WESTERN UNION Technical Review

Passive Reflector-Antenna Systems

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Intercity Facsimile Trunks

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Design of a Facsimile System

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Plan 8 Concentrators

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Passive Reflector-Antenna Systems

R. E. GREENQUIST and A. J. ORLANDO

Introduction

IN RECENT YEARS a new type of antenna system has come into use in the microwave radio relay field which enables simpler and more economical tower construction to be employed. The artist's sketch, Figure 1, shows a typical relay station using passive reflector-antenna systems. All of the radio equipment is located in the building at the base of the tower. Conventional parabolic antennas inside the building radiate through a low dielectric constant material (plexiglass, fiberglass, etc.) in the roof, and illuminate plane rectangular reflectors mounted at a 45-degree elevation angle at the top of the tower. These reflectors reradiate the energy incident upon them in a directive manner toward the next relay point.

There are, of course, many possible variations of this type of antenna system. Though the usual reflector is a 45-degree plane rectangular reflector, there is no reason why it cannot be oriented at angles other than 45-degree, nor why it need be rectangular or even plane. The feed antenna in the system is not restricted to the parabolic antenna but may be any of the directive antennas commonly used at microwave frequencies.

A variation of this system, and perhaps the first use of the plane reflector in this connection, is a plane reflector located at a point on the path between two active repeaters. The reflector cannot be considered a part of the antenna system of either repeater, in this case, but is a complete repeater in itself. Because the plane reflector merely reradiates the energy incident upon it, this repeater is termed a passive repeater in contrast to the usual repeater where power is added. The term passive reflector is used also to describe this type of repeater and the terminology has been carried over to describe the antenna system using a plane reflector in a similar manner.

Western Union became interested in this type of antenna system because of the large reduction in tower costs that could be effected, and the advantages inherent in having all of the radio equipment at ground level without resorting to a long wave-guide or coaxial cable transmission line between the radio equipment and the antenna.

Since no previous test information or experience was available, early in 1951 Western Union planned extensive tests of passive reflector-antenna systems to determine their performance characteristics. An experimental tower, shown in Figure 2, was erected at Monsey Heights, New York, and tests were conducted at this site and over the 27.8-mile path to the Western Union building in New York City. The test equipment and parabolic antennas were mounted on mobile antenna carts, as shown in Figure 3.

In conjunction with the test program, a theoretical study of the passive reflector-antenna system was made. The radiation characteristics of paraboloidal and plane reflectors are determined by applying the Huygens-Fresnel-Kirchoff concepts of physical optics to the reflector apertures.

Figure 1. Sketch of typical radio relay repeater employing passive reflector-antenna systems

The fact that methods of physical optics are applicable makes it easier to visualize what occurs in the antenna system because of the analogies to familiar light phenomena.

It might be well to mention that analogies between microwaves and light can be misleading if the levels of observation are not the same. Monochromatic light must be considered in any analogy because antenna radiation is essentially at a single frequency, that of the carrier. If radiations at light and microwave frequencies illuminate circular apertures ten wave lengths in diameter, the radiation patterns produced by the apertures will be identical. However, at 4000 megacycles the diameter of the aperture would be 30 inches, while at 5461 Angstroms, the visible green line in the mercury spectrum, the aperture would be 2.15×10^{-4} inches in diameter.

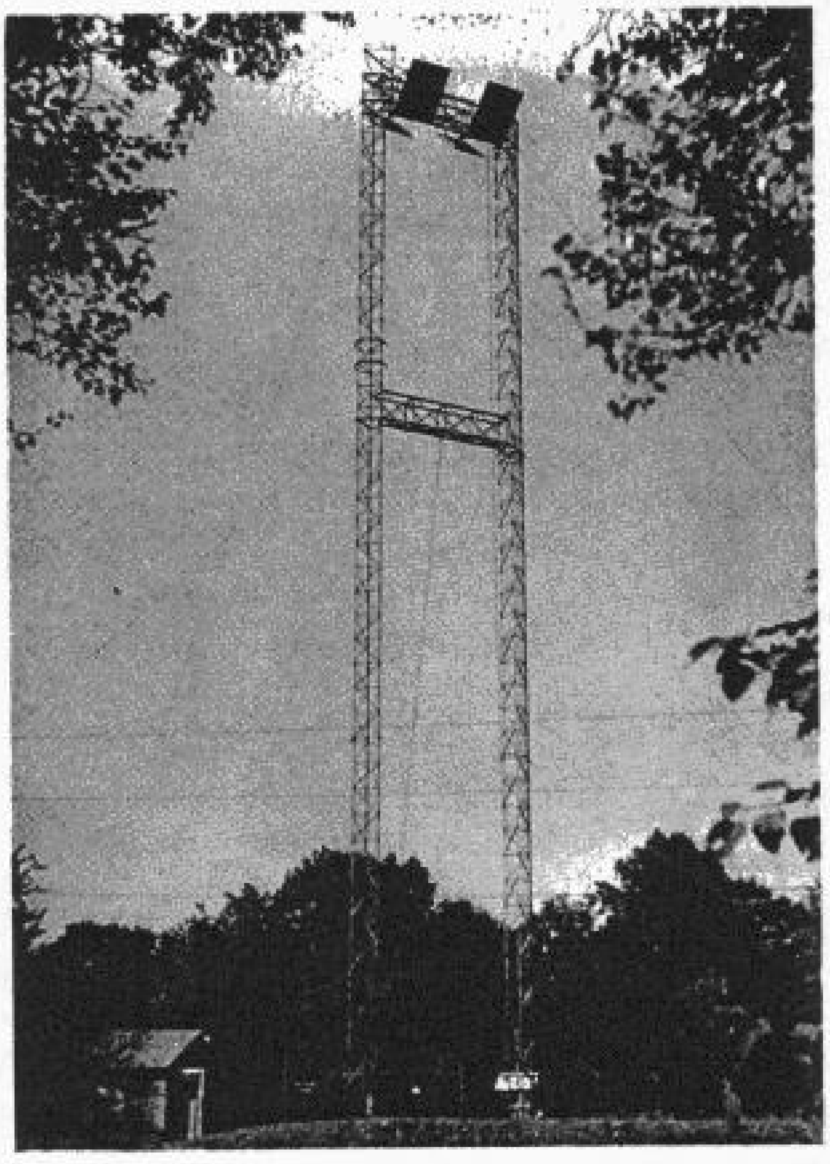

Figure 2. Experimental tower at Monsey Heights, New York

Apertures

The term aperture as used in antenna theory does not necessarily imply a physical opening. A reflector-type antenna defines an aperture which may be treated as though it were a physical opening in an infinite plane. This aperture is defined by passing a plane normal to the direction of the reflected energy in the immediate vicinity of the reflector so that there is a power flow through the plane over a finite area. That finite area is the aperture of the reflector and energy is considered to arrive at the plane of the aperture by methods of geometrical optics. When the size and shape of the aperture are defined and the field intensity and phase distribution across the aperture are known, the manner in which the field in the aperture arises is no longer a consideration in determining the radiation characteristics of the antenna.

With a paraboloidal reflector the plane is chosen through its mouth. Thus the power flow through the plane is confined to a circular region the same size and shape as the mouth of the paraboloid. The nature of a paraboloidal reflector is such that all energy incident upon it from its focal point is reflected and arrives in phase at the plane of its mouth. A paraboloidal reflector illuminated from its focal point can thus be treated as a circular aperture illuminated by a plane wave.

When a 45-degree plane rectangular reflector is considered, the plane is chosen coincident with the plane of the reflector thereby defining an aperture of the same size and shape as the reflector. Since energy illuminating the reflector is incident at an angle with the normal, a plane wave produces a phase distribution across the aperture which is not plane but varies linearly. In analyzing this condition, the assumption is made that the radiation pattern produced would be the same as that produced by a constant phase aperture rotated through an angle; that is, the aperture is projected upon a plane normal to the reflected rays and the projected aperture is considered to be illuminated by a plane wave incident normal to it. This assumption is valid only because highly directive antennas are being considered and most of the energy is confined to angles close to the direction of maximum radiation intensity where the approximation and the actual case differ by a negligible amount. The plane reflectors used in the Monsey tests were rectangular and of such dimensions that their projected areas were square when they were oriented at a 45-degree elevation angle. Thus these 45-degree plane reflectors can be treated as square apertures illuminated by a plane wave incident normal to the aperture.

Radiation Intensity

The Huygens-Fresnel-Kirchoff concepts of physical optics applied to both circular and square apertures have been extensively treated in the literature. Based upon these concepts, an expression for the radiation intensity Φ of an aperture can be derived as a function of the radiation intensity of an elemental Huygens' source Φ_o and the aperture diffractivity S. The radiation intensity in any given direction is defined as the power radiated from an antenna per unit solid angle in that direction.

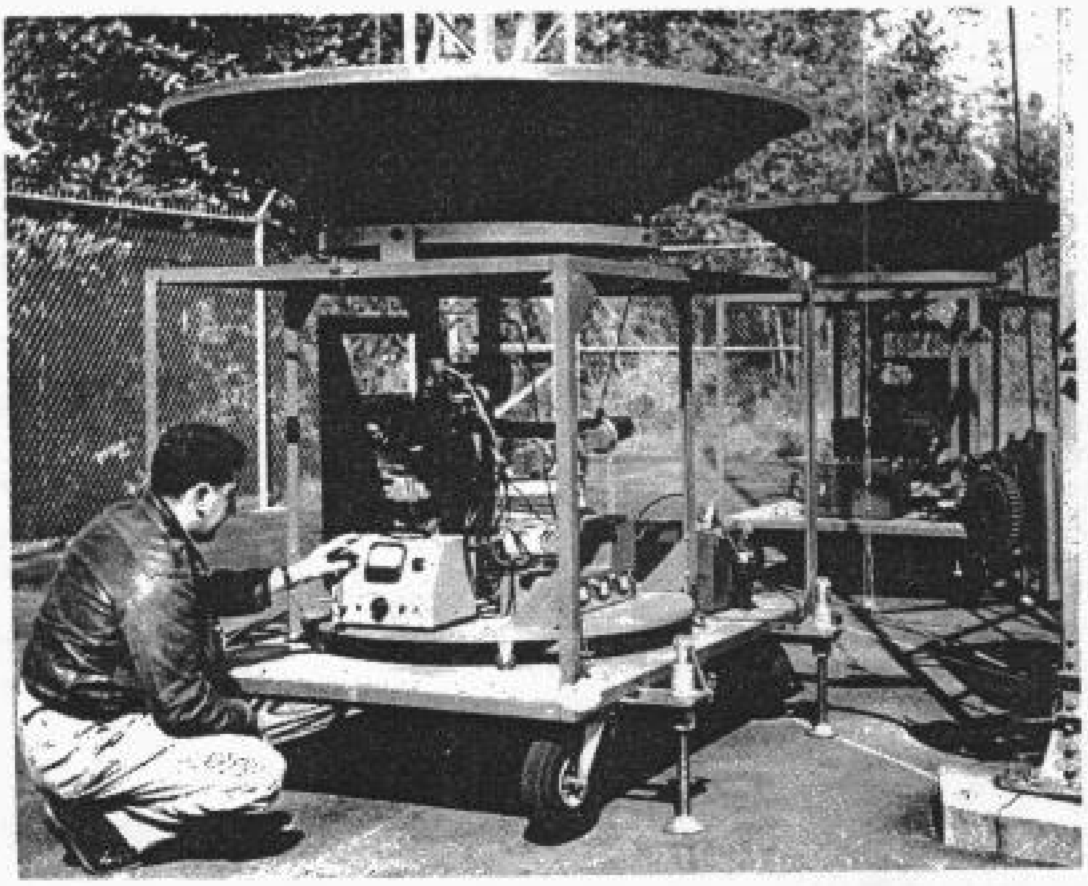

Figure 3. Mobile antenna carts and test equipment

$$\Phi = \Phi_o S^2 \text{ watts/solid angle.}$$

The radiation intensity of an elemental Huygens' source is given by the expression

$$\Phi_o = \frac{(E_o\, dx\, dy)^2}{8 \eta \lambda^2} (1 + \cos\theta)^2 .$$

The aperture diffractivity is a function of the manner in which the elemental Huygens' sources are arrayed in space and their relative field intensities and phases. Thus the aperture diffractivity relates the radiation intensity to the size and shape of the aperture and the distribution, both in amplitude and phase, of the Huygens' sources in the aperture.

It is the determination of the aperture diffractivities for the apertures encountered in the passive reflector-antenna system under discussion with which this article will be concerned. Since the phase distribution in all of the apertures under consideration is plane, or very nearly so, the discussion will not consider phase distribution other than plane. The aperture diffractivity of an aperture will then be considered as a function of the size and shape of the aperture and the field intensity distribution in the aperture.

Diffraction Zones

The radiation pattern of primary interest in antenna work is the Fraunhofer diffraction pattern of the antenna aperture. Such patterns are usually shown graphically, normalized with respect to the peak value, for one or both of the principal planes. The patterns are a graphical representation of the radiation intensity normalized and plotted as a function of direction. The direction is represented by θ, which is the angle measured away from the normal to the center of the aperture.

The Fraunhofer diffraction pattern of the aperture is the pattern which exists in what is called the Fraunhofer region of the diffraction field. Though no sharp transitions occur, there are three general zones in the diffraction field of the aperture which are discussed briefly in the

LIST OF SYMBOLS

θ	Angle measured away from the normal to the center of the aperture
ϕ	Angle representing planes perpendicular to the aperture and passing through the center of the aperture
$S(\theta,\phi)$	Functional expression for the aperture diffractivity
Φ	General expression for the radiation intensity
ρ	Radial distance from the center of the aperture to any point in the plane of the aperture
ρ_n	Radial distance normalized to a peak value of one with respect to the dimension in the principal plane of an aperture
p	Parameter which defines the degree of the circular aperture amplitude taper
P	Power
λ	Wave length
d	Diameter of a circular aperture
a	Dimension of a square aperture
h	Distance of separation between the parabolic antenna and the 45-degree plane reflector
s	Distance of separation between the 45-degree plane reflector and the distant antenna
η	Intrinsic impedance of free space
E_o	Electric field intensity of a Huygens' source
A	Aperture area
u	Reduced angle for a square aperture
v	Reduced angle for a circular aperture
$\Lambda_n(v)$	Spherical Bessel function of the nth order (tabulated)
δ	Illumination at the edge of the aperture in a principal plane
N_δ	Power normalizing factor
$C(x)$	Cosine Fresnel integral
$S(x)$	Sine Fresnel integral
α	Attenuation between isotropic antennas
G	Directive or power gain of an aperture
$\mathcal{G}$	System gain of an antenna or group of antennas
g	Gain factor

following paragraphs.

First is the near zone which exists in the first few wave lengths in the immediate vicinity of the aperture. The diffraction pattern in this zone is approximately that which would be obtained by considering geometrical propagation of rays through the aperture with only small variations across the wave front due to interference. The boundary of the field in this zone is sharply defined.

The next zone is called the Fresnel region and is characterized by the onset of diffusion and the disappearance of the sharp boundary. The major portion of the energy still appears to be propagating according to geometric optics but with more pronounced variations in intensity across the wave front due to interference effects.

The far zone is called the Fraunhofer region and the field in this zone appears to be diverging from a point source in the aperture. Once the Fraunhofer region has been reached there are no further changes in the nature of the diffraction field as the distance from the aperture is increased.

Although the transition between zones is gradual, the criterion for the minimum distance which can be considered in the Fraunhofer region has been arbitrarily set as L^2/λ or $2L^2/\lambda$ with the latter being preferred. The dimension L is the maximum dimension of the aperture. Later in this discussion it will be seen that the separation between component antennas in passive-reflector systems may fall between the criteria mentioned. However, the antennas are treated as though they operate in the Fraunhofer region and the gain is corrected by a factor, introduced later in the discussion, which takes into consideration the decrease in gain which occurs when they operate in the Fresnel region. Unless stated otherwise, the radiation characteristics of an antenna are those in the Fraunhofer region.

Aperture Diffractivities and Radiation Patterns

The expression for the aperture diffractivity of a *circular* aperture of diameter d, with a uniform field intensity distribution, is of the familiar form

$$S = \frac{\pi d^2}{4} \Lambda_1(v) \quad ,$$

where v is a reduced angle equal to $(\pi d/\lambda) \sin\theta$, and $\Lambda_1(v)$ is a spherical Bessel function. This expression represents the aperture diffractivity in all planes passing through the center of the aperture. The radiation intensity is then

$$\Phi = \Phi_o \left(\frac{\pi d^2}{4}\right)^2 \Lambda_1^2(v) \quad .$$

The maximum value of Φ occurs when $\Lambda_1^2(v)$ is maximum. This occurs at $\theta = 0$ degrees where $\Lambda_1^2(v) = \Lambda_1^2(0) = 1$. Thus,

$$\Phi_{MAX} = \Phi_o \left(\frac{\pi d^2}{4}\right)^2 \quad .$$

Since the apertures under consideration are highly directive, the obliquity factor $(1 + \cos\theta) \approx 2$ for small angles of θ.

For a given aperture Φ_o and $\left(\frac{\pi d^2}{4}\right)^2$ are constant and the radiation intensity varies directly as $\Lambda_1^2(v)$. This spherical Bessel function squared represents the normalized radiation pattern of the aperture. The function $\Lambda_1(v)$ is tabulated.

The circular aperture defined by the parabolic antenna in the passive reflector-antenna system under consideration is not uniformly illuminated. An aperture field distribution is produced by the primary feed (an E-plane sectoral horn) such that the illumination at the edge of the aperture is 10 db below that at the center. Spencer and Silver considered a series of circular aperture field intensity distributions of the form $(1 - r^2)^p$, where p was a positive integer, but in this analysis it was found that p need not be limited in this manner. The aperture field distribution was then approximated by $(1 - \rho_n^2)^{1/2}$, where ρ_n is the normalized radial distance $(\rho_n = 2\rho/d)$ from the center of the circular aperture to any point in the aperture. In the manner employed by Silver, the aperture diffractivity was found to be

$$S = \left(\frac{\pi d^2}{4}\right) \frac{2}{3} \Lambda_{3/2}(v)$$

in all planes passing through the center of the aperture. The radiation intensity is

$$\Phi = \Phi_o \left(\frac{\pi d^2}{4}\right)^2 \frac{4}{9} \Lambda_{3/2}^2(v) \quad ,$$

and the maximum value occurs at $\theta = 0$ degrees where $\Lambda_{3/2}^2(v) = \Lambda_{3/2}^2(0) = 1$. Thus,

$$\Phi_{MAX} = \Phi_o \left(\frac{\pi d^2}{4}\right)^2 \frac{4}{9} \quad .$$

The normalized radiation pattern of the aperture varies directly as $\Lambda_{3/2}^2(v)$ and values of the function $\Lambda_{3/2}(v)$ can be obtained from tables.

When a *square* aperture (of dimension a) is uniformly illuminated, the expression for the aperture diffractivity in any plane ϕ passing through the center of the aperture is given by

$$S = a^2\left(\frac{\sin A}{A}\right)\left(\frac{\sin B}{B}\right)$$

where $A = u \cos \phi$,

$B = u \sin \phi$,

and $u = \frac{\pi a}{\lambda} \sin \theta$.

Setting $\phi = 0$ degrees gives the aperture diffractivity in a principal plane as

$$S = a^2 \frac{\sin u}{u}.$$

The radiation intensity in the principal plane becomes

$$\Phi = \Phi_o \; a^4 \frac{\sin^2 u}{u^2}.$$

The maximum value of the radiation intensity occurs at $\theta = 0$ degrees and is

$$\Phi_{MAX.} = \Phi_o \; a^4.$$

The normalized principal plane radiation patterns vary directly as $\sin^2 u/u^2$, which is a tabulated function.

The square aperture in the passive reflector-antenna system is illuminated by a portion of the main lobe of the parabolic-antenna radiation pattern. The aperture field intensity distribution in the square aperture is thus $\Lambda_{3/2}(v)$ in all planes passing through the center of the aperture. This field intensity distribution is approximated by a circularly symmetrical parabolic distribution of the form $1-(1-\delta)\rho_n^2$. This approximation, which is restricted to that portion of the main lobe illuminating the square aperture, considerably simplifies the integration to determine the diffractivity of the square aperture. The illumination at the edge of the aperture (in a principal plane) relative to a peak value of one at the center is δ where $\delta \leq 1$. The variable ρ_n is the normalized radial distance from the center of the aperture to any point in the aperture $(\rho_n = 2\rho/a)$. The analysis is similar to that employed by Silver in his consideration of a rectangular aperture with a $1-(1-\Delta)x^2$ distribution in the x-direction and a uniform field intensity distribution in the y-direction. The aperture diffractivity in any plane passing through the center of the aperture is found to be

$$S = a^2 \left[\left(\frac{\sin A}{A}\right)\left(\frac{\sin B}{B}\right)(2\delta-1) + \left(\frac{2-2\delta}{3}\right)\left\{\left(\frac{\sin A}{A}\right)\Lambda_{3/2}(B) + \left(\frac{\sin B}{B}\right)\Lambda_{3/2}(A)\right\}\right].$$

The aperture diffractivity in the principal planes is obtained by setting the angle $\phi = 0$ degrees. The diffractivity reduces to

$$S = a^2 \left[\left(\frac{4\delta-1}{3}\right)\left(\frac{\sin u}{u}\right) + \left(\frac{2-2\delta}{3}\right)\Lambda_{3/2}(u)\right].$$

The radiation intensity in the principal planes is then

$$\Phi = \Phi_o \; a^4 \left[\left(\frac{4\delta-1}{3}\right)\left(\frac{\sin u}{u}\right) + \left(\frac{2-2\delta}{3}\right)\Lambda_{3/2}(u)\right]^2.$$

The maximum radiation intensity occurs at $\theta = 0$ degrees and is

$$\Phi_{MAX.} = \Phi_o \; a^4 \left(\frac{2\delta+1}{3}\right)^2.$$

The normalized principal plane radiation patterns vary directly as

$$\left[\left(\frac{4\delta-1}{3}\right)\left(\frac{\sin u}{u}\right) + \left(\frac{2-2\delta}{3}\right)\Lambda_{3/2}(u)\right]^2$$

and, as mentioned before, both $\sin u/u$ and $\Lambda_{3/2}(u)$ are tabulated functions.

With the radiation patterns of both the parabolic antenna and the square aperture known, it is possible to calculate the gain of a passive reflector-antenna system. To facilitate the development of the system gain expression, the following paragraphs will be devoted to the discussion of antenna gain definitions and to factors affecting the system gain.

Gain Definitions

The gain of an antenna may be defined, in general terms, as follows:

> "The measured gain of one transmitting or receiving antenna over another is the ratio of the signal power one produces at the receiver input terminals to that produced by the other, the transmitting power level remaining fixed."

The gain of an antenna is thus a ratio and must be referred to a base in order to be useful. This base can be any other antenna but it is common practice to choose as a standard a hypothetical isotropic antenna which radiates equally in all directions. When the isotropic antenna is used as a standard, its radiation intensity in all directions is equal to the total power divided by 4π, since there are 4π solid angles in a sphere. Thus,

$$\Phi_{ISOTROPIC} = P_{TOTAL} / 4\pi$$

watts/solid angle. The average radiation intensity of any antenna is equal to the total power divided by 4π solid angles, so that the concept of the radiation intensity of an isotropic antenna is equivalent to that of average radiation intensity.

When the total power that is being considered is the power delivered to the antenna, the gain is referred to as the power gain and is defined as follows:

> "The power gain in a given direction is 4π times the ratio of the radiation intensity in that direction to the total power delivered in the antenna."

This is equivalent to saying that the power gain of an antenna is the ratio of its radiation intensity to the radiation intensity of an isotropic antenna to which the same total power is delivered.

When the power radiated by the antenna is the total power that is being considered, the gain is referred to as the directive gain and is defined as follows:

> "The directive gain in a given direction is 4π times the ratio of the radiation intensity in that direction to the total power radiated by the antenna."

Thus the directive gain of the antenna is the ratio of its radiation intensity to the radiation intensity of an isotropic antenna radiating the same total power.

The difference between the power gain and the directive gain is the radiation efficiency, which is defined as follows:

> "The radiation efficiency is the ratio of the power radiated to the total power supplied to the antenna at a given frequency."

Since the antennas under consideration are highly directive, the value of the directive gain in the direction of its maximum value (often referred to as the directivity) becomes the important consideration.

In an antenna system there is power spilled over as one component of the system illuminates another. Thus the concept of system gain is introduced and it is defined as follows:

> "The system gain is 4π times the ratio of the maximum radiation intensity of the antenna system to the total power delivered to the primary antenna in the system."

System Gain of a Parabolic Antenna

In the treatment of parabolic antennas in this article, the system gain of a parabolic antenna system over an isotropic radiator has not been considered. The parabolic antenna is analyzed only insofar as it affects the performance of a passive reflector-antenna system. Thus, the field intensity taper in the paraboloidal reflector aperture has been studied only because it determines the radiation pattern of the parabolic antenna system. This, in turn, determines the illumination in the plane reflector aperture and the spillover power in the passive reflector-antenna system.

It is desirable to express the gain of the passive-reflector system in terms of its gain over an isotropic antenna, and to do this the gain of the parabolic-antenna system must be known. Rather than trying to analyze the parabolic-antenna system in a quantitative manner, this discussion will use the commonly accepted criterion for the gain of a parabolic antenna with a 10-db illumination taper.

$$G = \frac{4\pi A_{(EFFECTIVE)}}{\lambda^2} = \frac{\pi^2 d^2}{\lambda^2}(0.65)$$

where the 65 percent represents the combined effect of all the factors tending to reduce the gain. The factor is equivalent to reducing the aperture area to 65 percent of its physical area.

Gain Factor

The maximum gain of an antenna occurs when the field intensity distribution in the aperture is uniform and the phase front constant. Under these conditions the gain of the antenna is the ratio of its area to the equivalent area of an isotropic antenna. The equivalent area of an isotropic antenna is equal to

$$A_{ISOTROPIC} = \frac{\lambda^2}{4\pi},$$

and so the gain becomes

$$G_U = \frac{A}{A_{ISOTROPIC}} = \frac{4\pi A}{\lambda^2}.$$

When the field intensity distribution is nonuniform or the phase front is other than plane, the gain of the aperture is decreased. This decrease in gain can be accounted for by a gain factor $\mathcal{G}$ which is less than unity. The gain factor is defined as the ratio of the gain of the aperture to the gain of the aperture uniformly illuminated by a plane wave or

$$\mathcal{G} = \frac{G}{G_U} = \frac{G\lambda^2}{4\pi A}.$$

In the antennas under consideration, the phase fronts in the apertures are plane or very nearly so. Thus the apertures can be treated as constant phase apertures without introducing an appreciable error. The gain factor then becomes a function only of the field intensity distribution in the aperture.

Defined in this manner the gain factor is determined by two considerations: the peak radiation intensity produced with a given field intensity distribution, and the power required to produce this field intensity distribution across the aperture. Thus

$$\mathcal{G} = \frac{G}{G_U} = \frac{\left(\dfrac{4\pi\Phi_{2M}}{P_{T2}}\right)}{\left(\dfrac{4\pi A}{\lambda^2}\right)}$$

$$= \frac{\left(\dfrac{4\pi\Phi_{2M}}{P_{T2}}\right)}{\left(\dfrac{4\pi\Phi_{1M}}{P_{T1}}\right)} = \frac{\Phi_{2M}}{\Phi_{1M}}\,\frac{P_{T1}}{P_{T2}};$$

where Φ_{1M} is the maximum value of the radiation intensity with uniform illumination,

Φ_{2M} is the maximum value of the radiation intensity with nonuniform illumination,

P_{T1} is the total power to produce uniform illumination across the aperture,

and P_{T2} is the total power to produce nonuniform illumination across the aperture.

The field intensity distribution in the aperture being known, the Fraunhofer diffraction field intensity pattern can be obtained by integration over the aperture area. The field intensity at the center of the aperture is considered to be the same for all types of illumination taper. The radiation intensity pattern, which is the diffraction field intensity pattern squared, is thus obtained in terms of the taper parameter. Φ_{2M} can be obtained by substituting the proper value of this parameter and Φ_{1M} can be obtained by substituting the proper value of the parameter for uniform illumination. Since the maximum value that Φ_{2M} can have occurs when the aperture is uniformly illuminated (where $\Phi_{2M} = \Phi_{1M}$), the ratio Φ_{2M}/Φ_{1M} is always less than unity for nonuniform illumination.

In the integration mentioned above, the field intensity at the center of the aperture was considered the same for both uniform and nonuniform illumination. The power supplied to the aperture is not the same in both cases. Since the power density is proportional to the square of the field intensity, the power density over the aperture can be integrated and the total power found under both conditions of illumination. The power supplied to the nonuniformly illuminated aperture will always be less than that supplied to the uniformly illuminated aperture. Thus, the ratio P_{T1}/P_{T2} is always greater than unity for nonuniform illumination.

P_{T1}/P_{T2} and Φ_{2M}/Φ_{1M} being known, the gain factor can be calculated. Multiplying the power ratio P_{T1}/P_{T2} by the ratio of the peak value of the radiation intensities can be looked at from another point of view. Had the same power been supplied to the aperture under both conditions of illumination, then each point on the radiation intensity pattern of the nonuniformly illuminated aperture would have been multiplied by the ratio of the increased power level P_{T1}/P_{T2}. Then,

$$\mathcal{G} = \frac{4\pi\left(\frac{P_{T1}}{P_{T2}}\right)\left(\frac{\Phi_{2M}}{P_{T1}}\right)}{4\pi\left(\frac{\Phi_{1M}}{P_{T1}}\right)}$$

$$= \frac{\Phi_{2M}}{\Phi_{1M}}\ \frac{P_{T1}}{P_{T2}} .$$

The gain factor of the plane reflector illuminated by the parabolic antenna is determined by the foregoing method. A brief outline of the procedure is given here, the details of which are in an unpublished report by the authors. The maximum radiation intensity for a square aperture illuminated by a parabolic antenna was shown to be

$$\Phi_{MAX} = \Phi_0\, a^4 \left(\frac{2\delta+1}{3}\right)^2 .$$

For uniform illumination, where $\delta = 1$,

$$\Phi_{1M} = \Phi_0\, a^4 \quad ;$$

and for nonuniform illumination,

$$\Phi_{2M} = \Phi_0\, a^4 \left(\frac{2\delta+1}{3}\right)^2 .$$

The power distribution across the square aperture is of the form

$$\left[1-(1-\delta)\,\rho_n^2\right]^2$$

and it can be shown that the total power is

$$P_T = \Phi_0 \left(\frac{\pi d^2}{4}\right)^2 \frac{a^2}{h^2}$$

$$\left\{1 - \frac{4}{3}(1-\delta) + \frac{28}{45}(1-\delta)^2\right\}.$$

For uniform illumination, where $\delta = 1$,

$$P_{T1} = \Phi_0 \left(\frac{\pi d^2}{4}\right)^2 \frac{a^2}{h^2} \quad ;$$

and for nonuniform illumination,

$$P_{T2} = \Phi_0 \left(\frac{\pi d^2}{4}\right)^2 \frac{a^2}{h^2}$$

$$\left\{1 - \frac{4}{3}(1-\delta) + \frac{28}{45}(1-\delta)^2\right\}.$$

Then the gain factor for the square aperture illuminated by the parabolic antenna is

$$\mathcal{G} = \frac{\Phi_{2M}}{\Phi_{1M}}\ \frac{P_{T1}}{P_{T2}} ,$$

$$g = \left(\frac{2\delta+1}{3}\right)^2 \left[\frac{1}{1-\frac{4}{3}(1-\delta)+\frac{28}{45}(1-\delta)^2}\right].$$

Directive Gain of a Square Aperture

The directive gain of an aperture in a particular direction has been defined as the ratio of its radiation intensity in that direction to the radiation intensity of an isotropic radiator which radiates the same total power. The maximum value of the directive gain is called the directivity. For a given aperture the maximum value of the directivity is obtained when the aperture is uniformly illuminated and this gain is

$$G_u = \frac{4\pi A}{\lambda^2}.$$

When the illumination is tapered, the concept of gain factor g is introduced. This reduces the gain and the directivity is

$$G = \frac{4\pi A}{\lambda^2} g.$$

It has been found that the gain factor for the square aperture with the specific illumination provided by the parabolic antenna is

$$g = \left(\frac{2\delta+1}{3}\right)^2 \left[\frac{1}{1-\frac{4}{3}(1-\delta)+\frac{28}{45}(1-\delta)^2}\right].$$

The maximum directive gain for the nonuniformly illuminated square aperture is

$$G = \frac{4\pi a^2}{\lambda^2}\left(\frac{2\delta+1}{3}\right)^2 \left[\frac{1}{1-\frac{4}{3}(1-\delta)+\frac{28}{45}(1-\delta)^2}\right].$$

When the aperture is uniformly illuminated, equals one and the maximum directive gain is

$$G = \frac{4\pi a^2}{\lambda^2}.$$

Radiation Efficiency

There is a reduction in the maximum possible gain from a plane reflector by other factors which have not yet been considered. One of these factors is the heat loss caused by the currents on the surface of the reflector. This loss is small, and is estimated to be of the order of 1 percent. Thus, the efficiency due to heat loss is $\eta_{\text{HEAT LOSS}} = 0.99$. In the gain analysis which follows, the plane reflector is replaced by a square aperture which has gain both receiving and transmitting. For convenience the efficiency due to heat loss is divided between the two gains. In calculating the system gain, the product of the two aperture gains brings the $\eta_{\text{HEAT LOSS}}$ back to 0.99.

Another factor which reduces the gain is the reduction in effective area of the aperture due to the discontinuity in the field near the edge of the reflector. It is estimated that the area within a quarter wave length of the edge of the reflector is only 50-percent efficient. Thus the efficiency due to the edge effect is

$$\eta_{\text{EDGE EFFECT}} = 1 - \frac{\lambda}{2a}.$$

This factor will be applied to reduce the gain of the square aperture both receiving and transmitting.

It is important to understand that these efficiency factors are arbitrary. They have been estimated on the conservative side and will give a conservative efficiency factor. It is doubtful if a case will be encountered in practice where the efficiency factor for a reflector will be less than 90 percent. The average value for a system is about 95 percent.

Other factors can reduce the maximum possible gain of the reflector, but since they are not easily calculable, they are mentioned here only qualitatively. One of these factors concerns the phase front illuminating the plane reflector. The phase front is assumed to be plane which leads to a higher theoretical gain than can be achieved practically. Another phase factor which can reduce the reflector gain is the deviation of the reflector surface from a smooth plane. In practice these errors are kept to a minimum and neglecting their effects will not materially affect the system gain calculations.

Power Gain

The power gain was previously defined as the directive gain reduced by the radiation efficiency. The factors which modify the gain of the square aperture have been discussed in the preceding section. The power gain for a square aperture nonuniformly illuminated then is $G =$

$$\frac{4\pi a^2}{\lambda^2}\sqrt{0.99}\left(1-\frac{\lambda}{2a}\right)\left(\frac{2\delta+1}{3}\right)^2\left[\frac{1}{1-\frac{4}{3}(1-\delta)+\frac{28}{45}(1-\delta)^2}\right],$$

and the power gain for the uniformly illuminated square aperture is

$$G = \frac{4\pi a^2}{\lambda^2}\sqrt{0.99}\left(1-\frac{\lambda}{2a}\right).$$

Gain in the Fresnel Region

Normally antennas operate in the Fraunhofer region and the gain in this region is constant and independent of distance. However, in the passive reflector-antenna system, component antennas operate near the transition point between Fresnel and Fraunhofer regions and, on occasion, within the Fresnel region.

The gain of an antenna in the Fresnel region is not constant and independent of distance; it is less than the gain in the Fraunhofer region because a plane wave front in an aperture appears to points within the Fresnel region as though it were a quadratic phase error in the aperture. This point is discussed by Silver and a factor $\sin^2 x/x^2$ is developed which is the ratio of the gain of a uniformly illuminated circular aperture in the Fresnel region to the true Fraunhofer gain at infinity.

The circular aperture defined by the parabolic antenna is not uniformly illuminated and thus it is necessary to determine a correction factor for a circular aperture with a $(1-\rho_n^2)^{1/2}$ field intensity distribution. The correction factor is given by

$$\left[\left\{3\sum_{n=0}^{n=\infty}\frac{(-1)^n\left(\frac{\pi d^2}{4\lambda h}\right)^{2n}}{(4n+3)\left[(2n)!\right]}\right\}^2 + \left\{3\sum_{n=0}^{n=\infty}\frac{(-1)^n\left(\frac{\pi d^2}{4\lambda h}\right)^{2n+1}}{(4n+5)\left[(2n+1)!\right]}\right\}^2\right].$$

This is unwieldy, but the two series converge rapidly and their sum is closely approximated by

$$1-0.0684\left(\frac{\pi d^2}{4\lambda h}\right)^2.$$

The square aperture defined by the rectangular plane reflector must have its Fraunhofer gain modified in the same manner as has been done for the circular aperture. In the system gain analysis which follows, it will be seen that it is necessary to determine the correction factor for the square aperture only when it is uniformly illuminated. This correction factor is

$$\left[\frac{C^2\left(\frac{a}{\sqrt{2\lambda h}}\right)+S^2\left(\frac{a}{\sqrt{2\lambda h}}\right)}{\frac{a^2}{2\lambda h}}\right]^2$$

where C and S are cosine and sine Fresnel integrals.

Throughout the treatment of gain in this discussion, the gain in the Fraunhofer region is determined and, if the antenna operates in the Fresnel region or near the transition between the two regions, the correction factors are applied.

Spillover Power

The system gain of a passive reflector-antenna system can be determined once the parabolic-antenna diffraction pattern is known. One method of analysis is to use the radiation pattern of the parabolic antenna to determine not only the amplitude taper over the reflector, but also the power which spills past the reflector. With the amplitude taper known and the phase front assumed to be plane, the gain factor $\mathcal{G}$ can be calculated. This leads to the directive gain G of the reflector over an isotropic radiator which radiates the same total power impinging upon the reflector. The gain will become the passive reflector-antenna system gain $\mathcal{G}$ when it is reduced by the spillover power and the efficiency factors. The spillover power ratio is the ratio of the power impinging upon the reflector to the total power radiated by the parabolic antenna.

When the radiation pattern is the same in all planes perpendicular to the aperture, and is plotted as a function of v (where $v=(\pi d/\lambda)\sin\theta$), then it can be shown that the total power in the pattern is proportional to the volume under the radiation pattern. The power intercepted by the reflector is proportional to the fractional volume of the radiation pattern that is subtended by the reflector. With both the total power and the intercepted power being known, the spillover power can be calculated. The details of this method are discussed in the aforementioned unpublished report.

Analyzing the system gain in this manner may lead to a clearer understanding of the problem, but it is not the simplest approach. The system gains in the remainder of this paper will be determined from the more direct point of view of antenna gains over isotropic radiators and free-space attenuation between them. The system gain expression obtained in this manner is identical with that determined by the method of spillover power.

System Gain

The system gain of a passive reflector-antenna system will now be determined by considering the parabolic antenna as a transmitting antenna. If, instead, the antenna system were analyzed by considering the parabolic antenna as a receiving antenna, the result would be identical by the theorem of reciprocity.

The 45-degree plane reflector is replaced by a square aperture and the equivalent system to be analyzed becomes that shown in Figure 4. The square aperture and the parabolic antenna are separated by the distance h. The distance between the square aperture and the isotropic antenna is denoted by s, which is very large compared to h. The diameter of the parabolic-antenna aperture is shown as d and the square aperture has its dimension represented by a.

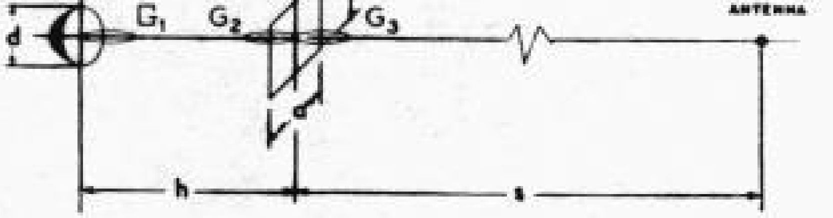

Figure 4. A passive reflector-antenna system with a square aperture replacing a 45-degree plane reflector

In Figure 4 the gains G_1, G_2 and G_3

refer respectively to the system gain of the parabolic antenna, the power gain of the square aperture receiving, and the power gain of the square aperture transmitting. When an aperture operates in the Fresnel region, a factor modifying the Fraunhofer gain is introduced. With these gains over isotropic radiators available and with the free-space attenuation between the component parts of the system calculable, the passive reflector-antenna system gain over an isotropic radiator can be determined.

The Fraunhofer system gain of the parabolic antenna over an isotropic radiator is given by

$$G_1 = \frac{\pi^2 d^2}{\lambda^2} (0.65) \; .$$

Since the parabolic antenna, as part of the passive reflector-antenna system, operates within its Fresnel region, then its Fraunhofer gain is modified to

$$G_1' = \frac{\pi^2 d^2}{\lambda^2} (0.65) \left[1 - 0.0684 \left(\frac{\pi d^2}{4 \lambda h} \right)^2 \right] .$$

The gain G_3 arises from a square aperture with a field intensity distribution determined by the parabolic-antenna radiation pattern which illuminates it. The Fraunhofer power gain of a nonuniformly illuminated square aperture was shown to be

$$G_3 = \frac{4 \pi a^2}{\lambda^2} \sqrt{0.99} \left(1 - \frac{\lambda}{2a} \right) \left(\frac{2\delta + 1}{3} \right)^2 \left[\frac{1}{1 - \frac{4}{3}(1-\delta) + \frac{28}{45}(1-\delta)^2} \right] .$$

Since the distance S over which the aperture is operating is in the Fraunhofer region, no modification is necessary.

The gain G_2 arises from a square aperture with a field intensity distribution determined by the isotropic radiator radiation pattern. Since the isotropic radiator radiates uniformly in all directions and the distance S is very large, the square aperture is uniformly illuminated. The power gain for the square aperture under these conditions was shown to be

$$G_2 = \frac{4 \pi a^2}{\lambda^2} \sqrt{0.99} \left(1 - \frac{\lambda}{2a} \right) .$$

The distance h over which the aperture operates is near or within its Fresnel region so that the Fraunhofer gain must be modified by the appropriate expression. The gain thus becomes

$$G_2' = \frac{4 \pi a^2}{\lambda^2} \sqrt{0.99} \left(1 - \frac{\lambda}{2a} \right) \left[\frac{C^2 \left(\frac{a}{\sqrt{2 \lambda h}} \right) + S^2 \left(\frac{a}{\sqrt{2 \lambda h}} \right)}{\frac{a^2}{2 \lambda h}} \right]^2 .$$

The calculations of gains over isotropic radiators have been made, so far, independently of power levels. If, however, the entire system is to be compared to an isotropic radiator to which the same total power has been supplied, then the power level of only one isotropic radiator in the system analysis is fixed. The successive isotropic radiators, to which gains in the system are referred, have power levels which depend upon the gains and losses which occur between them and the reference isotropic radiator. This change in power levels between isotropic radiators is normally accounted for by the free-space attenuation between them. However, in considering the plane reflector as two apertures and comparing their gains to two isotropic radiators, the difference in power levels between them is not accounted for. Thus a normalizing factor N_δ is introduced. Upon investigation this normalizing factor is found to be the reciprocal of the power normalizing term in the gain factor of the square aperture $N_\delta =$

$$\left[1-\frac{4}{3}(1-\delta)+\frac{28}{45}(1-\delta)^2\right].$$

Since the square aperture uniformly illuminated has a higher power level than the square aperture nonuniformly illuminated, N_δ reduces G_2' to

$$N_\delta G_2' = \frac{4\pi a^2}{\lambda^2}\sqrt{0.99}\left(1-\frac{\lambda}{2a}\right)$$

$$\left[\frac{C^2\left(\frac{a}{\sqrt{2\lambda h}}\right)+S^2\left(\frac{a}{\sqrt{2\lambda h}}\right)}{\frac{a^2}{2\lambda h}}\right]^2$$

$$\left[1-\frac{4}{3}(1-\delta)+\frac{28}{45}(1-\delta)^2\right].$$

The free-space attenuation between the parabolic antenna and the plane reflector is

$$\alpha_h = \frac{\lambda^2}{16\pi^2 h^2};$$

the free-space attenuation between the plane reflector and the isotropic radiator is $\alpha_s = \dfrac{\lambda^2}{16\pi^2 s^2}$; and the free-space attenuation between two isotropic radiators separated by a distance $h + s$ is

$$\alpha_{h+s} = \frac{\lambda^2}{16\pi^2(h+s)^2}.$$

In a system consisting of two isotropic antennas separated by a distance $h + s$, the path attenuation is $10 \log \alpha_{h+s}$ db. Using the passive reflector-antenna system the received signal is

$$10 \log G_1' + 10 \log N_\delta G_2' + 10 \log G_3 + 10 \log \alpha_h + 10 \log \alpha_s \text{ db.}$$

The difference between these two receiving levels is the passive reflector-antenna system gain G over an isotropic radiator,

$$G = 10 \log G_1' N_\delta G_2' G_3 \alpha_s \alpha_h - 10 \log \alpha_{h+s} \text{ db.}$$

Since the distance h is normally very small compared to s (in the Monsey tests $h = 140.8$ feet and $s = 27.8$ miles) the approximations can be made that $h + s \approx s$ and $\alpha_{h+s} \approx \alpha_s$. Thus, when $h \lll s$, the expression reduces to

$$G = 10 \log G_1' N_\delta G_2' G_3 \alpha_h \text{ db.}$$

By making the proper substitutions and combining terms, the passive reflector-antenna system gain over an isotropic radiator then becomes

$$G = \left(\frac{\pi^2 d^2}{\lambda^2}\right)(0.65)\left(\frac{4\pi a^2}{\lambda^2}\right)(0.99)$$

$$\left(1-\frac{\lambda}{2a}\right)^2\left(\frac{2\delta+1}{3}\right)^2\left(\frac{\lambda^2}{16\pi^2 h^2}\right)$$

$$\left[\frac{C^2\left(\frac{a}{\sqrt{2\lambda h}}\right)+S^2\left(\frac{a}{\sqrt{2\lambda h}}\right)}{\frac{a^2}{2\lambda h}}\right]^2$$

$$\left[1-0.0684\left(\frac{\pi d^2}{4\lambda h}\right)^2\right].$$

Combining constants, the expression further reduces to

$$G = 20 \log \frac{d}{\lambda}(2\delta + 1)$$

$$\left[C^2(X) + S^2(X)\right]\left(1 - \frac{\lambda}{2a}\right)$$

$$\left(1 - 0.0684\, y^2\right)^{1/2} + 4.50 \text{ db},$$

where

$$X = \frac{a}{\sqrt{2\lambda h}}\,,$$

$$y = \frac{\pi d^2}{4\lambda h}\,,$$

$$\delta = \Lambda_{3/2}\left(\frac{\pi d a}{\lambda 2h}\right),$$

$$C(x) = \int_0^x \cos\left(\frac{1}{2}\pi x^2\right) dx$$

(Cosine Fresnel Integral), and

$$S(x) = \int_0^x \sin\left(\frac{1}{2}\pi x^2\right) dx$$

(Sine Fresnel Integral).

Description of Gain Tests

The gain tests at Monsey compared the signal received through a passive reflector-antenna system to the signal received through a 4-foot parabolic antenna mounted adjacent to the plane reflector. A signal was transmitted from New York at 4060 mc and received at Monsey by a calibrated receiver, with a calibrated wave-guide attenuator between the antenna and the receiver. First the signal was received through the passive reflector-antenna system and the calibrated attenuator was adjusted to give a reading on a scale division of the calibrated receiver limiter current meter. The settings of the calibrated attenuator and the receiver limiter current were noted. The receiver equipment was then hoisted up the tower and connected directly to the 4-foot parabolic antenna. The calibrated attenuator was adjusted to give the same receiver limiter current reading that had previously been noted. The amount that the calibrated attenuator was changed was a direct measure of the gain of the passive reflector-antenna system over the 4-foot parabolic antenna.

The 4-foot parabolic antenna mounted on the tower was identical with that used to illuminate the plane reflector in two of the gain tests. In the other two tests a similar 6-foot parabolic antenna was used to illuminate the plane reflector. The measured gains are relative to the gain of the 4-foot parabolic antenna mounted on the tower, which is given by

$$G = \frac{\pi^2 d^2}{\lambda^2}(0.65)$$

$$= \frac{\pi^2(16)(0.65)}{0.0587} = 1750\,,$$

or

$$10 \log 1750 = 32.43 \text{ db.}$$

It is to be noted that this parabolic-antenna gain does not contain the correction for operation within the Fresnel region. When the parabolic antenna is mounted on top of the tower it is operating over a large path distance S and correction of its Fraunhofer gain is not necessary.

Theoretical and Experimental Gains

The experimental gains obtained at Monsey are passive reflector-antenna system gains over a 4-foot parabolic antenna; therefore, G must be reduced by 32.43 db in comparing theoretical and experimental gains. In Table I the gains for the four tests are tabulated for comparison. In each of the four cases the 45-degree plane reflector is of such dimensions that the equivalent square aperture is 6 feet by 6 feet.

TABLE I

COMPARISON OF EXPERIMENTAL AND THEORETICAL GAINS OF PASSIVE REFLECTOR-ANTENNA SYSTEMS TESTED AT MONSEY HEIGHTS, NEW YORK

DIAMETER OF PARABOLA d	DISTANCE OF SEPARATION h	SIZE OF APERTURE a	FREQ.	PASSIVE REFLECTOR-ANTENNA SYSTEM GAIN OVER AN ISOTROPIC ANTENNA G	PASSIVE REFLECTOR-ANTENNA SYSTEM GAIN OVER A 4-FOOT PARABOLIC ANTENNA G-32.43 db	
					THEORETICAL	EXPERIMENTAL
Feet	Feet	Feet	Mc	db		
6	90.25	6	4060	34.45	+2.02	+2.50
6	140.80	6	4060	33.87	+1.44	+0.55
4	90.25	6	4060	33.40	+0.97	+0.70
4	140.80	6	4060	31.39	−1.04	−0.75

In Table I it is seen that the theoretical values of gain agree reasonably well with the experimental values. The average difference is less than ±0.5 db. The magnitude of this difference is not unreasonable when all the variables in the gain analysis and in the experimental determination of the gain are considered. The assumptions and the approximations used in the theoretical determination of the gain have already been discussed. Another discrepancy between theoretical and experimental gains is due to the errors associated with the experimental technique.

Side-Lobe Levels

In a parabolic-antenna system the 10-db illumination taper is almost standard. Based upon this, it can be said that the first side lobe of a parabolic antenna theoretically is down about 21.3 db. The measured value of the first side lobe, however, is rarely below about 16 db. The rather large discrepancy between theoretical and measured levels is due primarily to phase errors. Side lobes arise from phase additions and the nulls from phase cancellations, so they are particularly sensitive to phase errors. The deviation of the reflecting surface from a true paraboloid and the size and location of the feed relative to a point source at the focal point of the paraboloid introduce phase errors in a parabolic-antenna system.

The side-lobe levels in a passive reflector-antenna system cannot be tied down in the same manner as is done with the parabolic antenna, for there is no standard illumination taper. The side-lobe levels vary depending upon the illumination produced at the edge of the reflector and this illumination, in turn, is a function of the component antennas and their separation.

The theoretical level of the first side lobe of a uniformly illuminated ($\delta = 1.0$) reflector with a square aperture is 13.3 db. When $\delta = 0.882$, the theoretical value decreased to 14.0 db and, at $\delta = 0.474$, the theoretical level of the first side lobe is 18.4 db.

A condition under which a value of $\delta = 0.882$ is obtained was tested at Monsey. At 4060 mc, a 4-foot parabolic antenna fed a plane reflector, with a 6-foot-square aperture, over a distance of 140.8 feet. The pattern was measured and the value of the first side lobe agreed exactly with the theoretical value of 14 db.

A value of $\delta = 0.474$ is produced by a 6-foot parabolic antenna feeding a plane reflector, with a 6-foot-square aperture, over a distance of 90.25 feet at 4060 mc.

This was the condition tested at Monsey which produces the lowest side-lobe levels.

The close agreement obtained between the theoretical and experimental value of the first side lobe of a passive reflector-antenna system is believed due to very little deviation in phase of the wave front incident upon the reflector from the plane wave front assumed in the analysis.

The conclusion is drawn that, although the side-lobe levels of a parabolic-antenna system are theoretically lower than those of a comparable passive reflector-antenna system, there is not very much difference realized between the actual side-lobe levels. Further, it is believed that if side-lobe levels are to be of major concern, reduction can be obtained without sacrificing other system characteristics. The nature of a passive reflector-antenna system is such that measures which will reduce side-lobe levels will increase the system gain at the same time. A reduction in side-lobe levels and an increase in gain can be obtained simultaneously by increasing the size of the reflector, the parabolic antenna, or both, under most normal operation conditions.

Mutual Coupling

The mutual coupling among passive reflector-antenna systems is relatively complex. Coupling exists among the paraboloids, among the plane reflectors, and between plane reflectors and paraboloids due to their radiation pattern side lobes. However, a major contributor to the coupling is reflections from nearby objects and the tower itself. The fact that the passive reflector-antenna system is so open makes it particularly susceptible to coupling by reflections. The presence of portions of the tower structure in the path of radiation within the antenna systems contributes an appreciable amount of the coupling by reflections.

In the mutual coupling tests conducted at Monsey, the passive reflector-antenna systems were oriented in all possible combinations of positions that might reasonably be encountered in an actual installation. Measurements of the local mutual coupling between passive reflector-antenna systems showed that values of the order of 55 to 60 decibels can be expected in almost all cases.

A comparison between a parabolic-antenna system and a passive reflector-antenna system indicates that the order of magnitude of the local mutual coupling is the same in both systems. Friis reports the coupling between parabolic antennas back-to-back to be 50 to 60 db and Brown reports it to be 40 db.

The mutual coupling between the parabolic antennas alone, in the positions they would occupy in the passive reflector-antenna systems, was measured and found to be of the order of 60 to 65 db. The system's coupling deteriorates by approximately 3 to 8 db due to reflections and coupling between the plane reflectors. The beam width of the parabolic antenna is a factor in determining the extent of the deterioration. The greater the beam width the greater the deterioration, due principally to the higher levels of the energy thrown into the tower structure, to be reflected.

In general, screens are not too effective in reducing the local coupling. They are most effective placed directly between the parabolic antennas when the paraboloids are level and close together. In this position they almost completely eliminate the coupling between the parabolic antennas. However, the coupling due to reflections is at least the same order of magnitude as the parabolic-antenna coupling alone, so that a maximum reduction of only about 3 db results from the complete elimination of the coupling between the parabolic antennas. When the screens are placed between the plane reflectors there is no significant decrease in local coupling. The conclusion is drawn, therefore, that the coupling between the plane reflectors alone is not a significant contributor to the local mutual coupling.

Moving the parabolic antennas out from under the tower and then tilting them toward the tower, to correspond to the change in elevation angle of the plane reflectors necessary to maintain the same direction of radiation from the plane reflector, produces no definite pattern of improvement in the local coupling. Separating the parabolic antennas tends to decrease the coupling, but the effect of tilting them is to throw more energy into the tower structure thereby increasing the coupling due to reflections. Tilting the parabolic antennas toward one another changes the local coupling due to interaction of their radiation patterns in a manner which is not predictable. The net result is that this method can either reduce or increase the local coupling, but in either case the change does not appear to be very great.

There appears to be no effective way to reduce coupling by reflections from the tower structure itself except to avoid large flat surfaces, such as the horizontal gratings on the bridges of the Monsey tower. It is believed that these gratings contribute about 1 to 2 db of coupling between passive reflector-antenna systems on opposite sides of the tower. When antenna systems are symmetrically located on opposite sides of the tower, such horizontal reflecting surfaces midway between them produce maximum local coupling. The closer the antenna systems are to one another, the greater the increase in coupling due to these surfaces. It is advisable, therefore, to avoid such reflecting surfaces in any installation where the mutual coupling in the antenna system is an important consideration.

As was mentioned previously, the mutual coupling between the parabolic antennas, which were part of the passive reflector-antenna systems, was measured to be between 60 and 65 db, and tests showed the rest of the passive reflector-antenna systems contributed the same order of magnitude of coupling as the parabolic antennas. It follows that coupling between systems of the order of 55 to 60 db cannot be achieved without parabolic antennas having mutual coupling of the order of magnitude of those used in the Monsey tests. This is mentioned because side-to-side coupling between parabolic antennas of the order of 60 to 65 db is exceptionally good. It is quite likely that most parabolic antennas in use do not approach this figure. In considering the illumination of parabolic antennas for use in passive reflector-antenna systems, it is suggested that the illumination at the edges of paraboloids be reduced to lower values than are commonly used, keeping in mind that decreased illumination at the edges means decreased gain and a wider beam width, which will increase the coupling due to reflections. A compromise must be made where the mutual coupling in the antenna systems is an important consideration.

The problem of coupling from a distant source is similar, but more serious, than that of local coupling. Unfortunately the sensitivity of the test receivers did not allow measurements greater than 35 db down. The coupling from distant sources, however, was always greater than 35 db, but there is reason to believe that it was not down more than 40 db. Screening between the antenna systems would probably be more effective than was the case for local coupling. However, this coupling must be recognized as a serious limitation on frequency assignments in radio relay systems employing passive reflector-antenna systems.

Summary

The advantages and disadvantages of a passive reflector-antenna system must be considered in conjunction with the frequency at which the system is to operate. The conclusions drawn in this discussion are based upon operation in the 4000-mc region, though the analysis is applicable throughout the microwave region.

From the tests and analysis of the passive reflector-antenna systems, it appears that their performance is comparable to that of parabolic-antenna systems operating under the same conditions. However, to take economic advantage of tower construction such as is used with passive reflector-antenna systems, parabolic-antenna systems would have to employ long wave-guide transmission lines between the antennas and the radio equipment at ground level. This would introduce losses and mismatches not present in a passive reflector-antenna system and the performance of the two systems could no longer be considered comparable.

The chief advantage of a passive reflector-antenna system, and it almost overshadows all other advantages and disadvantages, is the economies that can be effected in the tower construction at a relay point. If the performance characteristics which have been described can be tolerated, as in a four-frequency system, then a passive reflector-antenna system is the most economical antenna system. If the performance characteristics, principally in respect to the mutual coupling, are not adequate, there appears to be no way in which antenna systems with substantially better coupling characteristics can be employed without more costly tower construction.

The gain of the passive reflector-antenna system over the parabolic antennas in the system has aroused considerable interest. It is theoretically possible to obtain a 6-db gain using a plane reflector with a circular aperture, and a 5.12-db gain using a plane reflector with a square aperture. These values cannot be realized in any installation because the optimum conditions do not represent practical situations. The size of the parabolic antennas in the system would have to approach a point source, with a gain approaching zero db, in order to obtain these maximum values. Therefore, this "phenomenon" is only of academic interest.

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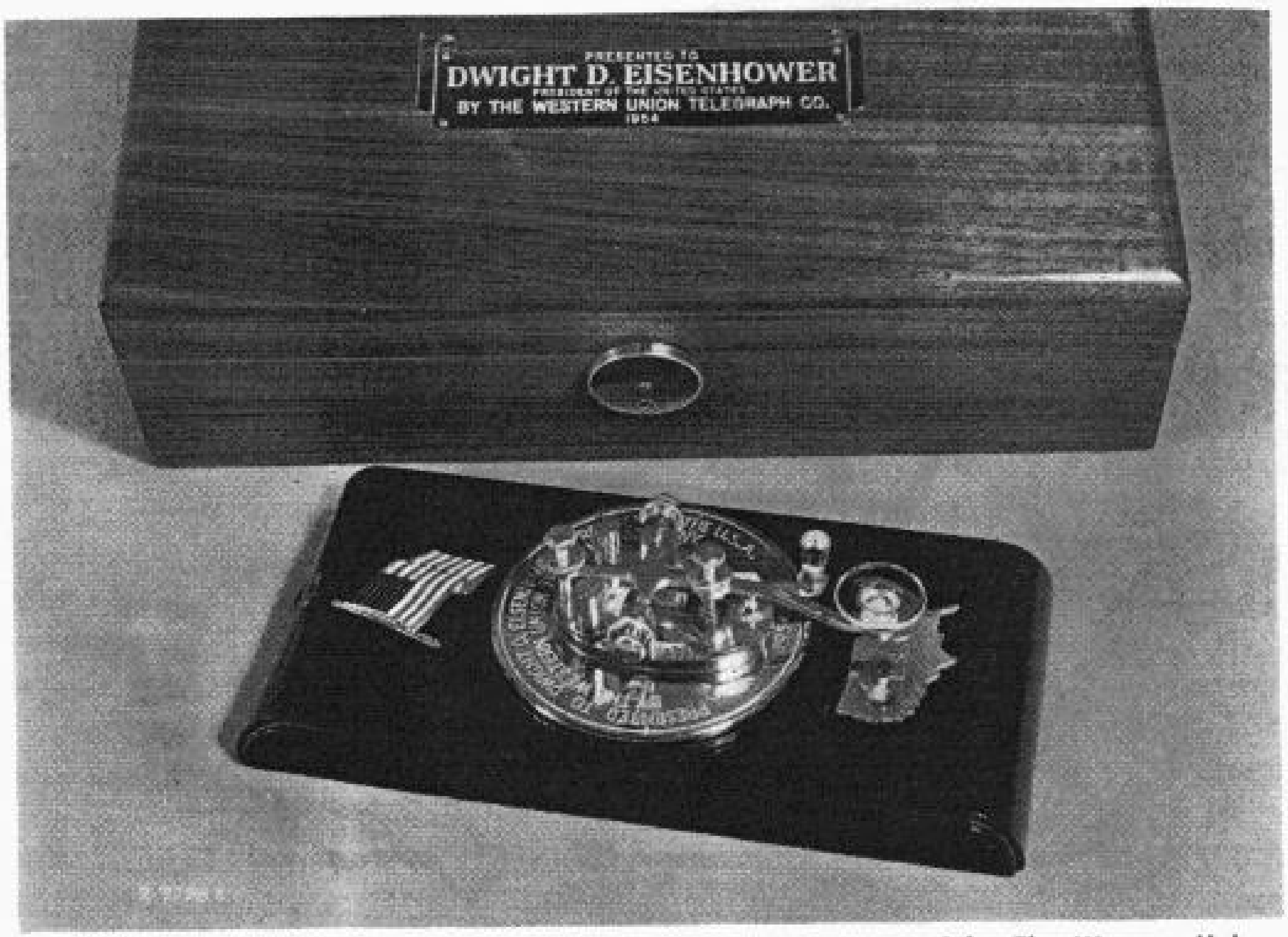


Golden telegraph key, symbolic of rapid communication, presented by The Western Union Telegraph Company to Dwight D. Eisenhower, President of the United States of America. The key with its clear plastic knobs is in polished gold as are the engraved medallion on which it rests, the U. S. A. map, and the nameplate on the walnut case. The flag is in gold and color; the base is polished black catalin. The key and case were designed by Messrs. J. Schmid and V. Weidner of the Plant and Engineering Department.

Intercity Facsimile Trunks

F. B. BRAMHALL

General

IN PLANNING for Western Union's future, a great deal of thought is being given to trunk-line operation by the facsimile method. The provision of transmission facilities for long distance facsimile and telegraphy has been the subject of more or less active study in many quarters since World War I. While the whole answer to the problem is not yet in sight, a basic understanding of some of its technical aspects may contribute to more helpful thinking on the subject.

Transmission facilities employed for intercity facsimile, at least for some time to come, will quite likely be "derived" carrier system voice bands about 3000 cycles wide. Intercity trunks will rarely if ever be physical pairs. Only in a few sparsely settled areas of the West and Northwest will the restricted bandwidth (300—2600 cycles) of the older designs of carrier systems be encountered. The economics of any long-haul intercity facsimile network will certainly not stand for an over-all system speed held down by these few restricted bandwidth links. The assumption then has been, from the beginning of trunk-fax planning, that all facilities would be "good" attenuation-wise from 300 to 3300 cycles. This means Type "J" open wire or Type "K" cable carrier or any of the coax systems designated by the type letter "L". There is no alternative, it seems, but to contemplate the uniform and universal transmission facility, the 3-kc band, and continue to develop our own multiplexing equipment for such Western Union wire and radio circuit expansion as is found desirable to meet this standard.

Amplitude Equalization

With 3-kc band attenuation reasonably flat over any single system link, we may expect no unsurmountable band restriction over circuits comprising two tandem-connected carrier system bands. Circuits involving three or more tandem-connected carrier bands would generally require over-all pre-established amplitude equalization. This requirement would very largely bar trunk-line circuit restorations by the expedient of patching-in separate carrier-derived sections. To make this more clear, let us consider a New York to Chicago facsimile trunk made up of a New York-Pittsburgh Western Union radio relay band, a Western Union wire carrier system band Pittsburgh to Cincinnati, and a leased carrier band Cincinnati to Chicago. The over-all facsimile band so made up will probably have "mop-up" amplitude equalizers at both ends, if it is a two-way circuit. Restoration of this circuit, in case of a Pittsburgh-Cincinnati failure, by the expedient of patching-in some other facility, Western Union or leased, in that section, would probably be impracticable. The over-all amplitude vs. frequency characteristic after such a restoration might well be unsatisfactory. Rather, restoration should be made by patching to another through New York-Chicago trunk which has been pre-equalized.

Delay Distortion (Why Fax Facilities Are Different)

In one particular respect, requirements imposed by facsimile working are more difficult than those encountered either in telephony or multiple-channel carrier telegraphy. Facsimile operation demands that attention be given to the length of time required for propagation of signals for the various frequencies involved. In telephony it is surprisingly unimportant if the different frequencies involved consume the same or different amounts of time in traversing the transmission circuit. In multiple-channel telegraphy we divide the 3-kc voice band into narrow slices. For instance, frequencies around 800 to 850 cycles go from New York to Syracuse via a conventional cable carrier band in about 3250 microseconds; frequencies in the neighborhood of 1600 cycles may go to

Syracuse in 3000 microseconds. *Precisely what are we talking about? What do these statements mean?* Well, they mean that forgetting all about the delays that happen within telegraph channel equipment, if we send a single start pulse from the same printer on two channels, one from the 825-cycle channel, and one the 1575-cycle channel, the receiving printer on the first channel will operate 0.25 milliseconds before the one on the higher channel. That situation is of no consequence in printing telegraphy. No one would ever discover that such was the fact, except an academically curious investigator. Nor should it be inferred from the figures quoted that delay within a derived voice band is inversely proportional to frequency. Far greater differences in delay are introduced by the filters, the impedance mismatches, and what we might call the man-made conditions of the band path than by the normal propagation constants of the wire transmission path. In other words, delay distortion is most commonly something the equipment designer inadvertently built into the system. Inadvertently isn't quite the right word either. Actually he was powerless to avoid building delay difference into his networks.

The relative delay encountered by the teleprinter carrier envelopes at various frequencies in a cable carrier system band is plotted roughly in Figure 1.

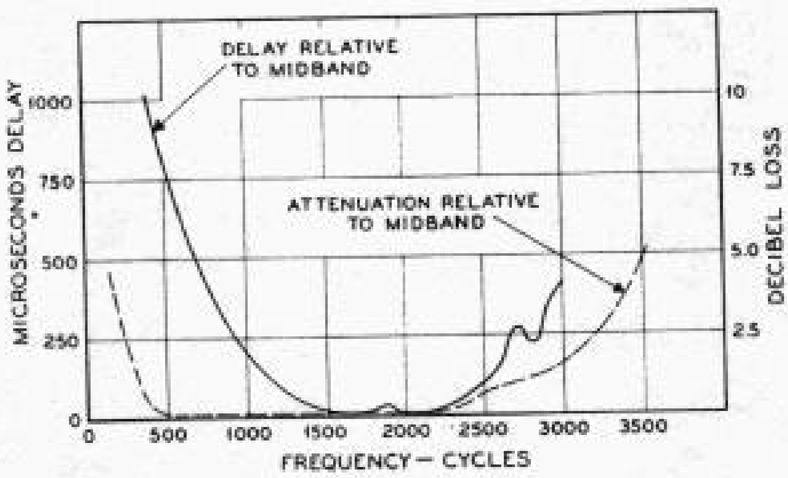


Figure 1. Attenuation and delay characteristics of typical carrier band

The approximate attenuation of the filters which restrict the band is also shown. It is a reasonable and an accurate conclusion that the steep sides of the filters have something to do with the fact that different frequencies encounter different delays in passing through such a band. It is apparent too that the region of minimum delay difference is a narrower region than the region of low attenuation.

Delay distortion can be corrected by making the signals pass through an additional network, which doesn't do too much to the attenuation but which introduces additional delay at those frequencies which come through too fast. These networks, however, are not simple. It isn't uncommon to find delay networks with anywhere from one to five dozen reactive elements, inductors and capacitors. When the techniques are well known and the measuring instruments and compensating networks are at hand, it is still a tedious time-consuming operation to delay-equalize a telephone transmission band and so convert it to a facsimile transmission band. The point here is that equalization isn't a simple adjustment that can be made in a few seconds, like balancing a duplex telegraph line. Still, on a long-term basis the man-hours and the annual charge on the delay compensating equipment wouldn't add much to the facility cost. What has made telephoto circuits so costly up to now is the relatively small demand. One circuit from City A to City B must be protected with another. Facsimile circuits cannot be built up on a moment's notice by the dispatcher by patching together sections A-B, B-C, and so forth.

The 3-kc carrier-derived transmission band will probably be considered standard transmission facility. The useable bandwidth on trunk-line facsimile circuits so derived, after amplitude and delay equalization, will be no more than 2100 cycles. This band will extend approximately from 750 to 2850 cycles. This 2100 cycles of amplitude- and delay-equalized band will, however, deliver just as good or maybe a little better facsimile copy than we are now accustomed to seeing from intracity feeders. By present double-sideband techniques, 180 rpm with an 8-1/2 inch circumference drum will be about top speed. These trunk bands will show degradation of copy sharply as speed is increased above the nominal 1050-cycle top modulation rate. With conventional double-sideband working, this corresponds to 14 or 15 square inches per minute.

Vestigial Sideband

Perhaps the most promising line of attack, if operating speed in excess of 15 square inches per minute is demanded, will be the vestigial-sideband method of working. It has long been known that either set of sidebands created by the amplitude modulation of a carrier contains the same information.

It is interesting to look specifically at the likely carrier and sideband relations for both double- and vestigial-sideband working in the predicted trunk facility fax band. For double sideband, the mid-point between 750 and 2850 is 1800 cycles. That is not high enough to allow the use of a chopper as a modulation method to good advantage. With an 1800-cycle chopper rate and a 1050-cycle modulation rate, the lower sideband and the signal frequencies overlap just a little too much. When the light chopper system is used as the modulation method, there's no way to avoid the effect of interference between the two. This effect is the one which Bell Laboratories and Signal Corps literature calls the *Kendall effect*. Any kind of a balanced modulator avoids this problem.

If a balanced modulator is used, then the group of frequencies from 1800 cycles down to 750 cycles contains precisely the same facsimile information as the group from 1800 up to 2850. The problem of how best to throw away one of these groups is the one which brings minor complications. The carrier frequency, 1800 in this case, cannot be completely suppressed. A filter must be used which cuts off gradually and uniformly as indicated by Figure 2.

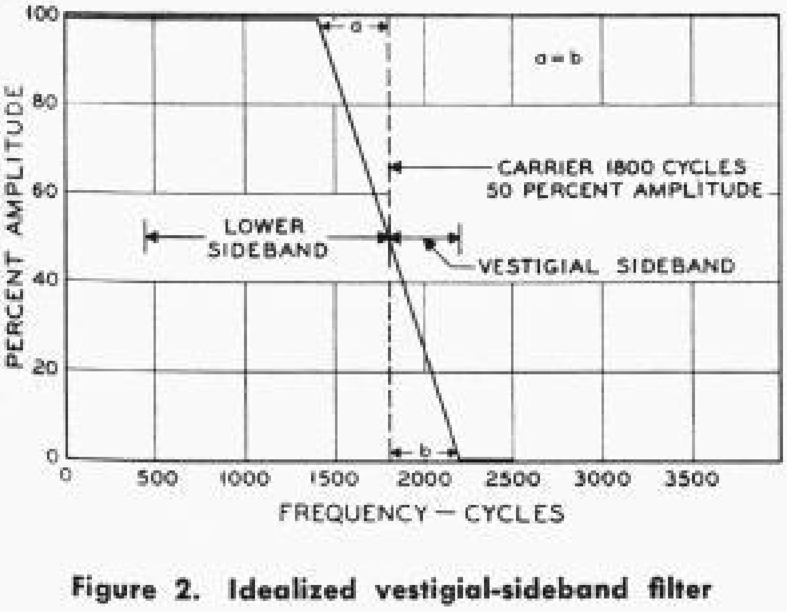


Figure 2. Idealized vestigial-sideband filter

It may be a help to display the effect of the vestigial-sideband filter in another way. Figure 3 shows the amplitude of all the frequencies that will come through the filter, if they are all sent in at uniform amplitude. Here we have the origin of the name *vestigial*. Only a trace, a vestige of the upper sideband, remains.

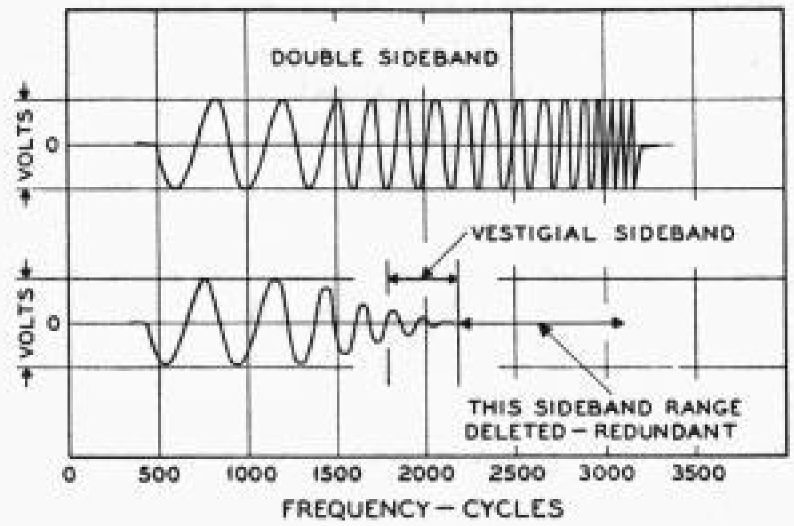


Figure 3. Signal amplitudes in double- and vestigial-sidebands

Figure 3 is interesting only as a comparison of the spectrum relations in vestigial- and double-sideband working. Interest shifts immediately to the practical extent of use of the frequency space made idle by the partial deletion of the redundant sideband. The attenuation characteristic of the attainable vestigial-sideband filter is of extreme importance. The precise degree to which the frequencies in the vicinity of the carrier are suppressed determines the shape of the signal pulses. But delay distortion, unfortu-

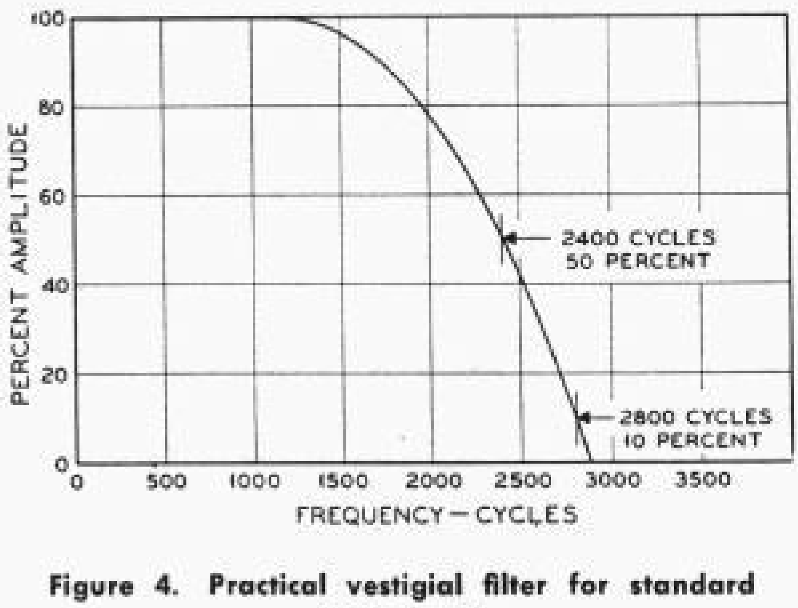


Figure 4. Practical vestigial filter for standard voice band

nately, is always associated with a cutoff point in a filter, even a vestigial filter. We never quite realize the ideal. A compromise has to be made between a desirable cutoff shape for the sideband-deleting vestigial filter and the delay distortion which it introduces. The most recent one developed for this purpose is shown by Figure 4.

It will be noted that this filter passes the designed carrier frequency, 2400 cycles, at half amplitude. For all practical purposes, it cuts off completely at 2800 cycles. Actually its amplitude response is down to 10 per cent of full amplitude at 2800, 400 above the carrier. Our definition of an ideal vestigial filter would call for its response to be about 90 per cent, then, at a frequency 400 cycles below the carrier. That point is 2000 cycles, where in fact we find the amplitude off about 20 per cent. The sacrifice in absolute symmetry about the carrier is made in the interest of low delay distortion.

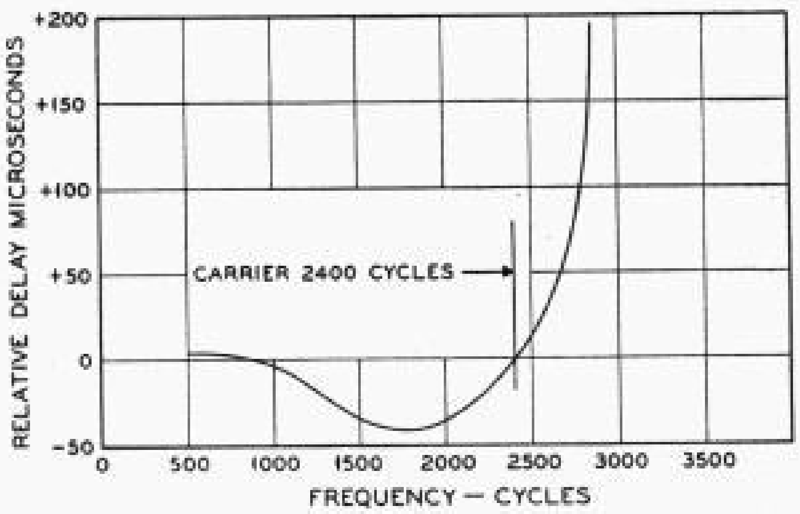


Figure 5. Relative delay of vestigial-sideband filter shown in Figure 4

Figure 5 shows what we consider a remarkable lack of delay distortion for this vestigial filter. The nonuniformity of delay does not exceed plus or minus 100 microseconds from the lowest useable frequency all the way up to about 2750 cycles. Maximum tolerable deviation from uniform delay is pretty commonly accepted to be about 200 microseconds per 1000 cycles of modulation rate. Beyond 2800, where the delay really gets out of hand, the attenuation of this filter exceeds 20 decibels. Here we have a principal criterion of a good vestigial filter in a nutshell. It must make sure that any frequencies which are delayed too much can't get through in sufficient magnitude to do any damage.

Although laboratory work on a system designed around this filter is not completed, we may conceivably be able to achieve a good signal shape at a fundamental repetition rate of 1650 cycles per second. This increase would permit of good facsimile working at approximately 22 square inches per minute with fair realization of 100-line definition.

These problems entailed in the measurement and correction of delay distortion are now the subject of intensive research in our own and in other laboratories. So also are those pertaining to vestigial-sideband working.

F. B. Bramhall specialized in communications at Pennsylvania State College, graduating in 1919, and came to the Engineering Department in 1920. Following early assignments on d-c telegraph transmission problems he headed the group which initiated Western Union development of electronic carrier telegraph systems. This development has continued under his direction, resulting in the equipment and system designs utilized in the Company's large-scale carrier applications. Since 1943, as Transmission Research Engineer, he has also directed telegraph transmission development generally, including work on telegraph relays and distortion measuring equipment, ocean cable transmission and submerged repeaters, and trunk circuit facsimile transmission. Mr. Bramhall is a Senior Member of IRE and a Fellow of AIEE. He has been Chairman of the Company's Committee on Technical Publication since 1949.

Design of a Commercial Facsimile System

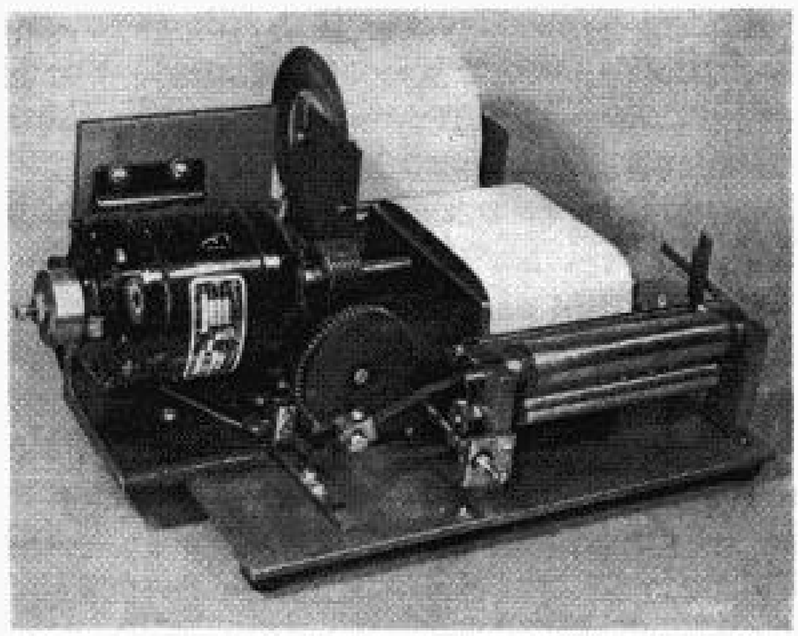
T. F. COFER

Historical

COMMUNICATION by facsimile methods is a very old concept. In 1843, when Morse telegraphy was still in the experimental stage, a Scot named Alexander Bain patented a facsimile system utilizing a clockwork "flat-bed" scanning arrangement traversing conducting information on a nonconducting background. Although the invention was unsuccessful its basic purpose was the continuing challenge of record communications: to permit the transmission of all symbols that anyone can write, indite, print, paint, stamp or stain on the sending blank. Reduction to fixed codes, thus limiting the transmission to arbitrary standardized symbols, would not be necessary with such a system. But even today record communications would welcome a practical, low-cost flat-bed scanner. Similarly present commercial facsimile systems, although extensive, have not yet attained world-wide nor even nation-wide scope although there are evidences that much progress is being made in that direction.

That Bain's clockwork and pendulum device failed is not surprising in the light of today's knowledge. It is astonishing that any practical transmission could have been accomplished at all without electric motors and with only the faintest knowledge of electrical transmission problems. True, in 1848, the principle of scanning copy on synchronously rotating cylinders was introduced by Bakewell, of England, and in 1869 a Parisian named d'Arlincourt suggested the "start-stop" method of phasing, togther with an improved speed control for synchronizing clockwork motors, involving the use of tuning forks. Several years later, when William Sawyer, of New York, applied the first electric motors to the drum and inserted a clutch between the motor shaft and the mechanism, the facsimile communication art had been known for 30 years but still had not progressed much beyond the experimental stage.

All of the early work on facsimile operations used conductive scanning; that is, the sending device depended upon a conducting wire stylus traversing a platen or cylinder where the symbols to be transmitted were either conducting on a nonconducting background or vice versa. Various means to obtain this feature included scraping areas from painted metal, writing on bright metal with nonconducting ink, or even embossing or indenting the symbols in thin metal sheets. All of these methods required special conditions of the subject copy,—almost as serious a deficiency as the requirement of arbitrary codes. But in 1873 an English telegraph engineer, Willoughby Smith, discovered the photoelectric properties of selenium quite by accident, thus opening a new field of electric research which later brought facsimile and even photographic reproductions, at a distance, to practicability.



An early experimental flat-bed scanner

For a while it appeared that the capabilities of the photocell had turned the interest of communication research away from the simple form of facsimile to the more exacting requirements of photographic transmission. Western Union operated a picture system called "Telepix" as early as 1924. But a practical commercial facsimile system was waiting for developments in many quarters: for carrier-frequency principles, which were worked out and polished up by the requirements of conventional communications; for inexpensive but reliable electronics, which were worked out and produced in quantity for home radio receivers; for modest but satisfactory control relays, which were evolved from the needs (of all things!) of pin-ball machines and "juke" boxes. But most of all the art needed stable primary power systems providing accurately controlled frequency at the power outlets in business houses as well as in communication centers.

Power frequency stability came with the merging of the initial community power companies into large systems; with the development of power transmission lines that could be combined into huge networks tying substations to power houses over large areas so that the pulse-beat of the electrical energy was steady and sure over all. And with accurate frequency control came a flood of synchronous motors, large, small, medium and tiny, designed for a multitude of diverse timing purposes and all standard stock items in the manufacturers' catalogs.

These things were important to the evolution of commercial facsimile but it still awaited the development of a practical recording paper. The early work had depended upon electrochemical action in a liquid, upon a paper dampened with a clear solution of a chemical that under the action of the electrical potential of a metal stylus would react with the stylus material and deposit an opaque chemical in the paper fibers. Such paper in the hands of understanding experts gives very good results. But Western Union engineers had tried and discarded wet paper for commercial facsimile purposes. Something more rugged and less critical was needed.

Then one day in 1934 a Western Union engineer, working on a piece of demonstration equipment for the Chicago World's Fair, needed a piece of black paper to shield a lamp bulb and happened to get the paper from the photographic laboratory. Much to his astonishment the black paper was sufficiently conducting to produce an electrical shock if included in the circuit of the lamp base. Call it accident or not, R. J. Wise was at the time also attempting to record the unbalance of duplex circuits. He immediately began experiments with this conducting paper. Between his basic work and the subsequent accomplishments of chemist B. L. Kline, a dry electrosensitive recording paper was developed that bridged the final gap in the chain of practicability for commercial facsimile operations. This paper was given the registered name "Teledeltos" in 1939.[1]

Western Union began experimental trunk circuit operations by facsimile in late 1935, extended service to a few branch offices the following year, and in 1938 installed a small number of customers' tie lines. The early equipment was somewhat expensive and inconvenient so that by 1941 only 200 circuits in four cities were in operation. World War II adversely affected further development in commercial facsimile for several succeeding years. The postwar planning group had not been idle, however, during this period. Under constant pressure by F. E. d'Humy, then Vice President of Engineering, to produce a small inexpensive transceiver, G. H. Ridings came up in 1946 with a prototype of the Desk-Fax.[2] This initial little machine produced facsimile operation stripped to bare essentials. Reversion to conductive scanning utilized the same stylus for sending and receiving but, as might be expected, required special sending blanks. These used a wax transfer sheet to produce nonconducting letters on a background of black conducting paper, the same material used as the base for "Teledeltos".

The original Desk-Fax, the bare essentials of facsimile

A pilot installation of Desk-Fax customer tie lines was made in Newark, N. J., in 1948. Thereafter, with a subsequently designed and highly practical concentrator,[3] facsimile tie-line telegram service expanded to 26 cities with about 2000 connected transceivers by 1951. By this time, however, an optical-scanning version of the Desk-Fax, still comparatively inexpensive, had been designed.[4] A new and larger concentrator with improvements based on experience with the earlier one had been developed for the new transceiver. As of the end of 1953 the round-number totals for Desk-Fax installations are 10,000 transceivers in 55 cities, with no end in sight.

Preliminary Considerations

Following the end of World War II, Western Union was in the position of having considerable experience with facsimile operation, an unqualified belief that the system had a proper place in recorded communications, and a fluid condition of telegraph thinking because of impending expansion of the reperforator switching method of general operations. Due to the latter installations, there was a definite opinion in some quarters that the teleprinter should become the primary communication device, replacing any other method of transmission including existing facsimile circuits as well as pneumatic tubes. For heavily loaded circuits that could be worked directly into the switching system, little argument could be raised against the complicated and expensive printers. For tie lines to customers' offices, however, the facsimile system could be shown to have definite advantages, especially for lines with light loads. Since both the direct and fringe costs of messenger service were rising rapidly it appeared that "terminal handling" by "Telefax" might offer increased speed of service with little or no increase in costs.

Terminal handling of telegrams received from, or to be sent on via teleprinters imposed limitations of the facsimile message to word text, thus allowing design for a smaller area of transmission than would be satisfactory for sketches or drawings. Restricting the distributing zone to local or intracity points generally insured the availability of synchronous primary power at all stations and limited the connecting lines to conservative lengths. It was therefore necessary only to design equipment that would be simple and foolproof in operation, have a long useful life, and have costs per circuit that could be proved-in by no more than five message transmissions per day, as a studied estimate.

The first Desk-Fax, using conductive scanning, pointed the way. Early operations indicated that most customers not only liked the Desk-Fax but much preferred it over either teleprinters or messenger service. Costs were found to be close to those estimated but the items charged to the "inexpensive" conductive scanning method proved to be a greater proportion than expected. The present design for optical Desk-Fax installations followed the principles to be described herein, some of which of course had been worked out in earlier developments.

Practical Design Principles

The maximum aim of a facsimile transmission system would be to lay down at the receiving end an exact duplicate of the sending copy just as the eye would see it. For a commercial facsimile system it is obviously necessary to discard color differences and reproduce only black and white. This restriction sounds simple enough but it will be found that it entails further agreement as to which colors will be transmitted as black and which as white. To avoid the harsh choice the transmission of several shades of gray will be found desirable. Also color filters may be necessary, as will be shown later, to adapt the copy appearance to monochrome viewing.

The art of "seeing" in itself suggests the process of sequential scanning. As is commonly known, the image obtained by the human eye covers a large area in general, but the area of exact information is comparatively small, hence in reading a printed page or looking at a drawing or photograph for details, the eye scans the display by moving over it in successive passes, usually from left to right and from top to bottom. The human with normal vision cannot absorb more than a few words at one time from the printed page, even with the elaborate multiple-circuit apparatus used by the eye. In a commercially practicable system limited to only one transmitting circuit the information available by facsimile methods in one scanning pass will be small indeed. Furthermore, since no "second look" will be allowable with a mechanical system, the facsimile scanning must be controlled to cover very thoroughly, the first time, the entire area which *might* contain information. (This necessity is the inherent inefficiency of facsimile transmission for purely general operation. An uncomplicated, inexpensive method of automatically eliminating the complete scanning of large areas containing no information would revolutionize facsimile efficiency.)

Element Transmission Methods

Transmitted intelligence generally consists of "bits" or small particles of information, each separate and complete like the pieces of a jig-saw puzzle. Similarly, if these bits are correctly assembled at the receiving end, the original material can be defined. Facsimile scanning, in principle, involves dividing the subject copy up into a number of small squares, like the ruling of graph paper. Each square is then a "bit" of information, which in facsimile practice means that it can be either "black" or "white" as may be necessary to delineate the material being copied. Facsimile transmission is therefore concerned only with means of putting down on the recording paper the sequence of black and white squares that appears before the sending scanner. The fineness of delineation of the copy is built-in initially,

Facsimile concentrators, old and new

The requirements of facsimile operation then evolve as "framing," which determines the top and bottom limits of the area of possible information; "phasing," which determines the right and left limits and keeps them in the proper sequence; and "information element transmission," which makes the marks on the record. How these were worked out for practical commercial operation will be described later.

the number of squares per inch in a scanning line and the number of scanning lines per inch depending upon the size of the pick-up device to be scanned over the copy. In conductive scanning this may be a metal wire stylus in contact with the copy. In optical scanning the viewing device may be a tiny spot of light projected on the copy or it may be a tiny spot at the focus of a lens system associated with a photocell. The actual recording device must, of course, have similar dimensions.

As mentioned earlier, the bits of information gathered over one scanning line must necessarily be small. For a commercially practicable system, however, they should be as large as possible commensurate with the dimensions of the marks on the sending copy, since the total number of "bits" per message determines the ratio of time of transmission and frequency band required. It happens that the human eye has been conditioned by paper textures and modern printing practices to expect marks several thousandths of an inch wide for delineating written matter. (Fifty years ago the common type faces were smaller and narrower.) A series of compromises, involving the natural rotation speeds available from synchronous motors energized with power at 60 cycles per second; the dimensions of the previously standard telegram blank; the maximum desirable transmission time; and the band-width available on ordinary voice-frequency transmission circuits, fix the practical facsimile scanning "bit" at 0.010 inch, and the normal scanning rate at three lines per second.

(An average voice-frequency circuit may be considered to be useful between about 200 and 3000 cps, having an effective band-width of 2800 cycles. With double-sideband modulation each sideband can be only half this width, 1400 cycles per second or 84,000 cycles per minute for the purposes of this computation. The standard Western Union telegram blank has a message area of about 8 by 3½ inches or 28 square inches to be scanned.

The size of the scanning bit for transmission of the message area in one minute and in two minutes can be compared as follows: For 1-minute transmission the 84,000-cycles-per-minute modulation must cover 28 square inches, or 3000 cycles per square inch. Each scanning cycle is considered to be one black and one white "bit," so this represents 6000 bits per square inch. Each bit is therefore the square root of one six-thousandth or 0.0129 inch, representing 77.5 lines per inch scanning. In the 8-inch scanning line there would be 620 cycles so 4.5 scans per second would be necessary to develop the frequency.

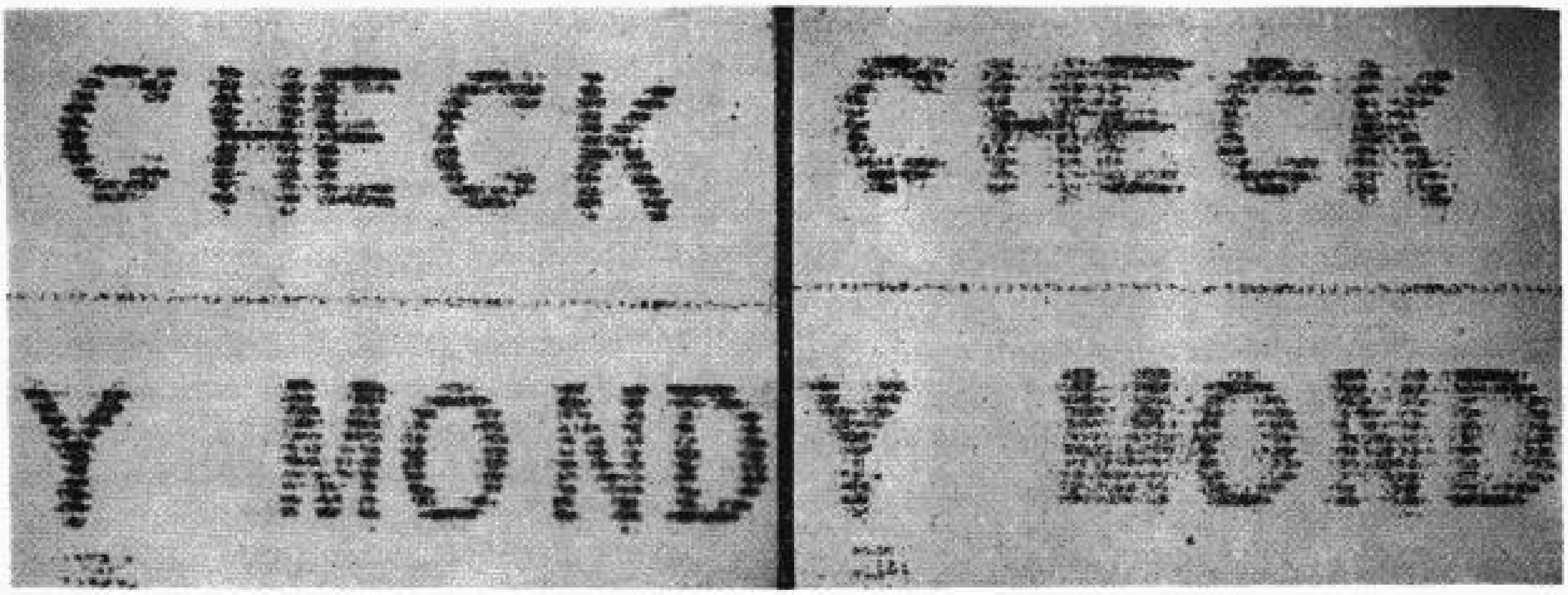
For 2-minute transmission the 84,000 cycles per minute needs to cover only 14 square inches giving 6000 cycles per square inch. Since this represents a total of 12,000 black and white bits per square inch, each bit can be the square root of one twelve-thousandth or 0.0091 inch, 110 lines per inch scanning. This would be 439 cycles per 8-inch scanning line needing about 3.2 scans per second to develop the modulation frequency.

As a compromise a "bit" of 0.010 inch was chosen giving 400 cycles per scanning line. Three scans per second was selected because this represents a drum rotation speed of 180 rpm, one-tenth of the normal 4-pole 60-cycle synchronous motor speed.)

In scanning lines almost 8 inches long at this rate, about 2400 of these 0.010-inch intervals are traversed per second. If these intervals are alternately black and white a fundamental frequency of nearly 1200 cycles per second will be generated. If actually it was desired to reproduce truly such a geometrical array of square black and white dots a still higher frequency would need to be transmitted. Since in general the copy contains marks much farther apart than the minimum distance, the 1200-cycle frequency can be considered to be the maximum necessary for recording purposes.

It would appear that facsimile operation would be practicable by transmitting only the frequency representing the black and white arrangement of the information elements. If direct transmission of the "dot frequencies" is attempted, however, it will be found that large areas of one solid color will produce very low frequencies, approaching zero. The presence of such frequencies complicates the design of transformers and other coupling devices in the circuit. Even if the copy is limited to typed characters the bottom frequency required will be low compared to the upper maximum. The ratio of top to bottom frequencies to be transmitted will therefore be at least several hundred to one. It is here that wire transmission limitations are introduced.

The transmission of alternating current over wire lines departs from perfection by the natural defects of the materials used for making up the circuit. Without



Smooth line

Line with sharp cutoff

Facsimile intelligence impulses may be displaced by line transmission distortion

here going into the details of the effect of imperfect insulating materials and of adjacent conductors, it can be shown that the linear speed at which wave trains travel over these lines varies with the frequency. Another article in this issue goes into this subject more fully. In the case of facsimile signals such alterations in arrival time, or "phase shifts," produce distortion in the received copy. (These distortions are also present in voice transmission but are generally of small importance to aural reception.)

It is possible to apply corrective measures against phase shifts and to include "d-c restoring" features in amplifiers, but these complicate the electric circuits. Such arrangements are useful mainly where other means are not readily available or where the higher efficiencies are needed in line connections. Facsimile circuits have been operated experimentally using direct transmission of the element "dot frequencies" and there is increasing interest in this method of operation. For commercial applications there are easier methods, however, — means not available to the early experimenters in the nineteenth century, which simplify the terminal apparatus at some cost in spectrum efficiency.

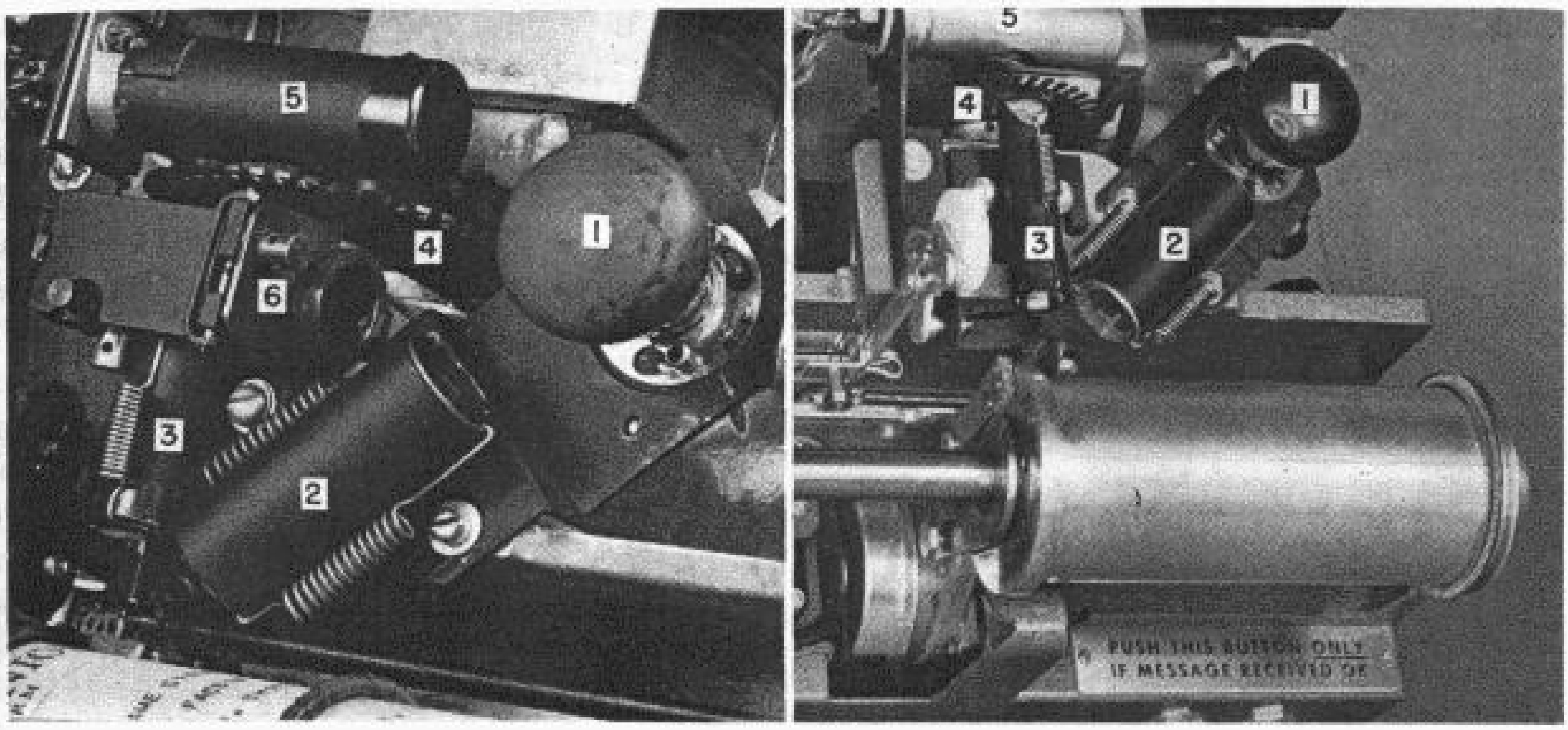
By applying the principle of carrier current, using the simplest arrangement producing "double sidebands," a frequency higher than the maximum dot frequency can be chosen as the "carrier." This frequency will be emitted when zero dot frequency, corresponding to one solid color, is required. For transmitting any other dot frequency, two frequencies, one above and one below the carrier by corresponding amounts, will be combined with the carrier frequency. These are called the "modulation frequencies." For best results with the most simple sending circuits, the carrier frequency should be at least twice the higher modulating frequency needed to delineate the copy. The ratio of top to bottom frequencies to be transmitted is therefore only three to one, including both sidebands, and the relative phase shifts are correspondingly small.

For a commercial facsimile system with a modulation frequency of about 1200 cps, a carrier frequency of approximately 2500 cps can be chosen, inferring a band between 1300 and 3700 cps for transmission purposes. In normal double-sideband transmission, however, it is not necessary to maintain the frequency of the carrier to close limits, nor is it mandatory to receive both sidebands at exactly the same levels or even in entirety. This feature enables the provision of adequate transmission with simplified equipment over lines that may greatly favor the lower sideband. These lines must have smooth exponential rates of amplitude decay with increasing frequency to realize this feature. Where filters or other sharp cutoff devices are introduced it may be necessary to provide corrective features even with the double-sideband system.

Optical System Design

For ease of maintenance and ruggedness the optical system of commercial facsimile apparatus must be as simple as possible. An automobile headlamp, painted black where desirable, provides a rugged concentrated filament with ample light output. A condensing lens system can be made to focus the light on a small area of the subject copy, at an angle of about 45 degrees. A simple lens system, at right angles to the copy, can be arranged to pick up the light from a spot 0.010 inch in diameter within the brightly lighted area and focus on a small hole in a shield in front of the photocell, thus guarding against dispersed light affecting the resolution. With available inexpensive lenses, it has been found that for a 0.010-inch spot, the aperture in the shield can conveniently be a round hole 0.012 inch in diameter, a size that can be drilled with ease into metal thick enough to provide mechanical strength without introducing undue parallax. Beyond the aperture the cone of light spreads out again. By placing the photocell at the proper distance away, an appreciable area of the cathode can be illuminated thus obtaining good output from the cell without over-saturation of one area. The direct-current output from the photocell can now be made to vary directly with the light reflected from the scanning spot on the copy. It has been found that a simple single-cathode photocell is preferable to the multiplier type for the light values available. Either gas-filled or high-activity vacuum cells give good results.

The photocell output is direct current and is very small in magnitude, requiring a preamplifier before the signals can be used satisfactorily to operate a conventional modulator. Although suitable direct-current amplifiers can readily be built, using voltage regulator tubes for stabilization, the added complications of preamplifier and modulator are unnecessary for limited commercial applications. Since the photocell output is to modulate another frequency in any case, it is convenient to introduce the "carrier" into the optical system, which can be done mechanically. Between the aperture and the photocell is a short distance where the light-beam cone is widening and here a chopper wheel can be interposed. This wheel is a thin metal disc, painted black,



Desk-Fax optical system, with and without self-inversion

1. Exciter lamp
2. Condensing lens
3. Pickup lens
4. Chopper
5. Photocell
6. Optical inverter

with square evenly-spaced teeth on the outer periphery. The tooth-width is chosen to just block the light beam, and just allow it to pass through between the teeth. The size of the wheel and the number of teeth are chosen so that a simple 60-cycle motor, not necessarily synchronous, can drive the wheel at a speed to produce interruptions at a rate of 2500 per second in the light beam. The output of the photocell, interrupted at this carrier frequency and amplitude-modulated by the reflected light intensity, can be amplified by a conventional audio-frequency amplifier. The chopper frequency approaches a sine-wave, the important harmonics being high enough to be ignored in most cases or to be removed by a simple R-C filter if required. A difference in output from the amplifier of at least 20 decibels is expected between reflections from "black" and from "white" in the optical system. Where purple ink is frequently used, as on telegrams, the addition of a "minus blue" filter in the light system has been found advantageous.

Inversion of Signals

It may be noted that the output signals from the photocell amplifier are inversely related to the copy; that is, the "white" areas reflect more light and therefore produce a higher level than the "black" areas. While such signals truly represent the copy and would be desirable for making photographic negatives, they are not suitable for direct recording on electrosensitive paper where high levels make marks and low levels do not. The optical scanning signals therefore must be inverted before the recording can be made in a "positive" sense.

The most advantageous place to locate the inversion apparatus depends upon the type of facsimile service. In a commercial facsimile system which comprises a communications center with a number of tributaries the ratio of transmitting and recording equipment at the center to the number of connected lines may be considerably less than one to one, depending upon the traffic density. The first Western Union Desk-Fax concentrators used a ratio of 1 to 5 but the later ones use a ratio of 1 to 10, having only 4 transmitters and 6 recorders to meet 100 incoming lines. For such an arrangement it is obviously desirable to associate as many functions as possible with the small number of units at the center, thus simplifying the construction and reducing maintenance of the apparatus at the tributary offices.

Signal inverters for use at facsimile concentrators are therefore separate electronic units which include not only the inversion function but also a mild automatic gain-control action. In addition, by partial control of the slope of the "black to white" level curve, the differential levels from black to white can be standardized at about 27 decibels. These inverters tend to adjust themselves automatically to background response from the photocells and will therefore give satisfactory results from copy on different colors of paper, provided the marks are appreciably blacker than their background.

For small installations of facsimile equipment, where the use of the separate inverter would only complicate the arrangement, an optical form of inversion associated with each transceiver has been found practical. This involves an additional lens system, with adjustable light intensity, passing light directly between the exciter lamp and the photocell via the chopper wheel. The chopper-wheel teeth then alternately pass light reflected from the copy and light arriving from the auxiliary lens system. An adjustment of the intensity of the latter, to equal the reflected light when scanning background, can be made to produce no appreciable a-c output from the photocell. Marks on the copy will then unbalance the system by reducing the reflected light and produce "positive" signals which can be reproduced directly. A crossed polaroid filter has been found useful for obtaining close adjustment of the light intensity. While this inverter arrangement operates quite well it is somewhat sensitive to substitutions of background colors other than the one used in the initial balancing.

Scanning Mechanisms

So far it has proved impracticable to move the comparatively large assembly of exciter lamp, lens system, and photocell at speeds necessary for scanning purposes. It is therefore necessary to move the subject copy with respect to the optical system. The simplest way to accomplish this relative motion and obtain continuous scanning at constant speed is to wrap the copy around a cylindrical drum of suitable diameter which can be rotated to develop the desired scanning rate in peripheral velocity. The required "line feed" at right angles to the drum rotation can be obtained either by moving the drum along its axis or, because the motion is slow and limited, by moving the optical assembly parallel to the axis of the drum.

Since the axial progression of scanning must be exactly associated with the drum rotation to obtain the desired uniform spiral scan of the copy, the principle of the lathe lead screw connected by gearing to the drum shaft was originally used. While this arrangement is very practical and is still utilized in some transmitters, the mechanical components must be carefully designed and manufactured to small tolerances. Much less expensive and more rugged is a drive which utilizes a small synchronous motor, separate from the drum motor, to furnish the axial motion via a rack and pinion. A simple clutch mechanism on the small motor plus a retractile spring permits "carriage return" without the mechanical complications of the half-nuts used on lathe lead screws.

It is of course necessary that the axial progression of scanning be very smooth and also that it be very closely parallel to the cylinder face in order to keep the optical system constantly in focus on the copy. Round rod guides have been found to be much more practical than lathe-bed type rectangular guides. To provide smooth frictionless travel, a type of bushing using ball bearings as pressure agents is used where the optical system is moved. Where the rotating drum moves axially, the sliding friction is largely overcome by the rotation, hence sleeve bearings of the oil-less type are sufficient. Outboard bearings on the drum shaft are desirable to improve maintenance of parallelism.

Rotation of the copy drum at the normal moderate speeds requires gears between the drum shaft and the driving motor if the latter is to have a reasonable number of poles. Although it is possible to obtain gears of superior quality that would give nearly linear torque transfer at any desired ratio, such gearing will

High-speed transmission requires hollow plastic drums

not remain in the proper state of perfection for very long periods. In consequence it is more practical to use much less expensive gears and obviate nonlinear effects by choosing ratios to obtain "cyclical" operation; i.e., the rotation of the drum in any given segment of each scanning line is due to the interaction of the same gear teeth. In this way "gear-pattern" distortion, unless extremely severe, is not apparent in the copy. While this restriction limits the drum rotational speeds available from 60-cycle synchronous motor drive, the ones obtainable are adequate for facsimile purposes. Backlash is absorbed by applying a friction brake to the driven shaft. A simple brake is adequate since only one direction of drive is used.

Holding the Copy

In addition to providing accurate alignment of machine parts, it is also necessary to hold the sending copy in proper position on the drum during the scanning process. Wrinkles or bulges in the paper cause out-of-focus defects. Skewed edges

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may be the cause of discontinuous lines in the recording.

Since in moderate speed systems it is practicable to wrap the copy on the outside of the drum, the problem is to position the wrap initially and maintain it subsequently. The copy page should be cut square to fit the drum with some overlap, and should be wound-on with the upper edge trailing to avoid windage troubles.

Since the recording has been found to be best if scanned along the line to be scanned by the eye in reading the record, the blanks should be designed with this fact in mind. A square shoulder or a lip machined into the drum at the end where scanning begins makes a convenient guide for wrapping the blank squarely. A lengthwise axial line marking the proper place for the inner edge of the overlap will locate the edges of the paper for phasing purposes and still further facilitate square wrapping. Small toroidal-shaped wire springs slipped over the drum provide a simple means of confining the paper after wrapping.

One or more of these springs, naturally called "garters," can be used to hold the blank in place but must not obtrude into the scanned area. To avoid this possibility and also to give positive smoothing in the scanned area, one spring garter may be arranged to be propelled along the drum just ahead of the scanning spot by a "garter pusher." Since the latter is usually a rounded stiff wire nearly touching the copy, its presence further requires that the paper lap be trailing in the direction of drum rotation to avoid tearing. The round contour of the toroidal garter springs facilitates their smooth propulsion along the copy by the pusher.

Where the copy to be sent is narrow and relatively stiff, as a ticket or coupon, spring garters may not be feasible for holding-down purposes. In such cases a special drum, recessed for the particular copy and with a cylindrical sliding transparent plastic cover, can be used but only where the scanning drums are removable. Where the drum is fixed in the machine, a flexible "window shade" plastic cover can be permanently attached to the drum with spring-loaded fastenings that will insure tightness on the drum after wrapping over copy of various thicknesses. This arrangement is excellent for all sizes of copy and has been used on a transmitter[5] which can hold down copy of any size between "a postage stamp and a legal brief."

An alternate arrangement for small size messages, permitting quick loading, is the "milk-bottle" type of drum. This device consists of a hollow transparent plastic cylinder with uniform parallel walls and one open end. Within is a spring-retracted weighted "umbrella-rib" assembly which flies open under the centrifugal force of rotation, and presses against the inside wall. A message rolled up and pushed into the milk-bottle drum while at rest is pressed against the inner wall by the "umbrella ribs" while scanning takes place through the plastic shell. A cover to be closed over the open end when the drum is in operation can include an outboard bearing.

At linear peripheral speeds exceeding about 50 inches per second it is difficult to hold copy on the outside of a scanning drum without some kind of tightly fitting plastic cover. For speeds in excess of 150 inches per second the plastic cylinder milk-bottle type is advisable. Thin copy will cling to the inner walls of such a cylinder at high speeds without the assisting umbrella ribs. The latter are usually added, however, to improve the smoothness of copy whose stiffness is greater than its weight.

This article will be continued in the next issue of TECHNICAL REVIEW.

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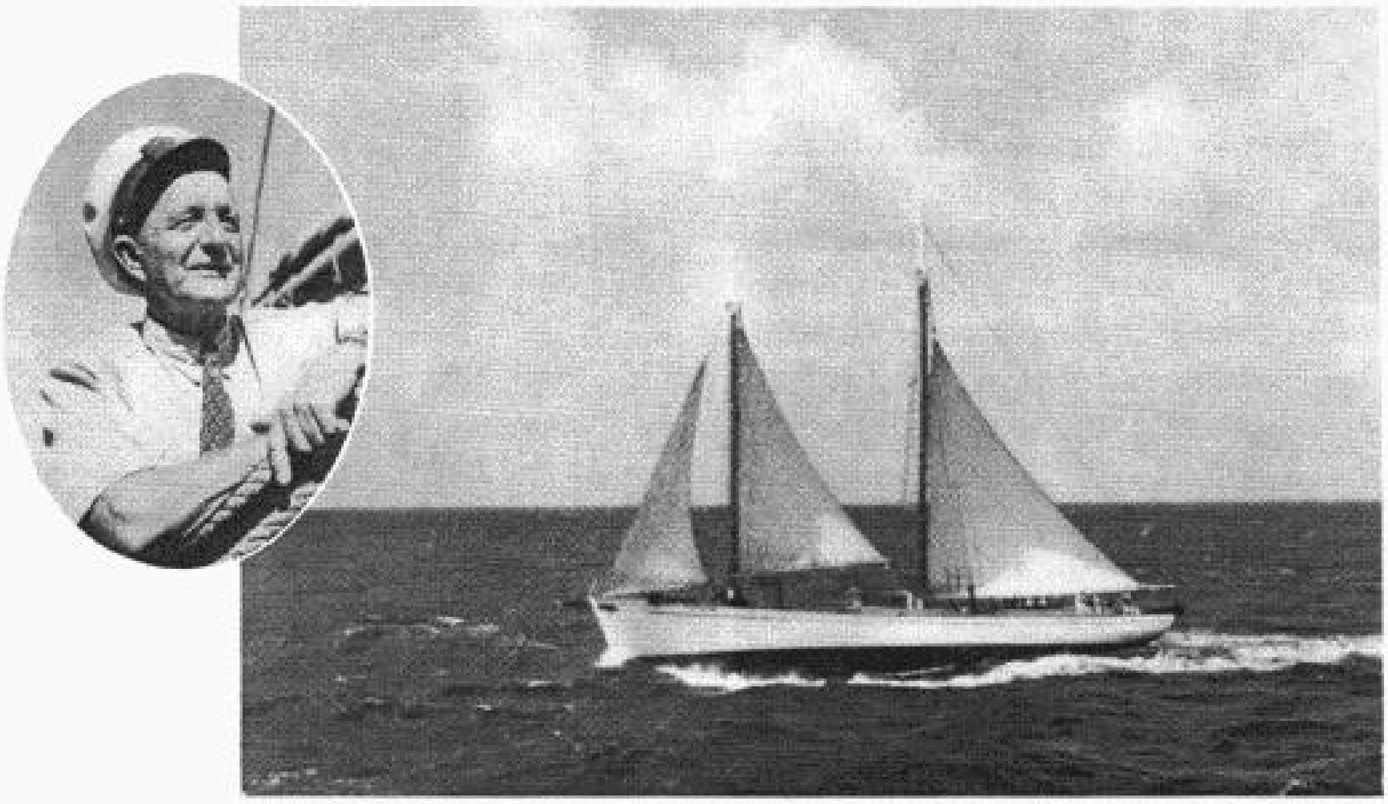

Photos courtesy Maurice Crosby of Halifax Mail-Star, and Bell Labs.

The cable schooner *Western Union*, a trim, twin-screw vessel operating out of Key West, Florida, and her master Captain Gerald R. Steadman.

The Telegraph Company's cable schooner *Western Union*, which normally plies shallower waters around Florida, Cuba and the Caribbean area, voyaged almost 3000 miles last year from her home port of Key West to Halifax and reurn for a cargo of submarine cable.

Usually such cargo is delivered by one of the company's ocean-going vessels—*Lord Kelvin* or *Cyrus Field*—but when both were busy at sea the yacht-like *Western Union* made the voyage north. She is a trim two-master of 92 tons gross, 96 feet over-all, and powered by two 40-horsepower engines but uses sail as well with favorable winds. She has a capacity of over 50 tons of heavy, shore end cable and is being equipped this year with improved cable handling machinery.

The *Western Union* frequently is chartered to assist in the maintenance of other company's cables in the Caribbean, and participated with C. S. *Lord Kelvin* in 1950 in the laying of new repeatered voice-frequency cables between Key West and Havana.

Built in 1939, she is the third cable schooner to be commanded by Captain Gerald R. Steadman, a veteran of more than 50 years at sea. Her crew, when cable work is being done, numbers 14 men.

With splendid cooperation from Thompson Enterprises, Inc., owners of turtle fisheries and a large fleet of fishing craft operating out of Key West, the cable schooner is provided with the finest of marine service facilities. The vessel is included in the International Communications Department's fleet.

A Small Office Teleprinter Concentrator—Plan 8

R. V. MORGENSTERN and H. BUCHWALD

DURING the period when nearly all traffic was handled by Morse methods, the heavy trunk circuits were duplexed. That is, a sending and a receiving operator, seated side by side, worked with a similar pair of operators at the distant office. All of the equipment necessary to permit duplex operation was mounted on the operating tables. It was the function of the operators not only to send or receive messages, but to make such adjustments of the instruments as were necessary to keep the circuit working satisfactorily. It was early recognized by the engineers that Morse operation and set adjustment were two separate functions.

The first step, therefore, was to remove the balancing equipment from the operating tables, leaving the operators free to devote their entire attention to the handling of messages. On those circuits which were not duplexed, the loads were frequently insufficient to keep an operator continuously busy. This was especially true of the way circuits which were cut in at many small stations along the railroads, and also of the lines connecting city branch offices to the central office.

To improve upon this condition, the Engineering Department developed Morse concentrators. For the city wires, which had only one station per line other than the main office, the problem was fairly simple. If the outer office called he could call only the main office, and the concentrator was arranged to light a lamp and keep it lighted until the main office answered. Eight lines were the usual number concentrated on four positions. Thus only the number of operators who could be kept continuously busy by the load of all eight wires needed to be assigned to any unit. This Morse concentrator is the familiar Plan 1 Concentrator, some of which are still in use.

With the introduction of teleprinters for branch office (or city line) service, it was at once recognized that, with concentration at the main office, this convenient method of transmission could be furnished to offices which did not have sufficient load to keep a wire continuously busy.

The first teleprinter concentrators were adaptations of the city line Morse concentrator. They accomplished their purpose, but it was foreseen that with the increasing growth of teleprinter service greater concentration would be required, or mounting operating costs in the main office would retard the growth of teleprinter service, particularly its extension to customers. This led to the multiple

Figure 1. A Plan 2 Concentrator installation in a large office

turret printer concentrator known as Plan 2. One hundred lines were selected as the unit group to be installed before any operator. This type of concentration was designed for large central offices in the cities. Figure 1 shows a Plan 2 installation in a large office.

For the smaller offices located in small towns, some form of concentration was also required to terminate tie lines of subscribers in the surrounding area. In some instances the Plan 1 Concentrator, which could easily handle the small number of tie lines involved, was utilized. Due to the space required by this concentrator, however, it was not very practical for use in small commercial offices where space is usually at a premium. This led to the

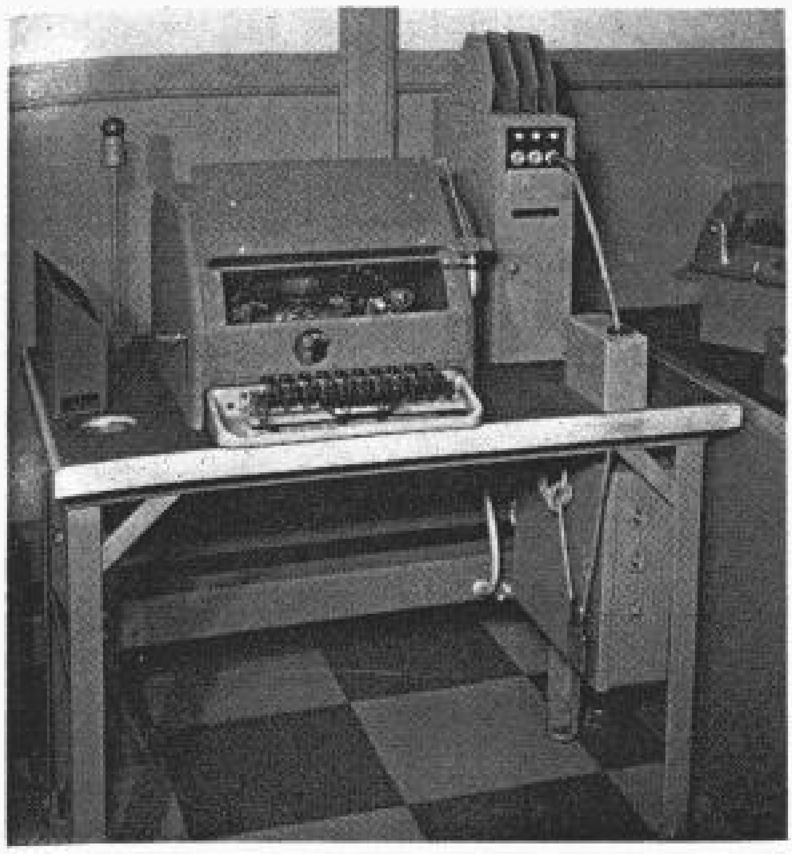

Figure 2. A Plan 3 Concentrator installation

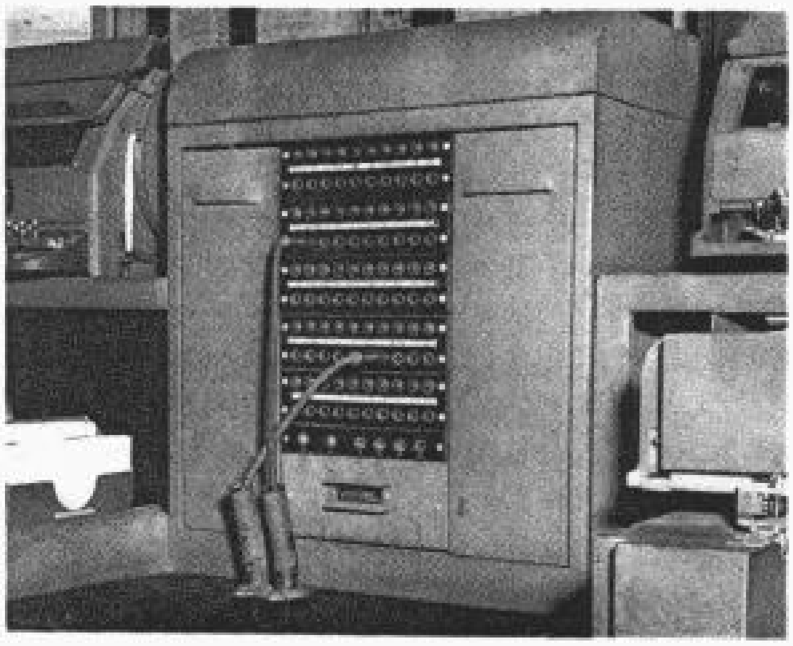

Figure 3. Plan 8 Concentrator Turret

development of the Plan 3 Concentrator, having a capacity of three tie lines. Where more than three tie lines had to be terminated, additional units were added to the operating tables as required. Figure 2 shows a Plan 3 installation.

An answer lamp, on the front of the concentrator cabinet located over the tie-line jack, lights when a call is placed by the subscriber. The branch office operator answers by plugging a cord circuit into the concentrator jack. Both the branch office printer and the subscriber's printer are connected in the line, with battery furnished by the concentrator.

Plan 8 Concentrator— General Considerations

As the number of tie lines to some of the smaller offices increased, more Plan 3 units were added until in some cases the installations became difficult to handle from an operating standpoint. When the fundamental planning for the large increase in the reperforator system was carried out, it was decided to move the tie-line and other circuits from the reperforator centers to branch and tributary offices; by 1946 it was evident that it would be necessary to design a new teleprinter concentrator for use in small offices. The resultant concentrator is known as Teleprinter Concentrator Plan 8.

It was desired to make this concentrator as flexible as possible and to secure maximum concentration with a minimum of expense. After study it was decided that the concentrator should be made for a maximum of 50 tie lines grouped in units of 10 and associated with an operating table holding four printers.

The use of a smaller turret for offices with fewer tie lines was considered. However, the idea of providing one turret concentrator housing, in which the number of tie lines terminated could be expanded from 10 to a maximum of 50 in steps of 10-line concentrator units, was adopted since it contributed to standardization of equipment. Experience indicated that four printers would, in most cases, handle 50 lightly loaded tie lines and if there were fewer tie lines one or more of the printers could be omitted. It was also decided that only tie lines and Class A circuits were to be terminated directly in the concentrator.

Studies soon showed that some of the larger offices in which Plan 8 Concentrators were to be installed had peak loads greater than could be handled with four teleprinters, and accordingly the concentrators would have to be arranged so that any number of them could be connected in multiple.

Concentrator Turret

The Plan 8 Concentrator Turret, Figure 3, combines into a compact unit all of the equipment required to terminate up to 50 teleprinter tie lines. This equipment is contained in a metal cabinet approximately 2 ft. by 2 ft. by 1 ft. The cabinet in turn is divided into five removable concentrator shelves, one line resistor shelf and one potential shelf. The tie-line circuits are connected to the resistor shelf of the cabinet. From there each tie line continues through a variable resistor and then, in groups of ten, are connected through a flexible cable to one of the removable concentrator shelves. Here each tie line is connected to a jack, answer lamp relay and a battery tap resistor. Figure 4 shows a concentrator shelf.

Access to the contacts of the answer lamp relays is obtained by removing rectangular panels fastened by friction catches to the cabinet. When necessary for maintenance, the entire concentrator shelf can be withdrawn from the cabinet without unsoldering the cable between the concentrator shelf and the resistor shelf.

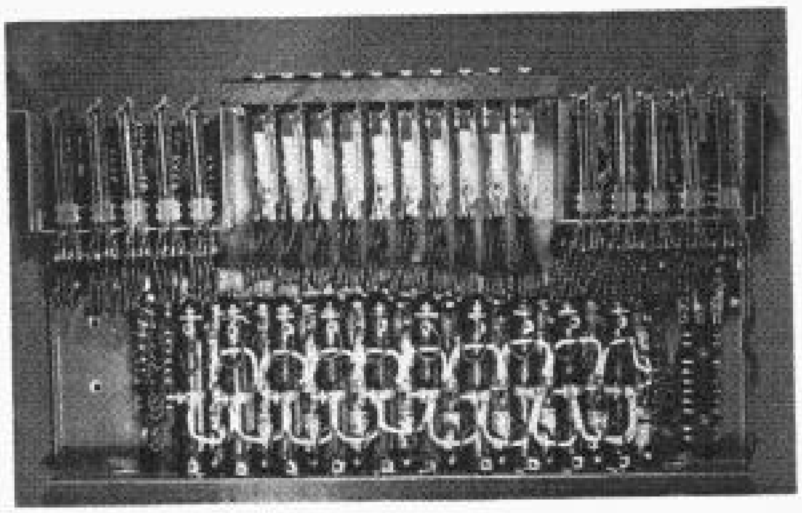

Figure 4. Concentrator shelf

The resistor shelf is located in the top of the cabinet and is accessible by opening a hinged cover. A resistor is associated with each tie line. The resistors are mounted in upright positions, in groups of ten for each concentrator shelf. They are connected between two rows of terminal blocks, one of which is used to terminate the tie lines, and the other to terminate the cable to the concentrator shelf.

The potential shelf located at the bottom of the concentrator cabinet contains fuses, toggle switches and a circuit breaker, and provides d-c power for the concentrator shelves. The potential shelf also contains three trunk jacks to the switchboard which are used in testing line circuits, and a fourth jack for "paste-overs." Two lamps are provided in the potential shelf to indicate the position of a lever key used to reverse the upper and lower cord circuits on the left side of the operating table.

Operating Table 5048

The first Plan 8 Concentrator operating table designed is shown in Figure 5 and is designated as Operating Table 5048-A. Only one concentrator shelf is shown in the cabinet, with filler plates in the spare positions. The table is 27 inches wide and 66 inches long; a concentrator turret is mounted on the top toward the rear and slightly to the right of center. Two double-decked teleprinters are mounted on each side of the concentrator cabinet, and four cord circuits and plug standards are located between a gumming desk and the front of the concentrator cabinet. The double-decked teleprinters on the left side of the table are normally used for sending to the tie lines. A lever switch adjacent to the lower printer is used to switch the cord circuits of the two printers. The two printers on the right-hand side of the table are normally used to receive from the tie lines, but any printer can be used either to send or receive.

Associated with each pair of the double-decked teleprinters is a wiring cabinet which is mounted under the table top.

Figure 5. Operating Table 5048-A

Each wiring cabinet contains the equipment necessary for two cord circuits, one for each teleprinter. The teleprinter cords and plugs pass through a slot in the table top to the jacks and receptacles in the top of the wiring cabinet which is suspended below the top surface of the table.

Figure 6 is a schematic wiring of two table cord circuits and a tie-line termination in the concentrator cabinet. The diagram does not include the cord circuits associated with the teleprinters on the right side of the table.

Each tie line has associated with it a jack, an answer lamp, an answer lamp relay, a variable line resistor and battery tap resistors. Each line is normally terminated to positive battery at the concentrator during idle periods. For the idle line condition, the answer lamp relay is held operated by the line current passing through the primary winding of the relay. With the relay energized, its two sets of contacts are in the open position. The operator at the customer's office indicates that she desires to send a message by momentarily depressing a button located on the operating table or console. This causes the line to open thus sending to the concentrator a spacing signal which releases the answer lamp relay at the concentrator.

The release of the answer lamp relay causes both sets of contacts to close. One set short-circuits the primary winding thus preventing the relay from operating again when the line closes. The second set of contacts completes a circuit which causes an answer lamp to glow, indicating the line which has a message to send. In addition, a supervisory lamp on top of the concentrator cabinet glows.

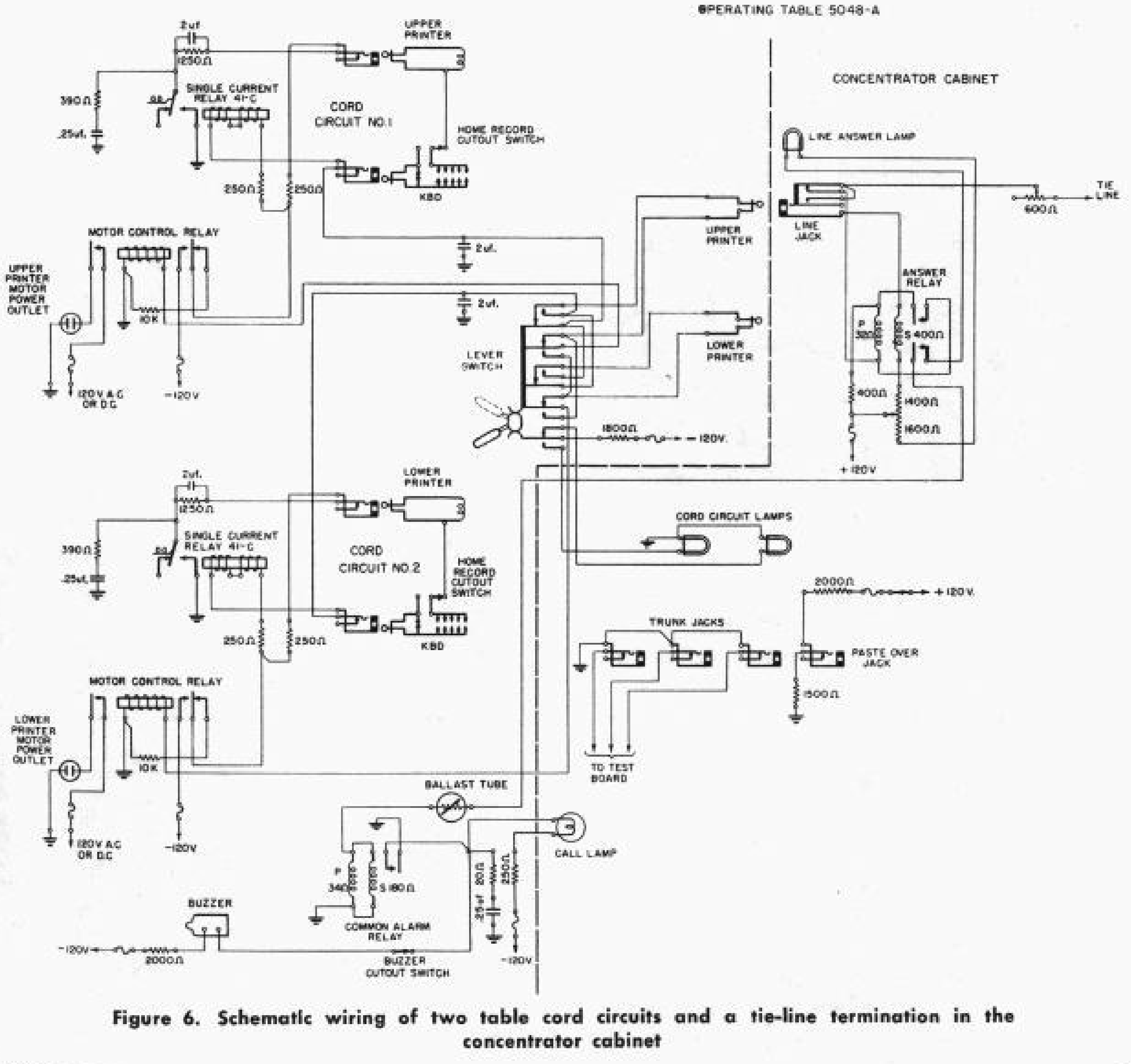

Figure 6. Schematic wiring of two table cord circuits and a tie-line termination in the concentrator cabinet

The operator answers the call by selecting one of the available cord circuits and plugging the associated plug into the line jack. As the plug is inserted a set of contacts on the jack opens, removing the positive battery from the line. Another set of contacts on the jack closes, to transfer the line to the tip of the jack. The line circuit is carried to the wiring cabinet of the 5048 Operating Table by the cord and teleprinter keyboard contacts, the windings of a Single Current Relay 41-C, to a contact on a power relay. Negative battery is applied to this contact when the power relay is operated.

A circuit is also established through the sleeve of the plug in the tie-line jack, so that a current flows from the battery tap resistor in the concentrator cabinet, through the secondary winding of the answer lamp relay, through the windings of the power relay in the wiring cabinet to ground. Both the answer lamp relay and the power relay are caused to operate. Operation of the former extinguishes the answer lamp, the power relay starts the teleprinter motor, and applies negative battery to the line. At the distant end, the customer's teleprinter motor operates upon the reversal of the line current.

The operator sends a "GA" (Go Ahead) to the tie-line office from the teleprinter keyboard. Upon completion of the message from the tie-line customer, the operator acknowledges that the message has been received and removes the cord circuit plug from the jack. Removing the plug restores positive battery to the line and releases the power relay which turns off the teleprinter.

If the operator at Operating Table 5048 has a message for a tie-line customer, she plugs a cord circuit into the correct jack and after getting a "go ahead" from the customer starts sending, using the keyboard on the lower left-hand printer. If the customer is slow in acknowledging receipt of the message, the operator moves the lever switch up, which transfers the lower printer into the cord circuit normally associated with the upper printer and vice versa. The operator can then plug up the second cord circuit and send to another customer while receiving an acknowledgment on the upper printer. Lights located in the potential shelf of the concentrator cabinet indicate which of the two cord circuits is connected to the lower printer.

To make teleprinter copy locally, one of the cord circuits on the table can be plugged into the "paste over" jack located in the potential shelf. This jack is arranged in a local circuit to supply a dummy line and also to operate the power relay associated with the teleprinter.

In general, tie-line conductors are brought direct to the Plan 8 Concentrator Cabinet without going through a switchboard. If a tie line is in trouble, the jack associated with it in the concentrator shelf can be patched to one of three trunk jacks located in the potential shelf by means of a double conductor cord and plugs. The trunk jacks in turn are carried to a test board where the tests can be made on the line.

Operating Table 5592-A

Provision is made in the 5048-A Table to accommodate cord and plug connections for a fifth and a sixth teleprinter, supplementing the four mounted on the 5048-A Table where they are not enough to meet the peak tie-line load conditions. These fifth and sixth teleprinters are usually employed only to receive messages from the tie lines. In those offices where it is necessary to increase the number of cord circuits an Operating Table 5592-A is used. This table mounts two double-decked teleprinters with their associated wiring cabinets and is installed

Figure 7. Operating Table 5048-A and Operating Table 5592-A

next to Operating Table 5048-A. In Figure 7, which pictures a portion of a Plan 8 installation in a large branch office, an Operating Table 5592-A is shown immediately to the right of a 5048 Table.

Multipled Concentrator Operating Positions

Where the peak load of the circuits assigned to an Operating Table 5048-A cannot be handled with six teleprinters, one or more additional Operating Tables 5048-A are connected in multiple with the first table. That is, to each tie line there are connected as many jacks as there are concentrator positions in multiple, one jack at each concentrator cabinet. From a traffic handling viewpoint all of the tables connected in multiple are operated alike. When a customer originates a call, an answer lamp lights on each table and is extinguished when any operator answers the call. Likewise, calls to any customer can be originated from any table.

However, in the design of the circuits, the concentrator cabinet located on the first operating table is a master unit which contains the answer lamp relays and line resistors, as well as answer lamps and jacks. All the other concentrators connected in multiple are auxiliary concentrators equipped only with jacks and answer lamps.

The fundamental operation of the concentrator circuits is the same as described for Operating Tables 5048-A except that one feature is added. All cord circuits are arranged so that if one teleprinter is plugged up to a tie line and the cord circuit plug of another teleprinter is inserted in the corresponding tie-line jack at a multipled concentrator cabinet, the second cord circuit will be inoperative.

This is accomplished as follows. Normally, when a cord circuit connection is made to the concentrator jack, (and as pointed out for the operation of single concentrators) a circuit is established from a source of battery in the concentrator cabinet, through the secondary winding of the answer lamp relay, the sleeve of the tie-line jack, the power relay winding in the wiring cabinet, to ground. This causes the power relay to operate, which starts the teleprinter motor and supplies negative battery to the tie line. In the cord circuits used in multiple concentrator operation, an increment relay replaces and controls the power relay. The increment relay has two windings, one high resistance and one low resistance.

Figure 8 is a schematic circuit illustrating two concentrator cabinets in multiple. In front of the tie-line jack at each concentrator cabinet is a teleprinter cord circuit with its increment relay. The high resistance winding on the increment relay is 500 ohms and the low resistance winding is 40 ohms.

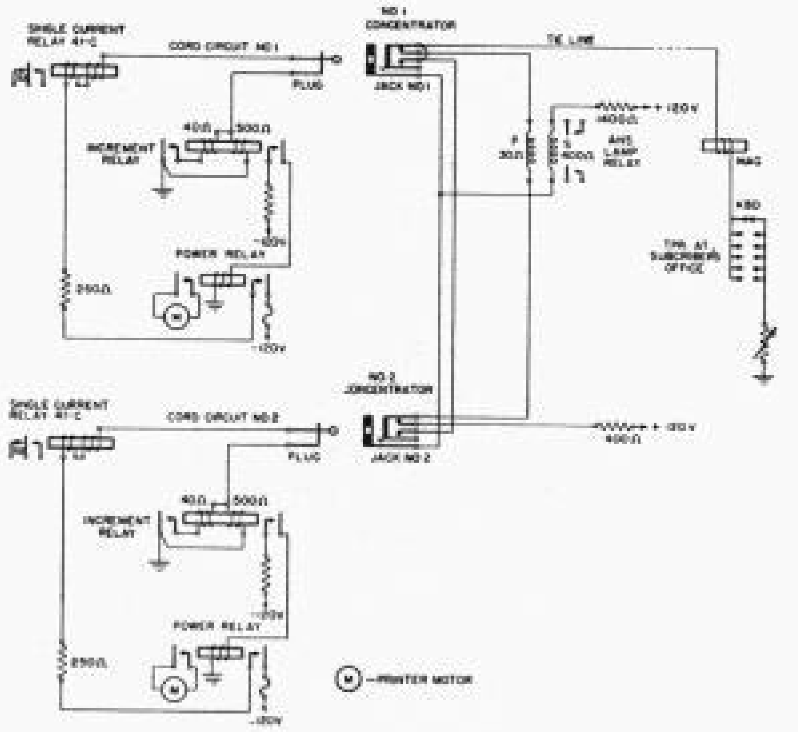

Figure 8. Schematic circuit of two concentrator cabinets in multiple

When the plug of cord circuit No. 1 is inserted into jack No. 1 at the first concentrator cabinet, the increment relay pulls up, connecting the 40-ohm winding in parallel with the 500-ohm operating winding. This reduces the voltage between the sleeve of jack No. 2 and ground to approximately 3 volts, which is insufficient to pull up the increment relay in cord circuit No. 2, should it be plugged into jack No. 2. Thus it is not possible for an operator to get a connection to a busy tie-line circuit.

Plan 8 Concentrators in offices having a sufficient tie-line load are provided with a "sending only" table at which messages are prepared in tape form and sent from a distributor-transmitter. Figure 9 shows a sending only table which is connected in multiple with the operating tables shown in Figure 7. Operator efficiency is increased by use of this table since messages may be prepared while others are being sent. As shown in the photograph, Operating Table 5534 is equipped with a concentrator cabinet to which the tie lines are brought.

Figure 9. Operating Table 5534-B

Two cord circuits allow connection to be made from the table equipment to any tie line. Each cord circuit contains a distributor-transmitter and a relay-operated monitor printer. Means are provided to prevent the monitor printer from copying traffic from the table to the tie line, while allowing traffic originating at the customer's office to register on the printer tape. Each cord circuit is also provided with a "stop on blank" arrangement to release automatically the distributor-transmitter clutch magnet.

The messages prepared in tape form are placed in the distributor-transmitter. The operator, noting the customer's call letters at the beginning of the tape, inserts the plug of the cord circuit associated with the lower distributor-transmitter into the proper tie-line jack. A push button located below the distributor-transmitter is operated and the message is sent to the customer's office. At the end of the message, the blanks perforated in the tape cause a relay in the cord circuit to release and stop any further transmission from the distributor-transmitter.

If the next portion of the perforated tape contains a message for another office and an acknowledgment is desired, the lever switch on the table is operated. This transfers the lower distributor-transmitter to the second cord circuit; the upper, with its associated monitor, is connected to the first cord circuit, which remains corded to the tie line to which the message has just been sent. This allows the customer's acknowledgment of the message to be received on the monitor printer, while the lower distributor-transmitter can be connected to the next tie line for transmission.

Since the sending table is always used in multiple with one or more Operating Tables 5048-A, its cord circuit is equipped with an increment relay which prevents the operator from getting in on a busy circuit.

One interesting feature of this table is that the lamps associated with each line jack are equipped with red lamp caps and have their circuits so arranged that they light whenever the tie-line circuit is in use at some other table. Thus instead of indicating an incoming call they indicate that the tie line is busy.

Teleprinter Tie-Line Concentrator Rack 6776-A

In certain offices it is necessary, because of space considerations, to limit the number of Operating Tables 5048-A installed. Under these circumstances Teleprinter Tie-Line Concentrator Rack 6776-A is used, with one or more Teleprinter Tie-Line Receiving Racks 6777-A. The concentrator rack is an angle-iron table 38 inches high by 24 inches deep and 33½ inches wide. A teleprinter tie-line concentrator cabinet is mounted on the table toward the right and rear on the table top. In front of the cabinet are as many as 10 cord circuits, 2 for each receiving rack. Included on the concentrator rack is a time stamp, a sent message file box and a message number sheet.

Teleprinter Tie-Line Concentrator Rack 6776-A and Receiving Rack 6777-A are used for receiving only, and are always

Mr. Morgenstern's biography appeared in the April 1953 issue of TECHNICAL REVIEW.

H. Buchwald entered Postal Telegraph service in 1929 as a student in the Company's teleprinter school. Shortly thereafter he was made supervisor of outside teleprinter maintenance in the New York City area. Upon graduating from Newark Technical School in 1938 with a degree of Associate Engineer in Electrical Engineering, he became Shop Foreman, and during Postal's semiautomatic program was transferred to the inspection department. Following merger of Postal and Western Union, Mr. Buchwald entered the D. & R. Department as senior engineering assistant, working on light beam transmission. Later he was transferred to Applied Engineering and subsequently made an engineer. He is presently engaged in work on teleprinter concentrators, repeaters, operating tables and wiring cabinets. Mr. Buchwald is an associate member of AIEE.

used in multiple with an Operating Table 5048-A or 5534-B. The receiving rack mounts two page printers, one above the other. Up to five receiving racks are associated with one concentrator rack. Only the upper position teleprinter is equipped with a keyboard, but by means of a lever switch on the receiving rack, the keyboard can be connected into either printer circuit. The receiving rack is 57 inches high, 26 inches deep and 24 inches wide. The electrical circuits of these two racks are the same as those of an Operating Table 5048-A.

As mentioned in the early part of this paper, the Plan 8 Concentrator was originally designed to handle Class A circuits only. These circuits are defined as those with battery at the office end supplying 70 milliamperes of line current to a ground at the distant end. Class A circuits are further limited in that the leakage due to wet weather must not exceed 30 milliamperes.

Due to the use in tie lines of small-gauge cable conductors leased from the Telephone Company, it was soon necessary to arrange some of the circuits in the concentrator cabinets so that they could work to positive battery instead of ground at the distant end. This necessitates making the idle line battery negative instead of positive. Except for the fact that polarized motor control cannot be used at the customer's office, these circuits are handled the same as Class A; that is, any of these tie lines can be handled from any operating position at the concentrator.

The next variation came when it was found desirable to terminate agency offices operated over Class B circuits directly in Plan 8 Concentrators. Since Class B circuits may have leakage currents as high as 60 milliamperes and normal line operating currents of 120 milliamperes, it was necessary to modify the cord circuit of one of the four operating positions on a 5048-A Table and assign it exclusively for use with Class B circuits. In addition, the answer lamp relays assigned to these circuits must have their line windings shunted by a resistor equal in value to the resistance of the winding.

The latest, but undoubtedly not the last, requirement to be met is the termination of Type 20 Carrier Channels on a half-duplex basis directly into a Plan 8 Concentrator which can also handle Class A, BT and B circuits. Without going into detail, this is accomplished by supplementing the wiring cabinets normally on a concentrator operating table with a switching cabinet. The polarity of battery on the sleeves of the jacks in the concentrator cabinet is made negative with respect to ground for carrier channel terminations and positive for all other circuits. A low impedance polar relay in that portion of the cord circuit associated with the sleeve of the tie-line jacks pulls up on negative polarity and arranges the line section of the cord circuit for operation with Type 20 Carrier Channels.

The arrangement enables any operating position except those assigned to Class B circuits to be used indiscriminately by the operator with Class A, BT, or Carrier Channel Terminations.

From the foregoing it can be seen that the Plan 8 Concentrator is a versatile means of terminating lightly loaded teleprinter circuits. Developments now contemplated will still further increase its utility.

Laboratory Equipment

In microwave laboratory tests and in the maintenance of radio relay systems, means of monitoring or measuring the frequency and power in a waveguide line often is required. Sometimes this is accomplished by the use of a directional coupler which accurately extracts a known amount of energy over a wide frequency range without adversely affecting transmission in the waveguide. However, in many situations it is satisfactory and much simpler to insert a probe into the waveguide to obtain the necessary power needed for measuring purposes. This arrangement is not as expensive and takes up less space than a directional coupler.

Necessary information for determining the probe length for a given amount of coupling, and the Voltage Standing Wave Ratio (VSWR) due to the presence of the probe in the waveguide has been provided in a graph. These curves are for a particular design of waveguide known as WR-229 with a probe made from RG-58/U coaxial cable mounted in the center of the broad face of the waveguide. As an example of their use, if a coupling of 20 db is desired, then from the curve marked "coupling" it is determined that the probe length must be about 0.35 inch long. Such a probe will result in a VSWR of approximately 1.12, or 1 db, as indicated on the VSWR curve.

One method of construction is to drill a hole 0.113 inch in diameter in the center of the broad face of the waveguide, center over the hole the flange of a UG291/U connector which has the head removed, and solder it to the waveguide. The jacket and outer conductor of the RG-58/U cable are stripped back to permit the inner conductor and dielectric to extend the desired distance into the waveguide, and the connector then assembled with the outer conductor of the cable fastened in the normal manner.—
H. E. Stinehelfer, Sr.