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Experimental Observations of Forward Scattering of Light in the Lower Atmosphere

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FOREWORD

This report is essentially a formal compilation of the results of a number of activities related to the propagation of light by scattering in the lower atmosphere. Some of the results have appeared in bits and pieces elsewhere, and for completeness it was felt desirable to present a somewhat more detailed exposition of the efforts. Although the general subject is that of forward scattered light, it is difficult to make an integrated entity of the separate topics, so that there may be an unavoidable air of discontinuity in the subject matter.

ABSTRACT

This report deals in part with the experimental results from seven measurements on the forward scattering of light by the atmospheric aerosol. The results of these ventures are the following:

1. Light scattered forward from a 50,000-w omnidirectional light source, when viewed from a point 45 km away below the horizon, was distributed on the horizon in a field 5 degrees high and 10 degrees wide. A small area, 25 min by 25 min on the horizon in the line-of-sight direction, contained 15 percent of the total horizon intensity.

2. Light scattered forward from a 10,000-w collimated carbon-arc light source which had a 1/2-degree beamwidth, was directed tangentially, and was observed from a point 45 km away below the horizon was distributed on the horizon in a field 5 degrees by 10 degrees. A small area 20 min wide and 17-1/2 min high on the horizon in the line-of-sight direction contained 50 percent of the total horizon intensity.

3. Airborne observations of forward scattered light from a searchlight beam 1/2 degree wide yielded on on-axis irradiance, at a range of 35 km from a horizontally pointed source, 550 times the irradiance at a point 115 meters above the geometrical edge of the beam.

4. Ground-based comparison of direct-line-of-sight irradiance and small-angle forward-scattered-light irradiance showed that in the wavelength interval 7500A to 9500A the direct light was 200 times the scattered light at a distance of 45 km when the meteorological range was 40 km.

5. Signals as a function of distance have been measured with the help of a mobile omnidirectional light source. The signal strength decreases inversely with the square of range and with an exponential attenuation out to the horizon, at which point there is a discontinuity which is a function of the meteorological conditions and is greatest when the meteorological range is high. Beyond the horizon the signal decay is influenced mostly by attenuation loss when the meteorological range is low (13 km) and primarily by inverse-square loss when the meteorological range is high (>60 km).

6. Ruby laser light was transmitted at night over the horizon to a distance of 45 km when both receiver and projector were 6 ft above water and were pointed at one another with 0-degree elevation. The laser output was 0.10 joule and the signal-to-noise ratio in the system was 45. It is estimated that the surface transmission of the 45-km path at 6943A was about 10^{-5}. Signals from a 1 to 2 joule laser have also been transmitted over

this path in daytime with a signal-to-noise ratio of 3 when the meteorological range was 20 km.

7. An over-the-horizon link was established on a continuous basis over a range of 45 km. Observation was for a period of 102 hours, during which the signal was received 62 percent of the time during the night and 57 percent of the time during the day. Two accidental interruptions of the measurements resulted in lost data during periods when the signal would surely have been received.

In addition, considerations of the problem of detecting forward scattered light in the daytime show that estimated results agree with the available experimental data. Considerations of the feasibility of using over-the-horizon propagation as a communications link leads to the estimation that communication between fixed points at Morse code rates is currently feasible over ranges of the order of 50 km in the daytime for meteorological ranges of 16 km or more, using a narrow-beam projector as source. Ship-to-ship communication would require sources of very high power or precise stabilization and pointing of existing high-intensity searchlight sources.

PROBLEM STATUS

This is an interim report on one phase of the problem; work on this and other phases is continuing.

AUTHORIZATION

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EXPERIMENTAL OBSERVATION OF FORWARD SCATTERING OF LIGHT IN THE LOWER ATMOSPHERE

INTRODUCTION

Light is scattered in the lower atmosphere primarily by suspended particulate matter which is generally present in varying concentration up to thousands of particles per ml with particle diameters ranging from 10^{-2} to 10^{2} μ. This aerosol is composed of industrial smokes, combustion exhaust products, various soil dusts, and sea salt and other hygroscopic particles as well as haze and fog particles. The latter generally consist of a small nucleus of particulate matter surrounded by a liquid water shell of varying thickness.

An important characteristic of atmospheric scattering is the asymmetry of the polar scattering function. This characteristic is shown in Fig. 1, which presents the symmetrical curve for molecular or Rayleigh scattering along with measured asymmetrical scattering functions for several real atmospheres and with two asymmetrical curves computed for two wavelengths (1-4). The computations were based on an aerosol model which assumed spherical particles of index of refraction 1.5 and a size distribution

$$\frac{dn}{d \log r} \propto r^{-3} \tag{1}$$

where dn is the number of particles in the particle size range $d \log r$, with r being the particle radius. Although scattering by the aerosol is a complex phenomenon which is a function of particle size, the wavelength of light, and the refractive index of the scattering material, the basic theory is well understood and scattering calculations are straightforward though tedius (5).

The scattering functions in Fig. 1 are seen to be greatest in the forward direction, within a few degrees of the direction of the incident beam. This strong forward lobe is one of the basic phenomena of importance in the transmission of scattered light signals over the horizon. However the complete angular scattering function for the aerosol is of importance in another application of light scattering in which atmospheric transmission is evaluated by measuring the backscattering from the aerosol (6). For the latter evaluation the basic requirement is that the signal scattered in the backward direction be a measure of the total scattering in all directions. It appears that this relationship holds frequently enough to be useful.

In atmospheric transmission measurements which involve a light source and a receiver, the flux collected by the receiving equipment is a function not only of the atmospheric losses but also of the geometry of the system, in particular, the collimation of the source and the field of view of the receiver. In all systems the measured flux is made up of both unscattered and scattered light, the relative magnitude of the scattered light being a function of the field of view of the receiver. The earliest experimental work on this problem was performed by Middleton (7) in dense fog and by Stewart and Curcio (8) in relatively clear air. In the clear air case it was found that the experimental data for an uncollimated source could be approximated by the relationship

$$T(\theta) = T + 0.5 \, (1 - T) \, (1 - e^{-\theta}) \tag{2}$$

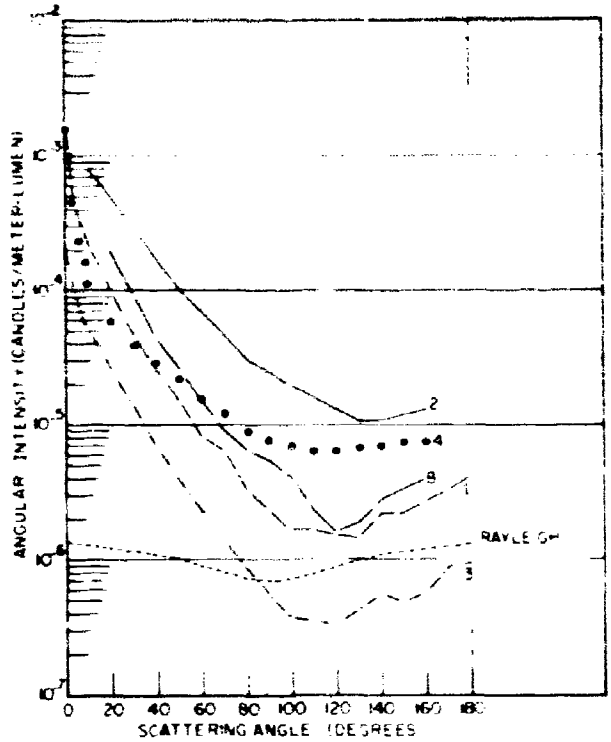


Fig. 1 - Measured visible wavelength scattering functions for several real atmospheres (curves 2, 4, and 8) and calculated scattering functions for a particular aerosol model at wavelengths 0.55 micron (curve 1) and 2.2 microns (curve 3)

where $T(\theta)$ is the transmission as indicated by a receiver with a field of view θ radians in diameter and T is the beam transmission measured by a receiver having an infinitely narrow field of view.

From these experimental results, it became apparent that any measurements of transmission are of value only if the field of view of the detector system is known - a conclusion which has significant implications for many problems including the thermal damage caused by nuclear weapons (9). Since, in many situations, the scattered light component is a relatively large fraction of the total flux transmitted through the atmosphere, the use of this scattered light for over-the-horizon transmission of information has also become an interesting possibility (10). A qualitative presentation of the behavior of light scattered forward from a collimated source with a 1/2-degree beamwidth is shown in Figs. 2 and 3 as observed on two nights of 50 km meteorological range from sites below the horizon.

In Fig. 3 the beam discontinuity seen in some of the pictures made from a range of 85 km occurs at an elevation of 5000 ft, which coincides with the height of the inversion which existed when these pictures were made. Of particular interest in the problem of transmitting light over the horizon is the relatively small and very bright illuminated area seen in Figs. 2 and 3 for zero-degree elevation of the projector beam. This is characteristic of the appearance of the horizon luminance when the source is collimated with small divergence. An uncollimated source also yields a spot but the isophot gradient away from the beam axis or spot center is less steep in this case.

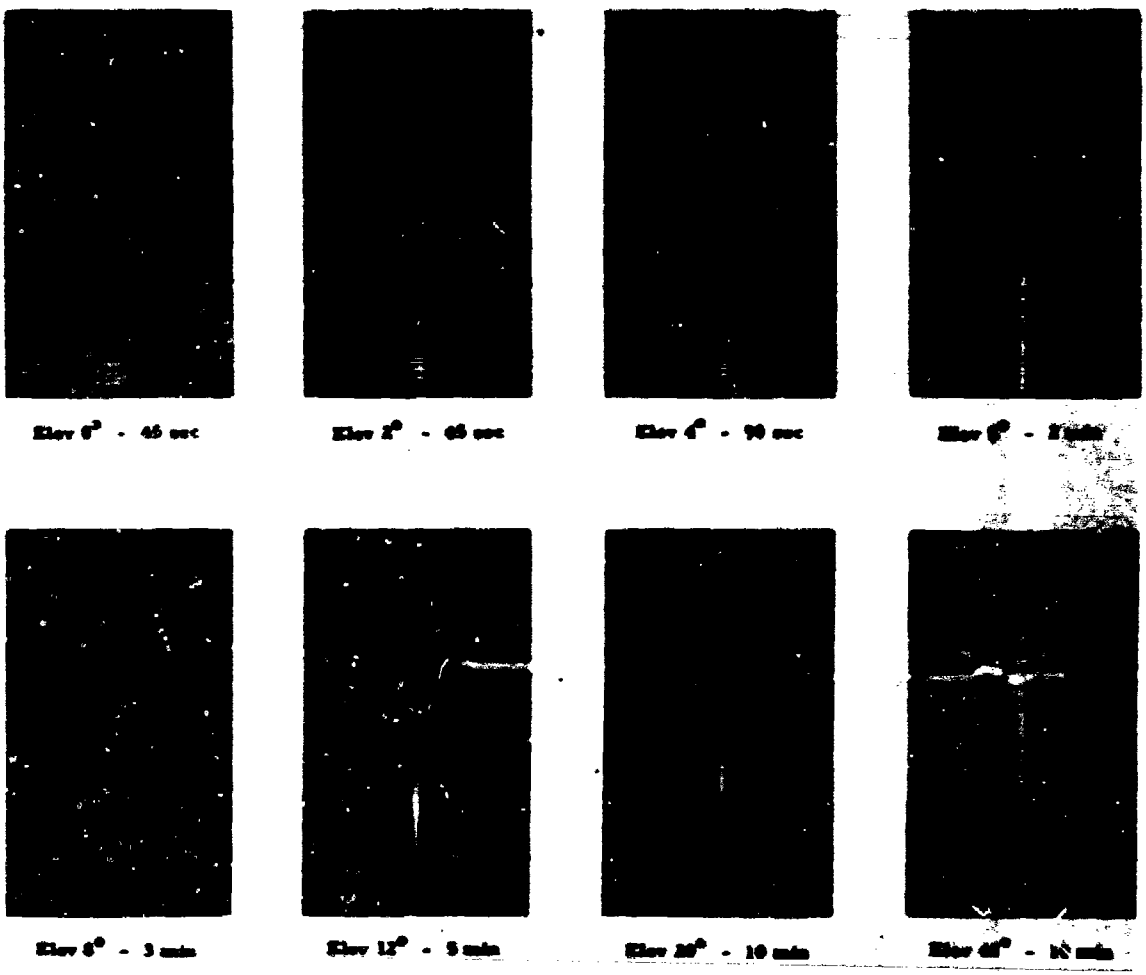


Fig. 2 - Searchlight beam observed from a point below the horizon and 45 km away. Beam elevation angles and photographic exposure times are given. An aircraft trail passes through the lower right photograph.

In general the problem of transmitting information over the horizon by forward scattered light is one of detecting the available signal which is distributed in some radiance pattern on the horizon in the presence of some background radiance (Fig. 4). Ideally one would like to find it feasible to detect significant light from an omnidirectional source in the presence of a daylight sky background on days when the meteorological range is perhaps 10 mi or less. There are some situations, however, where the omnidirectional requirement might be dropped and point-to-point directional signaling would be useful. In order to evaluate such possibilities, it is necessary to acquire some knowledge concerning the long-distance attenuation of light, the scattering properties of the atmosphere, the distribution of light on the horizon, the detection of small ac signals in a high ambient quasi-dc background, the nature of the background, etc. The paucity of available information on any of these subjects led us to institute some general atmospheric optics measuring programs and to conduct some field measurements designed to elucidate some of the specific problems associated with over-the-horizon signaling. This report deals with some of the specific concerns.

Fig. 2 - Searchlight beam observed from a point by low the horizon and 45 km away. Beam elevation angles and photographic exposure times are given.

Fig. 4 - Carbon-arc searchlight at 45 km against moonlit sky. The small bright spots are extraneous horizon lights viewed directly.

FORWARD SCATTERED LIGHT FROM A DIRECTIONAL LIGHT SOURCE IN DAYTIME

In order to evaluate in a simple manner the possibility of daytime operation, we arranged a measurement in which the horizon radiance from a searchlight below the horizon was compared to the horizon illuminated by a full moon. Figure 4 is a photograph which shows water-sky horizon radiance pattern produced by a 60-in. carbon arc searchlight below the horizon and pointed horizontally toward the camera which was 45 km away; the camera and searchlight were each about 1.5 m above sea level. In this instance the searchlight was pointed several minutes of arc to the left of the direction to the camera. The photograph was made when the full moon was at 30 degrees elevation to the east of the optical path, and the meteorological range* was estimated to be about 20 to 25 km. The photograph was made with a 4 x 5 Graflex using Royal X Pan film at f/2.5 with an exposure time of 5 sec. The horizon area which appears to be as bright as the nearby lights is caused by searchlight flux which was scattered through small angles of about 10 arc-minutes. The direct line of sight passed about 140 m over the camera.

A sensitometric evaluation of the film gave a relative intensity pattern (Fig. 5) of the horizon radiance caused by the carbon arc. The area studied subtended a field about 9 degrees in azimuth on the horizon and about 5 degrees in evaluation. The number in an individual block represents the average relative intensity value of the irradiance of the particular elemental area of the horizon. The horizon radiance pattern is characterized by an intensely bright area about 20 min wide and 5 min high which contains 25 percent of all the radiation scattered from the beam toward the receiver. Fifty percent of the scattered flux is in a field 20 min wide and 17.5 min high and 70 percent of the total flux is in a field 60 min wide and 35 min high.

The photograph (Fig. 4) was made in full moonlight; hence it was possible to make a direct comparison which showed the "hot spot," 5 min by 20 min on the horizon, to be about 200 times brighter than the moonlit sky at the horizon. If one assumes the solar horizon illumination to be 5×10^5 times the lunar horizon illumination, the bright spot may be estimated as 2.5×10^{-3} as bright as the daylight horizon in the visible spectral

*Meteorological range is defined as the distance for which the transmission measured by a receiver with a narrow field of view is 2 percent.

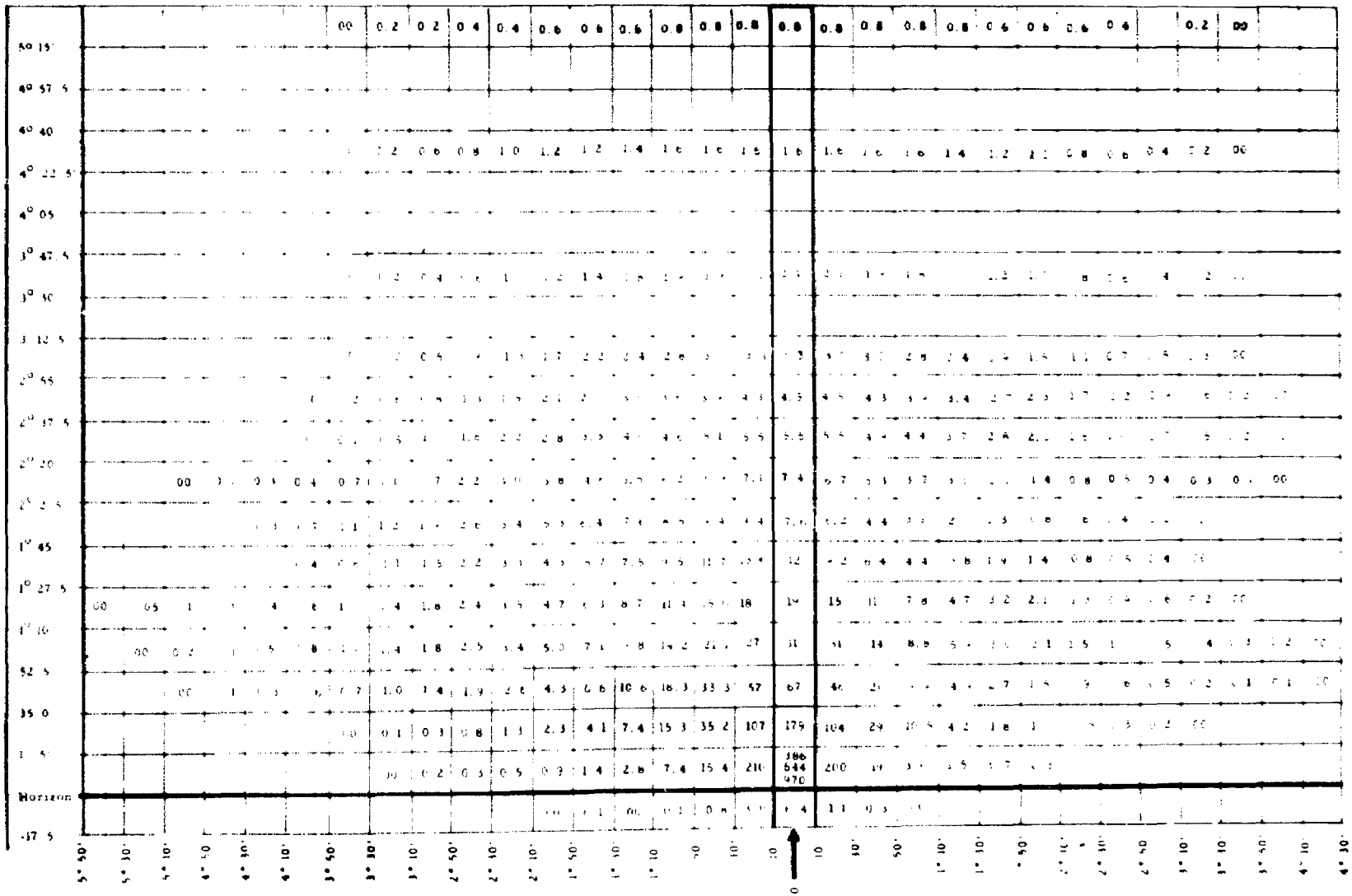


Fig. 5 - Relative intensity pattern of horizon radiance caused by a carbon-arc searchlight below the horizon and 45 km away

region. If the measurements were to be made at 1.0μ, a substantial improvement in spot radiance to background radiance would be expected because of reduced sky background (down 60 percent) and an improved scattered-signal beam transmission factor (up 20 times; see Fig. 12 in Ref. 10). The carbon arc has equal spectral radiance at 1.0μ and 0.55μ; hence the bright spot is expected to be about 2×10^{-2} as bright as the daylight horizon background at 1.0μ. A similar analysis shows that the bright spot will be about 7×10^{-2} as bright at the daylight horizon sky at 1.6μ and at 2.2μ.

The above calculations suggested that it was marginally feasible to detect scattered light in the daytime, and an attempt was made to detect the scattered light from the carbon arc below the horizon under daytime conditions at a range of 45 km. The detector system consisted of two photomultipliers mounted side by side at the focus of an f/5 mirror, 60 cm in diameter. The photomultipliers were filtered to respond to wavelengths around 1μ and were stopped down to have equal fields of view 5 min high and 20 min wide. The two fields had an angular separation of 2 degrees. The voltage outputs from the two detectors were connected in opposition as a differential system with zero output for identical flux inputs. Previous laboratory work with this system had shown that under certain stable atmospheric conditions a dc signal 10^{-3} as intense as a daylight signal at 1μ could be detected. However, in the actual daytime field test with the carbon arc 45 km away and below the horizon the random differential fluctuation in the two background signals were of the order of 10^{-2} of the background, and the weaker scattered light signal from the carbon arc was not detected. It appears that fluctuations in the background signal from adjacent fields in the horizon sky even on apparently clear and cloudless days make this dc system unsuitable for detecting the weak scattered light signals. Some other system which used space chopping techniques or a modulated light source would be required for the daytime detection of the signal. However, a subsequent attempt to detect a 1000-w, 120-cps modulated xenon lamp in a 36-in. projector was unsuccessful in daytime because of overloading of the photomultiplier detector by the daytime horizon sky background.

FORWARD SCATTERED LIGHT FROM AN OMNIDIRECTIONAL LIGHT SOURCE

In some of the possible situations in which one can conceive of using scattered light for communication it is of considerable importance to know the horizon illumination resulting from omnidirectional as well as directional light sources. In the preceding section the scattered light pattern, on the horizon, from a narrow-beam, high-intensity, directional light source was examined and it was found to consist of a small, 5 min by 20 min, relatively bright area on the horizon. The radiance of this spot was about 10 times more intense than that of the surrounding field. A similar measurement was made with a hemispherical omnidirectional ("2π") light source.

The 2π light source consisted of five 10,000-w tungsten lamps arranged in the array shown in Fig. 6. This array was mounted on a roof about 25 ft above ground and was clear of all near obstructions. The 50-ft trees in a wooded area 200 ft from the light array may have caused some obstruction in the easterly direction, but this was not apparent in the horizon brightness pattern. Figure 7 shows the water-sky horizon radiance pattern caused by the omnidirectional light source 45 km away below the horizon. The photograph was made on a clear moonless night when the meteorological range was estimated to be 20 to 25 km. It was made with a 4 x 5 Graflex on Royal X Pan film at f/2.5, with an exposure time of 10 min.

A sensitometric evaluation of the film gave the relative horizon radiance from the omnidirectional light source (Fig. 8) and shows that the radiation was contained in a field of about 9 degrees azimuthal width on the horizon. The pattern was evaluated in elevation up to 4 degrees 3 min, at which point it could not be detected above the night sky

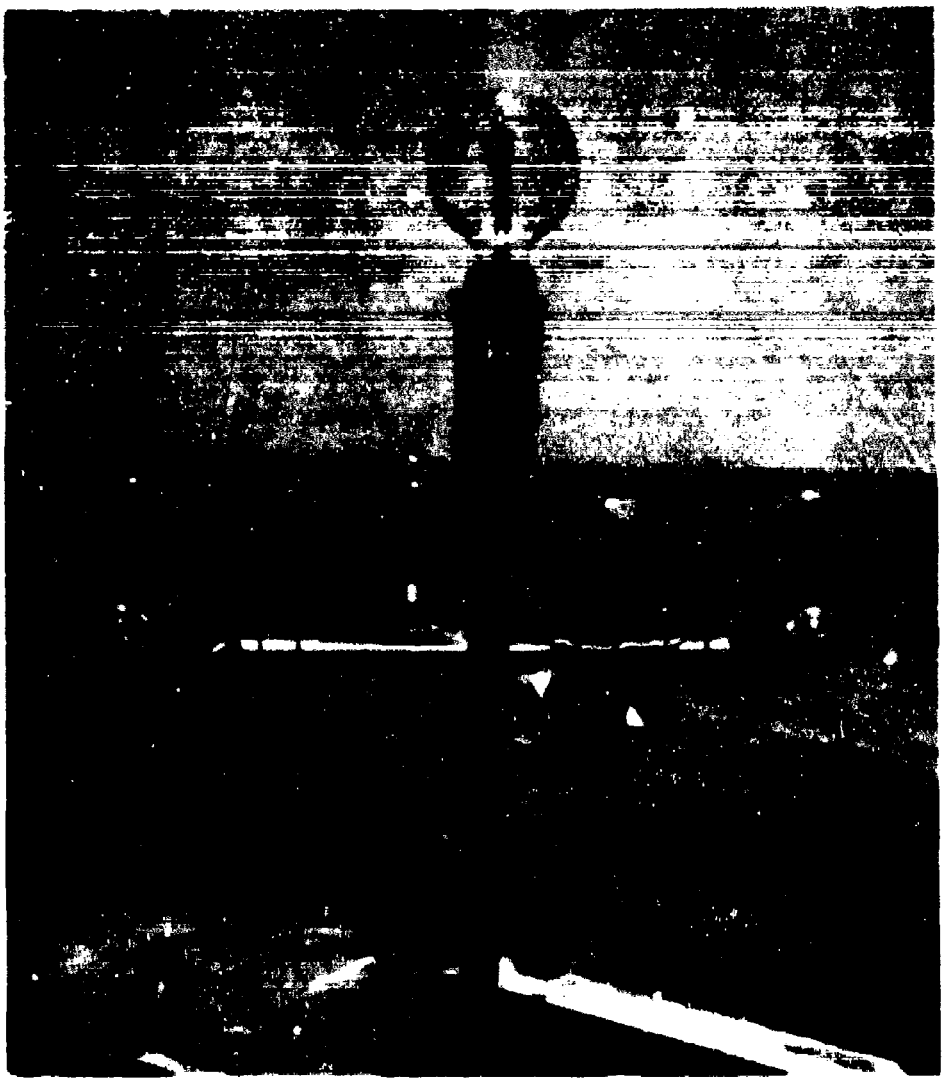


Fig. 6 - Tungsten light source of 50,000 w used for omnidirectional light transmission experiments

background. The number in each rectangular area represents an average relative radiance for that particular sector of the horizon sky. The pattern is characterized by a bright area 25 min wide and 25 min high which contributes about 14 percent of the total intensity and is located on the horizon symmetrically about the sighting direction from receiver to the omnidirectional light source. The most intense region in this small field is an area 10 min high and 25 min wide which contributes about 8 percent of the total intensity.

The horizon radiance patterns shown in Figs. 4 and 5 can be used in the estimation of the effect of receiver field of view on the signal-to-noise ratio (S/N) in a photoelectric system which is used to detect the scattered light signal against a uniform background horizon radiance. The limiting noise in the system is assumed to be shot noise caused by the background flux. The relative S/N has been computed for various fields of view for the directional and omnidirectional sources. The results shown in Table 1 indicate a maximum S/N when the angular field of view is 20 min wide and 10 min high for the

Fig. 7 - 50,000-w tungsten omnidirectional source at 45 km (center). The heavy exposure on left is an overexposure of Cove Point Lighthouse located 5 miles away.

Table 1
Relative Signal-To-Noise Ratio as a Function of Field of View*

Field of View (Width x Height)	Relative S/N	Field of View (Width x Height)	Relative S/N
Directional Source			
20' x 5'	2.26	20' x 1°27.5'	1.28
20' x 10'	2.65†	1° x 17.5'	1.73
20' x 17.5'	2.50	1° x 35'	1.42
20' x 35'	1.91	1° x 52.5'	1.23
20' x 52.5'	1.62	1° x 1°10'	1.10
20' x 1°10'	1.42	1° x 1°27.5'	1.00‡
Omnidirectional Source			
24' x 5'	0.69	76' x 5'	0.54
24' x 10'	0.99	76' x 10'	0.83
24' x 15'	1.11	76' x 15'	0.99
24' x 20'	1.13†	76' x 20'	1.06
24' x 25'	1.11	76' x 25'	1.09
24' x 30'	1.10	76' x 30'	1.10
24' x 35'	1.07	76' x 35'	1.11
24' x 40'	1.05	76' x 40'	1.10
24' x 45'	1.03	76' x 45'	1.10
24' x 50'	1.01	76' x 50'	1.09
24' x 55'	0.99	76' x 55'	1.09
24' x 1°	0.97	76' x 1°	1.07
24' x 1°10'	0.93	76' x 1°10'	1.05
24' x 1°20'	0.89	76' x 1°20'	1.02
24' x 1°30'	0.87	76' x 1°30'	1.00‡

*The background is assumed constant over the field. The limiting noise is considered shot noise in the background current.
† Maximum value.
‡ Values normalized to unity for the largest field.

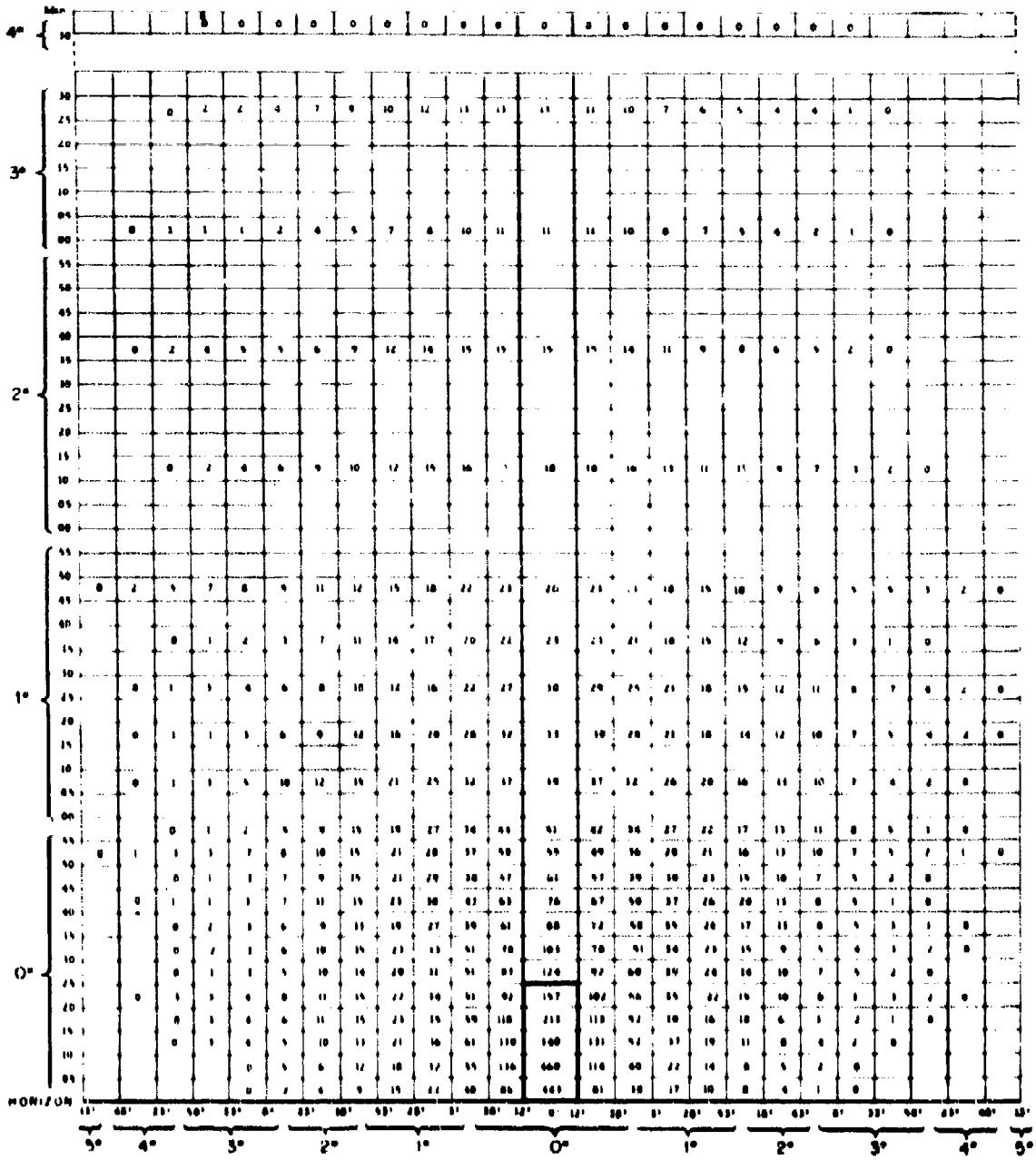


Fig. 8 - Relative intensity pattern of horizon radiance caused by a 50,000-w omnidirectional tungsten light source below the horizon and 45 km away

directional light and 24 min wide and 20 min high for the omnidirectional source, where the horizon radiance is more diffuse. However even when a viewing field as large as 1 degree by 1 degree is used, S/N is degraded (in either the directional or omnidirectional case) by only a factor of 2, so that the limiting system factor will usually be other parameters such as detector overloading and fatigue.

In Fig. 9 the relative vertical intensity through the most intense horizon area is compared for the omnidirectional source and the directional source. The two curves are

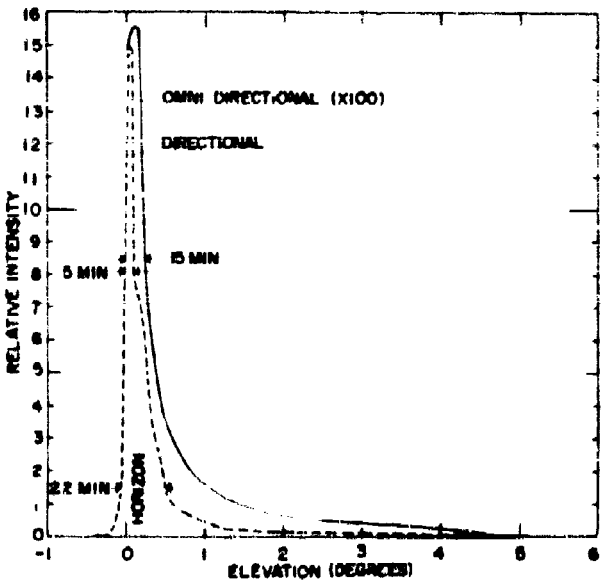


Fig. 9 - Vertical cross section through the region of maximum horizon radiance for directional and omnidirectional light sources below the horizon and 45 km away

normalized for the region 0 min to 10 min elevation. Actually the peak intensity of the directional light is about 100 times that from the 2π source. If one considers the total scattered light, the integrated scattered light from the collimated source is about 30 times that from the 2π source. Or on a power input basis, since 10,000 w in the collimated beam gives 30 times more scattered light than 25,000 w (assuming 50 percent loss to ground absorption) from the 2π source, 1 w in the collimated beam gives about 75 times more scattered light on the horizon than 1 w in a 2π tungsten source. Comparison of the curves in Fig. 9 shows that the relative intensity is greatest near the horizon for both sources and that the radiance from the omnidirectional source decays more slowly as a function of altitude. (The half-maximum intensity point was 5 min above the horizon for the searchlight beam and 15 min above the horizon for the 2π source.) As seen in Figs. 5 and 8 the extent of the scattered light area on the horizon is about the same for both sources of illumination.

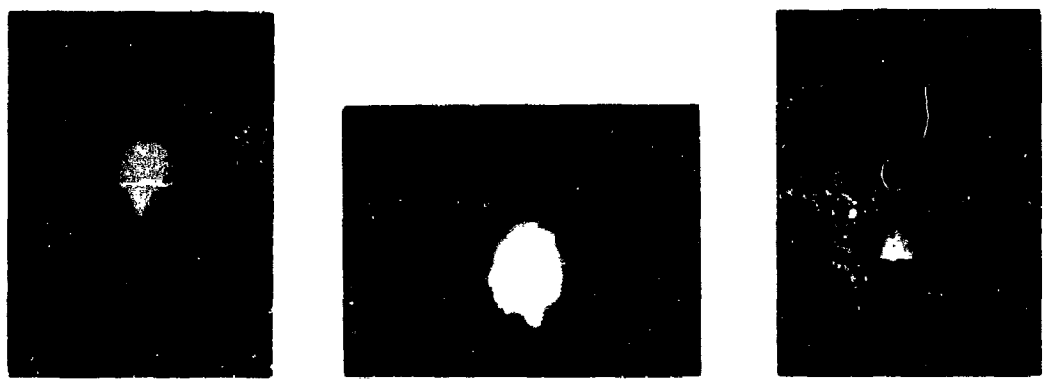
AIRBORNE OBSERVATIONS OF LIGHT SCATTERED FORWARD FROM A SEARCHLIGHT BEAM

On January 20, 1962, an observational flight was made with the purpose of obtaining pictures of a searchlight beam at several distances from the projector. The light source was a 60-in. carbon-arc searchlight with a beam spread of 1 degree. It was situated on the west side of the Chesapeake Bay at a point 40 m above mean high tide and pointed with a 1/2-degree angle in elevation toward the eastern shore on a bearing of 45 degrees. On the night of the experiment the atmosphere was clear and cloudless with a meteorological range of about 30 km, as monitored across the Bay by a transmissometer (11).

Aerial photographs were made at 35 km (900 m altitude) and at 112 km (2100 m altitude). From a knowledge of the geometry of the optical path and of atmospheric refraction and earth curvature, one can compute that the beam axis was 425 m above the ground at 35 km and 1875 m above the ground at 112 km. The lower and upper edges of the beam were 120 and 785 m above the ground at 35 km and were 925 and 2900 m above the ground

at 112 km. Since the photograph at 35 km was made at 0.9 km altitude, the aircraft was about 115 m above the geometrical edge of the beam. A photograph of the beam taken on the ground at the same distance was from a point 120 m below the beam.

Figure 10 shows photographs made from the aircraft and the ground. Figure 10(a) is of the searchlight as photographed from 900 m altitude, 115 m above the upper edge of the beam, at a distance of 35 km from the projector with an exposure of 1/2 sec on 35-mm Isopan Record at f/2.5. In Fig. 10(c), the beam is shown as it appears on the horizon from the ground 120 m below the beam and 35 km from the projector with an exposure of 1 sec on 4 by 5 Royal X Pan at f/4.5. Figure 10(b) is of the searchlight as photographed nearly on axis at 112 km from the projector using an exposure of 1.0 sec on 35-mm Isopan Record at f/2.5. The blurred appearance of Figs. 10(a) and 10(b) is caused by a combination of aureole around the source, atmospheric seeing fluctuations, and aircraft vibration.



(a) Searchlight at 35 km; 0.5-sec exposure at 0.9 km

(b) Searchlight at 112 km; 1-sec exposure at 2.1 km

(c) Searchlight at 35 km; 1-sec exposure at ground level

Fig. 10 - Photographs of a searchlight beam made from an aircraft and from the ground

The original negatives of Fig. 10 have been microphotometered and have been compared to similar calibrated film. This analysis shows that the integrated light collected in 1/2 sec at 900 m, Fig. 10(a), 35 km from the source slightly out of the beam, is about equal to the integrated light collected in 1 sec at 2.1 km altitude, Fig. 10(b), 112 km from the source nearly on axis, which indicates that irradiance at a range of 35 km at a point out of the beam is twice that at a range of 112 km at a point in the beam nearly on axis.

Further analysis shows the integrated light collected in 1 sec on the ground at 35 km is about 80 percent of that collected in 1/2 sec at 900 m altitude slightly out of the beam. From this it can be estimated that the irradiance on the ground, below the beam, was approximately 40 percent of the irradiance at a corresponding point above the beam.

A measurement was intended on the beam axis at the 35-km distance but was unsuccessful because of photographic difficulties. Accordingly, the axial beam irradiance can only be estimated from the measurement made at 112 km and an estimation of the path attenuation. It may be instructive to sketch the attenuation computation, and this is what is done in the following paragraph.

In the computation it is assumed that the vertical density gradient of particulate scatterers is proportional to $e^{-0.77h}$ where h is the altitude in km. The molecular vertical density gradient used was $e^{-0.138h}$. In previous work (10) equations have been developed to calculate attenuation coefficients along slant paths for small elevation angles. The attenuation coefficient for the total slant path length for scattering by particulate materials is

$$\sigma_p = 138\ \rho_0\ e^{(69b)^2} \int_{69b}^{\frac{D}{138}+69b} e^{-y^2} dy \tag{3}$$

where

ρ_0 = attenuation coefficient at the projector in km^{-1}

$b = 0.77 \sin\theta$ (θ = path elevation angle)

D = distance of the total slant path in km

$y = aD + b/2a$ $(a = 1/138)$.

For the tangential path, where $b = 0$:

$$\sigma_p = 138\ \rho_0 \int_0^{\frac{D}{138}} e^{-y^2} dy. \tag{4}$$

The attenuation coefficient for atmospheric molecular scattering along a small-angle slant path is

$$\sigma_M = 326\ M_0\ e^{(113b)^2} \int_{113b}^{\frac{D}{326}+113b} e^{-y^2} dy \tag{5}$$

where M_0 is the attenuation coefficient (km^{-1}) by molecular scattering at the projector. For the tangential path, where $b = 0$:

$$\sigma_M = 326\ M_0 \int_0^{\frac{D}{326}} e^{-y^2} dy. \tag{6}$$

The total attenuation coefficient (σ) along the slant path is the sum of Eqs. (3) and (5). From the estimated 30-km surface meteorological range, attenuation coefficients and transmission values have been calculated for the visible region at 0.55 μ for paths between the projector and points in and out of the beam as shown in Table 2.

From the experimental data and the calculations listed on Table 2 the irradiance on the beam axis at 35 km is computed to have been about 225 times the irradiance at a point 115 m above the geometric edge of the beam and about 550 times the irradiance on the ground.

GROUND-BASED COMPARISON OF DIRECT-LINE-OF-SIGHT IRRADIANCE AND SMALL-ANGLE FORWARD SCATTERED LIGHT

Recently a condition of abnormal atmospheric refraction enabled us to make ground-based observations of irradiance from a 45-km-distant light source which was directly

Table 2
Effective Attenuation Coefficient and Transmission
for Airborne Measurements

Location	Distance from Projector (km)	Attenuation Coefficient (km^{-1})	Path Transmission
Above beam	35	3.85	2.1×10^{-2}
On beam axis	35	4.34	1.3×10^{-2}
On ground*	35	5.12	6.0×10^{-3}
On beam axis	112	8.10	3.0×10^{-4}

*This is computed for the slant paths from the center of the common scattering volume to the projector and to the ground-based camera.

visible above the horizon for a while and later was just below the horizon. The changing abnormal atmospheric refraction caused the light to appear about 5 min of arc above the normal horizon at sunset and then gradually to go below the horizon about 3 hr later. The apparent elevation of a light source which is below the normal horizon is called looming and occurs when a strong temperature inversion exists at the water surface, i.e., when the air temperature increases rapidly with height near the water surface so that the density gradient is more negative than normal. A calculation shows that in order for the source to appear 5 min above the horizon the light path would have to have a radius of about 1/4 the earth radius or a curvature 4 times that of the earth's surface.

Figure 11 illustrates the experimental conditions under which the observations were made. The light source was a 1000-w, 120-cps xenon lamp in a 36-in. projector which gave a 1/2-degree beam and which was pointed horizontally down the Chesapeake Bay toward the receiver 45 km away. Irradiance measurements were made with an RCA 925 phototube, spectrally filtered to have a 2000A optical passband peaked at 8500A. The photocell preamplifier had an electronic passband of 500 kc. The detector was placed at the focus of a 60-cm diameter, 153-cm-focal-length collector mirror which produced a receiver field of view 35 min of arc in width and 45 min in height. It was estimated that a meteorological range of 40 km existed during the observations. When the projector appeared above the horizon the irradiance at the receiver was 8.2×10^{-4} w/cm^2 in the spectral band of the receiver. The scattered light irradiance from the projector just below the horizon was 4.1×10^{-6} w/cm^2, giving an irradiance ratio of 200 for the two conditions. This ratio is somewhat lower than the value of 550 for visible light derived from airborne and ground photographs taken at a distance of 35 km and meteorological range of 35 km described in the previous section and may well have been influenced by some residual abnormal refraction which persisted after the source had sunk below the horizon.

TRANSMISSION OF RUBY LASER LIGHT OVER THE HORIZON

The invention of the ruby laser has aroused much speculation on the use of this powerful light source as a possible means of communication. High peak power output in the range of megawatts and extremely narrow spectral bandwidth would appear to make this source extremely promising for this application.

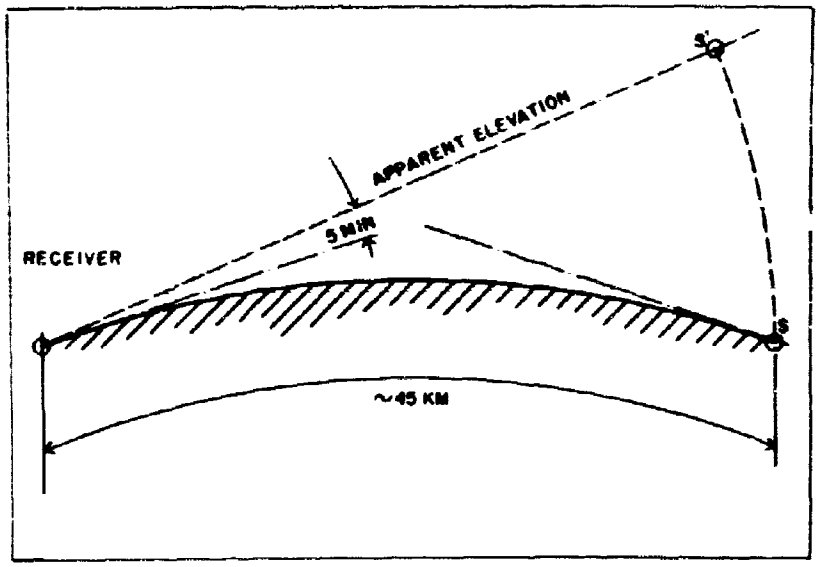


Fig. 11 - Illustration of abnormal atmospheric refraction where S, which is normally well below the horizon, appeared at S', about 5 min above the normal horizon

One of the first possible applications investigated, and reported in NRL Report 5941 (12), was the transmission of ruby laser emission through water. The experiment with ruby light was made at the David Taylor Model Basin in filtered Potomac River water, and this experiment confirmed a previous conclusion that the ruby laser light has extremely limited application for direct underwater communication because of severe attenuation.

When ruby light is considered in the air medium, however, the possibilities are much more favorable than they are in water because of the lower air attenuation factor. For an "ordinary" day with an "average" meteorological range of 25 km, the scattering attenuation coefficient (which depends on meteorological range) for air at 6943A is 1.3×10^{-6} cm^{-1} or about 2.5×10^{-4} that of clear water at the same wavelength.

Another factor to be considered in the transmission of ruby laser light is the effect of atmospheric absorption (13). As seen in Fig. 12 the spectral region of ruby laser emission is rich in atmospheric water vapor absorption lines, and any one of the lines may of course decrease the effective atmospheric transmission if it coincides with the wavelength of the ruby emission. Since the ruby laser emission (14) has been shown to be a function of temperature, it is apparent that if ruby laser light is to be transmitted through the atmosphere, some temperature control must be instituted to insure that the laser emission is at a wavelength free of water vapor absorption. From Figs. 12 and 13 it is clear that the ruby laser emission at room temperature (20°C) is at 6943A and is clear of water vapor absorption. However the emission at liquid nitrogen temperature (-195.8°C) is at 6934A and would be partially absorbed by the broad water vapor absorption line at 6933.8A. In the real situation where the ruby is cooled by liquid nitrogen, but not in intimate contact with the liquid nitrogen, the effective crystal temperature is a few degrees above that of liquid nitrogen and the ruby emission will occur at a region clear of the water vapor absorption line at 6933.8A.

The above remarks apply of course to any mode of propagation of ruby laser light through the atmosphere and are also pertinent to our present concern with forward scatter propagation. We were quite interested in using a laser as a narrow-beam source for

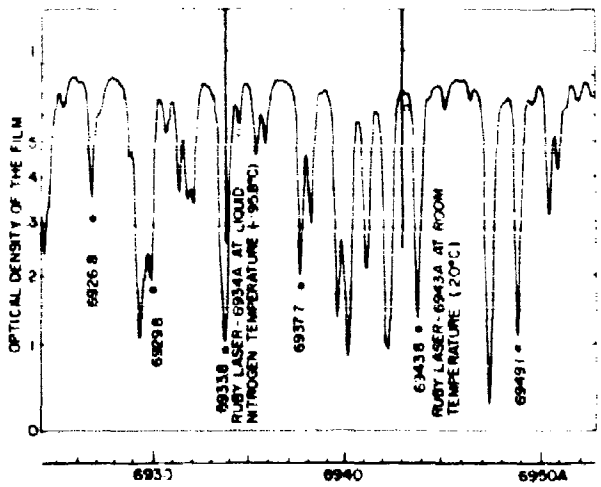


Fig. 12 - Absorption spectrum of 17 km of air at sea level in the spectral region of ruby laser light emission

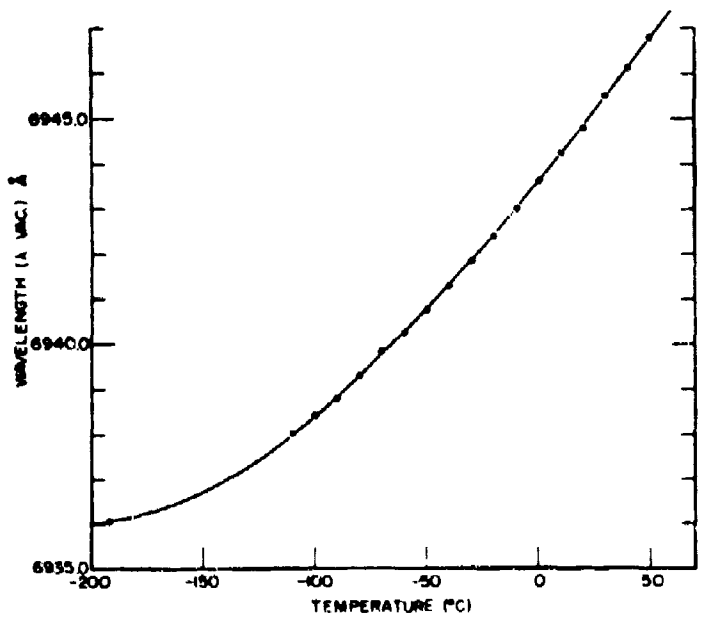


Fig. 13 - Wavelength of ruby laser light emission as a function of temperature (Ref. 14)

over-the-horizon propagation, and arranged a nighttime experiment in which we succeeded in propagating light from a pulsed ruby laser over the horizon down the Chesapeake Bay to a receiver 45 km from the laser with a resultant signal-to-noise ratio of about 35. The laser produced pulses of 0.10 joule in a beam which had an angular divergence of about 45 min and was elevated 1 degree toward the receiver. A detector system consisting of a Dumont 6912 photomultiplier plus a 3020 Corning filter at the focus of a 2-ft-focal-length f/1 collector mirror had a receiving field of 2 degrees and was elevated 1 degree toward the light source. The laser and receiver were about 6 ft above average

tide level. A low haze which blanketed the Chesapeake Bay during the test limited the meteorological range to 8 to 10 km, from which it is estimated that the surface transmission of the 45-km path was about 10^{-5}.

During 1963 the ruby experiment was repeated several times with some modifications in the receiver system and with a more powerful laser. The more powerful liquid-nitrogen-cooled ruby laser source had the following characteristics: output, 1 to 2 joules polarized; pulse length, 0.5 ms, integrated; beamwidth, 0.5 degree; pointing accuracy, within 10 arc-min in azimuth and elevation; wavelength, 6935.2A. The receiver system consisted of an RCA 925 photodiode at the focus of a 80-cm-diameter, 153-in.-focal-length mirror which gave a field of view 1/2 degree wide and 3/4 degree high. A Corning 2403 broadband cutoff filter limited the diode sensitivity to the spectral region from 6300A to 12,000A. A selected amplifier with a passband of from 8 cps to 40 kc helped reduce background noise.

Two experiments were performed. One was at night when the meteorological range was 40 km, and the other was in the daytime when the meteorological range was 20 km. In the nighttime experiment the signal-to-noise ratio was 125, the primary noise source being the amplifier in the receiver system. The daytime measurements, made 2 hours after sunrise, gave a S/N of about 3, where in this case the noise was primarily from the background illumination. It is estimated that with optimum narrow-band spectral and electronic filtering, a S/N of about 500 would be possible under similar daytime conditions with this laser source.

VARIATIONS OF SCATTERED LIGHT SIGNALS WITH RANGE

In addition to concerns about the behavior of forward scattered light from collimated or directional sources, there is also an interest in the light from uncollimated ("2π") sources. The latter were of particular concern in some measurements designed to study the variation of the over-the-horizon signal as a function of separation of source and receiver. Some crude studies of this nature, on directional sources, had been made earlier (10), and an attempt to predict the variation of signal with range had been made.

The variation of relative forward scattered flux with distance involves many factors, of which the most important are aerosol concentration as a function of altitude, scattering volume, cloud cover, and atmospheric slant path transmission. Of secondary importance are such factors as Rayleigh scattering and attenuation, and variation of scattering as a function of scattering angle. However where the separation distance does not exceed 90 km, the important factors which affect the relative signal strength are attenuation and the inverse-square loss, because variations in the other factors are relatively small for these short distances.

Recent measurements have used as a light source a high-intensity xenon flash lamp mounted about 10 ft above water level on the cabin of a small boat as shown in Fig. 14. This lamp was operated at 6000 joules input, which gave a 1-ms light pulse into 2π steradians. During the nighttime measurements the boat traveled a course across the Chesapeake Bay from CBA (the Chesapeake Bay Annex of NRL) and up the Choptank River for a total straight-line separation of 41 km. The receiving system, which had a 3-degree field of view, consisted of an S-1 surface photomultiplier at the focus of a 61-cm, f/1 collector mirror and was situated on shore about 3 m above mean water level. The meteorological range was monitored by a transmissometer operated over a 17-km path across the Bay.

Figure 15 is representative of data collected to date. The circled points represent data for "visible light" in the wavelength range 3500A to 6500A and the dotted points are for light between 7000A and 11,000A (near infrared). In the figure the data have been

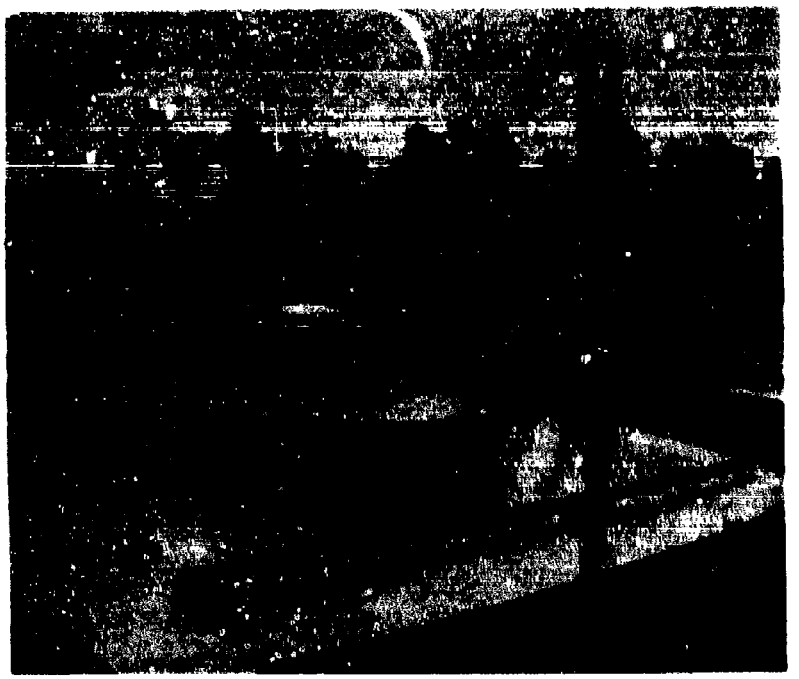


Fig. 14 - Boat-mounted flashlamp used in making measurements of scattered light as a function of distance

normalized at 5 km and the meteorological range was 13 km for both runs. Initial data points are at 4 km, at which distance the light was well above-the-horizon. The discontinuity at 11 km indicates the point where the light went below the horizon. Examination of the data shows that the near-infrared signal decayed at a slower rate than the visible signal up to the horizon discontinuity, underwent a greater loss at the horizon, and then became relatively stronger than the visible signal as the light source moved further beyond the horizon. The solid curve in Fig. 15 represents computed relative signals for visible light, normalized at 5 km, for direct-line-of-sight observation of the lamp excluding aureole (scattered light) and considering inverse-square and attenuation losses when the meteorological range was 13 km. Up to 11 km, the visible signals, which are direct plus aureole light, follow the curve fairly well up to the horizon break. Immediately beyond the horizon the signals are from aureole only and are relatively lower than the predicted values for direct-line-of-sight observation. However beyond 20 km the observed visible scattered light signals are stronger than the computed direct-line-of-sight signals for the experimental meteorological range of 13 km. At 41 km there was an observed S/N of 10 for visible light.

In Fig. 16 the data are for visible light observations made when the meteorological ranges were 13 km and 65 km. All data are again normalized to 5 km by multiplying the 13-km data by 3.7. The dashed curve, similar to the solid curve in Fig. 15, is a curve computed for line-of-sight signal with the assumption of a meteorological range of 65 km. The 65-km data follow the curve out to the horizon, while beyond the horizon the observed signal is relatively much weaker, which indicates a small ratio of scattered to direct light when the meteorological range is high. The data indicate that at the horizon the aureole signal is 20 percent and 5 percent of the total signal when the meteorological range is 13 km and 65 km respectively. An interesting feature of these data is the unexplained identical ratio of the normalized signals from 5 km to 11 km that exists for the two widely separated meteorological ranges.

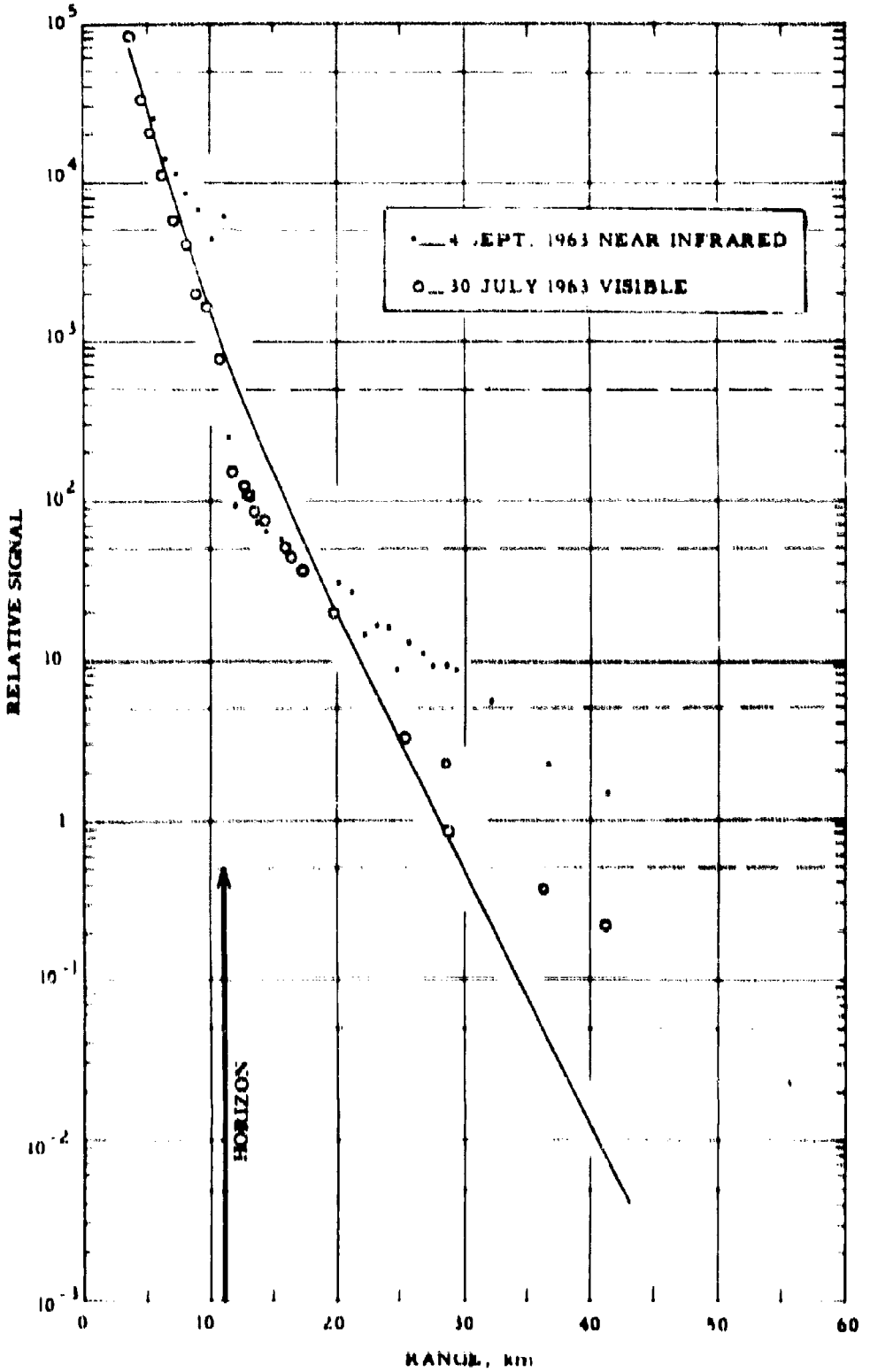


Fig. 15 - Behavior of scattered light at night as a function of distance for visible (4700A to 7000A) and near infrared (7400A to 10,000A) radiation when the meteorological range was 13 km

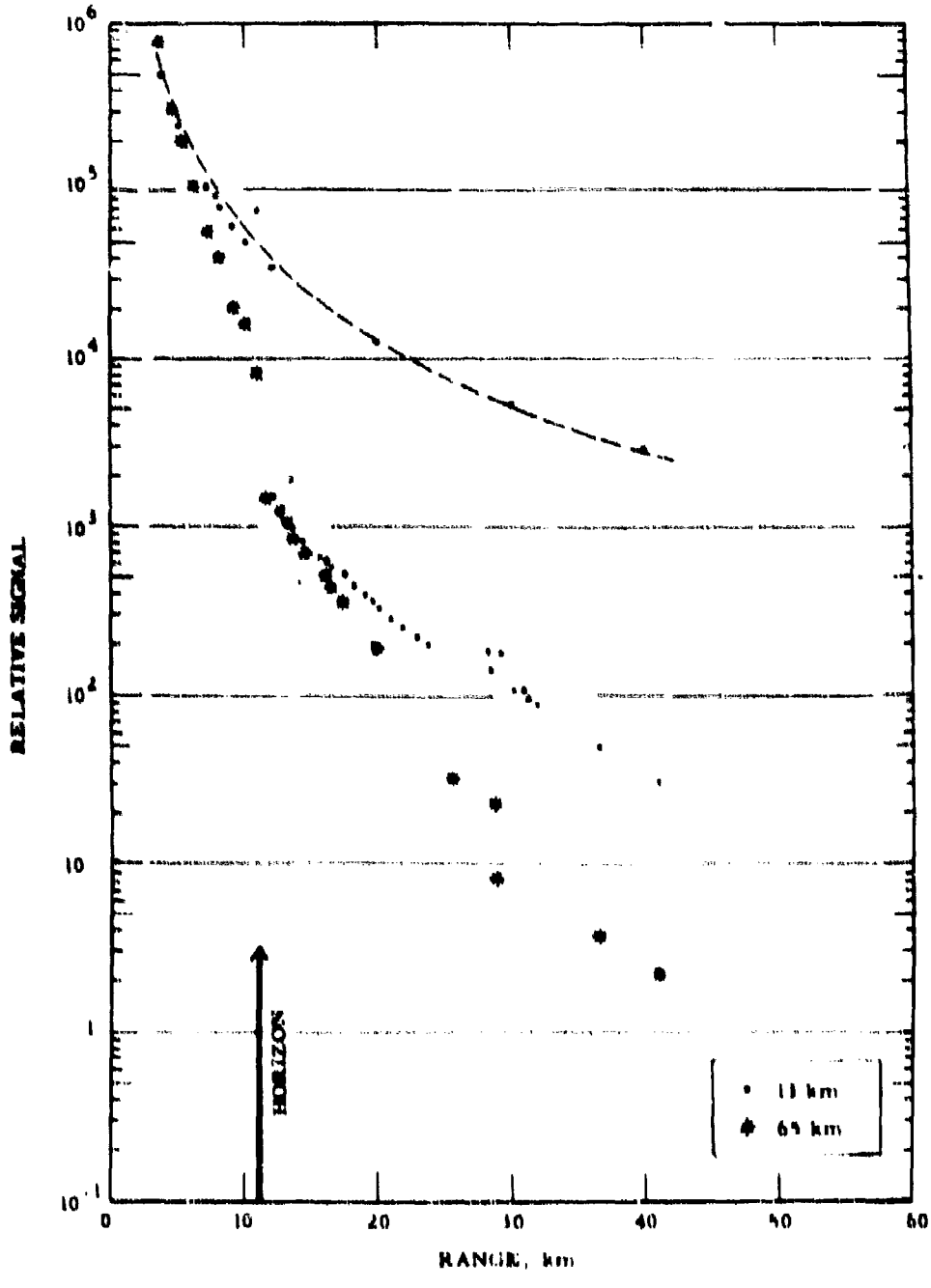


Fig. 16 - Behavior of scattered light as a function of distance for visible radiation (4700A to 7000A) when the meteorological range was 13 and 65 km

Figures 17 and 18 show data from a run made on September 30, 1963, where simultaneous measurements were made in the wavelength intervals 4700A to 7000A and 7400A to 10,000A by the 3-degree-field-of-view dual-channel detection system illustrated in Fig. 19. During the run, which extended over 90 km in a northerly direction up the Chesapeake Bay, the meteorological range changed from 32 km at the beginning of the run at 7:00 p.m. to 13 km at 10:00 p.m., when the light source was 55 km from the receiver. Range was determined by radar out to 40 km and by navigation markers beyond this point. The meteorological range changed within a period of about 15 min at 10:00 p.m. and then held steady at about 13 km to the end of the run at 4:00 a.m. Examination of Figs. 17 and 18 shows a discontinuity in the relative signals beginning at about 55 km, the range at the time the meteorological range began to drop. This also indicates that the change in meteorological range was general throughout the Northern Bay Area, since the meteorological range was actually monitored only across the Bay at a point near the receiver where the Bay is 17 km wide.

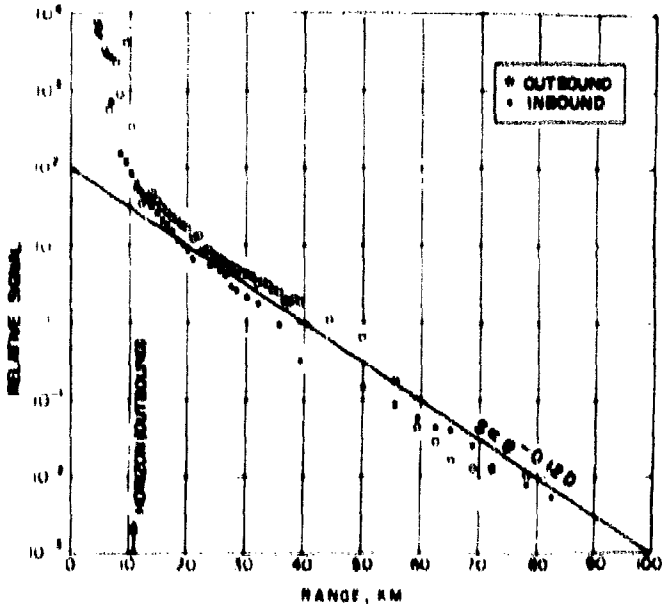


Fig. 17 - Behavior of visible radiation (4700A to 7000A) as a function of distance out to 82 km

As shown in Figs. 17 and 18 the visible signal was detected out to 83 km, where S/N was unity, while the infrared signal was detected out to 89 km where S/N was 2. Comparison of the data for the two spectral regions shows that the signal attenuation factor between 4 km and 83 km was 1.4×10^6 for visible (4700A to 7000A) light and 1.8×10^5 for infrared (7400A to 10,000A) radiation. The straight line through the data from below the horizon for visible light in Fig. 17 indicates an effective attenuation coefficient of about 0.12 km^{-1}, which is lower than the value obtained from the monitor transmissometer. In Fig. 18, which is for the infrared channel, the effective attenuation coefficient is 0.09 km^{-1}, which is 25 percent lower than for the visible channel. Measurements which were made on the outbound run, when the meteorological range was 32 km, indicate that at the horizon, the visible and infrared aureole contributions to the signal were about 23 percent and 9 percent respectively. On the inbound run, when the meteorological range was 13 km, the visible horizon discontinuity appears to be washed out, so that at the

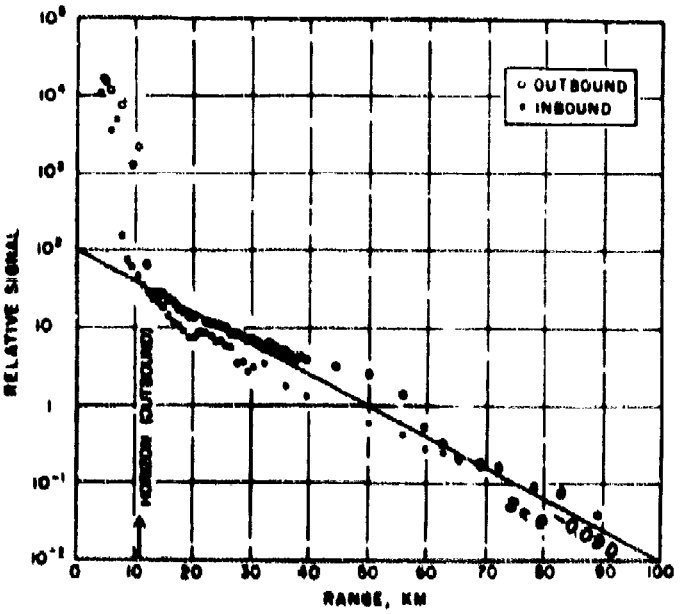


Fig. 18 - Behavior of near infrared radiation (7400A to 10,000A) as a function of distance out to 89 km

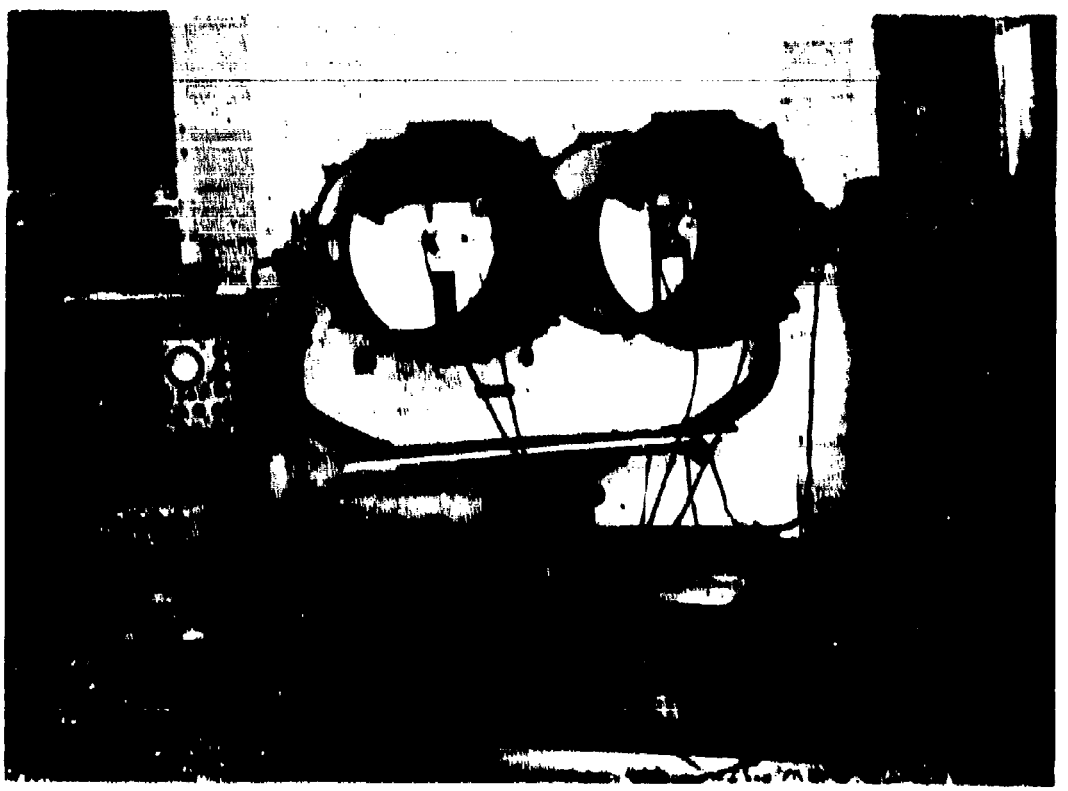


Fig. 19 - Dual-channel detection system used for scattered light and measurements

horizon, there is almost 100 percent aureole. In the infrared channel, there is an aureole of about 10 percent at the horizon; the signal discontinuity occurs at about 8 km, indicating a refraction change between the outgoing and incoming runs.

The experiments with the infrared channel have also been carried out in daytime to ranges of 22 km when the meteorological range was 15 km (Fig. 20). The runs were made in midday with the receiver pointed horizontally toward the eastern horizon. These daytime data show much irregularity, presumably because of refractive effects near the water surface. The variation in the distance to the horizon for the two runs is also a refractive effect. Detector noise caused by the high background illumination limited the detection range to 22 km, whereas at night the signal could be detected out to a range of 89 km when the meteorological range was 13 km.

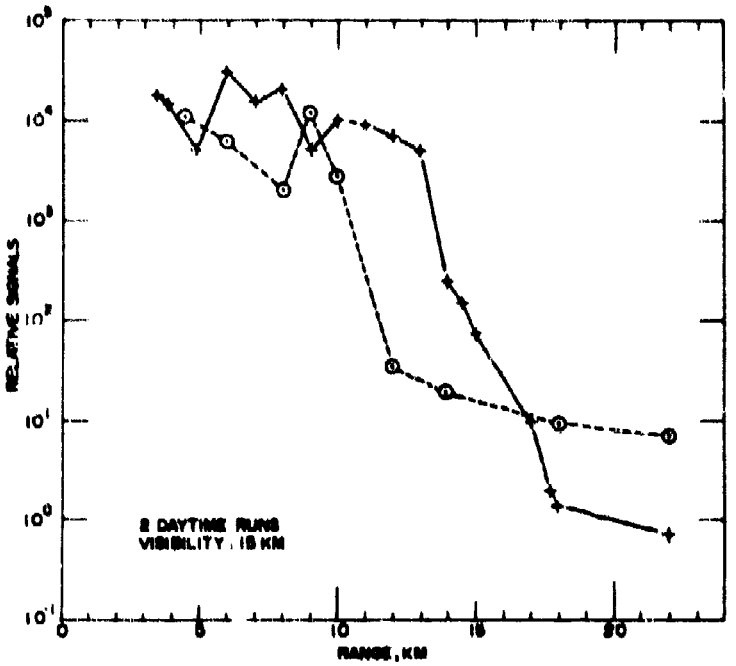


Fig. 20 - Behavior of near infrared radiation (7500A to 9500A) as a function of distance from daytime measurements

CONTINUOUS MONITORING OF AN OVER-THE-HORIZON LINK

Recently we have attempted to measure signals over-the-horizon on a night-and-day, around-the-clock basis along the overwater 45-km path between Tilghman Island and Cedar Point. The light source was a 120-cps ac mercury-xenon 1000-w compact arc source in a 36-in. f/0.33 projector which gave a beam 45 min wide and 70 min high which was pointed horizontally toward the receiver. The receiver consisted of a 925 phototube at the focus of a 153-cm-focal-length, f/5 collector; it was optically filtered to receive radiation in the spectral region 7500A to 9500A. Electronic filtering limited the frequency

response of the receiver system to a narrow band around 120 cps. A calculation based on the lamp manufacturer's data sheet (15) shows that the mercury-xenon lamp emits about 35 w in the spectral interval 7500A to 9500A.

Table 3 gives the available statistics, which were acquired with some difficulty. One unforeseen difficulty was the accidental closing of the trailer door on two occasions during periods of good meteorological range! An estimate of these lost data is included in the summary of Table 3. The meteorological range during the experiment was 20 km or better when the signal was received and 8 km or less during the periods of no signal reception. The accidental shutdowns occurred during periods of good meteorological range and have been included as times of probable receptions. The percentage time of signal reception compares favorably with Coast Guard nighttime visibility data (16) on the Chesapeake Bay which indicates that visibilities of 16 km or greater will prevail for 85 percent of the time (Table 4). (We assume that the Coast Guard definition of visibility corresponds to our definition of meteorological range.)

Table 3
Summary of Continuous Over-the-Horizon Monitoring
During a 168-Hour Run

	Monitor Time (hr)	Signal Received (hr)	Signal Received (percent of time)
Values for Time Trailer Door was Open			
Night	42	26	62%
Day	60	34	57%
Probable Values After Estimating for Periods Door was Accidently Closed			
Night	70	56	80%
Day	98	70	71%
Total Time . . .	168	126	75%

The records also reveal an unexpected fluctuation in the strength of the recorded signal. The appearance is of low-frequency scintillation which at times became quite intense. The fluctuation showed some indication of decreasing in intensity around sunrise and sunset - periods of relative thermal stability. It is possible that these fluctuations were in fact vertical wanderings of the narrow searchlight beam.

DETECTION OF FORWARD SCATTERED SIGNALS IN THE DAYTIME

The Theoretical Problem

In the concept of signaling over the horizon in daylight by means of scattered light, the problem is fundamentally one of detecting a small modulated signal in the presence of a large, relatively steady, dc background. The noise limit in this type of arrangement will ideally be shot noise in the background, and the system designer has the problem of maximizing his signal-to-noise ratio.

Table 4
Nighttime Visibilities at Various Coastal Points in the United States
(From Ref. 16)

Location	Percent of Time a Given Visibility Will Prevail	
	16 km	8 km
Coast of Maine (except Penobscot Bay)	72%	86%
Penobscot Bay, Maine	65%	80%
Massachusetts Bay	83%	87%
Nantucket and Vineyard Sounds	52%	78%
Long Island and Block Island Sounds	73%	86%
Lower New York Bay	80%	88%
Atlantic Coast: New Jersey to Cape Charles, Virginia	76%	87%
Delaware Bay and Entrance	85%	92%
Chesapeake Bay Entrance	80%	96%
Chesapeake Bay	85%	94%
Atlantic Coast: Cape Henry, Va., to Charleston, South Carolina	92%	93%
Atlantic Coast: Charleston, S.C., to Key West, Fla. (includes Greater Antilles)	95%	96%
West Coast of Florida: Key West to Tampa Bay	95%	96%
Gulf of Mexico	89%	94%
Southern California Coast: Eleventh C.G. District	78%	88%
California Coast: Twelfth C.G. District except San Francisco Bay Entrance	68%	82%
San Francisco Bay and Entrance	70%	86%
Coasts of Oregon and Washington except Columbia River Entrance	90%	95%
Columbia River Entrance	89%	92%
Straits of Juan De Fuca and Georgia of Washington	81%	90%
Puget Sound, Washington	87%	95%
Admiralty Inlet, Washington	82%	95%
Hawaiian Islands	95%	96%
Southeastern Alaska, Inside Passages	93%	95%
Lake Ontario	82%	94%
Lake Erie	75%	88%
Detroit River, Lake St. Clair, and St. Clair River	93%	96%
West Shore of Lake Huron and Straits of Mackinac	76%	90%
Lake Superior	91%	93%
Lake Michigan	80%	89%
Green Bay and Entrance, Wisconsin	87%	93%

There is of course another requirement - that there be enough signal to measure. Signal-to-noise calculations can sometimes be misleading unless the signal level is also considered.

If we consider a photoemissive detector with a cathode spectral responsivity S_λ (amperes per watt), viewing a background of spectral radiance N_λ (watts per steradian per unit area per unit wavelength interval) through a filter of spectral transmittance T_λ, and assume that the receiver field of view is Ω steradians, then the cathode current I due to the background is

$$I = 10^6 \int_0^\infty A\, S_\lambda\, N_\lambda\, \Omega\, T_\lambda\, d_\lambda \ \mu\text{amperes} \tag{7}$$

where A is the area of the flux-collecting objective. This current will give rise to a shot-noise fluctuation current I_n whose rms value is

$$I_n = 5.7 \times 10^{-7} \left[I(\mu\text{amp})\, \Delta f \right]^{1/2} \text{amp} \tag{8}$$

where Δf is the electronic communication bandwidth. The actual noise level in the system may exceed this if there are fluctuating components in the background. The magnitude of background fluctuations for sky background is presently the subject of some uncertainty. There are some indications that, at least for clear skies, the inherent fluctuations are very small. There are, however, some experimental groups which insist that daylight photoelectric systems are always limited by fluctuations in ambient light. This problem obviously needs clarification. For the present effort we assume that the limiting system noise will be that given by Eq. (8).

The signal will have some spectral radiance distribution $n_\lambda(\alpha, \beta)$ on the horizon, where α and β are altitude and elevation angles measured from some appropriate reference position. The signal in the system will be given by

$$10^6 \int_0^\infty \oint_\Omega A\, n_\lambda\, T_\lambda\, S_\lambda\, d\Omega\, d\lambda \ \mu\text{amp} \tag{9}$$

where the angular integral is taken over the field of view Ω. The signal-to-noise ratio is thus given by the expression:

$$\frac{A^{1/2} \int_0^\infty \oint_\Omega n_\lambda\, T_\lambda\, S_\lambda\, d\Omega\, d\lambda}{5.7 \times 10^{-7} \left[\left(\int_0^\infty S_\lambda\, N_\lambda\, T_\lambda\, \Omega\, d\lambda \right) \Delta f \right]^{1/2}} \tag{10}$$

which is a peak-to-peak, rms ratio and automatically implies that the system bandwidth is adequate to handle the peak-to-peak signals without distortion. If this is not so, one must take the signal Fourier components which fall within the communication passband.

Collector Area

Equation (10) shows that the signal-to-noise ratio improves with an increase in the dimensions of the receiver objective but that it improves only linearly, i.e., as the square root of the area. Accordingly one always wishes to use the largest feasible

collector. Probably, any "practical" system will use collectors smaller than 1 m in diameter. It will certainly not use a collector larger than 2 m in diameter.

Field of View

It seems axiomatic that one should reduce the angular field of view of the receiving system to include only those portions of the background which include signal components, but this can be formally shown to follow from Eq. (10). The argument is simply that a reduction of the acceptance solid angle from Ω_1 to Ω_2 causes a decrease in noise proportional to $(\Omega_2/\Omega_1)^{1/2}$ for a field of uniform background radiance. However if all of the signal is contained in the smaller field Ω_2, then no loss of signal is incurred in passing from Ω_1 to Ω_2. The net result is of course an increase in the signal-to-noise ratio. If the signal is distributed in some arbitrary fashion through the observed background field, then an elaborate calculation may be required to determine the optimum field of view. If the signal is well localized, then the field of view can always be narrowed if the problem is fixed-point-to-fixed-point communication, but reduction of the field may not be possible if either or both points are movable. In the latter case it may be necessary, for operational reasons, to open the field of view to well beyond the optimum. We shall, however, assume the fixed-point-to-fixed-point situation for scattered light communication. Earlier in this report (see Fig. 5) it was shown that the effective signal field, on the horizon, will be relatively small in angular subtense, but Table 1 indicates that there is a considerable latitude in the choice of field and that for fields up to 1 square degree the S/N variation is only of the order of a factor of 2. This conclusion may require modification if the conditions are other than those which prevailed at the time of the taking of the data in Table 1. However a decrease in meteorological range should effectively result in a broadening of the signal field; hence, one will not find it necessary to go to smaller fields as the weather worsens. The choice of a moderate field — 1/2 to 1 degree wide and 1/2 degree high — should be adequate.

Optical Filtering

The optical bandwidth may also be modified to maximize the signal and minimize the noise. If the background is relatively continuous spectrally, as in the sky, then an ideal situation would involve a relatively monochromatic signal. The product $T_\lambda S_\lambda$ (Eq. (9)) may then be adjusted to be significant only in a narrow region $\Delta\lambda$ around the signal wavelength, and signal-to-background discrimination is thus improved. Note, however, that if $\Delta\lambda$ is relatively broad (approximately 1000A) and the background is a continuous source like the sky, then crudely speaking the S/N difference for a wide-band source and a narrow-band source, each of the same total power, is about inversely equal to the square root of the optical passband. Going to a 10A-wide filter would probably decrease the noise by a factor of 10.

It should also be noted however that the current state of the art will not allow a significantly greater reduction in any simple manner. In principle, one could go to dispersing systems for spectral resolution, and it is probable that this is the only presently available technique which might approach the advantages to be expected from the very narrow line widths associated with lasers. It is quite reasonable to ask for a dispersing system with a spectral resolution of 0.1A. It appears to be unreasonable however to ask for this spectral resolution and a relatively wide field of view plus an adequate flux collection efficiency; these elements simply are not compatible. Hence, it is difficult to do very-narrow-band optical filtering in many flux collecting systems. This cannot be elaborated on here, but it is a practical problem which is frequently lost sight of in casual theoretical estimates. For example, if the spectral filter is a flat, narrow-band, interference filter, its passband is dependent on the angular divergence of the light which passes through it, and the bandwidth specification places a restriction on the allowable

divergence. For a fixed size of filter, this in turn puts interconnecting limitations on the angular field of view and the size of the collector, which are in turn related to detector size and system f/number.

The above digressions led us away from the fact that, all other things being equal, the concept of optical "narrow-banding" combined with adequate monochromatic sources can be expected to provide about one-order-of-magnitude improvement in S/N in the daylight case. It has frequently been suggested that for daylight signaling one might use a very narrow spectral line centered in a black Fraunhofer solar line. Because the Fraunhofer lines are not "black," there is a theoretical limit to this concept, and it is roughly about another ten-fold improvement in S/N, with all other things being equal and the analysis being made on the above terms. There remain however severe practical difficulties of the nature of those described above in the narrow-filter discussion.

Atmospheric Attenuation

There is the remaining problem of atmospheric attenuation, which is undoubtedly the controlling factor, because it is an exponential function and small changes in attenuation coefficient are equivalent to very large changes in S/N. To determine the feasibility of daytime operation over the horizon, one needs to know how signal depends on atmospheric transmission. Table 5 presents transmission values computed for four wavelengths over a 45-km path as a function of meteorological range. These computations are based on spectral attenuation coefficients which are typical of a 45-km (meteorological range) day and which were adjusted to other meteorological ranges by adding or subtracting, for each coefficient, the differential at 0.55μ. In addition, the effect of scattering or transmission has been approximated by including a contribution which varies linearly with the scattering coefficient σ; i.e., $T \propto e^{-\sigma d}$. The choice of the words "typical day" must be qualified somewhat, because there is no simple relationship between meteorological range and the spectral attenuation curve. Studies (17) made in the Chesapeake Bay area have shown wide variations in the σ vs λ curves. The data in Table 5 are, however, better than qualitative and at least show a correct wavelength trend and the magnitude of the attenuation handicap which must be overcome.

It will be noted that there is a general improvement as one moves to longer wavelengths, and this is a result of the general behavior of the atmospheric spectral attenuation coefficients, which tend to decrease with increasing wavelength for hazy days (18).

Table 5
Over-the-Horizon Transmission Factors to be Expected for Various Meteorological Ranges and Wavelengths

Meteorological Range (km)	$T_{0.55\mu}$	$T_{0.69\mu}$	$T_{0.85\mu}$	$T_{1.06\mu}$
45	2×10^{-2}	5.3×10^{-2}	7.7×10^{-2}	1.7×10^{-1}
27	2.5×10^{-3}	1.2×10^{-2}	2.3×10^{-2}	8.9×10^{-2}
20	3.3×10^{-4}	2.9×10^{-3}	7.1×10^{-3}	4.3×10^{-2}
10	9.7×10^{-8}	8.1×10^{-6}	4.5×10^{-5}	1.6×10^{-3}
5	4.2×10^{-15}	2.9×10^{-11}	8.9×10^{-10}	1.2×10^{-6}
2	1.1×10^{-37}	4.1×10^{-28}	2.2×10^{-24}	1.3×10^{-16}

This does not imply that infrared "penetrates fog" better than visible light - fog is relatively nonselective - but it acknowledges that ordinary atmospheres do tend to be somewhat selective in transmission and favor the red-to-near-infrared region. In general, then, if there is a choice of wavelength allowed, one should move into the near infrared to maximize the available signal.

There are really no other things that can be conveniently done to improve S/N. It is taken for granted that the source power is as great as it is possible to obtain. It should be emphasized that power, not intensity, is the key requirement. For line-of-sight problems, intensity (power per solid angle) is the governing quantity, but this is not so in the scattered light case. Thus low-power cw gas lasers would seem to be of little practical value in over-the-horizon problems.

Estimate of Noise and Signal

It is of interest to estimate the characteristics of a typical detection system in daylight. We assume the following system parameters:

Collector area (A) = 3×10^3 cm^2 (2-ft diameter)

Field of view (Ω) = 1.5×10^{-4} steradian (3/4 degree by 1/2 degree

Detector (S) = 1.4×10^{-3} amp/w (S-4 diode)

Sky spectral radiance N_λ = 10^{-6} w/cm^2-steradian-angstrom (agrees with measured values)

System transmission (T) = 0.5

Optical filter passband ($\Delta\lambda$) = 3×10^3 angstrom

Electronic passband (Δf) = 50 cps.

The background dc current I is given by

$$I = A\,\Omega\,S\,N_\lambda\,\Delta\lambda\,T \text{ amperes}$$

$$= (3 \times 10^3)\ (1.5 \times 10^{-4})\ (1.4 \times 10^{-3})\ (10^{-6})\ (3 \times 10^3)\ (0.5)$$

$$= 9.5 \times 10^{-7} \text{ amp}$$

$$= 0.95\ \mu\text{amp}. \tag{11}$$

The rms shot noise cathode current I_n is

$$I_n = 5.7 \times 10^{-7}\ (0.95 \times 50)^{1/2}$$

$$= 5.7 \times 10^{-7} \times 6.9 = 3.9 \times 10^{-6}\ \mu\text{amp}. \tag{12}$$

We might pause here to note that the technical problem is to detect a fluctuation of the above order of magnitude (10^{-6} μamp) in a current of about 1 μamp. With current of 1 microamperes into a load resistance of r ohms, it is necessary to have (independent of the passband)

$$r^{1/2}\,(I)^{1/2} > 2.25 \times 10 \tag{13}$$

in order to have the shot noise exceed the thermal noise in the load. In the present case $I \approx 1\,\mu$amp. Therefore

$$r \quad .1 \times 10^{4}\,. \tag{14}$$

The system should be quite capable of handling 50 cps with a load impedance considerably larger than the 51,000 ohms that Eq. (14) states is necessary. If, in a system of this sort, it becomes necessary for some reason such as the preservation of high-frequency response to keep r below the value given in Eq. (14), then it will be necessary to resort to some amplification of the cathode current by secondary multiplication before it is delivered to the load resistance and the amplifier.*

The peak-to-peak noise will be taken to be about 4 times the rms value†; hence the peak-to-peak signal must be of the order of $1.C \times 10^{-5}\,\mu$amp to be equal to noise and 3 times this to be readily detectable, or the peak-to-peak signal must be about 5×10^{-5} μamp. This corresponds to an input power of

$$\frac{5 \times 10^{-5}\,\mu\text{amp}}{1.4 \times 10^{-3}\,\mu\text{amp}/\mu\text{w}} = 3.6 \times 10^{-8}\ \text{w}$$

to the detector. This in turn corresponds to 7.2×10^{-8} w in the collector ($T = 0.5$) and a collector irradiance of

$$\frac{7.2 \times 10^{-8}}{3 \times 10^{3}} = 2.4 \times 10^{-11}\ \text{w/cm}^2$$

at the collector aperture.

If we assume that the source is a directed one and that the scattered light is distributed on the horizon in a pattern such as indicated by Figs. 4 and 5, then 25 percent of the flux (or 6×10^{-12} w/cm^2) is contained in an area 20 min by 5 min or 5.5×10^{-6} steradian. This requires

$$N \times 5.5 \times 10^{-6} = 6 \times 10^{-12}$$

which yields

$$N = \frac{6 \times 10^{-12}}{5.5 \times 10^{-6}} = 1.1 \times 10^{-6}\ \text{w/cm}^2\text{-steradian}$$

as the required apparent peak radiance of the horizon in the bright central core due to the source.

Earlier in this report it was estimated from Fig. 4 that under the measured conditions the bright central spot was about 2×10^{-3} times as radiant as the daylight horizon, and if the daylight horizon is taken to be about 3×10^{-3} w/cm^2-steradian in the region from 4500A to 7000A, one estimates that the spot radiance corresponded to about 6×10^{-6} w/cm^2-steradian. The above estimate indicates that a peak-to-peak signal which corresponded to a central radiance of about 10^{-6} w/cm^2-steradian could be detected in the daytime under the assumed conditions. This would correspond therefore to a source with a peak power about 1/5 that of the dc power of the carbon arc.

*It is assumed that the output from the load resistance is always amplified by a device whose intrinsic noise limit is lower than the thermal noise in the input load resistance.

†For Gaussian noise and average observing periods one expects a factor of between 3.5 and 4.0; we chose 4 to be pessimistic.

If the source were a pulsed ruby laser source, it would be necessary to open the electronic passband about 800 times to 40 kc with a consequent increase in noise of 28 times. This would require an irradiance of 8.1×10^{-10} w/cm^2 at the collector, or a laser peak power about six times that of the dc power from a carbon arc.

These estimates are not too far from the available measurements described earlier. That is, a carbon-arc has about 5000 w in the beam, and under essentially the conditions assumed about a modulated xenon arc with about 500 w in the beam was detected in daylight with a 30-cps passband, and a ruby laser of about 10,000 w peak power was detected in daylight with a 40-kc passband. The ratio of peak-to-peak signal to peak-to-peak noise was about 3 in each case.

An irradiance of 4×10^{-6} w/cm^2 for a meteorological range of 40 km was measured for the modulated xenon arc. The computation above suggests that an irradiance of about 3×10^{-11} w/cm^2 would be detected; hence an attenuation increase of about 10^5 could be tolerated. That is, the meteorological range could have decreased to about 8 km (Table 5, 0.85σ) and the signal would have been detected. For a ruby laser, one requires about 8×10^{-10} w/cm^2, which would require about a factor of 30 less in attenuation and a meteorological range between 15 and 20 km.

It appears therefore that daylight, point-to-point, scattered light signaling is feasible over ranges of about 45 km for meteorological ranges of the order of 15 km or more. The signaling could be at Morse code rates, using available sources, and could be at audio rates if adequately modulatable sources are available. The best region of the spectrum would be the near infrared. Source powers of the order of kilowatts would be required for broadband sources and megawatts for short-pulse sources. The requirement that the field of view be relatively small and that the source be collimated would probably preclude using this type of scattered light communication from ship to ship. It is of interest to note that in the Chesapeake Bay region, as indicated earlier, it would be expected that a point-to-point scattered light communication system would be operable 85 percent of the time, on the average. The scintillation observed in the scattered beam might be expected to degrade the signaling possibility, but our opinion is that this degradation will not be severe and that the above estimates are reasonable.

SUMMARY

This has been an account of various experiments concerned with forward scattered light in the lower atmosphere. Several measurements of irradiance when a light source was above and below the horizon indicate a ratio of 200 between the signals received in the wavelength interval 7500A to 9500A when the light source was above the horizon and when the light source was below the horizon at a distance of 45 km with a meteorological range of 40 km. On another occasion the ratio was 500 for visible light at a distance of 35 km and a meteorological range of 35 km.

Over-the-horizon experiments concerned with the spatial distribution of forward scattered light on the horizon show that with an omnidirectional source below the horizon 45 km from the receiver 5 percent of the total horizon flux was concentrated in a small area 25 min by 25 min on the horizon. When the light source was a 1/2-degree collimated beam, a small area 20 min by 17-1/2 min on the horizon contained 50 percent of the total flux.

Over-the-horizon signals as a function of distance have been investigated using an omnidirectional light source. The signal strength decreases inversely with the square of the range and with an exponential attenuation out to the horizon point, where there is a discontinuity which is a function of the meteorological conditions and is greatest when the meteorological range is high. Beyond the horizon the signal decay is influenced

mostly by attenuation loss when the meteorological range is low (13 km) and primarily by inverse square loss when the meteorological range is high (60 km).

Several experiments have been performed using a low-power ruby laser source in daytime transmission along a 45-km over-the-horizon path. A signal-to-noise ratio of 3 was obtained in daytime with a 1 to 2 joule laser when the meteorological range was 20 km. A nighttime measurement gave a signal-to-noise ratio of 45 using a 0.10-joule laser when the surface transmission at the ruby laser wavelength was about 10^{-5}.

From the results of these various measurements it appears probable that a limited day-and-night over-the-horizon communications system is possible from point to point, with the light being propagated over the horizon by forward scattering by the naturally existing aerosol in the lower atmosphere. Preliminary tests on a continuous day-and-night basis along the 45-km overwater path with a collimated source have yielded encouraging results in which the signal was detected 75 percent of the time when the meteorological range was 20 km or greater. The signal was not detected when the meteorological range was 5 km or less.

A theoretical discussion of the problem of detecting forward scattered light in daytime shows that estimated results agree with the available experimental data. Considerations of the feasibility of using over-the-horizon propagation as a communication link leads to the conclusion that point-to-point communication at Morse Code rates is currently possible over ranges of the order of 45 km in daytime for meteorological ranges of 15 km or more.

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13 ABSTRACT

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1. Light scattered forward from a 50.000-w omnidirectional light source, when viewed from a point 45 km away below the horizon, was distributed on the horizon in a field 5 degrees high and 10 degrees wide. A small area, 25 min by 25 min on the horizon in the line-of-sight direction, contained 15 percent of the total horizon intensity.

2. Light scattered forward from a 10,000-w collimated carbon-arc light source which had a 1/2-degree beamwidth, was directed tangentially, and was observed from a point 45 km away below the horizon was distributed on the horizon in a field 5 degrees by 10 degrees. A small area 20 min wide and 17-1/2 min high on the horizon in the line-of-sight direction contained 50 percent of the total horizon intensity.

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3. Airborne observations of forward scattered light from a searchlight beam 1/2 degree wide yielded an on-axis irradiance, at a range of 35 km from a horizontally pointed source, 550 times the irradiance at a point 115 meters above the geometrical edge of the beam.

4. Ground-based comparison of direct-line-of-sight irradiance and small-angle forward-scattered-light irradiance showed that in the wavelength interval 7500A to 9500A the direct light was 200 times the scattered light at a distance of 45 km when the meteorological range was 40 km.

5. Signals as a function of distance have been measured with the help of a mobile omnidirectional light source. The signal strength decreases inversely with the square of range and with an exponential attenuation out to the horizon, at which point there is a discontinuity which is a function of the meteorological conditions and is greatest when the meteorological range is high. Beyond the horizon the signal decay is influenced mostly by attenuation loss when the meteorological range is low (13 km) and primarily by inverse-square loss when the meteorological range is high (>60 km).

6. Ruby laser light was transmitted at night over the horizon to a distance of 45 km when both receiver and projector were 6 ft above water and were pointed at one another with 0-degree elevation. The laser output was 0.10 joule and the signal-to-noise ratio in the system was 45. It is estimated that the surface transmission of the 45-km path at 6943A was about 10^{-5}. Signals from a 1 to 2 joule laser have also been transmitted over this path in daytime with a signal-to-noise ratio of 3 when the meteorological range was 20 km.

7. An over-the-horizon link was established on a continuous basis over a range of 45 km. Observation was for a period of 102 hours, during which the signal was received 62 percent of the time during the night and 57 percent of the time during the day. Two accidental interruptions of the measurements resulted in lost data during periods when the signal would surely have been received.

In addition, considerations of the problem of detecting forward scattered light in the daytime show that estimated results agree with the available experimental data. Considerations of the feasibility of using over-the-horizon propagation as a communications link leads to the estimation that communication between fixed points at Morse code rates is currently feasible over ranges of the order of 50 km in the daytime for meteorological ranges of 16 km or more, using a narrow-beam projector as source. Ship-to-ship communication would require sources of very high power or precise stabilization and pointing existing high-intensity searchlight sources.

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