A SCATTER COMMUNICATIONS LINK
AT ULTRAVIOLET FREQUENCIES

by

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ABSTRACT

This thesis begins with a review of the theory for a general scatter communication channel. The expected performance of a scatter link at ultraviolet frequencies is calculated from this model. Choice of apparatus and limitations thereof are discussed in detail. Also included are the results from calibration experiments for the system. Experimental path loss data was not available at the time of writing.
ACKNOWLEDGEMENTS

Without help and encouragement from my thesis advisor, Professor Robert S. Kennedy and my supervisor and conscience at Lincoln Laboratory, Ralph V. Wood, this thesis would not have been possible. I extend my deepest appreciation to both of these men for the knowledge I gained. Also, I wish to express my thanks to groups 62 and 66 at Lincoln Laboratory for their help and cooperation. The aid of my wife, Bonnie, was invaluable.
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The Problem

At the present time, there are few low power communication channels covering the 20 to 100 mile distance range. Scatter channels, especially in the short wavelengths, may help fill this gap. Accordingly this thesis attempts to explore the feasibility of a scatter communications link at the near ultraviolet frequencies.

The theoretical basis for these experiments, which has been briefly researched,\(^1\) is included here for background information. Other questions for consideration include:

1. What apparatus need to be used to realize the system?
2. How should the apparatus be set up?
3. How can the system be calibrated?
4. What are the characteristics of the noise in the system?
5. Does or will the system work as described in theory?

The task of answering these questions is enormous. Consequently, this work, involving several people, including the author, is being carried out at M.I.T.'s Lincoln Laboratory. However, due to the short time allotted to this study as a Bachelor's Thesis, the primary concern of this paper is the choice of apparatus and realization of the system. Subsequent studies at Lincoln Laboratory will evaluate the performance of the system and the characteristics of the channel.
2. Theoretical Considerations

This system is intended for medium range use transmitting over the horizon. Rather than reflection off the ionosphere, this link relies on molecular scatter in the channel. The transmitter is aimed up at an elevation $\psi$, while the receiver is aimed to intersect the transmitted beam, as shown in Figure 1. Qualitatively, a few things may be said about the parameters illustrated. The received power $P_r$, is a function of the power density $p$, in the common volume $V$, the distance $r$ to the receiver from $V$, the scatter coefficient $\beta$, and the receiver collecting area $A_r$. Quantitatively we have,

$$P_r \propto \frac{p V \beta}{4\pi r^2} A_r$$  \hspace{1cm} 1)^2

If we assume that $p$ is uniform in the volume $V$, then

$$p \propto \frac{P_t}{d^2}$$  \hspace{1cm} 2)

Where $P_t$ is transmitted power, and $d$ is the edge of the "square" beam. Now if $\theta$, the receiver field of view, is small, and $r \theta$ is greater than $d$, then

$$V = r \theta d^2$$

therefore,

$$\frac{P_r}{P_t} \propto \frac{\beta A_r \theta}{4\pi \frac{r}{r}}$$  \hspace{1cm} 3)
Fig. 1. System Geometry
To make the proportionality an equality, a term needs to be added to account for signal losses going from the transmitter to the common volume, and from the common volume to the receiver. These losses, however, turn out to be small, and are not easily controlled by experiment. Whereas the path length is relatively fixed, $A_\tau$ and $\theta$ may be varied quite easily through at least an order of magnitude.

If we neglect for the moment losses due to path length, then

$$\frac{P_r}{P_t} \approx \frac{A_\tau \beta \theta}{4 \pi r}$$

Using values from the literature and dimensions from the following experiments,

- $r \approx 20$ km
- $A_\tau \approx 10$ cm$^2$
- $\beta \approx 10^{-6}$ m$^{-1}$
- $\theta \approx 1/5$ radians $= 11^\circ$

Then,

$$\frac{P_r}{P_t} \approx 10^{-15} = 150$ db loss$$

Losses due to path length are on the order of:

$$\text{loss} = e^{-\alpha L}$$

where,

- total path length $= L = 2r = 40$ km
- $\alpha = \text{extinction coefficient} = .1 $ km$^{-1}$
and therefore,

\[ \text{loss} = e^{-4} = 10^{-1.5} \gg 10^{-15} \]

As was assumed, path length losses are indeed small when compared to geometric losses. More precise results for the total path losses are shown in Figure 2.

In the above discussion, a few tacit assumptions have been made. The value of the scatter coefficient $\beta$ is of primary importance. This parameter unfortunately is affected a great deal by the weather. Although some work in this regard has been done, the clouds and/or haze increase both scatter and absorption coefficients in a manner not fully predictable. Clouds tend to drift, thus changing the channel. Other variable parameters are the size, shape, and the type of intersection for the common volume. It was assumed above that $\theta$ is greater than $\varphi$, thus the dependency on $\theta$. This type of intersection was chosen to obtain a large value for $p \cdot V$, in the simplest manner; $p$ was maximized by culminating the transmitted beam and $V$ was then increased by increasing $\theta$. This suggests using a long thin FOV as in Figure 3. In the above relationships, the length used was $r \cdot \theta$, thus assuming small $\theta$. However, in the presence of low clouds, $\theta$ should be large ($60^\circ$ or more) to collect ample energy. Thus the geometry will be changed considerably. High thin clouds, on the other hand, may act as a reflector similar to the ionosphere at RF, with uncertain results.
Fig. 2. 26 Km Path Loss vs. Height of Common Volume
Fig. 3. Types of Intersections

A. Small common volume, low noise;
B. Larger volume with excess noise;
C. Larger volume without excess noise.
3. The System in Brief

The experiments herein were performed between Westford and Lexington, Massachusetts, a distance of twenty-six kilometers. The transmitter, at Westford, consisted of a xenon flashtube mounted in a searchlight dish. A 5000 j pulse was flashed approximately once a second. This pulse yielded about 15 j in the passband of the receiver.

The receiver, at Lexington, consisted primarily of a photomultiplier tube and a counter. To determine the frequency of operation, the desired filter was placed in front of the phototube. Both the receiver area $A_r$, and the field of view $\Theta$, were adjustable, up to 80 cm$^2$ and 30$^\circ$ respectively. Each time the phototube detects an incident photon, it puts out a pulse. The ratio of detected to incident photons, the quantum efficiency, is about 0.25. The output of the phototube was connected to a counter. Thus the actual number of incident photons could be correlated directly with the counter output.

In a pulse of 10 j at 3000 A there are about 1.5 X $10^{19}$ photons. With a path loss of 150 db, there would be 15,000 photons at the receiver front end. A nominal insertion loss for filters, quantum efficiency, and counter error is 1/30. This leaves about 500 detected photons. A more precise tabulation is shown below in Table 1.

Preliminary experiments indicate that there are 300 detected photons per 15 j pulse, using 5$^\circ$ FOV, and 7 cm$^2$ receiving area, under clear sky conditions.\(^9\)
<table>
<thead>
<tr>
<th>Weather Condition</th>
<th>= 3200 A</th>
<th>3000 A</th>
<th>2900 A°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clear Sky</td>
<td>40,000</td>
<td>13,500</td>
<td>2,200</td>
</tr>
<tr>
<td>Moderate Clouds (600' Thickness)</td>
<td>1,100</td>
<td>360</td>
<td>65</td>
</tr>
<tr>
<td>Heavy Clouds (6000' Thickness)</td>
<td>40</td>
<td>14</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 1. RECEIVED PHOTONS PER JOULE TRANSMITTED\(^\text{10}\)

Assumed Conditions:

1. Distance between transmitter and receiver = 26 Km.
2. Receiver collecting area, \(A_r = 1\) Sq. foot
3. Receiver field-of-view, \(\theta = 60°\)
4. Details of the Apparatus

4.1 Transmitter

There are few narrow band sources at ultraviolet. Low pressure mercury arc lamps have a line spectrum, but not enough power. Lasers are very narrow band, but also low power. At this time, either high pressure mercury or xenon arcs must be used to achieve the necessary ten watts.

For continuous operation, the high pressure mercury arc is the best source known to the author. General Electric B-H6 or A-H6 (water cooled) is compact in size, has a 6mm arc, and radiates approximately 50 watts from 2800 to 3200 Å.\(^\text{11}\) (See Table 2 and Figure 4.) The AC power supply is commercially available, as is the cooling system. Because the small arc approximates a point source, the B-H6 can easily be focused using small optics.

The primary disadvantage of the A-H6 is that it is not designed to operate in the pulsed mode. With a continuous source, only path loss data can be obtained easily. Xenon flashlamps however, are designed to operate in the pulsed mode and still maintain high average power. Peak power is thus increased, as is S/N when compared to continuous operation.

\[
\text{S/N} = \frac{\text{OC \ ratio of \ period \ to \ on \ time} \times \text{Pave}}{
\]

The spectral output of xenon is more continuous than mercury, but this can be advantageous using present filters. With a line spectrum, the frequency of operation is fixed by the source. Using a continuous spectrum, only the receiving
TABLE 2. RADIATION FROM A-H6 WATER-COOLED CAPILLARY LAMP

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lamp watts</td>
<td>1,000</td>
</tr>
<tr>
<td>Lamp operating volts</td>
<td>840</td>
</tr>
<tr>
<td>Lamp operating current</td>
<td>1.4 amps</td>
</tr>
<tr>
<td>Arc length</td>
<td>6 MM</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Pyrex Water Jacket Watts radiated</th>
<th>Quartz Water Jacket Watts radiated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Below 2800 Å</td>
<td>---</td>
<td>33</td>
</tr>
<tr>
<td>2800 - 3165 Å</td>
<td>4.2</td>
<td>56</td>
</tr>
<tr>
<td>3165 - 3800 Å</td>
<td>53</td>
<td>80</td>
</tr>
<tr>
<td>Total U.V. below 3899 Å</td>
<td>57.2</td>
<td>169</td>
</tr>
<tr>
<td>Total visible 3800-7000 Å</td>
<td>236</td>
<td>244</td>
</tr>
</tbody>
</table>

Microwatts per Cm² at 1M*

<table>
<thead>
<tr>
<th></th>
<th>Pyrex Water Jacket Watts radiated</th>
<th>Quartz Water Jacket Watts radiated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Below 2800 Å</td>
<td>---</td>
<td>324</td>
</tr>
<tr>
<td>2800 - 3165 Å</td>
<td>49</td>
<td>725</td>
</tr>
<tr>
<td>3165 - 3800</td>
<td>784</td>
<td>1100</td>
</tr>
</tbody>
</table>

*Mounted with no reflector
Wavelength in Angstroms

Fig. 4. Spectral Emission of Mercury Arcs A. 31 atmospheres. B. 75 atmospheres. C. 165 atmospheres. D. 285 atmospheres. (E. B. Noel, Illum. Eng., 36, 243 (1941)).

The A-H6 operates at 110 atmospheres.
filters need be changed to shift the frequency of operation. In this way the channel can be more thoroughly investigated.

Due to the relatively long six inch arc, large optics are necessary to focus the FX-47 Xenon flash tubes. For this purpose a five foot diameter searchlight was set up a Millstone Hill in Westford. Two tubes were mounted horizontally through the focal point of the dish. The resulting beam has two main lobes about five degrees apart in elevation with each lobe about ten degrees wide in azimuth. (See Figure 5.) Since the peak output is quite large (greater than five megawatts), dangerous to look at and annoying to local residents, attenuation in the visible range is desirable. A small glass filter could be placed in front of the tubes (Figure 6) if such a high wattage attenuator is available. None was used for this series of experiments.

The associated circuitry includes a high voltage supply, cooling control, and synchronization circuits. To fire the flashtubes, a four section CL pulse shaping network was used (Figure 7). This gave a flat voltage pulse and a flat intensity pulse 1.4 ms long. The current waveform is more triangular in shape. Reasons for triangular rather than flat pulse are unknown to the author. (Figure 8). Normally light intensity is proportional to some power of the current density.\textsuperscript{13} This does not seem to be true in this case.

To achieve the \emph{S/N} ratio possible with pulsed mode operation, the transmitter and receiver must be properly synchronized.
Fig. 5. Transmitted Beam Pattern
Flashtubes are mounted in azimuth plane; intensity measured at 104 feet at 3350 Å.
Fig. 6. Transmitting Optics
A. Actual transmitter; B. Schematic drawing
Fig. 7. High Voltage Supply
Fig. 8. Waveforms for Transmitter Flash tubes

Power (input)
Intensity out (arbitrary units)
energy (in) = 4.9 kJ
An existing microwave link between Westford and Lincoln was used for this purpose. The triggering circuits are shown in the block diagram below, Figure 9.
Fig. 9. Synchronization Block Diagram
4.2 The Receiver

4.2.1 The Photomultiplier Tube

Due to the expected low level signals at the receiver, a large high gain, low noise front end is required. The optical equivalent of this is a photomultiplier tube with high quantum efficiency, large collecting area, and low noise count (dark current). The best tube for this purpose known to the author is the RCA 4522. Summary specifications are shown below:

RCA 4522\textsuperscript{14}
Quantum efficiency
2600A 25%
3600A 29%
4400A 25%

Dark Current
at 22\textdegree C 6x10^{-8} \text{amps}
or approx. 500Hz
Photocathode Diameter 4.5" \text{min.}
Current gain 3 \times 10^7
at 2000V
Number of stages 14

Note that the QE (quantum efficiency) is relatively flat throughout the region of interest, and that current gain is quite large. Both of these characteristics facilitate use of the tube in these experiments. High current gain (10^8 at 2500V) yields output pulses approx. 0.2V peak across 1K load. With such a large output, very little additional circuitry was required.

As has been shown previously in section 2, the received signal is weak enough to show marked quantum effects. For minimum insertion loss, a high QE is desirable. The QE of 25% is as high or higher than any other tubes known to the author.
Dark current is low enough at room temperature so that additional cooling is not required. Received signal plus noise ranged from 1 KHz to 1 MHz depending on the experiment performed; 500 Hz of this count was noise. Hence, the S/N ratio usually exceeds 1.0. The 4 1/2" photo cathode is larger than needed for the experiments described herein, but future experiments should take advantage of this feature.

Although the output from the 4522 is 0.2V, the counter would not count reliably at this level. To amplify the output pulse, a high gain video amplifier RCA 3001 was used. The 3001 comes in a T0-5 can (12 leads), runs on ± 6V, and is straightforward to use. For maximum high frequency gain, it was used open loop. No frequency compensation was needed. However, bypass capacitors are recommended on the supply voltages to damp positive feedback, even when using batteries. This arrangement worked well (see Figure 10); the output was 1.5V across 100Ω load.

To supply the dynodes, two voltage dividers were suggested by the manufacturer. The divider used here, "Typical Scintillation Counting," has a fast response, and is best suited for counting applications (See Figure 11). The total resistance of the divider is approximately 800KΩ, drawing 2.8 amps at 2500V.

An alternative tube with similar characteristics is the RCA 8575. It is a 2" diameter, 12 stage tube, with the same relative response as the 4522. The gain, however is 10^6, 20 db lower than the 4522.
Fig. 10. Receiver with Amplifier
Fig. 11. Voltage Divider for RCA 4522
4.2.2 Field of View

The receiver optics consist of field of view (FOV) restrictions, band pass filters, and attenuators. As shown earlier, a narrow azimuthal FOV is desirable for optimum S/N ratio. To increase the received signal level, keeping the S/N constant, the FOV may be increased in the vertical plane. For cloudy weather operation a large (60°) FOV in both planes appears most desirable.

To adjust the FOV, tubes of various lengths with restricting apertures were mounted in front of the photomultiplier, as in Figure 12. The FOV is then determined by the angle between the two diagonals of the cylinder cross section.

4.2.3 Filters

Using a 1 ns pulse, $10^{10}$ Hz would be the largest bandwidth (BW) needed for good fidelity. To obtain optimum S/N such a narrow band transmitter and receiver should be employed. Unfortunately, neither of these are available at the frequencies under consideration.

The bandwidth of the receiver is limited by optical filters placed in front of the photomultiplier. At visible frequencies filter bandwidths down to 1 Å (about $10^{12}$ Hz) are commercially available, but these suffer large insertion loss, and narrow field of view. In the near ultraviolet, there is a shortage of usable dielectrics, and the choice of filters is even more limited. As a compromise for trans-
Fig. 12. Receiver Optics
mitted power, and available filters, 100 A BW was selected.
The interference filters used have a transmission characteristic similar to the one shown in Figure 13. Transmission
of 20% to 30% in the passband is typical for this type of filter.

Several types of filters were investigated by the author for this application. Among them were liquid absorption, silver absorption, and interference filters.

Liquid absorption filters appear to be ideal at first glance for the present application. They offer high transmission, sharp cutoff, large attenuation of background, and large field of view.\textsuperscript{16,17} However, the liquid solutions do not stay homogeneous without constant stirring, and small impurities (especially iron), can drastically affect the transmission by reacting with the solute. Water also has the unfortunate property of freezing, making outside winter experiments difficult if not impossible.

Silver absorption and reflection was investigated without success. Noting that silver has a reflection coefficient close to 90% for frequencies above 3300A and drops to 10% at 3100A,\textsuperscript{18} it was hoped that a filter could be made using this property. A thin film (100A) of silver was hoped to have small total absorption and similar reflection properties. But it was found that both reflection and absorption changed, almost eliminating the frequency selection.\textsuperscript{19,20}
Fig. 13. Typical Interference Filter Response
Interference filters offer good rejection ($10^{-4}$) away from the passband; they are stable with age, temperature, and exposure, and are easily available. A narrow field of view is their major disadvantage. At $30^\circ$ from normal incidence, the peak transmission shifts about 80 A towards shorter wavelengths. Thus for any narrow band, large FOV applications, interference filters are of questionable value.

4.2.4 Counter

The total pulse width from the photomultiplier after amplification is approximately 80 ns (viewed on a 50 MHz oscilloscope). Therefore a 10 MHz counter with calibrated threshold was used, the CMC model 880 A. This threshold level was unexpectedly a major problem in obtaining repeatable data. As the threshold level changes, the count will also change due to variation in pulse height amplitude from the phototube.

To meaningfully interpret the number read from the counter, one must know what percentage of pulses are being counted. This involves understanding the pulse height distribution for the tube, and also knowing what level triggers the counter. This problem will be discussed later in the paper (Section 5.3).
5. System Calibration

To calibrate the system, two additional units are required: a standard source for the receiver, and a standard receiver for the transmitter. The expected output was calculated for the receiver sensing the standard source. This figure was used to check the results of the calibration experiment. A similar procedure was followed with the transmitter.

5.1 Standard Source

For the standard transmitter, a standard incandescent lamp was used. It consists of a quartz envelope, iodine cycle incandescent lamp, lamp stand, and a standard current supply manufactured by Electric Optics Association. Each lamp includes a measured calibration curve such as in Figure 14. The standard current supply includes a high resolution ammeter and protection circuitry for the lamp.

Several assumptions were made about the lamp to facilitate calculation of the expected receiver output:

1. At distances of 40 cm. or greater, the intensity is that of a point source. This results from the use of a small compact filament. Therefore, the inverse square law is valid in this range. Thus, at distance \( d \), the power at that distance \( P_d \) is

\[
P_d = P_{40} \left( \frac{40}{d} \right)^2
\]

2. Over the bandwidth (BW) of the filter (100A), the lamp output is constant. Such an assumption makes integration
Fig. 14. Standard Lamp Calibration Curve
over the BW much easier, without affecting the result greatly. (See Figure 15).

Other types of calibrated sources include those with line rather than continuous spectra. These sources would permit dropping assumption 2 pertaining to constant output in the filter BW. However, a line source is not able to calibrate several points within the region of interest. With a continuous source, calibration is possible using whatever filters the receiver incorporates.

5.2 Receiver Calibration
The phototube was calibrated using the above mentioned standard lamp. Since the phototube is such a sensitive device, approximately 60db of attenuation was needed to maintain the proper signal levels. To achieve this, the lamp was placed at a distance of 400 cm, the receiving aperture reduced to a .020" diameter hole, and a 2.0 Neutral Density (N.D.) Kodak Wratten Filter was used in conjunction with the passband filter. Assumptions used calculating the receiver output were:

1. The passband filter may be approximated as a rectangle of height T, the peak transmission of the filter, and the width BW, the half transmission bandwidth of the filter. Using this approximation gives very nearly the same area as under the actual transmission curve. (See Figure 16).

2. The lamp is a point source (see calibration lamp assumptions).

3. The .020" hole is a "good" pin hole, i.e. the pinhole is round, A-\(\pi r^2\), the edges are clean.
Fig. 15. Lamp Output in Passband of Filter
Fig. 16. Typical Filter Response and Approximation
4. The leakage around the 2.0 N.D. filter is small compared to the transmitted light.

5. The 2.0 N.D. Wratten filter has a response as shown in Kodak Catalogue B-3. At 3000A transmission is down to $10^{-3}$ and not $10^{-2}$ as in the visible.

6. The counter counts all the signal photon pulses (see calibration of counter).

Let:

$P_t =$ power density/10A at 40 cm radiated (transmitted) by lamp in the BW of the filter.

$P_r =$ power received by the phototube

$T_i =$ peak transmission of filter "i"

$BW =$ overall half transmission bandwidth for cascaded filter system

$A =$ area of receiving aperture

$d =$ distance from the source to the receiving aperture; 40 cm is the reference distance

then:

$$P_r = P_t \frac{BW}{10} \frac{40^2}{d^2} A T_1 T_2 \quad \text{(4)}$$

Letting,

$f =$ frequency of detected photons

$E =$ energy of one photon

$QE =$ quantum efficiency of photomultiplier

$$E = h \nu = h \frac{c}{\lambda} \quad \text{(5)}$$

$$f = \frac{P_r QE}{E} \quad \text{(6)}$$

The values used at 3100 A were:

$P_t = 8 \times 10^{-2}$ $\mu$watts/cm$^2$/10 A

$BW = 200$ A

$T_1 = .25$ (3100 A filter); $BW = 200$ A

$T_2 = 10^{-3}$ (2.0 N.D. Wratten filter at 3100 A)

$A = \frac{\pi}{4} (2 \times 10^{-2})^2 (2.54)^2 = 2.03 \times 10^{-3}$ cm$^2$

$d = 400$ cm
\[ P_r = 8.12 \times 10^{-9} \text{ } \mu \text{watts} \text{ from 4) } \\
\frac{h}{c} = 6.625 \times 10^{-34} \text{ js } \\
c = 3.00 \times 10^8 \text{ m/s } \\
\lambda = 3.10 \times 10^{-7} \text{ m } \\
\text{QE} = .28 \text{ at 3100 A from 5) } \\
E = 6.4 \times 10^{-19} \text{ J } \\
f = 3.5 \times 10^3 \text{ detected photons/s at 3100 A from 6) }

The values used at 3300 A were:

\[ P_r = .15 \text{ } \mu \text{watts/cm}^2/10 \text{ A } \\
\text{BW} = 200 \text{ A } \\
T_1 = .30 \text{ (3300 A filter); BW} = 200 \text{ A } \\
T_2 = 2 \times 10^{-3} \text{ cm}^2 \\
d = 400 \text{ cm }

\[ P_r = 3.65 \times 10^{-8} \text{ watts } \text{ from 4) } \\
\frac{h}{c} = 6.625 \times 10^{-34} \text{ js } \\
c = 3.00 \times 10^8 \text{ m/s } \\
\lambda = 3.30 \times 10^{-7} \text{ m } \\
\text{QE} = .29 \text{ at 3300 A from 5) } \\
E = 6.0 \times 10^{-19} \text{ from 5) } \\
f = 1.8 \times 10^4 \text{ detected photons/s at 3300 A from 6) }

The performance of the receiver came close to the calculated values. (See Table 3)

\begin{array}{|c|c|c|c|}
\hline
\lambda & \text{calculated} & \text{experimental} & \text{calibration} \\
\hline
3100 & 3.5 \text{ KHz} & 3.7 \text{ KHz} & 2.2 \times 10^{-4} \ast \\
3300 & 18 \text{ KHz} & 6.5 \text{ KHz} & 2.3 \times 10^{-4} \ast \\
\hline
\end{array}

\ast \text{ units are } \frac{\text{watts/cm}^2}{10 \text{ A detected KHz}} \text{ incident on the N.D. filter }

\begin{table}
\caption{RESULTS OF RECEIVER CALIBRATION EXPERIMENT}
\end{table}
The differences between calculated and experimental values were caused by both imperfections in experimental technique and errors in the assumptions used for calculation. The Wratten filter in particular may not have the transmission assumed. This type of filter is subject to changes with age and exposure.

5.3 PROBLEMS ENCOUNTERED WHILE CALIBRATING THE RECEIVER

The greatest single problem in obtaining repeatable data is the variation in pulse height from the photomultiplier tube. The 4522 is a fourteen stage tube; in each stage, the number of secondary electrons kicked out by an incident electron is a random process. Thus the total number of electrons, and the output pulse height are random variables (see Figure 17 Pulse Height Distribution). A two-to-one change in the threshold level of the counter can change the counted frequency by an order of magnitude or more. Part of this problem was alleviated by inserting the X10 amplifier mentioned previously. Using the larger amplitude pulse, the counter was less sensitive to changes in threshold level. The problem was finally solved by making a very careful calibration check of the counter itself (see section 5.4).

Another difficulty that arose was saturation of the phototube. It was found that using the receiver system as described above, the photomultiplier begins to saturate at about $10^6$ photoelectrons per second. Beyond this point, the population of secondary electrons alters the interstage electric fields so that the tube defocuses itself. As a result, pulse
Dashed portion indicates location of single photoelectron peak and is normalized to coincide with the dark pulse single photoelectron peak.

Solid line portion indicates dark-pulse spectrum.

Tube temperature = 22° C
Supply voltage = 2500 V
Integrating time constant = 10 s
R = 10k  C = 1000 F

One photoelectron pulse height = 4 counting channels

\[
\frac{32}{1} = 3.0 \times 10^4 \text{ counts/min.}
\]

\[
\frac{32}{4} = 2.2 \times 10^3 \text{ counts/min.}
\]

Fig. 17. Pulse Height Distribution
height decreases. This phenomenon was noted during early calibration experiments without using any Neutral Density (N.D.) filters. The calculated expected frequency was 3 MHz to 8 MHz depending on the filter, but the experimental frequency was only 1 MHz. Use of the 2.0 N.D. filter avoids this problem.

5.4 COUNTER CALIBRATION

Since the output pulse height of the photomultiplier varies, the threshold calibration of the counter becomes as important as the frequency counted. The most desirable type of counter would have both an upper and lower calibrated threshold. With such a device, an accurate pulse height distribution could easily be obtained. However, for these experiments, this type of counter was not available.

The CMC 880A is a 100 MHz direct input counter, 300 MHz with heterodyning. The threshold adjustment for the direct input appears outwardly to be calibrated. Among the various knobs are two input level controls, MULT and TRIG. MULT is in steps .1, .3, 1, 3, 10, 30, 100. TRIG is continuously variable from -6 to +6. The product of MULT and TRIG is the RMS voltage sensitivity of the counter. But with the signal from the phototube, the counter acts in the following manner: with the MULT set to .3, and TRIG at 0, the count is 0. As TRIG is slowly increased, the count rapidly rises. The maximum occurs with TRIG set to about +.5. After this point the threshold appears to be a calibrated lower limit. However, this was only true for MULT set to .3. Other settings of
MULT exhibited similar behavior of TRIG, but were obviously not calibrated. (See Figure 18).

Checking the calibration of the counter required an oscilloscope camera, Polaroid type 47 film (ASA 10,000), and quick fingers. Several pictures were taken of 20 $\mu$s samples of the phototube output. This was done using the single sweep mode of the Techtronix 547, at 2 $\mu$s/cm, and opening the shutter for at least the duration of the sweep. Several rolls of film were used to achieve satisfactory manual synchronization. (Type 47 film overexposes very easily, thus the need for quick hands.)

As the 20 $\mu$s samples were being taken, readings on the counter were taken at various threshold levels. The pictures were then analyzed for pulse height distribution by manual counting. This distribution was matched against the readings from the counter. In such a way, calibration was either established or verified incorrect. (See Figure 19, Sample Output.)

5.5 Standard Receiver

Calibration of the transmitter requires a standard receiver compatible with the signal level from the transmitter. Such a receiver was made using a calibrated RCA 935 photo diode and several filters. The 935 has an S-5 spectral response (as does the 4522), shown in Figure 20. The peak luminous sensitivity for the 935 is 43 ma/watt. But 30 $\mu$a is the maximum average anode current. Sufficient attenuation to keep the tube well within the specified limits was obtained
Fig. 18. Counter Threshold Calibration
Fig. 19. Sample Output of Receiver

Top: 20 μs sample; Bottom: one pulse
Fig. 20. S-5 Spectral Response
using a distance of 104 feet from the transmitter, a 3.0 N.D. filter, a passband of 100A, and 1/2" diameter aperture. Calibration of the 935 was performed without the 3.0 N.D. filter.

The 935 and its associated circuitry were mounted in a light-tight box with external optical attachments, as shown in Figure 21. The anode load was fixed at 1.0 MΩ and followed by a high impedance (10^4 MΩ) unity gain amplifier, LM 202. Anode to cathode voltage was 180 V. To attach filters and apertures, 2" diameter camera filter holders were selected which may be stacked up in any desired combination.

Calibration was performed similarly to the calibration of the 4522 (Section 5.2). A standard source with known output was correlated to the output of the 935. Again, the expected receiver output was calculated as a check for the calibration. Included in the assumptions for the calculations were:

1. The filter has a rectangular pass band, height T, and width BW.

2. The lamp is a point source, therefore the field is inverse square (see section on calibration lamp).

3. The lamp output is constant for the BW of the filter (see section on lamp).

4. All the light incident on the aperture falls on the photocathode.
Fig. 21. 935 Housing and Circuitry
This last assumption is the only one not previously explained. It permits calculating the power only in the aperture and thus eliminates the geometry of and the distance to the photocathode. Such an assumption is valid for all apertures less than the width of the cathode (5/8" min.). Equations for received power are the same as for the 4522.

\[ P_r = \text{Power received} \]

\[ P_t = \text{Power density/ 10A at 40 cm, radiated by the source} \]

\[ BW = \text{half power bandwidth of the filter system} \]

\[ T = \text{peak transmission of the filter system} \]

\[ A = \text{area of receiving aperture} \]

\[ P_r = P_t \frac{BW}{10} T A \]

From the received power, \( P_r \), the anode current may be calculated as follows:

\[ S = \text{absolute sensitivity at 3400 A} \]

\[ R = \text{sensitivity relative to 3400 A} \]

\[ C = \text{anode current} \]

\[ C = P_r R S \]

The values used and quantities calculated are summarized below in table 4.
<table>
<thead>
<tr>
<th>λ</th>
<th>Pₜ</th>
<th>BW</th>
<th>T</th>
<th>Pᵣ</th>
<th>R</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>4047</td>
<td>.74</td>
<td>88</td>
<td>.42</td>
<td>3.45</td>
<td>.82</td>
<td>122</td>
</tr>
<tr>
<td>3340</td>
<td>.18</td>
<td>100</td>
<td>.19</td>
<td>4.30</td>
<td>1.00</td>
<td>18.5</td>
</tr>
<tr>
<td>3130</td>
<td>.10</td>
<td>80</td>
<td>.16</td>
<td>.162</td>
<td>.95</td>
<td>6.6</td>
</tr>
<tr>
<td>2950</td>
<td>.055</td>
<td>150</td>
<td>.23</td>
<td>.241</td>
<td>.85</td>
<td>8.8</td>
</tr>
<tr>
<td>2537</td>
<td>.008</td>
<td>200</td>
<td>.07</td>
<td>.015</td>
<td>.75</td>
<td>0.5</td>
</tr>
</tbody>
</table>

A = 1.26 cm² (1/2" diameter aperture)

S = .043 a/watt

Distance from source = 40 cm

Table 4. 935 CALIBRATION CALCULATIONS

Voltages were measured using a Techtronix 547 oscilloscope and 1Al plug-in. Experimental results agree closely with the calculated values. Four out of the five points agree within 10%. The disagreement of the last point, at 4047 A is probably due to incorrect filter information. Originally the peak T was specified at .22 by the manufacturer. An analysis at Lincoln Labs on a Beckman Spectrometer shows a T of .42. However, the beam for analysis used is only 1/4" in diameter. Probably the transmission averaged over the entire filter is closer to .60. Below is a comparison of calculated vs. experimental results.
<table>
<thead>
<tr>
<th>λ</th>
<th>Calculated mV across 1 MΩ load</th>
<th>Experimental</th>
<th>Oscilloscope Vertical Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>4047</td>
<td>122</td>
<td>170</td>
<td>50 mV/cm</td>
</tr>
<tr>
<td>3340</td>
<td>18.5</td>
<td>20.0</td>
<td>5 mV/cm</td>
</tr>
<tr>
<td>3130</td>
<td>6.6</td>
<td>7.0</td>
<td>&quot;</td>
</tr>
<tr>
<td>2950</td>
<td>8.8</td>
<td>8.5</td>
<td>&quot;</td>
</tr>
<tr>
<td>2537</td>
<td>0.5</td>
<td>0.5</td>
<td>&quot;</td>
</tr>
</tbody>
</table>

Table 5. 935 CALIBRATION RESULTS

The close agreement in Table 5 shows the validity of the assumptions, which also increases the confidence of the 4522 calibration results.

5.6 Transmitter Calibration

Calibration of the transmitter is much more difficult to verify than previously mentioned calibrations. Very little information is available on the spectrum of xenon flash tubes below 3500 Å. From Figure 22, Spectral Distribution of the FX 47, the energy per 100 Å per joule input is about 8 x 10^-2. A 5,000 j pulse therefore, should yield about 40 j/100Å. This serves as a "ballpark" figure. The actual calibration was carried out using the 935 calibrated receiver at 104 feet from the transmitter. With the receiver fixed at this distance, the transmitter was swept in azimuth. At the peak intensity in azimuth, the transmitter was then swept in elevation. The results are shown in Figure 23 and Figure 4. Numbers in
Fig. 22. Spectral Distribution of the FX-47
Fig. 23. Transmitter Intensity at 104 Feet.
2500 V on two FX-47 flashtubes; 935 receiver with
3/8 inch round apertature, 3340 A filter, 100 A BW, and
3.0 N.D. filter.
Figure 23 indicate peak current in $10^{-9}$ amps, using 1/2" diameter aperture, 3130 A filter, 90 A BW, and 3.0 N.D. filter. From this plot, the average intensity and total power were calculated. The average reading for a rectangle 15' x 20' is "guessed" to be 0.3 µa, or 6.5 mw/cm²/10A. Thus the energy in a 1.4 ms pulse is about 15 j/100A at 3000A.

Repositioning the receiver in the maximum of the beam, intensity measurements were made at five different wavelengths: 2537 A, 2950 A, 3130 A, 3350 A, and 4047 A. After correcting for filter BW, filter T, and relative receiver sensitivity, the spectral response of the transmitter was determined from this data as shown in Figure 24.
Fig. 24. Spectrum of Transmitted Beam
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1. R.S. Kennedy, Lincoln Lab memorandum # 52L-1060, 1/29/68.


7. G. Flossieks, unpublished notes, 1/68.


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11. L.R. Koller, p. 68.


14. L.R. Koller, p. 175.


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