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Calculation of true heights of electron density in the ionosphere

by N. Ganesan, M.Sc. *)

Summary.

Following the work of Whale and Stanley [1], Shinn and Whale [2], and Jackson [3], curves have been obtained showing the variation of virtual heights of reflection with frequency for a linear layer. With the help of these curves some h', f records made at the Dr. Neher Laboratory at Leidschendam have been reduced to those of electron density as a function of true height. The effect of the earth's magnetic field has been taken into consideration in these calculations. This practical method seems to be accurate as such curves reduced in this manner have been found to agree with the actual data of electron densities at various heights obtained during the several rocket flights carried out over White Sands, New Mexico. All computations are for vertical propagation.

1. Introduction.

If a plane polarized electromagnetic wave enters the ionosphere in a vertical direction it propagates through a dispersive medium of gradually decreasing dielectric constant as a consequence of increasing electron density. As a result, the group velocity of the exploring wave decreases and becomes zero at a certain value of electron density depending on the wave frequency. At this point the wave is reflected back following the course in the reverse order. The frequency which corresponds to the maximum value of electron density is known as the critical frequency of the particular layer. Thus the critical frequency of the uppermost F_2 layer represents the critical frequency for the ionosphere as a whole and a wave whose frequency is greater than the critical frequency will not be re-

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*) Ionosphere Department, Dr. Neher Laboratory, Leidschendam, Holland.

flected and will get through the ionosphere. The plane polarized wave may be assumed to be the resultant of two circularly polarized waves rotating in opposite directions. In the Northern hemisphere the left handed wave is called the ordinary component and the other the extraordinary component. Due to the influence of the earth's magnetic field the propagation characteristics of the two components are affected in different ways.

A normal ionogram — the so called h', f record — contains the virtual heights of reflection as a function of frequency [4], since the delay time between transmission and reception of a pulse of given frequency indicates the virtual height for the particular frequency. The true heights are, however, less than the virtual heights.

In most of the older methods computations of true heights from virtual heights were made without taking into account (1) the influence of the earth's magnetic field and (2) the effect of collisions between electrons and gas molecules. Though the latter may not have much influence in the final results especially at high altitudes, the former does play an important part in the evaluation of group velocities. The influence increases at higher latitudes and it has been found that differences of as much as $50\,\%$ occur in estimates of layer thicknesses between neglecting and taking into account the effect of the earth's magnetic field at a latitude of about 60°. Also, in analysing some records inconsistent results are obtained by neglecting the field, such as two distinct values of electron densities at one and the same height. It is only along the regions close to the magnetic equator that the field may be neglected for the ordinary component.

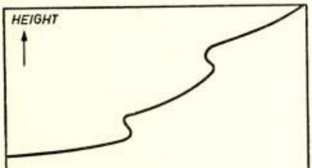

Fig. 1.
Typical electron density distribution as a function of height.

The ionosphere is assumed to be horizontally stratified, the region between any two layers having a constant electron density the value of which is nearly equal to the maximum value of the lower layer. This assumption seems to be accurate as verified with the actual electron density distribution data obtained from rocket flights [5]. Within a layer the electron density is approximately a linear function of height as shown in Figure 1.

2. The gyrofrequency.

The gyrofrequency is the natural frequency of rotation of ions around the lines of magnetic field of the earth, the ions being not subject to an electro-magnetic wave. Due to its small mass, the electron has a gyrofrequency comparable with the frequency of radio waves. If an electron comes under the influence of an electro-magnetic wave the frequency of which is greater than the gyrofrequency, the motion of the electron is elliptic, the ratio of the major and the minor axes of the ellipse varying directly with the strength of the earth's magnetic field and inversely with the frequency of the electro-magnetic wave.

The value of the gyrofrequency has been obtained from the general expression,

$$f_H = \frac{He}{2\,\pi mc} \tag{1}$$

where,

H = strength of the earth's magnetic field in oersteds.
e = charge of the electron ($= 4{,}77 \times 10^{-10}$ e.s.u.).
m = mass of the electron ($= 9{,}01 \times 10^{-28}$ gm.).
c = velocity of electro-magnetic waves in free space ($= 3 \times 10^{10}$ cm/s).

H was obtained for a given height by extrapolation of the experimental ground value by the inverse cube law,

$$H_h = H_\circ\,(r/r + h)^3 \tag{2}$$

where,

H_h = strength of the earth's magnetic field in oersteds, at height h.
$H_\circ$ = the field strength at ground level ($= 0{,}473$ oersted for Leidschendam).
r = radius of the earth ($= 6370$ km).
h = height under consideration (taken as 150 km).

The gyrofrequencies and values of H calculated for various heights are shown in Table 1.

3. Calculation of the group index μ'.

The well known expression for the (phase) refractive index μ, neglecting collisions, is

TABLE 1.

Height (km)	H (oersted)	f_H (Mc)
Ground level	0,473	1,33
50	0,465	1,31
100	0,455	1,28
150	0,445	1,25
200	0,431	1,21
300	0,412	1,16
400	0,396	1,11

$$\mu^2 = 1 - \frac{2x(1-x)}{2(1-x) - y^2 \sin^2\Theta \pm \sqrt{y^4 \sin^4\Theta + 4y^2 \cos^2\Theta (1-x)^2}} \tag{3}$$

where,

$$x = \frac{4\pi N e^2}{m p^2}$$

N = number of electrons per cm^3.

p = angular frequency of the exploring wave ($= 2\pi f$).

f = frequency of the wave.

y = ratio of gyrofrequency to exploring wave frequency ($= f_H/f$).

Θ = angle contained between the direction of wave propagation and the direction of the earth's magnetic field.

The upper (+) sign refers to the ordinary component and the lower (−) sign to the extraordinary one. Although no decision has been arrived at as to the inclusion or omission of the Lorentz polarisation term in expression (3), the tendency is towards the latter. It seems it can be safely neglected above 4,27 Mc/s of the exploring wave frequency.

Any computation for the contribution to the virtual height of a region of the ionosphere needs an exact knowledge of the group velocity of the wave of given frequency at that particular region. The group velocity is expressed in terms of a certain quantity μ', called the "group refractive index", the relationship being given by,

$$\text{Group velocity} = \frac{c}{\mu'} \tag{4}$$

where c is the velocity of electromagnetic waves in free space.

Now the group index is defined as,

$$\mu' = \mu + f\frac{\partial\mu}{\partial f} \tag{5}$$

where f is the exploring wave frequency.

At values of x approaching 1, μ tends to zero and hence it is not convenient to compute μ' from (5). As is commonly done, one calculates the product $\mu\mu'$ first. From (5) we get,

$$\mu\mu' = \mu^2 + \mu f\frac{\partial\mu}{\partial f} \tag{6}$$

Substituting the values of μ^2 and $\frac{\partial\mu}{\partial f}$ taken from (3) in (6) gives,

$$\mu\mu' = 1 - \frac{2x^2}{D} + \frac{x(1-x)}{D^2}fD' \tag{7}$$

Here,

$$D = 2(1-x) - y^2\sin^2\Theta \pm \sqrt{y^4\sin^4\Theta + 4y^2\cos^2\Theta(1-x)^2} \tag{7a}$$

$$fD' = 4x + 2y^2\sin^2\Theta \pm \frac{2\left\{-y^4\sin^4\Theta + 2y^2\cos^2\Theta(3x-1)(1-x)\right\}}{\sqrt{y^4\sin^4\Theta + 4y^2\cos^2\Theta(1-x)^2}} \tag{7b}$$

Although the product $\mu\mu'$ can be calculated by shorter methods by introducing a few approximations, expression (7) was used in order to get more accurate values.

In the limiting case when $x = 1$ for the ordinary component and $x = 1 - y$ for the extraordinary component, $\mu\mu'$ is given by the following,

$$\mu\mu' = 1/\sin^2\Theta \qquad \text{(ordinary component)} \tag{8}$$

$$\mu\mu' = \frac{2-y}{(1-y)(1+\cos^2\Theta)} \qquad \text{(extraordinary component)} \tag{9}$$

4. The ordinary component.

For the ordinary component the values of μ are obtained from relation (3). Figure 2 shows $\mu\mu'$ as a function of x. Thus from known values of μ and $\mu\mu'$, the quantity μ' is obtained.

As stated earlier with regard to the shape of the layer, it

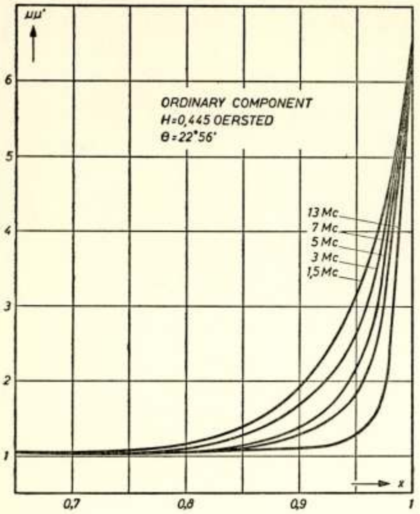

Fig. 2.

$\mu\mu'$ product for the ordinary component, Leidschendam, Holland.

is assumed that the variation of electron density with height is approximately linear. If z be the height measured vertically to the true reflection point, D the real thickness of the part of the layer extending from the bottom of the layer to the true reflection point, D' the apparent thickness corresponding to D for the particular frequency, we have the well known relation,

$$D' = \int_0^D \mu' dz \tag{10}$$

According to the above assumption this becomes,

$$D' = \frac{D}{x_1 - x_0} \int_{x_0}^{x_1} \mu' \, dx \tag{10a}$$

where x_1 and x_0 are the values of x corresponding to N_1 and N_0 respectively for the particular frequency, x_1 being in this case equal to 1. In order to evaluate the integral in (10a) we define a function Q as,

$$Q(f, x) = \int_0^x \mu' \, dx \tag{11}$$

Therefore,

$$D' = \frac{D}{x_1 - x_0} \left\{ Q(f, x_1) - Q(f, x_0) \right\} \tag{11a}$$

where $x_1 = 1$.

However, in regions where the electron density is constant, as is assumed to be the case where discontinuities occur in h', f records, this method cannot be used. In this case D' is given by,

$$D' = \mu' D \tag{11b}$$

As μ' tends to infinity when x tends to 1, the integral in (11) cannot be evaluated as it is. The following transformation is made use of,

$$t = \sqrt{1 - x}.$$

Therefore,

$$\int_{0}^{x} \mu' \, dx = -2 \int_{t=1}^{t=\sqrt{1-x}} \mu' \sqrt{1 - x} \, dt \tag{12}$$

Figure 3 shows $\mu' \sqrt{1 - x}$ as a function of $\sqrt{1 - x}$. The integral is then equal to twice the area under a curve for a given value of x. The curves in Figure 3 can be used directly to compute μ', D or D' whenever formula (11b) is used. Typical curves for the variation of the integral with x and for various frequencies are shown in Figures 4 and 5. To avoid crowding, Figure 4 shows curves for two frequencies only, 1,5 Mc/s and 13 Mc/s, and the values for other frequencies are obtained by taking the differences in value for these frequencies from

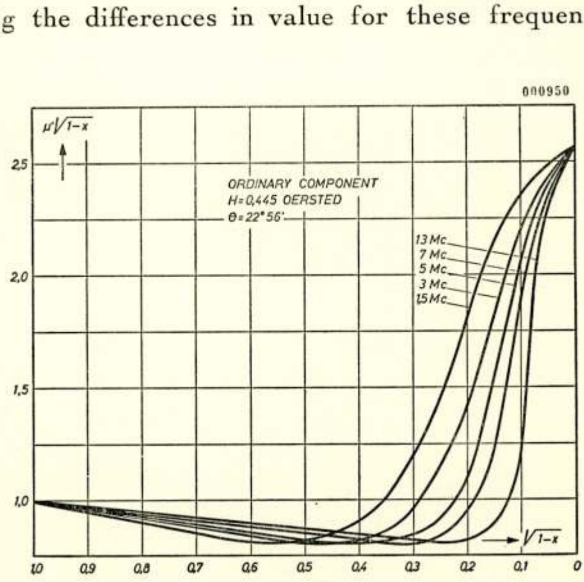

Fig. 3.

$\mu' \sqrt{1 - x}$ for the ordinary component,
Leidschendam, Holland.

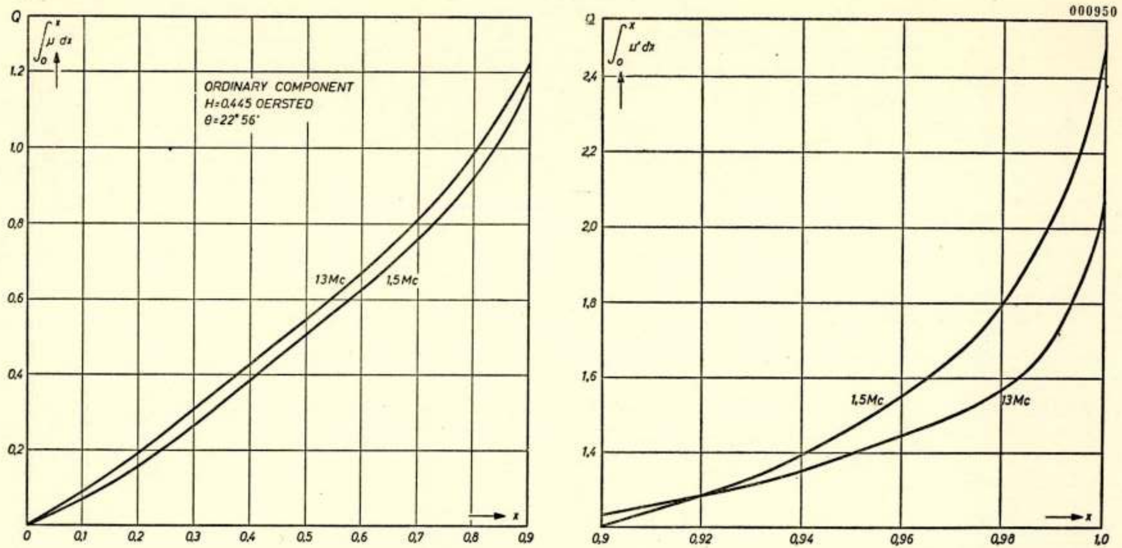

Fig. 4.

Q curves for the ordinary component, Leidschendam, Holland.

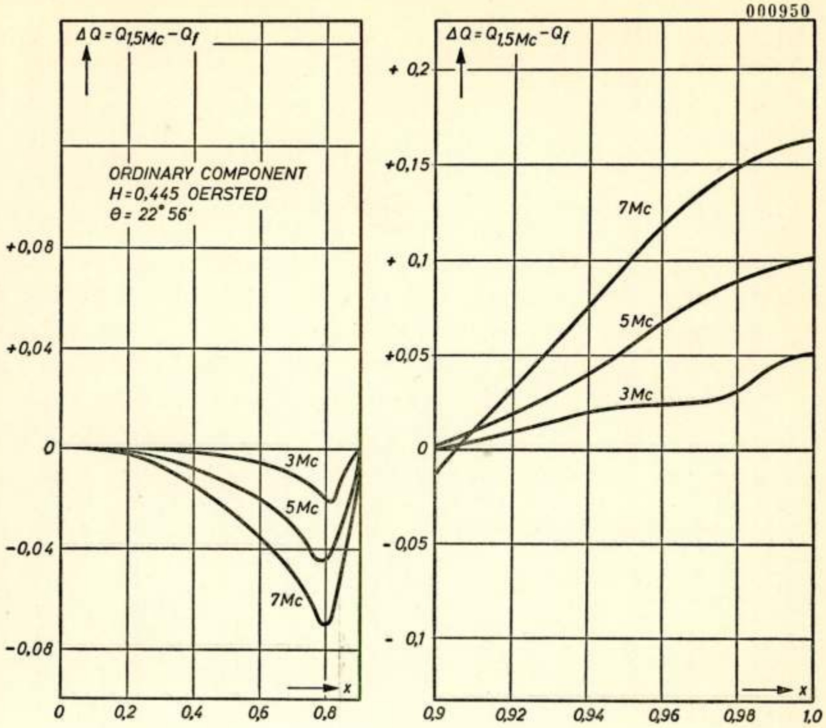

Fig. 5.

Interpolation values for Q curves, ordinary component, Leidschendam, Holland.

Figure 5 and adding them to the corresponding ones for 1,5 Mc/s found from Figure 4.

5. The extraordinary component.

For the extraordinary component reflection normally occurs for values of x given by $x = 1 - y$, if y is less than 1, i.e. for frequencies greater than the gyrofrequency. As only those values of y less than 1 are of interest with regard to h', f records these alone will be considered here.

Unlike the method of calculation used for the ordinary component, it is found convenient to plot μ^2 and $\mu\mu'$ as functions of $(x/1 - y)$ for the extraordinary component. In a similar way as indicated in the description for the ordinary component, the following transformation is used for evaluating the integral

$$\int_0^x \mu' \, dx,$$

$$t = \sqrt{1 - (x/1 - y)} \tag{13}$$

Therefore,

$$\int_0^x \mu' \, dx = -2(1 - y) \int_1^t \mu' t \, dt \tag{14}$$

By plotting $\mu' \sqrt{1 - (x/1 - y)}$ versus $\sqrt{1 - (x/1 - y)}$ the values of the integral in (14) are obtained in the same manner as for the ordinary component. Figure 6 contains the Q curves for the extraordinary component as a function of $x/1 - y$. In order to reduce a particular value to that corresponding to x, it must be divided by $(1 - y)$ for the frequency under consideration.

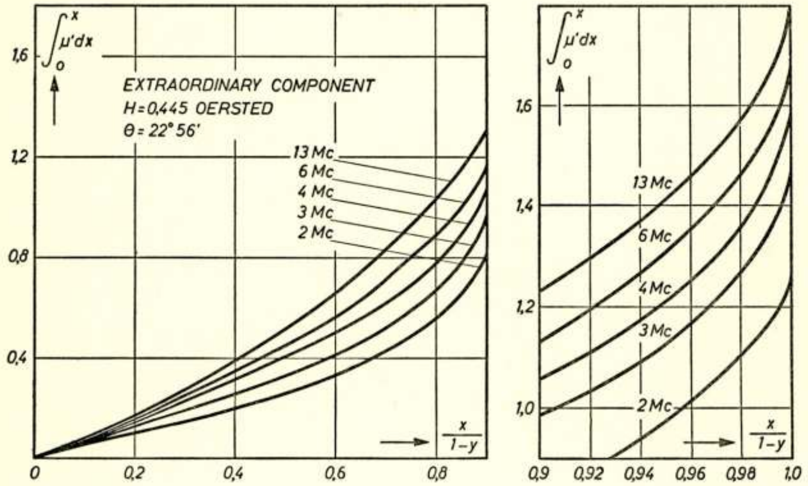

Fig. 6.

Q curves for the extraordinary component, Leidschendam, Holland.

6. Analyses of h', f records.

In the following method of analyses of h', f records made at Leidschendam, the ordinary component has been considered in particular. The curves for the extraordinary component may be used for checking the results.

The main difficulty in computing electron densities at various heights is in fixing a starting point, i.e. a height of known electron density. Hence some assumption has to be made in order to locate the lower limit of a certain layer. In view of the regularity shown by the E layer, the E trace on the h', f record is most suited for any such computation.

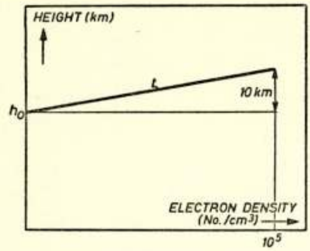

Fig. 7.
Straight line approximation of the lower limit of the ionosphere.

The electron density is assumed to increase linearly with height from h_0 ($N \approx 0$) at a rate of 10^4 electrons/cm^3 per km. This is represented by the straight line L in Figure 7. The contribution of this type of region to the virtual height for the ordinary component is calculated with the help of expressions (11a) and (12). This is shown in Figure 8 where apparent thickness $D' = (h' - h_0)$ is plotted versus frequency, where h' is the virtual height of reflection for the particular frequency. Figure 8 is used in the following manner for locating h_0.

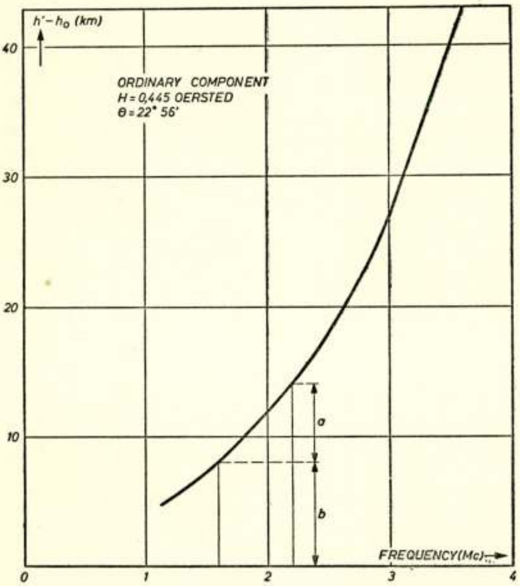

Fig. 8.
Curve derived from straight line approximation of fig. 7 and used for locating h_0 at Leidschendam, Holland.

In the h', f record under study two points well below the E layer critical frequency are chosen whose heights are given by h'_1 and h'_2 corresponding to the frequencies f_1 and f_2 respectively. Let h'_2 be the greater of the two and $h'_2 - h'_1 = a'$. Corresponding quantities a and b are found for these frequencies from Figure 8. By comparing Figure 8 with the actual h', f record under study the bottom of the E region is taken to be a straight line defined by,

$$h_0 = h'_2 - (a + b)\, a'/a \tag{15}$$

Now it will be shown how a h', f record can be transformed into one giving the electron density as a function of true height.

For reasons of facility the h', f record under study is first modified into one of virtual height as a function of electron density. After locating h_0 by the above method on this profile, the region between this point and the one corresponding to the electron density for the frequency f_2 is approximated by a straight line starting from h_0 and increasing at a rate of $(a'/a) \times 10^4$ el/cm^3/km. Let the point P_2 correspond to the upper limit of the straight line. Thus the height of $P_2 (= h_2)$ represents the true reflection height of the virtual point P'_2 whose height is h'_2. This is illustrated in Figure 9.

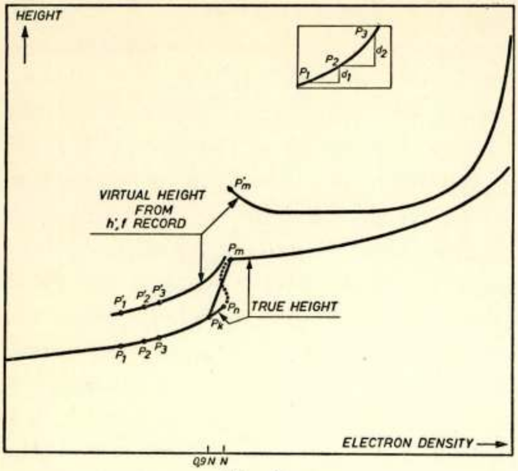

Fig. 9.

Typical curves showing virtual heights and derived true heights of electron density.

The true height h_3 of a neighbouring point P_3 corresponding to the virtual point P'_3 with critical frequency f_3 and electron density N_3 is obtained as follows.

We make use of the relation,

$$h'_3 = h_0 + d_1 + \frac{d_2 (Q_3 - Q_2)}{(x_3 - x_2)} \tag{16}$$

obtained from (11a), for the ordinary component.

In (16).

h'_3 = height corresponding to the point P'_3.
h_0 = height of the bottom of the E layer ($N \approx 0$).
$d_1 = h_2 - h_1$.
$d_2 = h_3 - h_2$.

$$x_3 = \frac{80,6}{f_3^2} N_3.$$

$$x_2 = \frac{80,6}{f_3^2} N_2.$$

$$Q_3 = \int_0^{x_3} \mu' \, dx.$$

$$Q_2 = \int_0^{x_2} \mu' \, dx.$$

N_3 and N_2 are the electron densities at P_3 and P_2 respectively. f_3 is the frequency corresponding to N_3 in Kc/s. The Q's are to be found from Figures 4 and 5.

In (16) all quantities except d_2 are known and so it can be easily computed. Thus the true height h_3 of the point P_3 corresponding to the virtual height h'_3 of P'_3 will be given by,

$$h_3 = h_0 + d_1 + d_2.$$

In this manner the analysis is carried out till the point which corresponds to the maximum electron density of the E layer where a discontinuity normally occurs. The analysis at this point makes use of the assumption that the region immediately above this point remains densely ionised as stated earlier. Referring to Figure 11 let P_m represent the true reflection point corresponding to the virtual point P'_m on the h', f record. If P_n represents the true reflection point corresponding to the maximum electron density of the E layer and if P_m and P_n are linked, then the assumed interlayer density would be too large. This region is therefore approximated by a straight line joining P_m and P_k where P_k is a point on the true E trace and the value of its abscissa is given by 0,9 N, N being the maximum electron density of the E layer. Practice has shown this to be a suitable approximation, and may also be used at other points where discontinuities are observed. In such a region of transition formula (11b) may be employed since μ' is constant. In analysing night time records, the lower part of the F layer is assumed to be linear and the analysis follows in the same lines as for the E layer.

7. **Results of measurements.**

Figures 10 and 11 contain typical records transformed to show electron densities versus virtual heights as well as true heights derived according to the described method. In Table 2 are shown the true heights of electron density maxima and the level of minimum ionisation (h_0). The h', f records were made at Leidschendam with a modern ionosphere sounding equipment [6]. Also shown in Table 2 are the virtual heights of points lying on the h', f records which correspond to 0,834 of the critical frequencies, such a height being sometimes taken as the true height of the level of maximum ionisation (method of Booker and Seaton).

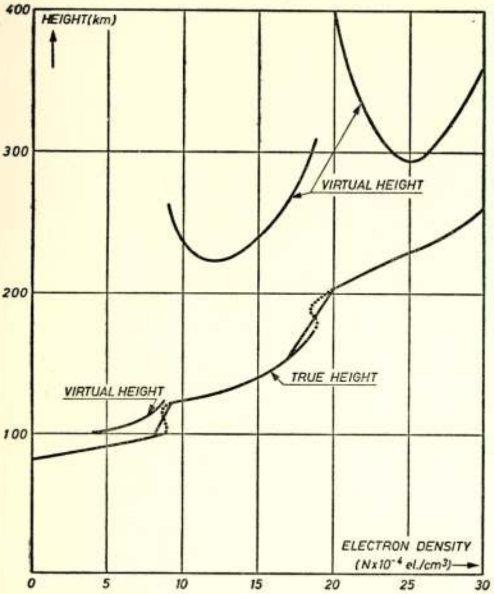

Fig. 10.

Analysis of h', f record, 7th. June, 1954, 4PM (Univ. time), Leidschendam, Holland).

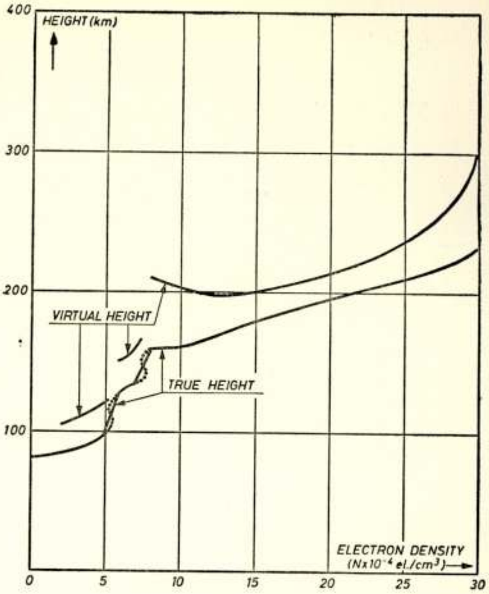

Fig. 11.

Analysis of h', f record, 21st. December, 1954, 12.30 PM (Univ. Time), Leidschendam, Holland.

TABLE 2.

Date and univ. time	Critical frequency f_c (Mc/s)	Maximum electron density No./cm³	h_o km	True ht. of max. el. dens. (km)	Virtual height (km)
4th June '54 (2 AM)	2,2	6×10^4	110	192	240
7th June '54 (4 PM)	4,9	30×10^4	80	260	300
21st Dec. '54 (12.30 PM)	4,9	30×10^4	80	230	245
25th Dec. '55 (3 AM)	3,4	$14{,}5 \times 10^4$	130	210	320
24th Feb. '56 (2.29 PM)	9,7	117×10^4	90	267	275
16th May '56 (10.59 AM)	4,8	29×10^4	85	185	350
16th May '56 (3.29 PM)	6,0	45×10^4	95	280	525

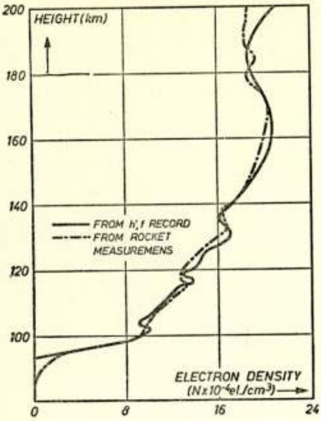

Fig. 12.

Electron densities computed from h', f record and comparison with rocket measurements, 10.00 Hours (MST) 7th May, 1954 [3].

The analyses so far carried out show that the F_2 layer behaves more regularly in its height variations than can be expected by inspection of the h', f records. This can be appreciated when one compares the day and night summer values with those during winter. Although the F_2 ionisation is much greater during the winter, heights are lower than those corresponding to the same values of electron density in summer. So it is clear that abnormal values of virtual heights often observed in h', f records are due to group retardation in the lower regions of the ionosphere. As stated earlier true heights derived by the method described have been found to agree with the actual data obtained from rocket flights at White Sands, New Mexico, as can be seen from the results of one such measurement reproduced in Figure 12.

Acknowledgements.

Many thanks are due to Dr. C. T. F. van der Wyck for his kind interest and guidance in the work and to Ir. P. L. M. van Berkel for his many valuable suggestions.

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Radio Relay Systems

by H. Stanesby, M.I.E.E.

Lecture delivered to the Nederlands Radiogenootschap on 5th March 1957.

1. Introduction.

Fig. 1.
Post office radio relay links February 1957.

The subject of my lecture, radio-relay systems, is of special interest at present because international agreement on many of their characteristics was recently obtained in the C.C.I.R.*) at Warsaw, and a considerable number of systems are now being built in various countries.

Time will not allow me to go into the history of radio-relay systems, although the earliest — very rudimentary in character — were incorporated in national telephone systems over 25 years ago. Nor will it allow me to describe the many different types that are now in use. However, the map in Fig. 1, showing the extent to which radio-relay systems have been installed in the United Kingdom, might be of interest. Because time is short, I shall concentrate mainly on the general characteristics of the larger-capacity systems used on both sides of the Atlantic to handle hundreds of telephone channels or television — the broadband systems — so called because the input

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*) Comité Consultatif International des Radiocommunications.

signal occupies a band of frequencies perhaps several megacycles per second wide. Then I shall refer briefly to the more-recently-developed tropospheric-scatter systems — systems which, although they have much smaller traffic-handling capacity, have some very interesting features.

2. **UHF and SHF wave-propagation.**

The systems I am considering operate on UHF and SHF*) frequencies ranging from about 500 to 10,000 Mc/s — very much higher than are used for really long-distance communications or even for television broadcasting; and I shall begin by considering radio-wave propagation at these frequencies.

At such frequencies there is no reflection from the ionosphere, so really long-distance propagation in a single hop is out of the question — unless, as has been suggested, the signals are reflected by the moon! Buth the troposphere, which extends up to 12,000m or so, does affect the propagation of these waves, and to a greater extent as the distance from the transmitter to the receiver increases. Normally the troposhere refracts and scatters the waves somewhat, and at times when it is not well mixed — when it is stratified — it may reflect them as well. The clear atmosphere is virtually transparent up to say 10,000 Mc/s, but at higher frequencies water vapour and oxygen cause some absorption, as is shown in Fig. 2. This figure also shows that rain, and to a lesser extent mist and cloud, affect trans-

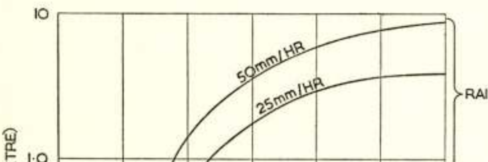

Fig. 2.

Attenuation due to atmospheric gases, fog and rain.

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*) UHF and SHF refer to frequency ranges of 300-3000 and 3000-30,000 Mc/s respectively.

mission somewhat — more at the higher frequencies. Apart from this absorption, the troposphere has four main effects which can conveniently be described in terms of what happens with light waves:

(a) The decrease of refractive index with height delays the apparent setting of the sun by curving the rays. For light, refraction at the horizon is nearly 35 minutes of arc, more than the angular diameter of the sun. For radio waves much the same happens, and as is illustrated in Fig 3, the ray curvature for a well-mixed atmosphere has the same effect as increasing the earth's radius by $\frac{1}{3}$.

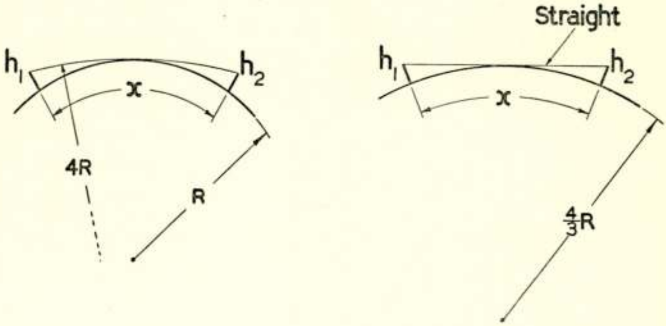


Fig. 3.
Illustration of allowance for normal atmospheric refraction by increasing effective earth radius.

(b) The variation of refraction with time causes stars to twinkle. It also causes fading of radio waves.

(c) After sunset there is still plenty of light for some time. If there were no atmosphere to scatter the light back it would immediately become pitch dark. It is the same with radio waves — the scattering of the waves by the atmosphere greatly increases the strength of signals well beyond the horizon as can be seen in Fig. 4.

(d) Finally, on occasions mirages occur. Similar conditions can cause the reflection of radio waves with the possibility of anomalous propagation, wave-interference and serious fading.

With this information it can be understood why there are two widely-different types of radio-relay system. The first in which signals are transmitted over a sequence of line-of-sight paths with stations at intervals of 50 km or so, and where only low power is needed because the path loss is relatively small. Then there are the so-called tropospheric-scatter systems

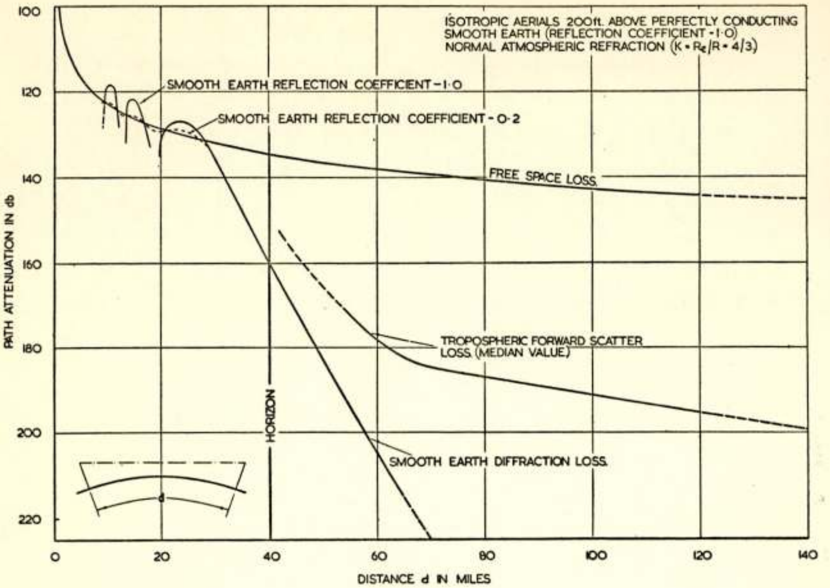


Fig. 4.
Variation of attenuation with distance. (2000 Mc/s)

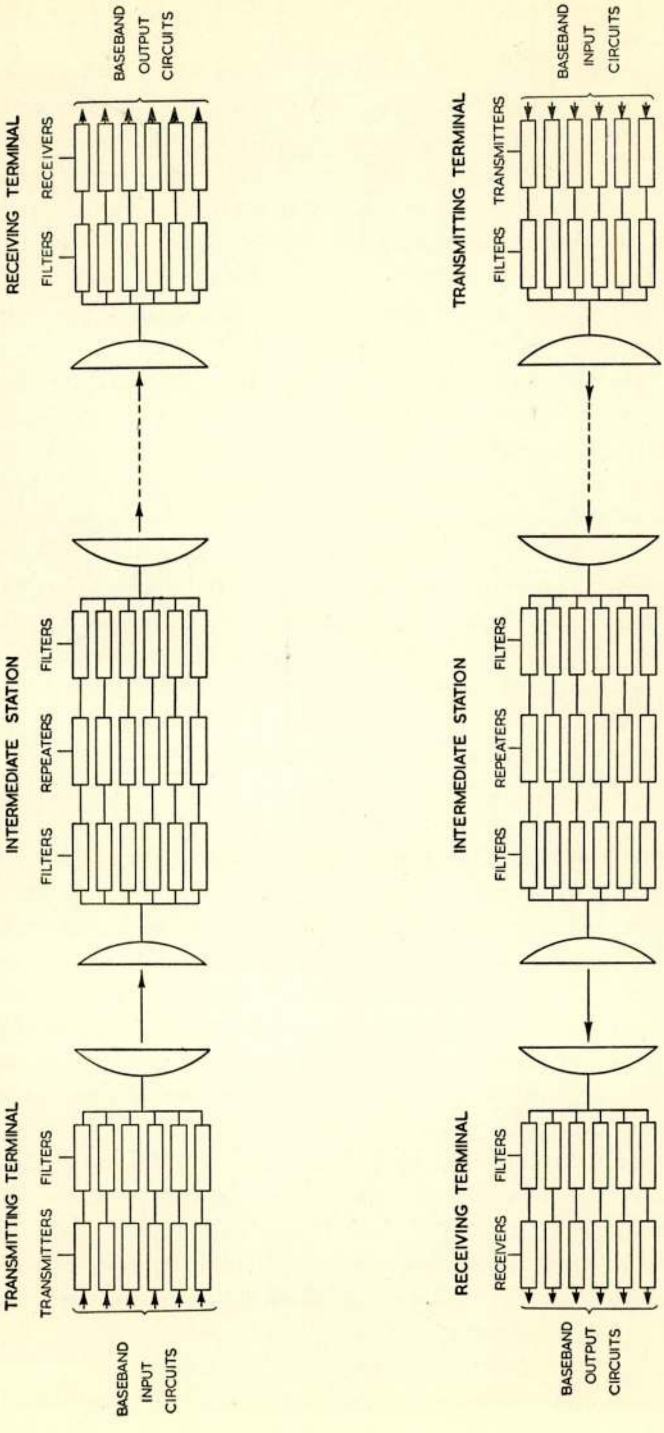
in which adjacent stations may be several hundred kilometres apart and much higher transmitter powers are needed.

3. Line-of-sight systems.

The paths used for the line-of-sight systems must not only be clear, but application of the wave-front principle of the famous Dutch scientist Huygens shows that to avoid unnecessary loss, major obstructions should be sufficiently removed from the line-of-sight for the path via an obstruction to be at least $\frac{1}{2}$ wavelength longer than the direct path. In practice, to allow for abnormal refraction conditions, we seek when choosing station sites to satisfy this condition for an effective earth radius of 0.7 times the true radius. Free-space propagation will then be approached for a large proportion of the time, although for perhaps 0.1 per cent of the time fading might rise to as high as 10 db.

I shall now briefly outline the form that a line-of-sight radio-relay system might take before considering its component parts and its characteristics in more detail.

In large-capacity radio-relay systems the radio-frequency carriers are frequency-modulated with a baseband spectrum, i.e.



Radio-relay system for six broadband channels.

Fig. 5.

an input signal, consisting of a hundred or more telephone channels or of television. Referring to Fig. 5, a number of such modulated carriers are fed through combining filters to a common aerial whence they are radiated in a narrow beam. Further along the route the carriers are received on a directional aerial, after which they are seperated, individually amplified and changed somewhat in frequency, recombined and re-radiated over the next section of route. This process is repeated at stations spaced on the average say 50 kilometres apart. Finally at the receiving terminal the carriers are seperated, amplified and the original baseband signals are recovered by demodulation.

Each of the carriers provides a broadband channel of communication, and a radio-relay system generally provides one or more such channels for each direction of transmission. Where there is need for only one working channel, providing a second channel may well be the most convenient way of guarding against equipment failure; and where two or more working channels are needed, perhaps for multi-channel telephony and television, if they have similar characteristics a common standby channel should suffice. If telephony is to be transmitted the individual telephone channels would normally be assembled by frequency-division multiplex in the baseband, in the way that has been recommended internationally for cable and radio systems by the CCITT*) and the CCIR respectively. This would facilitate interconnection. Television, however, is much more easily handled if the signals are applied, unchanged, to radio-relay systems, whereas for long-distance coaxial-cable transmission they must be raised somewhat in frequency — a complicated process which we are fortunate to escape.

Fig. 6 shows in more detail the major units that go to make up a terminal transmitter, a repeater and a terminal receiver, and the frequency-changing processes involved. The filters used for combining and separating different broadband channels are omitted to avoid complicating the diagram.

In a terminal transmitter the baseband signal, after amplification, might frequency-modulate a carrier either at the final radiated frequency, f_1, or at an intermediate frequency f_{if}, which is afterwards raised to the final frequency in a frequency-changer. The modulated carrier is then amplified before being fed with other carriers to the aerial.

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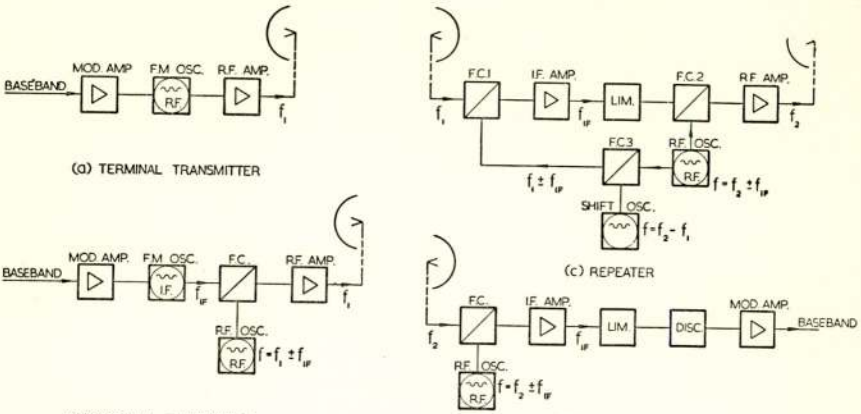
*) Comité Consultatif International Télégraphique et Téléphonique.



(a) TERMINAL TRANSMITTER

(b) TERMINAL TRANSMITTER

(c) REPEATER

(d) TERMINAL RECEIVER

Fig. 6.
Arrangements of terminal transmitters, terminal receivers and repeaters.

In a repeater the received carrier, f_1, after being separated from the other broadband-channel carriers, is reduced to intermediate frequency in a frequency-changer, amplified, limited and raised in a second frequency-changer to a frequency f_2 differing somewhat from the incoming frequency. Then it is further amplified before being combined with the other modulated carriers for onward transmission over the next section of route. The frequency shift, $f_2 - f_1$, which is small compared with the frequencies f_1 and f_2 themselves, is determined only by the frequency of the shift oscillator which can be crystal-controlled. Referring to the figure, an error in the higher-frequency "R.F. oscillator" does not therefore affect the value of f_2, it cancels out, although it affects the centering of the signal in the I.F. band.

If the shift oscillator is accurate no frequency error will be introduced in the R.F. signal by the frequency-changing processes, and errors will not accumulate along the route.

The limiter ensures that the input signal to the R.F. amplifier is held constant at its optimum value regardless of fading in the previous section of route.

The terminal receiver calls for little comment. In it the carrier is reduced to intermediate frequency, limited, and applied to a discriminator where the baseband signal is recovered.

The intermediate-frequency band used at all points should be the same regardless of the broadband channel involved. The CCIR has recommended a mid-band frequency of 70 Mc/s for all radio-relay systems operating above 1000 Mc/s, which makes it easy to interconnect broadband channels at intermediate frequency.

3.1 Techniques used in Line-of-sight Systems.

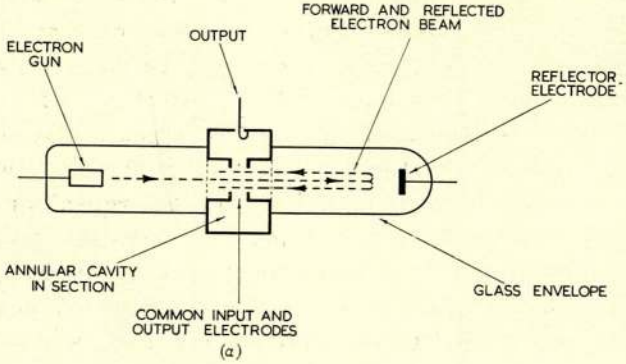
3.1.1 *Generation and Amplification of Oscillations.*

The generation and amplification of oscillations at frequencies of the order of thousands of megacycles per second presents major problems, and special valves are needed: Grounded-grid triodes can be used, but they must be specially designed with microscopic electrode-clearances to reduce electron-transit times, and with electrodes so shaped that they can form parts of resonant cavities. Moreover the gain per stage is relatively low, and hitherto, the alignment of amplifier chains has been difficult due to interaction between stages. I believe that considerable progress has, however, recently been made in the Netherlands in solving the alignment difficulties by using ferrite isolators.

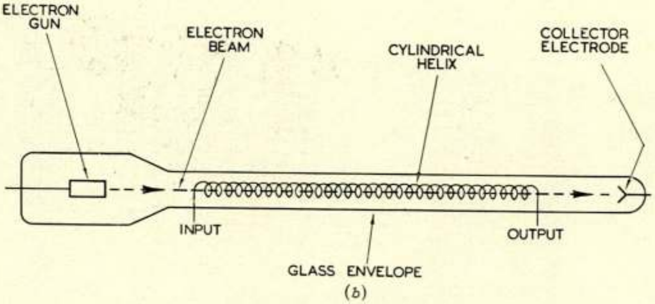
The alternative is to employ the principle of velocity-modulation, in which electron-transit time is an essential and not an undesirable factor. At a point in an electron-beam a longitudinally-applied radio-frequency electric field is made to vary the electron-velocity with time. Further along the beam these electron-*velocity* variations build up electron-*density* variations, i.e. electron-bunches, which give up some of their energy to suitably-placed electrodes leading to an output circuit. Variations of this theme are used in a number of different types of valve suitable for generating and amplifying UHF or SHF oscillations. Two types, the reflex-klystron and the travelling-wave valve, are shown diagrammatically in Fig. *7*.

In the reflex-klystron, widely used as an oscillator, the electron-beam is reflected back along itself by a reflector electrode, and the input and output electrodes are common. Velocity variations introduced in the outgoing beam give rise to density variations in the reflected beam, energy from which is used to sustain oscillations in a cavity connected to the electrodes.

The most direct way of frequency-modulating a carrier is to apply the baseband signal to the reflector-electrode of a reflex-klystron oscillator. The input signal power required is negligible, and linear frequency-deviations of several megacycles per second are readily obtainable. Alternatively, several different means are available for producing a modulated carrier at intermediate-frequencies and translating it to the desired radio frequency.



(a) REFLEX KLYSTRON



(b) TRAVELLING - WAVE VALVE

Fig. 7.
Velocity-modulation valves.

For amplification travelling-wave valves may be used; they operate by a process of interaction between a wave propagated along a cylindrical helix and an electron-beam passing axially through it. The input signal is applied to the first part of the helix and velocity-modulates the beam. Further along the beam electron-bunches appear and return more power to the helix than was absorbed from it initially, hence there is amplification. As much as 30 db gain per stage can be obtained over very wide bandwidths, the tuning adjustments are uncritical, and output powers of 5-15 watts are possible, depending on frequency.

In the United Kingdom, travelling-wave valves are generally used in large-capacity systems. Hitherto, because suitable low-noise valves could not be obtained, very-low-level UHF and SHF signals have not been amplified directly. They have been translated to an intermediate frequency, for which low-noise valves are readily available, and amplified and limited at that frequency. Then, if a repeater station is involved, the signal is raised again in frequency, and amplified in a travelling-wave valve amplifier to a level of 0.5—15 watts. But if it is desired to recover the baseband signal at a terminal station the signal is demodulated. Fortunately, low-noise travelling-wave valves have recently become available, and, for repeaters, the double-frequency-changing process is not now essential. Thus repeaters can be made with say four travelling-wave valves providing all the amplification, the small change in frequency needed before signals are passed to the next repeater-section being introduced

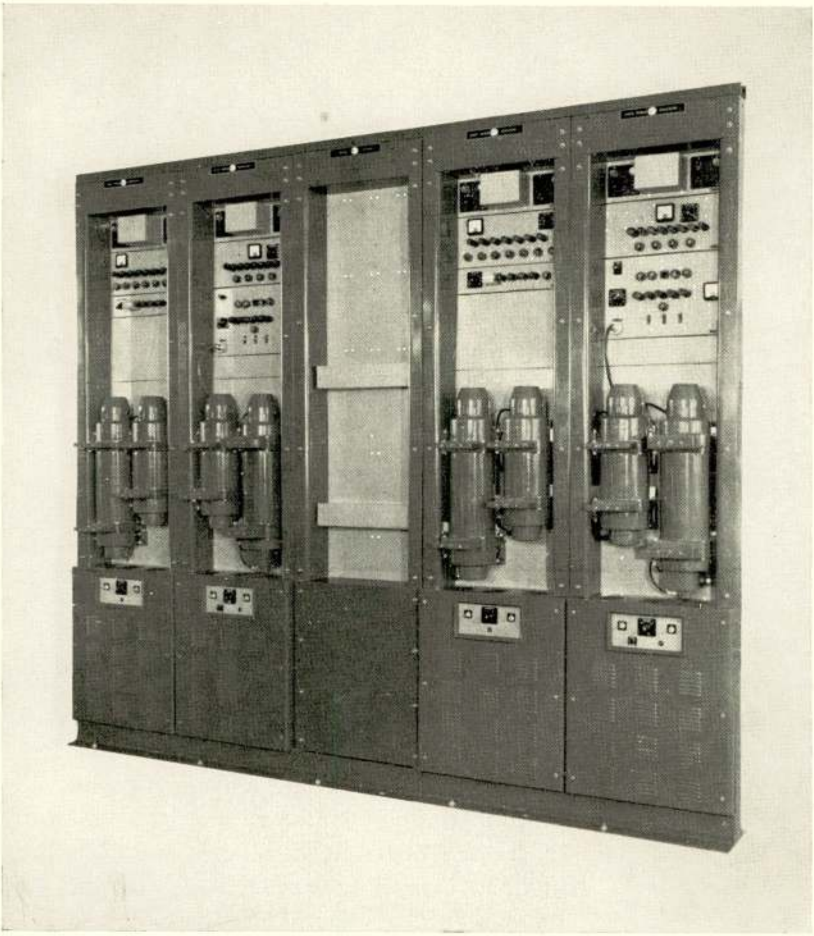


Fig. 8.
Two all-travelling-wave-valve repeaters.

in one of the travelling-wave-valve stages or in a separate crystal mixer. Two repeaters of this type are shown in Fig. 8.

3.1.2. *Frequency changing.*

The translation of a low-level received signal to an intermediate frequency is carried out in a low-noise silicon-crystal frequency-changer. The noise-factor is about 12 db; in other words, the random-noise output is some 12 db higher than that due to thermal noise in the circuit connected to the input terminals. For translating an IF signal back to UHF or SHF, however, a germanium-crystal frequency-changer is generally used, because much higher signal levels are involved.

As has already been mentioned, a travelling-wave valve can be used to introduce moderate changes in the frequency of a UHF or SHF signal, in, for example, an all-travelling-wave-valve repeater. If oscillations of a frequency equal to the desired change are applied to the electron-gun of a travelling-wave valve, they vary the beam-velocity and phase modulate any signal amplified by the valve. In this way high-level sidebands can be generated spaced on either side of the original signal by the desired frequency-change, and one can be selected with a filter. Such a frequency-changer has a *gain* of 10—20 db, whereas a crystal frequency-changer has a *loss* of 10 db or more.

3.1.3. *Combination and Separation of Broadband Channels*

A typical frequency pattern for a six-broadband radio-relay system is shown in Fig. 9. In any given repeater-section six go and six return channels are grouped in two adjacent bands, and at a repeater-station corresponding go and return channels are interchanged in frequency. The filters needed for combining and isolating these channels are made up of sections of waveguide, some forming resonant cavities and others forming connecting links and junctions. The filtering is more easily described in terms of reception rather than transmission: The combined signals

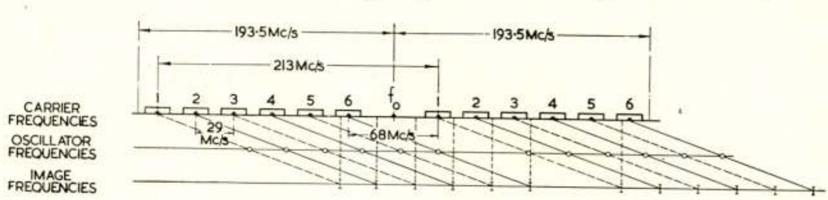


Fig. 9.

Radio frequency arrangement for six R.F. channels.

from the receiving aerial are passed through a series of branching filters where most of the signal power of each channel is diverted into a separate branch. One such filter is shown in Fig. 10. In each branch further selectivity is introduced by a filter consisting of a number of resonant cavities connected in tandem through sections of waveguide. A four-cavity filter of this type is illustrated in Fig. 11 with a curve showing the insertion-loss/frequency characteristic.

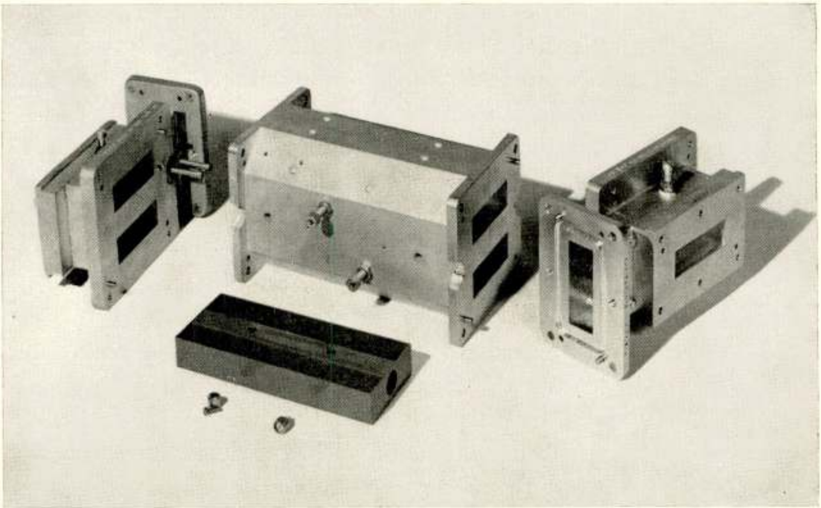


Fig. 10.
Branching filter for 4.000 Mc/s radio-relay system.

In a transmitter a similar arrangement of waveguide filters is used for combining broadband channels, but the direction of transmission is, of course, reversed.

3.1.4 *Aerial Systems and Feeders.*

At the high frequencies used for radio-relay systems it is possible to obtain very high directivity with aerials of moderate size, directivity being expressed as the ratio of the power radiated in, or received from, the desired direction, to that for an isotropic aerial used under the same conditions. At a given frequency the power gain of a properly-designed aerial, whether used for transmission or reception, is directly proportional to its area, and, for a given absolute area, the gain increases by 6 db if the frequency is doubled. The relationship between gain and frequency for a 10-ft diameter paraboloidal-reflector aerial is

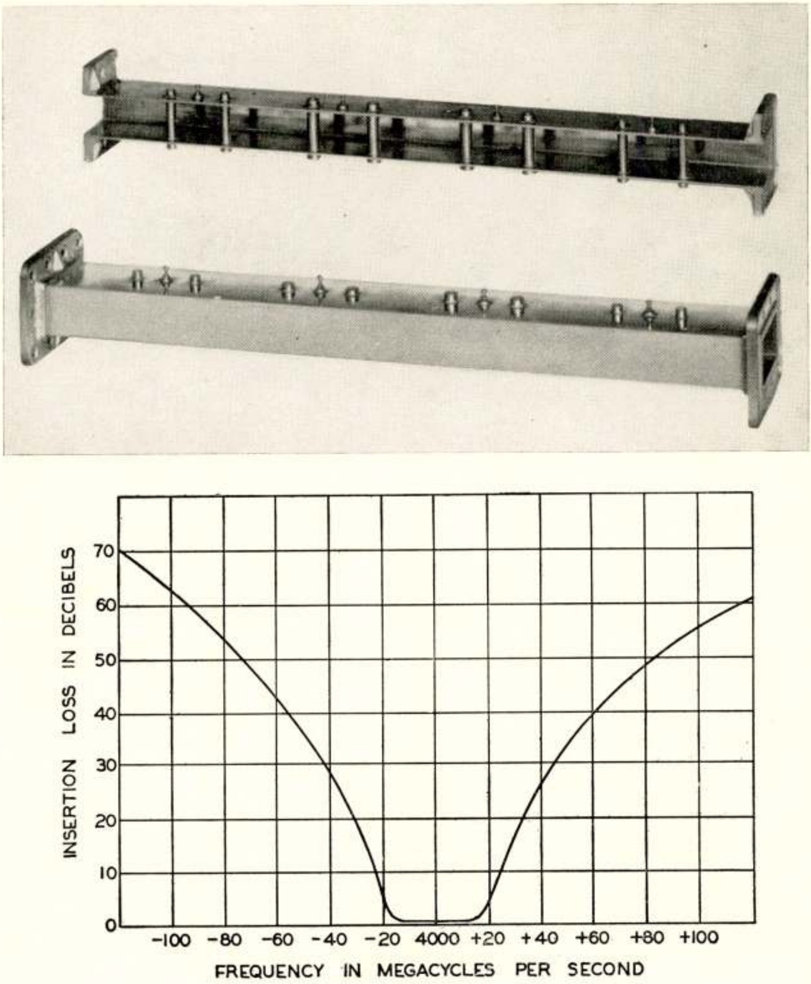
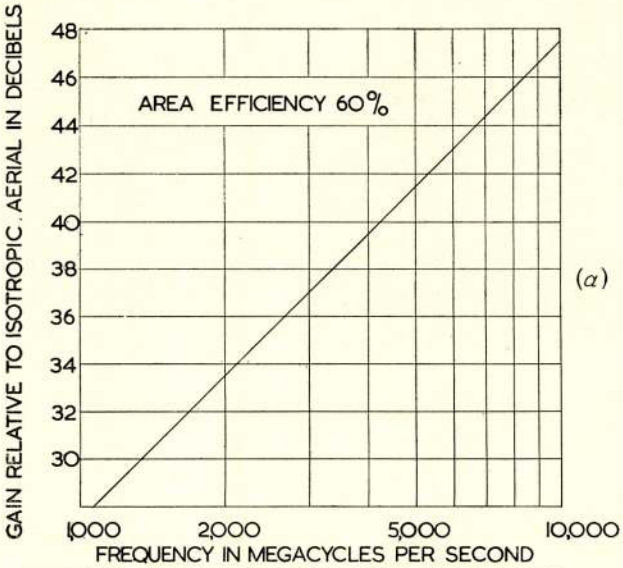


Fig. 11.

Construction and insertion-loss/frequency characteristic of 4000 Mc/s four-cavity waveguide filter

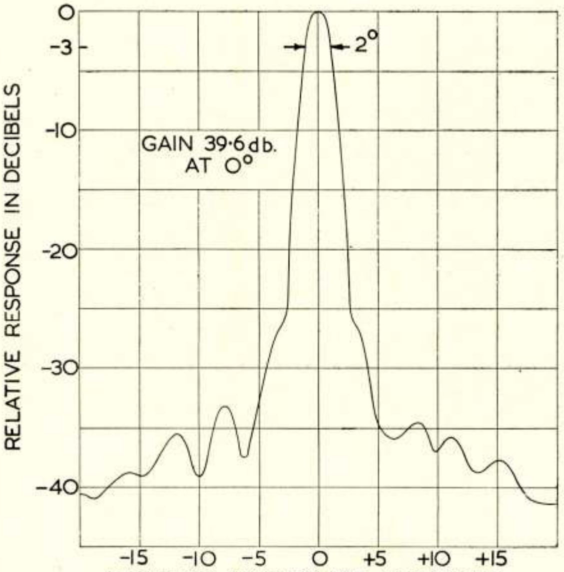
shown in Fig. 12, with a radiation diagram taken at 4000 Mc/s. High directivity is desirable, not only because it reduces the overal loss between transmitter and receiver, but because it reduces interference and multi-path propagation.

A typical aerial installation for a 4000 Mc/s repeater station is shown in Fig. 13. There are two 10-ft diameter aerials facing in each direction, one for transmission and one for reception, and each aerial is connected to the internal equipment by a feeder of rectangular-section waveguide.



(a)

(a) VARIATION OF GAIN WITH FREQUENCY



(b)

(b) RADIATION DIAGRAM AT 4,000 Mc/s

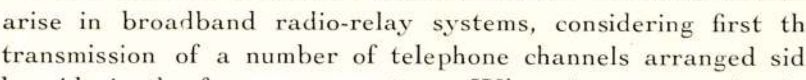
Fig. 12.
Performance of 10-foot-diameter paraboloidal-reflector aerial.

Fig. 13.
Intermediate repeater station, 4000 Mc/s radio relay system.

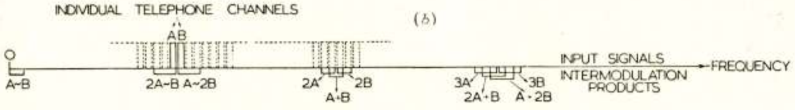
All the aerials are similar, but it is convenient to consider their action in terms of transmission: At the focus of the paraboloid the waveguide-feeder terminates in a small directional feed which distributes radiation over the surface of the reflector whence it is reflected in a narrow beam. The feed is designed to irradiate the reflecting surface without allowing appreciable energy to fall outside the periphery because this would give rise to backward and sideways radiation. In practice such an aerial can be made to have an effective gain equal to that of an ideal uniformly-irradiated paraboloid having 60-70% of the area, combined with sideways and backward radiation which is at least 40 db below that along the main beam.

3.2 Distortion and Noise.

I will turn for a moment to the distortion and noise that can arise in broadband radio-relay systems, considering first the transmission of a number of telephone channels arranged side by side in the frequency spectrum. When, in a communication system, currents of different frequencies are subject to non-linear distortion, spurious components arise, namely harmonic and intermodulation products, and if they fall near the original frequencies they might cause interference. Similarly, if a *band* of frequencies is subject to non-linear distortion, the harmonic and intermodulation products will fall in other bands which may overlap the first and give rise to interference. This is illustrated in Fig. 14. Interference and noise due to intermodulation constitute one of the major problems in designing radio-relay systems for multi-channel telephony.



(a) SECOND-ORDER & THIRD-ORDER INTERMODULATION PRODUCTS FOR TWO SINGLE-FREQUENCY SIGNALS.



(b) SECOND-ORDER & THIRD-ORDER INTERMODULATION PRODUCTS ARISING FROM TWO CHANNELS OF A MULTI-CHANNEL SYSTEM.

Fig. 14.

Illustration of the way in which intermodulation products can cause interference in multi-channel telephone systems.

The main advantages of using frequency-modulation instead of amplitude-modulation on broadband radio-relay systems are the signal/noise improvement, the fact that amplitude distortion need not be avoided in amplifying the modulated carrier, and the relative ease with which linear frequency-modulation characteristics can be obtained and the overall gain of a system can be held constant. For telephony, intermodulation, and hence non-linearity, must be kept at very low levels. Because, in frequency-modulation, the baseband signal is transformed into variations of the carrier frequency, the waveform of these variations must be faithfully preserved, otherwise non-linear distortion will result. Frequency is proportional to the *rate of change of phase with time*, and if a frequency-modulated wave is passed through circuits introducing phase-shift which varies with frequency, its instantaneous frequency will be changed slightly. If the phase-shift/frequency characteristic is *non-linear* it modifies the waveform of the frequency-excursions and distorts the baseband signal at the receiving end. Therefore, when multi-channel telephony is handled by frequency-modulation, the need for linear phase-shift/frequency characteristics is just as pressing as the need for *amplitude*-linearity in systems using amplitude-modulation, and in both cases departures from linearity cause intermodulation.

On the other hand, the transmission of television is relatively easy: There is no difficulty in keeping the baseband amplitude-frequency characteristic flat if wide band-widths are used, and this also ensures that there is little overall phase distortion. Neither is there difficulty in preserving sufficient linearity; small departures from perfection only alter the *tone gradations* of the picture slightly. Intermodulation as such is of no significance.

In planning radio-relay systems it is important that random noise and, where multi-channel telephony is involved, intermodulation noise should not exceed tolerable limits. Under non-fading conditions random noise is reduced relative to the signal by increasing the frequency deviation, but intermodulation is then increased because a larger frequency excursion is more likely to extend into regions where the RF and IF phase characteristics are non-linear. If other system parameters, e.g. transmitter-power, aerial-gain, etc., have been fixed, there is an optimum value for the deviation.

3.3 Frequency Pattern of Broadband Channels.

As their name suggests, broadband radio-relay systems occupy considerable frequency space. At the input and output terminals 600 telephone channels would occupy a baseband extending up to 2.54 Mc/s and 625-line television signals would extend up to at least 5 Mc/s. Even for low-deviation ratios each frequency-modulated carrier would therefore spread over 6 Mc/s or more. If six broadband channels are provided on the same system and different frequencies are used for the two directions of transmission, hundreds of megacycles per second of bandwidth are needed.

Fig. 9 shows the arrangement of broadband channels adopted by the CCIR at Warsaw last year jointly with an intermediate frequency of 70 Mc/s. Over any section of route the lower six channels would be used for one direction of transmission and the upper six for the other direction; and adjacent channels would use different polarizations to reduce the filtering needed for separation. At a repeater station the go and return channels would be interchanged in frequency in passing from one section of route to the next. The high-level signals being transmitted from the repeater station in either direction are then in different bands from the low-level signals being received, which reduces the likelihood of interaction.

There were many factors that influenced the choice at Warsaw, and here it is possible to mention only a few: (a) the images of receive channels should not fall in transmit channels, (b) the images of transmit channels should not fall in receive channels, and (c) referring to Fig. 6, harmonics of 213 Mc/s, the frequency used in shifting the location of broadband channels at a repeater station, should not fall near the frequency of oscillations derived from a mixer into which the 213 Mc/s is injected. This last requirement leads to preferred values for the centre frequency, f_o, of the frequency pattern, because for certain values of f_o, say 4003.5 or 2004.5 Mc/s, harmonics of the shift frequency, i.e. harmonics of 213 Mc/s, do not fall near any of the receive-beating-oscillator frequencies. If common-transmit-and-receive antennae are used, some of the sources of interference become potentially more dangerous, and the recommended arrangement for a system of three broadband channels on common-transmit-and-receive aerials is to use Channels 1, 3 and 5; or Channels 2, 4 and 6.

There is little doubt that the agreement reached at Warsaw will do much to facilitate the planning of international broadband radio-relay systems.

4. **Tropospheric-scatter systems.**

As has been indicated earlier, in the UHF and SHF bands the signal strength far beyond the horizon is far greater than it would be if there were no atmosphere, because, it is said, small-scale variations in the refractive index of the atmosphere to some extent scatter the waves around the curvature of the earth. However, there are others who claim that the signals travel far beyond the horizon because they are partially reflected by stratification of the troposphere, including the tropopause, the level at which the temperature ceases to fall with height — again about 12,000 m. Fig. 15 illustrates the mechanism: If two directional aerials are orientated so that the major lobes of their polar diagrams overlap, some energy radiated by one will be received by the other by scattering in the volume of the atmosphere where they overlap. The received energy varies inversely as a high power of the angle, Θ, at

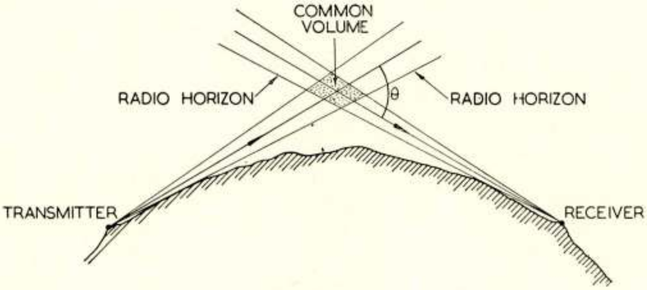


Fig. 15.
Geometry of tropospheric forward-scatter radio link.

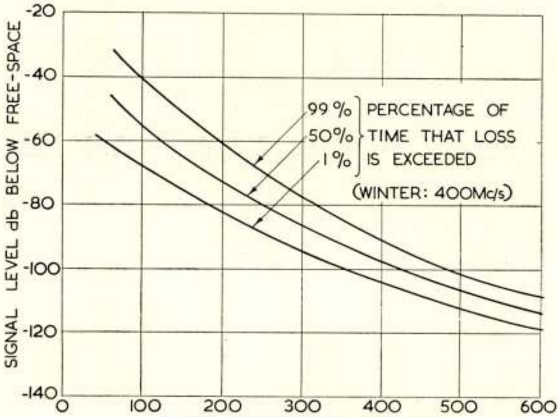


Fig. 16.
Variation of beyond-the-horizon propagation losses with distance (Lincoln Laboratory)

Fig. 17.
10 Metre aerial used for tropospheric-scatter communication.

which the two beams intersect, hence for minimum attenuation they should be directed towards the local horizon.

Because the aggregate signal is the summation of signal components from various parts of the scattering region the signal fades rapidly; moreover there is some variation of the median value from hour to hour, day to day and month to month. Fig. 16 illustrates the variation of field strength with distance on 400 Mc/s during the winter. It is interesting to note that field strength falls off more and more slowly as the distance increases.

It is found that there is little short-term correlation between the strength of signals received at points say 100 or more wavelengths apart at right-angles to the direction of propagation. Hence for these signals the power gain of aerials does not continue to increase in proportion to their area as the area is increased indefinitely. Nevertheless, it is profitable to use aerials up to say 50 wavelengths in diameter — approximately 20 metres diameter for a frequency of 800 Mc/s. This lack of correlation does, however, make it possible to use diversity reception and transmission with aerials that are quite close together. By using very high transmitter powers, very large aerials, perhaps 10 or 20 metres in diameter, and diversity, it is possible to transmit multi-channel telephony and television over 300 km or more without any intermediate station. A photograph of a 10-metre aerial used on such a system is shown in Fig. 17. The main elements of a tropospheric-scatter terminal using double-diversity reception are shown in Fig. 18. Such a station might work on frequencies upwards of 400 Mc/s.

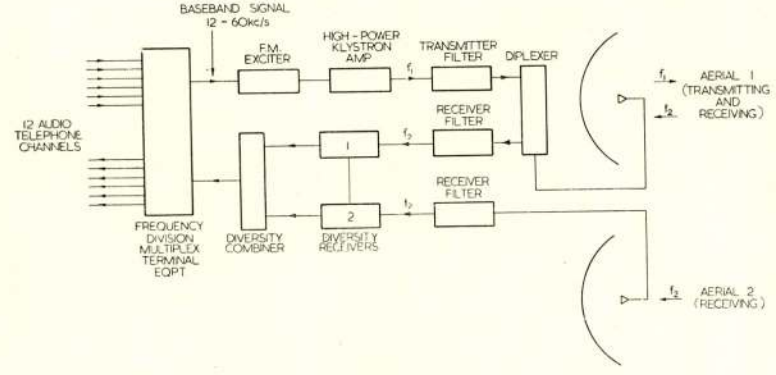


Fig. 18.

Tropospheric forward-scatter link equipment schematic.

To save money the transmitting aerial would also be used for reception, frequencies perhaps $5\,\%$ apart being used for the two directions of transmission.

In the last few years much work has been done on tropospheric-scatter systems for particular applications in which signal/noise ratios as high as those required to meet C.C.I.R. and C.C.I.T.T. requirements have not been regarded as essential. Very high standards are needed for links which may be incorporated in public-telephone connections thousands of miles long. Nevertheless I believe that in due course tropospheric-scatter systems will take their place in the Civil Telecommunications Network.

Acknowledgements

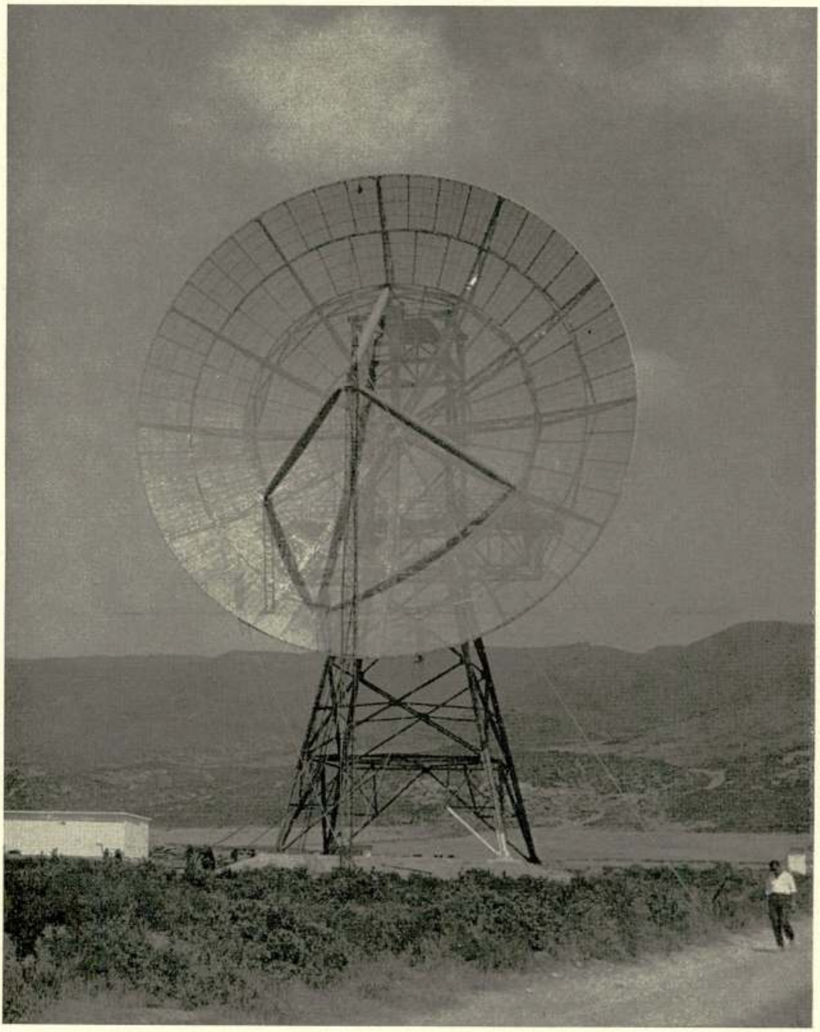
I acknowledge, with thanks, the permission of Marconi's Wireless Telegraph Co. and Standard Telephones and Cables to reproduce photographs of their equipment, and of the Institution of Electrical Engineers to reproduce certain figures and passages which were incorporated in my Chairman's Address to the Radio and Telecommunications Section of the Institution in October 1955.

DE STRAALZENDER-VERBINDING MINORCA-SARDINIE

Van de Nederlandsche Standard Electric Mij N.V. ontvingen wij een bericht over de onlangs in gebruik gestelde microgolfverbinding tussen Minorca en Sardinië, waaraan wij het volgende ontlenen.

Op 4 september 1957 werd de eerste directe commerciële telefoonverbinding tussen Italië en Spanje officieel in gebruik gesteld. Niet alleen is dit de eerste directe verbinding tussen deze beide landen, maar bovendien is dit de eerste commerciële toepassing in Europa van een nieuwe microgolftechniek, bekend als over-de-horizon-propagatie. Deze techniek wordt hier gebruikt om een afstand van 230 mijl tussen Sardinië en Minorca te overbruggen.

Men was oorspronkelijk algemeen de mening toegedaan, dat microgolven (radiosignalen met een golflengte van minder dan 1 m) zich hoofdzakelijk in een rechte lijn voortplanten en daarom alleen geschikt zijn voor verbindingen binnen



Het station op Sardinië

het optische bereik. Enkele geleerden twijfelden echter aan deze beperking. Bij proefnemingen op zijn jacht „Electra" in de Middellandse Zee stelde Marconi reeds vast, dat microgolfsignalen zich over een aanzienlijke afstand voorbij de horizon konden voortplanten. In 1941 werden verdere proeven op dit gebied in het Middellandse-Zee-gebied gedaan door A. G. Clavier van de International Telephone and Telegraph Laboratoria die Marconi's waarnemingen bevestigden. Bovendien werd gedurende de tweede Wereldoorlog vastgesteld, dat radarsignalen zich aanzienlijk verder kunnen voortplanten dan men zou verwachten op grond van de gangbare theorie.

Een groot aantal waarnemingen en proefnemingen zijn sinds de oorlog gedaan, en het is duidelijk vastgesteld dat zwakke maar redelijk constante signalen op afstanden van enkele honderden mijlen voorbij de horizon ontvangen kunnen worden.

Ten tijde van de oorspronkelijke proefnemingen was het nog niet mogelijk om praktisch gebruik te maken van dit verschijnsel, omdat er nog geen microgolfzenders van hoog vermogen beschikbaar waren, evenmin als voldoende gevoelige ontvangers. Tegenwoordig is deze apparatuur echter wel beschikbaar en verbindingen met microgolven over afstanden van enkele honderden mijlen zijn thans praktisch te verwezenlijken.

Voor straalzenderverbindingen, waarbij de aanwezigheid van water of andere geografische omstandigheden de bouw van relaisstations onmogelijk maken, is dit systeem dus bijzonder nuttig. Een aantal verbindingen van dit type zijn reeds in bedrijf voor militaire doeleinden, maar de verbinding tussen Sardinië en Minorca, die een onderdeel vormt van de verbinding tussen Italië en Spanje, is het eerste commerciële systeem, dat in bedrijf werd gesteld.

Behalve het gebruik van zenders van groot vermogen en zeer gevoelige ontvangers, zijn er nog enige andere factoren die in aanmerking moeten worden genomen om een betrouwbare werking van een dergelijk systeem te verkrijgen. Om een zo groot mogelijke signaalsterkte aan de ingang van de ontvanger te verkrijgen is het wenselijk dat de uitgezonden energie zo scherp mogelijk gebundeld wordt. Hiervoor zijn grote antenne-systemen nodig. Voor de Sardinië-Minorca-verbinding worden antennereflectoren toegepast van 20 meter diameter op ieder eindstation; deze concentreren de energie in een bundel met een breedte van 1—1½ graad.

Een ongewenste eigenschap van dit soort verbindingen is dat het gemiddelde signaalniveau wel redelijk goed is, maar er komen voortdurend variaties in het signaalniveau voor op een volkomen willekeurige manier. Men heeft echter vastgesteld, dat als het signaal op twee afzonderlijke antennes tegelijkertijd wordt ontvangen, de variaties in het ontvangen signaal op deze twee antennes niet tegelijkertijd optreden. Het is dus mogelijk twee antennes en twee ontvangers toe te passen op een dusdanige manier, dat aan de gecombineerde uitgang van deze ontvangers te allen tijde een bruikbaar signaal aanwezig is. Bovendien is vastgesteld, dat twee signalen, welke op verschillende frequenties worden uitgestraald, evenmin tegelijkertijd variëren en dus eveneens kunnen worden gecombineerd om een bevredigende werking te verkrijgen. Deze laatste methode wordt toegepast bij het Sardinië-Minorca-systeem.

Een enkele parabolische antenne van 20 meter diameter wordt gebruikt op ieder eindstation van de verbinding. Iedere antenne heeft twee stralers. Hiervan is de ene vertikaal gepolariseerd en de andere horizontaal gepolariseerd. Dit verschil in polarisatie wordt gebruikt om een goede scheiding tussen de zenders en ontvangers te bewerkstelligen. Een van de stralers wordt gevoed door twee verschillende zenders die op een verschillende frequentie werken, terwijl de straler met de andere polarisatierichting verbonden is met de beide ontvangers.

De over-de-horizon-propagatie kan zeer sterk verschillen in verschillende gedeelten van de wereld. Dit vindt zijn oorzaak in de uiteenlopende atmosferische gesteldheden.

Ten gevolge van deze propagatieverschillen en omdat de apparatuur vrij kostbaar is, is het wenselijk om proefnemingen ter plaatse te doen naar aanleiding waarvan de specificatie voor de definitief te installeren apparatuur kan worden opgesteld. Met de proefnemingen voor de Sardinië-Minorca-link werd tegen eind 1954 een aanvang gemaakt en deze proefnemingen werden voortgezet tot het eind van 1956. Bij deze proefnemingen werd samengewerkt door FACE (Fabrica Apparecchiature per Comunicazioni Elettriche Standard) en SIRTI (Società

Italiana Reti Telefoniche Interurbane) uit Milaan, SESA (Standard Electrica, S.A.) uit Madrid, en STL (Standard Telecommunication Laboratories) uit Londen.

De gedetailleerde uitwerking van het systeem en de vervaardiging van de radio-apparatuur werden verzorgd door de Federal Telecommunication Laboratories, de ontwikkelingslaboratoria van het International Telephone and Telegraph System in de Verenigde Staten van Amerika. De multiplex apparatuur voor 5 spraakkanalen en 3 telegrafiekanalen werd geconstrueerd door FACE. De antennes, de generatoren en het vele andere materiaal dat voor een dergelijke installatie nodig is werden geleverd door FACE in Italië en SESA in Spanje.

Uit het Nederlands Radiogenootschap

EXAMENS

Verslag van het examen voor radiotechnicus, radiomonteur en televisie-technicus, gehouden in april, mei, juni en juli 1957.

De schriftelijke examens voor radiotechnicus en radiomonteur werden gehouden op 8 en 15 april 1957. Wegens het geringe aantal candidaten werd voor televisie-technicus geen schriftelijk examen afgenomen.

De mondelinge examens vonden plaats op 27, 28 mei, 3, 4, 14, 17, 20, 21, 28 juni, 4 en 5 juli 1957.

Het resultaat van het examen vindt u hieronder vermeld.

SCHRIFTELIJK

	deelgenomen	vrijstelling	afgewezen
radiotechnicus	186	—	90
radiomonteur	216	3	70

MONDELING

	deelgenomen	afgewezen	her-examen	geslaagd
radiotechnicus	96	40	11	45
radiomonteur	149	47	12	90
televisie-technicus	5	1	—	4

HER-EXAMEN

	deelgenomen	afgewezen	geslaagd
radiotechnicus	4	1	3
radiomonteur	11	—	11

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Het adres van Ir. E. J. Nijenhuis is Acaciastraat 111, Den Haag.