NEAR INFRARED VOICE-CODE COMMUNICATION SYSTEMS

By *John R. Platt* [a]

INTRODUCTION

Object and Scope of Chapter

One of the principal military uses for the *near infrared* [NIR], 0.8 to 1.4 μ, sources, filters, and photodetectors described in Chapters 1, 2, and 3 is their assembly into complete systems for voice and code communication on an invisible "beam of light." Such systems are commonly called photophones, optical telephones, or the like. Voice systems based on several different principles were developed under NDRC auspices and will be described in this chapter. A few of these systems include provision for code operation. Systems which transmit code only will be taken up in the next chapter.

The voice systems cover a considerable range of sizes and military applications. A hand-held system (type W) weighs 25 pounds, has a beam angle of 5 degrees and an *average clear weather* [ACW] night range of 3 miles (see Sections 4.3.2 and 4.3.1). A system for aircraft weighs 60 pounds, has a beam angle of 15 degrees, and an ACW range of 4.5 miles (Section 4.4.3). A shipboard installation (type E) weighs 200 pounds, has a beam angle of 15 degrees, and an ACW voice range of 6.5 nautical miles but a code range of 9 nautical miles. In these systems the intensity of the light beam is modulated at audio frequencies. As it was feared that after a time such systems might be in danger of being received by enemy infrared receivers occasionally, work was also undertaken on devices which could offer still more security. One such device made use of high-frequency carrier waves and one used modulated polarization of the light beam. Another which has been considered would produce modulation by varying the wavelengths used for the communication.

Comparative mention will also be made of foreign and of American NIR voice systems which were not developed under NDRC auspices.

Estimates will be given of the expected performance of similar systems in the *intermediate infrared* [IIR], 1.4 to 6 μ, which would at present have somewhat more military security.

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4.1.2 Communication by Means of Near Infrared Radiation

Advantages of the Near Infrared Region

In principle, radiation of any wavelength region throughout the electromagnetic spectrum may be used for conveying energy in communication. Radio wavelengths are, of course, excellent for most uses, but for some military purposes they may have a dangerously great communication range and are subject to skip-distance phenomena and reception out of the line of sight even when ultrahigh frequencies are used in directed beams. For increased secrecy in combat communication it becomes desirable to go to still shorter wavelengths for which the beam can be sharply defined and the range definitely limited by the horizon or by atmospheric attenuation.[30]

At wavelengths shorter than the radar microwave region, radiation is not detected by tuned receivers but by thermoelectric elements in the region of long heat waves and by photoelectric detectors in the IIR region and at shorter wavelengths. Of these two types of detectors only the photoelectric devices have response times short enough to be used for receiving the audio-frequency variations in voice communication, and such communication is thus limited at present to wavelengths below 6 μ.

Optical communication systems require much higher powered transmitters than radio systems to obtain the same range for the same beam spread, even when atmospheric attenuation is neglected. This is partly because the effective "antenna" areas of practical photodetectors are much smaller than for radio; and partly because, even for equal received energy, photodetectors are less sensitive. This is because of the higher quantum energy required at optical frequencies to eject a photoelectron as compared with the quantum energy required at radio frequencies to set an electron in motion in an antenna. A narrow-angle optical system may, however, compare in range with a nondirectional radio system of the same power.

Sensitive photodetectors for the IIR region, from 6 to 1.4 μ, have been developed quite recently, and most work up to the present has been done in the NIR region, from 1.4 to 0.8 μ. In the visible region, between 0.8 and 0.35 μ, optical systems are limited to daylight use where a flash of light will not jeopardize security. Even in the *ultraviolet* [UV], below 0.35 μ, night use is risky, because although the UV radiation itself cannot be seen at night it will produce a strong and very visible fluorescence. In addition, as the UV is approached, atmospheric attenuation becomes serious. The development by the NDRC of UV systems is reported in the Summary Technical Report of Division 16, Volume 4, Chapter 6.

Considering these limitations on other spectral regions and the present American and foreign military interest in the NIR and IIR regions for various purposes, it seems likely that systems using these wavelengths will become increasingly important in future military short-range communication (under 10 miles), for instance between tanks, advanced infantry, and ships and planes in convoy or formation. One drawback of such systems at present is their loss of range in daylight, but recent photodetector developments promise great improvement in this respect.

Types of Military Applications

Almost all earlier NIR systems used *very narrow beams* (under 1 degree) for high security. These required fixed stations and tripod mounts and were unsuited to a mobile war. *Wide-angle systems,* with beams between 5 and 30 degrees, and even *all-around systems* with beams over 100 degrees wide give an intermediate security which still is much greater than that of radio. They can be hand-guided or in some cases need not be guided at all.

The military characteristics required in the project control numbers of the developments to be reported show rather well the most urgent military problems for which such NIR systems were desired. All these problems involve communication between mobile positions or moving units at short ranges, under conditions requiring radio and radar silence.

It may be noted in this connection that the use of the NIR system as a link between telephone lines across breaks or bad terrain, which has been a common feature in narrow-beam systems for land signaling, was not requested in any of the NDRC projects.

A comparison of the weights, angles, and ranges of the systems developed under NDRC auspices with those of earlier systems is given in Figure 1.

Ship Use. The type E system described in Section 4.4.2 was developed for secret night communication by voice within convoys at ACW distances up to 6.5 sea miles, code to 9 sea miles, with beam angles near 15 degrees, so that one ship could communicate with several others simultaneously. Its weight and power are compatible with ship operation. It can also be used for ship-to-shore harbor entrance communication.

The Touvet system described in Section 4.5.3 could be similarly used. It has similar voice range, with transmitter angle of 25 degrees and receiver angle of 2 degrees. It is an r-f system and offers a choice of six carrier-wave channels.

The type G system (not an NDRC development) described in Section 4.3.1 could be used for the same problem, but it has a narrow beam of 1 to 4 degrees and, consequently, more security against detection. It is to be mounted on a stabilized platform and guided by an auxiliary tracking system and is to have an ACW range of about 4 miles.

Aircraft Use. The *plane-to-plane* [P–P] system described in Section 4.4.4 was developed for secret communication between adjacent planes of B–29 bombing formations during the hours of approach to the target. The system was not completed because of the termination of the war, but it was designed to give angles of 120 degrees horizontally by 60 degrees vertically at the front and also at the rear of a bomber, with estimated ACW ranges of ½ mile in the daytime or 2 miles at night (with different circuits). Weight and power conform to Army Air Force requests.

The *plane-to-ground* [P–G] system described in Section 4.4.3 is for use in situations involving the maintenance of communications and transport of supplies by air at night to guerrillas, paratroops, or other isolated ground troops. The complete ground unit (type W, Section 4.3.2) weighs about 25 pounds and can be carried to earth on the person of a paratrooper. The complete plane installation of the P–G system would weigh 60 pounds and the transceiver

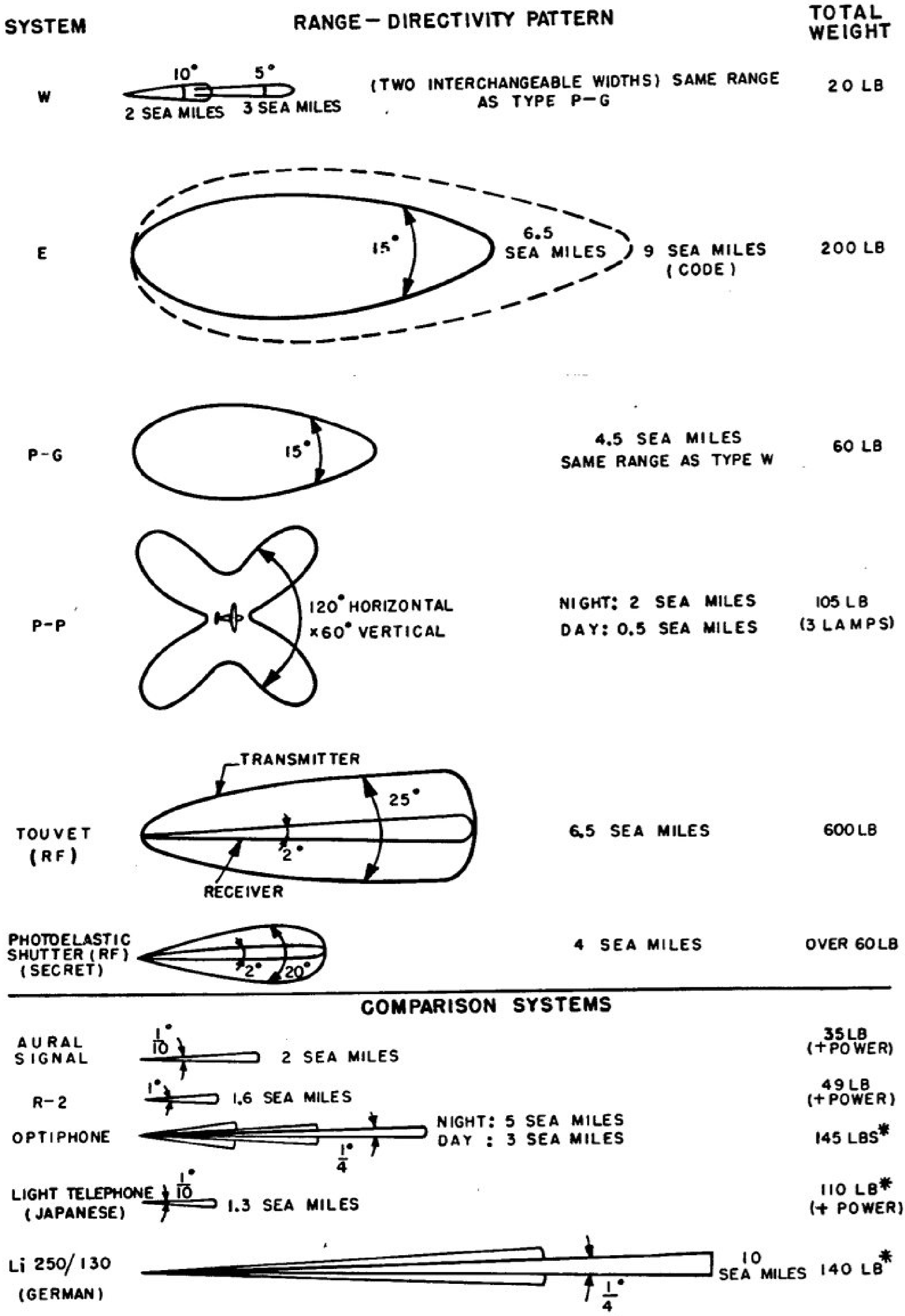

FIGURE 1. ACW ranges and angles of communication systems.

All patterns show ACW ranges between two similar systems, of which only one is shown. They are night-voice ranges except as indicated. Receiver and transmitter patterns are roughly identical except as noted. The P-P pattern is for planes flying parallel, but all other plots show the maximum range when the second system is pointing directly at the system shown. The starred weights refer to units produced to specifications for field use, which may be several times heavier than laboratory models of the same type.

would be hand-operated through a hatch door. The beam angles are about 15 degrees for the plane unit and 10 degrees for the ground unit. These are sufficient for making contact and maintaining communication between the hand-held units, which are guided with the help of auxiliary infrared electron telescopes. The ground-to-plane ACW range should be about 2 miles, plane-to-ground about 4 miles.

Ground Use. The ground unit of the plane-to-ground system just described was adapted from an ultraviolet hand-held unit developed for daylight communication between landing barges, with angles of 5 degrees and ranges up to 2 miles. The NIR adaptation (type W, Section 4.3.2) gives ACW ranges of 3 miles with the same beam angle and is most suitable for night communication. Apparently, NIR and UV sources and cells can be made interchangeable. Type W can be operated from the self-contained power supply for at least one hour. For longer operation, it may be connected to a 6-volt storage battery.

Mixed Use. If NIR systems become more common, communication between units of different types may become as usual as with radio. Most of the systems to be described will transmit to and receive from each other interchangeably.

In addition to the ship-to-shore and plane-to-ground arrangements described, there are other combinations. One might be ship to landing barge or beachhead, using type E, or preferably the stabilized narrow-beam type G on the ship and type W on the shore. Expected ACW ranges might be: type W (5 degrees) to type E, 3 sea miles; type E to type W, 4.5 sea miles.

Another combination would be ship to plane, from type E (which has high elevation angles) on the ship to the P–G system on the plane. The ACW ranges in either direction would be about 5 sea miles.

Since type W is portable and can be operated from a 6-volt battery, it is not restricted to ground use but may be carried on ships, planes, and tanks for short-range communication.

Various modifications of these systems have been proposed to give increased security in each of these applications, if and when enemy interception of messages should become a troublesome problem. It must be remembered that in most cases the added security is obtained at the expense of lowered efficiency and increased complexity.

Identification and Recognition. Another important military application of infrared radiation is the equipping of military units—ships, planes, tanks, infantry groups, trench positions—with secret, all-around view, continuously operated beacons broadcasting a unique signal, and with directed receivers so that the units are immediately identified as friendly by any other similarly equipped unit within range. Some systems designed exclusively for this purpose will be described in Chapter 5, but it should be pointed out here that the voice systems of the present chapter usually contain all the apparatus necessary for this purpose and can be adapted electrically with a minimum of revisions to do both jobs. Optically, the transmitters are not so well suited to do both jobs, as only the P–P system (Section 4.4.4) has the wide angle usually required for identification from all directions. However, the narrow-angle voice receivers could be used for search purposes, like the type D recognition system receivers described in Section 5.2, by sweeping them automatically and continuously around the horizon when they are not being used for communication. Further remarks on the duplication and overlapping of functions of the various systems will be found in Section 5.2.

The identification function was considered in the original request for development of the P–P system. The transmitters were to broadcast a code tone continuously when not communicating, and this tone was to be picked up on other planes by narrow-angle receivers bore-sighted with the guns so as to provide a warning signal when they were turned on a friendly plane. This function was later eliminated from the P–P system as the AAF decided to use another system for identification, but it could probably be performed by the P–P system with very little increase in weight or complexity.

Types of Systems

A beam of light or radiation has three properties: intensity, wavelength distribution, and polarization. The variation of any one of these by suitable modulation may be employed as the basis of a voice communication system. In a rough way, variation of intensity corresponds to *amplitude-modulation* [AM] in radio and variation of wavelength distribution to *frequency-modulation* [FM], although the analogies are not exact, since the receiver is not tuned to the "optical" frequency.

The desired property of the radiation is modulated at lower *audio* or *radio frequencies* (a-f or r-f). Simple a-f modulation involves AM in the modulating and receiving circuits, and systems of this kind will be called *amplitude-modulation systems,* even though the property of the *radiation beam* which is modulated may not be the optical amplitude. If photodetectors with very short response times are used, another kind of modulation may be employed, consisting of an amplitude-modulated r-f carrier wave on which is superposed either an AM or an FM audio signal (see Table 1). is now used, although some earlier studies involved sound pressure modulation of a manometric acetylene flame. For modulating the outgoing beam, electro-optical devices like the Kerr cell have been considered, but most military systems use mechanical modulation, with vibrating mirrors and beam-chopping devices in a-f systems or supersonic vibrations of some optical element in r-f systems.

Some NIR optical communication systems are arranged in Table 1 according to the optical property being modulated and the kind of modulation.

TABLE 1. Types of code and voice communication systems: (c) indicates code only; (v) voice only; [a] NCRC consultation; [s] NDRC study; systems in italics, NDRC developments.

1	2	3	4
		Optical property modulated	
Kind of modulation	Intensity*	Polarization	Wavelength
a-f (AM) Mechanically modulated (tungsten)	*Type D* (c) Type G[a] Type R-2 Type W (v) Light-beam telephone (Japanese) Li 50, Li 80, Li 250–130[s] (German)		*Spectral modulation system* (proposed)
Electrically modulated (tungsten)	*Type D-2* (c) ASE and others (British) F.F.115 and others (Italian)		
(gas)	*Type E* *Plane-plane* (v) *Plane-ground* (v) Aural signal unit (v)	Type L[a]	
r-f (AM) Mechanically modulated	Optiphone (a-f receiver only)	*Photoelastic shutter system*	
Electrically modulated	*V-M system* *Touvet system*		
r-f (FM)			

* There are two other intensity-modulated systems which do not fit easily into this table. One is an ordinary blinker code system which may be regarded as very low-frequency amplitude modulation. The other is a code or teletype Navy-developed system, type P, which makes use of very high-frequency spaced pulses of polarized light (see Section 5.1.2).

The modulation may be accomplished either by electrically modulating the radiation source or by using a constant-intensity source and modulating the outgoing beam. In the first case, electrical modulation of the current through a filament lamp (a-f) or through a gaseous discharge source (a-f or r-f) The modulation technique may determine the size, power, efficiency, and security of the source and in some cases the design of the receiver.

The large number of voice systems shown in column 2 indicates that the intensity-modulated a-f type of system is the simplest in design and construction. Most of the components of such systems are commercially available. The mechanically modulated systems are the lightest in weight; the electrically modulated ones can attain the highest efficiency of light utilization.

Security. Security against reception of intelligence by the enemy is called *message security*; security against detection by the enemy of the existence of a modulated infrared system is called *system security*. Since the systems of column 2 are numerous and simple, they have very little security of either kind when operated in close contact with the enemy. They have the NIR advantages of invisibility and limited range, and some also have the advantage of narrow-beam width, but they can all be received by any NIR a-f receiver. Speech-scrambling has not yet been used, but it could be incorporated in existing systems to improve message security. It would not affect system security.

American equipment for a-f detection of enemy NIR systems has been built (see Section 5.5). Presumably, foreign equipment for a similar purpose may shortly begin to limit the usefulness of the American systems shown in column 2. When that occurs, it may be possible to change some of the electrically modulated gas discharge sources to r-f FM, or to r-f AM with superimposed d-c, and thus make them secure against a-f receivers. Or it may be possible to go to systems like those in columns 3 and 4. Reception of intelligence from the transmitters of the systems in column 3 requires plane, or plane and quarter-wave, polarizing sheets over the receiver. Reception of intelligence from the transmitter of the recently proposed system listed in column 4 is more complicated, although the system promises to be simple to construct.

These added security devices all give message security. Greater system security may be obtained at present by using another wavelength region, the IIR. Work in the IIR requires a new type of detector cell, so far not extensively used, and it prevents reception of the message or detection of the source by the various and common NIR detectors.

The systems in columns 3 and 4 are necessarily less efficient than those in column 2 because of the additional complication of the equipment and the additional restrictions on the light beam introduced by the security devices. It is not yet certain whether the ranges of IIR systems will be as great as those of closely similar NIR systems.

4.1.3 Common Aspects of All Systems[b]

PRINCIPLES OF OPERATION

The operation of all these systems may be understood by referring to Figure 2, which is a schematic diagram of the type E system. Sound energy is converted to electrical energy by the microphone at the transmitter and is amplified by the audio-frequency amplifier to a level capable of modulating the transmitter current. This may be the current supplied to the source itself, if it is electrically modulated like the source in Figure 2, or it may be the current supplied to a mirror or other optical element located in the transmitter beam emanating from a

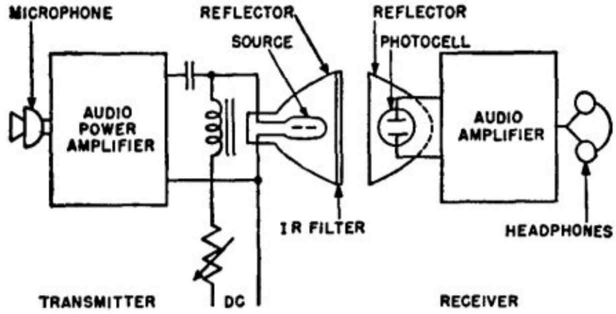

FIGURE 2. Block diagram of communication system.

steady source. The intensity, polarization, or wavelength of the radiation leaving the transmitter may thus, by one or the other of these methods, be made to vary in proportion to the modulating audio current and in accordance with the characteristics of the original sound. The reflector shown in Figure 2 may be replaced in other systems by a more complex transmitter optical arrangement. The radiation is directed toward the distant receiver through an infrared filter designed to eliminate the visible portion of the spectrum.

The small amount of infrared radiation reaching the receiver is concentrated by a mirror or lens upon the detector, which is generally a photoconductive or photoemissive cell. If the modulation is in the wavelength or polarization of the beam, it is converted to an intensity variation by a suitable device. The photocell current varies in magnitude with the intensity of radiation falling upon the cell, and the fluctuating current is a fairly accurate copy of the current modulated by the original sound at the transmitter. The fluctuating current is usually

[b] For list of symbols used in the equations of this section, see end of chapter.

changed by passage through a load resistor to a fluctuating potential which is applied to the input of the receiver audio amplifier. The electrical energy available at the output of the amplifier is converted again to sound by the headphones or loud-speaker. That these numerous conversions of energy can be accomplished without excessive distortion is indicated by the fact that conversation can be carried on over a distance of several miles with high intelligibility using systems based on such principles.

The Range Equation

The range of such a system depends on many factors such as the power and efficiency of the source, the responsivity of the detector, the beam angles, and the optical areas, but it depends most of all on the weather.[23,31] Knowledge of the relations between these variables is helpful in evaluating the components of a system or in predicting the overall performance of an untested system. The relations are formally independent of wavelength, and therefore the usual photometric (visible light) symbols may be used.

The fundamental range equation is

$$R_v^2 = I\frac{A}{F}, \tag{1}$$

where R_v is the vacuum range of a system, or the maximum distance that the receiver could be separated from the transmitter and still obtain intelligible communication if no atmospheric attenuation were present (at night, unless otherwise noted),

I is the maximum effective beam intensity (candlepower),

A is the gathering area, or entrance pupil, of the receiver optical system,

F is the effective threshold flux falling on the receiver which is required for just-intelligible communication.

The equation can be derived from the primary definition of intensity I as the flux F per unit solid angle, since A/R^2 is the solid angle subtended at the transmitter by the receiver. This equation must be modified to take account of losses, and it can be rewritten to express I and F in terms of other variables.

Atmospheric Attenuation

Transmission. The most serious loss is the result of absorption and scattering by fog, smoke, and dust in the atmosphere. The absorption of two or three small bands of water vapor in the NIR may be neglected. In the NIR the transmission obeys Lambert's law to a good approximation, so that if T is the fraction of light transmitted through unit distance of atmosphere ($T < 1.0$) then the fraction transmitted through R units is T^R.

The values of T for the visible and the NIR may be taken to be almost the same at any given time.

Operational Range. The measured limiting operational range R_T of communication in weather with transmission T may be much less than the vacuum range R_v. The illumination E in an attenuated beam falls off as[31]

$$E = \frac{I}{R^2}T^R. \tag{2}$$

The threshold illumination on a receiver must be the same at R_T for transmission T as at R_v for transmission unity, or

$$\frac{I}{R_T^2}T^R = \frac{I}{R_v^2},$$

and

$$R_T^2 T^{-R} = R_v^2. \tag{3}$$

The value of R_T as a function of R_v is plotted for several values of T in Figure 3. In practice, R_v must be computed from observed values of R_T and T, or it can be determined from measurements in the laboratory.

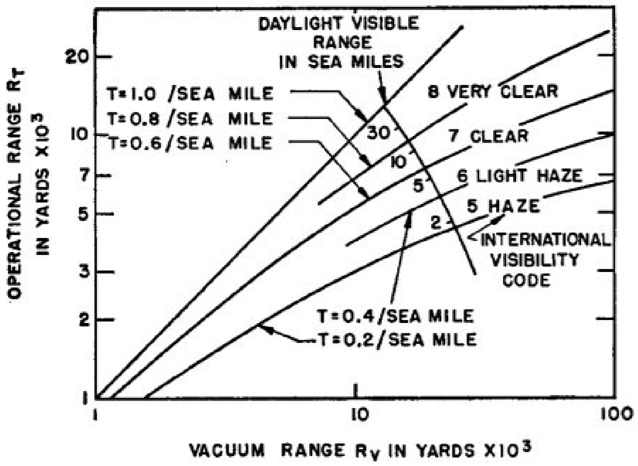

FIGURE 3. Atmospheric transmission and range.

Average Clear Weather. As R_v may be several times larger than actual ranges, it is convenient in comparing the performance of systems to specify another standard range, the range in average clear weather [ACW]. Usually ACW is taken by the Navy to refer to a transmission of 0.6 per sea mile, and this range would then be denoted by $R_{0.6}$ in equations (2) and (3). (The phrase "0.6 per sea mile" is the accepted substitute for the awkward exact expression, "$0.6^{1/\text{mile}}$," which is necessary if T^R is to be dimensionless.)

This value of T corresponds to a loss in signal of 4.5 db per mile, in addition to the reduction by the inverse square law. A convenient rough rule is that the rate of loss in ACW, at distances over 5 miles, is about 6 db per mile. Thus a change by a factor of two in any of the variables determining range (beam intensity, detector responsivity, receiver area) changes the ACW range by about 1 mile.

In ACW the daylight visible range, as defined later, is about 7 sea miles, and the code number is 7 (clear) in the International Visibility Code.

While the ACW range is an easily interpreted index of the military performance of a system, it is not so satisfactory for laboratory or theoretical comparison of systems as the vacuum range. The ACW range involves arbitrary and not easily verified assumptions about attenuation at the wavelengths used, and computing it requires troublesome logarithmic conversions and reconversions.[31] The vacuum range should be more widely adopted as the measure of communication system performance. In this chapter, for systems for which the vacuum range has not been computed, an attempt will be made to estimate it so that the various systems may be more easily compared on an absolute basis.

In order to compute R_v or the ACW range from measured operational ranges, the value of T during the operation must be known. This may be found either from estimates of daylight visible range or from instrumental determinations.

Daylight Visible Range. The daylight visible range, or limiting range at which large black objects can just be seen against a white sky, is proportional to [37,38]

$$\frac{1}{\log(1/T)},$$

and varies more rapidly with T than does R_T. The visible range in good weather is greater than the range of a communication system, becoming infinite for transmission unity when the communication range only becomes R_v, but in murky weather it may be less than the communication range. The relation of T to the visible range and to the index numbers used in the International Visibility Code is shown in Figure 3.

From visibility estimates values of T may be determined to an accuracy of about 0.1 per mile. Obviously, the daylight visible range can be used to determine T for a night operation only if the weather appears to remain almost unchanged in the interim. The *visible range* must not be confused with the *night visual range* [NVR] or range at which a filtered NIR transmitter can be detected by the dark-adapted eye.

Instrumental Determination of T. Several different instrumental methods, none of them very satisfactory, have been used to determine T. The transmission may be found from absolute measurement of the flux received on a photocell from a fixed radiation source at a fixed distance of several miles. Or the signal level of communication between a shore station and a moving ship may be plotted against the distance, and the transmission determined from equation (2).[16,17] A variation of the latter method is to use not the signal level but the brightness of the distant source (compared to a known local source) as observed in an optical telescope or electron telescope. Besides the obvious experimental problems in such determinations, a fundamental difficulty is that the transmission over any path is continually changing and a consistent set of values is therefore rare; the spread of such determinations may be less than 0.1 per mile only if the transmission stays fairly constant.

Some very rapid "twinkle effects" which have been reported as interfering with voice and code communication (see "Operational Tests" in Sections 4.6.2 and 5.2) are probably of refractive origin rather than being due to true variations in T, but of course they further complicate the problem of measuring T.

Transmitter Factors

Steady sources and electrically modulated sources of radiation have already been described in Chapter 1. Methods of mechanical modulation will be described in the subsequent discussion of individual systems.

Modulation. The maximum effective beam candlepower I, in equation (1), from a transmitter is proportional to the fraction z of the steady radiation which can be modulated by the impressed communication signal. Attainable values of z differ considerably for various modulation methods and for various types of sources. This difference is seen in Table 2,

TABLE 2. Efficiencies of various modulation methods.

Source and method	Modulation efficiency
Cesium-vapor lamp; electrically modulated (up to 5,000 c)	2.00
Concentrated-arc lamp; electrically modulated (1,000 c)	0.30
Tungsten lamp; electrically modulated (1,000 c)	0.30
Vibrating mirror, opaque grid	0.50
Vibrating mirror, prism grid (Li 250)	1.00
Spectral modulation	0.50
Cesium lamp polarization system	0.50 (ideal; actual near 0.25)
Supersonic diffraction (optiphone)	
r-f crest to trough	1.00 (ideal; actual near 0.70)
a-f crest to trough	0.50 (ideal; actual near 0.35)
Rare gas carrier-wave lamps	
r-f crest to trough	2.00*
a-f crest to trough	1.00*
Photoelastic shutter	
r-f, averaged over shutter	0.35
a-f, averaged over shutter	0.25 (ideal; actual near 0.06)

* The intensity without the modulation device is taken to be the average intensity over an r-f cycle of maximum amplitude.

which gives the modulation efficiency for various methods. Electrical modulation of the cesium-vapor and rare gas sources is seen to be the most efficient method. The modulation efficiency is here defined as the maximum crest-to-trough change of radiant intensity producible by an audio signal, relative to the steady unmodulated radiant intensity of the same beam (with the modulating device omitted in cases where it is external to the source and obstructs part of the beam). So defined, the term is applicable to all modulation methods; for electrically modulated sources, it is twice the modulation ratio defined in Chapter 1.

The value of z mentioned above may be taken to be the relative rms variation of intensity with respect to the mean d-c intensity. For a maximum steady tone, z is $\frac{1}{2}\sqrt{2}$ times the modulation efficiency; for voice signal it is usually half or less of this value, depending on the transmitter circuits.

Pass Band. Maximum communication range demands not only maximum modulation of the source light but also a suitable choice of the modulation frequencies. If the strong low frequencies of the human voice are allowed to pass through the transmitter amplifier, they may reach amplitudes of overmodulation while the high frequencies important for intelligibility are still very weak. By cutting out the low frequencies in the amplifier, more energy may be put into the intelligibility frequencies without overmodulation. If the cutoff, for example, is at 1,000 cycles, 86 per cent of the energy is removed, permitting an increase of 17 db in the modulation of high frequencies with a loss of only 7 per cent in intelligibility.

This possible improvement has not been appreciated in many of the designs to be discussed, and some project control numbers have actually specified voice pass bands from 100 to 1,000 cycles, which would give very much smaller communication ranges. The optimum band-pass for optical transmitters needs careful study similar to that which has been given sound-powered phones.[41]

Removal of the low frequencies of speech causes much of the naturalness and identifying characteristics of the individual voice to be lost. For military applications this is of little consequence. Other ways to increase the intelligibility output are discussed under "Amplification" in Section 4.4.2.

Narrow-Beam Systems. The effective beam candlepower I depends also on the optical system. Consider first a collimating system with precision optical elements, that is, a system which focuses an image of the source at infinity. On looking back into such a system from the center of the beam at a great distance away, the exit pupil A_t is seen to be completely filled and of brightness about equal to the surface brightness B of the source. Then the effective intensity is

$$I = e_t' hzBA_t, \tag{4}$$

where e_t' takes account of the transmission and reflection losses in the optical elements and h is the *effective holotransmission* [ehT] of any NIR filter in the beam.[43] If the system consists of a simple lens, or reflector, of focal length f, the solid angle Ω_t into which the beam goes is determined by the effective *projected* area of the source, a_0'.

$$\Omega_t = \frac{a_0'}{f^2}. \tag{5}$$

High Efficiency. Such a system may be made more efficient by increasing I or A_t, with no change in focal length or Ω_t. Or it may be made more efficient by increasing Ω_t through a decrease in f, with no change in A or I; in the latter case one way of utilizing the increased efficiency is by decreasing the source size and input power so as to restore the initial beam solid angle. Both these cases reach a limit when the largest practicable fraction e_t of the emergent flux φ from the source goes into the transmitter beam. The fraction e_t may be called the *transmitter efficiency*. Then

$$I = e_t hz \frac{\varphi}{\Omega_t}. \qquad (6)$$

For large values of e_t (over about 0.25), reflectors must be used. The minimum area (exit pupil) A_t required for them is given approximately by

$$A_t = e_t a_0 \frac{\pi}{\Omega_t}, \qquad (7)$$

where a_0 is the total luminous surface area of the source.

Since in most communication systems the highest efficiency is desired, equation (6) is fundamental. It is applicable also to noncollimating systems and wide-angle systems generally, with or without beam-spreading devices.

Usually, in the systems to be considered, the values of Ω_t were not so small nor the source areas a_0 so large as to make the efficient reflector size A_t prohibitive.

From the proportionality between a_0 and Ω_t in equation (7) we see the general rule for choosing the source for a given communication problem: wide angle, large source; narrow angle, small source.

The total emergent flux φ from a source may be thought of as proportional to the product of the input power and the *hololuminous efficiency* in hololumens per watt. This efficiency is of the order of 15 hlm per watt for all the sources considered here except the Western Union concentrated arc (Section 4.4.2); for the latter, it is only 3 to 5 hlm per watt for arc sizes near 100 watts.

Beam Solid Angle. Equation (6) implies that the beam has uniform intensity within angle Ω_t and zero outside. In practice, with most beam distributions considered here, equation (6) holds approximately if Ω_t is taken to be bounded by the directions in which the beam intensity falls to *half the peak intensity* [hpi]. Only hpi solid angles and beam widths will be used hereafter.

The relation between I and Ω_t is of the greatest importance in the design of optical communication systems. To obtain maximum intensity and communication range with minimum source power, the beam must be as narrow as possible for the desired purpose. For a given source, power, and optical efficiency, wide-angle systems are short-range systems.

Laboratory Methods. Candlepower distributions may be measured by placing a source or a transmitter optical system, as the case may be, on a rotating table and determining the response of a fixed detector at some distance away as a function of angle. The distance away must be great enough that the angle subtended by the source at the detector is small compared to the hpi width.

The ratio between the maximum candlepowers, I from a transmitter system and I_0 from its bare source alone (both a-c or both d-c measurements), is the *transmitter optics factor, O_t*

$$I = I_0 O_t. \qquad (6a)$$

The vacuum range R_v from a given transmitter to a given receiver may be determined in the laboratory by finding the maximum communication range from the bare source to this receiver and multiplying this value by $\sqrt{O_t}$.

If the source is too intense to measure the latter range directly in the laboratory space, it may be measured indirectly by reducing the source intensity by a known amount as follows.[9] A lens or mirror is set up so as to form a reduced image of the source, and so that the receiver can "see" only this image. The intensity from this image is less than the intensity of the source by a factor p^2/q^2, where p and q are the object and image distances from the lens or mirror. The communication range from the image to the receiver is thus less by a factor p/q than the range from the bare source itself.

Choice of Filter. Commonly, a maximum permissible NVR is specified in the requirements for an NIR system. The NVR is defined as the visual range limit of a transmitter to the dark-adapted standard eye in total darkness. It is determined by the kind of source, its holocandlepower, and the kind of filter, as discussed in Chapter 2.

The specified NVR should be made as great as is militarily feasible because the larger the NVR is, the greater the operational range can be for a given transmitter system. This results from the fact that the ehT and the *effective visual transmission* [evT] of a filter type vary together with changing optical density. Of course the filter type must be chosen from among those with satisfactory weathering properties and thermal and mechanical stability for military use. It should be a type which will make as great a differential as practicable between the ACW range and the NVR. This means it must have a high index of merit (see Chapter 2) if this can be obtained in conjunction with a reasonable ehT so that the input power needed to obtain the desired ACW range will not be excessive.

With a specified NVR and a chosen filter type, the thickness or density must then be chosen to bring the NVR right up to the specified limit so as to make the communication range as great as possible.

The NVR for a given transmitter may be determined by computations for the standard eye according to the methods outlined in Chapter 2, or it may be determined for actual observers in the laboratory, reducing the range by a known amount as described above under "Laboratory Methods," so that the test may be accommodated in a limited laboratory space.

Receiver Factors

The contribution of the receiver to the range is represented by the term A/F in equation (1).

Effective Threshold Flux (Signal Equivalent of Noise). The value of F depends on the spectral distribution of the radiation and on the spectral response of the detector cell. All other factors being equal, the type of cell chosen must naturally be that giving a maximum *signal-to-noise* [S/N] ratio for the given spectral distribution and audio- or radio-frequency distribution of the modulated radiation from the filtered NIR source. What the best source or filter is also depends on the cell; actually no one of them should be chosen independently, but all combinations should be studied to find the best for a particular problem. In addition, the value of F depends upon what fraction e_r of the flux falling on the receiver entrance pupil actually reaches the photodetector cell.

The threshold flux is determined by the limitation of intelligibility because of the noise in the cell and circuit. In circuits with low noise, the noise is generally a function of the effective cell area a and receiver band width Δf, as explained in Chapter 3. The ratio of the rms threshold signal to the rms noise, *threshold* S/N, depends on whether the communication is code or voice, on the kind of source and cell, and the circuits.[18a] This ratio may be lumped with other constants into a constant k.

Finally, then

$$F = \frac{k}{e_r}\sqrt{a\Delta f}. \tag{8}$$

This flux must be made as small as possible in order to obtain maximum range.

Bandwidth. One way to make F small is to decrease Δf. For carrier-wave [c-w] code reception it may be decreased until the tuned receiver circuit is set into self-oscillation.

For voice reception, when Δf decreases, the S/N ratio required for intelligibility increases, causing an increase in the constant k. The rate of increase of k depends on the shape of the frequency-response curve and the frequency of peak response. The experimental work on the type E system (see "Preamplifier" in Section 4.4.2) indicates that the values of $k\sqrt{\Delta f}$ and of the flux F required for speech intelligibility are a minimum for a peak response near 1,500 cycles per second with a bandwidth (6 db down) of about 700 cycles per second. In later work on the aircraft systems (see "Amplifier" in Section 4.4.3), it seems that better intelligibility may be obtained if this pass band is *not* sharply limited on the high-frequency side. The results of studies on pass bands and noise in sound-powered phones[41] and similar devices should be applied to this problem.

Cell Area and Solid Angle of View. Another way to make F small is to decrease the effective cell area a. With a given optical system this involves a proportional decrease in the solid angle of view Ω_v. The angle Ω_v will be taken as bounded by the directions in which the receiver response falls to *half the peak response* [hpr].

If a given hpr receiver solid angle is specified, it may be obtained with a smaller and smaller cell area (and higher and higher sensitivity) by decreasing the focal length of the receiver lens or reflector up to a certain point. The limiting cell area is given by the relation[18,23]

$$a = \frac{\Omega_v}{\pi}A. \tag{9}$$

In practice, as a result of optical aberrations, the minimum value of a is some 50 per cent greater than this value.

This limit is reached with an f/number of the optical system of about $f/0.5$ for a one-surface detector like a phototube; f/numbers down to about $f/0.1$ may be used with two-surface detectors like *thallous sulfide* [TF] photoconductive cells (see Chapter 3), if they are mounted with their sensitive surfaces parallel to the axis of a reflector. The effective cell area a of a two-surface detector mounted thus is approximately the area of the double surface. Such a detector thus can have twice the solid angle of view of the same size one-surface cell for the same effective mirror area.

Mirrors are required in order to attain either of these f/numbers. With further decrease of the focal length below the values implied by these f/numbers, the mirrors get deeper and deeper, and the average distance of the cell from the mirror surface increases. Then a must *increase* in order to keep Ω_v constant, which causes the attainable receiver sensitivity to decrease again.

For a maximum sensitivity, then, with a given A, the value of a required is given approximately by equation (9).

The smaller the angle of view required, the higher the sensitivity of the detector cell which may be used. This parallels the relation for transmitters between beam angle and intensity and leads again to the conclusion that a wide-angle system is a short-range system.

However, it is less important to have a small solid angle at the receiver than at the transmitter, since the best receiver sensitivity is inversely proportional only to the square root of the solid angle of view, while the transmitter intensity is inversely proportional to the beam solid angle itself.

Laboratory Methods. The directivity pattern of receiver response as a function of direction may be determined in the laboratory by placing the receiver on a rotating table to detect a weak source some distance away. The hpr angle of view may be found from this pattern.

If the photodetector and associated circuits are linear, the ratio of the maximum response of the cell in the optical system in a uniformly illuminated field to the maximum response of the cell alone is called the *receiver optics factor* O_r. In cells uniformly sensitive over their surface, O_r is equal to e_rA/a', where a' is the projected area of the cell. A bare cell may be used for laboratory range measurements, and the range so obtained multiplied by $\sqrt{O_r}$ gives the range for the assembled receiver optical system.

Backscatter. One practical limitation on receiver sensitivity in a two-way communication system is commonly the noise produced by radiation from the adjacent transmitter beam scattered back into the receiver by nearby objects or just by atmospheric haze. The backscatter from nearby objects may be avoided by proper location of the system.

The backscatter from haze has been shown theoretically [39] to be proportional to $\alpha^2\beta/d$, where α is the hpi beam width, β ($\geqq \alpha$) is the hpr receiver width, and d is the distance between centers of transmitter and receiver. It is not certain whether this analysis takes into account current ideas outlined above concerning the relation of receiver sensitivity to angle of view. But the general conclusion is certainly correct: the noise is large when the hpi and hpr angles are large, and also when transmitter and receiver are close together. The latter is commonly the case, the two units being placed together in a single transceiver head for convenience.

Backscatter in wide-angle systems having a transceiver head may make duplex operation impossible. In duplex, transmitter and receiver are continuously ready to operate, permitting great naturalness of conversation. But if the transmitter feeds back optically into the receiver, it may drown out the distant station, and send-receive operation must then be used, with the transmitter and receiver energized alternately, as with a press-to-talk button. In this case, the transmitter line must be filtered from any modulation or ripple when the system is in the receive condition. Even so, photocurrent noise from the remaining steady backscattered radiation may still be serious. If so, the transmitter intensity must be reduced or turned off altogether, either electrically or by a mechanical shutter, during reception, in order to achieve threshold sensitivity.

Daylight Operation. The noise produced by steady backscatter is trivial compared with that produced in phototube and TF cell receivers by daylight. The operational ranges of NIR systems in daylight may consequently be much decreased from night ranges. (Ultraviolet systems are not so much affected, as they can be filtered to receive only waves shorter than 2,900 μ where almost no sunlight comes through the ozone layer in the atmosphere.)

In vacuum phototubes, the noise increases as the square root of the d-c current, which is proportional to the total steady flux received. For a uniformly bright field of view, the flux is proportional to the product of Ω_v and A. With gas-filled phototubes and TF cells, the expression for the change produced by background light is less simple. The TF cells are less affected than either kind of phototube, but with these cells there is the additional complication that the cell resistance is decreased by the illumination, necessitating a change in the load resistor if optimum performance is to be maintained (see "Preamplifier," Section 4.4.4, for a circuit which may eliminate this complication). It seems that lead sulfide (PbS) photoconductive cells are very little affected by steady background light (Chapter 3).

With detectors which are affected markedly by background radiation, very narrow-angle systems are much less affected by daylight than are wide-angle systems both because the solid angle of view is smaller and because, with Army (land) systems at any rate, a smaller fraction of sky is included in this solid angle. The Lichtsprechers (Section 4.3.1), which have hpr angles of ¼ degree and PbS cells, seem to have no loss of range in daylight. The Japanese light-beam telephone mentioned in Section 4.3.1 has an iris diaphragm over the receiver cell to give a large angle at night and a small angle in the daytime.

This Japanese system and some other phototube systems with hpr widths less than 1 degree showed changes of about 20 per cent between the night and day vacuum ranges,[9] but the cells used had very high noise which would reduce the apparent size of the effect. The daylight vacuum range of the Signal Corps optiphone (Section 4.5.1), which has a similar receiver, seems to be less than the night range by a factor of about 3. In one test on TF-cell receivers with all-around view, background illumination equivalent to an overcast north sky caused a loss equivalent to a factor of 3 in vacuum range, even with proper load resistor adjustment (see "Preamplifier," Section 4.4.4).

Probably none of the systems to be described (except perhaps those using PbS cells) will work if sunlight falls on the receiver. An NIR filter and a sunshade over the receiver may materially improve daylight communication with the wide-angle systems and use of a PbS cell may bring still greater improvement. More experimental work on these points is needed.

Experiments with operation of a wide-angle TF-cell receiver in the presence of searchlights, star shells, and gun and shell flashes are reported under "Operational Tests" in Section 4.4.2.

Revised Range Equation

Combining equations (1), (6), (8), and (9), we have for the limiting vacuum range

$$R_v^2 = \left(\frac{e_t e_r}{k\Delta f}\right) hz \frac{\varphi A}{\Omega_r \sqrt{a}}, \qquad (10a)$$

or

$$R_v^2 = \left(\frac{e_t e_r \sqrt{\pi}}{k'\Delta f}\right) hz \frac{\varphi \sqrt{A}}{\Omega_t \sqrt{\Omega_r}}, \qquad (10b)$$

or

$$R_v^2 = \left(\frac{e_t e_r \pi}{k''\Delta f}\right) hz \frac{\varphi \sqrt{a}}{\Omega_t \Omega_r}. \qquad (10c)$$

The change from k to k' and k'', in equations (10b) and (10c) respectively, is introduced to take account both of the deviation of actual systems from the ideal limit case given by equation (9) and also of certain geometrical factors which depend on the shape of the detector cell.

Equations (10b) and (10c) are generally the most useful in designing a communication system since they involve the solid angles explicitly, and these are usually among the first military characteristics specified. The last equation has the further advantage that it involves the detector cell area explicitly, and this quantity may be fixed by commercial availability for cells of a given type.

The ranges R_v are of a different order of magnitude from the limiting ranges encountered, for example, in radio communication. Thus the maximum value of R_v theoretically obtainable from a 100-watt source with beam widths of about 15 degrees, 18-inch mirrors, and present detector cells is of the order of 50 miles. This corresponds to an ACW communication range of about 8 miles. While this short range is unsatisfactory for many military purposes, it does offer the advantage that the range of enemy detection, even with specially designed search receivers, is also limited to distances of the same order of magnitude.

Auxiliary Equipment

A number of auxiliary devices are commonly used with NIR communication systems, such as NIR image-forming devices (image tubes) for visual sighting on a distant source; stabilized platforms (stable tables) with NIR, IIR, or *far infrared* [FIR], 8 to 13 μ, training devices to maintain alignment automatically especially with narrow-beam systems; and test or monitoring devices to check transmitter and receiver operation.

Image Tubes. The types now used on equipment to be described include the charged-phosphor type AM metascopes and types C_3 and C_4 electron telescopes. These are described in the Summary Technical Report of Division 16, Volume 4.

Stabilized Platforms. Wide-angle systems, with beam angles over about 5 degrees, depending on the military use intended, may be mounted on gimbals and manually trained on the distant source with the help of an image tube. All-around systems, with beam angles over some 100 degrees and the resulting great reduction in range and security, are used only where manual guiding is very undesirable and where a transceiver is to be fixed in position on a moving craft or vehicle.

Narrow-angle systems, with beams less than 5 degrees, may be used from moving stations only if the systems are automatically guided. They may be guided by focusing radiation from the distant station on a split detector cell and applying the amplified differential signal from opposite halves or quadrants of the cell to a driving motor. This motor then rotates the apparatus so as to keep the distant station centered in the field of view. The cell may respond to an NIR source or beacon or it may respond in the IIR or FIR to the naturally emitted heat radiation from the other station (provided it is a ship or a heated vehicle).

If the NIR is used the cell might be the detector cell of the communication system, though cells and circuits for such an arrangement have not been worked out; the distant source might be the communication source, although an all-around beacon is better as the systems are then not so troublesome to line up initially.

For Navy use, where the only variable coordinate of the distant ship station is its azimuth, tracking is simplified by mounting the system on a gyroscopically stabilized horizontal platform; then only a two-element tracking cell is needed. The transceiver units must be very light in weight to be used with present platforms. In experimental BuShips tests successful tracking from such platforms to ±½ degree of arc[c] has been obtained with FIR systems trained on small ships at distances up to 4 miles in average weather.

Test Devices: Microbeacon. Source monitoring devices are necessary for checking proper transmitter operation in some of the polarization systems, but for most voice systems to be described the operation is adequately monitored by simple visual or image-tube observations without any additional apparatus.

Similarly, detector cell and receiver operation is usually checked simply by listening for the characteristic hiss of cell noise in earphones or loudspeaker and noting the increase in noise produced by placing a light, a match, or a cigarette in the field of view. For more guarded and accurate field testing, two portable *microbeacon* test sources have been constructed by University of Michigan Contract NDCrc-185.[40]

The first microbeacon, shown in Figure 4, is operated from a 110-volt 60-cycle per second a-c ship supply. It consists of a small tungsten lamp whose light is modulated by a sector disk used as a mechanical chopper at 90 or 1,500 cycles per second as desired. A virtual image of the source is formed by the polished surface of a steel ball, the intensity being thus diminished as discussed in "Laboratory Methods," in Section 4.1.3. The light from the image passes out of the box through an aperture covered by a suitable NIR filter. A variable resistor in series with the tungsten lamp has a dial calibrated to read the emergent NIR flux in mile-holocandles (see Appendix).

In operation the beacon is held at some standard distance, such as 10 feet, from the receiver to be tested. It is pointed at the receiver and the lamp resistor is adjusted until the code tone can barely be detected above the noise. The receiver is pronounced satisfactory or unsatisfactory according as the emergent flux from the beacon is then below or above some specified maximum allowable value.

The second microbeacon[40] is an ingenious, constant, and simple device, which was constructed for checking the operation of the plane-to-plane recognition system (Section 5.3), but which would be equally applicable, with appropriate frequency changes, to any other NIR receiver. A ¼-watt neon

[c] Information supplied by courtesy of Section 660E, Bureau of Ships.

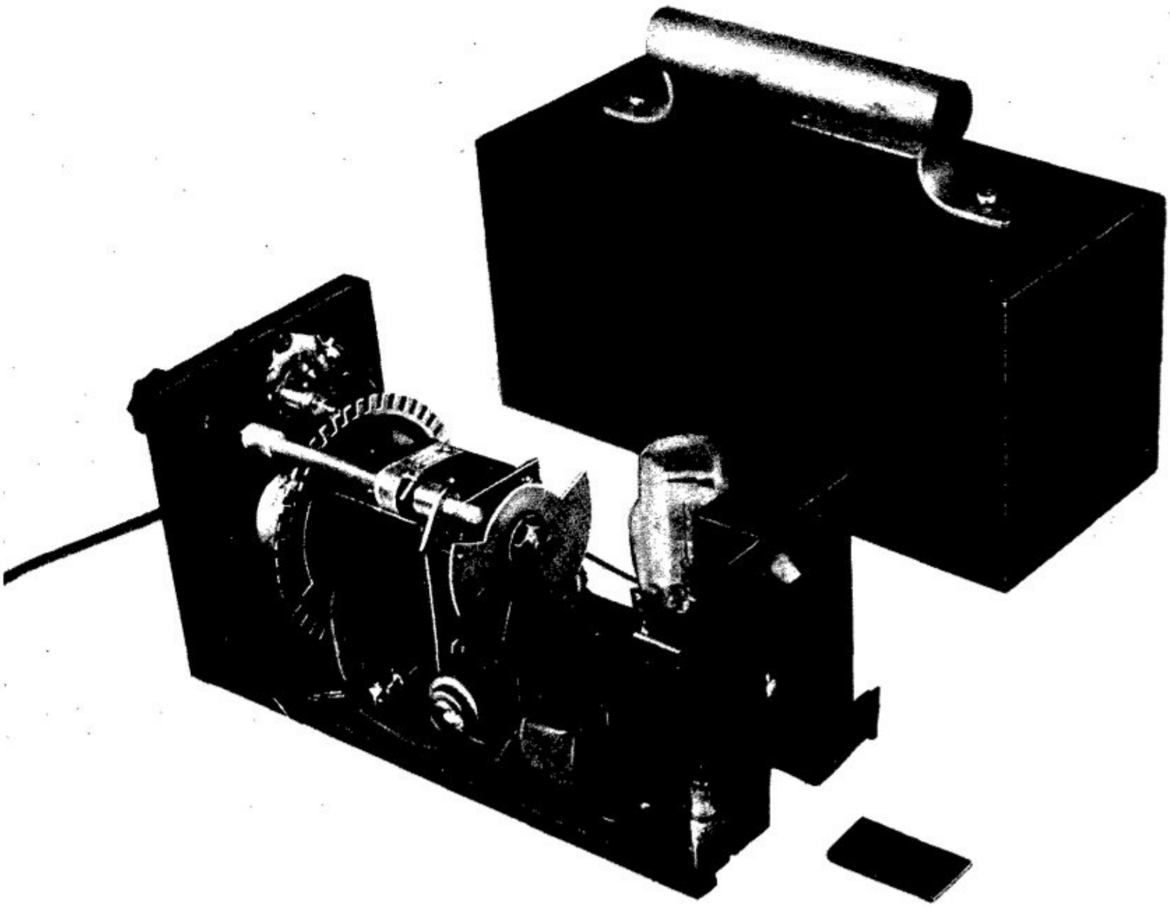

FIGURE 4. Microbeacon test source, with cover removed.

lamp acts both as a 90-cycle per second relaxation oscillator and as a source of light. Two other neon lamps serve as voltage regulators to compensate for the aging of the 200-volt batteries, and one of these lamps serves as an indicator of battery deterioration. The unit, including batteries, is in a box 3x4½x10½ inches in size, and may be held in one hand in front of the receiver to be tested. The intensity and frequency of the lamp are almost independent of temperature or of the age of the battery.

One of the code systems to be described in Chapter 5 also has a build-in microflux lamp for testing receiver operation. Such a method could be easily adapted for use in the voice systems discussed in this chapter, if desired.