

5.2.2 Frequency stability.

The frequency stability of the radiometer was checked by monitoring each of the critical reference frequencies. The H. P. frequency counter 5245L/5257A, with an accuracy better than $10^{-10}$ was checked against the Haystack station standard and found to agree within the 8 digit readout of the counter to less than 1 digit or $10^{-9}$. The X-band reference was continually monitored during observations and would drift on the order of 2 kHz during a 10 hour observation period. As the frequency circuits were monitored, this deviation would be periodically corrected. The 60 MHz and 100 MHz reference oscillators in the primary phase lock loop were measured against the Haystack standard using a counter and recorder and found to have a peak-to-peak frequency deviation of around 2 Hz with a long term drift over one hour of 14 Hz.

These two reference frequencies and the X-band reference determine the absolute stability of the 98 GHz oscillator frequency to less than 20 kHz over ten hours. The ripple or "jitter" on the 98 GHz klystron
was measured to be less than 2 kHz as measured by the PLS-160 calibrated frequency discriminator.

5.2.3 Correlator checkout.

The operation of the entire radiometer-correlator system was checked by inserting a 10th harmonic of an independently phase locked X-band source into the balance coupler arm. The resulting spectrum is shown in Figure 5.2-5 and the marker shifted 1 MHz is shown in Figure 5.2-6. It was standard procedure always to check the operation of the system using a marker.

5.2.4 Radiometer image response.

The very strong marker was also used to check the image response of the radiometer. With constant X-band marker power, the marker frequency was shifted to the image frequency of the radiometer (101.73683 -6.2 GHz for a 105 MHz 2nd I.F.). The precision attenuator was then lowered to give the same signal power at the second I.F.

This measurement showed that the image response was attenuated by 20 dB, but the assumption is made that the harmonic generator transfer response is constant with a change in X-band frequency of 600 MHz. It is not known if this is true, so all spectral measurements assumed a double side band response, a conservative assumption.

5.3 Observation Procedures.

Absorption and emission measurements were made at the Haystack Field Station of Lincoln Laboratory, Westford, Massachusetts. Broadband emission measurements were made at M.I.T., Cambridge, Massachusetts, from the Compton Laboratory roof, and at Lincoln Laboratory, Lexington, Massachusetts, from the D building roof.
Figure 5.2-5 Marker Frequency at $f_0 = 101.73684 \text{ GHz}$.
Figure 5.2-5 marker Frequency at $f_0 = 101.73684 \text{ GHz}$.
Figure 5.2-6 Marker Frequency at 101.73583 GHz.
5.3.1 Observations at Haystack Field Station.

The Haystack spectral line analysis is described in detail in Conant and Meeks (1968). The "1-bit autocorrelator", described by Weinreb (1963), is the hardware portion of the system. It is a 100-channel data processor which has an effective resolution of 1/40th the input bandwidth. The input bandwidths available are 20, 4, 1.2, 0.4, 0.12 and 0.04 MHz. The 4 MHz bandwidth was normally used for the night emission spectra, so the frequency resolution was 100 kHz. All the bandwidths below 4 MHz are part of the same processor and are routinely used by radio astronomers to study spectral lines from space. The 20 MHz bandwidth is an addition to the basic processor and has not been checked out in the sense that a known radio astronomical signal has been seen with it. So, the data derived from the 20 MHz bandwidth channel was used with caution.

A Univac U-490 computer coupled to a high speed printer produces almost "real-time" plotting of the spectra. Within 5 seconds after the end of the integration period the data is Fourier transformed, but the high speed printer takes 20 seconds to print the output data format consisting of the bandpass characteristic, the numerical data, and the spectrum, along with numerous subsidiary calculations.

The integration periods are selected in 30 second increments, with periods up to 999x(\(\frac{1}{2}\) minute), or about 500 minutes, possible. In addition, the data is recorded on magnetic tape for post real time processing, so that extremely long equivalent integration times can be accumulated. Several integrations in the 18,000 to 22,000 second range
have been made using this technique.

The data could also be "massaged" by subtracting spectra taken under
different conditions, changing plot scales or ordinate positions, and
adjusting base line slopes to make it easier to interpret the data.

When the Version VIII radiometer was moved to Haystack for the
observations beginning September 14, control circuits were installed
between the hut where the radiometer was located and the computer
processor control console. Besides the digital output of the computer
an analog synchronous detector output was also continually recorded on
two different Sanborn recorders in the control room and a H. P. strip
chart recorder in the hut. The total power output of the radiometer
was also continuously recorded in the control room. Any change in
system operation, for example a phase lock loop opening, was immediately
apparent and could be corrected. If this occurred during an integration,
the correlator would be stopped, the accumulated spectrum erased, and
a new integration started after the discrepancy was corrected.

The synchronous detector output in the hut was used to balance
the antenna temperature against the reference load. Balance to less
than $10^0\text{K}$ was easily achieved using the strip chart output as a guide,
and the balance would be checked by the digital output. One of the
calculations performed by the computer was the antenna temperature at
intervals of 1/10 the selected integration time, (e.g. every 3 seconds
for a 30 second integration period). The rms deviation was also
calculated, and the mean and rms deviation of the antenna temperature
for the entire integration was also calculated. If the antenna tempera-
ture was more than $20^\circ$K out of balance, the balance noise tube attenuator would be readjusted. An exception was the observations of the antenna temperature versus time (see Table 3, 21-22 Sep.), when the antenna temperature changes due to weather were of interest.

In addition to the synchronous detector outputs, the frequency discriminator in the 98 GHz primary phase lock loop was continuously monitored on an oscilloscope in the control room. The X-band reference frequency was counted continuously by a H. P. direct reading frequency meter and checked at about $\frac{1}{2}$ hour intervals. If the frequency deviated more than 1 kHz from nominal, the X-band reference phase lock loop was retuned.

The calibration of the radiometer was performed from the control room. The waveguide switch and the calibration noise tube were remotely controlled. The calibration sequence was done in synchronism with the computer. The noise tube was turned on and allowed to stabilize for about a minute. A one minute integration with the noise tube on was followed by a like period with the noise tube off. A dummy 30 second observation was then performed on the noise tube termination. The computer output would then give the system temperature plus the normal three page output. The bandpass characteristic, the baseline, and the digital data output were checked for obvious discrepancies.

Prior to the taking of data, a turn-on procedure was followed. After warmup and klystron lock (the phase lock synchronizers were normally left on to improve stability), the X-band reference was shifted with the 98 GHz klystron power supply settings held constant. The
primary loop was checked to see that the loop I.F. signal and image frequency were about 320 MHz apart and of the correct value (the X-band reference was always on a counter). The X-band reference was set to the desired value and the primary lock loop established.

The tenth harmonic of 10.173683 GHz was then used as a line simulator. By applying an independently locked X-band signal of that frequency to the harmonic generator, the 10th harmonic was easily seen on the spectrum analyzer as a C.W. signal in the second I.F. bandpass, about 10 dB above the noise level. After checking that the marker moved the correct direction as the frequency was shifted, a spectrum would be taken with the correlator to check its operation.

If the system was working properly, the radiometer system temperature was measured and calibrated using the noise tube followed by the precision attenuator set to 17.9 dB for a 100⁰K noise signal. The system was then ready to take data.

With the post real time processing, different spectra were compared by subtraction. Since the emission line was to increase at night, a 4,000 sec. load switched run, taken before sunset, was subtracted from an equal run after sunset; a run taken before sunrise was subtracted from an equal run after sunrise; and an hour run after mesospheric sunset was compared to an hour run ending before sunrise in the mesosphere to detect any spectral change between those times. The results of those tests are given in Chapter 6.

5.3.2 Broad band emission measurements.

The broad band emission measurements made at MIT and Lincoln Labora-
tory used the processor described in detail by Waters (1970). The I.F. band centered at either 60 MHz (48 MHz wide) or 105 MHz (160 MHz wide) was power split into the corresponding number of channels. Following amplification and detection, the signal was converted to a digital signal by a voltage to frequency converter, up-down counted in synchronism with the Dicke switch, and the accumulated counts punched out on paper tape. The paper tape data was punched onto cards, which were then read into a computer and processed.

Because of a spurious signal that could not be located, a five step cycle had to be followed. First an integration was performed on a matched load followed by a calibration integration, a signal (sky) integration, a matched load integration, and finally another sky integration. The gain of each channel was determined by the calibration run, and the average of the two comparison runs was subtracted from the average of the two signal runs. Thus the "real time" was five times the equivalent integration time.

That the spurious signals were time invariant was checked by both Waters and the author. Both a matched load and the antenna aimed into microwave absorber produced flat spectra with peak-to-peak noise values as predicted.
6. **EXPERIMENTAL RESULTS.**

Observations were conducted from March to December 1970 concurrently with the radiometer development program. Meaningful data was received, however, only from the last radiometer configuration which was built at the end of August. The effects of both ozone and water vapor were observed.

6.1 **Summary of Observations.**

In Table 3 is listed a summary of all the experiments of an observational nature performed during the year. All times are local time (L.T.). The \( T_{\text{ref}} \) was measured with a laboratory thermometer in the proximity of the reference matched load so that an absolute value of the antenna temperature could be obtained. It is estimated that the \( T_{\text{ref}} \) is accurate to within about two degrees Kelvin. The weather data was obtained from either the Boston weather service or the L.G. Hanscom Field meteorologist. In some cases, the dew point was measured at the Haystack Observatory, and when compared to the other two sources, agreed within a few degrees.
<table>
<thead>
<tr>
<th>Date</th>
<th>Location</th>
<th>Time</th>
<th>$T_{sys}$ ($^\circ$K)</th>
<th>N.T. BAL (dB)</th>
<th>Weather</th>
<th>$T_{ref}$ ($^\circ$K)</th>
<th>Ant-Temp ($^\circ$K)</th>
<th>R.H./D.P.</th>
<th>Experiment</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>15 Dec</td>
<td>L.L.</td>
<td>1500-1700</td>
<td>4500</td>
<td>7.8</td>
<td>Clear</td>
<td>160</td>
<td>164</td>
<td></td>
<td>Emission</td>
<td>One good run, balance noise tube failed</td>
</tr>
<tr>
<td></td>
<td>MIT</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td>8.0</td>
<td>275</td>
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<td>170</td>
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<td>N.T. Bal (dB)</td>
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<td>Experiment</td>
<td>Results</td>
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<td>8.25</td>
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<td>Emission</td>
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<td>278</td>
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<td>Erratic operation, tape</td>
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<td>48</td>
<td>166</td>
<td>79 R.H.</td>
<td>System tests</td>
<td>punch hung up</td>
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<td>0001-2000</td>
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<td>30.53 F</td>
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<td>22 Oct</td>
<td>H.</td>
<td>6400</td>
<td>13</td>
<td>288</td>
<td>Emission</td>
<td>Frequency stability checked, observations cancelled by rain</td>
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<td>1700-2400</td>
<td>289</td>
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<td>55 D.P.</td>
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<td>21 Oct</td>
<td>H.</td>
<td>4146</td>
<td>9.5</td>
<td>287</td>
<td>Sunset Emission</td>
<td>Good observations of Temp. vs. Time; fronts very evident</td>
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<td>47 D.P.</td>
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<td>287</td>
<td>Sunset Emission</td>
<td>Good data; could not tune wavemeter to frequency</td>
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<td>4</td>
<td>174</td>
<td>27 D.P.</td>
<td>Simulated line</td>
<td>attempt</td>
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<td>1700-0800</td>
<td>287</td>
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<td>Clear</td>
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**TABLE 3 (CONT.)**
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<th>Date</th>
<th>(T_{\text{sys}}(^\circ\text{K}))</th>
<th>Location</th>
<th>N.T. Bal</th>
<th>Weather</th>
<th>Experiment</th>
<th>Experiment</th>
<th>Results</th>
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<tbody>
<tr>
<td>17 Oct</td>
<td>4910, 4500 8.1</td>
<td>H.</td>
<td>4, 20</td>
<td>166</td>
<td>49 R.H.</td>
<td>278</td>
<td>Sunset Emission, (T_a) vs (T_{\text{sys}})</td>
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<td></td>
<td>1700-0800 282, 278</td>
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<td>Nothing evident in 60 MHz band</td>
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<tr>
<td>14 Oct</td>
<td>3327 9.5</td>
<td>H.</td>
<td>4</td>
<td>217</td>
<td>90 R.H.</td>
<td>286</td>
<td>Night Emission-Sunrise Emission</td>
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<tr>
<td></td>
<td>2200-0800 293</td>
<td></td>
<td>Light Clouds</td>
<td></td>
<td></td>
<td></td>
<td>Long integration; (\tau = 22,000) sec, (\Delta T_{\text{rms}} \approx 0.2^\circ\text{K})</td>
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<td>13 Oct</td>
<td>4400 10.4</td>
<td>H.</td>
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<td>237</td>
<td>65 D.P.</td>
<td>291</td>
<td>Night Emission-Sunrise Emission, Baseline,</td>
</tr>
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<td>Klystron supply malfunctioned</td>
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<td>0800-1200</td>
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<td>Lost lock on klystron at 2400. High beam current. Good data beforehand. (\Delta T_{\text{rms}} \approx 0.6^\circ\text{K})</td>
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<td>Lost lock on klystron at 2400. High beam current. Good data beforehand. (\Delta T_{\text{rms}} \approx 0.6^\circ\text{K})</td>
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<tr>
<td>6 Oct</td>
<td>5555 9.8</td>
<td>H.</td>
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<td>216</td>
<td>60 D.P.</td>
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<td>System Calibration, (T_a) vs Elev. angle,</td>
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<td></td>
<td>2300-0600 289</td>
<td></td>
<td>Varied</td>
<td>Clear</td>
<td></td>
<td></td>
<td>Night Emission</td>
</tr>
<tr>
<td>Date</td>
<td>Location</td>
<td>Time</td>
<td>$T_{sys}(^{\circ}K)$</td>
<td>N.T. Bal</td>
<td>Weather</td>
<td>Ant-Temp $(^{\circ}K)$</td>
<td>Alt-in-Hg.</td>
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<td>5 Oct 4  H.</td>
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<td>285</td>
<td>4980</td>
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<td>287</td>
<td>43 D.P.</td>
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<td>2000-2300</td>
<td>286</td>
<td>3840</td>
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<td>286</td>
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<td>293</td>
<td>4950</td>
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<td>290</td>
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<td>0001-0600</td>
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<td>7847</td>
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<td>259</td>
<td>72 D.P.</td>
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<td>21 Sep 4  H.</td>
<td>0001-0100</td>
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<td>5800</td>
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<td>Date</td>
<td>T$_{sys}$ ($^\circ$K)</td>
<td>N.T. Bal</td>
<td>Weather</td>
<td>Experiment</td>
<td>Results</td>
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<td>BW (MHz)</td>
<td>Temp ($^\circ$K)</td>
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<td>Time</td>
<td>T$_{ref}$ ($^\circ$K)</td>
<td>Ant-Temp</td>
<td>R.H./D.P.</td>
<td>Alt-in.Hg.</td>
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<td>20 Sep</td>
<td>5700</td>
<td>4</td>
<td>Horn</td>
<td>Dish</td>
<td>Horn found to give lower T$_A$; could not push marker through system.</td>
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<td></td>
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<td>14 Sep</td>
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<td>Observations cancelled</td>
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<td>3 cycles at 3.7 min.</td>
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<td>Date</td>
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<td>T_{sys} (°K)</td>
<td>N.T. Bal</td>
<td>Weather</td>
<td>Temp (°K)</td>
<td>Time</td>
<td>T_{ref} (°K)</td>
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<td>Date 1970</td>
<td>( T_{sys}(^\circ K) )</td>
<td>N.T. Bal</td>
<td>Weather</td>
<td>Experiment</td>
<td>Results</td>
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<td>( BW(MHz) )</td>
<td>(dB)</td>
<td>Temp((^\circ K))</td>
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<td>Time</td>
<td>( T_{ref}(^\circ K) )</td>
<td>Ant-Temp</td>
<td>R.H./D.P.</td>
<td>Alt-in.Hg.</td>
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<td>Good baseline</td>
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<tr>
<td>H.</td>
<td>4</td>
<td></td>
<td>Rain</td>
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</tr>
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<tr>
<td>29 Jun</td>
<td>4400</td>
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<td>Freq. switched, 3rd L.O. Poor baseline w/freq. switching, then</td>
<td>Total power on sun-off first T.W.T. replaced.</td>
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<td>sun, Emission total powers between Zenith and 60(^\circ)E.</td>
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<td>Could not hold lock.</td>
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<td>0600-1200</td>
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<td>15 Jun</td>
<td>20</td>
<td>Clear</td>
<td>Emission, Total power</td>
<td>No line evident</td>
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<tr>
<td>H.</td>
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<td>Zenith vs 25(^\circ)Elev. angle</td>
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<tr>
<td>31 May</td>
<td>20</td>
<td>Clear</td>
<td>Absorption, Drift scan, No spectral line, good base</td>
<td>Subtract spectrum before line</td>
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<tr>
<td>H.</td>
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<td>sunset from after sunset,</td>
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<td></td>
<td></td>
<td>Absorber in front of horn</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Date</td>
<td>Location Time</td>
<td>T_{sys} (°K)</td>
<td>N.T.Bal (dB)</td>
<td>Weather</td>
<td>Temp (°K)</td>
<td>Experiment</td>
<td>Results</td>
</tr>
<tr>
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<td>-----------</td>
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<td>---------------------------------------------</td>
</tr>
<tr>
<td>28 May</td>
<td>0700-1500</td>
<td>20</td>
<td></td>
<td>Clear</td>
<td></td>
<td>Dicke switched absorption 6&quot; dish, on</td>
<td>Total power, no line evident</td>
</tr>
<tr>
<td></td>
<td>H.</td>
<td>20</td>
<td></td>
<td></td>
<td>R.H./D.P.</td>
<td>source, off source</td>
<td></td>
</tr>
<tr>
<td>8 May</td>
<td>1400-2100</td>
<td>20</td>
<td></td>
<td>Clear</td>
<td></td>
<td>Dicke switched horn vs noise tube, presunset</td>
<td>No line</td>
</tr>
<tr>
<td></td>
<td>H.</td>
<td>20</td>
<td></td>
<td>then</td>
<td></td>
<td>emission</td>
<td></td>
</tr>
<tr>
<td></td>
<td>cloudy</td>
<td></td>
<td></td>
<td></td>
<td>R.H./D.P.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>24 Apr</td>
<td>1200-1700</td>
<td>20</td>
<td></td>
<td>Clear</td>
<td></td>
<td>Absorption</td>
<td>Good base line</td>
</tr>
<tr>
<td></td>
<td>H.</td>
<td>20</td>
<td></td>
<td></td>
<td>R.H./D.P.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>22 Apr</td>
<td>1900-2000</td>
<td>20</td>
<td></td>
<td>Clear</td>
<td></td>
<td>Absorption</td>
<td>No line</td>
</tr>
<tr>
<td></td>
<td>H.</td>
<td>20</td>
<td></td>
<td></td>
<td>R.H./D.P.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16 Apr</td>
<td>1000-1100</td>
<td>20</td>
<td></td>
<td>Clear</td>
<td></td>
<td>Dicke switched and total power,</td>
<td>No line</td>
</tr>
<tr>
<td></td>
<td>H.</td>
<td>20</td>
<td></td>
<td></td>
<td>R.H./D.P.</td>
<td>Absorption</td>
<td></td>
</tr>
<tr>
<td>15 Apr</td>
<td>0900-1500</td>
<td>20</td>
<td></td>
<td>Clear</td>
<td></td>
<td>Dicke switched</td>
<td>No line</td>
</tr>
<tr>
<td></td>
<td>H.</td>
<td>20</td>
<td></td>
<td></td>
<td>R.H./D.P.</td>
<td>Absorption</td>
<td></td>
</tr>
<tr>
<td>Date</td>
<td>Time</td>
<td>Location</td>
<td>$T_{sys}$ ($^\circ$K)</td>
<td>N.T. Bal</td>
<td>Weather</td>
<td>Experiment</td>
<td>Results</td>
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<tr>
<td>13 Apr</td>
<td>1300-1600</td>
<td></td>
<td>Clear</td>
<td></td>
<td></td>
<td>Dicke Switched, Marker</td>
<td>Unlocked marker produced 5 MHz wide feature.</td>
</tr>
<tr>
<td></td>
<td>H.</td>
<td></td>
<td>20</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12 Apr</td>
<td>1300-1800</td>
<td></td>
<td>Clear</td>
<td></td>
<td></td>
<td>Emission</td>
<td>No line.</td>
</tr>
<tr>
<td></td>
<td>H.</td>
<td></td>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11 Apr</td>
<td>1300-1800</td>
<td></td>
<td>Frequency Checks</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>H.</td>
<td></td>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 Apr</td>
<td>1500-1800</td>
<td></td>
<td>System Checkout</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td>H.</td>
<td></td>
<td>4, 20</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15 Mar</td>
<td>EK</td>
<td></td>
<td>System Tests</td>
<td></td>
<td></td>
<td>3 GHz L.O. drifts</td>
<td></td>
</tr>
<tr>
<td></td>
<td>EK</td>
<td></td>
<td>High clouds</td>
<td></td>
<td></td>
<td>Line evident</td>
<td></td>
</tr>
<tr>
<td>11 Mar</td>
<td>EK</td>
<td></td>
<td>Windy, Absorption</td>
<td></td>
<td></td>
<td>Line evident</td>
<td></td>
</tr>
<tr>
<td>1500-1700</td>
<td></td>
<td></td>
<td>High clouds</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Date</td>
<td>Location</td>
<td>Time</td>
<td>T_{sys} (^{\circ}K)</td>
<td>N.T. Bal (dB)</td>
<td>Weather</td>
<td>Experiment</td>
<td>Results</td>
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<td>---------</td>
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</tr>
<tr>
<td>9 Mar</td>
<td>EK</td>
<td>120</td>
<td></td>
<td></td>
<td>Absorption</td>
<td></td>
<td>Sun temp = 2244^{\circ}K</td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>1600-1800</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8 Mar</td>
<td>EK</td>
<td>120</td>
<td></td>
<td></td>
<td>Absorption</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1500-1700</td>
<td></td>
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</tr>
<tr>
<td>7 Mar</td>
<td>EK</td>
<td>120</td>
<td></td>
<td></td>
<td>Absorption</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>1200-1800</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 Mar</td>
<td>EK</td>
<td>120</td>
<td>Light clouds</td>
<td></td>
<td>Absorption</td>
<td></td>
<td>to heavy</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1500-1700</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8 Jan</td>
<td>EK</td>
<td></td>
<td>System Test</td>
<td></td>
<td></td>
<td></td>
<td>System N.F. 25.3 dB</td>
</tr>
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</tr>
</tbody>
</table>
6.2 Experimental Spectra.

6.2.1 Narrow-band mesospheric spectra.

The presence of a sharp line in the night emission spectra was sought as evidence of the nocturnal increase in mesospheric ozone. A line was never detected despite measurements under many different conditions. The results of the observations considered significant are given in Table 4. Observations during periods when the surface water vapor content was greater than 15 gr/m$^3$ were rejected as the sky was too opaque.

A representative observation is shown in Figure 6.2-1. This was taken in the one hour period after mesospheric sunset, when the diurnal variation should occur. It is significant that at the time of the observation the ground water vapor content was low, around 3.5 gr/m$^3$, so the atmospheric water vapor attenuation is less than that used to predict the emission line. The predicted line, reduced by a factor of two to account for the assumed double sideband response of the radiometer, is that computed in paragraph 3.2. The peak-to-peak variation of the noise is assumed to be $6 \Delta T_{\text{rms}}$, so the minimum detectable signal, $\Delta T_{\text{rms}}$, is about 0.5$^\circ$K. The 0.2$^\circ$K/MHz slope is assumed to be instrumental but may be caused by water vapor attenuation. Other spectra, corresponding to the days in Table 4, are shown in Figures 6.2-2 to 6.2-5. The spectra have not been edited and are extracts of the processor output. In interpreting the 20 MHz bandwidth spectra, only the center 10 MHz is valid since a 10 MHz filter was used for image rejection before the second converter. The integration periods were accumulated normally in ten minute periods with a calibration performed between integrations.
<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>(\rho_{\text{H}_2\text{O}}) ((10^{-24}\text{g/m}^3))</th>
<th>Integration Time (sec)</th>
<th>(\Delta T_{\text{rms}}) (°K)</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>22 Oct</td>
<td>1800-1900</td>
<td>13</td>
<td>4,000</td>
<td>0.3</td>
<td>Post sunset (20 MHz)</td>
</tr>
<tr>
<td>20 Oct</td>
<td>1800-1900</td>
<td>4</td>
<td>4,000</td>
<td>0.2</td>
<td>Post sunset (4 MHz)</td>
</tr>
<tr>
<td>17 Oct</td>
<td>1800-1900</td>
<td>3.5</td>
<td>4,000</td>
<td>0.5</td>
<td>Post sunset (4 MHz)</td>
</tr>
<tr>
<td>18 Oct</td>
<td>2300-0400</td>
<td>5.5(Avg)</td>
<td>22,000</td>
<td>0.15</td>
<td>Night emission (4 MHz)</td>
</tr>
<tr>
<td></td>
<td>0630-0730</td>
<td>8.5</td>
<td>4,000</td>
<td>0.3</td>
<td>Post sunrise (4 MHz)</td>
</tr>
<tr>
<td>14 Oct</td>
<td>2200-2300</td>
<td>9.9</td>
<td>2,400</td>
<td>0.3</td>
<td>Night emission (4 MHz)</td>
</tr>
<tr>
<td></td>
<td>2400-0100</td>
<td>9.9</td>
<td>3,000</td>
<td>0.25</td>
<td>Night emission (20 MHz)</td>
</tr>
<tr>
<td></td>
<td>0400-0800</td>
<td>9.9</td>
<td>3,600</td>
<td>0.4</td>
<td>Night emission-Post sunrise (4 MHz)</td>
</tr>
<tr>
<td>6 Oct</td>
<td>2300-0600</td>
<td>12</td>
<td>19,279</td>
<td>0.2</td>
<td>Night emission (4 MHz)</td>
</tr>
<tr>
<td>5 Oct</td>
<td>2200-0230</td>
<td>8</td>
<td>4,000</td>
<td>0.4</td>
<td>Night emission E-plane Vertical (4 MHz)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8</td>
<td>4,000</td>
<td>0.4</td>
<td>Night emission E-plane Horizontal (4 MHz)</td>
</tr>
<tr>
<td>24 Sep</td>
<td>2300-0400</td>
<td>10.5</td>
<td>4,000</td>
<td>0.6</td>
<td>Night emission, High resolution (0.4 MHz BW)</td>
</tr>
</tbody>
</table>
STAELIN I OZONE SEARCH, 101 GHZ, RUDZKI
SUNSET EMISSION MSMT, HORN NORTH, 30 DEG ELEV.
TREF = 9C, TANT = -106.8, NT BAL 8.1 DB, TEMP = 41F.
WX: BOS1700, T=43, RH=49, ALT29.92R,N WIND 25, SKY CLEAR.
T(21-181)

Figure 6.2-1 Night Emission Spectra,
17 October 1970

$T = 42 / 4$ seconds

$4 \text{MHz}_2$ Bandwidth

17 October 1970, 19:30

Predicted Night Spectrum (Hunt, 1966b)

Predicted Day Spectrum
Figure 6.2-2 Emission spectra, 20 and 22 October 1970.
Figure 6.2-3 Emission Spectra 15 and 16 October 1970.
Figure 6.2-4 Emission Spectra 14 and 15 October 1970.

\[ \tau = 3613 \text{ s, } Bw = 20 \text{ MHz} \]

\[ \tau = 2407 \text{ s, } Bw = 4 \text{ MHz} \]
Figure 4.2-5 Emission Spectra 25 September and 7 October 1970.
The base line was stable, and the system temperature would change about 500°C over one hour. This represents a gain change of less than $\frac{1}{2}$ dB. Since this was a gradual change, much slower than the 5 Hz switch rate, it is felt that the Dicke switching was effective.

6.2.2 Broadband stratospheric spectra.

In addition to the search for the mesospheric emission line, a search for the stratospheric ozone emission line was also made, at the suggestion of Professor D. Staelin. If successful, detection of the line would confirm both the operation of the radiometer and the frequency of the ozone line. The width at half height of the stratospheric ozone line is about 50 MHz, so a broad band system was required.

The Version VIII radiometer was used to make broad band emission measurements using the MIT Digital Synchronous Detector System designed by Waters (1970). The emission spectrum taken on the night of September 2, 1970 is shown in Figure 6.2-6. The predicted spectrum is the day emission spectrum and it has been reduced by a factor of 2. The temperature scale is marked with respect to the balanced antenna temperature.

The spectrum was taken by directing the antenna beam against a moveable aluminum reflector. The reflector was raised such that the effective beam angle was a $60^\circ$ elevation angle and the spectrum shown in Figure 6.2-7 was obtained. The integration time for $60^\circ$ elevation angle was shorter, 4.3 minutes vs 6.7 minutes for the $20^\circ$ elevation angle.

To check that the feature was not in the system, a spectrum was taken with the horn surrounded by microwave absorber. The spectrum,
Figure 5.2-5  Broadband Emission Line, 20° Elevation Angle.
Figure 6.2-7 Broadband Emission Line, 60° Elevation Angle."
Figure 6.2-8, was flat, and the peak-to-peak noise was within the limits expected.

6.3 Effects of Water Vapor.

The calculations of the anticipated spectra were made assuming a surface water vapor density of 5 gr/m$^3$ with a 15 km breakpoint to a constant mixing ratio of $2 \times 10^{-6}$ above 15 km. During the course of the experiments, the effects of the water vapor became very evident. Surface vapor densities above 15 gr/m$^3$ were almost opaque at 101.7 GHz.

The sky was scanned in elevation angle on three occasions. On 24 September, the horn antenna was aimed at a 30$^\circ$ elevation angle and a tiltable reflector directed the beam to different angles. On 28 September and 6 October, the horn was at a 0$^\circ$ elevation angle and the reflector was tilted to produce effective beam angles from 0 to 90 degrees.

Plots of the measured antenna temperature (corrected as noted in paragraph 5.2.1) are shown in Figure 6.3-1. The increase in temperature for $\rho_{\text{vap}} = 10.5$ gr/m$^3$ on 24 September is believed to be caused by the side lobes directed against the hut. The variations with angle of the predicted values are consistent with the measured values. But, the measured change in antenna temperature with vapor density is not so pronounced. The difference between $\rho_{\text{H}_2\text{O}} = 8$ gr/m$^3$ and $\rho_{\text{vap}} = 12$ gr/m$^3$ is within experimental error.

The measured effective antenna temperature at constant elevation angle but varying surface water vapor content is shown in Figure 6.3-2. Note that the water vapor content was measured primarily at either L.G. Hanscom Field, 15 mi. away, or in Boston, about 25 mi. away. The
Figure 6.2-8 Spectrum of Absorber in Front of Antenna.
Compared to brightness temperature

--- Observed Antenna Temperature

--- Computed Antenna Temperature

--- Computed Brightness Temperature

Figure 6.3-1 Observed Antenna Temperature versus Elevation Angle.
Figure 6.3-2  Observed Antenna Temperature at Varying Surface Water Vapor Densities and Constant Elevation Angle.
scatter of data points for the higher vapor densities could be explained by the expected density variation with location. Also, since many of these measurements were made at night, the very probable presence of unseen clouds could contribute to the increase in temperature at the high concentrations. But, the divergence of the measured curve from the predicted $T_B$ at low concentrations at this elevation angle is interesting. The total opacity at this angle is about 0.59 nepers for a 5 gr/m$^3$ concentration with water vapor contributing 0.37 nepers. The data suggests that at low concentrations, the atmosphere is more opaque, but at high concentrations the water vapor is more opaque than computed.

One definite conclusion that can be made is that the model is reasonably accurate around a density of 5 gr/m$^3$ (fortuitously!). The computed $T_A$ point takes into account the antenna side lobe contributions and is very close to the measured value.

6.4 Variation of Antenna Temperature with Time.

Another interesting experiment was performed on the nights of 20 and 21 October. When the temperatures vs time were plotted for the mornings of 7 and 14 October, a rapid rise in antenna temperature was observed between sunrise at 40 km and surface sunrise. These are shown in Figure 6.4-1.

To confirm this observation, measurements of antenna temperature vs time were made through sunrise on 15 and 18 October and through both sunset and sunrise on 20-21 October. On the morning of 21 October, a front moved through the antenna beam shortly after dawn. The effect of the clouds, Figure 6.4-2, was very evident with a rise of 20°K. Since
Figure 6.4-1 Antenna Temperature versus Time, Sunrise, 7 and 14 October 1970.
Figure 6.4-2  Antenna Temperature versus Time 21 October 1970.
no increase at sunrise was observed on the three days, it was concluded that the rise in temperature observed on 7 and 14 October was caused by either a cloud or a parcel of moist air in the beam.

Out of curiosity, the antenna temperature was monitored from 1700, 21 October to 0700, 22 October. The sky was clear at the start, but a violent weather system moved through the antenna beam beginning around 1800. The record is shown in Figure 6.4-3. At 2300 the frequency of the radiometer was shifted 200 MHz and about a 10° change in temperature resulted. The change could have been attributed to the ozone line, but more likely it was an atmospheric effect in view of the rapid variations of antenna temperature.
Figure 0.4-3: Antenna Temperature versus Time 21-22 October 1970.
7. CONCLUSIONS AND DISCUSSION

7.1 Conclusions.

Our experiments do not support the analysis of Hunt which predicts that the mesospheric ozone near 70 km altitude increases diurnally to around $5 \times 10^{10}$ cm$^{-3}$ at night from a daytime concentration of about $10^9$ cm$^{-3}$.

We have considered the effect of the tropospheric and lower stratospheric ozone changes. Ozonesondes are launched from L.G.Hanscom Field each Friday afternoon*. The ozone profiles from these probes were used in the model and the expected line calculated. Figure 7.1-1 contains a typical observed ozone concentration profile to 30 km and the mid-latitude ozone concentration profile used for the calculations. The difference between the two emission lines is negligible, being on the order of $1/2^0$. The predicted night mesospheric line is insensitive to the changes in ozone profile below 30 km that occur in the vicinity of Bedford, Massachusetts.

To check the possibility that the ozone distribution at night was different from Hunt's calculated one, several ozone profiles were modeled as shown in Figure 7.1-1. The profile of Reed, a sharp peak distribution at 76 km, and exponential decreases from the concentration at 50 km with different slopes were used. Most observations and theories agree to about 50 km, so that is the breakpoint chosen.

* The assistance of W. Hering and T. Borden, Air Force Cambridge Research Laboratory, is gratefully acknowledged. Unfortunately, the simultaneous ozonesonde-radiometer experiment of September 17-18 had to be cancelled because of rain, even though the sondes obtained useable data.
The anticipated line strengths in a 4 MHz bandwidth are shown in Figure 7.1-2. The sensitivity of our instrument is adequate to detect a 20K line strength in this bandwidth.

We conclude, therefore, that if the mesospheric ozone increases at night, it does not exceed an exponential distribution with a concentration of $10^9$ cm$^{-3}$ at 80 km. Our observations indicate that the night concentration is similar to the concentration observed by Johnson, et. al. and Hilsenrath's daylight probe.

7.2 Discussion.

The question of why the mesospheric ozone concentration does not increase at night might better be phrased as should the ozone concentration increase at night in the mesosphere. The answer lies in the equations of the photochemical theory which predicts it. In short, the reaction rates are so poorly known that a positive statement based on these equations is unjustified.

Consider the calculations of Paetzold (1961). Just varying K I-1 and K II-6 one and two orders of magnitude respectively changed the night ozone concentrations almost one order of magnitude as shown in Figure 2.3-1. Yet neither rate reaction is well known.

Even rate constants measured in the laboratory are suspect. Hunt (1966b) tried to reconcile the value of K I-6 measured in the laboratory by Kvitte and Vegard (1947) as $10^{-16}$ cm$^3$ sec$^{-1}$ with the value of $10^{-10}$ cm$^3$ sec$^{-1}$ estimated by Dalgarno and Walker (1964) to explain the 6300 Å observation of Noxon (1962). If the $10^{-16}$ cm$^3$ sec$^{-1}$ laboratory value were used, good agreement with the entire day ozone profile was
Figure 7.1-2 Comparison of Calculated Brightness Temperatures and System Sensitivity.
obtained. If the value deduced from an atmospheric measurement were used, the equilibrium concentration at the ozone maximum was an order of magnitude too high, \( > 10^{13} \text{ cm}^{-3} \) and the \( [O_3] \) concentration at 70 km was about \( 5 \times 10^{10} \text{ cm}^{-3} \), almost the predicted night value. So the rate constants are in disarray and measurements are sorely needed.

Another weakness in the photochemical theory is that dynamical equilibrium is assumed. Neither molecular and eddy diffusion, nor the large scale transport of ozone from the tropics is considered in the theory. It is a crude theory from this point of view.

The water vapor concentration in the mesosphere affects the ozone concentration appreciably. See Waters (1970) for an extensive bibliography on atmospheric water vapor. When Hunt added water vapor to his model (1966a in contrast with 1966b) the computed night concentration of ozone at 80 km dropped by a factor of 30. (Figure 2.5-1) The water vapor mixing ratios used by both Bates and Nicolet and Hunt are shown in Figure 7.2-1. It may be significant that at 70 km Bates and Nicolet used slightly higher water vapor concentrations than did Hunt (1966b). The night ozone concentration predicted by Bates and Nicolet is within the upper limit observed in this experiment. It is of further interest to note that Hesstvedt (1964) concluded that the water vapor mixing ratio begins to drop off from \( 2 \times 10^{-4} \) at 68 km to about \( 5 \times 10^{-6} \) at 80 km. This is much higher than that used by either Bates and Nicolet or Hunt, but the ozone concentration computed by Hesstvedt is correspondingly much lower. Hesstvedt found that the ozone number density at 70 km was \( 2 \times 10^6 \) and that there was no diurnal change in the ozone
Figure 7.2-1 Model Water Vapor mixing Ratios.
concentration. Since so few measurements of either water vapor or ozone have been made above 50 km, it would only be speculation to say that water vapor mixing ratios around $10^{-5}$ at 70 km account for the low mesospheric ozone concentration.

Consider the experimental data supporting a night increase in ozone as given in Figures 2.6-1 and 2.6-2. Carver, et. al. measured the absorption of the U.V. radiation reflected from the moon, while the temperature of the sun in these frequencies is only surmised. Reed measured the absorption of the night airglow at 100 km, but subsequent corrections to the data place the measurements in doubt (Maeda and Aikin, 1967). There appears to be only one isolated measurement of Hilsenrath (1970) and only one data point of the set which suggests a night concentration significantly higher than the day concentration.

The preliminary results of Noxon’s twilight observations are not consistent with an increase in ozone, at least during twilight*. He observes the radiation at 13,000 A from the first excited state of the $O_2$ molecule ($^1\Delta_q \rightarrow ^3\Sigma_g^+$) that occurs in the reaction:

$$O_3 + h\nu[I\omega] \rightarrow O_2^* + O(^1D)$$

$$h\nu (13,000 \text{ A})$$

Now, if $[O_3]$ increases due to:

$$O_2 + O + M \rightarrow O_3 + M,$$

the emission at 13,000 A should increase as $[O_3]$ increases for a given

I (λ) from the sun. Similarly, if I (λ) decreases (as during twilight) and if [O₃] increases (as predicted), hν(13,000Å) should remain constant. But, hν (13,000Å) decreases significantly. Therefore, either [O₃] does not increase, at least during twilight, or the rate of increase is slower than predicted. Both alternatives raise doubt about the validity of the photochemical theory as applied by Hunt and others.

To state that the ozone concentration increases at night implies that the concentration can be measured both before the event occurs and after the event occurs. Of all the techniques used, only a microwave radiometric observation can readily make that kind of an observation. The result shows that the ozone concentration does not increase above an exponential distribution reaching $10^9$ cm$^{-3}$ at 80 km.
8. RECOMMENDED FURTHER RESEARCH.

Further research growing out of this thesis may go in several directions. As the radiometer is presently configured, several projects can be undertaken. Improvements are also expected in hardware development, so guidelines for equipment utilization are also presented.

8.1 Experiments with the Present Radiometer.

The effects of water vapor are not exactly as predicted. Further studies of antenna temperature vs elevation angle with different water vapor densities should be made. It is a relatively simple but long term experiment.

Microwave spectroscopy in this frequency range is hindered by the lack of suitable detectors. Normally a crystal detector following the absorption cell is used in microwave spectroscopy. In W-band, the tangential sensitivity of a detector is around -30 dBm, and modulated signals can be detected by narrow band amplifiers down to about -50 dBm. The C.W. power level of the marker frequency used to check the radiometer operation is estimated to be below -100 dBm. If the radiometer were used as a detector for microwave spectroscopy, many orders of magnitude in sensitivity and dynamic range would be gained.

Before microwave sensing of the ozone profile becomes a reality, concurrent measurements in-situ and by a radiometer must be made simultaneously to establish absolute confidence in the results. Therefore a rocketsonde-radiometer measurement should be made. A joint experiment with Goddard Space Flight Center would be most desirable.
8.2 A "Dream" Radiometer.

Several problems surfaced in this research. The MIT 20 Channel Digital Synchronous Detector system must be debugged. The present system requires a real time 4 times as long as the equivalent integration time because of the spurious noise. This is the same as a 3 dB increase in system temperature. So correcting the correlator will increase the system sensitivity by a factor of 2.

The Digital Processor is important to further work because a processor must be available on call in contrast to the Haystack system which must be reserved a month ahead of time. To make an atmospheric measurement, using Haystack, the equipment must be in working order at Haystack, the time must have been reserved previously, and the weather conditions must be suitable. These conditions were met only about 50% of the time during this experiment. If a reliable processor were available at MIT, the equipment could be held ready, then observations made when the weather conditions are suitable. Then, if the equipment malfunctions, a laboratory is available in which to perform the maintenance. This facility is lacking at Haystack. An alternative is a data link between MIT and Haystack.

The loss introduced by the ferrite switch is large, on the order of 2-3 dB. If the switch is eliminated the system temperature decreases by that amount. So, future spectral systems in the millimeter range should be frequency switched. Almost all of the equipment needed is available as off-the-shelf items. The experience gained from the Version VI and VII radiometers shows that switching can be accomplished in
the primary phase lock loop. All that is needed is a broad band amplifier-phase detector in about the 200-400 MHz range. Lower frequencies could be used instead, but then problems may arise with spurious signals in the final I.F.

Another improvement that can be made is to improve the first I.F. amplifier. The T.W.T. used in the Version VII radiometer had a noise figure of over 5 dB. If it were replaced by a 1 dB parametric amplifier, a 4 dB improvement in system temperature would be immediately realized. The 94 GHz klystrons are now on hand, so the only major cost would be for the params. Uncooled X-band params with 800K temperatures (170 cooled with a closed circuit cryogenic system) are available with a 500 MHz bandwidth (source: ComTech Laboratories, Inc., or Micro-Mega Corp.). These are all solid state amplifiers and would be ideal for a good I.F. strip.

If these parts could be obtained, an ideal general purpose radiometer could be put together. To keep the signal path as low-loss as possible, only a calibration-balance coupler is used between the antenna and mixer as shown in Figure 8-1. The calibration and marker generation (the marker is invaluable for frequency checking) are performed off-line.

The high I.F. allows enough image and signal band separation to enable terminations or filters to be built at the signal frequency. This is one of the keys to low noise mixer development in the E.H.F. range, and the availability of low noise X-band I.F. amplifiers makes this feasible. With the "dream" arrangement shown, a 100 GHz system
Figure 8-1 Proposed Radiometer.
temperature of around 1000°K is quite feasible. Then it should be possible to obtain reliable data for studying the profile inversion.
APPENDIX A - MILLIMETER WAVE MIXER DIODES

A-1. DISCUSSION.

This section presents the detailed assembly techniques for manufacturing diodes to be used at millimeter frequencies. The diode package, Fig. A-1, is the latest step in package design which has evolved from diodes originally used in 60 GHz. mixers. Figures A-2, A-3, A-4, and A-5 show the double-ended integral choke, single-ended integral choke, miniature, and final package, respectively. Figure A-6 shows the comparative sizes of diode packages currently used in microwave mixers.

The latest package is more versatile than the integral choke package since the frequency dependent chokes are external to the package and can be changed as desired. It is better electrically than a pill-prong package, since the contact to the diode can be made electrically far from the signal waveguide, thus reducing contact resistance losses. The package is rugged, having been subjected to axial tensions as high as 40 gr. and temperature cycling from -40°C. to +40°C. with no degradation in performance. Finally, mixer-amplifier noise figures as low as 6.4 dB, single sideband, with a 1.8 dB I.F. amplifier noise figure have been measured by the author using this diode.*

* The author wishes to acknowledge the assistance of R. Chick in this measurement. The diode mount was designed by R. Boyden.
Die Stud
No. 22 Copper Wire X
0.240 ± 0.005 in. long

Quartz Sleeve, 0.100 ± 0.002 in. long
ID = 0.026 ± 0.001
OD = 0.043 ± 0.002

Adjust Spacing for Guide Height

Gallium Arsenide "Honeycomb" Die,
Soldered with 50% Indium 50% Tin

Alternate Mounting of Whisker

1 or 2-mil dia Hard Drawn Gold Whisker Ultrasonically Bonded to Stud
A-2. Component parts.

The diode package is made of two identical gold plated copper studs, a semiconductor diode, a sharpened gold whisker, and a quartz sleeve. The preparation of each of these parts will be discussed, followed by a discussion of the assembly procedures.


The cleanliness of all the parts is very important. The strength of the bond between the quartz and the studs depends upon the cleanliness of the parts. The diode chip can deteriorate if any residue is allowed to remain on its face, and there is evidence that handling the chip by the face with a vacuum tweezer not cleaned immediately before using can lead to failure of the quartz layer and probably the diode, even though the diode chip was cleaned later. Figure A-7 is an example of this type of failure.

Several satisfactory cleaning techniques have been developed, although they may possibly be improved. The basic chemicals used are:

A. Deionized water (10 megohm or better resistivity)
B. Trichlorethylene, electronic grade
C. Acetone, electronic grade
D. Ethyl alcohol, 200 proof
E. Bendix 25-I cleaning solution concentrate
F. Ammonium hydroxide, reagent grade

The standard procedure for cleaning metal studs, studs with whiskers,
Figure A-7. 3.5 diameter junctions on 0.014" square chip. The circular outline is the deterioration of the quartz layer.

Figure A-8. Trial cut through quartz tubing.
and tinned die studs follows:

A. 3-5 minutes in ultrasonic cleaner in bath of Bendix 25-I to which have been added 2 drops of concentrated ammonia/10 ml. of solution.

B. 3-5 minutes in ultrasonic cleaner in bath of deionized water.

C. Rinse in ethyl alcohol and dry using canned air.

The procedure for cleaning a mounted die is to submerge it in acetone heated to just below the boiling point. The acetone will boil at the end with the die, and the turbulence created by the bubbling appears to be very effective in removing residues from the die. The mounted die should not be cleaned ultrasonically as the back contact usually comes off.

A-4. Preparation of quartz sleeves.

The purpose of the quartz sleeve is to hold the diode together mechanically. Since its volume is large, the lowest loss material available is used. Quartz has a dissipation factor of $22.5 \times 10^{-4}$ at 25 GHz*, the lowest of any solid suitable for this use. However, it is difficult to use due to its hardness and high melting point.

Since the diode must fit into a diode mount where close tolerances must be held, the outside diameter (O.D.) of the quartz is held to a

maximum of 0.043" with a -0.002" tolerance. Similarly, the studs must fit into the quartz with sufficient clearance for assembly, but not with so much that the epoxy will not bond. Holding the inside diameter (I.D.) to 0.026" + 0.001" is satisfactory.

There is no quartz manufacturer or processor willing to make quartz sleeves to these dimensions at reasonable cost*; therefore, a statistical selection process is used. An I.D. gauge, consisting of a standard numbered drill (0.025") in a pin vise, and an O.D. gauge, consisting of a precise 0.043" hole drilled in an aluminum bar are given to a glass blower. The glass blower then draws short lengths of quartz tubing that fit as close as possible to the gauges. After cutting the pieces into finished lengths and sorting the finished pieces, a yield of about 10% within tolerance can be had.

The short pieces of quartz tubing are cemented into 90° vee grooves cut into boron nitride blocks with Crystal Bond 509 Adhesive (manufactured by Aremco Products, Inc., Briarcliff Manor, New York). The melted adhesive is allowed to fill the inside of the tubes by capillary action. Additional adhesive is flowed around the tubes to give them adequate support during the sawing step. Figure A-8 shows a block with tubes mounted and cut.

The tubes are cut to length (0.100" ± 0.002") using a diamond saw, then removed from the block by soaking in hot acetone. About three or

* Quotations received from local quartz houses range from $3.75-$20.00 per piece in lots of 250. R. Chick, personal communication.
four more rinses in clean, hot acetone, followed by about a five minute run in an ultrasonic cleaner in hot acetone removes all the adhesive. The sleeves are then sorted by I.D., O.D., and length.

A-5. The Semiconductor Diode.*

To make gallium arsenide (GaAs) diodes of this type requires equipment normally found in any planar semiconductor fabrication laboratory. This assumes that a slice of GaAs having the proper substrate and epitaxial characteristics is available. The GaAs slice used in this work** had the following characteristics:

**Substrate**
- Orientation \( \langle 1, 1, 1 \rangle \)
- Resistivity \( 7.0 \times 10^{-4} \) ohms cm
- Tellurium dopant

**Epitaxial layer**
- Doping density \( 5.35 \times 10^{17} \) cm\(^{-3}\)
- Mobility \( 1640 \) cm\(^2\) volt\(^{-1}\) sec\(^{-1}\)
- Resistivity \( 7.1 \times 10^{-3} \) ohms cm
- Thickness 0.8 micron
- Tellurium doped

* The assistance of C. A. Burrus, Bell Telephone Laboratories, Murray Hill, New Jersey is gratefully acknowledged. This technique was developed by him.

** GaAs slices furnished through the kind assistance of Mr. Jules Witteborn and Mrs. Beth Tarrants of the Air Force Materials Laboratory and Mr. 'Frosty' Williams and Mr. John Burd of the Monsanto Company.
The slice was of exceptionally high quality, having been made in a research environment as contrasted to a production environment. The etch pit density, one measure of quality, was less than $10^2 \text{ cm}^{-2}$.

The processing is begun by sawing the slice into $0.200''$ squares with a carborundum saw. Only small squares are used as the failure rate overall is about 50%. Thus, if a particular run is a failure, the whole slice is not lost. Conversely, if the run is a success, it establishes a baseline of success that other runs should at least meet or surpass.

The slice is prepared for sawing by mounting it on a mounting block with crystal bonding adhesive, substrate layer down, with a coating of black wax on top to protect the epitaxial layer. After sawing, the wax is removed with alcohol and chloroform; the crystal bond cement is removed with hot acetone.

A para-lytic oxide layer 6-7 thousand Angstroms thick is next deposited onto the epitaxial layer. It is essential that all of the adhesive be removed; a cleaning procedure used is to immerse the square in 10% water solution of NaCN for $\frac{1}{2}$ minute, rinse in deionized water and alcohol, and dry by forced air. To produce a bubble free oxide layer, prerun the apparatus for at least a week, then at least a half hour before inserting the GaAs.

The square is then cemented to a block, oxide layer down, and the substrate layer lapped away. A nominal thickness is 0.006'' but 0.004'' thick squares can be handled. The back contact is plated onto the substrate using commercially available plating solutions. A light combination of tin and nickel is first deposited, then pure nickel from a
nickel ammonium chloride mixture (approximately 7-8 m.a. for 1 min.), and finally pure gold (approximately 7-8 m.a. for $\frac{1}{2}$ min.). The deposit is then alloyed at 400-500° C. for about ten minutes.

The diode contact holes are then opened in the quartz layer. Three coats of KTFR 3:1 are applied on a 10,000 R.P.M. centrifuge, then baked, and exposed. The resist is post-baked after developing and the holes are etched in a gentle ultrasonic bath of ammonia bifluoride for about 30 seconds. The color changes are then watched in a 1000X microscope after short etches of a few seconds until all the quartz is removed. The resist is removed with J-100, then the square is cleaned sequentially in trichlorethylene, acetone, deionized water, and alcohol.

The contacts are plated next. The square is cleaned ultrasonically in a solution of 5% sodium hydroxide to which has been added 1-2 drops of hydrogen peroxide. After the foaming stops, the square is cleaned for about 10 seconds. The piece is rinsed in deionized water and immediately placed in the gold plating bath. Ultranex-N (or Allerex) plating solution is used. The contacts are pulse plated using 40 m.f.d. capacitors charged to about 45 volts. The buildup of gold is watched under a microscope to prevent extra gold from "mushrooming" or overlaying the quartz. Ideally the gold should fill the hole about half-way.

The square is then sawed into squares of convenient size. Ten mil squares are convenient, but the size can be tailored to the application. The square is mounted with de-waxed shellac on a block and cut with a diamond saw to size. After cleaning with alcohol, the diodes are ready to be mounted.
A-6. The Die Stud.

The die studs are made from #22 bare copper wire (0.0253" dia.) that is cut to length (0.240" ± 0.005") using the jig shown in Fig. A-9. For ease in assembly the corners are rounded slightly in a jeweler’s lathe using an Arkansas stone. After a thorough cleaning the studs are gold plated about 50 millionths of an inch.

One end of a stud is timed with Indalloy solder (50% tin, 50% indium, supplier: Indium Corp. of America, Utica, N. Y.) using only enough solder to coat the end of the stud. The vise, Fig. A-10, is used to heat the die stud. Special X Flux (supplier: Chem. Specialty Division, Shoaz Polish Mfg. Co., 1013 W. Oklahoma Ave., Milwaukee, Wisconsin) has been found to be satisfactory, but it still leaves a light residue which is difficult to remove.

After tinning, the studs are cleaned thoroughly to remove any excess flux, then dried. An absolute minimum of flux is applied to the solder. A handy way to do this is to touch a flux dispenser to a microscope slide, leaving a dot of flux about 1 mm in diameter. Then a probe made from a jeweler’s pivot broach mounted in a pin vise is used to transfer a small amount of flux from the dot to the stud. A die is centered on the top of the stud and the solder is brought to the melting point. The die can be pushed down using a clean slide, and the heat is removed. As a check on the solder joint, push against the side of the die with a thin pair of tweezers. A good solder joint will withstand enough force to chip the side of the diodes. The height of the die face above the die stud is then measured for future use.
Figure A-9. Diode stud cutting jig.

Figure A-10. Soldering vise.

Two methods of mounting the gold whisker to the stud are used. If a Kulicke and Soffa ultrasonic bonder is not available, the whisker must be soldered to the stud. But, since the etchant used to point the whiskers attacks the solder, causing a failure in the bond, the whiskers must be soldered into a hole drilled in the end of the stud. "Spirec" center drills, 0.0034" in diameter have been found to be the best to drill a hole about 0.005" deep. The gold wire, soldered to a scrap piece of wire mounted in a micromanipulator, is bent into a "C" curve. It is then centered in the hole and solder is applied. The solder must not be heated too high as the eutectic point for gold in tin is low (about 70°C) and the whisker will simply dissolve in the gold. After soldering, the whisker is cut to a length about 0.020" longer than the desired finished length.

The preferred method of bonding is using an ultrasonic bonder since one operation is required versus three for the alternate method (drilling, bending whisker, and soldering). The jig adapting the "hot column" of the bonder to hold the studs is shown in Fig. A-11, while the bonder is shown in Fig. A-12. The whisker is bonded to one side of the stud so that the pad does not overlap the end. The "L" curve is put in while drawing out the wire through the bonding chisel, and a hydrogen flame cutoff tool is used to cut off the whiskers. A finished whisker is shown in Fig. A-13.


The gold whisker can be electrolytically pointed by one of the
Figure A-11. "Hot column" adaptor jig.

Figure A-12. Whisker bonder.
Figure A-13. Bonded whisker.

Figure A-14. Whisker pointing jig.
following solutions: potassium cyanide, sulfuric acid, or hydrochloric acid. A dilute solution (10% by volume) of hydrochloric acid was found to be the safest and to be fairly rapid.

A platinum wire in a beaker of the solution formed one electrode and the whisker stud in a pin vise formed the other electrode. Normally 1V r.m.s. across the solution produced enough current to etch 10 mils of 1 mil wire in about 30 seconds.

The pointing jig is shown in Fig. A-14. A micrometer indicator is used to measure the length of wire in the solution which will be etched away. With practice, it is possible to hold a length tolerance to \( \pm 0.001" \). This is required since the separation of the two stud faces is controlled by the whisker length and the die height. The aspect ratio (length of taper/diameter) of the whisker point is important both mechanically and electrically. The tip of the point must be smaller than the diode contact to avoid overlay M.O.S. capacitance, yet the taper must not be so slender that it can be sheared easily. Three different aspect ratios are shown in Fig. A-15. The most rugged point has an aspect ratio of about 1, and it can be made by "machining" the point with the etchant, alternately touching the point to the solution and withdrawing.

A-10 Diode Assembly.

The assembly of the diodes consists of making contact to one of the junction dots, deflecting the whisker a known amount to stabilize the contact and to lower the series resistance, and finally bonding the two studs to the quartz sleeve.

The jig used to assemble the diodes is shown in Fig. A-16. It con-
Figure A-15a. Concave point.

Figure A-15b. Long slender point.

Figure A-15c. Ideal aspect ratio point.
Figure A-16. Diode assembly jig.

Figure A-17. Diode components prior to assembly.
sists of an invar column supporting an axial drive mechanism on the top and a rotational drive mechanism on the bottom. Two chucks hold the studs during assembly, with the top chuck electrically insulated from the rest of the jig, but connected to a curve tracer. The center-to-center alignment of the two chucks is to within 0.001", and the axial travel is true to within 0.0001" over \( \frac{1}{2} \)" of travel.

A closeup of the mechanism and the parts of the diode prepared for assembly are shown in Fig. A-17. Figure A-18 shows the point a few microns above the surface of three different sized dots. The point and its reflection in the quartz layer are aligned on a particular dot using the rotational movement of the lower chuck. Contact to the dot is made by lowering the point a micron at a time until a diode characteristic appears on the curve tracer. By avoiding heavy contact pressure, the point can be reused in the event the diode characteristic is not satisfactory. In this way, several diodes on each chip can be probed since the point is rarely on the center line; in fact, no effort is made to make it that way. Thus, the diodes which can be probed lie on the circular locus of radius equal to the misalignment of the whisker.

When a satisfactory diode characteristic is obtained, the top stud is lowered an amount necessary to crush the gold point into the cup formed in the quartz layer. This step determines the ultimate ruggedness of the diode since the more force on the whisker, the more lateral shock it can withstand. For the 2 micron dot size, a 3 micron deflection of the whisker by the upper stud is adequate to stabilize the point and fill the cup with crushed gold. The 5 micron dot size allows a great deal
Figure A-18a. 8 μm diameter junction being probed.

Figure A-18b. 3.5 μm diameter junction being probed.

Figure A-18c. 2 μm diameter junction being probed.
more force to be applied, but, there is evidence that the value of "n" in the exponent exp (qV/nkT) may be pressure dependent.*

The quartz sleeve is next raised by the micromanipulator probe until it is centered on the diode. Eccobond Kwik (Emerson and Cummings) epoxy is used to bond the quartz and studs together. A small drop is transferred to the top of the sleeve by a probe and allowed to flow between the stud and sleeve by capillary action. The epoxy sets quite rapidly, so enough must be applied to fill the area between the stud and quartz. After the probe has been removed from the bottom, epoxy is applied to the bottom of the sleeve and allowed to set.

The epoxy is supposed to set in one minute and gain full strength in 12 hours. But, after a 15 minute curing period, the diode is rigidly bonded. As a check, the top micrometer is raised, applying the full spring tension of 40 gr. to the diode. If the bond breaks, the parts were probably dirty or the epoxy layer was too thick to ensure a good bond and the diode would probably have failed later. If the contact holds, the diode is removed from the chuck and is ready to be used.

* C. A. Burrus, personal communication.
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BIOGRAPHICAL NOTE

John Edward Rudzki, Jr. was born April 17, 1932 in Pittsburgh, Pennsylvania. He attended the Carnegie Institute of Technology under a Professional Promise Scholarship, 1949-1950. After being called to active military service in 1950, he won a competitive appointment to the U. S. Military Academy at West Point. His work "The Determination of the Sodium Content of the Blood" was reported at the Eastern Colleges Science Conference in 1954. He graduated as a Distinguished Cadet for academic achievement in 1955. After service in Germany, he entered Rensselaer Polytechnic Institute under an Army fellowship where he received the M.S.E.E. in 1962. His thesis was entitled "A Ten-Kilogauss Magnet for Plasma Research." The author served as an Assistant Professor in the Department of Electricity at the U. S. Military Academy from 1962 to 1965. He was nominated by the Academy as an outstanding teacher to compete for a Danforth Foundation Teaching Grant. While at the Academy, he attended graduate school in Physics at the Stevens Institute of Technology. From 1965 to 1967 he managed the U. S. Air Force's Electromagnetic Compatibility Research Program at the Rome Air Development Center where he won a fellowship to MIT in 1967. At present, he is a Lieutenant Colonel in the U. S. Air Force.

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