PHOTOMETERS ON THE SATELLITE AURORA 1

by

Vincent Beauchamp Wickwar

September, 1968
RICE UNIVERSITY

PHOTOMETERS ON THE SATELLITE
AURORA 1

by

Vincent Beauchamp Wickwar

A THESIS SUBMITTED
IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

Thesis Director's Signature:

Houston, Texas
September 1968
ABSTRACT

Photometers on the Satellite

Aurora 1

by

Vincent Beauchamp Wickwar

Uses of photometer and combined photometer-particle measurements from a satellite are discussed with respect to increasing understanding of geophysical phenomena. Several potential observational possibilities are explored at greater length, particularly in the ultraviolet. A description of Aurora 1 with emphasis on the ultraviolet and quadrant photometers is given. The system including the complete satellite and its orbit is considered with respect to acquiring photometer and combined photometer-particle measurements. Quantum efficiency variation in the ultraviolet photometer at long wavelengths is presented and interpreted as arising from color center formation in the photocathode. Photometer calibration is treated in considerable detail starting from basic definitions and derivation of important formulas. Finally there are appendices on the status of ultraviolet interference filters and sodium salicylate for ultraviolet calibration.
## TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>I. STATEMENT OF OBJECTIVES AND ACCOMPLISHMENTS</td>
<td>1</td>
</tr>
<tr>
<td>II. SCIENTIFIC INTRODUCTION</td>
<td>5</td>
</tr>
<tr>
<td>III. THE PHOTOMETERS</td>
<td>32</td>
</tr>
<tr>
<td>IV. SYSTEM EVALUATION AND PERFORMANCE</td>
<td>40</td>
</tr>
<tr>
<td>A. Daytime Observations - Earth and Atmospheric Radiance</td>
<td>40</td>
</tr>
<tr>
<td>B. Atmospheric Absorption and Albedo</td>
<td>43</td>
</tr>
<tr>
<td>C. Observational Effects of Magnetic Orientation at High Altitudes</td>
<td>43</td>
</tr>
<tr>
<td>D. Different Fields of View for SPECS and the Photometers</td>
<td>44</td>
</tr>
<tr>
<td>E. Van Allen Belt</td>
<td>45</td>
</tr>
<tr>
<td>F. Daytime and Twilight Observations - Light Scattered off the Satellite</td>
<td>45</td>
</tr>
<tr>
<td>G. Solar Exposure</td>
<td>47</td>
</tr>
<tr>
<td>H. Wide Passband Photometry</td>
<td>48</td>
</tr>
<tr>
<td>V. QUANTUM EFFICIENCY ENHANCEMENT IN 541G's</td>
<td>50</td>
</tr>
<tr>
<td>A. Experimental Results</td>
<td>50</td>
</tr>
<tr>
<td>B. Possible Explanation</td>
<td>57</td>
</tr>
<tr>
<td>C. Implications</td>
<td>64</td>
</tr>
<tr>
<td>VI. PHOTOMETER CALIBRATION</td>
<td>69</td>
</tr>
<tr>
<td>A. Geometric Factor(s)</td>
<td>74</td>
</tr>
<tr>
<td>1. UV Geometric Factor</td>
<td>75</td>
</tr>
<tr>
<td>2. Quadrant Geometric Factors</td>
<td>80</td>
</tr>
<tr>
<td>B. Output(s) as a Function of Relative Intensity</td>
<td>85</td>
</tr>
</tbody>
</table>
C. Absolute Calibration 88
   1. Angular Factors 91
   2. Spectral Factors 97
   3. Quadrant Absolute Calibration 102
   4. Interpretation of Quadrant Output 109
   5. UV Absolute Calibration 112
D. Influence of Orientation Magnet 117
E. Temperature Dependence 118
F. Voltage Dependence 123
G. Particle Dependence 125
H. Scattered Light 127
I. History Dependence 129

VII. APPENDICES
1. UV Interference Filters 132
2. Sodium Salicylate for Ultraviolet Detection: Wavelength Constancy of its Quantum Yield 138

VIII. ACKNOWLEDGEMENTS 142
IX. BIBLIOGRAPHY 143
X. FIGURE CAPTIONS 158
XI. FIGURES 164
STATEMENT OF OBJECTIVES AND ACCOMPLISHMENTS

As stated in the Abstract the thesis describes the photometers on Aurora 1 and some possible satellite photometer and photometer-particle detector measurements. While I believe the approach taken in the following sections is the most straightforward for organizing and presenting the myriad of facts involved, it tends to obscure four objectives I attempted to accomplish. Therefore the objectives and a list of accomplishments are given below.

The satellite Aurora 1 is one of a sequence by Dr. B. J. O'Brien, between Injun III and the Owls, which is designed for auroral studies and includes in the payload both photometers and particle detectors. There has been a considerable evolution in the photometers from those on Injun I and Injun III, and there is the possibility of further evolution. Thus the first objective is to show the advantages, mentioned below, to be gained by these more complicated photometers. The ultraviolet photometer extends observation to relatively unstudied wavelengths, in this case 1430Å to 1800Å. The Lyman-Birge-Hopfield emissions in this region cannot yet be properly predicted by current theory. Thus there are already many possibilities for latitude and local time surveys as well as correlation with particle spectra and input-output studies. Furthermore, these ultraviolet observations can be obtained over sunlit portions of the earth, for the first time allowing extensive observation of auroral morphology for a different orientation of the earth-sun line and earth-magnetic axis and hence auroral zone-magnetospheric tail configuration. There is less contami-
nation by scattered light and man-made sources enabling much more data to be gathered and also for the first time suggesting the possibility of partially correcting visible data for some of these problems, including albedo variations. The quadrant by being able to measure relative intensities accurately over a long period of time can help identify and determine the emission phenomena. By its small size, weight, low power requirements and lack of moving parts it can be used in even very simple satellites. Suggestions are made for future use of an ultraviolet quadrant and for use of a background channel in the visible quadrant photometer.

The second objective is to describe the new photometers as they exist in Aurora 1. Since they represent only a stage in satellite photometer evolution it is important to document the present design. The use of ruggedized photomultiplier tubes and passive protection against strong light is the same as on Injun I and Injun III. The new front ends for the quadrant and ultraviolet photometers are vital to their performance. They are discussed in detail. Results from programs I had developed to aid in evaluating the present and designing new UV-type collimators are given. Information on the development of ultraviolet interference filters is presented. In future satellites it may be possible to use such a filter to improve long wavelength rejection, but no existing filter met the needs of Aurora 1.

The third objective is to give a detailed treatment of photometer calibration. In doing so I have attempted to use a coherent set of units and resolve some potential sources of confusion in the use of "Rayleigh" and "solid
angle". The first extensive calibration of a quadrant is given. The data reduction that I did and presentation demonstrate what should be done so that the output can be easily interpreted by computer in terms of incident intensities. I have further given the broad-band ultraviolet calibration in a two part fashion that would enable comparison with the work of other experimenters and/or updating for revision of the proposed emission spectrum if the procedure were widely adopted. While this procedure seems obvious it has yet to appear in the literature. Several sources of uncertainty, up to a factor of 2.5 in the ultraviolet absolute calibration, are given. The size of these uncertainties would detract little from proposed measurements for Aurora 1 because many need only relative intensities. Where absolute measurements are needed the present calibration would be good enough to provide more information than already known. But going into detail on procedures and finding the uncertainties leads me to recommend changes for the Owls. Because of the spatial resolution to be given by the Owl TV system and the much lower Owl orbits they are more suited for input-output measurements for which better absolute calibration could be used with advantage. The most important changes should be use of an extended source for quadrant absolute calibration and a change in the ultraviolet front end or electronics to raise or more reliably measure the output current for an IBC I aurora.

The forth and most important objective combines the last one with the Aurora 1 system, including its orbit, to determine what measurements could be made from the satellite. The process involves determining when measurements would be
free of contamination by sunlight, moonlight, particle radiation, man-made sources, etc., and conversely finding criteria for determining the presence of such contamination so that the data could be eliminated or corrected. These determinations are a vital part of any photometric measurement because they dictate what data is worth looking at and the validity of results to be obtained from it. In this case it is shown that emission observation is restricted to the invariant latitudes above about 61°, even before orientation. The great value of an ultraviolet photometer stated in the first objective, is shown in much greater detail. Although a complication arises in its use because of variable long wavelength response. This response is treated here for the first time. It is of importance to experimenters using this type photomultiplier tube and perhaps others as well. The advantages of a lower orbit are set forth and improvements for later satellite photometers are suggested. The most important has to do with reducing light from the sun scattering in the front ends into the photometers for large angles of incidence.
SCIENTIFIC INTRODUCTION

There are many atomic and molecular radiation phenomena in the earth's atmosphere. Initially the nonthermal radiation was all attributed to auroras, especially because of the prominence of forbidden atomic oxygen lines at 5577Å, 6300Å and 6364Å. However by 1931 it was apparent that there were two phenomena (Chapman, 1967). While many of the same emissions were present in both, their spatial and temporal behavior and spectra differed. Now there are considered to be at least ten different phenomena, Table 1. This section considers the possibility of increasing our understanding of some of these with photometer and combined photometer-particle measurements from a polar orbiting satellite.

As with most geophysical phenomena these ten or so are part of long chains of physical processes starting at the sun with alternate links of energy transport and transformation. Photon emission is but one of the transport mechanisms. The chains may fork or branch giving rise to different phenomena such as solar flares to both PCA events and magnetic storms. But the ends of some of the forks may come together as in the $N_2^+$ first negative band system emission associated with both PCA events and intense discrete auroras associated with magnetic storms. Understanding increases as more of the chains and links become known and more of the forked sections are related. It is only then that spatial, temporal and spectral characteristics and/or variations of one phenomenon can be accounted for and related to other phenomena. Because controlled experiments in the traditional sense of an isolated system with measured inputs and outputs can rarely be conducted for these phenomena
TABLE 1

**ATMOSPHERIC EMISSIONS**

**Types of Aurora**

Elvey (1965) and Hultqvist (1967):
- Ordinary discrete displays
- Polar glow
- Discrete polar cap
- High red arcs
- Intermediate red arcs

Sandford (1967):
- Ordinary discrete displays
- Polar glow
- Mantle
- Red line
- Proton excited

**Types of Airglow**

*(based on excitation)*

- Chemical reactions and recombination
- Resonance or fluorescence
- Simultaneous with photoionization or photodissociation
- Photoelectrons

**Other**

- M or SAR arcs
  *(perhaps the high red arcs or red line emission listed above)*
advances have historically been made by the combination of theory and correlation of observations. One of the oldest such correlations is between solar flares and bright discrete auroras. Especially since the advent of rockets and satellites these studies have been supplemented, as well as extended, by measurements of some inputs like solar wind, particles precipitated into the atmosphere and extreme ultraviolet radiation from the sun.

The altitude, mobility and comparatively long lifetime of a satellite are of advantage to photometric measurements for both extended observation for correlation studies and direct comparison to particle input for input-output studies.

Satellite observation of these phenomena, unlike ground observations, can be made irregardless of weather conditions. However in the visible for downward observations weather and surface reflectance variations do give rise to an albedo variation, and hence a measurement uncertainty, of about 20% (O'Brien and Taylor, 1964). Since the emissions also occur above the ozone layer measurements can be extended below the 3000A wavelength cutoff for ground observation and perhaps to earth pointing photometers under sunlit conditions. Of utmost importance for establishing energy chains, charged particles precipitated into the atmosphere can be monitored as they pass the satellite. Provided there is no particle acceleration mechanism below it those in the loss cone follow magnetic field lines into the atmosphere (O'Brien, 1967b).

A satellite's orbital motion takes it over many parts of the earth - all of it for a polar orbit. Thus depending on orbit and orientation system or photometer deployment
regions ranging from belts about the equator or circles about a pole to the whole earth can be observed. However the motion introduces an ambiguity into comparisons of measurements made at different times and hence locations; temporal and spatial dependence cannot be separated for a single set of measurements. Which dependence dominates in a given situation depends upon the characteristic time and size of the phenomena. This ambiguity also exists for rockets. O'Brien has wanted to explore it with a rocket having two identical payloads that separate shortly after launch and drift apart (Westerlund, 1968). He also considered doing it with two Rice/ONR Aurora 1 satellites launched simultaneously into nearly the same orbit (private communication). The Rice/NASA Owl satellites to be launched into similar polar orbits may occasionally offer that possibility.

This ambiguity is usually thought of when considering rockets and satellites, but there is a corresponding one for the restricted situation of a stationary grounded observer looking in one direction. For him it is time changes due to either time dependence or motion of the object viewed.

Because of its long life compared to a rocket, a satellite partially resolves the ambiguity for a regularly occurring phenomenon by enabling comparison of many orbits. In so doing the effects of various parameters such as local time or geomagnetic activity must be determined or taken into account. For infrequent events the ambiguity is not resolved but an orbiting satellite is at least able to make observations. A rocket by contrast often could not be prepared and launched at the opportune time.
Since the distinction between aurora and airglow based upon particle precipitation, more observations of emissions and particle precipitation have suggested that auroras can be divided into many phenomena. There may also be one or more phenomena that are not due to energetic precipitated particles. Both sets are listed in Table 1. The airglow are the usual night, day and twilight varieties divided according to excitation mechanism instead of time. While many emissions appear in common their ratios vary, sometimes greatly. Hence it is important to always observe several spectral regions. Typical 5577Å and 3914Å intensities and ratios are given in Table 2 for some of the phenomena from the previous table. Such a table further enables computation of the relative contributions of the phenomena to a particular emission and would enable relating ground and satellite observations. The polar glow aurora has been associated with PCA events and hence solar cosmic rays (Sandford, 1967, and references therein). Two types of electron and proton precipitation distinguished on the basis of energy spectra, Figures 1 and 2, are described by Burch (1968a, b). Therefore a major clarification and increase in understanding of the radiation phenomena can occur by comparisons with particle type and energy spectra. The first such satellite comparison was by O'Brien and Taylor (1964) for electrons with \( E \geq 40 \) kev. An example is given in Figure 3.

If the result is positive, much can be learned about the links between incident particles and photon emission. For a given precipitation event, photon-particle and photon-photon (of different wavelengths) comparisons provide
<table>
<thead>
<tr>
<th>Phenomena</th>
<th>Typical 5577A Intensity</th>
<th>Typical 3914A Intensity</th>
<th>I(5577): I(3914)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discrete Visual Aurora</td>
<td>~ 1 KR</td>
<td>~ 1 KR</td>
<td>1:1 to 2:1</td>
<td>Chamberlain (1961a)</td>
</tr>
<tr>
<td>Polar glow</td>
<td>≤ 100 R</td>
<td>≤ 10 KR</td>
<td>1:14 to 1:140</td>
<td>Brown (1964)</td>
</tr>
<tr>
<td>Mantle Aurora (morning maximum)</td>
<td>~ 750 R</td>
<td>~ 300 R</td>
<td>1:2 to 1:3</td>
<td>Sandford (1967)</td>
</tr>
<tr>
<td>High Red Arcs</td>
<td>0</td>
<td>0</td>
<td>Monochromatic at 6300A (and 6364A)</td>
<td>Elvey (1965) Sandford (1967)</td>
</tr>
<tr>
<td>Proton Excited Aurora</td>
<td>1 KR</td>
<td>1.7 KR</td>
<td>1:1.7</td>
<td>Eather (1968)</td>
</tr>
<tr>
<td>Airglow due to night-time Recombination</td>
<td>400R</td>
<td>5 R</td>
<td>≥ 80:1</td>
<td>O'Brien, et al. (1965)</td>
</tr>
<tr>
<td></td>
<td>250R</td>
<td>0</td>
<td></td>
<td>Broadfoot and Hunt (1966)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0</td>
<td></td>
<td>Chamberlain (1961a)</td>
</tr>
<tr>
<td>M or SAR Arcs</td>
<td>0</td>
<td>0</td>
<td>Monochromatic at 6300 (and 6364A)</td>
<td>Roach and Roach (1963)</td>
</tr>
</tbody>
</table>
requirements that intervening links involving primarily atomic physics and photochemical reactions must account for. For several events the effects of scaling the input can be studied, and eventually minima and maxima strengths found. These in turn may have to be accounted for by a feedback mechanism (for instance Maehlum and O'Brien, 1968) or by links earlier in the chain. Additionally extended observations and correlation studies may enable other branches of the chains to be identified on the basis of spatial, temporal or other dependences. This type of survey can more quickly and thoroughly be done from a satellite than from the ground. Once a causal relation has truly been established photometer observations can to some extent substitute for particle measurements in showing where particle precipitation is occurring.

If the emission phenomena cannot be identified with particle precipitation, determination of its dependences is even more important for they contain clues about how energy is transported into the emission region. This development of a phenomenological description enables correlation and theoretical studies as is traditional for geophysical phenomena.

In the foregoing, satellite photometer and combined particle-photometer observations are discussed in terms of how they can be expected to contribute to understanding of complex geophysical phenomena, particularly emission phenomena. Part of it is specific in showing characteristics of satellites as observing platforms and that several different phenomena are to be expected, while part is general in discussing the manner by which these measurements can be used
to gain understanding. Correspondingly more would be learned by adding other types of detectors. In what follows some particular examples for potential satellite photometer observations are considered in more detail. Later sections then introduce restrictions imposed by the Aurora 1 satellite, orbit and instrumentation.

Not only can visible emissions be compared with the energy spectra of precipitated and trapped particles, but both can be compared to ultraviolet emission. The ozone layer containing about $1.4 \times 10^{19}$ molecules/cm$^2$ concentrated between 15 and 40 km (Goody, 1964) long frustrated observations short of $\sim 3000$A because of absorption in the Hartly bands. The approximate absorption cross sections with a maximum of $1.08 \times 10^{-17}$ cm$^2$ at 2553A is given in Figure 4 (Inn and Tanaka, 1953; Watanabe, 1958; Goody, 1964). From a balloon at 29.3 km the solar spectrum had been observed to 2875A in 1934 (Watanabe, 1958). The solar spectrum, let alone airglow or aurora, was not observed at shorter wavelengths until an NRL team flew a spectrometer on a captured V-2 rocket 10 October 1946. From 55 km they were able to observe to 2300A (Tousey, 1961). Ultraviolet dayglow from OI at 1304A was observed by an NRL team nearly a decade later, October 1955, from an Aerobee rocket. The first satellite ultraviolet measurements were by a Lockheed team another decade later, 9 November 1965, of auroras in the Lyman-Birge-Hopfield bands of $N_2$ (and perhaps OI at 1304A). Table 3 for dayglow, Table 4 for nightglow and Table 5 for aurora present information on most of the published ultraviolet observations since. Satellite measurements are so indicated.
### TABLE 3

**UV DAYGLOW**

<table>
<thead>
<tr>
<th>Emission</th>
<th>Observed Wavelengths (Angstroms)</th>
<th>Observed Zenith Intensity</th>
<th>Observation</th>
<th>Theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>NI $^4S - ^4P$</td>
<td>1200</td>
<td>0.4 kR</td>
<td>Fastie, et al.(1964)</td>
<td>Donahue (1966) and references [multiple scattering]</td>
</tr>
<tr>
<td>Lyman α</td>
<td>1216</td>
<td>5-12 kR</td>
<td>Fastie, et al.(1964); Clark, et al.(1967a) [satellite]; Fastie (1968); Heath (1968)</td>
<td>Donahue and Fastie (1964) [multiple scattering]; Donahue (1965) [multiple scattering]; Green and Barth (1967) [photoelectrons, 1.5 kR]</td>
</tr>
<tr>
<td>OI $^3P - ^3S$</td>
<td>1302,4,6</td>
<td>2-6 kR</td>
<td>Chubb, et al.(1958); Fastie, et al.(1964); Fastie and Crosswhite (1964); Donahue and Fastie (1964); Fastie (1968)</td>
<td>Green and Barth (1967) [photoelectrons, 1.2 kR]</td>
</tr>
<tr>
<td>[OI] $^3P - ^5S$</td>
<td>1355,8</td>
<td>0.4-0.8 kR</td>
<td>Fastie, et al.(1964); Heath (1968)</td>
<td>Green and Barth (1967) [photoelectrons, ~15 kR according to Heath for this situation].</td>
</tr>
<tr>
<td>$N_2^+$, V-K</td>
<td>1435-2000</td>
<td>1.5 kR</td>
<td>Heath (1968)</td>
<td>Green and Barth (1967) [photoelectrons, ~15 kR according to Heath for this situation].</td>
</tr>
<tr>
<td>NO, γ</td>
<td>2050-2800</td>
<td>1 kR above 70 km for 1-0 band at 2149A</td>
<td>Barth (1966a)</td>
<td>Barth (1966a) [single scattering]</td>
</tr>
</tbody>
</table>
### TABLE 3 (continued)

#### UV DAYGLOW

<table>
<thead>
<tr>
<th>Emission</th>
<th>Observed Wavelengths (Angstroms)</th>
<th>Observed Zenith Intensity</th>
<th>Observation</th>
<th>Theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>N₂, 2 PG</td>
<td>3000-4000</td>
<td>0.4 kR above Barth (1966b) [see 165 km for Noxon (1967) for 0-0 band at information]</td>
<td>~3380A</td>
<td>Nagy and Fournier (1965) [photoelectrons, 0.4 kR above 170 km, 2 kR above 100 km]; Green and Barth (1967) [photoelectrons, 15 kR]</td>
</tr>
<tr>
<td>Emission</td>
<td>Observed Wavelengths (Angstroms)</td>
<td>Observed Zenith Intensity</td>
<td>Observation</td>
<td>Theory</td>
</tr>
<tr>
<td>-------------------</td>
<td>---------------------------------</td>
<td>---------------------------</td>
<td>----------------------------------------------------------------------------</td>
<td>---------------------------------------------</td>
</tr>
<tr>
<td>Lyman $\alpha$</td>
<td>1216</td>
<td></td>
<td>Byran, et al. (1967); Kupperian, et al. (1958); Kupperian, et al. (1959); Donahue and Fastie (1964)</td>
<td>Donahue (1966) and references</td>
</tr>
<tr>
<td>$O_2$ Herzberg</td>
<td>2300-2800</td>
<td>600 R</td>
<td>Tousey (1958); Hennes (1966); Reed and Blamont (1966) [satellite]</td>
<td>Chamberlain (1961a)</td>
</tr>
<tr>
<td>$[^3 \Sigma_u^- - X \Sigma_g^-]_g$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[OI] $^3P - ^1S$</td>
<td>2972</td>
<td>9 R</td>
<td>Hennes (1966)</td>
<td></td>
</tr>
<tr>
<td>OI $^3P - ^3S$</td>
<td>1302, 4, 6</td>
<td>NONE</td>
<td>Byram, et al. (1967); Donahue and Fastie (1964)</td>
<td></td>
</tr>
<tr>
<td>Line Emission</td>
<td>1150-1630</td>
<td>&lt;350 R</td>
<td>Morton (1962)</td>
<td></td>
</tr>
<tr>
<td>Continuum</td>
<td>1150-1630</td>
<td>&lt;18 R/A</td>
<td>Morton (1962)</td>
<td></td>
</tr>
<tr>
<td>Atomic Emissions</td>
<td>Observed Wavelengths (Angstroms)</td>
<td>Observed Zenith Intensity*</td>
<td>Observation</td>
<td>Theory</td>
</tr>
<tr>
<td>------------------</td>
<td>---------------------------------</td>
<td>---------------------------</td>
<td>-------------</td>
<td>--------</td>
</tr>
<tr>
<td>Ni $^4S - ^4P$</td>
<td>1200</td>
<td>0.5 kR</td>
<td>Miller, et al. (1968)</td>
<td>Barth (1968)[320R]</td>
</tr>
<tr>
<td>Ly α</td>
<td>1216</td>
<td></td>
<td>Crosswhite, et al.(1962); Clark, et al. (1967b) [satellite]; Miller, et al. (1968)</td>
<td></td>
</tr>
<tr>
<td>OI $^3P - ^3S$</td>
<td>1302,4,6</td>
<td>14 kR</td>
<td>Murcray (1966); Miller, et al. (1968)</td>
<td>Stolarski and Green (1967) [18 kR]; Barth (1968)</td>
</tr>
<tr>
<td>[OI] $^3P - ^5S$</td>
<td>1355,8</td>
<td>0.4 kR</td>
<td>Miller, et al. (1968)</td>
<td>Stolarski and Green (1967) [9 kR]; Barth (1968)</td>
</tr>
<tr>
<td>Ni $^2D - ^2P$</td>
<td>1493</td>
<td>0.3 kR</td>
<td>Miller, et al. (1968)</td>
<td>Barth (1968)[85R]</td>
</tr>
<tr>
<td>[OI] $^3P - ^1S$</td>
<td>2972</td>
<td></td>
<td>Crosswhite, et al.(1962)</td>
<td></td>
</tr>
</tbody>
</table>

*IBC II Aurora
<table>
<thead>
<tr>
<th>Molecular Emissions</th>
<th>Observed Wavelengths (Angstroms)</th>
<th>Observed Zenith Intensity*</th>
<th>Observation</th>
<th>Theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>N$_2$, LBH $^1\Pi_g - X^1\Sigma_g^+$</td>
<td>1200-2200</td>
<td></td>
<td>Fastie, et al. (1961); Crosswhite, et al. (1962); Isler and Fastie (1965); R. G. Johnson, et al. (1967) [satellite]; Miller, et al. (1968); Aurora 1, 1967 [satellite]</td>
<td>Green and Barth (1965) [70 kR up to 688 kR with cascading]; Stolarski and Green (1967) [≥130 kR]; Barth (1968)</td>
</tr>
<tr>
<td>N$_2$, V-K $^3\Sigma_u^+ - X^1\Sigma_u^+$</td>
<td>2300-3400</td>
<td>10 kR</td>
<td>Fastie, et al. (1961); Crosswhite, et al. (1962)</td>
<td>Green and Barth (1965) [127 kR up to 235 kR with cascading]; Broadfoot and Hunten, (1964) [32 kR]; Stolarski and Green (1967) [32 kR with quenching]</td>
</tr>
<tr>
<td>N$_2$, 2PG $^3\Pi_u - B^3\Sigma_g$</td>
<td>2800-3400</td>
<td></td>
<td>Fastie, et al. (1961); Crosswhite, et al. (1962)</td>
<td>Green and Barth (1965) [25 kR]; Broadfoot and Hunten (1964) [5 kR]; Stolarski and Green (1967) [19 kR]</td>
</tr>
<tr>
<td>N$_2$, G-K $^1\Sigma_u^+ - B^3\Pi_g$</td>
<td>2850-3000</td>
<td></td>
<td>Crosswhite, et al. (1962)</td>
<td></td>
</tr>
</tbody>
</table>

*IBC II Aurora
However just being above the ozone layer does not solve all ultraviolet observing problems. Figure 4 also gives the appropriate absorption cross sections for O$_2$ in the Schumann-Runge bands and continuum longward of 1400A (Watanabe, 1958), while Figure 5 gives the column densities for base altitudes above 100 km for average sunspot conditions and 21 hours (Anderson and Francis, 1966). As with the Hartley bands of O$_3$ these cross sections are thought to be independent of temperature and pressure (Goody, 1964). Therefore the attenuation is proportional to the amount of matter and hence the resultant intensity is given by a simple application of the Lambert-Beer Law. Figure 6 shows absorption between 1400A and 1800A for radiation propagation upward from various levels above 100 km. (It applies in particular to LBH observations from the Rice University/ONR Aurora 1 satellite, 1967-65B, and the Rice/NASA Owl satellites.) There is O$_2$ absorption at shorter wavelengths as well. Table 6 gives the approximate unit optical depth in O$_2$ for the observed atomic emissions that are effected. Thus with the possible exceptions of Lyman-$\alpha$ and the OI triplet at 1302.4, 6A there would be considerable O$_2$ absorption for auroras or airglow originating below 130 km. Much of the visible nightglow (Chamberlain, 1961a), aurora (Rees, 1963; Romick and Belon, 1967) and dayglow (Wallace and McElroy, 1966) does originate between about 90 and 130 km. There is little reason to expect ultraviolet emissions to originate much higher. Therefore an urgent problem for satellite UV input-output studies is to determine the amount of absorption and/or the emission height and O$_2$ distribution.
TABLE 6

UNIT OPTICAL DEPTH IN O₂ OF UV ATOMIC EMISSIONS

<table>
<thead>
<tr>
<th>Emission</th>
<th>Wavelength</th>
<th>Approximate $\sigma$(O₂)</th>
<th>Approximate altitude $\tau=1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>NI $^{4}\text{S} - ^{4}\text{P}$</td>
<td>1200A</td>
<td>$10^{-18}$ cm$^2$</td>
<td>105 km</td>
</tr>
<tr>
<td>Lyman $\alpha$</td>
<td>1216A</td>
<td>$10^{-20}$</td>
<td>75 km</td>
</tr>
<tr>
<td>OI $^{3}\text{P} - ^{3}\text{S}$</td>
<td>1304A</td>
<td>$4 \times 10^{-19}$</td>
<td>95 km</td>
</tr>
<tr>
<td>[OI] $^{3}\text{P} - ^{5}\text{S}$</td>
<td>1355A</td>
<td>$7 \times 10^{-18}$</td>
<td>120 km</td>
</tr>
<tr>
<td>NI $^{2}\text{D} - ^{2}\text{P}$</td>
<td>1493A</td>
<td>$10^{-17}$</td>
<td>125 km</td>
</tr>
</tbody>
</table>


$^{+}$O₂ model above 100 km from Anderson and Francis (1966) for average sunspot conditions and 21 hours, below 100 km from Brinkmann, et al. (1966).
The two exceptions, at least, have another problem — resonance scattering. Noxon (1967) indicates that it should not be a problem for the forbidden oxygen lines at 1355, 8A and Miller, et al. (1968) indicate correspondingly that fluorescence should not be a problem in the LBH bands. Such scattering occurs to much greater heights than $O_2$ absorption because diffusive equilibrium prevails implying that the lighter the particle, greater its scale height. Because of multiple scattering complex radiative transfer problems have to be solved, however the energy dependent line profiles (Eather, 1967) of atomic hydrogen emissions in proton auroras may make the problem much easier for Lyman $\alpha$.

But resonance scattering in Lyman $\alpha$ day and nightglow has provided a means of examining the geocoronal hydrogen (Donahue, 1966 and references) or finding its diurnal and solar cycle variations. More work is needed on that problem. Trying to account for the 1304A dayglow taxes the ability to solve multiple scattering problems because of broad line profiles (Donahue and Fastie, 1964; Donahue, 1965). Fluorescence in the gamma bands of NO has enabled Barth (1966a) to determine the amount of atmospheric NO, a minor constituent but one important to the formation of the D-layer because of its altitude and $2.0 \times 10^{-18}$ cm$^2$ (Watanabe, 1958) ionization cross section for Lyman $\alpha$.

Absorption by $O_3$ and $O_2$ on the other hand may have an advantage for downward observations. It may reduce radiance from the sunlit earth and atmosphere sufficiently to enable observation of sunlit auroras. Those on the sunlit side of the earth have been studied extensively during the polar night, but practically not at all for sunlit conditions.
when the sun-geomagnetic axis are in a different configuration. Particle precipitation (Burch, 1968a) indicates that they exist as do actual measurements of 5577A and 6300A at IBC I and II levels by Noxon (1963) using a scanning polarimeter (Noxon, 1968) and measurements of 4278A and 5577A at an IBC I level by Silverman, et al. (1964) from a rocket. However neither of these two methods is suitable for a survey of such auroras. The possibility of such measurements from a satellite arises from the sharp absorption induced decrease in radiance near 3000A, Figure 7. It is for near coincidence of subsolar and subsatellite points. But at least above 2000A it is a weak function of angular separation of these points, decreasing by about two for a separation of 75° to 80° (Coulson, 1959; Dowling and Green, 1966). The radiance between 1400A and 2800A is given in greater detail in Figure 8. From these radiance curves the possibility of detecting an LBH aurora is later assessed for the Aurora L type photometers which have a small but finite visible response.

The derivation of the two curves is as follows. Coulson (1959) calculates an upward flux F for λ > 3150A at the top if a non-absorbing, Rayleigh, plane parallel atmosphere having a Lambert reflector at the bottom. The sun is above. F is converted to radiance R by

\[ R = \frac{F}{\pi} \]

and a surface reflectance of 0.25 is used.

Between 1800A and 3000A O₃ prevents ground and cloud reflection. It furthermore greatly attenuates Rayleigh scattered radiation, indicating that most scattering above
2000Å occurs below 40 to 60 km. Green (1966) and Dowling and Green (1966) analytically derive the radiance due primarily to Rayleigh scattering by all atmospheric constituents and absorption by O$_3$ and O$_2$ between 2000Å and 3400Å. Krasnopol'skiy (1966) does the same thing, but includes scattering lower in the atmosphere and from the earth at longer wavelengths. Figure 7 includes their results. Also included between 1790Å and 3300Å is a rocket spectrum obtained by Barth (1966b). Measurements between 1600Å and 3200Å have been made by Hudson, et al. (1967) from the Air Force Office of Aerospace Research Satellite OV 1-10, but to my knowledge no results have been published.

Being unaware of published measurements or calculations between 1400Å and ~ 1750Å, a region important for later calculations, an estimate had to be made.

That the radiance falls so drastically between 3250Å and 2750Å is an indication that at long wavelengths most of the radiance originates below the O$_3$ peak concentration at about 25 km. Between 2000Å and 3200Å there is a trade-off between absorption by ozone and loss of scattering centers with altitude. As a result most of the radiance originates between 40 and 60 km. Below 2015Å the ozone absorption coefficient again increases, Figure 4, but remains less than at 2550Å. Thus the very intense low altitude radiance is again avoided, even neglecting O$_2$ absorption.

Since Rayleigh scattering is nearly proportional to $\frac{1}{\lambda^4}$ and solar irradiance is known (Detwiler, et al., 1961; F. S. Johnson, 1965), Figure 8, an upper bound can be set for the unknown radiance in terms of that at longer $\lambda$. It is an upper bound because little O$_2$ absorption has been
included. For every $\lambda_S$ between 1400A and 2035A there is a $\lambda_L$ between 2035A and 2375A such that the ozone absorption coefficients are identical. At these wavelengths there are solar irradiance $F_S$ and $F_L$. Given atmospheric radiance $R_L$, the upper bound for $R_S$ is

$$R_S < \left(\frac{\lambda_L}{\lambda_S}\right)^4 \frac{F_S}{F_L} R_L.$$ 

In Figure 8 is a set of $R_L$ for $2035 \leq \lambda \leq 2375$A and the computed upper bounds.

$O_2$ absorption below 1750A reduces the radiance such that the region which contributes most scattering is raised, as happened at longer wavelengths with $O_3$. At about 115 km the reduction in neutral particle number density with respect to 50 km, (Brinkmann, et al., 1966) is of the same order as the attenuation at 1400A for a light ray entering and leaving. Thus in a crude way one can say that most of the scattered light that could be observed from above at 1400A would have originated near 115 km. Some effects of $O_2$ can be added by multiplying the previous upper bounds for $R_S$ by

$$\exp \left[-2\sigma(\lambda_S) \int_{115} \int n(h) dh\right]$$

where $\sigma$ is the absorption cross section of $O_2$ and $n(h)$ is the number density of $O_2$ as a function of altitude. This result is also indicated in Figures 7 and 8.
At most shorter wavelengths the radiance is probably less. \( O_2 \) is still an effective absorber at most wavelengths with unit optical depth near 100 km or above preventing Rayleigh scattering at great atmospheric depths. The solar continuum decreases below 1400A but has superimposed on it many line emissions. Those most likely to interfere with auroral emissions would be Lyman \( \alpha \) and the OI triplet at 1302,4,6A (Detwiler, et al., 1961 for the spectrum) because of resonance scattering. Table 3 gives the dayglow intensities looking up. Because of the great optical depth, \( \sim 10^5 \) at 100 km (Donahue and Fastie, 1964), for the oxygen triplet in atomic oxygen the signal looking down is most probably no greater. The optical depth for Lyman \( \alpha \) in hydrogen is \( \sim 0.5 \) at 120 km (Donahue, 1966) during the day. Hence in addition to dayglow by resonance there might be a contribution from Rayleigh scattering in the wings of the wide solar emission line. But the NRL team has not observed a strong daytime signal from above (Kupperian, et al., 1959).

Another measurement that could be easily made from a satellite because of the \( O_3 \) absorption is the amount and height distribution of \( O_3 \). The theoretical calculations of the earth and atmospheric radiance between 2000A and 3200A are based on these. Hence when measurements and calculations become good enough the problem can be inverted. Krasnopolskiy (1966) discusses the inversion. Some measurements have been made and reported (R. M. Friedman, et al., 1963; Lebedinskiy, et al., 1966; Krasnopolskiy, et al., 1966; Hudson, et al., 1967), but no extended survey has been published that I am aware of which is directed to the little understood features
of the O$_3$ distribution. One such feature is an increase in concentration in polar regions during the winter when photochemical reactions cannot proceed as usual (Goody, 1964 and references therein).

Presumably the O$_2$ distribution between a satellite and the O$_3$ layer could be found in a similar fashion once the O$_3$ distribution was known. Such determination would be helpful for absorption corrections to at least dayglow and/or sunlit aurora measurements.

The foregoing ultraviolet discussion indicates the possibilities of making measurements in that spectral region and reviews some that have been made. Theoretical studies to explain and predict some of the observations have been made. Those involving resonance or fluorescence to account for the Lyman alpha, OI triplet and NO $\nu$ bands have already been mentioned. But as reviewed by Wallace and McElroy (1966) solar photons may transfer their energy to atoms and molecules in other ways to produce dayglow. Green and Barth (1967) have attempted to calculate ultraviolet UV intensities for excitation by photoelectrons. These complex calculations attempt to account for every intervening link. They depend upon the photoelectron production rate, electron impact cross sections for N$_2$, O$_2$ and O, degradation of electron energy, transition probabilities, Frank-Condon factors, quenching coefficients and atmospheric model. In auroras the distinguishing energy transport mechanism is energetic particles. Green and Barth (1965) and Stolarski and Green (1967) (and correction, Green, 1967) similarly have calculations of UV auroral intensities starting from streams of monoenergetic electrons. These papers are important for
trying to consider and evaluate intervening links. But since many steps are involved, some parts of which are unknown, it is not surprising that there are discrepancies. Satellite observations would help to find and correct them.

Furthermore the reported observations provide a starting point for interpreting signals from wide bandpass photometers, such as the ultraviolet photometer on Aurora 1 for 1450A to 1800A. Early auroral predictions had both O$_2$ Schumann-Runge and N$_2$ Lyman-Birge-Hopfield emissions in that interval (Chamberlain, 1961b). Only LBH has been observed. Isler and Fastie (1965) and Miller, et al. (1968) attribute much of the emission between 1273A and 2200A to it, the rest coming from OI at 1302,4,6A, [OI] at 1355,8A and NI at 1439A. Except for the NI, which is weak, they have found nothing but LBH between 1365A and 2200A. Identification is made by comparing observed intensities to calculated normalized intensities, assuming excitation due to electron collisions as opposed to cascading and deexcitation due to radiation.

The photometer can moreover be calibrated, assuming their identification, in terms of emission from the complete LBH band system. However as discussed earlier, Figure 6, there is strong absorption below 1800A which diminishes the importance of such a calibration unless absorption can be estimated and corrected for.

If a spectrometer were used such that the relative intensities of individual bands were measured, corrections could be determined for an assumed emission spectrum and that spectrum checked. However, for a wideband photometer, correction attempts must start with the particle energy spectrum, assumed emission spectrum and a model atmosphere.
If the excitation cross section is like that for $N_2$ ionization, as suggested very cautiously in Miller, et al. (1968), then an emission profile can be calculated following Rees (1963), the absorption calculated and a correction factor found.

The above calibration relies heavily on an assumption that appeared correct for two rocket observations. It is that there is no excitation of LBH due to cascading. Green and Barth (1965) and Stolarski and Green (1967) give predictions for both cases. If as mentioned the excitation cross sections are similar to those for 3914A or if they are measured the possibility of cascading under some circumstances could be determined by long term comparison of LBH to 3914A or the energy spectrum of incident particles respectively.

In the night airglow nothing has yet been reported between 1450A and 1800A. Observations by Morton (1962) between 1150A and 1630A set upper limits of 350 R for line emission other than Ly $\alpha$ and 18 R/A for continuum emission. These limits have to be lowered. Dayglow observations by Heath (1968) with the same photocathode-window combination as Aurora 1 indicates an emission. On the basis of calculations by Barth (1966b) of Frank-Condon factors times albedo for single fluorescent scattering and Green and Barth (1967) for photoelectron excited dayglow, and his photometer sensitivity he expects an order of magnitude more signal from the Vegard-Kaplan band system of $N_2$ than from the LBH system. Hence he interpretes the signal as arising from 1.5 kR of $N_2$ V-K. However he further shows this intensity is about an order of magnitude below that predicted by Green and
Barth (1967), who have not included collisional deactivation. No estimate is made of that factor.

Additionally the reported UV measurements and future ones will somewhat clarify the use of energy precipitated during auroras. Chamberlain (1961b,c) finds about 18 ergs/sec cm$^2$ of energy known to be emitted in the visible, near ultraviolet and infrared during an IBC III aurora. That intensity aurora implies 100 kR of 5577Å which according to Table 2 means 50 to 100 kR of 3914Å. As discussed below, that implies 100 to 200 ergs/sec cm$^2$ of precipitated electrons. Thus the efficiency for producing known radiation is about 9% to 18% instead of his expected 85%. To account for more energy he then proposed strong ultraviolet emissions, particularly in the Schumann-Runge bands of O$_2$ and Lyman-Birge-Hopfield bands of N$_2$. In partial agreement Green and Barth (1965) put 40% of the energy from 30 kev electrons into far ultraviolet emissions, but only a small part of that into LBH unless there is cascading. Results from Stolarski and Green (1967) are unclear on this point. Observations by Miller, et al. (1968), which supposedly had the most reliable calibration of the rocket measurements by Fastie's team, show approximately the same photon intensities for LBH and 3914Å. Thus it represents about 1% of the electron energy. Murcray (1966) appears to have seen large UV fluxes, but they are difficult to interpret. The energy problem has yet to be understood.

One of the important relations so far found for precipitated particles and emitted radiation is between electron energy flux and 3914Å intensity. It is based on the similarity of cross sections for total ionization and
electron impact excitation of the 0-0 band of $N_2^+$ by NG, and on the expenditure of 35 eV per ion pair produced in $N_2$ by fast electrons (Dalgarno, et al., 1965). Comparing that reference to Davidson (1966) and compromising gives an efficiency of $3.8 \times 10^{-3}$ to within 30% for converting electron energy into 3914 A radiation in an $N_2$ atmosphere. This relation is extended to atmospheres of mostly $N_2$ and $O_2$ by maintaining 35 eV per ion pair and having the efficiency proportional to the percentage of $N_2$. For 1, 10 and 30 keV electrons incident on an atmosphere 45% $N_2$, 45% $O$, and 10% $O_2$ Stolarski and Green (1967) calculate between 32 and 33 eV per ion pair in basic agreement with the above statement. Note that the efficiency falls sharply if the initial electron energies are below 100 eV (Dalgarno, 1964). In the region between 100 and 120 km where Rees (1963) shows most auroral ionization occurring his model atmosphere has about 65% $N_2$. Thus the efficiency becomes $2.5 \times 10^{-3}$ which implies 0.5 kR of 3914 A per erg/cm$^2$ (column) sec. of precipitated electrons.

Because of present uncertainties in various chains there are some further foreseeable uses of satellite photometer observations. One such involves ionospheric acceleration mechanisms for auroral particles. There are presently observations that can be interpreted as conflicting. Agreement between measurements of the ratio of protons to alphas precipitated into an aura and in the solar wind (Reasoner, 1968; Reasoner, et al., 1968) and between measurements and predictions of the ratio of backscattered to precipitated electrons (Burch 1968a) are indicative of an acceleration mechanism far above the auroral zone. However monoenergetic precipitated electrons (D. S. Evans, 1967), abnormal pitch-
angle distributions (Mozer and Bruston, 1966; Cummings, et al., 1966; see discussion Maehlum, 1968a) and electric field measurements (Mozer and Bruston, 1967) have been interpreted as indicating local ionospheric acceleration or perturbing mechanisms. If operating some of the time below a satellite during an electron aurora they could appear as a change in the ratio of 3914A radiation to precipitated electron energy.

Another involves 6300A arcs and glows at all latitudes. In this case there are correlations, theoretical studies and speculations that appear to conflict. Dalgarno (1964) gives a critical heat flux density that enables the electron temperature to rise above the ion temperature. At high altitudes they could differ by more than a factor of three producing some excitation of the ¹D level of OI. He suggests the M-arcs may be due to precipitated low energy electrons (about 400 eV so that they do not penetrate deeply, exciting N₂⁺ or the ¹S level of OI) producing the heat flux density. Maehlum (1968b) similarly suggests that the polar winter F-region ionization be due to precipitated low energy electrons and consequently as another branch of the chain there should also be 6300A emission. It appears that Krassovsky (1968) accounts for the same ionization by an influx of low energy protons at big pitch angles and that he associates them with 6300A emission. There are other suggestions of proton excitation that are discussed by Eather (1967). Krassovsky (1964) further proposes excitation of 6300A by heating due to ionospheric currents or magneto-hydrodynamic waves. Cole (1967) in contrast suggests that M or SAR arcs and some high latitude red arcs are the result
of heat conduction down tubes of force for the cooling of electrons and protons in the Dst main phase ring current. In a different approach Megill and Carleton (1964) suggest ionospheric electric fields, $\vec{E} \perp \vec{B}$, accelerating electrons to produce the necessary electron heating.

Another involves long term studies of latitudinal, spatial, and height variations and spectral, magnetic activity and solar cycle correlations of airglow intensity. Best (1965) has discussed the possibility of making some of these observations from unoriented satellites. Lebedinsky, et al. (1966) made some observations from Cosmos-45. Reed and Blamont (1966) made some latitudinal observations and attempted altitude profiles from OGO-II. Sparrow, et al. (1968) made some observations from OSO-B2. Elliot, et al. (1967) reported having made latitudinal studies from OV l-10. But seemingly as O'Brien (1967a) indicated the great potential for satellite observation of nightglow has yet to be achieved.

In addition to the geophysical studies there is the possibility of making some astronomical observations, particularly of stars of star fields. Which one, depends on the field of view and accuracy of orientation. Simultaneous TV pictures as are to be possible on the Rice/NASA Owl satellites would further facilitate these observations.

Besides the foreseeable studies the results themselves and future theory may suggest other studies and uses of the data. Already UV surveys by the Lockheed team (R. G. Johnson, et al., 1967) have found "radiation across the polar cap area for an appreciable fraction of the cases studied". Similarly Aurora 1 observed UV emission poleward of the auroral zone. These have to be more fully explored.
THE PHOTOMETERS

There are many facets to the quadrant and ultraviolet photometers. In this section they are discussed in terms of the Aurora 1 payload, their component parts and the data telemetered to ground. In following sections orbital system performance and calibration are considered.

Figure 10 depicts Aurora 1 at one instant along its circular path, a path that takes it within a fraction of a degree of the poles at an altitude of about 3875 km. It is shown oriented along geomagnetic field lines passing through the satellite, a condition approximately realized about a month after launch (Burch, 1968a). The 21.4 kg satellite includes three scientific instruments:

(1) a switchable proton electron channeltron spectro-meter, SPECS, detecting particles incident along the magnetic field lines and precipitating into the atmosphere of the northern hemisphere,

(2) a quadrant photometer, and an

(3) ultraviolet photometer, both pointing down the field lines so that emissions, if any, can be correlated with the incident particles.

The quadrant can detect the $^1D_2 - ^1S_0$, 5577A, and $^3P_2 - ^1D_2$, 6300A, lines of atomic oxygen and the 0-0 band, head at 3914A, of the $N_2^+$ first negative band system, $B^2\Sigma_u^+ - X^2\Sigma_g^+$. The UV passband, 1450A to about 1800A, allows detection of many of the $N_2$ Lyman-Birge-Hopfield bands, $a^1\Pi_g - X^1\Sigma_g^+$. SPECS is described in O'Brien, et al. (1967) and Burch (1968a). The quadrant is described in Criswell and O'Brien (1967) and in the following pages along with the UV photometer.
Aurora 1 is pictured in Figures 11 and 12. It was conceived of and its realization directed by Dr. O'Brien. The mechanical design was executed by Ramon Trachta, the electrical by Harold Killen.

Figures 13 and 14 show the two photometers. Each consists of a front end, an Electro-Mechanical Research, Inc. (EMR) package containing a high voltage power supply (and logic for the quadrant) and photomultiplier tube (PMT), signal conditioning electronics and mechanical assembly.

Dr. D. Criswell did much of the development of the two photometers, especially the front ends, and some of the calibration procedures at Rice. He further supervised obtaining some of the calibration data. I became involved with development of interference filters for both photometers. I took the relative UV quantum efficiency measurements and to a lesser extent was involved initially in other calibration procedures. Furthermore, and most important I reduced and analyzed the calibration data.

The front ends are discussed under calibration as are the quadrant interference filters, but UV interference filters are in a separate section, Appendix 1.

The EMR 601A-M3 and 549A-4006 packages have been described in part by Criswell and O'Brien (1967). The 601A-M3, having but one channel, lacks the logic and switching capability of the other. But the power supplies are similar. Use of the 549A-4006 logic is described below in relation to Aurora 1.

Schematic representations of the PMT's are given in Figure 15. The idea of combining a photocathode, from a photocell, with a series of secondary emitting surfaces,
dynodes, was first executed barely more than 30 years ago at RCA, Zworykin, et al. (1936). Lallemand (1949) at the Paris Observatory introduced the venetian blind dynodes with field shaping screen as a good method for both controlling electron motion and having secondary emission. Causse (1960) welded these dynodes onto kovar rings which were then fused to Corning 7052 glass rings. This different construction technique gives very rugged tubes that are additionally free from several sources of noise involving electrical, light or ion feedback.

An EMR, then ASCOP, PMT of this design was first orbited on Injun 1 in July 1961 by O'Brien, et al. (1964). It worked successfully, although frustratingly, for 18 months. Since then this basic design with varying photocathode arrangements and number of dynodes has been used almost exclusively on American rocket and satellite borne photometers.

Sommer (1955) of RCA rediscovered (Sommer, 1957) and introduced multialkali photocathodes. Actually they are a combination of alkalis and antimony and as such are very similar physically to the much older Cs-Sb photocathode (Spicer, 1958). The E photocathode of the quadrant is one of these, Cs-Na-K-Sb.

While the Cs-Sb and Cs-Na-K-Sb photocathodes are sensitive in the ultraviolet, spectrally selective ones would often be more useful where UV radiation is weak and visible strong, as for solar and most blackbody radiation. Such photocathodes followed from the research of a group at General Electric on photoelectric yields, particularly but not exclusively in alkali iodides. Philipp and Taft
(1956) give the yield of Cs-I which EMR introduced as its G photocathode (Rome, 1964). There will be occasion to refer to their articles on alkali iodides later in an attempt to account for enhancements of the long wavelength yield of Cs-I.

These three photocathodes are compared in Figure 16 from Rome (1964).

The 573E quadrant PMT represents a departure from these other photomultipliers in that it is a multichannel instrument. The cathode is cut into quarters, as seen in Figure 15. Each quarter has its own high voltage connection but share the same dynodes and anode. Each is on when its voltage is the same as the bias electrode, off when it is 20V positive. According to EMR the leakage between quadrants is less than 10^-12 A while dark current at room temperature for 10^6 gain is the order of 10^-9 A. The cathode voltages can be varied to commutate the quarters at rates between 1.2 and 800 channels/second, the switching taking 0.5 msec.

The quadrant concept was first executed by EMR (Rome, et al., 1964), in the form of a small star-tracker. At that time they suggested its use for broad band ultraviolet spectroscopy using a different window material over each quarter. It was extended for Rice University to the bigger quadrant PMT first used on Aurora 1 for visible filter photometry, because the original small photocathode made the optical focusing impractical (O'Brien, private communication).

The Rice electronics consists of an analog-to-digital, A/D, converter and a one-shot to prepare the pulses for a scaler. They were developed by Tariq Aziz. The former is described in Criswell and O'Brien (1967).
As a unit there are some characteristics of the photometers that need special mention. Protection from very intense light like the sun, or the sunlit earth for the quadrant, is completely passive. It is accomplished by the front end design (see the section on quadrant geometric factor), high dynode resistors and current limiting high voltage power supplies (see the section on history dependent factors).

There are no in-orbit calibration devices built into the photometers. For launch, reliance is initially placed on the ruggedness of the EMR PMT's. Experience at Rice indicates a gross change in one of the five PMT's shake tested. On that particular 541A the focusing electrode shook loose. O'Brien and Taylor (1964) mention problems with two other 541A's encountered with Injun 1 and Injun 3. Good before and after gain data is to be kept for shake tests of the eight or more photometers for the Owl satellites. This data should indicate better the reliance that can be so placed. In-orbit stability of calibration is initially assumed because of a 50 hour burn-in each tube experienced at about 10 μA. More information on burn-in is given in the section on history dependent factors. As a secondary procedure, in-flight calibration is feasible by observing airglow layers, which are concurrently observed from below, and stars. For the UV the first is impossible while the second is difficult because few stars, particularly in the southern hemisphere, have been accurately observed by rocket or satellite. The basic equations for stellar absolute calibration are derived in the absolute calibration section.
The photometer sensitivity in orbit is five to ten times what it is in the laboratory because the temperature was designed to be and is between $+10^\circ{C}$ and $-5^\circ{C}$ instead of the room temperature of $22^\circ{C}$. Sensitivity is discussed more fully in the sections on absolute calibration and temperature calibration.

With respect to design of satellite photometers for airglow and auroral observations the UV photometer, except for its passband, is nearly identical to the Injun 1 photometer. However the quadrant represents an advance over single channel photometers in terms of two more observing channels plus dark current, with little sacrifice in power, size or weight. Furthermore it is an advance over other multichannel photometers. It is more effective in power, size, weight, lack of moving parts, and time resolution while sacrifices a little in ease of design, calibration and data reduction as well as sensitivity. In Table 7 the Aurora 1 photometers are compared with (1) the Injun 1 photometer (O'Brien, et al., 1964; O'Brien and Taylor, 1964; and Criswell and O'Brien, 1967) and (2) the Main Body Photometer on OGO-II (Reed and Blamont, 1966; and Criswell and O'Brien, 1967). To begin to make a fair comparison with the Main Body Photometer two quadrants should be considered. The weight becomes 3.4 kg, the size $33 \times 16 \times 12 \text{ cm}^3$ and the power 0.56 W. Note that even the total satellite, Aurora 1, is only $62 \times 31 \times 31 \text{ cm}^3$ and consumes 3.5 W.

A functional block diagram of the photometers and of parts of Aurora 1 are given in Figure 17. The telemetry is a five-channel FSK/FM/PM system. Outputs from the scalers and commutator or SPECS voltage indicator frequency modulate
## TABLE 7
### PHOTOMETER COMPARISONS

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Injun 1</th>
<th>Aurora 1</th>
<th>OGO-II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photometer</td>
<td>5577A</td>
<td>UV</td>
<td>Quad</td>
</tr>
<tr>
<td>Photometer weight</td>
<td>0.7 kg</td>
<td>0.7 kg</td>
<td>1.7 kg</td>
</tr>
<tr>
<td>size</td>
<td>33x5x5 cm³</td>
<td>23x5x10 cm³</td>
<td>33x8x12 cm³</td>
</tr>
<tr>
<td>power</td>
<td>0.2 W</td>
<td>0.23 W</td>
<td>0.28 W</td>
</tr>
<tr>
<td>Maximum sensitivity</td>
<td>~ 10 R</td>
<td>~ 100 R of LBH</td>
<td>~ 35 R of 3914A</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>~ 35 R of 5577A</td>
</tr>
<tr>
<td>Dark Current Measurement</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Channels excluding d.c.</td>
<td>1</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Built in Calibration</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Intense Light Protection</td>
<td>Passive</td>
<td>Passive</td>
<td>Passive</td>
</tr>
<tr>
<td>Commutation</td>
<td>-</td>
<td>-</td>
<td>Electrical</td>
</tr>
<tr>
<td>Switching Rate</td>
<td>-</td>
<td>-</td>
<td>Used at 5 channels/sec.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Adjustable from 1.2 to 120 channels/sec.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Feasible to 800 channels/sec.</td>
</tr>
</tbody>
</table>
their respective standard IRIG subcarriers. These in turn are frequency-multiplexed and phase modulate the 137.140 MHz carrier. A telemetry record is shown in Figure 18.

The satellite was tracked by the Naval Space Surveillance Network while the telemetry was received at Rice, Tromsø and at several STADAN stations.

All systems are on continuously unless voltage falls below a certain level. Then once every 24 hours there is an internally generated attempt to turn the satellite on. It succeeds if the batteries have charged sufficiently.

The quadrant diagram in Figure 17 shows the simultaneous use of quadrant and satellite clocks and the cathode 1 reset. The quadrant can be controlled by its internal clock, an external one or a combination, as done here. The former is set to a rate slightly below that of the Aurora clock to which it then synchronizes, thus giving up control. However should the latter fail the internal one is a back-up and takes over control. The cathode 1 reset is important for data reduction should the switching partially fail. Provided it works, it guarantees that channel 1 will reappear every 0.8 seconds.
SYSTEM EVALUATION AND PERFORMANCE

The second section suggested a wide range of possible photometer and photometer-particle measurements. In this section the Aurora 1 system, including the satellite and its orbit, is considered in relation to various spurious and real sources of radiation to determine its limitations.

Daytime Observations - Earth and Atmospheric Radiance

The daytime visible intensity, (Figure 7), as seen through the quadrant interference filters (Table 15, page 100) is approximately equivalent to $10^6$ kR at 3914A, 5577A and 6300A. Additionally, if the quadrant response were linear in intensity the resultant output would be above $10^{-3}$ A, sufficient to saturate the photometer. Thus no visible auroras or airglow would be seen under sunlit conditions. However, as indicated previously it was hoped that the UV photometer might do so and indeed this was the major reason for its inclusion in the satellite.

The feasibility can be evaluated from calculations for D-1 UV and measurements by it and by Lockheed in November 1965. The radiance in Figures 7 and 8 is for near coincidence of subsolar and subsatellite points assuming the photometer is looking toward the center of the earth. While this assumption is not always true for Aurora 1 it does hold on occasion at all latitudes before orientation and in the polar region afterward. Now let us consider airglow at low latitudes. The albedo induced radiance combines with the responses of D-3 UV from Figure 22, which are very similar to those of D-1, to give Figure 23. (The variable quantum efficiency is discussed in a separate section.)
The $3 \times 10^{-9}$A to $1 \times 10^{-7}$A generated between 2500A and 5000A is at least as great as the $2$ to $3 \times 10^{-9}$A generated between 1400A and 2400A indicating the real possibility of a varying long wavelength contamination. For the same sun-satellite geometry D-1 during pass 016, Figure 55, had an earth-signal of $2 \times 10^{-8}$A which combined with the uncertainties in absolute calibration and estimated radiance is within the predicted range. The predicted $5 \times 10^{-9}$A signal for no enhancement is equivalent to 100 kR of LBH. On the other hand Green and Barth (1967) predict 3.6 kR of LBH and 2 kR of V-K for photoelectron excited dayglow in the spectral region to which a 541G with sapphire window is most sensitive. Heath (1968) indicates 2 kR of V-K would give the same photometer response as 20 kR of LBH. Heath's results further suggest that the dayglow intensity is less than predicted but is photoelectron induced and hence a maximum at the subsolar point. Thus in the region where this dayglow would be most intense it would be masked in the UV photometer by an order of magnitude greater albedo-signal.

The background signal from a photometer pointing down over sunlit auroral zones depends on the angle between sun and satellite, with apex at the center of the earth, and the angular dependence of the albedo. This angle is no longer nearly zero. Without reduction only the brightest auroras, brighter than IBC III, could be observed according to the observation by Miller, et al. (1968) that LBH and 3914A $N_2^+$ N$^+$G have nearly the same intensity in Rayleighs. Longward of 2000A Coulson (1959) and Dowling and Green (1966) indicate decreases of no greater than about a factor of two for a 75° to 80° angular separation. Because of $O_2$
absorption the decrease would be greater below 1800A. Lockheed observed UV auroras, between 1250A and 1800A, on a few daytime auroral zone crossings during three days of low geomagnetic activity (R. G. Johnson, et al., 1967) against a low albedo background (J. E. Evans, et al., 1966). By contrast they observed auroras on most nighttime passes. Assuming the albedo prevented other daytime observations indicates a reduction most likely sufficient to detect LBH associated with IBC II auroras. However they do not indicate the sun-satellite angle. Near the terminator, ~ 98° sun-satellite angle, the background for Aurora I observations on 11 October 1967 was photomultiplier dark current, equivalent to ~ 100 R of LBH which as indicated would be expected from an IBC 0 aurora. The quadrant was saturated. Thus it appears that sunlit LBH can be detected with the Aurora I UV photometer.

It was also hoped that before orientation UV data would be usable for studying the O₃ distribution. In view of the proposed large signals centered near 3200A and 1700A which are only slightly controlled by O₃, that study no longer seems possible. If the peak at 3200A could be eliminated, then the signal at 1700A might give information on the amount of O₂ present.

Ultraviolet interference filters may be developed sufficiently, Appendix 1, some day to eliminate much of this visible light. They would at best allow detection of ultraviolet signals two orders of magnitude less than the eliminated visible signal. A quadrant made with windows having different wavelength cutoffs could detect signals about an order of magnitude below the visible signal.
Signals from small spectral regions are obtained by subtracting those from overlapping extended regions after allowing for internal scattered light (see section on interpretation of quadrant signals). If one window were calcite, shielded on the outside by sapphire (Heath and Sacher, 1966; and Sacher, 1967), the signal above 2030A could be determined.

Atmospheric Absorption and Albedo

Since a wide passband UV photometer is used attempts to correct for $O_2$ absorption have to be based upon particle measurements as discussed in the first section.

Albedo changes inherently limit visible observations to an uncertainty of about 20%. While there is no problem of visible extinction there is ultraviolet absorption by $O_2$ and $O_3$. It effectively gives rise to a constant zero albedo for auroral LBH. If relative accuracy better than 20% were desired comparison of auroral visible and ultraviolet would be able to smooth some of the albedo signal.

Observational Effects of Magnetic Orientation at High Altitudes

Magnetic orientation is discussed extensively by Burch (1968a). Since the photometer optical axes are tangent to the magnetic field lines after orientation, Figure 19 drawn with dipole field lines, shows that only the region north of 61° invariant latitude can be observed from a 3875 km orbit. This region barely includes the auroral zones, Figure 20. Hence mid and low-latitude phenomena could only be observed after orientation. Additionally the curvature
of dipole field lines between 1.61 R_e and 100 km is such that at a given moment the photometers and SPECS are observing different \( \vec{E} \) lines and hence \( \Lambda \). From an expanded version of Figure 19 one can solve graphically for the different \( \Lambda \) regions, Figure 21. However one cannot simply translate differences in \( \Lambda \) into time differences because Aurora 1 does not pass over the magnetic pole on every pass. For most data the time differences are between 1 and 3 minutes, a time long compared with the stability of many visible auroral features. Another consequence of not passing the pole and curved field lines is that the photometers can detect radiation from higher \( \Lambda \) than SPECS can detect associated particles. Furthermore, near this northern limit there is a longitudinal discrepancy between the photometers and SPECS. These two effects enter above 80° and thus should affect the polar region, not the auroral zone.

Misalignment of Aurora 1 along \( \vec{E} \) can further affect measurements. One degree of satellite or photometer misalignment causes a maximum of 1.6° error in \( \Lambda \), about a minute in time.

Coordinated studies can be made, but dependence on constancy of particle fluxes for periods of two minutes or so limits the comparisons. Both these problems would be improved significantly for a satellite at lower altitude (as was the initial goal for the hitch-hiking Aurora 1 payload).

**Different Fields of View for SPECS and the Photometers**

The photometers observe an area about 400 km in diameter while the SPECS observe particles streaming nearly straight
down the field lines. Hence the photometers derive most of their response from sources other than the measured particles (even ignoring curved field lines) and may not show the short term time variations observed in the particle measurements. It should also be realized that the large photometer viewing area may only be partly illuminated by auroral radiation. Intensity interpretation on the basis of uniform brightness may be considerably in error. Hence input-output comparisons have to be made and used with great care. This disparity also means that time corrections are not exact because light from the center of the field of view was at the edge about a minute earlier. Both these problems will be improved by the presence of TV pictures as planned for the more complex Rice/NASA Owl satellites.

Van Allen Belt

At the Aurora 1 altitude the orbit traverses regions of hard inner zone Van Allen particles. Despite some lead shielding there is a considerable bremsstrahlung-induced dark current (Figure 56, and discussion in the calibration section). It is sufficient to prevent mid and low latitude photometer observations before orientation. However, it is below threshold for at least the UV north of about 61° invariant latitude.

Daytime and Twilight Observations - Light Scattered off the Satellite

As shown crudely in the calibration section these photometers, especially the quadrant, are very susceptible
to sunlight or earth and atmospheric radiance scattered in the front ends. Data from pass 016 shows that the quadrant reaches maximum output when the sun is less than about 90° from the optical axis or when the sunlit earth is less than about 30°. The UV is affected when the sun is less than 65° from the optical axis, but unaffected by the sunlit earth until it is within the field of view.

Unless the presence of this type contamination can be determined it is best avoided by eliminating potentially contaminated data. It also prevents study of the zodaical light.

Figure 20 gives an indication of when Aurora 1 and the region it observes are in geometric darkness. The Figure is drawn for a satellite in a noon to midnight polar orbit on 22 June at 1.61 earth radii. A dipole magnetic field is assumed and magnetic coordinates used. The same satellite is again considered on 23 September and 22 December. The orbital plane changes orientation about 1° per day with respect to the earth-sun line. Thus in September the orbital plane lies along the 06 to 18 hour meridian. This idealized orbit is close to the 01 to 13 hour orbit into which Aurora 1 was launched on 29 June 1967. Thus after orientation it is apparent that the quadrant is useless due to scattered sunlight until late fall when the observed part of the auroral zone is in darkness. However, even at that time the data would have to be chosen carefully to ensure that Aurora 1 was not in direct sunlight as the sun-viewing direction angle would be less than 90°. The quadrant would be much more useful in a lower orbit and with a better sun shield.
The UV is most apt to be contaminated coming out of the earth's shadow facing the sun, as in summer and winter. However, shortly after emerging the sun-photometer axis will be greater than 65°. Its capability of detecting UV auroras then depends mostly on its long wavelength sensitivity.

**Solar Exposure**

Great solar intensity creates other problems besides scattered light. The photometers have only passive protection from direct sunlight as described in the calibration section. Upon exposure the maximum current, saturation, is obtained. Concomitantly there is a rise in dark current which decays away slowly - to auroral level within a few minutes. Figures 27 and 58 give an indication of the times involved. Longer the exposure, longer the decay time. Hence the situation is considerably aggravated by scattered light in the sunshields enabling quadrant saturation to occur for the sun near 90° from the optical axis or the sunlit earth near 30°. The UV photometer starts to respond at 65° from the sun. Decay in the quadrant can at least be partly monitored by finding the dark current. However the equations given for that in the calibration section assume equal dark current in each channel - an assumption that breaks down in this situation.

Additionally exposure to intense ultraviolet can change the long wavelength response of 541G's, Figure 22. The possibility of solar exposure doing it is discussed in the section about enhancement. Fortunately this increased
visible sensitivity decreases with time such that after orientation and after the orbital plane differs from the noon-midnight meridian it returns to a much lower value. The times involved are perhaps the order of a month, but the temperature dependence has yet to be found for Cs-I. More research is being done on this problem.

**Wide Passband Photometry**

With wide passband photometry there is always the possibility of contamination by spurious sources. Sunlight and earth and atmospheric radiance have already been discussed. Less obvious is contamination by weaker sources. Eather (1967), and Noxon (1968), mention results that have to be seriously questioned because of the possibility, in addition to the sun, of moonlight, spectrally adjacent auroral or airglow lines and continuum. Sparrow and Ney (1968) furthermore discuss light from cities, oil well flare gas, lightning and passing satellites.

Moonlight reflected off the earth does affect visible photometers, but apparently did not affect the Lockheed UV measurements (R. G. Johnson, et al., 1967). It can now be eliminated in the visible by rejecting data when the moon is above the horizon. In auroral studies slowly changing airglow and dark current can be eliminated by motion modulation, a method analogous to chopping only a desired input and measuring the output fluctuations. It is, in fact used by O'Brien and Taylor (1964). The effect of continuum and nearby line emissions depends on the spectrum observed plus the passband.
Since most discrete sources originate below the $O_3$ layer they would present no UV hazard even if they radiated in the UV. By the location of most cities and oil wells the ground region viewed by Aurora 1 should be comparatively free of them. Similarly arctic region observations should be comparatively free of lightning (O'Brien and Taylor, 1964). Furthermore any substantial increase in visible auroral radiation should be matched by an ultraviolet increase. Therefore if it is not, contamination should be considered. High time resolution in the telemetry system should also enable lightning to be found and eliminated.

Contamination from extended sources and/or continuum could be taken into account if measurements were made at wavelengths slightly removed from the emissions of interest (and not coinciding with other strong emissions). With spectrometers and tilting filter photometers (Eather and Reasoner, 1969) such measurements are made routinely. They could also be made with a quadrant photometer using one of the three regular observing channels. One channel of interest would be lost but more data from the other channels would be reliable. In this fashion two quadrants could provide four channels of interest, corrected for dark current, internally scattered light and background. An ultraviolet quadrant has already been discussed for determining contamination above 2030A.
QUANTUM EFFICIENCY ENHANCEMENT IN 541G's

As previously mentioned the total quantum efficiency of an EMR 541G-05M-14-15600 can undergo substantial enhancement in the visible. Figure 22 gives an indication of the magnitudes involved. Experimental results are presented. They are discussed in terms of the available literature and some implications are presented.

Experimental Results

The phenomenon was first recognized at Rice by C. Schwaninger when he realized that the roomlight response of the UV photometers was variable and abnormally high. He and I then noticed that exposure to either intense 1470A radiation or 2537A radiation affected in the visible quantum yield.

Figure 24 gives the response of D-1 UV to radiation at four wavelengths after brief, but unknown, exposures to 1470A xenon radiation. After 100 seconds the yield at 3914A was enhanced 22 times over that of the previous day, while at 5577A it was enhanced more than 260 times. D-3 UV behaved in almost the same manner for the same test. Five other 541G's have since been shown to behave qualitatively in the same fashion.

Having established the existence of this phenomena for all the 541G's checked at Rice more extensive tests were conducted on D-3. They mostly involved the decay 15 or more seconds after the exciting radiation is extinguished. Thus Figure 24 further indicates that the yield decreases smoothly from the A/D saturation level during the first 15 seconds. However no claim is made here that the decay
mechanism in the first few seconds is the same as it is later.

Figure 25 shows that the decay curves have a history dependence. It shows the output of D-3 for 3914A radiation after four successive 10-second exposures to xenon at 1470A from an EMR 582-05M source held against the photocathode window. The typical spectral output of such a lamp, according to EMR, is given in Figure 26. Integrating under the curve gives $5 \times 10^{13}$ photons/sec. Some $O_2$ present in the experimental situation reduces that number to $10^{13}$ photons/sec. If all the photons reached the photomultiplier and if its output were linear the anode current would be $8 \times 10^{-3}$ A. Instead it is the maximum saturation current, $1.8 \times 10^{-5}$ A.

After several saturations for a given time (critical) and decay for a given time (not so critical) the enhancement time dependence becomes repeatable: an enhancement plateau is established. The top curve in Figure 25 is the plateau. For extended measurements it is of course very convenient to obtain such a condition that is repeatable.

Figure 27 shows decay measurements at three wavelengths and dark current for the same plateau. The dark current is included in the light response curves. At no time does the decay appear to be exponential. It is slower. The four curves are replotted in Figure 28. They very closely follow power laws. Absolute quantum yields can be derived from the current data because the lamp used was calibrated against EPT-1070 and the filters have known transmittances.

The enhanced total quantum yields at 3914A, 5577A and 6300A in Figure 22 are derived from these curves or their extrapolations.
The yield between 1450A and about 2800A is found by combining the absolute calibration data of D-1 and D-2 with the EMR data for D-3. The yield at 2537A is treated as constant. Actually it is 13% low 15 seconds after creating a xenon plateau but returns to normal within three minutes. In addition its value is nearly on the lines extended from longer wavelength points.

Because of the straightness of the lines that can be drawn between 2500A and 6300A for the first 500 seconds of this plateau, it appears in the simplest approximation that any line for the plateau will be straight. In this vain a line drawn between 2800A and 3914A is extrapolated speculatively to 5577A and 6300A, for the pre-excitation measurements. Thus measurements made after several months in darkness are treated like those made shortly after achieving a plateau. An upper bound at 5577A is consistent with this line. This line, however, does not necessarily represent the lowest values of total quantum yield. More measurements would be needed for clarification.

So far the longest time for which a decay curve has been measured is about 550 seconds. However, the response has been compared before and after a $1.32 \times 10^5$ second interval during most of which the photomultiplier was off but exposed to scattered light from fluorescent lamps. The predicted results according to the power laws are all too high, the error increasing with wavelength - 46%, 290% and 500% - but are small considering the extrapolation is over three orders of magnitude and light may have been deactivating the electron source. Thus decay occurs whether the photomultiplier is on or off, and it approximately follows power laws.
On the other hand sensitization is greatly improved if the photomultiplier is turned on. If it is off during a 10 second xenon exposure the dark current is increased a factor of 10, instead of nearly $10^3$, 15 seconds after extinction. Preliminary results have not shown any significant enhancement at 3914Å under the same conditions before sensitization. Nor have 10 second and longer xenon exposures affected decay after a plateau has been achieved.

Furthermore it is difficult to determine with this type photomultiplier whether the plateau height depends on the light intensity, cathode current or both. Since the anode current is designed to be nonlinear near its maximum or saturation level and the interdynode voltages vary, the anode current cannot be related to either the cathode current or the incident photons. The relationship between incident photons and cathode current is similarly unknown since the voltage dependence of the first dynode collection efficiency is as unknown as that voltage.

This study could be better conducted with an unpotted 541G-05M used as a photodiode during excitation and as a photomultiplier for enhanced response. Such a setup would be convenient because likely cathode current due to the xenon source is about $3 \times 10^{-7}$Å while 3914Å response, the greatest so far, has been of the order of $10^{-13}$Å. Our laboratory electrometers read $10^{-12}$Å.

It is even difficult to make assumptions about the collection efficiency and obtain information by varying the distance between cathode and source. The Xe 1470Å radiation is strongly absorbed while the Hg 2537Å source is large in extent and weak. Thus in both cases the inverse square law does not apply.
Another potentially useful study, especially for comparison to the preceding and the literature, would be the plateau height as a function of the duration of enhancing radiation.

The agreement of plateaus in Figures 25 and 27 establishes that at 3914A the quantum yield is linear over a range of 15 in intensity because Figure 25 has been corrected by that amount for inverse square. This result is to be expected however, when the source is not intense enough to significantly deactivate the electron source. Such is the case, as shown later.

Wavelength dependence of enhancement has not yet been resolved. The xenon source at 1470A and mercury source at 2537A can both induce the changes. It remains to be shown

(1) that the relative plateau levels of 3914A, 5577A and 6300A are the same for both sources,
(2) that they decay the same, and
(3) whether the photon fluxes needed depend on the relative quantum efficiencies.

In addition it remains to be shown whether radiation at longer and shorter wavelengths can induce the changes.

Returning to the shape of the decay curves, Figures 29, 30 and 31 show their dependence on intensity of the lamp viewed after enhancement. The usual 10 second xenon plateau is employed. The cycle time is about six minutes. The usual decay at 3914A, 5577A and 6300A is compared with the decay after 3 minutes exposure to (1) a bare tungsten bulb or (2) no light. In detail the curves are different. In common, the tungsten lamp somewhat deactivates the electron
source. To a much lesser extent the filtered tungsten lamp also deactivates the source. And the source itself is deactivated with time as usual.

The sensitizing occurs with the bombardment of about $10^{14}$ photons at 1470A. By contrast in 180 seconds the filtered lamp supplies $2 \times 10^{14}$ photons at 3914A, $5 \times 10^{15}$ at 5577A and $4 \times 10^{15}$ at 6300A. Or more important the photocathode emits about $6 \times 10^8$ electrons due to 3914A, $10^8$ due to 5577A and $10^7$ due to 6300A. The number of emitted electrons is a small fraction of the incident photons, as it should be.

Since the current at 5577A and 6300A after 195 seconds of continuous irradiation is about 20% lower than after irradiation for 15 seconds beginning after 180 seconds of darkness the number of electrons emitted in the first case during 180 seconds is an appreciable fraction of those that could have been. Furthermore this fraction is maintained for the rest of the measurement. Thus the apparent source of ionizable electrons is 20% lower due to the irradiation.

At 3914A the situation is different. The long term difference between curves is constant, but between 195 and 225 seconds it is variable. This pattern is repeatable. However at 3914A on the basis of the long term difference it appears that less than a few percent of the electron sources have been ionized.

In the three graphs, data after 180 seconds of exposure to a tungsten lamp is easier to interpret. The curves for constant illumination at the measured wavelength show the rate of quantum yield decay, which as indicated above is largely spontaneous at room temperature, increasing with
wavelength. If the enhanced yields at 3914Å, 5577Å and 6300Å were due to one type of ionizable center then I would expect the decay induced by exposure to a tungsten bulb to either be identical or at least vary monotonically with wavelength. However the decay behaves differently. Comparing the responses after 180 seconds in darkness and after irradiation the follow emerges. The response decreases by a factor of 3.5 at 3914Å while asymptotically it decreases by 6.8 at 5577Å and 4.0 at 6300Å. Thus it appears that there are at least two ionizable centers that contribute to the observed enhancement.

But in addition to a straight-forward reduction in the number of ionizable centers, (as occurs at 3914Å) something else happens upon exposure to a tungsten lamp at 5577Å and 6300Å. For simple destruction the two yield curves should be separated by a constant factor independent of time. They are after 45 seconds at 5577Å and 90 seconds at 6300Å. In the interval the yield is higher than expected, particularly at 6300Å, and decreases faster in time than by the usual mechanism.

The peculiarity at the two longer wavelengths is consistent with the tungsten bulb activating another ionizable center less stable than the usual one(s).

In summary there are five major experimental results that theory must account for:

1. Great enhancement in quantum efficiency long-ward of ~ 2500Å shown in Figure 22,
2. Enhancement decay, approximately as a power law, at room temperature,
(3) Existence of several sources of enhancement as shown by
(a) wavelength dependence of signal decay when exposed to strong light
(b) transient increased yield near 6300A due to strong light,

(4) Possibility of initiating enhancement with radiation at both 1470A and 2537A,

(5) Necessity of having the PMT turned on.

Possible Explanation

Figure 32 shows the quantum yield of D-3 and several samples of Cs-I (Philipp and Taft, 1956). The similarity of long wavelengths fall-offs is striking. So are the quantum yields. Their results indicate unchanging yields below 2060A, variable above. Analogous results are found for K-I and Rb-I (Apker and Taft, 1950 and 1951 respectively). Hence their work on quantum yields, particularly on alkali halides, is a starting point for an explanation.

Alkali halides in general have been studied extensively. F. Seitz (1946) observed

"Almost every field of physics possesses a few problems which merit particular attention, both because they occupy a central position and because one has reasonable hope that, as a result of their inherent simplicity, they may eventually be understood in a complete fashion... In the field of solids, the properties of the alkali halides have an enduring interest, since these crystals have continuously yielded to persistent investigation
and have gradually provided us with a better and better understanding of some of the most interesting properties of all solids."

However, almost all the quantum yield research has been done by L. Apker, E. A. Taft, J. Dickey and H. R. Philipp at the General Electric Laboratory, Schenectady, using a type of photodiode arrangement. Their interpretations of the variable yield are in terms of ionization of defects, particularly F-centers, but also impurities. Thus one has recourse to the extensive literature on color centers in alkali halides.

An F-center is thought to be an electron bound at a negative ion, halogen, vacancy (Seitz, 1954). Also F-centers can be generated in a specimen by a beam of electrons, general ultraviolet radiation or light in the fundamental absorption band. X-rays can be added to this list. Unfortunately Seitz does not discuss the effects of "general ultraviolet radiation" quantitatively. This question is important later because the G.E. group uses radiation in the fundamental absorption band which is centered near 2220Å at room temperature for Cs-I and K-I (Taft and Philipp, 1957). By contrast the measurements at Rice used radiation at about 1470Å. In theory these radiations produce excitons, excited electron-hole pairs, each of which in secondary processes either produces or ionizes an F-center depending on their number density (Seitz, 1954 and Dexter and Heller, 1951).

F-centers absorb radiation in the F-band which is often in the visible part of the spectrum and thus is responsible for the name "color centers". For K-I the F-band is at
about 6500A (Seitz, 1954). For every quantum absorbed in that band two F-centers disappear and an F'-center (Seitz, 1946) appears with its concommitant F'-band absorption at longer wavelengths. An F'-center is an F-center that acquires another electron. Radiation in the F'-band destroys F'-centers creating F-centers. However, F'-centers are most stable only below temperatures of the order of 100°K.

Philipp and Taft (1956) interpret the variable response of Cs-I in Figure 32 as a function of the incident wavelength:

2060A to 2360A -
creation of excitons and subsequent formation and ionization of F-centers.

2360A and above -
direct ionization of F-centers.

The differences between a single crystal and a thin film evaporated in the presence of excess cesium can be accounted for qualitatively by the number of F-centers present.

A prerequisite for F-center formation is a halogen ion vacancy in the crystal structure. Dislocations appear to provide enough vacant lattice sites for considerable formation even in well made virgin crystals (Seitz, 1954). Philipp and Taft (1957) show that for thin evaporated films of K-I the maximum yields from exciton induced and direct ionization of F-centers are up by a factor of 10 from good single crystals. Furthermore the presence of excess alkali would mean extra halogen ion vacancies. Thus the combination of thin evaporated film and excess cesium probably accounts for the larger number of F-centers and greater yield for the
upper curve. In part to minimize the possibility of excess cesium in making G photocathodes EMR evaporates pure CsI (M. G. Winter, private communication).

The reductions in yield at 2060A and 2220A are interpreted as direct ionization of F-centers being more efficient than the indirect exciton ionization. Under these circumstances the first two fundamental absorption peaks at these wavelengths absorb much of the incident radiation causing relative minima in direct ionization without providing more indirect ionization. Note that indications of this structure appear in the total quantum efficiency curves for D-1 and D-2, Figure 51.

Figure 33 from Apker and Taft (1952) shows enhancement occurring in K-I at 2190A due to a flux density of $2 \times 10^{11}$ photons/cm$^2$ sec. The relative yield is proportional to the rate of F-center ionization. Initially as F-centers are formed the rate is proportional to time. Asymptotically the rate of ionization approaches the rate of creation and a maximum number is reached, more than two orders of magnitude greater than initially. The yield for all wavelengths greater than about 2060A should increase, but no information exists on relative amounts. Although Figure 32 suggests that enhancement increases with wavelength. If this were so it would correspond to the 541G data. No information exists on the effect of much more energetic radiation far below the fundamental absorption bands, such as 1470A. The lack of yield change at 2537A is inconsistent with the color center interpretation, but so is the enhancing radiation. This question would have to be examined more carefully in the laboratory.
Figure 33 also shows the decay of K-I yield at 400°K. A replot in Figure 34 shows that it obeys a power law between at least 2 and 40 minutes, while the 541G data follows such a law between at least 30 seconds and 7 minutes. This thermal decay has a strong temperature dependence. The 75% decline that takes ~8 minutes at 400°K takes 60 hours at 300°K (Apker and Taft, 1950).

Taft and Apker (1951) find a separate increase in the yield of Rb-I longward of 5000Å at 85°K. Because of its disappearance upon irradiation at 6530Å and its instability at room temperature they attribute it to F'-centers. Similarly, Philipp and Taft (1957) found F'-centers in K-I at 80°K. Again they vanish at room temperature. The transient response increases at 5577Å and 6300Å found in 541G's are by analogy most likely F'-centers. They occur after creation of F-centers and exposure to strong radiation in the F-band, in the same wavelength region and are highly unstable at room temperature. To my knowledge, if this interpretation is correct, this is the first report of F'-centers in Cs-I.

To evaluate an explanation based upon color centers in Cs-I one must now ask how many of the 541G experimental results can be accounted for without inconsistency or contradiction. The magnitudes and wavelength dependence of the visible enhancement are consistent with F-centers. The observation of what would be F'-centers appearing after exposure to a tungsten bulb that would destroy F-centers is further consistency. The power law thermal decays of visible enhancement agree with the type decay of F-centers in K-I. To attribute these similarities to F-centers in Cs-I implies that the enhancing radiation at 1470Å must be
creating excitons just as does radiation close to 2220A in the fundamental absorption bands. Then why does the yield at 2537A not increase upon exposure to this same 1470A radiation? Why also does there appear to be at least one different ionizable center, at 5577A between 3914A and 6300A? Why does the PMT tube have to be turned on?

The observation at 2537A is one point between 1470A and 3914A. Observations at other intermediate wavelengths should be made before condemning the explanation because of this apparent discrepancy. Furthermore equally detailed observations should be made with enhancing radiation at these other wavelengths. They would afford better comparison with the G.E. research and help determine if the 1470A radiation was producing new effects.

The possible ionizable centers in the visible may well be more complicated than just F-centers as assumed here. There might be impurities. Also the G.E. group have mentioned no decay curves like Figures 29, 30 and 31 which show preferential deactivation at 5577A. Thus this result might be a new observation rather than an inconsistent one.

To discuss the need for having the PMT on or off would probably take greater theoretical understanding of color center formation than at least I now have. Hence this point remains in abeyance.

An alternative to color centers in Cs-I is color centers in the Mg-O secondary emitting surface of the silver dynodes. Less is known about these color centers. Much of it is in Stevenson and Hensley (1961) from which Figure 35 of the quantum yield is adopted. The given yield is for pulverized crystals of Mg-O. However a less detailed curve
in Philipp and Taft (1957) for a thin evaporated film is at most a factor of 10 greater between 2000A and 3700A, with most of this discrepancy between 2000A and 2600A.

The former set of authors claim the yield is highly variable longward of about 2535A.

If enhancement takes place at the first dynode rather than the cathode one stage of multiplication does not occur. Since the gain per dynode is about 2.5 the Mg-O quantum yield curves must be reduced by 2.5 relative to the Cs-I curves. An initial problem arises with Mg-O if its yield is constant below 2500A and if enhancement begins to occur about 2500A in 541G's. Since the effective Mg-O yield is about 50 lower at that wavelength there would have to be a very sharp Mg-O enhancement at 2500A, so sharp that its yield would be greater for many Angstroms longward of that wavelength than below! Thus measurements of possible 541G enhancement near 2500A again become important.

A second problem is simply the great disparity of gains that would have to be overcome. At 3500A for instance which is closer to a measured value for D-3, the effective Mg-O efficiency is \( \sim 10^{-9} \) electrons/photon when unenhanced. For the PMT it is \( \sim 8 \times 10^{-6} \) 15 seconds after xenon enhancement. The Mg-O starts out with a factor of 100 disadvantage initially. Unfortunately neither D-3 data exists at 3500A nor Mg-O yield data, that I am aware of, at 3914A.

However, Stevenson and Hensley do have data on the wavelength dependence of quantum efficiency enhancement at 3980A. They have a good value near 2537A but there is no flux data for D-3 there. But they state that while inconclusive their data indicates that every photon below
about 2500A is equally efficient at causing enhancement. There is an increase of $10^{-18}$ per incident photon. Thus an increase of 400 would take $4 \times 10^{20}$ incident photons. By contrast Figure 25 shows a similar enhancement at 3914A shortly after the first exposure of D-3 for many months when $10^{14}$ photons were incident at 1470A. Again, lack of data does not make this discrepancy of $10^6$ as devastating as it normally would.

Stevenson and Hensley further observe that a two to three order of magnitude enhancement near 3980A would decay away in a few minutes at room temperature. In D-1 as shown in Figure 24 there is a drop of two orders of magnitude in the first 10 seconds at 3914A. Aside from this initial drop there is a further decline of 2 or 3 in the next ten minutes, Figure 27. This initial drop may be nothing more than the dark current falling. Thus there appears to be a clearer discrepancy on this point than on any other.

While Mg-O enhancement is still a possibility, I think it is a very remote one. Thus seemingly an explanation lies with distinguishing between F-centers and other defects in Cs-I.

**Implications**

Three implications are given: the first involves use of 541G-05M's and probably other PMT's with Cs-I photocathodes and ultraviolet transmitting windows, and second involves photomultipliers with other types of photocathodes, and the third involves research in solid state physics.
A 541G has to be used very carefully in certain situations or combination of situations:

(1) Long exposure to intense UV giving about 1 µA anode current or shorter exposure to much more intense UV radiation,

(2) The presence of very strong longer wavelength sources,

(3) Low temperature.

If the first situation exists the visible response may be enhanced. Furthermore if F-centers in the photocathode provide the explanation they any signal due to radiation above ~ 2060 Å could be enhanced. Or turning the situation around the only unenhanced signals would be those from radiation below ~ 2060 Å. However, if the second situation also exists then these signals may be contaminated by the longer wavelength light. If only the second situation exists contamination depends upon PMT history because of long enhancement lifetime. The third situation applies if that lifetime has a strong temperature dependence, as do F-centers in K-I. It then aggravates the other two situations.

The first situation is not a common one but it has been encountered many times while preparing these photomultipliers for use as wide passband photometers for Aurora 1 and Owls. It occurs first during aging when they are operated for 50 hours at about 10 µA. It then occurs during some test setups and calibration tests - most noticeably angular response, output as a function of intensity, temperature dependence of output and dark current decay.
Of greater danger, it might occur in orbit when the sun is viewed directly. A one inch diameter photocathode pointing at the sun would receive the same number of photons per second between 1450A and 1750A as received from the xenon lamp at 1470A in the enhancement studies. Solar intensity, Figure 9, increases a further two orders of magnitude by 2537A at which wavelength enhancement can still occur. Hence the concern is justifiable. Experimental results from Aurora 1 where the effective photometer area is only about 0.02 square inches are inconclusive so far. An important laboratory result would be a curve of enhancement as a function of wavelength.

The second situation is very common. It is usually the reason why these PMT's are used. When used as wide passband photometers it is encountered in the laboratory under roomlight conditions and is certainly the case when looking at sunlit planets. The danger would also exist for filters with poor longer wavelength blocking, for instance interference filters with second order at ~1500A, and for spectrometers with poor scattering characteristics.

Combination of the first two situations creates a problem for ultraviolet quadrants or several separate PMT's used in the same fashion because enhancement of the individual photocathodes would differ. Hence the signal obtained by subtracting channels could be severely contaminated.

The third situation is not as likely to occur for this type photomultiplier as for those with Cs-Sb photocathodes because of the very low thermal dark current. However when used in conjunction with visible PMT's, as on the Rice satellites, the temperature may be lowered to gain visible
sensitivity. Hence the possibility does exist. A valuable laboratory result would be curves of decay time as a function of temperature.

Such curves should also be made at elevated temperatures. Presumably the long decay times could be shortened considerably. If this were so the last step before mounting one of these photomultipliers in a satellite would be to give it a heat treatment to remove enhancement acquired in the laboratory. It would also help in making it practical to find the previously mentioned curve of enhancement versus wavelength. Otherwise it would be difficult, at least time consuming, to ensure "zero" enhancement at the onset of all measurements.

The previous comments were directed toward PMT's with Cs-I photocathodes. However, if the F-center explanation were correct the statements would pertain to at least all other alkali halide photocathodes. Taft and Apker (1953) show an impurity-type yield at long wavelengths in Cs-Te very similar to the F-center yields in Cs-I. They produced it with excess cesium, but do not discuss stability or F-center production. Sommer and Spicer (1965) show K-Sb and Cs-Au yield curves where the long wavelength response has been increased. They mention "defect emission" but again do not discuss stability.

Even if many photocathodes do have varying yields it is quite understandable that the variation was not previously discovered. Most photomultipliers until recently have had glass windows preventing UV transmission and thus probably preventing color-center formation. Even with UV windows most PMT's have been operated at low light levels
and for short enough times that comparatively few color centers would be present. However, there is a possibility that some of the variability in photocells found by Foitzik (1958) may be accounted for in this fashion.

For their research on quantum yields the G.E. team used what in essence is a diode. An instrument capable of working as a photodiode and as a photomultiplier, as suggested earlier, would greatly improve measurement capabilities. Being able to study the decay of visible quantum yield has already led, in this case, to the discovery that there is more than one source of photoelectrons (other than F'-center) between 3914A and 6300A. It has also led, presumably, to observing F'-centers at room temperatures instead of liquid nitrogen temperatures. The nature of the decay itself should furthermore be able to provide information about the photoelectron sources.
PHOTOMETER CALIBRATION

Photometer calibration is summarized in Table 8. The object is to extract meaningful data from the photometers—intensities for emissions of interest. On the one hand there are basic elements that apply under conditions easily obtained and duplicated in the laboratory. While on the other hand there are often, but not always, modifications to adapt to changed orbital conditions.

There can be considerable confusion about units when discussing absolute calibration because some authors use radiometric units as in A.S.A. (1953) while others use units more familiar to radiative transfer and astrophysics as in Chamberlain (1961a). [Despite the name, photometric units, also in A.S.A. (1953), are of no use in what follows. Since there is no chance for confusion they will not be mentioned again.] In addition there is the Rayleigh introduced by Hunten, et al. (1956) and further discussed by Chamberlain (1961a).

To avoid added confusion, especially since I am following no single convention, many units involving light, excluding the Rayleigh, are defined in Table 9. The Rayleigh is discussed below. In addition many units involving interference filters are defined in Table 10.

The Rayleigh may be considered in two fashions. In the first it is a measure of intensity or surface brightness. Given an intensity $I$ and the number $4\pi$

$$IR = \frac{4\pi I}{10^6}$$

and has units of megaphotons/sec cm$^2$sr. Thus, whenever
TABLE 8
### TABLE 9

**LIGHT DEFINITIONS**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Name</th>
<th>Definition</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_\lambda$</td>
<td>Spectral flux</td>
<td>Total number of photons between $\lambda$ and $\lambda+d\lambda$ making a perpendicular crossing of a specified surface in a second.</td>
<td>Photons/sec A</td>
</tr>
<tr>
<td>$\pi F_\lambda$</td>
<td>Spectral flux density</td>
<td>Spectral flux per unit area</td>
<td>Photons/sec cm$^2$A</td>
</tr>
<tr>
<td>$H_\lambda$</td>
<td>Spectral irradiance</td>
<td>Same as spectral flux density</td>
<td>Photons/sec cm$^2$A</td>
</tr>
<tr>
<td>$I_\lambda$</td>
<td>Spectral intensity</td>
<td>Spectral flux density per unit solid angle in a given direction</td>
<td>Photons/sec cm$^2$srA</td>
</tr>
<tr>
<td>$N_\lambda$</td>
<td>Spectral radiance or spectral surface brightness</td>
<td>Same as spectral intensity, but used when referring to an emitting surface</td>
<td>Photons/sec cm$^2$srA</td>
</tr>
</tbody>
</table>

Whenever these quantities are integrated over wavelength the subscript $\lambda$, the word "spectral" and the A$^{-1}$ are dropped. Following Chamberlain (1961a) "Photons/sec" is used in place of "erg/sec" or "watts" and consequently a "d\lambda" is used in place of "dv".
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Name</th>
<th>Definition or Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T(\lambda)$</td>
<td>Transmittance</td>
<td>Incident spectral flux/transmitted spectral flux.</td>
<td>None</td>
</tr>
<tr>
<td>$\lambda_m$</td>
<td>Wavelength of maximum transmittance</td>
<td>The wavelength such that $T(\lambda_m) = T_{\text{max}}$.</td>
<td>A</td>
</tr>
<tr>
<td>$\Delta\lambda$</td>
<td>Bandwidth</td>
<td>Width of the filter between the two</td>
<td>A or nm</td>
</tr>
<tr>
<td></td>
<td>$T(\lambda) = T(\lambda_m)/2$. It is an estimate of $W$.</td>
<td>A or nm</td>
<td></td>
</tr>
<tr>
<td>$W$</td>
<td>Effective Bandwidth</td>
<td>$W = \int T(\lambda)d\lambda/T_{\text{max}}$. This is nearly the same as $\Delta\lambda$.</td>
<td>A or nm</td>
</tr>
<tr>
<td>$W_T_{\text{max}}$</td>
<td>T=1 equivalent width</td>
<td>$W_T_{\text{max}} = \int T(\lambda)d\lambda$, the width of a filter with T=1 centered at $\lambda_m$ that would transmit as many photons/sec as the actual filter for a wavelength-independent source.</td>
<td>A or nm</td>
</tr>
<tr>
<td>$F$</td>
<td>Finesse</td>
<td>$F = \frac{\lambda_m}{W}$. This is like a Q-factor.</td>
<td>None</td>
</tr>
<tr>
<td>$C$</td>
<td>Constant</td>
<td>$C = T(\lambda_m)/T(\lambda_s)$ where $\lambda_s$ is specified.</td>
<td>None</td>
</tr>
</tbody>
</table>
intensity, radiance or surface brightness appears it may be converted to Rayleighs by multiplying by $4\pi/10^6$. In the second it is a measure of the apparent integrated emission rate. The second interpretation only exists because it can be related to the first, as shown in Chamberlain (1961a).

If the isotropic emission rate in photons/cm$^3$ sec is $F(r)$, then for no atmospheric scattering or absorption he shows that the resultant intensity at the end of a centimeter square column of emitting atmosphere is

$$I = \frac{1}{4\pi} \int_0^\infty F(r) \, dr.$$

The seemingly arbitrary $4\pi$ is a consequence of this second interpretation. In this case it has units of steradians and

$$1R = \frac{1}{10^6} \int_0^\infty F(r) \, dr = \frac{4\pi I}{10^6}$$

is the apparent emission rate in megaphotons integrated along a cm$^2$ column. It then has units of megaphotons/sec cm$^2$ (column).
Geometric Factor(s)

As seen in Figures 36 and 37 of the UV and quadrant front ends the hardware limiting the fields of view and receptor areas are quite different. For this reason the two photometers are discussed separately, even though determination of the geometric factor is in principle similar.

The geometric factor \( g \) is the product of detector area \( A \) and solid angle of view \( \Omega \), \( g = A\Omega \). It is important in determining sensitivity to sources of intensity \( I \) which fill the field of view because \( Ig \) gives the number of photons per second incident upon the receptor.

Depending on the situation \( A \) is defined by the receptor area itself or, as in these cases, by the front end. Each photometer has an angular response function \( B(\theta) \) given in Figures 38 and 39 where \( \theta \) is the angle between a parallel beam of light and the photometer optical axis. The solid angle for circular symmetry of the field of view is \( \Omega = 2\pi \left(1 - \cos\theta_{\circ}\right) \) where \( \theta_{\circ} \) is that angle which would allow an ideal front end having

\[
B(\theta) = 1 \text{ for } -\theta_{\circ} \leq \theta \leq \theta_{\circ}
\]

\[
B(\theta) = 0 \text{ for } \theta > |\theta_{\circ}|
\]

to admit the same flux density as an actual front end. Under most circumstances it is difficult to determine what \( \theta_{\circ} \) is. For that reason the following convention has been adopted: the estimated half angle is that angle \( \theta_{\circ} \) for which \( B(\theta_{\circ}) = \frac{1}{2} \).

In the section on absolute calibration the meaning of \( \theta_{\circ} \) is further clarified and an expression found for it.
The results of such calculations are applied in this section to the UV collimator. They are pertinent for discussing a possible source of systematic error.

**UV Geometric Factor**

The geometric factor is determined by either the collimator and photocathode area or by the collimator alone if it limits the receiver area. Thus the desired value of $g$ comes from a balance between minimum intensity and spatial resolution obtainable for a given combination of collimator and PMT. Spatial resolution is the more important parameter in this case because of the high altitude. Nothing is achieved by viewing a greatly extended area if the source does not fill it. Even a $3^\circ$ half angle means that the field of view at 100 km for a 3875 km orbital altitude is a circle of radius about 200 km.

There are two collimator configurations with axial symmetry that give small fields of view. They are shown schematically in Figure 40. The first, a cylinder, is defined by two coaxial circular apertures of the same size. The second, a modified cylinder, is defined like the cylinder but with an additional coaxial circle of smaller radius midway between the other two.

Table 11 gives dimensions for two collimators and Figure 41 gives their calculated angular response curves, $B(\theta)$. Collimator a is a narrow cylinder while b is the same cylinder modified with a small central aperture. Note how the field of view becomes much sharper. It is the Aurora 1 collimator designed by David Criswell and shown in Figure 36. Table 12 gives their properties based on the
TABLE 11

DIMENSIONS FOR THE TWO AXIALLY SYMMETRIC COLLIMATORS IN FIGURES 40 AND 41

<table>
<thead>
<tr>
<th>Collimator</th>
<th>R, inches</th>
<th>r, inches</th>
<th>L, inches</th>
</tr>
</thead>
<tbody>
<tr>
<td>a, cylinder</td>
<td>$8.35 \times 10^{-2}$</td>
<td>-</td>
<td>3.00</td>
</tr>
<tr>
<td>b, modified</td>
<td>$8.35 \times 10^{-2}$</td>
<td>$3.12 \times 10^{-2}$</td>
<td>1.50</td>
</tr>
<tr>
<td>cylinder</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
TABLE 12

Collimator Comparison

<table>
<thead>
<tr>
<th></th>
<th>Small Cylinder</th>
<th>Aurora type Collimator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Working definition of half angle:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\theta_0$</td>
<td>1.29°</td>
<td>2.64°</td>
</tr>
<tr>
<td>$\Omega$</td>
<td>$1.57 \times 10^{-3}$ sr</td>
<td>$6.66 \times 10^{-3}$ sr</td>
</tr>
<tr>
<td>$A$</td>
<td>0.141 cm$^2$</td>
<td>0.0198 cm$^2$</td>
</tr>
<tr>
<td>$g$</td>
<td>$2.22 \times 10^{-4}$ cm$^2$ sr</td>
<td>$1.32 \times 10^{-4}$ cm$^2$ sr</td>
</tr>
</tbody>
</table>

Actual half angle:

<table>
<thead>
<tr>
<th></th>
<th>Small Cylinder</th>
<th>Aurora type Collimator</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta_0$</td>
<td>1.58°</td>
<td>2.64°</td>
</tr>
<tr>
<td>$\Omega$</td>
<td>$2.36 \times 10^{-3}$ sr</td>
<td>$6.64 \times 10^{-3}$ sr</td>
</tr>
<tr>
<td>$A$</td>
<td>0.141 cm$^2$</td>
<td>0.0198 cm$^2$</td>
</tr>
<tr>
<td>$g$</td>
<td>$3.33 \times 10^{-4}$ cm$^2$ sr</td>
<td>$1.31 \times 10^{-4}$ cm$^2$ sr</td>
</tr>
<tr>
<td>$B(\theta)$</td>
<td>0.39</td>
<td>0.50</td>
</tr>
<tr>
<td>% increase in $\Omega$ and $g$</td>
<td>50%</td>
<td>-</td>
</tr>
</tbody>
</table>
dimensions, the B(θ)'s, and both definitions of half angle. Comparing them, the modified cylinder has a larger solid angle as well as a sharper cutoff. However, its area is much smaller with the result that g is less. The actual half angle for an extended source is the same for b, but much larger for a. The estimated half angle becomes a worse approximation as the cutoff becomes less sharp. In this case the resultant error in Ω and g is about 50%. Thus it should be noticed that the use of any estimated half angle may be the source of considerable systematic error.

The calculated curves are found assuming parallel rays from infinity either passing down the collimator to the receptor or being absorbed at the collimator walls. As the angle θ between collimator axis and parallel light increases the detector area perpendicular to the incident radiation goes down by cosine of θ and more of the remaining area becomes shadowed. The values obtained are thus the best for that configuration. Two programs that I had made are available for the calculations. Such calculations could be useful in deciding which type collimator to use and later to judge the construction and angular response measurement.

The dimensions picked for the three-aperture collimator are those of the flight collimator. It is pictured in Figure 36. Measured and calculated response curves are in Figure 38. The experimentally determined half angle and solid angle are 2.9° and 8.0 x 10⁻³ sr compared with the theoretical 2.64° and 6.6 x 10⁻³ sr. Since there are
five collimating units the area is $9.9 \times 10^{-2}$ cm$^2$ and the geometric factor $7.9 \times 10^{-4}$ cm$^2$-sr.

The disagreement between calculated and experimental results for the first decade and a half is to be expected due to reflections in the collimator and beam divergence from a small source less than a meter away. The discrepancy between $0^\circ$ and $2^\circ$ is most probably due to photocathode nonuniformity, to which this type collimation is very sensitive. Beyond four degrees the agreement of the two measurements for positive angle is the result of similar test setups. As seen in Figure 36 there are several surfaces upon which light can scatter. Such scattering is very noticeable with the naked eye. It explains the existence of wings at large angles. Its amount depends on the surface. An attempt had been made to paint the collimator with 3M 101-C10 Black Velvet paint. Nonuniformity in covering would cause different wing formations.

The wings could be improved by threading the inside of the cylindrical apertures or more drastically by adopting a construction similar to the schematic drawing of Figure 40.

A complication affecting these angular response measurements is that they were made in vacuum because an EMR 582-05M xenon source at 1470A was used. Assuming that the reflectivity properties of black paint in the collimators change slowly with wavelength it would be advantageous to make future measurements in air using a low pressure mercury arc at 2537A. The source can be placed further from the photometer and tests are simpler to perform and duplicate. This radiation can also be used for linearity calibration and is discussed in the section on output as a function of intensity.
Quadrant Geometric Factors

For the quadrant photometer, an optical system, consisting of a filter, lens and field stop for three of the quarters, replaces the collimator in determining $g$ (see Figure 37 and Criswell and O'Brien [1967]). The most important reason for using an optical system was to increase $g$ while preserving $\Omega$, i.e. enlarge $A$, and hence gain sensitivity. But there is a further reason that arises from the multichannel nature of this photomultiplier.

Since the photocathode is semitransparent radiation can pass through one quarter and reflect off the dynode structure or electrostatic focuser back onto another quarter inducing a false signal. It turns out that light reflected in the photomultiplier is the greatest source of cross talk between channels. For a nearly parallel beam that reflects off the dynode structure the cross talk signal can nearly equal the proper signal (R. Culver, private communication). The rejection of this false signal increases as the beam incident on the photocathode departs from parallel since more of the light has to undergo several reflections and concommitant absorption before reaching the cathode again.

The light emerging from a collimator as on the UV photometer is highly parallel whereas the parallelism of light emerging from lenses varies, decreasing as the focal length decreases for the same angle of view. Thus a short focal length lens is required to maximize channel independence. More is said on rejection in the section on output as a function of intensity.

A field stop is needed in the lens focal plane to determine the field of view. Normally for a circular field of view the field stop can have a circular aperture with
its center on the optical axis. For the quadrant photometer this situation is modified because each lens is asymmetrically shadowed by the common supports and borders of the lenses and filter. As a result an off-axis location has to be found for the three field stops such that the field of view is nearly symmetric about the optical axis, and hence identical for all three observing quarters.

The remaining important part of the optical system is the set of interference filters used to isolate auroral emissions around 3914A, 5577A and 6300A, see Table 15, page 100. Not only is the spectral isolation important for the science but simplifies the lens design (D. Criswell was able to design lenses to minimize both coma and spherical aberration for monochromatic light) and by occurring early in the system reduces the amount of scattered light. These two factors are important for sharp angular cutoffs initially and continued cutoff at large angles.

For the three observing quarters of the quadrant the detector area is determined by a combination of nylon retaining pieces and metal seats for the lenses. The area is $3.12 \text{ cm}^2$. The error is negligible for the calculation of $g$ in comparison with $\Omega$.

The information discussed below was obtained using nearly a point source six to seven meters from the quadrant. For the distance between lens centers, about 2.4 cm, the divergence of the beam was about $1^\circ$, and hence was small enough when considering each lens that the angle and field of view should be unaffected. However determination that the quadrant axis was pointing at the source is very critical as it affects the relative positions of the quadrant axis.
and each channel axis. This determination was done quite crudely making it difficult to attach great significance to comparisons of the fields of view. Data from simultaneous measurements would have been useful at this point. However, the results given here are an indication of what could be done.

Figure 39 shows a typical angular response curve, while Figure 42 shows how this information has been used to determine the angle of view. Six data points representing the angle from the optical axis at which half maximum response occurs are plotted at azimuthal positions around that axis corresponding to three lens cross sections. A projection of each lens in its relative position with respect to the quadrant axis is given for orientation. Trial and error produces a circle that minimizes the squared radial deviations. It is drawn between the points along with two other circles showing the first estimated standard deviation. For the information available a circle is the easiest figure to fit and the most likely circles have radii that vary little. Table 13 summarizes results related to the geometric factor. The error given is the first estimated standard deviation. θ and its error and everything derived from them apply in so far as the circular approximation applies. Note that the geometric factor is about 40 times that of the UV due to increased receiver area.

The small estimated standard deviations at 5577Å and 6300Å, about three times the reading accuracy of the data, indicate that the circular approximation cannot be too far wrong. Improved focusing using a device I designed and a
### TABLE 13

**QUADRANT GEOMETRIC FACTORS**

<table>
<thead>
<tr>
<th></th>
<th>3914A</th>
<th>5577A</th>
<th>6300A</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Area A</strong></td>
<td>3.12</td>
<td>3.12</td>
<td>3.12</td>
</tr>
<tr>
<td>in cm$^2$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Half Angle $\theta$</strong></td>
<td>3.05±0.4</td>
<td>3.35±0.2</td>
<td>3.05±0.2</td>
</tr>
<tr>
<td>in degrees</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Solid Angle $\Omega$</strong></td>
<td>(9±2)×10$^{-3}$</td>
<td>(11±1)×10$^{-3}$</td>
<td>(9±1)×10$^{-3}$</td>
</tr>
<tr>
<td>in sr</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Geometric Factor $g$</strong></td>
<td>(2.8±0.7)×10$^{-2}$</td>
<td>(3.4±0.4)×10$^{-2}$</td>
<td>(2.8±0.3)×10$^{-2}$</td>
</tr>
<tr>
<td>in cm$^2$-sr</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
carbon arc in the case of 3914A, should improve the data from the quadrant photometers for the Owls. This improved data and several more cross sections would help to show the limitations of this approximation.

Figure 43 shows the three fields of view in relation to one another. It is a combination of the circles from Figure 42 resulting from a superposition of the optical axes while maintaining the relative lens orientations with respect to the quadrant axis, taken as pointing toward the source. The imperfect matching of the circles shows the difficulty in finding the correct size of the field stops. It may further show the difficulty in finding their correct position, or it may show the difficulty in orienting the quadrant.

There are several further aspects of the optical system that do not enter as directly into the calibration but nonetheless affect data from the quadrant. The position of the lens and field stop combination relative to the photocathode is important. If the field stop is too close the photocathode could be damaged by direct sunlight; if too far cross talk would be increased. Sunlight further has to be considered because it reflects off the sunshield into the optical system. Data from pass 016 indicates the quadrant may be saturated by sunlight even when directed 90° from the sun. The more this light can be suppressed in the future, as by putting circular lines on the sunshield, the less time the tube will need to recover from saturation and the more time it will have to so recover.
Output(s) as a Function of Relative Intensity

Below $10^{-6}$ amperes the relationship between light intensity and anode current in both the 541G's and 573E's is linear. Above that it is not. However the A/D converters on the satellite were adjusted to give a maximum count rate of 36 KC at about $10^{-6}$ amperes. The telemetry could not resolve higher frequencies. Remaining deviation from linearity is due primarily to the A/D converter. In Figures 44, 45 and 46 are the quadrant linearity calibration and scattered light signals, while in Figure 47 is the A/D linearity calibration for the UV photometer. As described above all the curves are very similar at high count rates. The dark current has been subtracted from the quadrant curves, but not the UV curve. This latter curve exhibits a problem that appears in some A/D's at low count rates. For either increased temperature or humidity the curve becomes less linear. In orbit the lowest rate observed is 0.8. Assuming it is associated with dark current between $2 \times 10^{-12}$ A (10°C) and $6 \times 10^{-13}$ A (-5°C) as indicated in the temperature section, an estimated count rate dependence on current and hence intensity is made.

This problem is more apparent for the UV than the quadrant because of its greater current range. From dark current to A/D saturation the UV covers $6 \times 10^{-12}$ A to $10^{-6}$ A while the quadrant covers $5 \times 10^{-10}$ A to $10^{-6}$ A at room temperature and $5 \times 10^{-11}$ A to $10^{-6}$ A at 0°C.

The reason for plotting count rate against relative intensity (quadrant) and current (UV) is the use made of these calibrations in conjunction with the absolute calibration.
D. Criswell obtained the data on linearity, rejection and absolute for the quadrant using a mirror-attenuator he designed. To improve the data I calibrated the attenuator in the visible and near UV using another photomultiplier at anode currents small compared to the dynode resistor chain current, both of which were measured.

On the quadrant linearity curves the vertical distance between the two lines, where they are parallel, represents the amount of light scattered from one channel into the others. The signal induced in three channels when light is incident on the fourth could be due to scattered light, or perhaps electrical cross talk. However electrical cross talk can be ruled out. At high light levels where the output becomes nonlinear in the exposed channel it remains linear in the unexposed channels. The same amount of light is scattered into each of the other quadrants. But the amount scattered depends on wavelength. At 3914A 1/100 of the incident beam is scattered into each of the other channels whereas at 5577A and 6300A 1/50 is scattered. The reflectance of the coating on the electrostatic focuser is apparently strongly dependent on wavelength.

A simpler experimental procedure than the attenuator is inverse square. With care 2537A radiation from a mercury vapor lamp may be used with the UV photometer. Curcio, et al. (1953) and Baum and Dunkelman (1955) both found the absorption coefficient in air at sea level to be about $2 \times 10^{-3} \text{m}^{-1}$ in a wavelength region about 2500A. Gerharz (1965) shows that there is no absorption line at 2537A. Thus there is about 2% absorption over a path of 10 meters.
Koller (1965) discusses mercury vapor lamps in general. For stability they must be kept at constant temperature as well as current. Childs (1962) discusses the use of a Pen Ray model 11 SC-1 lamp as a standard at 2537A. It contains a mixture of mercury and argon. I had C. Schwaninger design and build a temperature stabilizer for this type lamp so that it could be used under various temperature conditions.

Care must be taken because some mercury lamps also emit a lot of 1849A radiation which causes non inverse square signals in two ways. The 1849A radiation to which a 541G can easily respond is strongly absorbed in the Schumann-Runge bands of $O_2$ thus decreasing faster than $1/r^2$. This absorption dissociates $O_2$ enabling formation of $O_3$ which in turn absorbs strongly at 2537A. These problems can be avoided if the lamp envelope does not transmit 1849A, or minimized by a combination of moderate air circulation and a filter that cuts off between 1849A and 2537A. Pellicori (1964) has curves for several such filters, the best appearing to be Schott BG-24 and Corning C.S. 9-54. In contrast to those curves Heath and Sacher (1966) show calcite, $CaCO_3$, also to be good.
Absolute Calibration

Absoluteness is first considered in terms of sources and detectors for visible and ultraviolet. Then the problems arising from differences in

1. angular dependence and extent, and
2. spectral dependence

of radiation from calibration sources and aurora or air-glow. The quadrant and UV absolute calibrations are discussed and a means derived to separate the data for each quadrant channel.

Visible

In the region 2500-7500 Å, and further into the infrared, absolute calibration is derived from blackbody sources. The spectral radiance, in power units, is given by Planck's radiation law

\[ N_\lambda = \frac{2c^2 h}{\lambda^5} \frac{1}{e^{hc/\lambda kt} - 1} \]

While very accurate calibration can be performed with a blackbody it is not the most convenient laboratory apparatus. Since many tungsten filament bulbs exist that have stable output over many hours and have repeatable output when turned off and on again, it is convenient to make secondary standards.

Since 1960 the National Bureau of Standards and Eppley Laboratories, under contract, have been issuing tungsten ribbon filament lamps, G.E. type 30A/T24/17, as secondary standards of spectral radiance. They have a maximum output
uncertainty of about 5%. The lamp and its calibration are described by Stair, et al. (1960). Then Stair, et al. (1963) introduced a 200 W spectral irradiance source, which has more recently been displaced by a 1000 W source.

These absolute sources usually fill only part of the photometer field of view. As is shown later it would be more convenient and more accurate if they were to completely fill it. Furthermore they emit more light than needed.

It is possible to use these radiance or irradiance sources with a MgO coated screen to obtain an extended source (Kulkarni and Sanders, 1964, together with Blacker and Gadsden, 1966). More convenient and lower intensity sources are the Saskatoon-type low-brightness sources (LBS's) described by Broadfoot (1964), Broadfoot and Hunten (1964) and Hunten (1967). They consist of a stable bulb, a calibrated set of apertures, and one or two diffusing layers all housed in a small box. The major restriction to their portability is a source of stabilized voltage. The possibility of varying the brightness is unusual and can be convenient. Prydz and Ulset (1968) have considered ZnS electroluminescent lamps for extended radiance sources. They have been made to emit throughout the visible and are stable. However they may have to be operated with a.c. current above 60 Hz and are quite temperature dependent.

A convenient and highly portable LBS is a disk of radio-active-excited phosphor (Kulkarni and Sanders, 1964; Blacker and Gadsden, 1966). However their radiance may vary erratically with time.

One last calibration "source" should be mentioned because of its possible use for inflight calibration — the
stars. Roach (1956) describes, for IGY airglow observers, how to use stellar irradiances for absolute calibration.

Between 1022A and 2500A absolute calibration depends on the spectral sensitivity properties of detectors calibrated at longer or shorter wavelengths. It is established between 250A and 1022A by the photoionization of rare gases (Samson, 1967). Whereas above 2500A it is established with a standard of spectral radiance as described above in conjunction with filters or with a standard of total irradiance as described by Stair, et al. (1967).

The basic detector is the thermopile. It was first used in the region 900A to 2000A by Packer and Lock (1951). When properly blacked (Harris, et al., 1948; Harris and Cuff, 1956; Smith, 1961; and Johnston and Madden, 1965) and photoelectron losses do not cool the couples (Johnston and Madden, 1965), thermopiles have a response that depends solely on energy. With their use further corrections have to be made for either transmittance variations of the window or pressure dependence of the sensitivity.

To obtain greater sensitivity a photomultiplier behind a fluorescent screen is often calibrated against a thermopile. The most common fluorescent compound is sodium salicylate, NaSal, because its quantum yield is nearly constant over a wide wavelength range, is high and is relatively stable. Sometimes the quantum yield of NaSal is assumed constant, and then used to transfer calibration from a wavelength like 2537A down (Appendix 2). Alternatively a NO ion chamber is used to establish absoluteness at 1216A and NaSal is used from there. The photoionization cross sections of NO used to make such measurements depend
on a combination of NaSAl and thermopile. They have an uncertainty of 10% according to Watanabe (1954).

Within the range 1022A to 2500A Samson (1967) mentions the possibilities of synchrotron radiation and plasma arcs approximating black bodies.

Angular Factors

Most absolute sources are Lambertian radiance sources such that the radiance obeys $N(\theta) = N_0 \cos \theta$, using the notation of Tables 9 (page 71) and 14. Aurora and airglow are often approximated by homogeneous, optically thin planes which obey $N(\theta) = N_0 \sec \theta$. The inbetween case, $N(\theta) = N_0$, which would exist inside a sphere of uniform surface brightness or a homogeneous, optically thick emitting substance, is the simplest.

Using the notation of Table 14, and a detector with a circularly symmetric field of view, the flux to reach a small area $dA_0$ of the detector is

$$dP = \int \frac{dA}{R} B(\theta) dB' = \int \frac{dA \cos \theta}{r^2/\cos \theta} B(\theta) dB'$$

$$= dA_0 \int \frac{N(\theta) \cos^3 \theta}{r^2} \frac{r^2 \sin \theta}{\cos^3 \theta} d\Phi B(\theta) dB'$$

$$= 2\pi (dA_0) \int N(\theta) \sin \theta B(\theta) d\theta$$

(1)
Source of radiance $N(\rho)$

\[ r = R \cos \theta, \quad \rho = R \sin \theta = r \tan \theta \]

\[ dB = (\rho d\phi) d\rho = (r \tan \theta \, d\phi \, d\rho) \]

\[ = (r \tan \theta \, d\phi) \frac{r \, d\theta}{\cos^2 \theta} = r^2 \frac{\sin \theta}{\cos^3 \theta} \, d\phi \, d\theta \]

\[ dA = dA_0 \, \cos \theta \]

**TABLE 14**
While this expression is exact, it is rather inconvenient to use because of the form of $B(\theta)$ and its variation over the detector surface.

It would be most convenient to consider $B(\theta)$ applying equally to every $dA$, such that

$$P = 2\pi A \int_0^\pi N(\theta) \sin \theta B(\theta) d\theta$$

and to consider an ideal $B(\theta) = 1$ for $\theta \leq \theta_0$ and 0 for $\theta > \theta_0$. Then

$$\int_0^{\theta_0} N(\theta) \sin \theta B(\theta) d\theta = \int_0^{\theta_0} N(\theta) \sin \theta d\theta.$$  \hspace{1cm} (3)

A goal in this development is to find a $\theta_0$ that can be used to determine the solid angle. Equation (3) is a possibility, but it depends on $N(\theta)$. The solid angle should be a property of the detector, not of the detector and source. However, if the radiance were considered equal from all directions $N(\theta) = N_0$, then the collimator characteristics would control the result. Hence

$$\int_0^{\theta_0} \sin \theta B(\theta) d\theta = \int_0^{\theta_0} \sin \theta d\theta = 1 - \cos \theta_0$$

or

$$\cos \theta = 1 - \int_0^\pi \sin \theta B(\theta) d\theta$$

\hspace{1cm} (5)
using the ideal $B(\theta)$ on the right side of Equation (4).

The solid angle is then

$$\Omega = \int_0^{2\pi} \int_0^\theta \sin \theta \, B(\theta) \, d\theta \, d\phi = 2\pi \int_0^\theta \sin \theta \, d\theta = 2\pi (1 - \cos \theta_0).$$

(6)

The relationship between $\Omega$ found from $\theta_0$ in Equation (5) and from an estimated $\theta_0$, as in $B(\theta_0) = \frac{1}{2}$, is analogous to that between $W$ and $\Delta \lambda$ for interference filters, Table 10, (page 72). Examples of the differences, which increase as $B(\theta)$ becomes flatter, are given in the section on geometric factors for the UV collimator.

Returning to Equation (2) with a source obeying $N(\theta) = N_0$ over solid angle $\omega$ we get

$$P = N_0 A \int_0^{2\pi} \int_0^\pi \sin \theta \, B(\theta) \, d\theta \, d\phi$$

which using Equation (6) gives

$$P = N_0 A \Omega \text{ for } \omega \geq \Omega$$

(7)

and

$$P = N_0 A \omega \text{ for } \omega \text{ contained within } \Omega.$$  

(8)

In other words, the flux is determined by $\Omega$ if the source
at least fills the field of view, by \( w \) if the source is completely within \( \Omega \).

The other radiance functions can be represented in series form when small angles are considered:

\[
N(\theta) = N_o \cos \theta = N_o \left( 1 - \frac{1}{2} \sin^2 \theta \right)
\]

\[
N(\theta) = N_o \sec \theta = N_o \left( 1 + \frac{1}{2} \sin^2 \theta \right).
\]

Excluding terms of order \( \theta^2 \) in \( N(\theta) \), Equations (7) and (8) are again obtained. This excluded term is

\[
N_o A2\pi \int_0^\pi \sin^3 \theta \frac{B(\theta)}{2} \, d\theta.
\]

For all \( \theta \) below \( \theta^0 \) this integral is less than 1% of the main integral. Since \( B(\theta) \) starts to fall sharply beyond about 3\(^o\) with the Aurora 1 photometers this integral contributes nothing compared with the errors in \( B(\theta) \) and lack of homogeneity in aurora and airglow. Hence the three \( N(\theta)'s \) may be considered identical in this situation when the sources fill the field of view.

Thus extended Lambertian sources can be used to calibrate photometers for auroral or airglow observations. Furthermore from two applications of Equation (8) a source of radiance \( N_1 \) subtending \( w_1 < w_2 \leq \Omega \) provides the same flux as a source of radiance

\[
N_2 = N_1 \frac{w_1}{w_2}
\]
subtending $\omega_2$. Thus sources of differing angular extent can be compared, or specifically a source $N_o$ of extent $\omega$ can be used to calibrate a detector with field of view $\Omega$. The equivalent radiance $N$ filling $\Omega$ and giving rise to a signal is

$$N = N_o \frac{\omega}{\Omega} \tag{9}$$

By again comparing fluxes this last result can be extended to sources of known irradiance $H$ which are within the field of view. The flux is

$$P = HA. \tag{10}$$

Hence the equivalent radiance is

$$N = \frac{H}{\omega}. \tag{11}$$

For sources and detectors satisfying the conditions used to derive Equations (9) and (11) with known $N_o$ or $H$ it is possible to find a set of ordered pairs, $N$ and detector output. This set of paired numbers, with one or more members, is the absolute calibration when all sources have the same spectrum. It is fitted to the curve of output versus relative intensity to extend the absolute calibration to all outputs. Corrections for spectral differences are considered shortly.

The most accurate and easiest way to find $N$ is to use an absolute radiance source for which $\omega > \Omega$. Then $N = N_o$. Combining this source with a relative calibration and an absolute source of radiance $N_\omega$ or irradiance $H$, $\omega < \Omega$. 
can find $\Omega$ by comparing the fluxes in Equations (7), (8) or (10):

$$\Omega = \frac{N}{\omega} \quad \text{or} \quad \Omega = \frac{H}{N_0}.$$  

However, when an extended source is not available $\Omega$ has to be calculated from $B(\theta)$.

**Spectral Factors**

The spectral differences of absolute sources and auroral or airglow sources enter because photometer sensitivity is a function of wavelength. Since the photometers are used in a d.c. amplification mode the spectral sensitivity is given by

$$T(\lambda)Q(\lambda)$$  

where $Q(\lambda)$ is total quantum efficiency, i.e. the product of gain and quantum efficiency, and $T(\lambda)$ is filter transmittance. Thus the output in electrons per second is

$$\int P(\lambda)T(\lambda)Q(\lambda)d\lambda = A\Omega \int N(\lambda)T(\lambda)Q(\lambda)d\lambda = \frac{i}{e}$$  

where $P(\lambda)$ is spectral flux, $N(\lambda)$ is either a real or derived spectral radiance which fills the field of view, $i$ is negative current and $e$ is charge of an electron. Equation (13) is used in several ways for the quadrant and UV photometers to obtain sets of ordered pairs of intensity and output relevant to the sources being measured.
However Equation (12) has to assume that photometer gain is constant and hence that the output in Equation (13) is a linear function of flux or radiance. This linearity is true over much of the Aurora 1 photometer range but not all of it, as pointed out previously. Figure 48 shows how to correct calculated linear output to nonlinear photometer output using a curve of the latter as a function of relative intensity. Calculated and observed curves are plotted so that they coincide at an output for which the photometers have the gain used in \(Q(\lambda)\). Output and gain can be picked for the photometers so that a linear region of the observed curves coincides with the calculated ones. Then looking at the Figure it is obvious that an observable output \(B\) would arise from the same input \(I\) used to calculate \(A\). Having shown this correction is possible for such nonlinearity spectral differences can be investigated with Equation (13).

For the quadrant the passbands are severely restricted by interference filters. Let each wavelength of maximum transmittance be \(\lambda_o\). Within each passband \(Q(\lambda) \cong Q(\lambda_o)\) and for tungsten filament lamps and radioactive excited sources \(N(\lambda) \cong N(\lambda_o)\). Thus Equation (13) becomes

\[
N(\lambda_o)Q(\lambda_o) \int T(\lambda) d\lambda = N(\lambda_o)Q(\lambda_o)WT_{\text{max}} = \frac{i}{e} \tag{14}
\]

Within each passband Chamberlain (1961a) shows one major emission feature. At 5577A and 6300A they are line emissions: the intensity is \(I_{\lambda'} = I(\lambda')\delta(\lambda-\lambda')\). Thus we get

\[
I_{\lambda}Q(\lambda_o)T(\lambda) = \frac{i}{e} \tag{15}
\]
dropping the primes and using $Q(\lambda) \approx Q_0(\lambda)$. Figure 49 shows the $N_2^+$ 0-0 band with head at 3914Å for a typical aurora. However the relative intensity of the bands vary depending on temperature and sunlight. Since most of the light is at 3914Å (more than indicated in the Figure because its intensity scale is nonlinear) and because of the uncertainty in relative line intensities this emission is treated as a 3914Å line emission.

Equating the outputs in (14) and (15)

$$I_\lambda = N(\lambda_o) W \frac{T_{\text{max}}}{T(\lambda)}$$

for the intensity of an auroral or airglow emission that would cause the same output as the calibration source. The absolute calibration previously derived from pairs of $N_o$ and output has now to be multiplied by the spectral correction factor $W T_{\text{max}}/T(\lambda)$ derived from the interference filter. Corrections to these factors are calculated later to account for temperature changes. $N(\lambda)$ is given in Figure 50 and filter data in Table 15 (page 100). These are combined with A/D data to give intensity as a function of count rate in Figures 44, 45 and 46. Remember that these curves are only suitable for interpreting quadrant output when the auroral or airglow emissions account for most of the radiation reaching the photocathode.

The calibration procedure for the UV is different because of a much wider passband coupled with calibration sources far from constant in output and uncertain auroral emission spectra. It involves finding $Q(\lambda)$ and subsequent referral to it for proposed emission spectra.
TABLE 15
QUADRANT FILTER DATA

<table>
<thead>
<tr>
<th>λ₀ (nm)</th>
<th>Temperature</th>
<th>κ</th>
<th>λₘ (nm)</th>
<th>T_max (°C)</th>
<th>Δλ (°C)</th>
<th>W</th>
<th>WT_max (°C)</th>
<th>T_λₒ</th>
<th>Finesse</th>
<th>W T_max</th>
</tr>
</thead>
<tbody>
<tr>
<td>3914</td>
<td>-30°C</td>
<td>0.27 A/°C</td>
<td>3908</td>
<td>0.368</td>
<td>33.2</td>
<td>0.348</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>22°C</td>
<td>0.27 A/°C</td>
<td>3922</td>
<td>0.368</td>
<td>33.0</td>
<td>36.7</td>
<td>13.5</td>
<td>0.323</td>
<td>107</td>
<td>41.8</td>
</tr>
<tr>
<td>5577</td>
<td>-30°C</td>
<td>0.29 A/°C</td>
<td>5573</td>
<td>0.558</td>
<td>35.0</td>
<td>0.53</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>22°C</td>
<td>0.29 A/°C</td>
<td>5588</td>
<td>0.555</td>
<td>34.8</td>
<td>38.4</td>
<td>21.3</td>
<td>0.44</td>
<td>145</td>
<td>48.4</td>
</tr>
<tr>
<td>6300</td>
<td>-30°C</td>
<td>0.25 A/°C</td>
<td>6288</td>
<td>0.501</td>
<td>49.8</td>
<td>0.46</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>22°C</td>
<td>0.25 A/°C</td>
<td>6301</td>
<td>0.501</td>
<td>49.4</td>
<td>53.9</td>
<td>27.0</td>
<td>0.50</td>
<td>117</td>
<td>54.1</td>
</tr>
</tbody>
</table>

Temperature, λₘ, T_max, Δλ, WT_max and T_λₒ from Thin Film Products, Inc. data.
The emission source is a monochrometer. Combining its output \( P(\lambda') \delta(\lambda-\lambda') \) with no filter reduces Equation (13) to

\[
P(\lambda)Q(\lambda) = \frac{i}{e}
\]

or

\[
Q(\lambda) = \frac{i}{eP(\lambda)}.
\]

Since \( P(\lambda) \) is known and \( i \) is measured in the linear region or linearized, \( Q(\lambda) \) in electrons per photon can be plotted as a function of \( \lambda \) as in Figures 22 and 51.

For any continuous or line source of spectral intensity \( I(\lambda) \) or \( I_\lambda \delta(\lambda-\lambda_i) \) respectively there is an intensity

\[
I = \int I(\lambda)d\lambda \quad \text{or} \quad I = \sum_i I_\lambda \delta(\lambda-\lambda_i) \quad (16)
\]

to be associated with an output from Equation (13)

\[
\frac{i}{e} = A\Omega \int I(\lambda)Q(\lambda)d\lambda \quad \text{or} \quad \frac{i}{e} = A\Omega \sum_i I_\lambda Q(\lambda_i). \quad (17)
\]

\( I \) and output form the sets of ordered pairs needed to transform output as a function of relative intensity into a function of absolute intensity.

As stated in an earlier section it appears that the dominant auroral emission within the UV passband is the LBH band of \( N_2 \). Isler and Fastie (1965) and Miller, et al. (1968) list the relative intensities for excitation by
collision with electrons and radiative deexcitation. Table 16 has the intensities of the strongest bands in rayleighs within the UV passband. They account for 40% of the photons in a 10 kR LBH emission. The ordered pair from the line emission version of Equations (16) and (17) is 10 kR of LBH for $4.4 \times 10^{-10}$ A output. Since current and intensity are linearly related over much of the UV range this absolute calibration is added to Figure 47. However it can only be approximate at best because atmospheric absorption by $O_2$ has not been taken into account. That correction has to be done when something is known about the height profile of the particular LBH emission being observed.

A continuous source discussed previously is the earth's UV albedo. Figure 23 shows the calculation involved in Equation (17). Since the albedo radiation has been considered contamination it has been discussed only in terms of the LBH absolute calibration.

Quadrant Absolute Calibration

A G.E. tungsten ribbon filament lamp, EPT-1070 calibrated by Eppley Laboratory, was used as a small spectral radiance source for the quadrant calibration. A mirror system focused light from an area of the filament onto an aperture of known area. Except for mirror reflectances the radiances are identical for the source and its real image, a statement which is formerly the same as saying that surface brightness is not a function of distance to the observer. The proofs are parallel. Thus if two mirrors are used as recommended by Stair, et al. (1960), the spectral
TABLE 16

BAND INTENSITIES WITHIN THE D-1 PASSBAND

For 10 kr of Lyman-Birge-Hopfield*

<table>
<thead>
<tr>
<th>λ</th>
<th>V'-V&quot;</th>
<th>Rayleighs</th>
<th>λ</th>
<th>V'-V&quot;</th>
<th>Rayleighs</th>
</tr>
</thead>
<tbody>
<tr>
<td>1444</td>
<td>3-2</td>
<td>203</td>
<td>1611</td>
<td>0-3</td>
<td>116</td>
</tr>
<tr>
<td>1450</td>
<td>0-0</td>
<td>27</td>
<td>1615</td>
<td>4-6</td>
<td>29</td>
</tr>
<tr>
<td>1464</td>
<td>1-1</td>
<td>318</td>
<td>1627</td>
<td>1-4</td>
<td>105</td>
</tr>
<tr>
<td>1473</td>
<td>5-4</td>
<td>94</td>
<td>1631</td>
<td>5-7</td>
<td>11</td>
</tr>
<tr>
<td>1479</td>
<td>2-2</td>
<td>10</td>
<td>1647</td>
<td>6-8</td>
<td>46</td>
</tr>
<tr>
<td>1489</td>
<td>6-5</td>
<td>70</td>
<td>1658</td>
<td>3-6</td>
<td>120</td>
</tr>
<tr>
<td>1493</td>
<td>3-3</td>
<td>166</td>
<td>1672</td>
<td>0-4</td>
<td>72</td>
</tr>
<tr>
<td>1501</td>
<td>0-1</td>
<td>87</td>
<td>1674</td>
<td>4-7</td>
<td>150</td>
</tr>
<tr>
<td>1508</td>
<td>4-4</td>
<td>161</td>
<td>1687</td>
<td>1-5</td>
<td>202</td>
</tr>
<tr>
<td>1515</td>
<td>1-2</td>
<td>120</td>
<td>1690</td>
<td>5-8</td>
<td>53</td>
</tr>
<tr>
<td>1530</td>
<td>2-3</td>
<td>230</td>
<td>1703</td>
<td>2-6</td>
<td>102</td>
</tr>
<tr>
<td>1539</td>
<td>6-6</td>
<td>15</td>
<td>1735</td>
<td>4-8</td>
<td>53</td>
</tr>
<tr>
<td>1555</td>
<td>0-2</td>
<td>129</td>
<td>1736</td>
<td>0-5</td>
<td>34</td>
</tr>
<tr>
<td>1560</td>
<td>4-5</td>
<td>71</td>
<td>1752</td>
<td>5-9</td>
<td>86</td>
</tr>
<tr>
<td>1576</td>
<td>5-6</td>
<td>110</td>
<td>1752</td>
<td>1-6</td>
<td>170</td>
</tr>
<tr>
<td>1584</td>
<td>2-4</td>
<td>166</td>
<td>1768</td>
<td>2-7</td>
<td>230</td>
</tr>
<tr>
<td>1591</td>
<td>6-7</td>
<td>38</td>
<td>1769</td>
<td>6-10</td>
<td>53</td>
</tr>
<tr>
<td>1600</td>
<td>3-5</td>
<td>191</td>
<td>1784</td>
<td>3-8</td>
<td>114</td>
</tr>
</tbody>
</table>

*Adapted from Isler and Fastie (1965) and Miller, et al. (1968) for excitation by collisions with electrons and deexcitation by radiation. 4.0 kr occur within the passband.
radiance $N_{\lambda}$ at a defining aperture is

$$N_{\lambda} = R_{1\lambda} R_{2\lambda} N_{\lambda \text{known}}$$

where $R_{1\lambda}$ and $R_{2\lambda}$ are the mirror spectral reflectances and $N_{\lambda \text{known}}$ is the spectral radiance attributed to the lamp, Figure 50.

Very small apertures and neutral density filters had to be used to reduce light intensity sufficiently to make measurements which are then combined with angular data and filter data as previously described to obtain absolute calibration data points. They are given along with nominal aperture sizes and nominal neutral density transmittances in Table 17. The absolute curves are given in Figures 44, 45 and 46. The estimated first standard deviations are given in Table 18. They are expressions of the uncertainty in $N_{\omega}$ due to aperture area and neutral density filters. Also given are the estimated first standard deviations of the $\Omega$'s. These two uncertainties can be combined as they are independent and enter into consideration because of $N' = N \frac{\omega}{\Omega}$. They are combined with the 5% uncertainty for the lamp.

With further calibration of apertures and neutral density filters the random error could be reduced. With more measurements the variation obtained for $\theta_0$ could perhaps be reduced. But the possibility of systematic error in the choice of half angle still exists. From the UV-collimator calculations comparing estimated and actual half angles, Table 12 (page 77), it is apparent that there is a systematic error in the cylindrical collimator of
<table>
<thead>
<tr>
<th></th>
<th>3914A**</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Aperture Diameter</td>
<td>0.0135&quot;</td>
<td>0.0210&quot;</td>
<td>0.0420&quot;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Filter Transmittance</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Intensity</td>
<td>15 kR</td>
<td>35 kR</td>
<td>140 kR</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Count Rate</td>
<td>1320 cps</td>
<td>2100 cps</td>
<td>14,800 cps</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>5577A</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Aperture Diameter</td>
<td>0.0135&quot;</td>
<td>0.0135&quot;</td>
<td>0.0135&quot;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Filter Transmittance</td>
<td>0.1</td>
<td>0.5</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intensity</td>
<td>21 kR</td>
<td>105 kR</td>
<td>210 kR</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Count Rate</td>
<td>1790 cps</td>
<td>9130 cps</td>
<td>15,700 cps</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>6300A</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Aperture Diameter</td>
<td>0.0135&quot;</td>
<td>0.0135&quot;</td>
<td>0.0210&quot;</td>
<td>0.0135&quot;</td>
<td>0.0135&quot;</td>
</tr>
<tr>
<td>Filter Transmittance</td>
<td>0.01</td>
<td>0.1</td>
<td>0.1</td>
<td>0.5</td>
<td>-</td>
</tr>
<tr>
<td>Intensity</td>
<td>4.9 kR*</td>
<td>49 kR</td>
<td>119 kR</td>
<td>244 kR</td>
<td>488 kR</td>
</tr>
<tr>
<td>Count Rate</td>
<td>1090 cps</td>
<td>1200 cps</td>
<td>2550 cps</td>
<td>7090 cps</td>
<td>13,000 cps</td>
</tr>
</tbody>
</table>

*This point not used; **Assuming line emission at 3914A
TABLE 18

UNCERTAINTY IN QUADRANT D-2 ABSOLUTE CALIBRATION

<table>
<thead>
<tr>
<th>Deviations or Uncertainties</th>
<th>3914A</th>
<th>5577A</th>
<th>6300A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apertures and Neutral Density Filters</td>
<td>40%</td>
<td>-</td>
<td>20%</td>
</tr>
<tr>
<td>Solid Angle</td>
<td>26%</td>
<td>11%</td>
<td>16%</td>
</tr>
<tr>
<td>Lamp</td>
<td>5%</td>
<td>5%</td>
<td>5%</td>
</tr>
<tr>
<td>Total</td>
<td>71%</td>
<td>16%</td>
<td>41%</td>
</tr>
</tbody>
</table>
about 50%. With the possible exception of neutral density filters these sources of uncertainty and possible systematic error would be greatly reduced by using an extended source. (Neutral density filters might have to be used in calibration of the extended sources.)

The dark current count rate is about 25 at room temperature and 2.5 at -5°C, the middle of the temperature range experienced by Aurora 1. From the absolute calibrations the intensities equivalent to 25 counts/sec are found. They are in Table 19.

More dark current equivalent intensities, also in Table 19, were derived using a disk of radio-activated phosphor. It was #56394 of U.S. Radium Corporation, supplied by Dr. R. H. Eather. However this radiance source was difficult to use because of its low radiance, compared to quadrant sensitivity.

On the same occasion Dr. Eather's 5577A and 6300A photometers and the quadrant were pointed at various parts of the sky. The LBS was used to calibrate his photometers which in turn measured the background continuum and line emission. These two measurements were combined with the quadrant filter transmittance curves to give another, albeit more indirect, absolute calibration. The resultant dark current equivalent intensities were also given in the same Table.

Still another set were derived starting from the EMR spectral sensitivities and gain. In addition the Thin Film Product's filter transmittance information, geometric factor and gain loss during burn-in were used. $3 \times 10^{-10}$ A was taken as the current equivalent to 25 counts/sec. However
TABLE 19

COMPARISON OF DARK CURRENT EQUIVALENT INTENSITIES
(25 counts/second or $3 \times 10^{-10}$ A for 22°C)

<table>
<thead>
<tr>
<th></th>
<th>3914A</th>
<th>5577A</th>
<th>6300A</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPT-1070</td>
<td>360 R</td>
<td>360 R</td>
<td>1160 R</td>
</tr>
<tr>
<td>Eather's LBS</td>
<td>200 R</td>
<td>80 R</td>
<td>1400 R</td>
</tr>
<tr>
<td>Zenith Night Sky</td>
<td>-</td>
<td>190 R</td>
<td>150 R</td>
</tr>
<tr>
<td>Horizon Above Houston</td>
<td>-</td>
<td>200 R</td>
<td>320 R</td>
</tr>
<tr>
<td>Calculated from EMR,</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thin Film Products,</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>and Rice Data</td>
<td>17 R</td>
<td>28 R</td>
<td>62 R</td>
</tr>
</tbody>
</table>
the current could be twice that. The conversion for the A/D used is not known accurately.

For as yet unexplainable reasons this last determination indicates a sensitivity 10 to 20 times the others. Many of the calculations and much of the data are used in all the calculations, thus eliminating them as possible sources of error. The spectral sensitivities are typical of that type photocathode. The dark current count rate suggests the gain cannot differ appreciably from $5 \times 10^5$. The use of two absolute sources for the other measurements eliminates that variable to the extent that they support each other.

The LBS and Eppley calibrations support each other at 3914A and 6300A, but not at 5577A while the Eppley and night sky observations support each other at 5577A but not at 6300A. The inconsistency between LBS and sky calibrations at 5577A and 6300A is very curious indeed. Because of the poor data and single measurements, I am however not inclined to put much faith in them.

The best measurements and those dependent least upon stability of all parameters over time are those based on EPT-1070. Hence they are used for the absolute calibration curves and in the matrix equations to follow.

This type discrepancy can best be resolved when data reduction keeps pace with data taking. But because of the lack of good quadrant data from Aurora 1 it has not been further investigated since launch.

**Interpretation of Quadrant Output**

Having established absolute calibration for each quadrant channel and the proportion of light scattered into
the others, it remains to be shown how incident intensities are found from the outputs. The absolute curves cannot usually be used in a straight-forward fashion because of the scattered light.

Let \( I_j \) (\( j = 1, 2, 3, 4 \) to indicate 6300A, 5577A, 3914A and d.c. respectively) be the three incident intensities and dark current. Let \( c_i \) stand for the four nonlinear known outputs. They can be converted to linear functions of intensity \( O_i \) with the absolute curves. It is more convenient, however, to use just one of these curves and scale intensities to compensate for different channel sensitivities. Here we will use the 5577A curve and then the dark current equivalent intensities to determine scaling. Thus each \( O_i \) becomes the 5577A equivalent output of the \( i^{th} \) channel.

Let the dark current equivalent intensities be \( S_j \). Furthermore let the dark current be represented by some equivalent amount of 5577A radiation, \( I_{d.c.} \). Thus we also have \( S_{d.c.} = S_{5577} \). Then \( (S_{5577}/S_j)I_j \) is the equivalent 5577A intensity measured for each \( I_j \). Now the four inputs \( (S_{5577}/S_j)I_j \), and outputs \( O_i \) to the system are linear and in the same units, intensity of 5577A sources.

Let \( f_{ij} \) represent the fractional amount of light scattered from the \( j^{th} \) channel into the \( i^{th} \). We will later assume the dark current is the same in all channels and set \( f_{i4} = 1 \) at that time. Since the \( f_{ij} \) are nonzero the inputs and outputs are coupled and hence the existence of four linear equations:
As was discussed in the section on output versus relative intensity the same fractional amount of light is scattered from one channel into each of the other three for D-2. Let that fraction be $f_j$. Then

$$f_{ij} = f_j \quad i \neq j$$

$$= 1 \quad i = j$$

Using the $f_j$ given previously and the $S_j$ given in Table 19 for the EPT-1070 calibration, the equations become

$$\begin{bmatrix}
O_{6300} \\
O_{5577} \\
O_{3914} \\
O_{d.c.}
\end{bmatrix} = \begin{bmatrix}
1 & f_{12} & f_{13} & f_{14} \\
f_{21} & 1 & f_{23} & f_{24} \\
f_{31} & f_{32} & 1 & f_{34} \\
f_{41} & f_{42} & f_{43} & 1
\end{bmatrix} \begin{bmatrix}
I_{6300} \\
I_{5577} \\
I_{3914} \\
I_{d.c.}
\end{bmatrix} = \begin{bmatrix}
S_{5577} \\
S_{3914}
\end{bmatrix} \begin{bmatrix}
0.31 I_{6300} \\
I_{5577} \\
I_{3914} \\
I_{d.c.}
\end{bmatrix}$$
Temperature effects, considered later, can be taken into account by finding the new $S_j$'s or some other convenient expression of relative sensitivity.

From the "scattering matrix" and the $S_{5577}/S_j$'s it is apparent that 5577A and 3914A should have the least contamination problem, while it is worse at 6300A. For equal incident intensities of these three wavelengths, and no dark current, the percentage of the signal representing contamination is

- 10% at 6300A
- 2% at 5577A
- 3% at 3914A

Since 6300A auroral emissions are usually weaker, that channel suffers relatively more contamination. The dark current channel suffers contamination proportional to the intensity incident on the other channels.

Thus on most occasions when $I_4$ is needed and on occasions when there is a large disparity in intensity the four equations must be solved to determine those intensities.

**UV Absolute Calibration**

Some of the difficulties in absolute UV calibration and aging of PMT's are shown here. D-1 and D-2 UV are compared extensively. Table 20 gives the total quantum efficiencies at 1470A and 2537A supplied by EMR. M. G. Winters (private communication) indicates the quantum efficiency measurements have an uncertainty of 15%. Gain stability is unknown. However the 50 hour burn-in information for the Owl satellite 541G's indicate very high
# TABLE 20

**EMR TOTAL QUANTUM EFFICIENCIES FOR D-1 AND D-2 UV**

<table>
<thead>
<tr>
<th>Quantum Efficiency</th>
<th>( \lambda )</th>
<th>D-1</th>
<th>D-2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1470A</td>
<td>8.5 ( \times ) 10(^{-2})</td>
<td>4.3 ( \times ) 10(^{-2})</td>
</tr>
<tr>
<td></td>
<td>2537A</td>
<td>6.5 ( \times ) 10(^{-5})</td>
<td>3.8 ( \times ) 10(^{-5})</td>
</tr>
<tr>
<td>Gain</td>
<td></td>
<td>1.1 ( \times ) 10(^5)</td>
<td>3.2 ( \times ) 10(^5)</td>
</tr>
<tr>
<td>Date</td>
<td></td>
<td>16 December 1965</td>
<td>27 December 1965</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total Quantum Efficiency</th>
<th>( \lambda )</th>
<th>D-1</th>
<th>D-2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1470A</td>
<td>9.4 ( \times ) 10(^3)</td>
<td>1.4 ( \times ) 10(^4)</td>
</tr>
<tr>
<td></td>
<td>2537A</td>
<td>7.2</td>
<td>1.2 ( \times ) 10(^1)</td>
</tr>
</tbody>
</table>
stability, much higher than for PMT's with visible photocathodes. Figure 51 shows two relative quantum efficiency curves I made fitted to the EMR total quantum efficiencies. The curves were made in Dr. S. Tilford's laboratory at the Naval Research Laboratory (NRL) using a one meter Baird-Atomic vacuum monochromator. They depend upon a constant quantum yield for sodium salicylate.

While the constancy of NaSal quantum yield is questionable an extensive survey of the literature leads me to believe that an uncertainty of 60% for this wavelength interval is reasonable (Appendix 2). However, the relative measurements at each wavelength should be very accurate. The error bars give an indication of the first standard deviation for these measurements.

The first discrepancy appears in relative spectral response. EMR finds the same ratio at both wavelengths. If the Rice curves are assumed identical at 1470A, D-2 has declined by a factor between 1.5 and 5 relative to D-1 at 2537A, or D-1 has increased relative to D-2. Full use is made of all error bars at both ends to derive these factors.

The second discrepancy is in gain. EMR finds D-2 to have 1.5 to 2.5 greater gain than D-1 at both wavelengths. The Rice results indicate D-1 has 1.5 to 2.5 greater gain than D-2 at 1470A. At 2537A the results are worse. Combining these factors indicates a minimum gain discrepancy between 2.2 and 6.2 for D-1 relative to D-2.

Since the minimum gain discrepancy is used, the spectral and gain discrepancies given are independent. They are furthermore, independent of any spectral peculiarities of
the NaSal used at NRL because they do not depend on spectrally constant quantum yield. Hence they indicate either an error at EMR, or changes in both gain characteristics and spectral response of one or both PMT's since leaving EMR.

The result of these discrepancies is to indicate that each curve of $Q(\lambda)$, total quantum efficiency, has an uncertainty of $\sim 2.5$. Hence absolute calibrations using these curves are uncertain to within a factor of 2.5.

The $Q(\lambda)$ curve for D-1 with Equations (16) and (17) leads to such an absolute calibration for a chosen $I(\lambda)$ or $I_{\lambda}^{i}$. The application to LBH giving 10 kR of LBH for $4.4 \times 10^{-10}$ A (Table 15, page 100, and the absolute scale of Figure 47) has already been described.

Because of electronic limitations at the low current levels and low measured UV intensities it is important for the Owl satellites that we consider increasing the effective area of the UV photometer at least a factor of two. Such a change has to be balanced against less sharp angular cutoffs. When combined with the larger solid angle and lower altitude of the Owls there would be an order of magnitude signal increase for the same aurora. Or the electronics should be improved at the low current levels.

In addition to the middle ultraviolet response of the photometer, the near ultraviolet and visible response have to be known for evaluating data taken over sunlit portions of the earth. As described in another section that response is highly variable. While no evidence is presented there for long term variation at 2537A, that phenomenon might be involved in the spectral discrepancy between the two calibrations of D-1 and D-2. Total quantum efficiency curves for D-3 between 1400A and 6300A are presented in Figure 22.
They are used elsewhere to find the earth response for co-incidence of subsatellite and subsolar points, Figure 33.

Similarly, rejection of radiation from Lyman α at 1216Å and the OI triplet at 1304Å should be known. However an attempt made to find a rejection factor for Kr at 1236Å proved only that the source emitted much radiation above 1430Å.
Influence of Orientation Magnet

Signals from the UV photometer were compared with and without a flight-type magnet in its proper Aurora 1 position. Signals were introduced between about $10^{-12}$ A and $10^{-6}$ A. The magnet had no detectable effect. We would also expect little effect for the quadrant, since as seen in Figure 12 it is further from the magnet and the angles between the optical axis and B-field are about the same.
Temperature Dependence

Since most parts of the photometers - filters, photocathodes, dynodes, power supplies and A/D's - are temperature sensitive there are two important considerations:

(1) the resultant change in absolute calibration and other characteristics in going from room temperature to satellite temperature, and

(2) the measurement uncertainties for fluctuations in satellite temperature.

Initially, in the 01 to 13 hour local time orbit as on pass 018, the thermistors on the quadrant and UV A/D boards indicated temperatures in the range $-3^\circ C$ to $-8^\circ C$. While on pass 864, when in a 06 to 18 hour local time orbit, they indicated about $10^\circ C$. These were within design goals.

Generally the PMT dark current decreases and sensitivity increases as temperature decreases. The EMR wrap-around power supplies partially offset the latter increase because their output voltage falls with temperature.

Figure 52 shows the aggregate temperature changes of the UV photometer. The A/D saturation level remains essentially constant. For about 5500 c/s the signal increases about 10% in going from $22^\circ C$ to $10^\circ C$ and an additional 10% in going to $-5^\circ C$.

When properly measured the UV dark current varies proportionally to temperature. It falls to 1/3 in going from $22^\circ C$ to $10^\circ C$ and to 1/10 in going to about $-5^\circ C$. These changes are essentially the same as for quadrants. These strong temperature dependences are in accord with thermionic emission giving rise to the dark current. The
current density for such emission is given to a good approximation by the Richardson-Dushman equation

\[ j = (1-R)AT^2 \exp \left( - \frac{\Phi}{kT} \right) \]

where \( j \) is in \( \text{A/m}^2 \), \( R \) is the probability that an excited electron will be reflected back into the solid, \( A \) is a universal constant with value \( 1.2 \times 10^6 \text{A/m}^2 \), \( \Phi \) is the thermionic work function, \( k \) is the Boltzmann constant and \( T \) is the absolute temperature (Vernier, 1963).

Difficulties arise in making measurements for the whole photometer because of the evident A/D sensitivity to humidity at low count rates, shown in Figure 47. It is difficult to distinguish between temperature and humidity dependence when both vary, as in tests conducted in the Houston atmosphere. Furthermore, for the photomultiplier itself as well as the photometer there is the danger of measuring visible response instead of dark current, especially if response is being measured at various light intensities. This danger can only be avoided by properly darkening the temperature chamber.

So far A/D count rate versus current has yet to be well determined between \( 6 \times 10^{-13} \) and \( 8 \times 10^{-12} \text{A} \). The data from Aurora 1 show a minimum count rate of 0.8 c/s at both \(-5^\circ\text{C}\) and \(10^\circ\text{C}\). Combining 0.8 cps with dark currents of \( 6 \times 10^{-13} \) and \( 2 \times 10^{-12} \text{A} \) at \(-5^\circ\text{C}\) and \(10^\circ\text{C}\) respectively gives the estimated curves of current versus count rate in Figure 47 for low count rates. This low count rate region is important because dark current, instead of particle radiation, determines the threshold in the auroral zone.
10% and 20% corrections for 10°C and -5°C respectively could be made to the linearity calibration, but they have not been included in Figure 47. Spectral dependence on temperature could be investigated, but it has been assumed constant for this thesis.

The quadrant has the same possible temperature dependences as the UV, plus changes in the interference filters. The low current A/D problems do not arise because of its higher dark current. Unfortunately a combination of interference filter effects invalidated the flight photometer thermal calibration. I briefly looked at D-7 without an A/D converter to get an indication of a quadrant's behavior in the here-to-for unique environment encountered by the satellite.

Figure 53 shows the response of all four quarters to 3914A as a function of temperature. A temperature chamber fitted with a quartz window was placed at the end of an optical bench. A G.E. 6.5A/T4Q/1CL-200W lamp seasoned for 3 hours at 6.6A d.c. was used at 6.0A d.c. on the bench to illuminate a piece of ground glass which the quadrant faced. The lamp position determined the ground glass brightness. Its spectral output changes slowly enough with wavelength that a maximum error of about 4% is introduced by a 3914A filter (see below) over a 60°C range. If need be the actual error could be found and eliminated, but it is clearly tolerable here. The dark current change, as mentioned, is very similar to that of the UV. More extensive calibration than this could be done by the above method with assembled quadrants and A/D's, but the quality of quadrant data from Aurora 1 does not require it.
There is a temperature dependent wavelength shift for interference filter passbands. It has the form $T(\lambda, \tau) = T(\lambda + \kappa(\tau - \tau_o); \tau_o)$ where $\tau_o$ and $\tau$ are initial and final temperatures, and $\kappa$ is a temperature coefficient having units $\text{A/}^\circ\text{C}$. To a first approximation the transmittance curves retain their shape. Assuming linearity, $\kappa$'s are given in Table 15, page 100, for the quadrant filters. They are derived from the $-30^\circ\text{C}$ and $+22^\circ\text{C}$ curves supplied by Thin Film Products. When applied to the transmittances at 6300A, 5577A and 3914A Figure 54 results, giving the temperature dependence. These curves show the importance of filter width and the relationship between $\lambda_m$ and $\lambda_o$. The wider the filters, the easier it is to keep $T_{\lambda_m}$ and $T_{\lambda_o}$ close for a given temperature change. However, no matter what the width, if $(dT/d\lambda)_{\lambda_o}$ is large initially there is a big $(dT/d\tau)_{\lambda_o}$ change.

A word of caution about filter transmittance curves and aging must be added here. According to Edward Barr of Thin Film Products (private communication) these filters shift about 3A to shorter wavelengths within 6 months after manufacture and then stabilize. Such a shift would have approximately the same effect as a $12^\circ\text{C}$ reduction in temperature in Figure 54. In other words, after 6 months a new curve where all abscissa values were 3A/$\kappa$ higher would be a more appropriate starting point for corrections. Aging is a reason for buying interference filters with $\lambda_m$ about 3 A higher than needed at least six months before launch and monitoring the changes. Such a procedure adds to the calibration stability after launch.
Filter wheel #4 used on the quadrant was 4 months old when launched. Again, because of the quadrant data from Aurora 1, aging correction is omitted, but the temperature corrections based on Figure 54 are calculated to give a feeling for their magnitude.

For operation at -5°C the sensitivity increased by

- 3% at 6300A
- 24% at 5577A
- 13% at 3914A.

For operation at 10°C the sensitivity increases by

- 0% at 6300A
- 16% at 5577A
- 10% at 3914A.

A sensitivity increase of +X_j% (X ≥ 0) due to filter transmittance changes, or due to any other changes, can be accounted for in the absolute calibrations and data interpretation by increasing the ordinates in Figures 44, 45 and 46 by 1 + X_j/100 and multiplying the S_i by 1 + X_i/100 where i equals j and 5577A in succession. Alternatively if just the matrix equation, Equation (18), is used then (S_5577/S_j)I_j can be changed to

\[
\frac{S_{5577}}{S_j} \cdot \frac{I_j}{1 + \frac{X_j}{100}}
\]

and the old 5577A absolute curve can be used.
Voltage Dependence

As the batteries on Aurora 1 cycle, the voltage on the 28 volt bus applied to the photometers varies. Information on it is provided by the telemetry. It has varied between at least 27 and 33 volts, as expected.

The A/D converter is primarily affected by voltage changes, though extreme voltages on the 28 volt bus will effect the high voltages delivered to the photomultipliers. Some calibration data were derived and are given here.

For count rates between about 5000 and 7500/sec at various temperatures, the 28V bus was varied between 26 and 30 volts keeping the other (low voltage bus) at 7V. Table 21 shows variations in output of the UV photometer at 0°C for bus voltage variations. The quadrant behaves in a similar fashion.
TABLE 21

VOLTAGE DEPENDENCE D-1 UV

Output about 5000 counts/second at 0°C

<table>
<thead>
<tr>
<th>Volts</th>
<th>Relative Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>26</td>
<td>1.22</td>
</tr>
<tr>
<td>27</td>
<td>1.03</td>
</tr>
<tr>
<td>28</td>
<td>1.00</td>
</tr>
<tr>
<td>29</td>
<td>0.92</td>
</tr>
<tr>
<td>30</td>
<td>1.03</td>
</tr>
</tbody>
</table>
Particle Dependence

X-rays, due primarily to energetic charged particles in the Van Allen belts striking the satellite causing bremsstrahlung, increase the background count rate or dark current. Energetic secondary electrons are created at the photocathode and dynodes which in turn collide with other electrons energizing them. They then appear many times over at the anode. Thus the most critical area from which anode current arises is the photocathode and the first few dynodes.

When in the laboratory the top of Aurora 1 was irradiated with about $6 \times 10^6 \text{ mev/cm}^2\text{sec}$ of X-rays due to $50 \text{ kev}$ electrons, the count rates became $3 \times 10^3$ and $1 \times 10^4$/sec respectively for the UV and quadrant. For protection in orbit the cathode and first few dynodes were wrapped with $1.8 \text{ gm/cm}^2$ of lead.

Figure 55 shows the responses of the quadrant and UV on pass 016, before orientation. The photometers are looking at earth, space, sun, space and back again. The period appears to be about 69 seconds, although it nearly repeats every $34\frac{1}{2}$ seconds. The maxima and minima can be plotted separately giving an envelope of values as done in Figure 56 for much of pass 016 for the UV.

By following the lowest curves in A it is quite apparent that the UV tube is affected by the trapped radiation. The maximum induced count rate is about $1200 \text{ c/s}$, equivalent to one megarayleigh of LBH, at the equator. The background drops to close to the thermionic dark current level by the auroral zones.
The particle induced quadrant signal should be about $4 \times 10^3 \text{ c/s}$. It is hard to tell because of the slow decay after intense light-induced dark current.

The particle background even with the amount of lead used, very effectively prevents midlatitude airglow observations before orientation. This situation is associated with, and indeed caused by, the fact that the actual "hitch-hiked" orbit is so much higher than the original planned-for orbit. Scientifically, we had no control over this change.
Scattered Light

The greatest sources of scattered light on the satellite for the respective photometers are the quadrant sun shield and the UV collimator. Figure 55 shows quadrant and ultraviolet data for a daylight portion of pass 016. The earth-satellite-sun geometry is shown in Figure 57. Aurora 1 is spinning in a complicated fashion (Burch, 1968a), scanning the earth and sun. These solar UV peaks are among the widest found, suggesting that the photometers may be pointed very close to the sun. The period is about 69 seconds, but nearly repeats itself every 34.5 seconds. The UV starts to respond to the sun 7 seconds before closest approach, and the quadrant 10 seconds. If the satellite motion were a flat spin with a 34.5 second period the angles between sun and optical axis for initial response to the sun would be 75° and 105° respectively. If instead it were a cone of half angle 63°, the angles would become 65° and 90°. Figure 57 shows that a cone of half-angle 63° is not unreasonable as an approximation and that it could not be much smaller. Using the same cone, the earth at 190630, Figure 55, for 10^3 counts/second subtends 67° out of a possible 77°. Again, this angle is reasonable.

The quadrant responds, albeit starting from a much higher count rate, to the earth at 190630 and 190740 about 3.5 seconds before the UV. Its response drops 2.5 seconds after the UV. Such discrepancy suggests misalignment of the photometers, because if anything the quadrant should be slower to fall, as it is with the sun. Using a 3-second early rise time and the 63° half angle cone it appears
that scattered sunlight from the earth and atmosphere affect the quadrant for about 30° before it is pointing at the earth. The UV rise time is fast enough for the earth that scattering is not a problem.

Thus in a crude fashion it is shown that the quadrant data can be easily contaminated by the sun, at an angle of ~ 90°, and by the sunlit earth, ~ 30°. Thus if there were data for the winter months extreme caution would have to be exercised in using it. The UV which appears to be sensitive to the sun at an angle of about 65° is a much smaller problem. In the autumn the photometer-sun axis is about 90°. In summer and winter problems could arise as the satellite first comes out of shadow. The UV is then best on the dayside of the earth.

This type of calibration is hard to perform in the laboratory, especially for the UV, because of the need for a source that is both small and intense. It could not have been done on Aurora 1 had not the switching circuit malfunctioned, turning the UV on before orientation. Even so it is rather crude because of the lack of directional information.
History Dependence

There are both reversible and irreversible changes in photomultipliers to be considered. Most occur under high current operation, though perhaps not all.

Fatigue, the loss of gain after extended high current operation is for the most part permanent. It has to be considered in relation to long-term photometer calibration, especially when the photometers are not protected from the direct sun or sunlit earth, and are subjected to bremsstrahlung X-rays from the hard inner-zone electrons. Concomitant with high current operation is increased dark current. Its decay, like fatigue depending on maximum current and duration, is important for determining at what level signals can be detected.

The UV photomultiplier has another concomitant effect which also decays away like enhanced dark current. Its long wavelength sensitivity increases greatly. This phenomenon is discussed extensively in a separate section.

Because of its much earlier introduction, Cs-Sb has been studied far more extensively as a photocathode than Cs-I or Cs-K-Na-Sb. It was introduced in 1936 by Gorlick (Sommer, 1951). Miyake (1961) and in greater detail Jedlicka (1962) have studied fatigue effects. At currents densities of 10 µA/cm² there are sharp decreases in gain, 50% in 2½ hours. For lower currents densities the fatigue is less. Jedlicka (1962) says "the decrease of the response when illuminated reminds one of an exponential curve; however, when trying to approximate it by a simple exponential curve one comes to the conclusion that there is a more complicated dependence".
Dynodes may also cause problems. Keene (1963) looked at fatigue in an EMI 6256 photomultiplier. Using 6 dynodes he had an output of 2 mA initially. After 5 minutes it had fallen and leveled off at 1/3 that value. The gain fully returned with a 3 minute respite from the light. For lower currents this effect was much less. He attributed the reversible loss of gain to a temperature rise in the dynodes, since the secondary emission factor of semiconductors is inversely proportional to temperature.

Assuming that cathodes and dynodes on the UV and quadrant behave in a similar fashion with respect to critical current levels as in the foregoing examples the same precautions were taken as on Injun 1 and Injun 3 (O'Brien and Taylor, 1964). The EMR 541A with its Cs-Sb photocathode, on Injun 1, was the first satellite photomultiplier. It worked without drastic change for the 18 month life of the satellite.

The photocathode current density is limited by

(1) power supplies limited to between 2 and 20 μA,
(2) optical systems that do not focus on the photocathode, and
(3) lead shielding.

The first limits the current, the second increases electron emitting cathode area, and the third reduces the duration of high current induced by bremsstrahlung.

The current limited supplies also protect the dynodes. But in addition the light level for which the maximum current is experienced is increased by having large dynode resistors, 15.6 and 40 megohms respectively for the UV and quadrant.
Engstrom and Fischer (1957) describe this technique. The effect is to give the anode current a logarithmic dependence on intensity at high levels. (The curves showing output as a function of intensity only barely show this effect, if at all, because of A/D saturation at 2 \( \mu \)A.)

The exponential quality of fatigue was taken into account by a 50-hour aging at the maximum current level. For quadrant D-2 the gain decreased by 3.65 whereas for 6 Owl quadrants it decreased between 2.2 and 11.5. By contrast the UV's decreased very little. No information is available to show whether the decrease had the appearance of an exponential, or what happened to the gain several hours and days afterward.

From Aurora 1 data for a 3\( \frac{3}{4} \) month period no drastic change can be found in the photometer operations.

These efforts to minimize long term irreversible changes also help the short term reversible ones such as dynode recovery and dark current decay. The smaller an anode current and shorter its duration the lower the dark current and the faster its decay.

For currents within the linear region of the photometers the decay time is of the order of a second or less. It is a problem when the photometers are saturated, i.e., the anode current reaches its maximum level.

Figure 58 is the quadrant dark current decay after 5 minutes exposure to a sunlit landscape. Figures 27 and 28 show the UV decay after 10 seconds of exposure to an EMR 582-05M xenon lamp. The entire lamp output (about \( 10^{13} \) photons/second) is equivalent to the solar flux between 1450A and 1750A hitting a one inch diameter photocathode at 1 A.U.
Appendix 1

UV INTERFERENCE FILTERS

To increase the probability of seeing daylight ultraviolet auroras, especially since enhanced visible sensitivity became a possibility, efforts have been made to find a filter with long wavelength rejection yet high transmittance about 1600Å. D. Criswell started these efforts with Thin Film Products and I have continued them, in particular with Thin Film Products and Professor Baumeister at the University of Rochester. A suitable filter was not available for Aurora 1 but one may become available for the Owls.

A suitable filter requires transmittance above 0.20 between 1450Å and 1750Å so that sensitivity is not too greatly decreased. By 3200Å the transmittance has to have fallen by $10^3$ for the long wavelength radiance to become negligible (Figure 23). Transmittance below 1450Å is uncritical because the sapphire window of a 541G-05M PMT has a sharp lower cutoff.

There is a review of window and filter information in Samson (1967). Pellicori (1964) and Pellicori, et al. (1966) give detailed information on windows and organic filters. The windows discussed all begin to transmit in the ultraviolet and continue into the visible. Cutoffs are listed for many in Table 22. Small spectral regions can be isolated by subtracting responses through two or more. But several detectors must be used as on Mariner 5 (Barth, et al., 1967) or a UV quadrant as suggested by Rome, et al. (1964). More fundamental, however is the imprecision in subtracting two large signals to find a
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>LiF</td>
<td>1050</td>
<td></td>
<td>1050</td>
</tr>
<tr>
<td>MgF₂</td>
<td>1150</td>
<td></td>
<td>1130</td>
</tr>
<tr>
<td>CaF₂</td>
<td>1225</td>
<td></td>
<td>1230</td>
</tr>
<tr>
<td>NaF</td>
<td>1230</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SrF₂</td>
<td>1280</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BaF₂</td>
<td>1350</td>
<td></td>
<td>1335</td>
</tr>
<tr>
<td>Al₂O₃, Sapphire</td>
<td>1425</td>
<td></td>
<td>1435</td>
</tr>
<tr>
<td>Fused Silica</td>
<td>1570</td>
<td></td>
<td>1595 (Dynasil)</td>
</tr>
<tr>
<td>ADP</td>
<td>1800</td>
<td></td>
<td>1780</td>
</tr>
<tr>
<td>NiSO₄(H₂O)₆</td>
<td>1930</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Schott BG-24</td>
<td></td>
<td>2050</td>
<td></td>
</tr>
<tr>
<td>CaCO₃, Calcite</td>
<td>2100</td>
<td>2200</td>
<td>2030</td>
</tr>
<tr>
<td>Corning 9-54, Vycor</td>
<td>2200</td>
<td>2200</td>
<td>2185</td>
</tr>
<tr>
<td>Schott UG-5</td>
<td>2200</td>
<td></td>
<td>2200</td>
</tr>
<tr>
<td>Diamond</td>
<td>~ 2300</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CsBr</td>
<td>~ 2300</td>
<td></td>
<td></td>
</tr>
<tr>
<td>KI</td>
<td>2370</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CsI</td>
<td>~ 2400</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Corning 9-53</td>
<td>2700</td>
<td></td>
<td>2700</td>
</tr>
<tr>
<td>Polystyrene</td>
<td>2750</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Corning 0-54</td>
<td>3050</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plexiglass</td>
<td>3500</td>
<td></td>
<td>3500</td>
</tr>
</tbody>
</table>
small one. Organic filters do isolate a passband, but they have not been made for spectral regions below 2000A.

An interference filter seems more promising. Very good ones are made in the visible using layers of dielectric with alternating high and low indices of refractions. However, for lack of a nonabsorbing high-index dielectric below 2400A (Schroeder, 1962), a simpler construction has to be used in the middle ultraviolet.

Figure 59 adapted from Schroeder (1962) and Bates and Bradley (1966) shows schematically two metal-dielectric-metal interference filters. The top layer of MgF₂ is an interference film to reduce reflection losses at the air or vacuum-metal interface. A pair of Al layers determine the peak transmittance while MgF₂ or other dielectric in-between determines the order of interference. The filter at left is the simplest such filter. The one at the right is a stack of two such filters. The former has a transmittance peak at \( \lambda_1 \) due to first order interference, and subsequent peaks at approximately \( \lambda_1/n \) for \( n = 2, 3, \ldots \) where \( n \) is the order of interference. \( \lambda_1/n \) is only approximate because the indices of refraction are complex.

Figure 60 shows first order results that Harrison (1968) obtained at the University of Rochester. The wide bandpasses and low contrast should be noted. Figure 61 from Bates and Bradley (1966) shows that wide bandpasses are to be expected for first order filters. The curve comes from optical constants measured above 2000A and extrapolated below. The "X"'s are for values from their filters.
Contrast can be increased by stacking two filters. Thin Film Products used this technique on first order filters. The curve in Figure 62, found by the Geophysical Corporation of America, shows attenuation of 100 by 2800Å but peak transmittance below 0.03.

Another way of increasing contrast is to use higher orders. These first order filters would have a second order transmittance maxima below 1000Å which would be absorbed by the substrate. But filters with second order maxima about 1600Å have first order maxima about 3200Å. Hence despite initially greater contrast due to narrower bandwidth they cannot be used in this situation, not even stacked with a first order filter. However a third order filter at 1600Å has maxima near 2400Å and 4800Å. It might be usable, especially if stacked with a first order filter. Bates and Bradley (1966) have produced second order filters at 2000Å and above. Third order, shorter wavelengths and stacking of mixed orders have yet to be tried.

It is impossible to predict results because of a general lack of knowledge of optical constants in the middle ultraviolet. Furthermore techniques have not yet been perfected. Yet the results in Figure 60 suggest that the desired wavelength region can be reached, while those in Figure 62 suggest that the required rejection at 3200Å might be attainable. It is to be hoped that through a combination of improved techniques, different stacking arrangements and perhaps new materials both the high maximum transmittance and large rejection can be found.

Stability of these interference filters have to be further examined. Most visible interference filters change
slightly with vacuum (Hennes and Denkelman, 1966), temperature and age. Bates and Bradley (1966) and Thin Film Products (Robert Johnson, private communication) have noticed aging effects in the ultraviolet. Otherwise little is known.

In addition ultraviolet, particle and X-ray radiation in space can adversely affect many optical materials. Presumably color centers are created which change the absorption and hence refraction and other characteristics. Heath and Sacher (1966) and Sacher (1967) investigate such changes in UV window materials for electron and proton fluxes respectively. Their total fluxes simulate one year exposures in polar orbit at about 1300 km. Most other investigations, for much larger fluxes and energies, are not as applicable.

Their results show that the electron flux causes more change than the proton flux and, at least for fused quartz, more change than bremsstrahlung X-rays created by electrons incident on a 6.4 mm thick piece of sapphire. Of LiF, CaF$_2$, BaF$_2$, MgF$_2$ and Al$_2$O$_3$ which have cutoffs at 1450Å or below only BaF$_2$ and Al$_2$O$_3$ are practically unchanged. MgF$_2$ however is changed least (Figure 2, Heath and Sacher, 1966) in the region of the UV photometer passband.

Thus a filter substrate would best be BaF$_2$ or Al$_2$O$_3$. MgF$_2$ could still be used for dielectric spacer but should be protected by having the substrate outermost.

While the absorption feature with its maximum at 2600Å in MgF$_2$ might be used in a substrate to decrease the bandwidth of a filter centered at 1600Å, it has little effect at 3200Å where most needed. Unfortunately the rate of
formation, rate of bleaching by UV radiation, and temperature dependence of the absorption feature are unknown. For these reasons there is no compelling reason for using MgF$_2$ to take advantage of this absorption feature. Nor do any of the other substrates have potentially convenient absorption features near 3200Å.

Thus for a UV photometer centered on the LBH bands MgF$_2$ remains a usable dielectric in earth orbit, especially if shielded. BaF$_2$ appears to be the best substrate.
Appendix 2

SODIUM SALICYLATE FOR ULTRAVIOLET DETECTION:
WAVELENGTH CONSTANCY OF ITS QUANTUM YIELD

Early work on NaSal by Déjardin and Schwégler (1934), F. S. Johnson, et al. (1951) and Watanabe and Inn (1953) indicated that it had the nice properties of high and constant quantum efficiency over a wide spectral range, at least from 1000A to 3500A. It was also indicated that the coatings were highly stable. For these reasons the NaSal-photomultiplier detector combination became a working standard in the UV.

As more experimenters compared the relative response of NaSal and thermopiles, discrepancies with this picture developed. They are such that Samson (1967) in his review of NaSal concludes that it is a convenient secondary standard so long as it is calibrated against a thermopile before or after each use.

But for those who cannot do as Samson suggests one must look at what is presently known about NaSal to determine the limits of its usefulness. First the factors that appear to be constant and then those that are either in question or limiting are discussed. It is the latter two categories that determine uncertainty.

The fluorescent decay time is so small compared with most detector response times that it does not affect measurements. Most determinations of the decay time lie between 7 and 12 nsec (Samson, 1967). The fluorescent emission spectrum, Figure 63, is independent of wavelength from 275A to 2537A (Samson, 1967), and probably to 3500A (Hammann,
1958). At a given wavelength and temperature the area under the curve is proportional to intensity. The temperature dependence is small, being about 0.2% per °C if the change is linear between 80°K and 300°K. While the relative fluorescent quantum efficiency does appear to be a function of wavelength, it has the same dependence on thickness at all wavelengths between at least 584A and 2200A (Samson, 1967). Figure 64 gives the thickness dependence (adapted from Nygaard, 1964) found at 2537A. It agrees with Samson's curve.

Masuda and Seya (1965) indicate between 900A and 1700A that the form of NaSal, solvent and method of application are important. Between 1400A and 1700A they show a 25% relative spectral variation between samples of different origin, 5% for spray versus emulsion application, and 10% for ethyl alcohol versus water as solvent. The last two variations appear to cause a monotonic increase or decrease in the ratio with wavelength, thus a 10% variation in 300A might become 40% in 1200A. This type monotonic change in the response ratio presumably accounts for some of the discrepancies that exist in the literature. For example, Allison, et al. (1964) with one method of application report the same q.e. at 1216A and 1610A to within 1 or 2%. On the other hand Samson (1964) and Smith (1961) with another show a 20% increase toward longer wavelengths for fresh samples.

Above 2000A the influence of these three factors is apparent in comparing the work of Hammann (1958), and Kristianpoller and Knapp (1964), Figure 65. The data in both cases are for 1.6 mg/cm² and 0.2 mg/cm² thick layers.
Hammann prepared his samples by sedimentation using highly refined gasoline as the solvent. Kristinapoller and Knapp prepared some of theirs in that fashion and some by spraying a saturated solution of NaSal in an unspecified solvent, but they do not label their samples. At about 2000\(\text{A}\), 2700\(\text{A}\) and 3500\(\text{A}\) for Kristianpoller and Knapp and at 3500\(\text{A}\) for Hammann the thickness versus quantum efficiency curve breaks down. The discrepancy at 3500\(\text{A}\) does not affect the Aurora 1 calibration and may be associated with approaching the emission spectrum. It will be neglected. The problem at 2700\(\text{A}\) is associated with an absorption hole at that wavelength. But note that for samples between 0.2 and 1.6 mg/cm\(^2\) it produces an error of at most 30\% from constant quantum efficiency. The problem at 2000\(\text{A}\) is unexplained and appears smaller. Hammann's curves by contrast agree between 2300\(\text{A}\) and 3400\(\text{A}\) to within 5\%. Furthermore his 1.6 mg/cm\(^2\) curve may increase very slightly at 2700\(\text{A}\). Assuming no experimental errors a consistent interpretation of these results is that (1) the thickness versus quantum efficiency relationship may break down at some longer wavelengths and (2) the preparation and application may cause discrepancies between samples of the same thickness. In both cases for the given range of thicknesses, which are typical of most samples used, the maximum error appears to be 30\%.

Combining this 30\% uncertainty with a possible monotonic wavelength change at shorter wavelengths gives an uncertainty approaching 60\%.

Another problem exists - stability. Knapp and Smith (1964) find evidence of radiation fatigue at wavelengths
below 1600Å. However they had 0.03 mg/cm² samples and comment that the effect decreases with increasing thickness. Allison, et al. (1964) have no effect for what were most likely thicker samples. But no flux data is given. This effect appears insignificant for most usages.

However, the combined data of Knapp and Smith (1964) and Allison, et al. (1964) indicate that exposure to a diffusion-pumped chamber as opposed to an air or vac-ion-pumped chamber causes a decrease in quantum efficiency, increasing toward shorter wavelengths. Since the data available does not extend above 1650Å it is hard to estimate the full effect of such aging. Thus within present evidence it appears that one can let ±60% stand as the uncertainty that the quantum yield of a given layer of NaSal is constant between 1400Å and 2900Å.
ACKNOWLEDGEMENTS

I would particularly like to thank Professor B. J. O'Brien for making this project possible and for his assistance throughout its duration. In addition I would like to thank Commander C. W. Causey of ONR for his continued interest in the project, Drs. H. Friedman and S. Tilford of NRL for the use of facilities and assistance in part of the ultraviolet calibration, and Dr. D. R. Criswell for starting much of this research. Thanks are due to many individuals at Rice University and in the Space Science Facilities at Rice for their help and support, in particular to Tariq Aziz, W. F. Fenley, Jr., and C. Schwaninger. Thanks and congratulations to Mrs. J. Fleming for the typing of this manuscript and to the Drafting Department for the drawings.

This research was supported in part by the Department of the Navy, Office of Naval Research, under contract Nonr-4964(1) and the National Aeronautics and Space Administration under contract NAS6-1061.
BIBLIOGRAPHY


Donahue, T. M., and W. G. Fastie, Observation and Interpretation of Resonance Scattering of Lyman $\alpha$ and OI(1300) in the Upper Atmosphere, Space Res. IV, 304, 1964.


Gerharz, R., Atmospheric Absorption of a 100 m Path for the Spectral Region \( \lambda \) 2400 to 9000\( \lambda \), *J. Atmos. Terr. Phys.*, 27, 1191, 1965.


FIGURE CAPTIONS

Figure 1: Hard and soft spectra of precipitated electrons. From Aurora 1 (Burch, 1968a).

Figure 2: Hard and soft spectra of precipitated protons. From Aurora 1 (Burch, 1968a).

Figure 3: Trapped and precipitated electrons, E > 40 keV, and 3914A auroral emission. From Injun III (O'Brien and Taylor, 1964).

Figure 4: Approximate absorption cross sections of O$_2$ and O$_3$ between 1400 and 2900A.

Figure 5: O$_2$ column densities above base altitudes between 100 and 250 km.

Figure 6: O$_2$ attenuation between 1400 and 1900A for emission between 100 and 160 km and detector above 250 km.

Figure 7: Radiance of earth and atmosphere between 1500 and 5000A for approximate coincidence of subsolar and subsatellite points (at which the detector is pointing).

Figure 8: Detail between 1400 and 2800A from Figure 7.

Figure 9: Solar irradiance averaged for ±25A over lines and continuum between 1400 and 2900A.

Figure 10: Drawing of Aurora 1 in orbit showing relation of detectors to magnetic field lines in the northern hemisphere after orientation.

Figure 11: Photograph of Aurora 1. Apertures to both photometers visible.

Figure 12: Drawing showing the interior of Aurora 1.
Figure 13: Cutaway drawing of quadrant photometer.

Figure 14: Cutaway drawing of UV photometer.

Figure 15: Cutaway drawings of both photomultiplier tubes.

Figure 16: Typical quantum yields of Cs-I, Cs-Sb, and Cs-Na-K-Sb for semitransparent EMR photocathodes, Rome (1964).

Figure 17: Block diagram of the parts of the Aurora 1 system involving the photometers and their output.

Figure 18: 15 seconds of telemetry record from the first pass of Aurora 1. We can see the $2^2$ and $2^6$ scaler changes and cathode 1 indicator on the UV channel. The quadrant is saturated, although a little less so for the covered channel.

Figure 19: Dipole field lines above the earth to the altitude of Aurora 1. SPECS measures particles moving down these lines while the photometers view tangential to them.

Figure 20: Regions of darkness for a satellite launched 22 June into a noon-to-midnight orbit at the altitude of Aurora 1, the atmosphere below the satellite at 100 km, and that portion of the atmosphere at 100 km which would be seen by photometers looking parallel to $\vec{B}$ from the satellite when in darkness. Since the coordinates are magnetic there are minimum and maximum values for each of these regions of darkness depending upon the relative orientation of the sun, north pole and north magnetic pole.
Figure 21: For a $\Lambda$ value for Aurora 1, and hence for the particles measured by the SPECS, an expanded version of Figure 19 enables one to find a $\Lambda$ for the region at 100 km viewed by the photometers. This Figure relates these $\Lambda$'s.

Figure 22: The total quantum efficiency of D-3 UV from 1430 to 6300A. Variability is shown between 2500 and 6300A.

Figure 23: The response of D-3 UV to the radiance of earth and atmosphere between 1500 and 5000A (by combining Figures 7 and 22).

Figure 24: Enhancement decay of D-1 UV at four wavelengths between 0 and 125 seconds after xenon exposure.

Figure 25: Enhancement decay of D-3 UV at 3914A after first four 10 second xenon exposures. Plateau established by the fourth exposure.

Figure 26: Irradiance of EMR 582-05M xenon sources.

Figure 27: Decay in D-3 UV of dark current and enhancement at 3914A, 5577A and 6300A for up to nine minutes.

Figure 28: Log-log plot of Figure 27 showing power law dependence.

Figure 29: Decay at 3914A (29), 5577A(30), and 6300A(31) between 195 and 360 seconds contrasted after exposure to a tungsten bulb, regular decay as in Figure 27, and darkness for the first 180 seconds after enhancement.

Figure 30: Comparison of quantum yields for D-3 UV and Cs-I (Philipp and Taft, 1956) between 1430 and 5900A.
Figure 33: Enhancement and its decay at 2190A in K-I.

Figure 34: Log-log plot of decay from Figure 33 showing power law dependence.

Figure 35: Quantum yield of MgO between 1200 and 3600A.

Figure 36: Collimator for ultraviolet photometer.

Figure 37: Front end of quadrant photometer.

Figure 38: Measured and calculated angular response of D-1 UV for the collimator in Figure 36.

Figure 39: Angular response at 3914A for quadrant D-2.

Figure 40: Schematic representation of two axially symmetric collimators.

Figure 41: Calculated response of the two collimators in Figure 40 for the dimensions in Table 11, page 76.

Figure 42: Half-angles and estimated standard deviations for the quadrant lenses with reference to their placement looking from the PMT out. The channel optical axes are at the center of the lenses in this drawing.

Figure 43: Superposition of the half-angles from Figure 42 for coincidence of the optical axis for each lens.

Figure 44: The absolute calibration at 3914A(44), 5577A(45) and 6300A(46) for quadrant D-2. Also the output as a function of intensity and the intensity scattered into each of the other three channels.

Figure 45: Absolute calibration and output as a function of intensity for D-1 UV. The absolute assumes excitation of the LBH bands of N₂ by electron collisions followed by radiative deexcitation (Table 16, page 103).
Figure 48: It relates linear and nonlinear output when output is plotted versus relative intensity. For a calculated linear output A there is a relative intensity I and hence an instrumental output B.

Figure 49: A microphotometer tracing of the $N_2^+$ 1NG 0-0 band for a "typical" aurora.

Figure 50: The output of the secondary standard EPT-1070 used for most absolute calibrations reported here. It is a G.E. 30A/T24/17 tungsten ribbon-filament lamp.

Figure 51: Total quantum efficiencies of D-1 and D-2 UV's between 1430 and 2850A.

Figure 52: Temperature dependence of D-1 UV at two different signal levels between -20° and 50°C.

Figure 53: Temperature dependence of quadrant D-7 at four different signal levels between -15° and 40°C.

Figure 54: Temperature dependence of the quadrant filter transmittances at 3914Å, 5577Å and 6300Å between -30° and 22°C.

Figure 55: Quadrant and UV signals due to the sun, sky and earth for 2 minutes 20 seconds of pass 016 from Aurora 1.

Figure 56: Envelopes of UV signals due to the sun, sky and earth for much of pass 016. The lowest signals clearly show the particle induced background dark emission.

Figure 57: Approximation to the earth-satellite-sun geometry needed to produce the signals in Figure 55.

Figure 58: Dark current recovery of quadrant D-2 after a 5 minute exposure to reflected sunlight.
Figure 59: Schematic diagrams of two interference filters.

Figure 60: Transmittance of three first-order interference filters made at the University of Rochester.

Figure 61: Predicted and measured bandwidths of first-order interference filters having a transmittance of 0.25.

Figure 62: Transmittance of a Thin Film Products' stack of two first-order interference filters.

Figure 63: The emission spectra of sodium salicylate.

Figure 64: Relative quantum efficiency of sodium salicylate as a function of thickness (adapted from Nygaard, 1964).

Figure 65: Relative quantum efficiencies of sodium salicylate at each of two thicknesses by two teams.
ELECTRONS/cm$^2$ ster ev sec

PRECIPITATED ELECTRONS

UTC 1200 1 MINUTE

MLT (Hr.) 225 221 222

D. E. E

96-163 ev

150-820 ev

1700-3600 ev

10,800-19,500 ev

ELECTRON ENERGY (ev)

Figure 1
Figure 2

Precipitated Protons

Rev. 156  July 18, 1967

UT (Hr. Min.)  MLT (Hr.)  L(RE)

96-163 ev  155-790 ev  1750-95000 ev

Protons/cm² ster ev seec

10^5  10^4  10^3  10^2  10^1

Proton Energy (ev)
Approximate Absorption Coefficients of $O_2$ and $O_3$

$O_2$ adapted from Watanabe (1958)

$O_3$ adapted from Watanabe (1958), Goody (1964) and Inn and Tanaka (1953)
COLUMN DENSITIES OF O₂

Derived From A. D. Anderson & W. E. Francis (1966)
Average Sunspot Conditions
21 Hours

Number of Molecules / Cm² (column)

Base Altitude in Kilometers

Figure 5
Figure 6

O₂ ATTENUATION
Observer above 250 km
Model from Anderson and Francis (1966)
Average Sunspot Conditions
21 Hours

Wavelength in Å
RADIANCE OF EARTH AND ATMOSPHERE

For Approximate Coincidence Of Subsolar And Subsatellite Points

Modification of theoretical Calculation by K.L. Coulson (1959)
Adaptation of theoretical Calculation by V.A. Krasnopolskii (1966)
Adaptation of theoretical Calculation by J. Dowling, Jr. and A.E.S. Green (1966)
Rocket spectrum toward nadir from 168 km by C.A. Barth (1966 b)
Assumed initial condition
Radiance calculated from initial condition
Connecting pieces for model used to find response of D-3 UV

Figure 7
Radiance of Earth and Atmosphere for Approximate Coincidence of Subsatellite Points

2355 A - 2375 A Initial conditions adopted for calculation

2370 A - 2800 A Calculation of initial conditions used to find response of D-5

Figure 8
SOLAR IRRADIANCE

averaged for ±25 over lines and continuum
Detwiler et al (1961) and F.S. Johnson (1965)
Figure 15
PHOTOCATHODE QUANTUM YIELDS

M. Rome (1964)

Figure 16
Figure 19

DIPOLe FIELD LINES RELATING SATELLITE POSITION TO PHOTOMETER LINE OF SIGHT
MAXIMUM & MINIMUM DARKNESS
for Orbit Similar to that
of Aurora I

North Magnetic
Pole
Summer Solstice
22 June
Autumnal Equinox
23 September
Winter Solstice
22 December
Magnetic Equator
at 1.61 RE
Midnight
Max.
Min.
Twilight
Midnight
Max.
Min.
Auroral Zone
Region Viewed by Photometers

Invariant Latitude $\Delta$

Satellite in Geometric Darkness
Region Viewed when Satellite in Darkness
100 km in Geometric Darkness

Auroral Zones from Feldstein (1966)

Figure 20
Δ OF PHOTOMETERS AS A FUNCTION OF Δ OF AURORA Ι AND PARTICLES

Δ of Tangent to B Line at 100 Km

Δ of B Line at 1.61 R_E

Asymptote

Figure 21
TOTAL QUANTUM EFFICIENCY
OF D-3 UV

Tube gain 1.1 × 10^5.
Excitation by Xenon at 1470 A
for 10 sec. at 1.8 × 10^5 A.
1400 A to 2800 A from EMR
and modelled after D-1 and D-2.
3914 A, 5577 A and 6300 A data
obtained 11 March 1968 and 12 March 1968.

Total Quantum Efficiency in
Electrons/photon

After 400 seconds decay
After 15 seconds decay

After several months on the shelf

Wavelength in A

Figure 22
RESPONSE OF D-3 UV TO RADIANCE OF EARTH AND ATMOSPHERE FOR COINCIDENCE OF SUBSOLAR AND SUBSATELLITE POINTS

Figure 23
After saturation with xenon source at:

- 3914 Å — ○
- 4278 Å — □
- 5577 Å — △
- 6300 Å — x

**Figure 24**

Counts/second vs. Time in Seconds
RESPONSE OF D-3 UV AT 3914 A

After successive 10 sec. exposures to xenon 1470 Å radiation

a. The xenon induced $1.8 \times 10^{5}$ Å
b. Initially the 3914 Å response was $7.6 \times 10^{11}$ Å
c. About 4 min. between exposures.

Anode Current in $10^{-8}$ Amperes

Gain Increase $t = 20$ sec.
690
610
530

Gain Increase $t = 100$ sec.
440
410

Gain Increase $t = 180$ sec.
390
4th Plateau

3rd Exposure
360

2nd Exposure
320

1st Exposure
230

Time in Seconds

Figure 25
Figure 26

IRRADIANCE OF
EMR 582-05M
XENON SOURCE
Figure 28

RESPONSE OF D-3 UV
10 sec. Xenon Plateau

Time in Seconds

Anode Current in Amperes

Dark Current

6300A

5577A

3914A

10^{-8}

10^{-9}

10^{-10}
RESPONSE OF D-3 UV AT 3914 Å

For 10 sec. Xenon Plateau Under Three Conditions

Anode Current in Amperes

Dark Current

Time in Seconds

Figure 29
RESPONSE OF D-3 UV AT 5577A
For 10 sec Xenon Plateau Under Three Conditions

Figure 30
RESPONSE OF D-3 UV AT 6300 A
For 10 sec, Xenon Plateau Under Three Conditions

Anode Current in Amperes

Tungsten Bulb

6300 A

Dark Current

6300 A

Time in Seconds

15 45 90 135 180 225 270 315 360

Figure 31
COMPARISON OF Cs-I QUANTUM YIELDS

--- Philipp and Taft (1956)
--- Present Results with D-3 (divided by the 1.1 x 10^5 gain).
Plateau due to 10 sec. of Xenon
at 1470 A producing 1.8 x 10^5 A
anode current.

Thin film evaporated in presence
of excess Cs

Electrons
photons

15 sec. decay

400 sec.
decay

Single
crystal

Several months
on the shelf

Wavelength in A

Figure 32
RELATIVE QUANTUM EFFICIENCY OF K-I AT 2190 A

Apker and Taft (1952)

Enhancement due to $2 \times 10^{11}$ photons/cm$^2$ - sec at 2190A

Decay at 400°K

Figure 33
QUANTUM EFFICIENCY OF MgO

Pulverized Crystal
Stevenson and Hensley (1961)

Figure 35
Figure 37

SUN SHIELD FILTERS LENSES Baffle LIGHT Baffle & FIELD STOPS

QUADRANT FRONT END AURORA

SUN SHIELD

FRONT VIEW

REAR VIEW
Figure 39

394A Angular Response of Quadrant D-2

Angle in Degrees
Away From Photometer
Toward Photometer Axis
Response

10-1  10-2  10-3  10-4
15  10  5  0  -5  -10  -15
SCHEMATIC REPRESENTATION OF TWO AXIALLY SYMMETRIC COLLIMATORS

Figure 40

CYLINDER

MODIFIED CYLINDER

R

R

r

J

J
CALCULATED ANGULAR RESPONSE FUNCTIONS:
TWO AXIALLY SYMMETRIC COLLIMATORS

a. Cylinder
b. Cylinder modified to give 
   Aurora I Collimator

Response

Angles in degrees

Figure 41
ESTIMATED HALF-ANGLES

Quadrant D-2

Angle in Degrees

Figure 42
SUPERIMPOSED FIELDS OF VIEW

Quadrant D-2

Figure 43
LINEARITY AND ABSOLUTE CALIBRATION
FOR QUADRANT D-2 AT 3914 A

Counts/second

Kilorayleighs

Other 3 Channels

3914 A Channel

Δ Absolute
○ Relative
At Room Temperature ~ 20°C
Line Emission Approximation

Figure 44
LINEARITY AND ABSOLUTE CALIBRATION
FOR QUADRANT D-2 AT 5577 A

Kilorayleighs

Other 3 Channels

5577 A Channel

Absolute
Relative
At Room Temperature ~ 20°C

Counts/second

Figure 45
LINEARITY AND ABSOLUTE CALIBRATION
FOR QUADRANT D-2 AT 6300 A

At Room Temperature ~ 20°C

Figure 46
RELATING LINEAR AND NONLINEAR OUTPUTS

Figure 48
MICROPHOTOMETER TRACING OF O-O $\mathrm{N}_2^+$ FIRST NEGATIVE BAND

A. Vallance Jones and A.W. Harrison (1955)

Head O-O Band 3914 A
Head I-I Band 3884 A

P BRANCH

R BRANCH

Figure 49
OUTPUT OF TUNGSTEN RIBBON-FILAMENT LAMP
EPT-1070

Microwatts sr-nm-mm$^2$
of source

Wavelength in Angstroms

Figure 50
TOTAL QUANTUM EFFICIENCIES OF D-1 AND D-2

Absolute by EMR  16 and 27 Dec 1965
Relative by RICE  3 – 5 May 1967
Figure 52

TEMPERATURE DEPENDENCE OF D-1 OUTPUT

Counts/second

Temperature °C

Figure 52
THERMAL RESPONSE OF QUADRANT D-7 TO 3914 A

Temperature in °C

Figure 53
TEMPERATURE DEPENDENCE OF QUADRANT FILTER TRANSMITTANCE AT $\lambda_0$

- $\lambda_0 = 6300$ A
- $\lambda_0 = 5577$ A
- $\lambda_0 = 3914$ A

Figure 54
UV AND QUADRANT RESPONSE
Pass 016, 1 July 1967, λ ≈ 43°
Southbound

Counts/Second

Time in Hours-Minutes-Seconds

Figure 55
ENVELOP OF UV RESPONSES
Pass 016, 1 July 1967
Southbound

Counts
Second

Invariant Latitude \( \Lambda \)

Figure 56
EARTH-SATELLITE-SUN GEOMETRY

19 Hours 07 Minutes, 1 July 1967

Figure 57
DARK CURRENT RECOVERY
Quadrant D-2
5 Minute Exposure to
Reflected Sunlight

Counts
Seconds

Time in Minutes

Figure 58
SCHEMATIC DIAGRAMS OF SINGLE (a) AND TWO-STACK (b) Al-MgF$_2$-Al INTERFERENCE FILTERS

Figure 59
TRANSMITTANCE OF FIRST-ORDER INTERFERENCE FILTERS

Harrison (1968)

Transmittance

Wavelength in Å

Figure 60
INTERFERENCE FILTER BANDWIDTHS

First-Order Filters

$T_{\text{max}} = 0.25$

Bates And Bradley (1966)

Figure 61
Figure 62

TRANSMITTANCE OF INTERFERENCE FILTER BY THIN FILM PRODUCTS

Stack of Two 1st Order Filters
Sapphire Substrate
$T_{\text{max}} = 0.027$ at 1675 A
$\Delta \lambda = 430$ A

Wavelength in A
EMISSION SPECTRA OF SODIUM OF SALICYLATE

Excited at 2537 Å
Kristianpoller and Knapp (1964)

Relative Intensity

~22° C
80° K

Wavelength in Å

Figure 63
RELATIVE QUANTUM EFFICIENCY VERSUS THICKNESS OF SODIUM SALICYLATE

Excited at 2537 A
Nygaard (1964)

Thickness in mg/cm²