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A SURVEY OF ULTRAVIOLET COMMUNICATION SYSTEMS

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ABSTRACT

This report contains a review of ultraviolet communication systems developed during the period 1926 to 1950. Sources of radiation used in these systems were carbon arcs, low pressure mercury arc lamps, gallium lamps, and nitrogen filled tubes. Receivers were, in most cases, multiplier phototubes; however a fluorescent telescope and metascopes were also used. Several of these systems had most of the radiation concentrated in the 2536A mercury line, a region where the atmospheric attenuation is very high. Others attempted only to limit the radiation to the invisible portion of the ultraviolet spectrum, i.e., below about 3500A. None of the systems were reported to have worked well during daylight operations.

Data on the transmission of the atmosphere in the ultraviolet region and on filters, sources, and receivers are included.

A communication system for directional or beacon operation during daylight or nighttime with at least a 10-mile range on an average day is considered feasible. The source would use a mecury-xenon arc lamp or a nitrogen filled tube. Improved signal-to-noise ratio will be obtained if the source is pulsed. The receiver would use a multiplier phototube with an interference type filter.

PROBLEM STATUS

This is a survey of the present state of the art on one phase of this problem; work is continuing on other phases.

AUTHORIZATION

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A SURVEY OF ULTRAVIOLET COMMUNICATION SYSTEMS

INTRODUCTION

When dealing with problems in the ultraviolet region, such as the use of ultraviolet radiation for communication, it is convenient to have assembled in one document information for making preliminary evaluations. This document attempts to provide this function and contains data on atmospheric transmission, filter materials, sources, and receivers mainly for the middle and near ultraviolet regions.

Succeeding reports will present experimental data obtained during various atmospheric conditions with equipment designed to improve the signal-to-noise ratio of signals transmitted in the ultraviolet region.

ATMOSPHERIC TRANSMISSION

The selection of a system can be started by examining the attenuation of the atmosphere and ruling out those wavelengths which are obviously unsatisfactory.

Energy radiated from a point source is diminished in two ways as it is propagated through the atmosphere. The irradiance varies inversely as the square of the distance from the source due to the spreading and is exponentially attenuated with distance because of absorption and scattering. Thus

$$I = \frac{I_0}{R^2} e^{-\sigma R} \qquad (1)$$

where I_0 is the irradiance of the source, R is the range, I is the irradiance at a distance R, and σ is the attenuation coefficient.

In order to have a complete coverage of the processes of atmospheric transmission one might start by examining the transmission of a perfectly clear atmosphere. With a perfectly clear atmosphere the visual range is not infinite because of scattering by the gas molecules in the atmosphere. This effect is called Rayleigh scattering and can be expressed mathematically by the equation

$$\sigma = \frac{32\pi^3}{3n\lambda^4} (\mu - 1)^2 \qquad (2)$$

where σ is the attenuation coefficient, n is the number of particles per cm^3 at STP, and μ is the index of refraction. A typical value of n is 2.568×10^{19} at 760 mm Hg and 15°C (1); $(\mu - 1)$ for dry air can be found from tables (2) and is the order of 2700×10^{-7}. A plot of Eq. (2) for wavelengths from 2000A to 9000A is shown in Fig. 1.

Meteorological visual range has been defined as

$$V_m = \frac{1}{\sigma} \ln \frac{1}{C} \qquad (3)$$

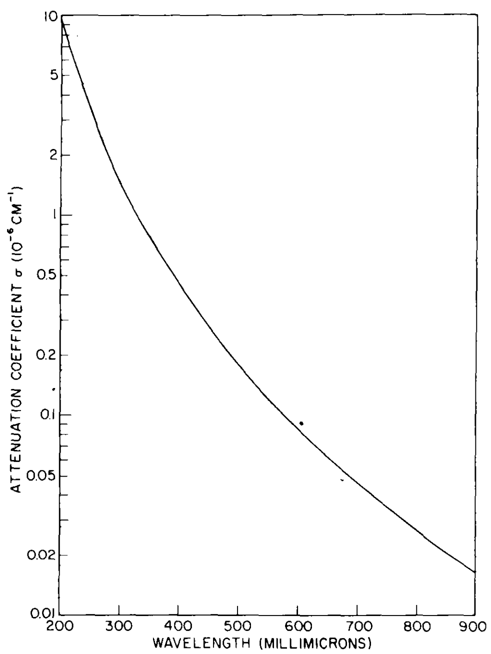

Fig. 1 – Rayleigh scattering in pure air at STP

where C is the brightness contrast as defined by the expression

$$C = \frac{B_B - B_0}{B_B} \tag{4}$$

in which B_B is the brightness of the background and B_0 is the brightness of the object in question. It can be seen from Eq. (3) that C is related to the visual range by

$$C = e^{-\sigma V_m}. \tag{5}$$

A value of 0.02 has been used by many workers as a standard for the brightness contrast When the value 0.02 is substituted in Eq. (3) the visibility equation becomes $V_m = 3.912/\sigma$.

The visual range with a perfectly clear atmosphere can now be obtained from Eq. (3) using the attenuation value from Fig. 1 at a wavelength of 5500A. The visual range is found to be 318 km or about 170 nautical miles over a horizontal path at standard atmospheric conditions. These calculations have been made to show that the factors other than molecular scattering limit the range at all wavelengths even under ideal conditions, since ranges of the order of 170 miles are not normal. In real atmospheres, scattering by haze is the predominant attenuating mechanism in the visible spectrum.

An indication of actual visual daylight ranges realizable with different atmospheric conditions is given in Table 1. The code used, which is roughly a geometric progression, was for many years the International Scale of Visibility. Columns (4) and (5) were added for reference.

In order to relate the numbers in Table 1 to the attenuation constant, consider the case of a hazy day where the visibility is 1 to 2 miles (code No. 4 or 5). The corresponding

Table 1
International Scale of Visibility

(1) Code No.	(2) Description	(3) Daylight Visual Range	(4)	(5) Attenuation Coefficient	(6)	(7) Transmission	(8)
		Metric	Nautical	per km	per naut mi	per km	per naut mi
0	Dense fog	50 m	55 yd	78	144	10^{-38}	3.2×10^{-42}
1	Thick fog	200 m	220 yd	19.3	35.8	4.5×10^{-9}	2.5×10^{-16}
2	Moderate fog	500 m	550 yd	7.7	14.3	4.4×10^{-4}	6.2×10^{-7}
3	Light fog	1000 m	1100 yd	3.9	7.2	0.02	7.5×10^{-4}
4	Thin fog	2 km	1.1 mi	1.92	3.56	0.142	0.028
5	Haze	4 km	2.2 mi	0.96	1.78	0.38	0.168
6	Light haze	10 km	5.5 mi	0.38	0.71	0.68	0.49
7	Clear	20 km	11 mi	0.192	0.356	0.83	0.7
8	Very clear	50 km	27 mi	0.075	0.145	0.33	0.86
9	Exceptionally clear	130 km	71 mi	0.0298	0.055	0.98	0.95
10	Theoretical pure air	316 km	170 mi	0.0123	0.0227	0.99	0.97

attenuation constants are 19.6×10^{-6}/cm to 9.8×10^{-6}/cm, much larger than the value of 0.123×10^{-6}/cm corresponding to Rayleigh scattering alone, which was shown above to result in a theoretical range of 170 miles. Even on an exceptionally clear day when the visibility is 27 miles the attenuation factor is 0.784×10^{-6}/cm (compared to 0.123×10^{-6}/cm for Rayleigh scattering), so in most cases Rayleigh scattering is negligible compared to other attenuating factors.

Equation (3) is based on the ability to distinguish a black object against a uniformly illuminated horizon sky. Ideally the object should subtend 1/2 to 1 degree in each dimension. Wooded ridges are frequently used as the black object, since they have a very low reflectance and therefore appear black.

The nighttime visibility of lights is determined by observing the candlepower of a lamp which just disappears or, alternately observing the distance at which a 100-candlepower lamp is visible. In either method a table is required to correlate the night range with the daytime visibility assuming that the atmosphere was the same. Table 2, taken from Ref. 3, relates the day and night visual range for the same atmosphere.

Table 2
Comparison of Day and Night Visual Ranges

Daytime Visibility	Visual Range at Night for Lights of*			
	1 cp	10^2 cp	10^4 cp	10^6 cp
27 yd	38 yd	53 yd	70 yd	87
55	69	111	139	174
110	125	204	269	347
220	226	371	525	689
550	451	829	1240	1690
1100	738	1490	1-1/3 mi	2 mi
1-1/4 mi	1140	1-1/2 mi	2-1/2	3-2/3
2-1/2	1650	2-1/2	4-2/3	7
4-1/2	1-1/4 mi	3-3/4	7-1/2	12
6-1/4	1-1/3	4-3/4	10	16
12-1/2	1-1/2	7-1/2	18	30
18	1-2/3	9	24	44
31	1-3/4	11	34	67

*An ordinary tungsten bulb rated at 40 watts has a candlepower of about 32, and a 100-watt tungsten bulb has a candlepower of about 100; a 1000-watt mercury-xenon lamp has an output of 52,000 lumens or a candlepower of $52{,}000/4\pi = 4100$ candles.

THE SPECTRUM

Factors which limit the range in one wavelength region can often be neglected in other regions; therefore an examination of the spectrum will be made, starting at the shorter wavelengths in the ultraviolet.

Different portions of the spectrum are usually assigned names as a matter of convenience. One classification is the following: far ultraviolet below 2000A, middle ultraviolet from 2000A to 3000A, near ultraviolet from 3000A to 4000A, and visible region from 4000A to 7000A.

Far Ultraviolet

Only a brief discussion is needed to dispense with the far ultraviolet region. The air is so opaque at these wavelengths, even over a path length of a few meters, that communication is unlikely. Only in the upper atmosphere, where the absorption by ozone and other gases is small, would use of these wavelengths be practical. For example, up to a height of 12 km the radiation from the sun at wavelengths below 2900A is negligible because of the absorption by atmospheric gases. This is illustrated by Fig. 2, which shows the spectral absorption coefficient of oxygen to be 100 cm^{-1} base e at 1300A and 1 cm^{-1} base e at 1800A. At the peak value, where the absorption coefficient is 480 cm^{-1}, radiation in passing through 1 cm of oxygen is reduced to 1.7×10^{-12} of its original value.

Other gases also absorb strongly in the far ultraviolet. Nitrogen has weakbands at 1000A to 1450A and strong absorption from 800A to 1000A. Water vapor has an absorption continuum from 1435A to 1860A.

The data for Fig. 2 were obtained (4) by measuring the transmissions of very pure samples of oxygen and ozone at STP. When these graphs in Fig. 2 are used, it is necessary to determine the total amount of gas present over the path length.

The atmosphere is approximately 21 percent oxygen; therefore the attenuation coefficient for oxygen is obtained by taking 0.21 of the value obtained from the graph and multiplying by the path length in the same units for which the constant is given.

Since the amount of ozone in the atmosphere is variable, the total amount in a horizontal path is not so easily determined. This is discussed in more detail in following paragraphs.

Middle and Near Ultraviolet

The middle and near ultraviolet regions, that is wavelengths lying roughly between 2000A and 4000A, will be examined next.

Absorption by Ozone – A plot of the absorption coefficients for the most absorbing gases has been prepared from data in the Handbook of Geophysics (4) and is shown in Fig. 2. It will be noted that the peak absorption due to ozone occurs at 2553A and has a value of about 325 cm^{-1}. In order to determine the attenuation coefficient per km over a horizontal path it is necessary to know the amount of ozone in the atmosphere at the surface of the earth. The amount is variable, ranging from 0 to 0.02 parts per million (ppm) in the winter and from 0 to 0.07 ppm in the summer (5). Dobson (6) has collected data from many parts of

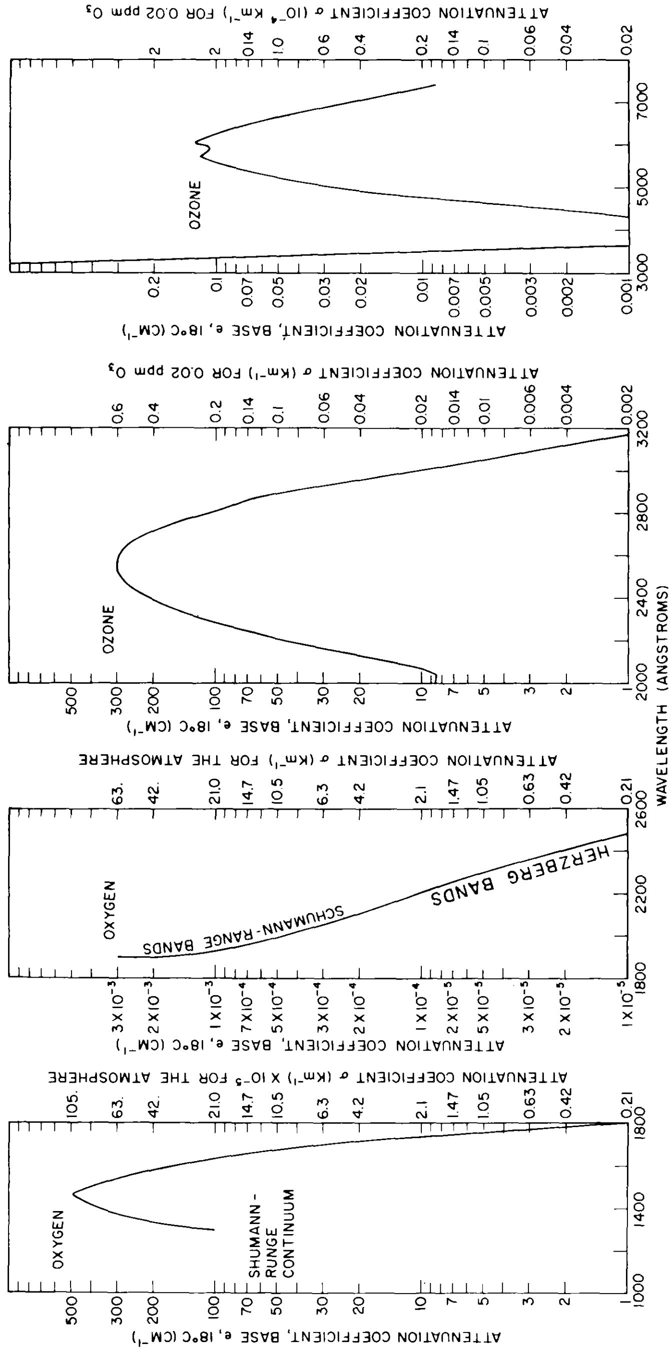

Fig. 2 – Absorption coefficients of oxygen and ozone

the world on the amount of ozone at various altitudes and climatic conditions. It has been determined that the greatest annual variations occur at high latitudes and that in general the amount of ozone varies inversely with pressure, temperature, and density of the air.

Absorption by Oxygen – Oxygen, a strong absorber in the far ultraviolet has relatively weak absorption bands in the middle ultraviolet. These are the Herzberg bands from 2400A to 2600A as shown in Fig. 2.

Absorption by Other Gases – Nitrogen transmits freely from 1450A to the visible. Carbon dioxide absorbs weakly in the region 2000A to 3000A. Sulfur dioxide absorbs strongly from 2700A to 3160A, but there is usually very little SO_2 present. Nearly all the rest of the atmospheric gases occur in fixed amounts and have neglibible absorption in the region 2000A to 3200A.

Experimental Data on Horizontal Attenuation

All of the factors pertaining to atmospheric attenuation discussed so far have been of a relatively constant nature, permitting the attenuation coefficient to be calculated for any given wavelength. This is not strictly true where ozone absorption is involved; however, the maximum attenuation can be determined from the maximum amount of ozone present of 0.07 ppm.

Dunkelman, Stewart, et al. have measured the horizontal attenuation of ultraviolet and visible light by the lower atmosphere at night in city, desert, and sea atmospheres under conditions ranging from fog to exceptionally clear air. Their results indicate that when visibility is poor the attenuation coefficient may be 100 times the value for pure air.

Figure 3 roughly summarizes the data from Dunkelman's (7) report in that it shows the maximum and minimum values of attenuation obtained during these measurements. The flat portion of the curve between 3000A and 4500A, due to scattering by fog, would probably have extended through the whole spectrum had data been taken at all wavelengths.

Fog particles are reported by meteorologists to have radii of about 10μ to 100μ. Since their diameters are always larger than any wavelength in the region 2000A to 7000A, it is unlikely that any particular wavelength or color of light will penetrate fog better than any other wavelength or color.

OPTICAL MATERIALS AND FILTERS FOR THE ULTRAVIOLET

Optical materials are usually categorized according to their index of refraction, transmittance, and absorbance or density. Transmittance is usually expressed in percentage, not corrected for surface reflection. That is, if a plate has a transmittance of 90 percent and 4 percent reflection from the front and rear surfaces, the total energy transmitted is 82 percent. Transmittance is defined as the ratio of the radiant power transmitted by a sample to the radiant power incident when the incident beam consists of parallel radiation normal to the surface of the sample. Density (absorbance) is the logarithm to the base 10 of the reciprocal of the transmittance.

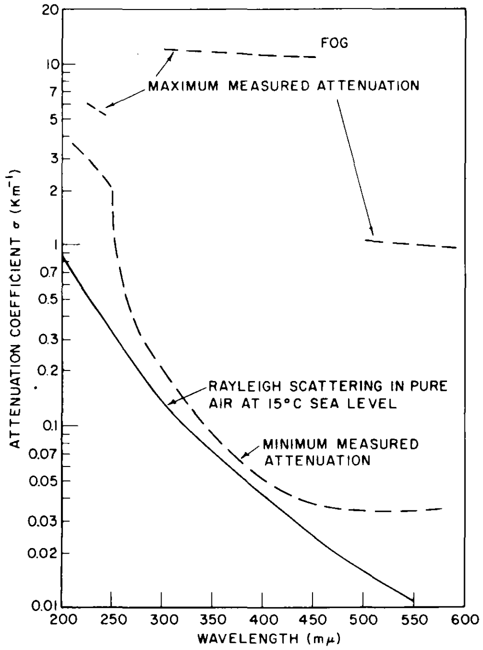

Fig. 3 - Atmospheric attenuation coefficients measured by Dunkelman, Stewart, et al. (7)

The transmission of a sample varies with its thickness in accordance with the equation

$$\frac{I}{I_o} = e^{-\alpha t}. \tag{6}$$

Types of Filters

Filters can be classified according to their construction or mode of operation. The most common types include solution filters, colored glasses, gelatin stained with dyes, and interference filters. Other types are the selective reflection filter, scattering filter, polarization filter, and refraction filter. Characteristics of the filters are transmittance, reflection, sharpness of cutoff, bandwidth, leakage outside the passband, and possibly angular field of view.

Glasses

The ability of glass to transmit ultraviolet is determined largely by its iron content. Amounts as small as 0.01 percent occurring as impurities affect the transmission of the glass.

Ordinary window glass 1 mm thick is practically opaque to wavelengths shorter than 3000A (8). Table 3 gives the value of the absorption coefficient of window glass for several wavelengths. Using these values of α , the curves of Fig. 4 were drawn for two thicknesses of window glass.

Pyrex (the trade name for a borosilicate glass made by Corning Glass Co.) is heat and chemical resistant and has much better transmission properties than ordinary window glass.

Table 3
Absorption Coefficient of Window Glass

Wavelength (Angstroms)	α (cm^{-1})
3150	7.6
3200	5.0
3400	1.29
3600	0.45

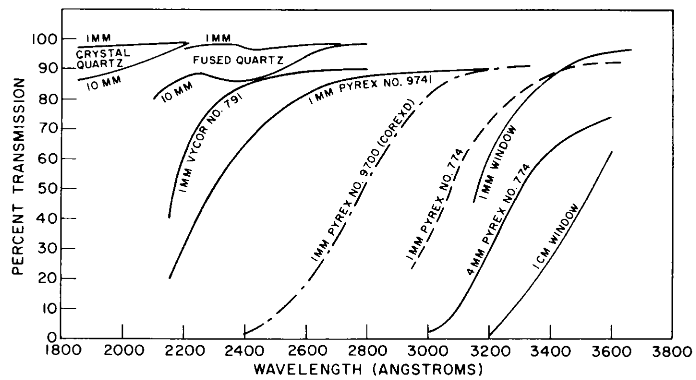

Fig. 4 – Transmission of various types and thickness of materials

Referring to Fig. 4, it is seen that Pyrex glass No. 774 transmits at much shorter wavelengths than window glass, dropping to 30-percent transmission at about 3000A.

Other Pyrex type glasses suitable for ultraviolet transmission are Corex D, Pyrex No. 9741, and Vycor No. 791. Corex D is useful for bulbs on sunlamps as it transmits the erythema or sun tanning wavelengths which are most effective at about 2967A while cutting out the less desirable germicidal mercurcy line at 2537A. The most effective wavelength for germicidal effectiveness is 2600A, dropping to very little bactericidal action at 3200A.

The Vycor glasses approach silica in their properties but can be fabricated at lower temperatures than quartz. A curve for 1-mm-thick Vycor No. 791 is shown in Fig. 4.

Quartz

Quartz, both fused and crystal, transmits in the far ultraviolet region. However, as can be seen from Fig. 4, crystalline quartz has higher transmission than fused quartz.

Crystals

The halides which transmit well in the infrared region also transmit well in the ultraviolet. Calcite ($CaCO_3$), fluorite (CaF_2), and rock salt (NaCl) are often used in optical instruments for ultraviolet. A thickness of several centimeters of fluorite, for example, has 50-percent transmission at 1860A. The absorption coefficients for wavelengths from 1860A to 2800A are given in Table 4 as listed by Koller (8).

Table 4
Absorption Coefficients for Calcite, Fluorite, and Rock Salt

Substance	Wavelength (Angstroms)	Absorption Coefficient (cm^{-1})	Thickness for 50% Transmission (cm)
Fluorite	1860	0.22	3.15
Calcite	2150	3.36	0.21
	2300	1.25	0.56
	2400	0.58	1.20
	2500	0.40	1.73
	2600	0.29	2.39
	2700	0.20	3.46
	2800	0.16	4.33
Rock Salt	1860	0.36	1.93
	2100	0.26	2.67
	2310	0.15	4.62
	2800	0.046	15.1

Glass Filters

A large number of glass filters are commercially available with transmissions of 30 to 90 percent in portions of the ultraviolet region. Many of these also have some transmission in the visible and infrared regions. The transmission of a number of colored glasses manufactured by several companies is listed in the Handbook of Chemistry and Physics (9).

The transmission of several ultraviolet transmitting glass filters manufactured by Corning Glass Works is shown in Fig. 5. The only one having no transmission in the visible

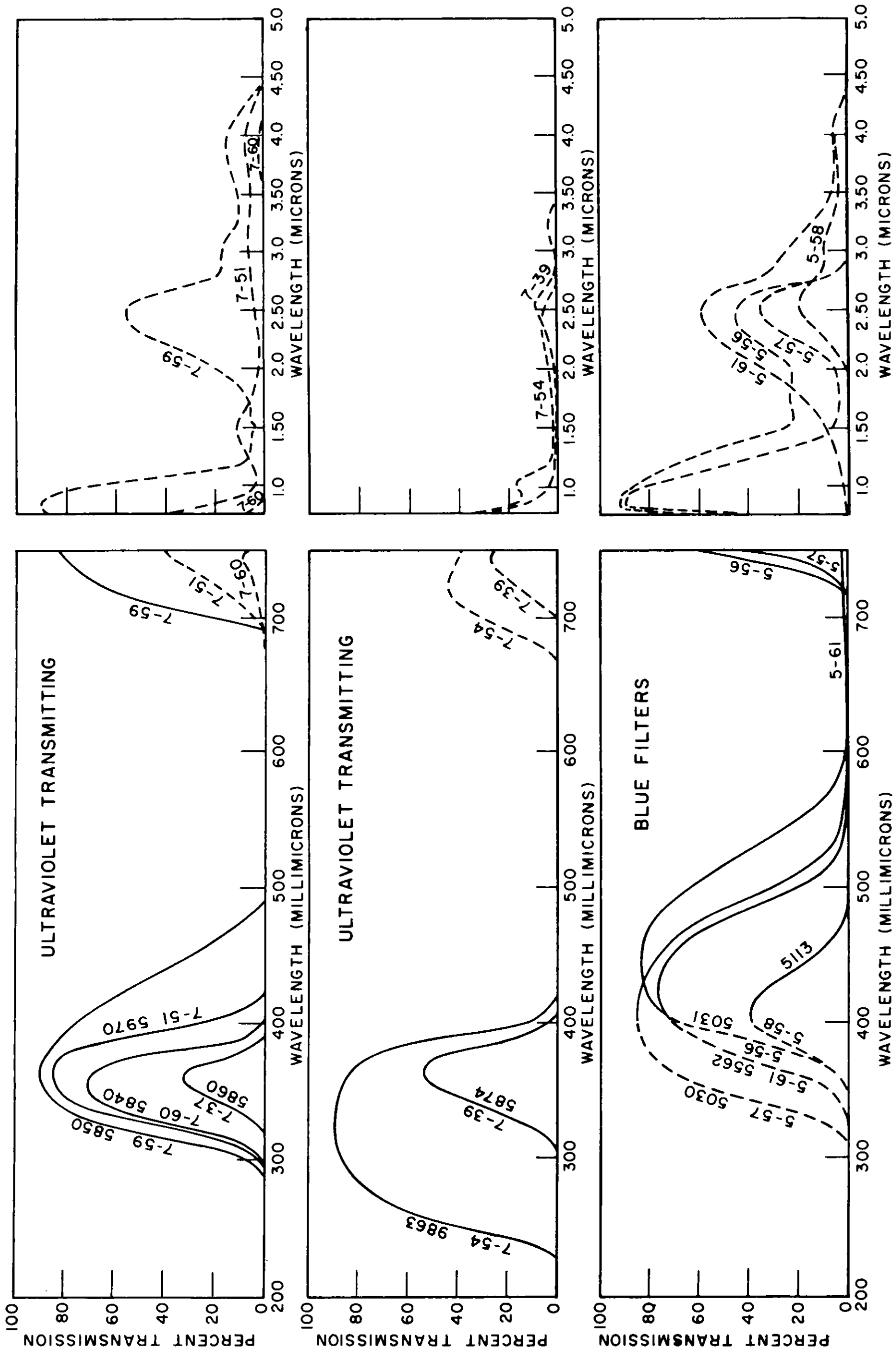

Fig. 5 - Ultraviolet transmitting glasses (Corning Glass Works)

is 7-37. Its transmission in the ultraviolet lies between 3200A and 3900A. A filter used frequently for ultraviolet work is the 7-54, which transmits from about 2300A to 4200A. However, it will be noted that it also transmits in the visible region. The dashed portions of the curves indicate that there is no control of the transmission in these regions. Number 7-54 is not resistant to heat shock, however, and is affected some by atmospheric conditions.

Transmission of Water

Although water alone might not be used as an ultraviolet filter, it could be used as a vehicle for other materials. Therefore its transmission is considered in this section.

Hulburt (10-12) found that the absorption coefficients for extremely pure water were more than 10 times those calculated due to scattering. Figure 6 shows the absorption coefficients for pure water in the region 2000A to 7000A.

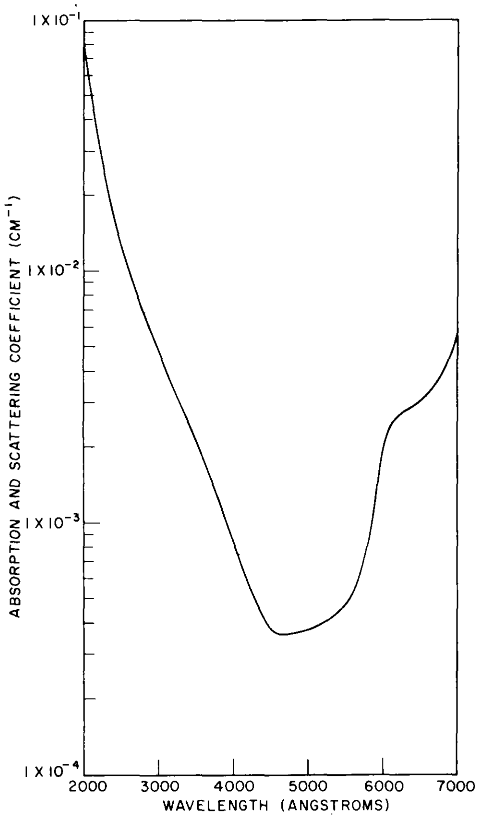

Fig. 6 - Ultraviolet absorption coefficients of water

The transparency of pure water in the near ultraviolet region is shown by Fig. 7, which is a plot of the transmission of 10 cm and 100 cm of water using the absorption coefficients of Hulburt.

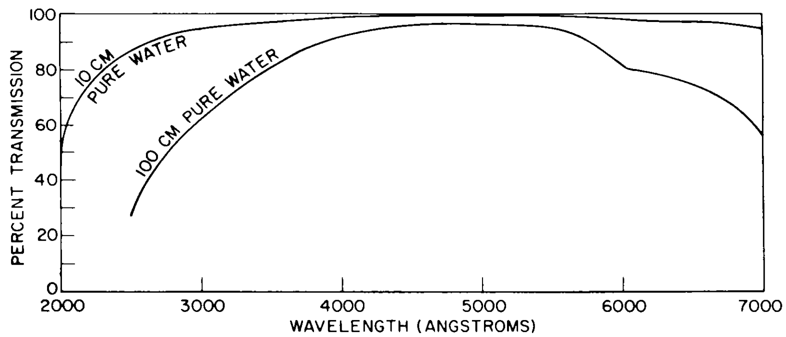

Fig. 7 – Transmission of pure water

Plastics

The spectral transmission of several common plastics is shown in Fig. 8. These are all of different thicknesses, and this should be taken into account when comparing their transmittance. For example, compare the calculated transmission of a 0.003-inch thickness of Saran (vinylidene chloride) with the measured transmission of a 0.003-inch thickness of polyethelene at 2500A. From Fig. 8 the transmission of a 0.0005-inch-thick sample of Saran is 80 percent. From Eq. (6) the transmission of a 0.003-inch thickness of Saran is found to be 44.5 percent, which is very close to the measured value of 46 percent shown in Fig. 8 for polyethelene.

Chemical Solutions

The absorption of various chemical substances can be found by reference to the International Critical Tables (13).

Kasha (14) found that a 5-cm optical path of an aqueous solution containing 240 grams per liter of $NiSO_4 6H_2O$ and 45 grams per liter of $CoSO_4 7H_2O$ would transmit 50 percent of the incident radiation between 2400A and 3200A, as shown by curve A in Fig. 9. Not shown is a hump of 1.5 percent peaked at 5700A. Potassium chromate (curve B) has a good transmission maximum at 3130A, the wavelength of a strong group of mercury lines.

Cupric sulfate is useful for removing the infrared in conjunction with filters which separate the ultraviolet and visible. Its transmission is shown by curve A in Fig. 10. In this same figure, curve B shows the combination of a Corning 7-54 filter with a cupric sulfate cell for removing the infrared and visible.

Cation-X (2,7-dimethyl-3,6-diazocyclohepta-1,6-diene perchlorate) in polyvinyl alcohol films is used to eliminate long-wavelength response. The absorbance of films of polyvinyl alcohol incorporating cation-X are reproduced in Fig. 11 from Ref. (15).

Miscellaneous Filters

McBride and Olsen (15) have summarized the present state of the art in optical materials and have included a good list of references on this subject. They have a very good summary on the preparation of chemical filters such as nickel sulfate hexahydrate crystals and on alkali metals.

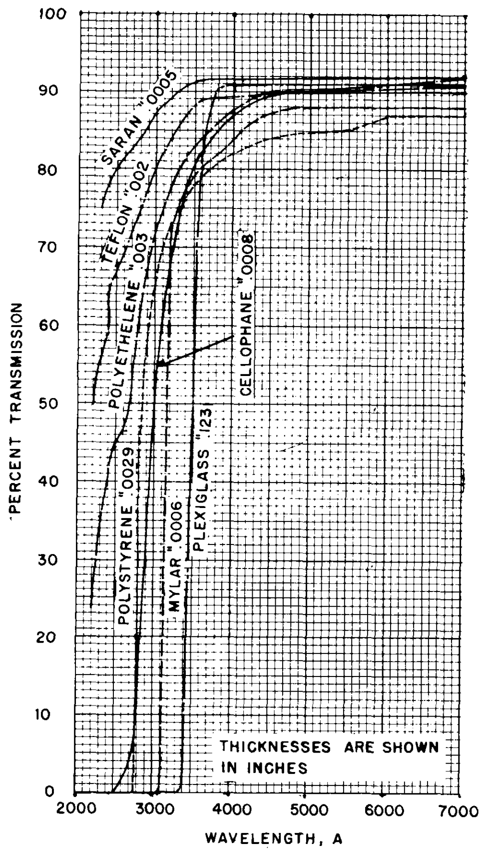

Fig. 8 – The spectral transmission of some common plastics

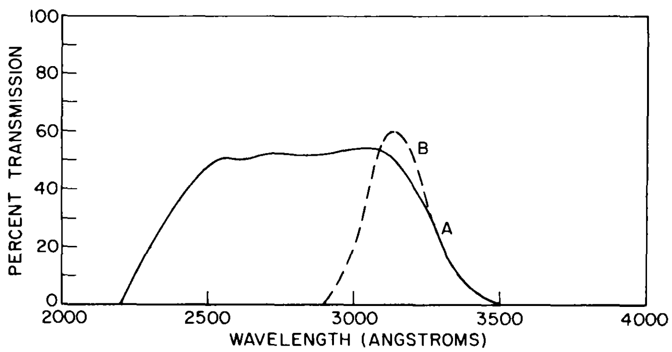

Fig. 9 – Transmission of a 5-cm path of (A) $NiSO_4 6H_2O$ and $CoSO_4 7H_2O$ and (B) potassium chromate

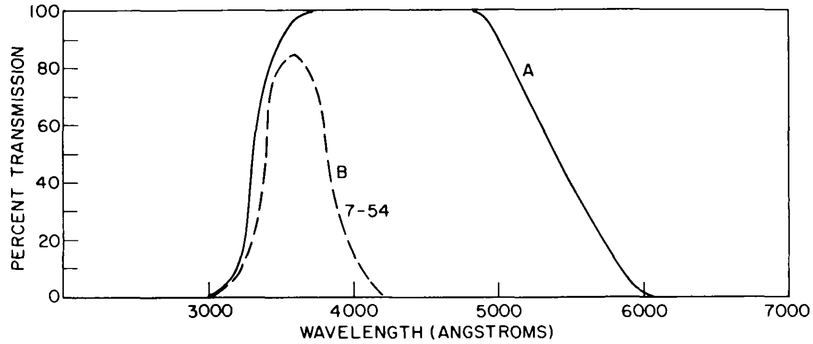

Fig. 10 - Transmission of (A) cupric sulfate and (B) cupric sulfate plus glass filter 7-54

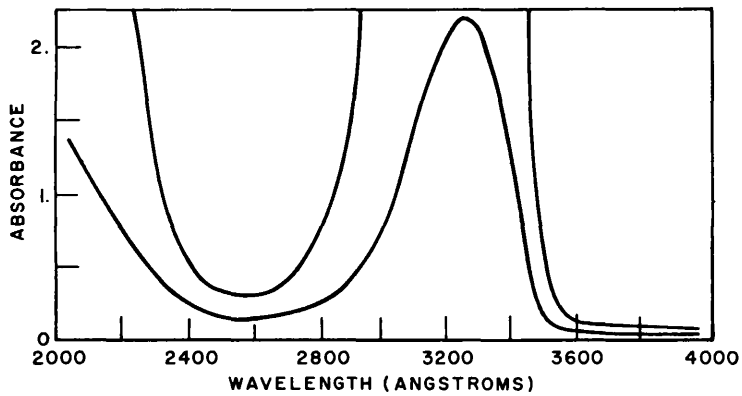

Fig. 11 - Absorbance of films of polyvinyl alcohol incorporating cation-X

The "G" filter was developed by White (16) to exclude all visible light from a gallium arc lamp. This filter consists of a sandwich of nickel sulfate sorbital complex between a plate of polished fused silica and a plate of Corex 9863. A thickness of 3.5 mm of the complex and 3.5 mm of the Corex has a transmission of 65 to 74 percent in the region 2800A to 3000A, where the gallium lines are strong. The nickel sorbital complex was developed to obtain a solid filter with the characteristics of nickel sulfate in water.

Interference Filters

Interference filters may either transmit or reflect light over a narrow spectral range. A transmission filter consists of two highly reflecting semitransparent metal films separated by a spacer. The separation of the films, (which is half a wavelength or a multiple thereof) determines the wavelength of the passband. A first-order filter has a separation of half a wavelength and a bandwidth, between wavelengths where the transmission is half the maximum, of less than 200A (17). A second-order filter has a bandwidth of less than

100A. Transmission values at the peak vary from 30 to 50 percent. Interference filters are available through the region from 2400A to 12,000A. They are also available with the transmission at the undesired order blocked out.

Figure 12 from Ref. 17, shows the response of a typical first-order filter designed for maximum transmission at 6490A. The manufacturing tolerance is ±150A and the half-width a maximum of 200A. Figure 13, from Ref. 17, is a spectrophotometric curve of a typical second-order filter for 5460A having a half-width of 70A. Note that the first-order filter has 29-percent transmission in the ultraviolet at 3460A and the second-order filter has third-order transmission of 35 percent at 3780A. When the undesired orders are not blocked out, these filters can, of course, be used as narrow-band filters at any of the orders which are transmitted.

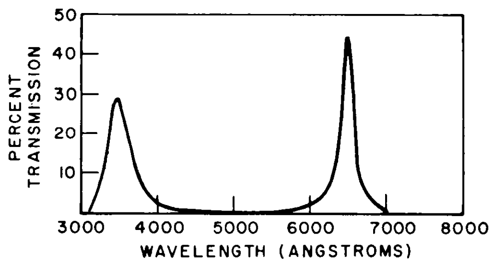

Fig. 12 - Transmission of a first-order interference filter

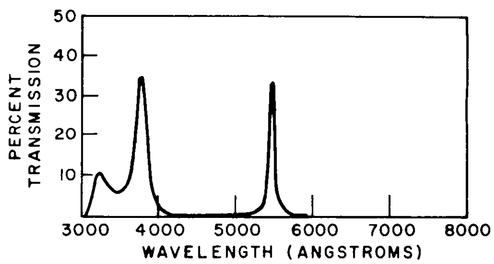

Fig. 13 - Transmission of a second-order interference filter

When the angle of incidence of the radiation is not normal to the filter the passband shifts to shorter wavelengths. Also the passband becomes a doublet with increasing separation as the angle of incidence is increased. A first-order filter peaked at 6500A will have doublets at about 6050A and 6250A when the angle of incidence becomes 30 degrees. A second-order filter might, for example, have doublets which are shifted from a single peak at 6500A for an incident angle of 30 degrees, to 5150A and 5450A at 60 degrees.

DETECTORS FOR THE ULTRAVIOLET

Detectors for the ultraviolet include thermocouples, photocells, ionization chambers, chemical reactions, and photographic plates.

Photographic Films and Plates

Photographic processes are most useful when it is desired to record the spectral characteristics of a source or signal and a suitable spectrometer is available.

Photographic techniques might be used during the development of a communications system, but it is not likely that they will be used in the final system discussed in this report. Therefore, no further discussion is necessary. Reference 18 contains information on the characteristics of ultraviolet sensitive films.

Thermocouples

Thermocouples and bolometers are useful for making absolute measurements over a wide range of wavelengths. The receiving element of a thermocouple, thermopile, or bolometer can be blackened so that it will have uniform response over any desired region.

The response time of a wide-spectral-range thermocouple is in some cases as long as a second or more. The sensitivity is also poor compared to many other types of detectors such as phototubes. Havens (19) predicted that the ultimate sensitivity or minimum detectable power of a thermocouple or bolometer is about $\Delta P_{min} = 3 \times 10^{-12} A^{1/2} \tau^{-1}$ watts, where A is the area in mm^2 and τ is the time constant in seconds. This sensitivity is approached within a factor of 2 to 3 in practice with some thermal devices designed for specific applications.

When compared with the sensitivity of a multiplier phototube of 10^{-14} watts (20,21), the best thermopiles are about 10,000 times less sensitive and have a much longer response time.

Phototubes

Phototubes and multiplier phototubes operate at wavelengths of a few hundred angstroms up through the near infrared depending on the type of window material and the cathode material. A technique, analogous to overcoating of photographic plates, can be used whereby the incoming radiation causes the receiver to fluoresce, emitting light to which the phototube is sensitive.

The efficiency of detectors can be given in terms of the quantum efficiency, that is, the number of electrons "generated" or emitted by a detector per photon impinging on it. Figure 14 shows the quantum efficiencies for a number of photosensitive cathodes (reproduced from a chart by International Telephone and Telegraph Co., Fort Wayne, Indiana). The spectral response of the surfaces is also shown in units of amperes per watt.

An idea of the sensitivity of a photo detector can be gained by first assuming that each quantum releases one electron. In this case

$$\frac{\text{amperes}}{\text{watt}} = \frac{10^7 e\lambda}{hc} \approx 8 \times 10^{-5}\lambda \tag{7}$$

where e is the electronic charge, 1.602×10^{-19} coulomb, λ is the wavelength in angstroms, h is Planck's constant, 6.625×10^{-27} erg sec, and c is the velocity of light, 2.99×10^{18} angstroms/sec. Before the photoelectric effect can take place, the photon must impart enough energy to the electron to overcome the work function of the photo surface. The resulting quantum yields are the order of 1 to 12 percent for the common surfaces, as shown on Fig. 14.

The advantage of multiplier phototubes over diode phototubes is mainly the reduction of noise obtainable with a multiplier type compared to that of a phototube and an amplifier. The current amplification of tubes with nine and ten dynode stages is from about 10^5 to 2×10^6.

The equivalent noise input of a phototube is the incident flux which when modulated in a stated manner produces an rms output current equal to the rms noise current within a

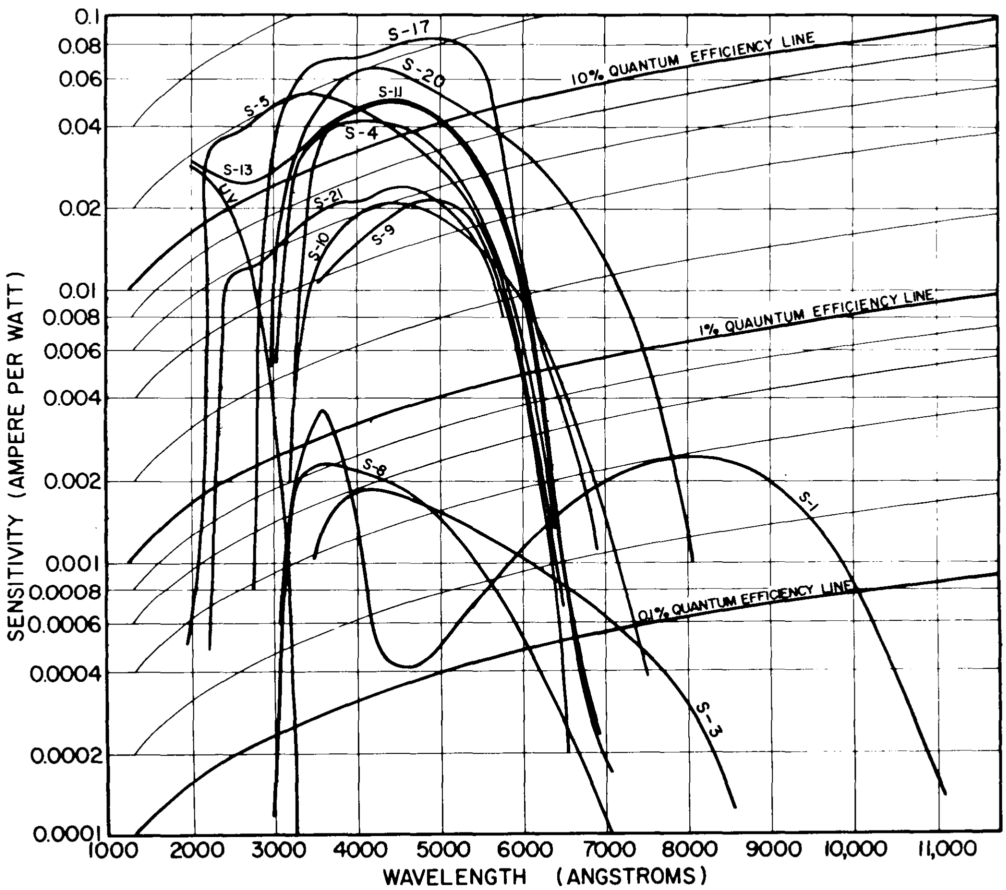

Fig. 14 - Photosensitive cathodes

specified bandwidth. For a 1P28 multiplier phototube, which has an S-5 response and nine stages, the equivalent noise input is 7.5×10^{-13} lumens with a square wave modulated source at 2870°K and a 1-cycle-bandwidth amplifier. When monochromatic radiation at 2537A is used in the measurement (in place of the 2870°K tungsten source), the equivalent noise input is 8×10^{-16} watts. This is about what one would expect, since a lumen is 0.00147 watt at the peak sensitivity of the eye, near 5600A, and the 1P28 is slightly more sensitive in the middle ultraviolet.

The signal-to-noise can be improved by a factor of 100 by cooling the tube with liquid air.

Having determined that the minimum detectable signal for a 1P28 multiplier is about 8×10^{-16} watts, we might wish to know the magnitude of the output signal for a given amount of radiation. Referring to the data sheet for this tube one finds that with 1000 volts distributed equally (100 volts each) between the cathode and first dynode, between each succeeding dynode stage, and between the dynode and anode, the sensitivity to radiation at 3400A is 61,800 μamp/μwatt.

This figure can also be determined approximately by multiplying the cathode sensitivity by the current amplification. For the 1P28 the cathode sensitivity is 0.05 μamp/μwatt and the gain is 1.25×10^6; hence the sensitivity is $0.05 \times 1.25 \times 10^6 = 62{,}500$ μamp/μwatt.

The sensitivity of a type 935 vacuum phototube, which also has an S-5 response, is given as 0.043 μamp/μwatt with 250 volts on the anode. Thus it can be seen that the multiplier tube, besides providing a large output signal with a low noise level, has more efficient coupling between the cathode and dynode than does the diode to its output load resistor by a factor of 0.05/0.043.

For absolute measurements each tube would have to be individually calibrated, since all the values quoted are merely typical of a particular type of tube. In reference to Fig. 14, the S-4, S-5, S-9, S-11, S-17, S-19, and S-21 cathodes are cesium-antimony but the finished tubes vary in the manner in which the cathode is processed, whether it is opaque or semitransparent and the type of envelope material, thereby resulting in the different types of responses.

"Solar Blind" Receivers

Full advantage can not be taken of the high sensitivity of multiplier phototubes when they are used in daylight, since they are easily saturated by the ambient light. This has led to the development of "solar blind" cells for use in the ultraviolet region.

For use in the middle ultraviolet the most promising photocathodes are cesium telluride and rubidium telluride. The curve marked UV in Fig. 14 has this type of cathode. The long-wavelength cutoff of these "solar blinds" is not sharp enough to completely eliminate their response to sunlight at ground levels as evidenced by measurements of Dunkelman, Hennes, and Fowler (22). They found that the radiation at 2537A necessary to give the same signals as full sunlight varied from 6.7×10^{-6} to 1.7×10^{-5} watts/cm^2 for three diode phototubes and one multiplier phototube, all with Cs-Te cathodes.

Photon Counters and Ion Chambers

Photon counters and ion chambers are simple and compact and have great sensitivity. They can be designed for operation at almost any wavelength. The properties of these two types of detectors are reviewed by Friedman (23) and in the literature. Since this report does not cover the far ultraviolet, these detectors will not be elaborated on here.

Chemical Detection

Two chemical methods of detecting ultraviolet radiation have been compared with results obtained with photoelectric methods (24) with good results. Chemical methods are more applicable to experimental work and will not be discussed here.

SOURCES OF RADIATION

Because of the difficulty of generating high power monochromatic radiation in the ultraviolet region the sources discussed in this section include those having considerable output in the visible and infrared regions.

Incandescent Sources

The total radiation at all wavelengths from a heated body is well represented by the Stefan-Boltzmann law,

$$W = \sigma A(T^4 - T_0^4) \tag{8}$$

where $\sigma = 5.67 \times 10^{-12}$ watt cm^{-2} deg^{-4} for a perfect blackbody, A is the area in cm^2, T is the absolute temperature of the radiator, and T_0 is the absolute temperature of surroundings. It is easily verified that as the temperature of the body is raised the radiated energy increases at a rapid rate because of the fourth-power relation

The spectral distribution of energy from a true blackbody can be determined from Planck's formula,

$$E_\lambda = \frac{C_1}{\lambda^5\left(e^{C_2/\lambda T} - 1\right)} \tag{9}$$

where C_1 is determined by the units and incremental bandwidth desired and is equal to 1.177×10^{-12} watts per cm^2 per unit solid angle per cm interval.

To convert C_1 to other conditions use the form (25)

$$C_1 = \text{constant} \times \frac{(\text{wavelength})^5 \times \text{power}}{\text{area} \times \text{wavelength interval}}.$$

Thus, for the radiation from one side of a surface of a 1-cm-area blackbody with the wavelength expressed in microns and the wavelength interval equal to 0.1μ,

$$C_1 = \frac{1.177 \times \pi \times 10^{-12} \times (10^4)^5 \text{ watts}}{\text{cm}^2 \times 10^5} \tag{10}$$

$$= 3.697 \times 10^3 \text{ watts cm}^{-2} \text{ per } d\lambda \text{ of } 0.1\mu. \tag{11}$$

Since $C_2 = 1.432$ cm deg, then if wavelength is expressed in microns, C_2 would become 14,320 μ deg.

The solid curve of Fig. 15 shows the radiation from a 3000°K blackbody. It will be noted from the other curves on this figure that as the temperature is lowered the total output drops and the peak of the curve shifts to longer wavelengths. The peak radiation occurs at a wavelength determined by the equation

$$\lambda T = 2890 \ \mu \text{ deg.} \tag{12}$$

For the 3000°K source the peak radiation occurs at 0.963μ and for the 1000°K at 2.89μ, both in the infrared region.

By using Planck's equation, or more conveniently, by use of tables prepared by Lowan and Blanch (26), the percent of energy in any spectral interval can be determined. With a 3000°K source only 0.2 percent of the total energy lies in the ultraviolet region between 0A and 4000A. About 8 percent is in the visible, and the remainder is at longer wavelengths.

Typical operating temperatures of common types of incandescent lamps are listed by Koller (8). The highest operating temperature of a standard lamp is 2990°K for a 1000-watt

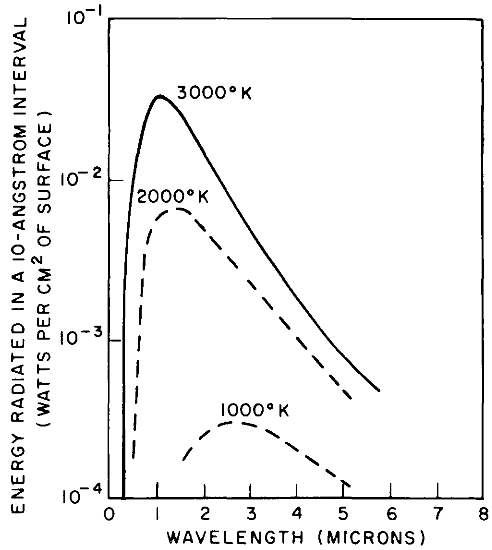

Fig. 15 - Blackbody radiation from sources at temperatures of 1000°K, 2000°K, and 3000°K

bulb. The total ultraviolet output is 3.27 watts or 0.33 percent. Between wavelengths of 3800A and 7600A, the visible region, the output is 185 watts.

Mercury Arc Lamps

Mercury arcs provide a fairly efficient means of generating ultraviolet radiation because of the large number of short-wavelength lines in the mercury spectrum. Table 5 lists the ultraviolet emission lines of mercury. There are several strong mercury arc lines in the visible, at wavelengths longer than these, which are not listed in the table.

Mercury arcs are characterized as being low pressure or high pressure, and although all the mercury lines are present in all mercury arcs, the strength depends on the pressure, which is in turn a function of temperature.

Typical high-pressure ac operated mercury arc lamps are the Uviarc and GE H-4. When the Uviarc is operated with 560 watts input, the output at wavelengths less than 3800A is 118.6 watts. Table 6, compiled from data on p. 38 of Ref. 8, lists the spectral distribution of energy from the Uviarc. The spectral distribution of energy for a 250-watt (UA-2) Uviarc lamp is also given in Ref. 8. The spectrum is similar to that in Table 6.

The Uviarc lamp has a thermionic cathode for starting the arc and to make ac operation possible. Rather than having an excess pool of mercury, a limited amount is used so that it is completely ionized in operation. This makes the pressure relatively insensitive to ambient temperature changes.

Mercury Vapor Sunlamps

A sunlamp, as its name implies, is one whose output resembles that of the sun on a clear day. Since they are used primarily for an erythemal reaction, the output below 2800A is filtered out. The S-1, 400-watt sunlamp radiates 7.7 watts between 2800A and 3800A and 45 watts in the visible region between 3800A and 7600A.

Table 5
Ultraviolet Emission Lines of Mercury
(Wavelengths in Angstroms)

1269.7	2399.4	3021.50
1527	2482.7	3125.6
1592	2534.8	3131.56
1599	2536	3131.84
1650	2652	3341.48
1677.9	2698.9	3650.15
1783.3	2752.8	3654.83
1798.7	2803.5	3662.87
1849	2847.7	3663.27
1942	2893.6	3906.4
2224.7	2967.28	3983.99
2378.3		4046.56

Xenon and Mercury-Xenon Lamps

High pressure arc lamps of various wattages for operation on ac and dc are also available from Hanovia Chemical and Manufacturing Co. The types listed in their bulletin are given in Table 7.

The energy from these lamps is radiated as both a continuum and as lines. The total radiated power from the 1000-watt mercury-xenon lamp is 480 watts for the spectral range 2000A to 14,000A. Heat from the quartz envelope and the tungsten electrodes accounts for much of the infrared radiation, which extends to about 50,000A. A table of the spectral distribution is shown in Table 8. It is seen from this table that 14 percent of the radiated energy is in the ultraviolet region from 2800A to 4000A, 40.5 percent is in the visible from 4000A to 7000A, and 45.5 percent is in the infrared from 7000A to 14,000A. This ignores a small amount at longer wavelengths. Note that the greatest amount of energy over any small region is radiated by the line spectrum, the strongest one being at 5790A in the visible.

The xenon compact arc is somewhat less efficient than the mercury-xenon arc, having an output of 280 watts for 1000 watts input in the region 2000A to 14,000A. The distribution of energy is much different, as shown in Table 9. Here, only 4.6 percent is in the ultraviolet, 23.8 percent is in the visible, and 71.6 percent is in the infrared region.

Low Pressure Mercury Arc

Mercury arc lamps operated at low pressures radiate the mercury resonance line at 2537A almost to the exclusion of all others. At low pressures the mean free path is longer than at high pressures and the probability that atoms will radiate at the resonant frequency before collision with high energy electrons is large.

Childs (27) has investigated a low pressure mercury arc* as a calibration source. He found that 92 percent of the output originated in the 2537A mercury resonance line. At 1 meter the 2537A irradiance was 3.9 μwatt/cm^2. The irradiance changes less than 2 percent for power supply variations from 105 to 130 volts ac, environmental temperatures of 19.4°C and 26.8°C, and ambient air flows of 11.2 and 14.7 cm/sec. After 16 hours of operation there was no decrease in the output.

*Model 11 SC-1, Black Light Eastern Corp., Port Washington, L. I., N. Y.

Table 6
Distribution of Radiation from a Mercury Vapor Arc in Quartz (Uviarc Lamp)

Wavelength (Angstroms)	Energy Radiated (watts)	Milliwatts/cm^2 1 meter from Arc
6234	1.7	0.017
5700	31	0.31
5460	22	0.22
4960 and 4358	20	0.20
4045 and 3906	17	0.17
3660	35	0.35
3341	3.9	0.039
3130	24	0.24
3025	12	0.12
2967	5.	0.05
2925, 2893, and 2803	4.5	0.045
2752 and 2700	2.8	0.028
2652	8.4	0.084
2571	3.4	0.034
2537	9	0.090
2482, 2400, 2360, and 2300	8.4	0.084
1942 and 1849	2.2	0.022

High Voltage Lamps

Mercury and xenon lamps for experimental studies were described by Dacey and Hodgins (28). The mercury lamp, operating at 6000 volts, 100 ma ac, radiated 6×10^{15} quanta per second at 1850A. The xenon lamp, operating at 5000 volts at 120 ma, also on 60-cps ac, radiated 1×10^{15} quanta per second below 1470A.

Table 7
Hanovia Compact Arc Data

Lamp Type	Dimensions (in.)	Filling	Watts	Volts	Amps	Candles per mm^2	Arc Length (mm)	Lumen Output	Control Number
60 Cycles AC									
510C1	4 × 3/4	Xenon	150	22	8.5	75	3.85	3,000	29100
510B1	4 × 3/4	Xe Hg	225	30	8.5	175	3.85	11,000	29100
507C	7 × 1-3/4	Xenon	800	32	28	160	6.5	24,000	29147
517A	7 × 1-3/4	Argon Hg	1000	65	18	240	6.5	52,000	29148
537B	7 × 1-3/4	Xe Hg	1000	65	18	220	6.5	52,000	29148
DC Arc Lamps									
538C	7 × 1-3/4	Xenon	900	32	28	180	6.5	29,000	29146
528B	7 × 1-3/4	Xe Hg	1000	65	16	220	6.5	52,000	29149

Table 8
Spectral Energy Distribution of Xenon-Mercury Compact Arc Lamps

Spectral Range (Angstroms)	Percent	Lines (if any)
Ultraviolet		
2000 to 2100	0.040	-
2100 to 2200	0.150	-
2200 to 2300	0.227	-
2300 to 2400	0.445	-
2400 to 2500	0.595	2482 Hg
2500 to 2600	0.577	2537 Hg
2600 to 2700	0.803	2652 Hg
2700 to 2800	0.556	-
2800 to 2900	0.766	2804 Hg
2900 to 3000	1.080	2967 Hg
3000 to 3100	1.340	3025 Hg
3100 to 3200	1.880	3130 Hg
3200 to 3300	0.960	-
3300 to 3400	1.210	3341 Hg
3400 to 3500	0.980	-
3500 to 3600	1.020	-
3600 to 3700	3.850	3660 Hg
3700 to 3800	1.000	-
3800 to 3900	0.880	-
3900 to 4000	0.725	-
Visible		
4000 to 4100	2.720	4045 Hg
4100 to 4200	0.670	-
4200 to 4300	0.620	-
4300 to 4400	3.383	4358 Hg
4400 to 4500	0.572	-
4500 to 4600	0.572	-
4600 to 4700	0.540	-
4700 to 4800	0.516	-
4800 to 4900	0.528	-
4900 to 5000	0.723	4916 Hg
5000 to 5100	0.586	-
5100 to 5200	0.644	-
5200 to 5300	0.778	-
5300 to 5400	0.905	-
5400 to 5500	6.780	5461 Hg
5500 to 5600	0.932	-
5600 to 5700	0.912	-
5700 to 5800	8.600	5790 Hg
5800 to 5900	0.800	-
5900 to 6000	0.766	-
6000 to 6100	0.775	-
6100 to 6200	0.775	-
6200 to 6300	0.782	-
6300 to 6400	0.782	-
6400 to 6500	0.786	-
6500 to 6600	0.786	-
6600 to 6700	0.786	-
6700 to 6800	0.820	-
6800 to 6900	0.840	-
6900 to 7000	0.847	-
Infrared		
7000 to 7100	0.835	-
7100 to 7200	0.824	-
7200 to 7300	0.825	-
7300 to 7400	0.825	-
7400 to 7500	0.725	-
7500 to 7600	0.660	-
7600 to 7700	0.627	-
7700 to 7800	0.600	-
7800 to 7900	0.591	-
7900 to 8000	0.592	-
8000 to 8100	0.537	-
8100 to 8200	0.478	-
8200 to 8300	1.500	8256 Xe
8300 to 8400	0.508	-
8400 to 8500	0.506	-
8500 to 8600	0.480	-
8600 to 8700	0.508	-
8700 to 8800	0.511	-
8800 to 8900	1.230	8819 Xe
8900 to 9000	0.977	8952 Xe
9000 to 9100	1.000	9041 Xe
9100 to 9200	1.230	9162 Xe
9200 to 9300	0.512	-
9300 to 9400	0.735	9374 Xe
9400 to 9500	0.482	-
9500 to 9600	0.755	9513 Xe
9600 to 9700	0.480	-
9700 to 9800	0.478	-
9800 to 9900	1.173	9800 Xe
9900 to 10000	1.200	9923 Xe
10000 to 10100	0.462	-
10100 to 10200	2.358	10140 Hg
10200 to 10300	0.453	-
10300 to 10400	0.453	-
10400 to 10500	0.452	-
10500 to 10600	0.528	-
10600 to 10700	0.436	-
10700 to 10800	0.426	-
10800 to 10900	0.417	-
10900 to 11000	0.406	-
11000 to 11100	0.405	-
11100 to 11200	0.405	-
11200 to 11300	1.292*	-
11300 to 11400	0.388	-
11400 to 11500	0.384	-
11500 to 11600	0.379	-
11600 to 11700	0.374	-
11700 to 11800	0.362	-
11800 to 11900	0.358	-
11900 to 12000	0.354	-
12000 to 12100	0.346	-
12100 to 12200	0.342	-
12200 to 12300	0.613†	-
12300 to 12400	0.332	-
12400 to 12500	0.328	-
12500 to 12600	0.322	-
12600 to 12700	0.318	-
12700 to 12800	0.314	-
12800 to 12900	0.308	-
12900 to 13000	0.308	-
13000 to 13100	0.305	-
13100 to 13200	0.301	-
13200 to 13300	0.295	-
13300 to 13400	0.292	-
13400 to 13500	0.290	-
13500 to 13600	1.290‡	-
13600 to 13700	0.287	-
13700 to 13800	0.285	-
13800 to 13900	0.280	-
13900 to 14000	0.278	-

*Hg line 11290 A.
†Hg line 12240 A.
‡Hg line 13670 A.

Table 9
Spectral Energy Distribution of Xenon Compact Arc Lamps

Spectral Range (Angstroms)	Percent	Xe Lines (if any)
Ultraviolet		
2000 to 2100	0.019	-
2100 to 2200	0.026	-
2200 to 2300	0.036	-
2300 to 2400	0.051	-
2400 to 2500	0.064	-
2500 to 2600	0.107	-
2600 to 2700	0.126	-
2700 to 2800	0.149	-
2800 to 2900	0.203	-
2900 to 3000	0.237	-
3000 to 3100	0.236	-
3100 to 3200	0.242	-
3200 to 3300	0.271	-
3300 to 3400	0.287	-
3400 to 3500	0.282	-
3500 to 3600	0.420	-
3600 to 3700	0.452	-
3700 to 3800	0.470	-
3800 to 3900	0.505	-
3900 to 4000	0.540	-
Visible		
4000 to 4100	0.570	-
4100 to 4200	0.617	-
4200 to 4300	0.641	-
4300 to 4400	0.660	-
4400 to 4500	0.669	-
4500 to 4600	0.752	4501, 4525
4600 to 4700	0.925	4624
4700 to 4800	0.809	4734
4800 to 4900	0.752	4929
4900 to 5000	0.738	4923
5000 to 5100	0.718	-
5100 to 5200	0.738	-
5200 to 5300	0.720	-
5300 to 5400	0.718	-
5400 to 5500	0.694	-
5500 to 5600	0.682	-
5600 to 5700	0.668	-
5700 to 5800	0.727	-
5800 to 5900	0.807	-
5900 to 6000	0.835	-
6000 to 6100	0.875	-
6100 to 6200	0.882	-
6200 to 6300	0.892	-
6300 to 6400	0.897	-
6400 to 6500	0.935	-
6500 to 6600	0.935	-
6600 to 6700	0.973	-
6700 to 6800	0.975	-
6800 to 6900	0.978	-
6900 to 7000	0.985	-
Infrared		
7000 to 7100	0.980	-
7100 to 7200	0.945	-
7200 to 7300	0.863	-
7300 to 7400	0.867	-
7400 to 7500	0.877	-
7500 to 7600	0.848	-
7600 to 7700	0.830	-
7700 to 7800	0.823	-
7800 to 7900	0.791	-
7900 to 8000	0.614	-
8000 to 8100	0.622	-
8100 to 8200	0.854	-
8200 to 8300	2.026	8231, 8280
8300 to 8400	0.900	8346
8400 to 8500	1.070	8409
8500 to 8600	0.573	-
8600 to 8700	0.588	-
8700 to 8800	0.646	-
8800 to 8900	1.110	8819
8900 to 9000	2.780	8952
9000 to 9100	1.700	9045
9100 to 9200	2.410	9162
9200 to 9300	0.652	-
9300 to 9400	2.680	9374
9400 to 9500	0.712	-
9500 to 9600	2.920	9513
9600 to 9700	0.720	-
9700 to 9800	0.750	-
9800 to 9900	2.460	9800
9900 to 10000	4.210	9923
10000 to 10100	0.980	-
10100 to 10200	0.918	-
10200 to 10300	0.809	-
10300 to 10400	0.848	-
10400 to 10500	0.930	-
10500 to 10600	0.923	-
10600 to 10700	0.887	-
10700 to 10800	0.897	-
10800 to 10900	0.995	-
10900 to 11000	1.000	-
11000 to 11100	1.045	-
11100 to 11200	0.995	-
11200 to 11300	0.940	-
11300 to 11400	0.899	-
11400 to 11500	0.781	-
11500 to 11600	0.754	-
11600 to 11700	0.733	-
11700 to 11800	0.738	-
11800 to 11900	0.773	-
11900 to 12000	0.892	-
12000 to 12100	0.867	-
12100 to 12200	0.771	-
12200 to 12300	0.698	-
12300 to 12400	0.683	-
12400 to 12500	0.669	-
12500 to 12600	0.691	-
12600 to 12700	0.697	-
12700 to 12800	0.718	-
12800 to 12900	0.788	-
12900 to 13000	0.798	-
13000 to 13100	0.713	-
13100 to 13200	0.648	-
13200 to 13300	0.618	-
13300 to 13400	0.616	-
13400 to 13500	0.612	-
13500 to 13600	0.610	-
13600 to 13700	0.608	-
13700 to 13800	0.605	-
13800 to 13900	0.590	-
13900 to 14000	0.578	-

The Gallium Lamp

White (16) described in detail the construction of a gallium arc lamp with a large percentage of the output in the ultraviolet. The lamp is filled with pure gallium iodide and a gas mixture consisting of 20 mm of argon and 5 mm of neon. It is energized from a transformer having an open circuit voltage of 1500 volts and operates with a current of about 25 ma.

The spectral distribution of the energy radiated by the lamp is listed in Table 10. The gallium arc lines are also shown in this table. The most intense lines in the ultraviolet are at 2874A, 2943A, and 2944A. The most intense lines radiated are at 4032A and 4172A.

Table 10
Spectral Distribution of Energy from a
Gallium Arc Lamp

Wavelength Band (Angstroms)	Milliwatts/Steradian	Gallium Arc Lines
2448 to 2472	0.3	2450
2472 to 2498	0.1	
2498 to 2524	0.5	2500
2524 to 2550	1.5	
2550 to 2607	0.0	
2607 to 2639	0.8	
2639 to 2671	0.5	2659
2671 to 2705	0.04	
2705 to 2741	0.7	2719
2741 to 2854	0.0	
2854 to 2897	4.7	2874
2897 to 2921	0.2	
2921 to 2968	9.1	2943 2944
2968 to 3018	0.03	
3018 to 3601	0.0	
3601 to 3696	0.07	
3696 to 3798	0.02	
3798 to 3909	1.2	3872
3876 to 3989	6.1	
3989 to 4110	19.1	4032
4110 to 4244	18.1	4172
4244 to 4391	0.08	
4391 to 5232	0	
5232 to 5512	0.07	5360
5512 to 5835	0.02	
5835 to 6215	0	
6215 to 6672	0.07	
6672 to 7210	0.05	
7105 to 7760	0.2	
7760 to 8545	0.6	
8848 to 9418	0.5	

When this lamp is covered by a "G" filter (16), it is invisible to the unaided eye beyond 5 to 10 yards. With a 2-inch or a 5-inch metascope using ultraviolet phosphor buttons it can be seen clearly at 1 mile and possibly 2 miles on an average clear night (atmospheric transmission 40 percent per mile (16)).

The Magnesium Spark

Intense pulses of ultraviolet radiation can be generated in the magnesium high voltage spark. A high voltage is discharged between magnesium electrodes in air, carbon dioxide, or other gases. Either ac or dc operation is feasible. The output from the magnesium spark consists mainly of the four lines 2791A, 2796A, 2798A, and 2803A.

The Carbon Arcs

By using specially cored carbons, high intensity outputs in the ultraviolet region are attainable with carbon arcs. Figure 16 shows the spectral distribution of energy from a carbon arc using cored carbons designated as U-carbon*. This arc was operated from an ac source and drew 60 amperes with 50 volts across the arc. Both ac and dc operation of the carbon arc is possible. With dc operation, only the positive carbon is cored.

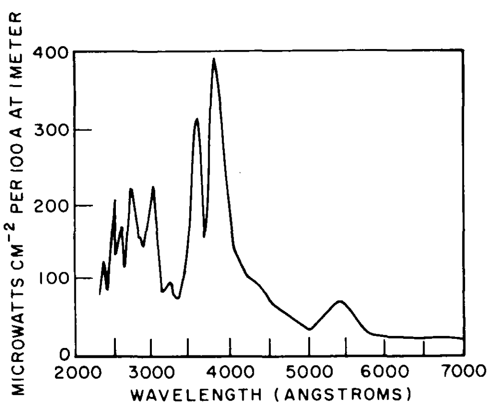

Fig. 16 - Spectral distribution of energy from a carbon arc with U-carbon electrodes

Gaseous Discharges

A unique type of gas discharge lamp (29) was developed at Northwestern University for use in a pulsed-time modulation system. Tubes filled with nitrogen at approximately 10 mm Hg emitted the second positive nitrogen bands. Flash durations were the order of 0.1 microsecond at repetition rates up to 100,000 per second. Both internal and external electrodes were used. Atube filled with 10 mm Hg tank nitrogen and flashed with 8 kv at 4 ma emits band spectra from about 2200A to 5000A. Special circuits were required to prevent the discharge from being continuous.

*Prepared by National Carbon Co.

In other experiments on gaseous discharges, Richardson (30) used gas filled tubes without electrodes. The gases were excited by coils around the tubes using a frequency of 120 Mc/sec. Neon gave the highest visual efficiency while nitrogen was found most suitable for pulsed discharges. Gases which were used included neon, helium, xenon, nitrogen, mercury vapor, and krypton.

SOLAR RADIATION

If one wishes to operate ultraviolet equipment in the sunlight it is necessary to determine the extent to which the receiver will be affected by solar radiation. The amount of solar flux at a particular location depends on the altitude, latitude, climatic conditions, the time of day, and the season. Measurements of solar energy have been made in various localities, and some of the results are discussed in the following paragraphs. The regions of interest for this report are the middle ultraviolet and the near ultraviolet. The absorption by ozone has an important bearing on this problem.

The amount of atmosphere traveled relative to the amount directly overhead is called the air mass. When the sun is in the zenith the air mass is 1.0. The air mass is almost equal to the secant of the zenith distance (or 90 minus the altitude).

Figure 17 shows the spectral distribution of solar radiation for three different conditions. The curve labeled M = 1.05 is a spectral plot of the energy in watts cm^{-2} per 10A band with an air mass (M) of 1.05 at Washington, D. C. (31). An air mass of 1.05 corresponds to a zenith distance of about 18 degrees.

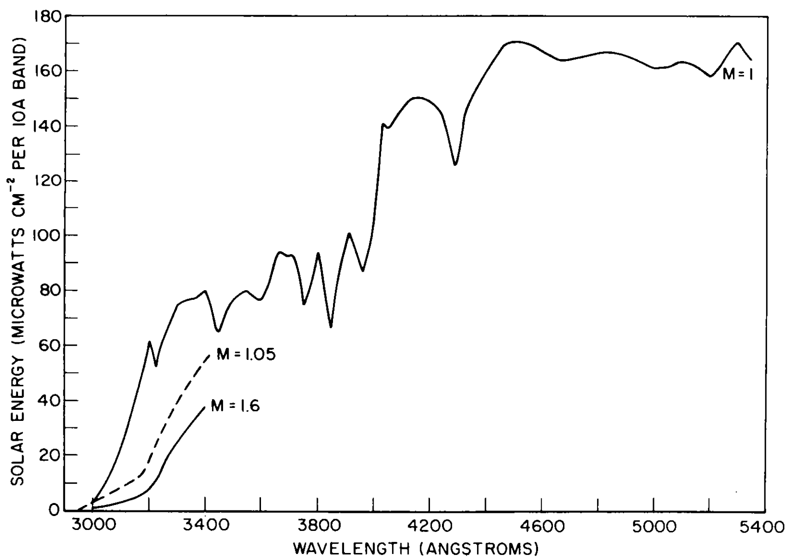

Fig. 17 - Spectral distribution of solar radiation traveling through the air mass directly overhead (M = 1) and at zenith angles such that M = 1.05 and 1.6

The data of the curve labeled M = 1.6 were plotted from the same source as the curve M = 1 and show the decrease in radiation reaching the earth when the air mass is 1.6. An air mass of 1.6 is equivalent to a zenith distance of about 51 degrees or an altitude of about 39 degrees.

The curve M = 1 was plotted from data taken at an altitude of 11,190 feet at Climax, Colorado (32). The curve shows approximately the mean values of radiation for four days in September 1951. The original data are arranged in a table having values for M = 0, 1, 2, and 3; however the curve in Fig 17 is for M = 1 only. At this altitude of 11,190 feet 35 percent of the total sea-level atmosphere lies below the location of the station at Climax.

The absorption bands shown in Fig. 17 are the result of Fraunhofer lines.

Figure 18 (33) is a typical representation of the manner in which the solar radiation intensity varies with the time of day and the season in Washington. These plots show that the maximum radiation incident on a horizontal plane occurs in June at noon. The observations were made on four very clear days. The spectral region is for wavelengths of 3132A and shorter.

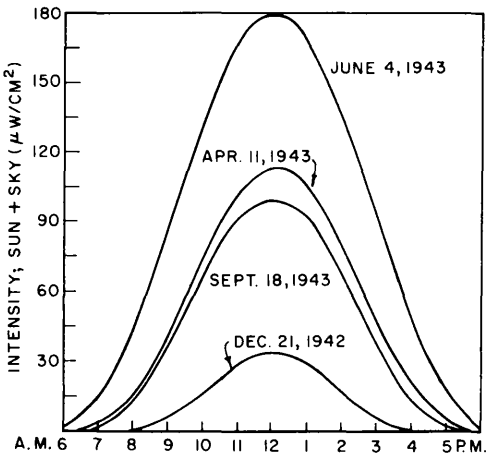

Fig. 18 - Daily and seasonal variations in intensity of ultraviolet radiation observed on four very clear days in Washington, D. C.

Figure 19 shows the extent to which the atmospheric transmission is affected by ozone absorption. The data plotted in Fig. 19 were used in determining the conditions during the time the measurements were made at Climax. The straight line is a plot of atmospheric transmission when only Rayleigh scattering is present. This line was plotted from Eq. (2) for Rayleigh scattering. At wavelengths shorter than 3400A there was absorption by ozone. The difference in ordinates between the straight line and the observed data at any particular wavelength indicates the ozone absorption. The optical absorption data were correlated with the amount of ozone by the use of absorption coefficients for ozone gas. About 0.21 cm of ozone at STP is a typical value for latitudes near those of Climax and Washington, D. C.

Measurements of global radiation (sun plus sky) taken on a horizontal surface in the Swiss Alps at Davos Observatory (34) are plotted in Fig. 20. These data show how the solar radiation varies as a function of the altitude of the sun from 15 degrees to 50 degrees

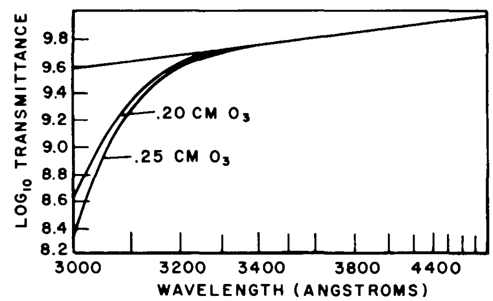

Fig. 19 – Atmospheric transmittance at Climax, Colorado; total ozone above the observing station

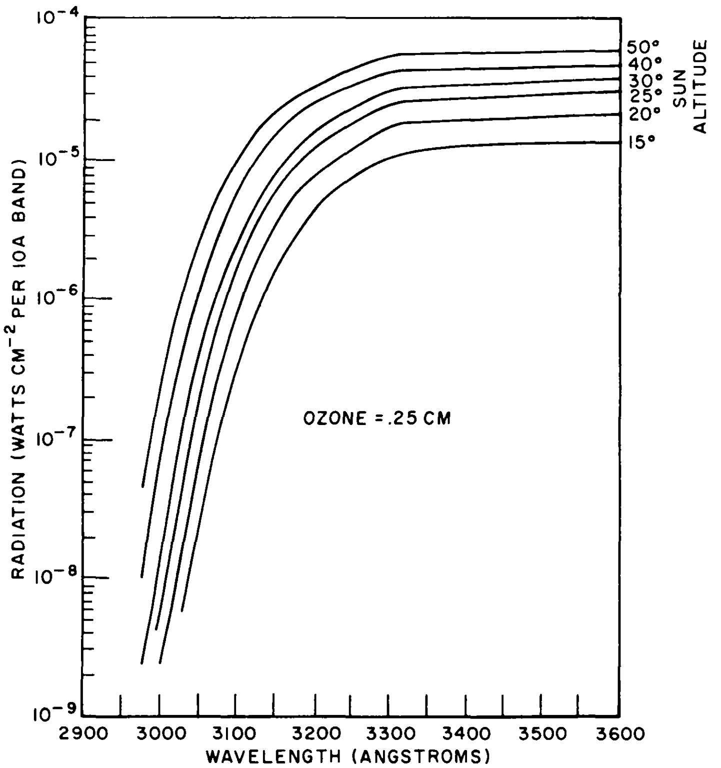

Fig. 20 – Solar radiation in the Swiss Alps

and also the spectral variation for wavelengths from 2900A to 3600A. The total amount of atmospheric ozone was 0.25 cm. Typical recordings from which these curves were plotted show the signal merging into the noise level of the equipment at wavelengths of about 2950A. It was found that the atmospheric ozone in the Swiss Alps (Lat. 45°48'N, Long. 9°49'E) in amounts from 0.2 cm to 0.3 cm caused variations of the intensity of the sky and sun radiation at 3000A of from 8 to 16 times.

DISCUSSION OF COMMUNICATION SYSTEMS USING ULTRAVIOLET RADIATION

Basic Considerations

At long ranges, the eye may be able to detect a signal light, but if the light is near the threshold level, communication will be difficult or impossible. Factors of from 2 to 150 times the threshold candlepower are reported (35,36) to be necessary for communication. At night, however, the intensity is likely to be above the threshold at the ranges of interest. One can easily confirm from the following discussion the fact that communication with visible sources at night at a range of 12.5 miles presents no problem when security is not required, provided the atmosphere is not foggy. For example, consider a summer day when an island or ship against a horizon background is visible at 12.5 miles and the atmosphere has a slightly hazy appearance. With reference to Table 2, a daytime visibility of 12-1/2 miles corresponds to a nighttime condition where a 100-candlepower of approximately a 100-watt tungsten bulb is visible 7-1/2 miles and a 10,000-candlepower bulb 18 miles. This refers to a bare bulb with no optics.

The flux density of sources at any distance can be calculated from the equation

$$F = \frac{It}{\pi D^2} = \frac{I e^{-\sigma D}}{\pi D^2} \tag{13}$$

where F is the luminous flux (lumens), D is the distance from the source to the receiver, t is the transmission, σ is the attenuation coefficient, and I is the luminous intensity (candlepower).

If the lamp is now placed at the focus of a parabolic mirror directed toward the receiving position, the apparent luminous intensity of the whole mirror is

$$I_A = \pi R^2 B \rho \tag{14}$$

where ρ is the reflectance of the mirror, R is the radius of the mirror, and B is the luminance or brightness (candles/unit area). Equation (14) applies to a source which is not a point source and where the observer is sufficiently far away that the mirror is uniformly illuminated. Equation (14) can be substituted in Eq. (13) to determine the flux density when a parabolic reflector is used.

The effect of the parabolic reflector is to cause a source of a given brightness to appear to be a source of greater area and the same brightness. For example, a circular source with no reflector has a luminous intensity of $\pi B r^2$ candles, where r is its radius. When placed at the focus of a parabolic reflector the luminous intensity is $\pi B R^2$, where R is the radius of the mirror.

The 100-candlepower lamp which was visible at 7-1/2 miles with no reflector, might have a luminous intensity of 150 times this when placed at the focus of a 12-inch-diameter mirror. It would then be visible for over 18 miles. The 1000-watt mercury-xenon beacon with a Fresnel lens has a candlepower of 100,000.

The above discussion is intended to show that where security is not a consideration, visual communication at night is easily achieved with existing equipment, for both directional and all-around operation.

During daylight the situation is quite different. A light viewed against a bright background is much more difficult to see because of the lower contrast ratio. Knoll, Beard, Tousey, and Hulburt (35) determined the threshold of point sources of light in fields of different brightness. Quoting from their report, on an average day with the sun above 40 degrees the background brightness is 200 candles/ft^2 or 6.76 lamberts. They further define an average day as one in which the transmission is 0.6 to 0.7 per sea mile, which from Table 1, is seen to be a clear day. From Table 3 of their report, one finds that a 12-inch searchlight of 100,000 candlepower has an observed threshold of 4 to 11 miles (average of 6.8 miles) and a 24-inch searchlight of 100,000,000 candlepower has a threshold of 9.5 to 19 miles (average of 14.7 miles) on an average day. At this point it might be noted that the 2-1/2-kw mercury-xenon beacon has a candlepower of 100,000. Their comments are that for signaling purposes the candlepower of a light should be 30 to 150 times greater than that required for a threshold range. These values are somewhat more pessimistic than the values of 1.7 to 25 found by Dunkelman (36). Regardless of the factor it is worth noting that Dunkelman found experimentally that on an average day, in which the transmission was 0.57 per sea mile, the maximum range of the 100,000-candlepower beacon for code messages sent at 5 to 7 words per minute was 1.7 miles. All of these facts indicate the need for enhancing the signal-to-noise ratio during daylight.

A Brief History of Ultraviolet Communications

A few previous experiments in ultraviolet communication are described in the following paragraphs to illustrate the extent of prior efforts.

Early work in the field of ultraviolet communications includes that of Hulburt at the Naval Research Laboratory. The report (37) "Signalling and Detection with Ultra-Violet and Infra-Red Radiation" summarizes the work done at NRL from 1926 through 1933. The ultraviolet signaling system described in this report consisted of a 3-kw, 30-inch searchlight with impregnated carbons and an ultraviolet filter. Mounted to the side of the searchlight and accurately pointed in the same direction was a telescope of good light-gathering power with a screen of fluorescent material in the focal plane of the objective. The ultraviolet efficiency of the source was less than 0.5 percent and the efficiency of the receiver in converting the ultraviolet to visible light was less than 1 percent. With this equipment, two darkened ships were able to locate and communicate with each other at a maximum range of 4 miles. The maximum range obtained on a clear night was 6 miles. The lights were visible at 1 mile with binoculars.

White (16) was concerned with communication by ultraviolet in the region where it is entirely invisible to the unaided eye. Therefore filters, sources, and receivers were developed primarily for the wavelength region 2500A to 3000A. The ranges which are quoted are based on an average day, which he defines as having a visible transmission of 60 percent per mile and an ultraviolet transmission (2700A to 2900A) of 40 percent per mile.

One system which he developed used a gallium source housed in a 6-inch-diameter reflector with a 25-degree horizontal and 15-degree vertical beam. With a "G" filter this source was not visible to the unaided eye more than a few yards. With a phosphor metascope as a receiver the range was 1 to 2 miles. When a 1P28 multiplier phototube at the focus of a 10-inch-diameter f/1 mirror was used for receiving, voice communication was possible up to 3 miles. The daytime range was only a few hundred yards because of the filter required to exclude sun light from the receiver.

A low pressure mercury arc lamp was found to have better efficiency at 2537A than that of the gallium lamp at 2900A. However, due to the higher atmospheric attenuation, the two had about equivalent ranges.

A 400-watt high pressure mercury arc lamp at the focus of a 6-inch-diameter parabolic mirror was tried with an "A" filter (16), which passed the 3630A and 3130A lines. This could be seen with the unaided eye for some distance. A "B" filter restricted the output to the 3130A line, but the light was visible at 1 mile. The range with a metascope was 5 to 10 miles.

Table 11 summarizes some of the systems considered feasible by White. Vacant entries represent unsatisfactory combinations.

Table 11
Systems Considered Feasible by White (16)

Receiver	Time	Range for the Indicated Source (yd)		
		400-watt High Pressure Mercury Arc	50-watt Gallium Lamp, 2800A	Carbon Arc 65 amp dc, Grid Modulated, 6° × 6° Beam
Phosphor	Day	-	200	-
Metascope	Night	6000	2,000	-
Photomultiplier	Day	-	-	4,500
2° × 2° field	Night	-	-	79,000

The Elcon Laboratory, Inc., under a contract with the Federal Aviation Agency (38), investigated the possibility of providing a collision warning system operating in the ultraviolet spectrum and having a range of 10 to 15 miles. This system could conceivably be used for communication by code.

The source used for their experimental program consisted of a G. E. Type G15 T8 15-watt low pressure mercury lamp with a polished reflector designed to produce a beam 15 inches × 30 degrees. The receiver was a 1P28 multiplier phototube mounted in a reflector with an area of 0.3 m^2 and a field of view of 0.03 radians. The 2536A mercury line was the source of most of the signal. The output of the lamp at this wavelength is about 3.6 watts. The lamp was operated from a 15-cps supply, and a 30-cps synchronous detection system was used at the receiver.

Operation was mainly at night to avoid large signals from a solar background. Consistent reception was achieved over a 2.3-km range as long as the visibility equaled or exceeded 2.3 km. The maximum practical range with this system was concluded to be 2.2 miles with a 15-mile visibility.

Another system using mercury germicidal lamps was developed by Northwestern University (39) for the Evans Signal Laboratory. In this case an 8-watt lamp was pulsed and amplitude-modulated using a potential of 3300 volts. The peak power was found to be about 30 kw and the average power about 3.9 watts. Four-watt and 15-watt lamps were also pulsed, the 15-watt lamps being somewhat freer from jitter.

A pulse time modulated light beam communication system was developed by Northwestern University for the U. S. Navy (29,40). The source for this system was a gas filled tube developed by Northwestern. When the tube was filled with nitrogen at 10 mm pressure, and pulse time modulated with 7.5 kv, the output of the band system extended from about 2200A to 5000A. The duration of the flash was about 0.1 microsecond, and the peak of the energy was in the near ultraviolet. The reflector was a 14-inch-diameter Alzac aluminum parabolic mirror giving a field of view of 7.5°. The receiver used a 1P21 multiplier phototube at the focus of a 16-inch parabolic Alzac reflector and had an optical beamwidth at half intensity of 3 degrees horizontal and 8 degrees vertical.

This system was demonstrated in Washington, D. C., with a path length of 5 miles between the Main Navy Building and NRL. The tests were conducted at night using a Corning No. 9863 filter to eliminate interference from tungsten lights. Communication in full sunlight was not possible. The atmospheric transmission was measured at 5500A and extrapolated to 4000A using curves from Ref. 41. When the transmission was 0.4 per mile or better at 4000A, noise-free transmissions over the 5-mile path were possible. The vacuum range of the equipment was 50 miles.

It should be noted that none of these systems were reported to have good daylight capabilities.

In the Elcon experiments and one of the Northwestern University equipments standard low pressure (germicidal) mercury arc lamps were used. These are highly efficient ultraviolet lamps in that virtually all the radiation is at one wavelength, 2536.5A. Unfortunately this is also very close to the peak absorption of ozone.

In order to evaluate the losses due to atmospheric absorption by ozone and oxygen and Rayleigh scattering the data shown in Table 12 were tabulated at wavelengths of 2536A, 2950A, 3600A, and 5460A from Figs. 1 and 2. These wavelengths were selected for the following reasons: 2536A is the wavelength of maximum output from a low pressure mercury arc, 2950A is the approximate cutoff for solar radiation, 3600A in the near ultraviolet was picked at random, and 5460A is a visible line emitted by a mercury arc lamp.

From Table 12 it is seen that in a pure atmosphere the intensity of a source radiating at 2536A is reduced by a factor of 5.28×10^7, whereas one at 5460A is reduced but 1.24 times at 10 miles. In a real atmosphere the attenuation is much greater and less selective with wavelength. This is borne out by the measurements of Dunkelman (7), shown also in the table. The data for scattering by fog cover only the region from 2900A to 4500A; however the attenuation is virtually constant over a wide range of wavelenghts.

From Table 12 it is concluded that a source which radiates mainly at 2536A is undesirable because of the high absorption by ozone. From the viewpoint of absorption by gases the interval 3500A to 4000A appears to offer least attenuation, but in a real atmosphere experimental results show that scattering by haze and fog are the dominant sources of attenuation and the selection of a "best region" may be less critical than one might suspect.

The nitrogen filled lamps and accompanying circuits developed at Northwestern University and NRL would appear to be the most promising sources for an ultraviolet system, since a large percentage of the output is in the middle and near ultraviolet region.

Table 12
Absorption by Ozone, Oxygen, and Rayleigh Scattering

Wavelength (Angstroms)	Attenuation Coefficients (base e, km^{-1})			Total σ for 10 miles	$e^{-\sigma x}$ where x = 10 sea miles (18.5 km)	Measured Attenuation Coefficient (Ref. 7)	
	21 Percent Oxygen	0.02 ppm Ozone (= 0.002 cm km^{-1})	Rayleigh Scattering			Pasadena	Fog
2536	0.05	0.59	0.325	17.8	$\frac{1}{5.28 \times 10^7}$	33	-
2950	-	0.048	0.16	3.86	$\frac{1}{46.7}$	14	160
3600	-	0.35×10^{-5}	0.07	1.3	$\frac{1}{3.67}$	11	150
5460	-	1.6×10^{-4}	0.0123	0.226	$\frac{1}{1.24}$	≈ 3.3	-

Selection of Components for a Communication System

For initial work the 1000-watt mercury-xenon arc is a good source because it has fairly good output in the region 2500A to 2900A (about 12.8 watts) and is convenient to use.

For daylight operation a narrow-band interference filter can be used at the detector to exclude solar radiation. According to the manufacturer's data, an all-dielectric interference filter is available peaked at 2800A (or above) with a half-power bandwidth of 100A and a transmission of 20 to 40 percent. This filter would still have some transmission at 2950A; however preliminary experiments indicate that daylight operation is feasible with some solar radiation present. Another method for greatly reducing the amount of solar radiation at the detector is by use of a dichroic mirror which reflects ultraviolet and transmits visible radiation.

The encouraging results obtained with nitrogen filled tubes indicate the need for further evaluation of such sources.

The signal-to-noise ratio of the system can be further increased by the use of pulsed sources. Keene and Richardson (30) have shown that one might expect a pulsed voice system to have a signal-to-noise ratio 32 times that of a cw system and a code system using a pulsed source to have a signal-to-noise ratio 100 times that of a cw system, for equal average powers.

Detectors

Assuming that the best signal-to-noise ratio and a high sensitivity are desired, the most suitable detector is a multiplier phototube. If the detector must measure radiation in absolute units without frequent calibration a diode phototube will be more satisfactory. Otherwise a multiplier phototube is more desirable because of its high gain and low noise level.

Since the major problem is to detect a source during the daytime, it would be highly desirable to have a photocathode which is sensitive to long wavelength ultraviolet, yet is insensitive to solar radiation which would tend to saturate it. Such tubes are available but, as explained in Ref. 22, have some response to solar radiation. These tubes are still under development and are relatively expensive as compared to other types. Therefore, it is probably more desirable to select another type, using the curves shown in Fig. 14. A photosensitive cathode with S-5 response will provide adequate sensitivity in the middle and near ultraviolet regions.

Electrical Circuits

No mention has been made of the electrical and electronic circuits, since these involve techniques which are well known and will vary according to the application of the detected signal.

In most cases the source will be operated from a 60-cps power supply, so that the radiated energy will consist of 120-cps pulses. If communication by only code is anticipated, an amplifier synchronously tuned to 120 cps and having a fairly narrow bandwidth should be used. However, if pulsed sources are used, a wide-band system is required.

Circuitry used in obtaining experimental data will be included in a following report.

Component Development

There are several areas where an improvement in components, if of significant magnitude, would result in greatly improved performance of an ultraviolet communications system.

The available sources have been shown to have output in the ultraviolet, visible, and infrared regions. In most cases the ultraviolet output at the desired wavelengths is a very small percentage of the total output. The only exception considered here was the low pressure mercury arc. It has a low average power capability, and the maximum output at 2536A is too greatly attenuated by the atmosphere to be highly useful.

The ultraviolet filters which are available have a maximum of 40-percent transmission and usually less. The attenuation outside the desired bands is not great enough to exclude interference from solar radiation.

Photoelectric cells are sensitive to a very wide spectral region, and therefore maximum use cannot be made of their capabilities during daylight operation. "Solar blind" cells have not yet reached a state of development where they are completely solar blind.

CONCLUDING REMARKS

An examination of theoretical and experimental atmospheric transmission data leads to the conclusion that the region or some portion of the region between 2800A and 4000A is the most promising portion of the ultraviolet spectrum for communications systems using presently available components.

An investigation of other types of sources such as lasers and plasma arcs and other regions of the spectrum are authorized under this Task Order but are not considered in this report.

From preliminary field tests, daylight operation using a mercury-xenon arc, xenon arc, or nitrogen gas discharge as a source and a photodetector with a narrow-band filter appears feasible. A pulsed source with high peak power output will provide a better signal-to-noise ratio.

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Attn: Technical Library	1
OCSigO	
Attn: Ch., Research & Dev. Div.	1
USAELRDL, Ft. Monmouth, N. J.	
Attn: USAELRDL Liaison Office	3
DDC	
Attn: TIPDR	20
Office of the Director of Defense (R&E)	
Attn: Technical Library Branch	2
BJSM	6
Applied Science Laboratory, New York NavShipYd, Brooklyn, New York	
Attn: Code 9410, Mr. Sidney Feldman	1
U. S. Naval Communication System Hdqrs. Activity, 3801 Nebraska Ave., N. W., Wash. 25, D. C.	1
CDR, Naval Forces Continental Air Defense Command, Ent AFB, Colorado Springs, Colo.	1
Defense Communication Agency, Dept. of Defense, Pentagon	
Attn: Dir., Res. & Dev. Div.	1
CDR, USAF Security Service, San Antonio, Texas	
Attn: DCS/Communications-Electronics, Directorate of Systems Engineering (ESI)	1
NRL	
Attn: Code 7300	4