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"To promote the advancement of radio, electronics and kindred subjects by the exchange of information in these branches of engineering."

(from the objects of the Institution)

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RECENT ADVANCES IN RADIO ASTRONOMY*

The Government, through the Department of Scientific and Industrial Research, and the Nuffield Foundation have decided jointly to provide a steerable radio telescope for Manchester University. The total cost is expected to approach £336,000, half of which will be paid by the Nuffield Foundation and half borne on the vote of the D.S.I.R.

The first large telescopes were built in Great Britain by Herschel and Rosse during the 18th and 19th centuries, but this early advantage in astronomy has not been maintained, since giant telescopes require clear skies and extremely good atmospheric conditions if their full advantages in exploring the depths of space are to be realized. For this and other reasons the great telescopes of the 20th century have been built in America on Mount Wilson and Mount Palomar. In 1920, the 100-in. telescope on Mount Wilson showed that the Milky Way was a system of stars far more extensive than hitherto imagined, and that it would take nearly 100,000 years travelling with the speed of light to traverse it. From that time the sequence of discoveries has continued until recently when the 200-in. telescope on Mount Palomar revealed star systems which are hundreds of millions of light years distant.

A surprising feature associated with this revelation is the evolutionary coincidence by which man's eyesight is able to penetrate the atmosphere of the earth. The human eye is sensitive to that part of the spectrum which constitutes visible light, and it is only this small region which can penetrate the earth's atmosphere without absorption. Any radiation from space which has a wavelength beyond the red end of the spectrum or less than the violet end of the spectrum is completely absorbed. It is only in the intervening small gap or "window" that the absorption is small enough to allow appreciable radiation to reach the earth's surface. Thus, if man had evolved with eyes sensitive in the infra red or ultra violet part of the spectrum we should have no knowledge whatsoever of the outer universe—our vision would be blanketed as thoroughly as on a cloudy night, no matter how big a telescope we used. This restriction of vision has never worried astronomers. For over half a century it has been well known that most of the energy output of a hot body, such as the sun or the stars, lies in this visible gap and hence it has been believed that our view of the universe has been as complete as the best telescopes allowed.

The origins of radio astronomy date back to 1931, when Jansky discovered that radio waves were reaching the earth from outer space. The existence of a gap or window in the atmosphere in the radio wave region had been known for some time. At the long-wave end—at about 20 or 30 metres wavelength—it is cut off by absorption in the ionosphere: at the short-wave end—at a wavelength somewhat below 1 cm—by molecular absorption in the atmosphere. It was no doubt appreciated that any emissions coming from space could be picked up on the earth if their wavelength fell in this band, but no one considered that this region of the spectrum would have any interest to astronomy. Little notice was taken of Jansky's discovery, and by

* Notes submitted by the Department of Scientific and Industrial Research.

the end of the second world war it was generally accepted that these radio emissions were being generated by atomic processes in the rarefied hydrogen gas in interstellar space.

At the close of the war, however, radio and radar techniques were applied to this problem by groups of workers in England and Australia. In the first experiments the receiving aerials were of conventional types, receiving radiation in a beam of say 10 or 20 deg wide, and the early results of Jansky were confirmed. But the resolution of these radio telescopes was very poor indeed compared with the resolution of even a small optical telescope and it seemed unlikely that they could give much further information about the origin of these radio waves. By 1948 developments led to the construction of a new type of radio telescope which, to a certain extent, overcame the severest difficulties of resolution. In principle these systems used two separate aerials spaced by several hundred metres, the signals from the two aerials being connected to the common input of a radio receiver. Whereas the reception pattern of a single aerial consists of a main broad lobe which narrows as the size of the aerial is increased, the reception pattern of these spaced-aerial "interferometers" consists of a close-packed system of lobes. As the Earth rotates and this lobe system sweeps over the sky, the intensity of the signal in the receiver output will remain steady, or vary only slowly, provided the source of the radiation subtends an angle large compared with the separation of the lobes. If, however, the radio signals are coming from a source which subtends an angle small compared with the lobe separation, then the signal at the receiver output will go through a series of maxima and minima.

In 1948, groups of workers in Sydney and Cambridge used radio interferometers to study the radio emissions from the Galaxy, with the most startling results. An intense source of radio emission with an angular diameter of less than 8 min of arc was discovered in the constellation of Cygnus, and an even more intense source in Cassiopeia. The most remarkable feature of this work was not so much the discovery of localized sources of intense radio emission, but the complete inability to identify them with any particular visual objects in the sky. Although lacking the precision of optical telescopes, the radio interferometers can position these intense sources with considerable accuracy. In the region of space which contains the Cygnus and Cassiopeia sources there are, of course, many visible stars, but none of outstanding visual characteristics. In fact, the most recent conclusion is that no star brighter than 16th or 17th magnitude is near either the Cygnus or Cassiopeia radio source. Since the original work in 1948 many more of these localized sources of radio emissions, or radio stars, have been located, but no one has yet been able to identify any object or class of visual objects in the Galaxy with the source of these radio emissions.

The question arises immediately as to the number of these radio stars contained in the Galaxy. So far, the number discovered has increased with improvements in the sensitivity of the radio equipment. It seems likely that the hundred or so now known are merely the nearest and most intense of a very large number in the Galaxy. With the unaided eye, or with a small telescope, the Milky Way appears as a diffuse patch of light, and it is only with the larger instruments that this diffuse appearance can be seen to be due to the existence of myriads of stars. A similar situation is believed to exist with the radio stars, and the radiation which is received from the direction of the Milky Way appears diffuse because present radio telescopes are not good enough to resolve it into radio stars. From the strength of this unresolved emission and from the strength of the signals received from the known radio stars it is possible to make an intelligent guess at the total number of radio stars in the Galaxy. The answer is very surprising—the population of radio stars in the Galaxy must be very similar to the population of the visible stars. The paradox is astonishing. The Galaxy contains some hundred thousand million stars which emit light and can be seen with the human eye and telescope. Does it also contain a similarly vast number of dark objects which generate intense radio waves and can only be seen by the radio telescope? The problem of the nature of these radio stars is certainly one of the most puzzling in present day astrophysics.

Meanwhile, Dr. A. C. B. Lovell (Professor of Radio Astronomy at Manchester University) was making a different attack on the problem of resolution at Jodrell Bank (the University's Experimental Station in Cheshire). A giant radio telescope, 220 ft. in diameter and receiving only in a single very narrow beam was constructed and with its aid radio waves were detected from the great nebula in Andromeda, 750,000 light years distant. The implications of this experiment are far-reaching: the only reasonable conclusion is that the radio stars must populate the Andromeda nebula as well as the Milky Way system, and a comparison of the total radio emissions of the two stellar systems indicates that their radio star population must be very similar. These are merely two nebulæ in an assemblage of millions of similar ones scattered throughout the universe. It therefore seems highly probable that the objects which generate these radio emissions exist in all the external nebulæ and the most recent experiments strongly support this view. The detection of the radio emission from the Andromeda nebula with the large radio telescope has recently been followed by the measurement of similar emissions from five other individual nebulæ, both with the radio telescope at Jodrell Bank and with the radio interferometer at Cambridge. Perhaps even more significant is the detection of radio emissions from three great clusters of nebulæ which are far too closely grouped to be resolved individually by the beam of the radio telescope.

During the last few years equally startling results have been obtained in other branches of radio astronomy. The atmosphere of the sun has been found to emit radio waves and the study of these emissions is throwing new light on the conditions in the solar atmosphere. Also when the solar surface is disturbed by sun spots very intense radio emission is received on the Earth, for the solar flares which occasionally occur in the region of sun spot groups are accompanied by immense bursts of radio energy. The solar corpuscular streams of charged atomic particles which are then ejected take about 24 hours to reach the earth and then cause severe terrestrial disturbances, such as fade outs of long-distance radio communication and displays of the aurora borealis. Radio astronomy also provides a new method of studying the aurora. Pulses of radio energy are transmitted through the radio telescopes and their reflection from the auroræ enable them to be studied under all conditions of daylight and cloud. These new solar and aurora studies seem destined to be a powerful factor in the study of the sun and of solar terrestrial relationships.

An important application of radar technique to astronomy has been in the study of meteors. It has been possible to study the activity of the daytime sky and the existence of great streams of meteors incident on the sunlit hemisphere of the earth have been revealed. These move in short period orbits and whether they are associated with comets, disintegrated minor planets or have some other origin, is not yet known. The controversy as to whether half the meteors come from interstellar space has, however, been settled, and it can now be concluded that all meteors are confined to the solar system. Radio techniques have also given new methods for the measurement of the very high velocities with which these meteors enter the atmosphere. The radio pulse technique has also been used to obtain echoes from the moon, thus providing a new avenue for the investigation of the ionosphere and of the lunar surface.

The aperture of the new radio telescope is a little larger (250 ft.) than the fixed one at Jodrell Bank; it is completely steerable and will be able to transmit or receive signals from any part of the sky. It will be used in all aspects of radio astronomy, although the main task will be to continue the study of the galactic and extragalactic radio emissions with particular reference to the number and nature of the dark radio stars. It will also be used to plot the intensity of the radiation, particularly from those important regions of the Milky Way system which are obscured from normal vision by the great dust clouds in interstellar space. The secondary tasks will include solar and terrestrial studies, meteors, the moon and perhaps the nearer planets. It is confidently expected that this great instrument will do for radio astronomy what the large telescopes in America have done for classical astronomy.

INSTITUTION NOTICES

The Patron of the Institution

Her Majesty The Queen has been graciously pleased to grant her Patronage to the Institution.

Members will recall that His late Majesty King George VI became Patron of the Institution in 1946.

Honours

The Council offers its congratulations to the following member who was honoured in the first Birthday Honours List of Her Majesty's reign—

Appointed a Member of the Most Excellent Order of the British Empire:

Frederick George Diver (Member)

(A brief biography of Mr. Diver was published on page 270 of the May *Journal*).

The President-Elect

At a meeting of the General Council held on May 21st, 1952, it was unanimously recommended that Mr. W. E. Miller, M.A.(Cantab.) should be elected President for the year 1952-3.

Mr. Miller, who has been a Member of the Institution for 20 years, was elected a Vice-President in 1949. He was previously Chairman of Council.

Obituary

It is with very great regret that Council has learned of the death of Dr. William Wilson (Member). Dr. Wilson, who was 69 years of age, had been in poor health for some time.

Born in Kineton, Warwickshire, Dr. Wilson emigrated at an early age to New Zealand. He gained Scholarships to Canterbury University College, obtaining his B.Eng. in 1906 and the M.Sc. degree of Auckland University College in 1910. The degree of Doctor of Science was conferred on him by the University of New Zealand in 1935.

During the Great War he came to England, and in 1917 he joined the firm with which he was to remain for the rest of his life, the General Electric Co., Ltd., Witton, eventually becoming Manager of the Development Laboratory.

Dr. Wilson will be well known to members for his extensive work in the industrial application of electronics. In this field he held many patents and was the author of several books, in addition to contributing the section on "Industrial Electrification" in the Encyclopaedia Britannica. He presented important papers before several Sections of the Institution on "The Application of the Cathode Ray Oscillograph to Engineering," and on "Electronics in Heavy Industry" which were both published in the *Journal*.

Dr. Wilson was elected a Member of the Institution in April, 1944, and for some time served on the Committee of the Midlands Section of the Institution. His help and advice were at all times freely available to members.

Annual General Meeting

The Council announces that the 27th Annual General Meeting of the Institution will be held on Wednesday, October 8th, 1952, at the London School of Hygiene and Tropical Medicine. The Agenda of the meeting will be published in the August issue of the *Journal* together with the Council's nominations for election.

Any member who wishes to nominate a member or members for election to the Council must deliver such nominations in writing to the Secretary, together with the written consent of such person or persons to accept office if elected, not later than 21 days after the circulation of the Council's list of nominations.

The Burnham Committee—
Acceptance of the Graduateship Examinations

In the July, 1951 issue of the *Journal* (page 246), it was announced that Associate Membership of the Institution, with certain provisions, was approved by the Burnham Committee as a degree equivalent for teachers in Further Education establishments.

The Burnham Committee has now announced that it has also approved Associate Membership as being equivalent to a degree for teachers in Primary and Secondary Schools.

The actual wording states that the Graduate Allowance is payable to Associate Members of the Institution who have qualified by passing the Graduateship Examination not earlier than May, 1951. An Associate Member will be deemed to have satisfied this requirement if he has passed parts IIIa, IIIb and IV of the examination not earlier than May, 1951, having satisfied the requirements for parts I and II under the regulations of the Institution in force before that date.

The recognition is, of course, subject to the additional condition that the holder of the qualifications is otherwise eligible for the status of qualified teacher.

THE APPLICATION OF NEGATIVE FEEDBACK TO FLYING SPOT SCANNERS*

by

R. Theile, Dr.Phil.† and H. McGhee†

A Paper presented at the Fifth Session of the 1951 *Radio Convention on August 23rd in the Cavendish Laboratory, Cambridge*

SUMMARY

The paper analyses the performance of a television transmitting system using the flying spot principle, in which the signal is applied as feedback to the control electrode of the scanning cathode ray tube. A system using such an overall feedback in negative polarity possesses several advantages over the normal method of operation of these devices.

The main advantage is a convenient control of the "tone rendition" (gamma) of the transmitted picture when working in conjunction with normal gamma increasing receiving equipment. Gamma control may also be necessary in film scanning to compress the wide range of film transparency into the limited tone scale available in television pictures. Problems introduced by the time delay existing in the feedback loop are discussed. The influence of feedback on the appearance of screen afterglow is analysed and finally the effect on the signal-to-noise ratio is considered.

1. Introduction

The idea to replace mechanical scanning methods—such as the Nipkow disc—by a cathode ray tube in the television transmitter was the first step towards an all-electronic system.[1,2] Electronic flying spot scanners have since proved to be practical and useful devices, and present-day technique, when applied to film transmission,[3,4] produces high-quality pictures, as evidenced by the B.B.C. television service.

The basic principle of a cathode ray tube flying spot scanner is illustrated in the three sketches comprising Fig. 1. The essential components are the flat-faced scanning tube with the conventional means of focusing and deflecting the scanning beam, and the photocell, usually combined with a secondary emission multiplier in order to obtain optimum signal-to-noise ratio. The transparency or picture to be televised is placed between the tube and the photo-multiplier. The first two examples in Fig. 1 refer to the transmission of slides (transparent pictures), the simplest scheme being indicated in (*a*) where the slide is placed in contact with the front plate of the scanning tube and a photocell with a small aperture is positioned some distance away. While the luminous spot traces out the raster on the screen, the

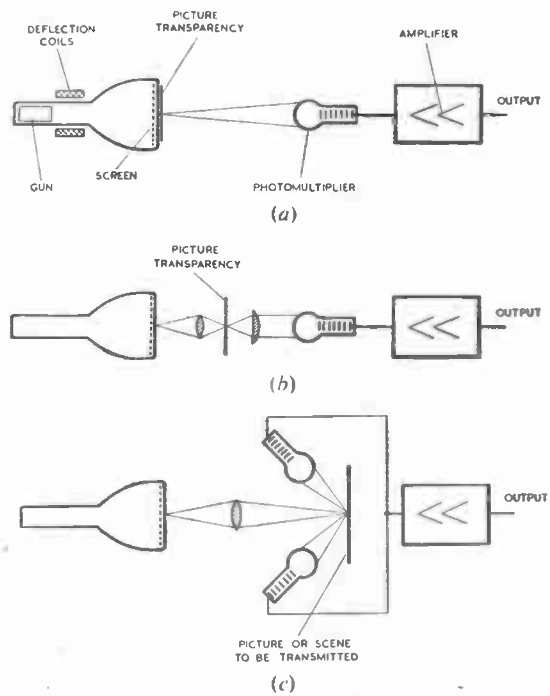


Fig. 1.—Three examples of flying spot scanning with cathode ray tubes using different optical arrangements.

* Manuscript received August 17th, 1951.
† Pye, Limited.
U.D.C. No. 621.397.611.2.

light received by the photocell is modulated by the local transparency of the slide and in this manner the picture content is transferred into a sequence of electrical impulses. Whilst this arrangement can be very useful as a simple and inexpensive signal generator, an optical imaging process, as shown in Fig. 1*b*, is required to produce pictures of high quality. Here the plane of the screen is imaged on to the slide, the transmitted light being collected and passed to the photo-electric surface. Finally Fig. 1*c* shows the method of televising opaque pictures or scenes. The raster is again imaged on to the object and an arrangement of photo-multipliers picks up the diffusely reflected light which changes from point to point according to the picture content.

It is obvious that the flying spot scanner is unsuitable for studio and field television, but for film transmission and special purposes—slides, captions, etc.—pictures of excellent quality can be obtained. The pictures are especially free from spurious signals and the black level is constant.

On the other hand there are some disadvantages to be considered: for example, the fact that the signal generated is always proportional to the transmission factor of the film makes gamma reduction necessary, since the cathode ray tube at the receiver has a non-linear control characteristic which considerably increases the contrast in the highlights. Gamma-reduction is also necessary to compress the wide contrast range existing in films into the limited tone scale available in television. Successful gamma control devices have been developed in the past[5–8] and are in current use, employing stages of non-linear amplification. In these arrangements the amplitude and the black level of the signal must be held within close limits to ensure correct operation. The schemes in use function quite satisfactorily but involve some complexity in the video amplifier chain.

Another problem, as was early realized,[2] is introduced by the phenomenon of screen afterglow (see Fig. 15*a*) which causes defects in the picture similar to those produced by a poor high-frequency response in the video amplifier, i.e. signal integration. It can be corrected by corresponding differentiating circuits. As the screen decay characteristic is not a simple exponential form, compensation is effected by an approximation using several time constants in the correcting amplifier, which have to be carefully adjusted.

This paper deals with the application of negative feedback to flying spot scanners where the scanning tube itself is included in the feedback loop. Preliminary experiments have shown that, in addition to the expected benefits and difficulties inherent in any feedback system, some advantageous effects result in respect of gamma and screen afterglow correction. As no description of such a scheme seems to have appeared in print, it was considered worth while to make a more detailed analysis, the result of which is presented for discussion in the following sections.

2. Effects of the feedback application if no screen afterglow is present. Feedback as a gamma control

Figure 2 illustrates the system of overall feedback discussed. For simplicity the arrangement of Fig. 1*a* is chosen.

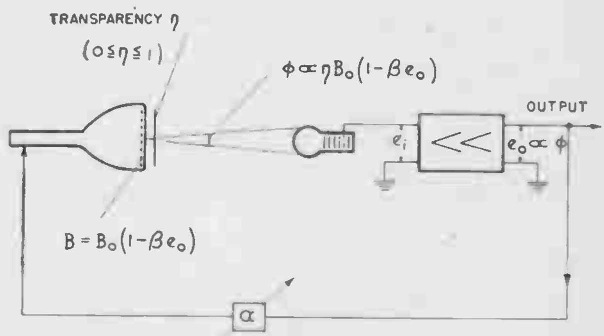


Fig. 2.—The principle of overall negative feedback applied to a flying spot scanner.

The video amplifier produces an output voltage e_0 which is proportional to the light falling on the photocell, e_0 changing from zero (corresponding to "black") in a unidirectional sense. The feedback is introduced by modulating the beam current of the scanning tube in such a manner that the screen brightness decreases with increasing output voltage e_0. Assuming in the first instance that the control characteristic of the scanning tube is linear, the brightness B of the luminous scanning spot changes continuously from the quiescent value

B_o (no modulation, $e_o = 0$) down to the value B, where

$$B = B_o (1 - \beta e_o)$$

In this equation β is the feedback coefficient determined by the slope of the tube control characteristic and an external feedback control (α in Fig. 2) which is a suitable amplifier or attenuator. In order that the polarity of this feedback be negative, the voltage e_o must have the proper phase. In the practical example of modulating the control grid of the scanning tube, the feedback voltage must be negative, i.e. white signals swinging the control grid more negative towards cut-off.

It is obvious that the amplifier output voltage e_o and the instantaneous screen brightness are controlled by the transparency η of the slide or film in opposite senses in such a way that if the transparency along the scanning path is great, the scanning spot brightness is low and vice versa, i.e. a negative picture appears on the screen of the scanning tube. Thus the feedback tends to equalize the light flux passing through the entire slide.

It can be shown that the transfer characteristic, i.e. the relation between the output voltage e_o and the transparency η is modified by the feedback; this will now be analysed for the ideal case in which the signal e_o is only decided by the instantaneous brightness of the scanning spot; in other words, effects of screen afterglow are neglected.

The light from the luminous spot after penetrating the slide is given by*

$$\phi = c_1 \eta B_o (1 - \beta e_o)$$

where c_1 is a constant

The output voltage e_o is proportional to this light

$$e_o = c_2 \phi$$

where c_2 is a constant, the value of which is dependent on photo-sensitivity, multiplier and amplifier gain, coupling network between phototube and amplifier, etc.

Therefore

$$e_o = c_1 c_2 \eta B_o (1 - \beta e_o)$$

Solving for e_o we get

$$e_o = \frac{c_3 \eta}{1 + c_3 \beta \eta} \quad \ldots \quad \ldots \quad \ldots \quad (1)$$

where $c_3 = c_1 c_2 B_o$

* η in this analysis is assumed to be the linear light transmission factor, i.e. black corresponds to $\eta = 0$ and peak white to $\eta = 1$.

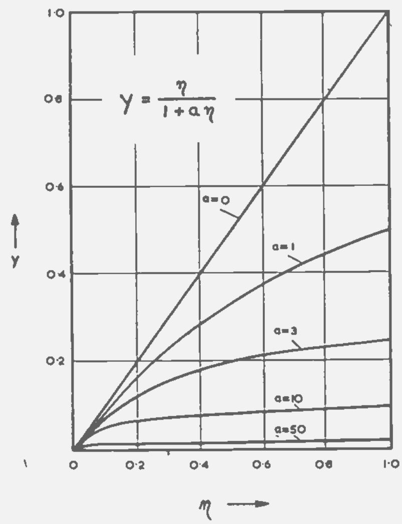


Fig. 3.—A family of curves illustrating the output signal in a flying spot scanner as a function of the slide transparency η with different degrees of overall feedback.

This is the transfer characteristic of a flying spot scanner with feedback. It is clear that the relation between the signal e_o and transparency η is no longer linear, the nature of the non-linearity being most suitable for gamma correction, with the advantage of easy adjustment by variation of β. The shape of the transfer characteristic (1) is given by the relation $y = \frac{\eta}{1 + a\eta}$ which is plotted in Fig. 3 for five values of $a = c_3 \beta$. With $a = 0$ which corresponds to normal non-feedback operation, the transfer characteristic is straight, i.e. the output amplitude is proportional to the light transmission factor η of the slide. In this mode of operation the signal is an exact translation of the tone scale but, because of the non-linear control characteristic of the receiving tube, the half-tone reproduction in the viewed picture is unfaithful. If now feedback is applied, e_o is progressively reduced as higher values of transparency are considered. The excursion e_o is less and the relation between e_o and η is non-linear. The loss of output voltage can easily be made good by supplying additional gain after the feedback loop; this may be considered as the price to be paid for the introduction of negative feedback, but any other gamma-control system entails loss of gain in the picture regions compressed.

It is interesting to examine the transfer characteristic when the loss at $\eta = 1$ is just equalized, i.e. if an additional gain of $(1 + a)$ times is provided. Such a family of curves is shown in Fig. 4. Here it is evident that the slope of the function e_o decreases as η increases. The application of feedback is therefore most suitable for compensating the receiver characteristic, and for reducing the high-light contrast of the televised picture to the required extent, as the curves for greater values of a indicate.

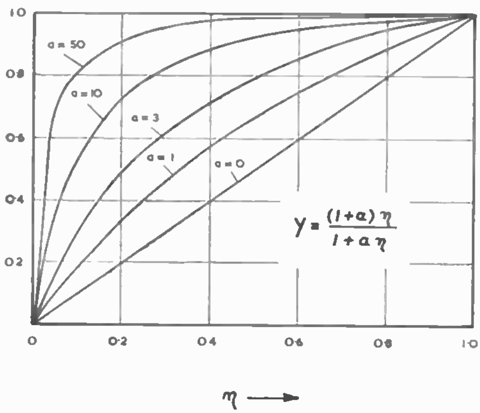


Fig. 4.—The characteristics of Fig. 3 set to have the same range of contrast.

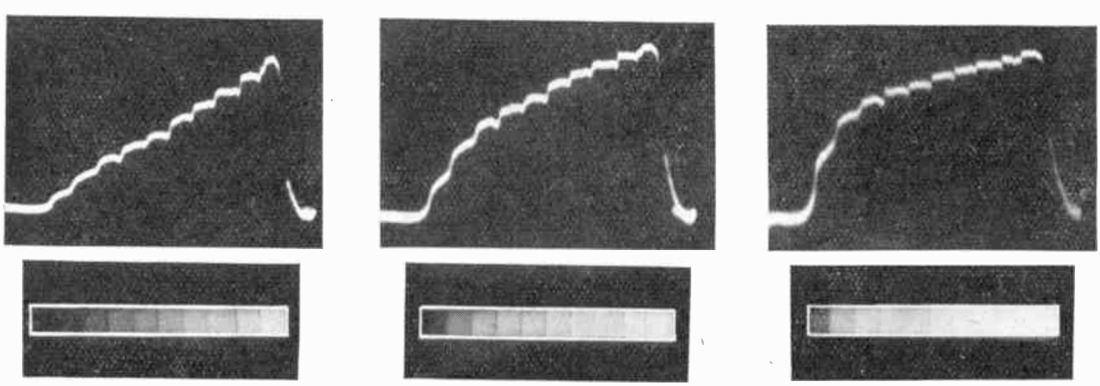
An elegant adjustment of picture tone rendition results if the setting of the feedback coefficient β (by varying α in Fig. 2) is mechanically coupled with the gain control of the additional amplifier. A continuous change of transfer characteristic is thus obtainable, the black level and the range between black and peak white remaining constant—the characteristic bending between these limits. It is felt that this is a major advantage of the system.

Practical results obtained with an experimental flying spot scanner are shown in Fig. 5, which correspond to the theoretical curves of Fig. 4. The various values of η were generated by scanning a test pattern consisting of ten vertical strips of different transparency, the value of η increasing from left to right linearly, i.e. in the direction of scanning.

Figure 5 shows, in the upper group, oscillograms of the line waveform and, immediately below, a few lines of the corresponding half-tone picture, as viewed on the receiving tube.

Figure 5*a* corresponds to normal operation, no feedback, $a = 0$. Here the oscillogram is a staircase waveform of equal steps. Application of feedback expands the region of low transparency with compression of the higher steps, as shown in Fig. 5*b* for a medium—and in Fig. 5*c* for a high degree of feedback. The visual effect of increasing feedback is that details in the black areas are magnified with corresponding loss of detail in the high-light region.

Comparison of Figs. 4 and 5 reveal a slight difference in the degree of compression at high values of feedback and transparency. This is because we assumed the scanning tube control characteristic to be linear which is, of course, only true over a certain range (small to medium values of e_o, dark parts of the picture). As soon as the voltage swing extends into the region of appreciably reduced slope, the effective feedback is less, with the result that the transfer characteristic plotted in Fig. 4 becomes less



(*a*) (*b*) (*c*)

Fig. 5.—Tone rendition without, and with, the application of feedback.

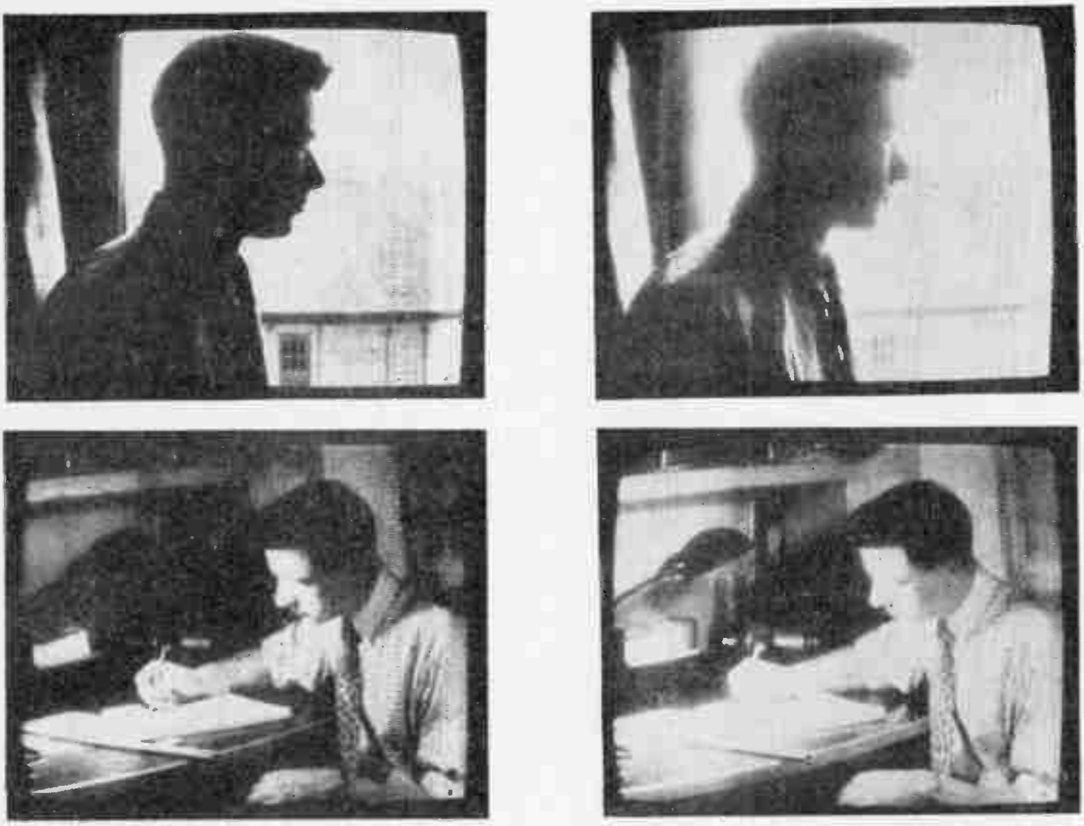


Fig. 6 —Half-tone pictures with, and without, feedback applied.

asymptotic at high values of η and a. This is not an undesirable feature as quite often a large expansion of darker tones is necessary with a compression, but not elimination, of the high-light details.

On the other hand, by the inclusion of a non-linearity in the feedback control α, complementary to the curvature of the tube characteristic, the theoretical curves can be approached. With other suitable non-linearities in the feedback loop, further modifications of the overall transfer characteristic are possible. It would lead too far to discuss all these alternatives, which could also include partial positive feedback in some regions of the tone scale, as the question of an optimum transfer characteristic is a very complex one.[9] It is definite, however, that the insertion of negative feedback achieves the gamma correction necessary for the receiving cathode ray tube to produce a pleasing half-tone scale. The reduction in gamma is illustrated in the four pictures comprising Fig. 6 where two slides are reproduced by an experimental flying spot scanner with and without the application of feedback. The reproduction of these pictures involves several photographic processes, which introduce further unavoidable contrast changes but, nevertheless, they show clearly the enhanced contrast in the darker shades, together with reduced contrast in the high-light areas. A high value of feedback is used to emphasize these effects, and hence light greys and whites are almost indistinguishable.

The application of feedback requires the usual considerations to obtain complete stability. In this connection the problem of overall time delay is of some interest. The feedback must take effect with a delay not greater than the time resolution of the system, otherwise distortion, instability, etc., will occur. A flying spot scanner incorporating the feedback principle must be designed with a minimum time delay

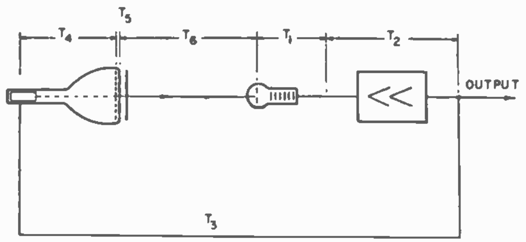


Fig. 7.—Statement of delay times existing in a flying spot scanner with overall feedback.

in all sections as outlined in Fig. 7. The time elapsing from a light spot falling on to the photo-surface and the consequent light flash due to feedback action is expressed by the sum of the individual delay times T_1-T_6. T_1 is the response time in the photo-tube determined by the delay of photo-electron emission, electron transit time to the first dynode, the total delay due to the secondary emission process in each multiplier stage, and the sum of the secondary electron transit times from stage to stage, the transit times being the deciding contribution. It can be assumed[10] that T_1 is of the order of 10^{-8} sec. The delay T_2 in the video amplifier is a major contribution to the overall delay. As electron transit time in the valves is of negligible influence, T_2 is almost entirely due to the time constants introduced by the unavoidable stray capacitances. It will be shown that by a suitable design of multi-stage amplifier a minimum delay is possible. T_3 is the time required for the electrical information to pass from the amplifier output to the modulating electrode of the scanning tube. T_4 is the transit time of the electrons forming the scanning beam. T_5 is the excitation time of the screen material and, finally, T_6 is the time taken for the emitted light to reach the photo-surface.

It is the aim to keep the overall delay time to a minimum. The absolute minimum is set by T_3 and T_6: thus the arrangement must be compact. With a good design T_3 and T_6 can be smaller than 10^{-8} sec. The transit time T_4 is of the order of some 10^{-9} sec in conventional scanning tubes operated normally. T_5 can be assumed[11] to have a value not greater than 10^{-8} sec.

As the amplifier delay time T_2 can be appreciable, it is advisable to concentrate the predominant portion of the required gain into the multiplier photo-tube, but, because of limitations in the output power of conventional electron-multipliers, an external amplifier with a gain of some hundred times is usually necessary. While considering the design of multi-stage video amplifiers, it was found that if a certain gain G_n is to be attained using n identical stages, an optimum number of stages (i.e. an optimum amplification per stage) exists, as is now shown.

A conventional type of video amplifier will be considered composed of n valves connected by suitable interstage coupling networks. Only one of these is shown in Fig. 8, where a shunt peak method of compensation is chosen. The time delay τ introduced by one stage is proportional to the time constant formed by the anode load resistor R with the stray and electrode capacitances C. The total amplifier delay time is thus given by

$$\tau_n = nKRC \qquad \text{.......................(2)}$$

where K is a constant in the frequency range in which there is no appreciable amplitude and phase distortion. The value of K depends on the type and degree of the frequency compensation used at the upper region of the passband. For example $K = 1$ for an uncompensated stage and about 0·5 for the shunt peak circuit.[12] In (2) the value of R is decided by the overall gain required and the available number of stages, as the overall gain is given by

$$G_n = (g_m \,.\, R)^n$$

where g_m is the working slope of the amplifier valve.

The relation (2) can be re-written

$$\tau_n = \lambda \,.\, n \sqrt[n]{G_n} \qquad \text{...................(3)}$$

$$\lambda = KC/g_m$$

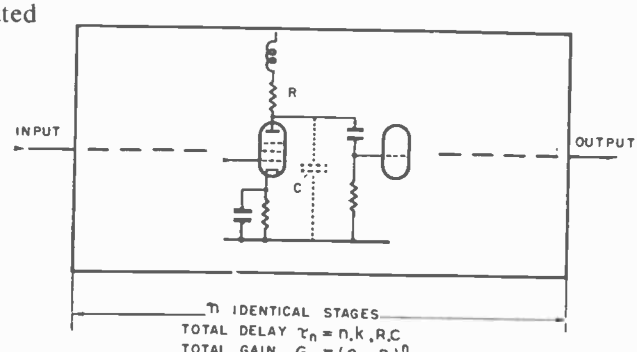


Fig. 8.—Conventional video amplifier comprising n *identical stages.*

Inspecting equation (3) it can be shown that there is a minimum value for τ_n as n is varied. In order to find this minimum the function τ_n is differentiated with respect to n. We get

$$\frac{d\tau_n}{dn} = \lambda \sqrt[n]{G_n}\left(1 - \frac{\log G_n}{n}\right)$$

The minimum condition leads to the interesting result

$$n = \log G_n \quad \text{or} \quad G_n = \epsilon^n \quad \ldots\ldots\ldots\ldots(4)$$

Minimum delay is achieved if the overall gain is obtained by using n identical stages of gain $\epsilon = 2{\cdot}718$. A good amplifier design therefore necessitates the use of a large number of low-gain stages rather than few stages of high gain.

The minimum overall delay of a multi-stage amplifier is from (3) and (4)

$$\check{\tau}_n = n\,K\,\epsilon\,C/g_m$$

If, for example, a total gain of about 1000 has to be achieved, seven stages are required and the minimum delay $\check{\tau}_n \simeq 3{\cdot}10^{-8}$ sec with $g_m = 7$ mA/V, $C = 20$ pF and $k = \frac{1}{2}$.

Even if this degree of amplification is necessary, the delay T_2 is still of the order of the other delay contributions.

It can be said now that the total delay time in the feedback loop does not prevent the adoption of the new technique in flying spot scanners for the 405-line system (3 Mc/s band-width) as the total delay can be restricted to less than 10^{-7} sec. However, it is apparent that in higher definition systems the delay problem sets the bandwidth limit up to which the scheme can be applied. Experiments with a scanner operating on British standards were completely satisfying; no difficulties with stability and high-frequency distortions were encountered.

3. The Effects of Screen Afterglow

The existence of afterglow, or persistence, means that at any instant the photocell receives light, not only from the point under the scanning beam, but also the integrated decaying light emitted from the screen areas previously scanned. As a first approximation the light decay of the screen material after excitation can be assumed to be of a single exponential form, hence

$$B = B_0 \epsilon^{-\frac{t}{\tau}}$$

A general expression for the signal output taking such afterglow effects into account will now be derived with the aid of Fig. 9. Ignoring the flyback intervals, the scanning spot can be imagined as tracing out a continuous line at constant velocity as indicated. The effective light falling on the photocell has to be evaluated, and, in the first instance, the transparency of the slide interposed between screen and cell is assumed to be 100 per cent ($\eta = 1$) in all parts of the picture. At the instant t the spot is in the position S and at this instant the light collected is given by the instantaneous component plus the light emitted from the decaying afterglow measured from t backwards—theoretically to minus infinity. The light $d\phi$ falling on the photocell instantaneously from any elementary area scanned during dt' is proportional to the charge thrown on to the screen material within this time[2]

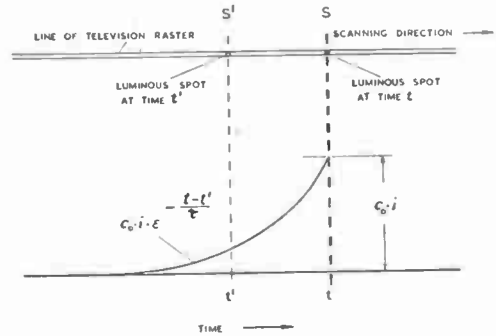


Fig. 9.—Schematic for the analysis of screen afterglow phenomena.

$$d\,\phi = c_o . q = c_o . i\; dt'$$

c_o being a constant, the value of which depends on the screen efficiency, electron velocity, etc., and i being the scanning beam current. The light from any of these elementary areas scanned at the time t' before t has a value at t of $d\phi_t$, which is determined by the exponential decay during the time difference $t - t'$ passed since S′ was excited. As $d\phi$ has to be multiplied by the decay factor $\epsilon^{-\frac{t-t'}{\tau}}$ it results in

$$d\phi_t = d\phi\,\epsilon^{-\frac{t-t'}{\tau}} = c_o i\;\epsilon^{-\frac{t-t'}{\tau}}\,dt'$$

The curve in Fig. 9 shows this factor as a function of t', the ordinates representing the amplitude of the light originating from an excitation at t' as seen at the time t. If $t' = t$ (no decay time) the amplitude is equal to that of the instantaneous value $c_o i$. If, however, the excitation took place long before t the contribution at t is negligible. The amplitude curve, therefore, decreases from t exponentially with increasing time difference $t - t'$.

If now a slide, with varying transparency, is interposed, the light received by the photocell is filtered. $d\phi_t$ therefore has to be multiplied by the transparency existing at S′, i.e. at the time t'.

Hence

$$d\phi_t = c_{oi}\, \eta\,(t')\, \epsilon^{-\frac{t-t'}{\tau}}\, dt'$$

The total light flux falling on the photocell at the time t is then the integral of these elementary contributions over the time from minus infinity to t

$$\phi_t = c_{oi} \int_{-\infty}^{t} \eta\,(t')\, \epsilon^{-\frac{t-t'}{\tau}}\, dt' = c_{oi}\, \epsilon^{-\frac{t}{\tau}} \int_{-\infty}^{t} \eta\,(t')\, \epsilon^{\frac{t'}{\tau}}\, dt'$$

The output signal is proportional to ϕ_t

$$e_o = c_2\, \phi_t$$

Hence

$$e_o = c\epsilon^{-\frac{t}{\tau}} \int_{-\infty}^{t} \eta(t')\, \epsilon^{\frac{t'}{\tau}}\, dt' \qquad \ldots \qquad \ldots \qquad (5)$$

with

$$c = c_o c_2\, i$$

This is the general form of the output voltage of a flying spot scanner using a screen material with a single exponential decay.* By assigning simple functions to η, particular solutions may be obtained, which illustrate the effects of screen afterglow quite clearly. For example, if η jumps between zero and a constant value ($\eta = 1$), as illustrated in Fig. 10, the expression for e_o can easily be evaluated, giving the distortion introduced when a step function is scanned.

In Fig. 10 a scanning line X — X is considered crossing a black field with a white vertical bar. The corresponding transparency is shown in the centre of the diagram. Applying (5) we obtain for the first interval

$$e_o = 0 \qquad t_o \leqq t \leqq t_1$$

For the second interval we obtain

$$e_o = c\, \epsilon^{-\frac{t}{\tau}} \int_{t_1}^{t} \epsilon^{\frac{t'}{\tau}}\, dt'$$

* To be strictly accurate the spot size must also be taken into account, but the simplified analysis is sufficient to indicate the general effect of screen afterglow under the influence of feedback.

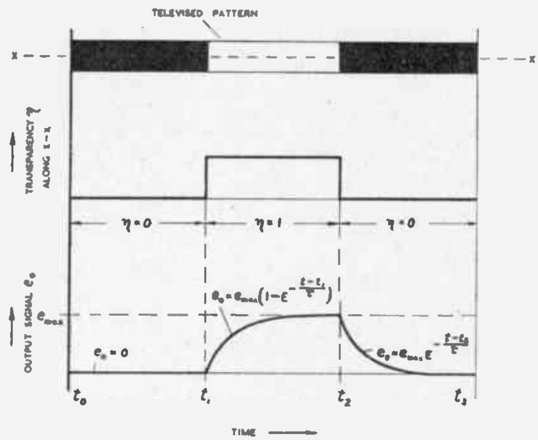


Fig. 10.—Distortion produced by screen afterglow in the reproduction of a vertical white bar on a black field. The waveform exhibits one line.

$$e_o = e_{max}\left(1 - \epsilon^{-\frac{t-t_1}{\tau}}\right) \qquad t_1 \leqq t \leqq t_2$$

$$e_{max} = c\,\tau$$

It is evident that the sharp transition at t_1 is not reproduced faithfully but appears as an exponential build-up with the time constant τ. If it is assumed that τ is small compared with the interval $t_2 - t_1$, e_o will have reached its maximum value e_{max} at t_2, where the transparency η returns to zero.

For the final interval the output voltage becomes:

$$e_o = c\, \epsilon^{-\frac{t}{\tau}} \int_{t_1}^{t_2} \epsilon^{\frac{t'}{\tau}}\, dt'$$

giving

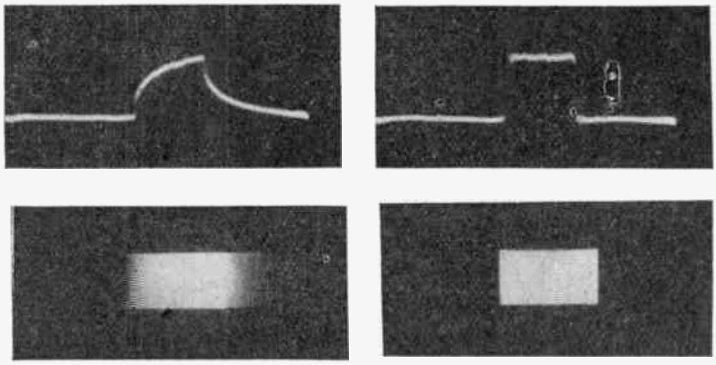
$$e_o = e_{max}\, \epsilon^{-\frac{t-t_2}{\tau}}\left(1 - \epsilon^{-\frac{t_2-t_1}{\tau}}\right)$$

which, under the assumption that $(t_2 - t_1) \gg \tau$ simplifies to

$$e_o = e_{max}\, \epsilon^{-\frac{t-t_2}{\tau}} \qquad t \geqq t_2$$

which shows that the return to black is reproduced by an exponential decay with the time constant τ.

The results obtained in practice are in accordance with the above analysis as shown in the oscillogram and picture, Fig. 11a. The slide transmitted was black except for a rectangular



(a) (b)

Fig. 11.—Television pictures and oscillograms displaying the line waveform generated by scanning a white rectangle on a black field. (a) *uncorrected, illustrating streaking and integration due to screen afterglow,* (b) *corrected by a suitable differentiation in the video amplifier.*

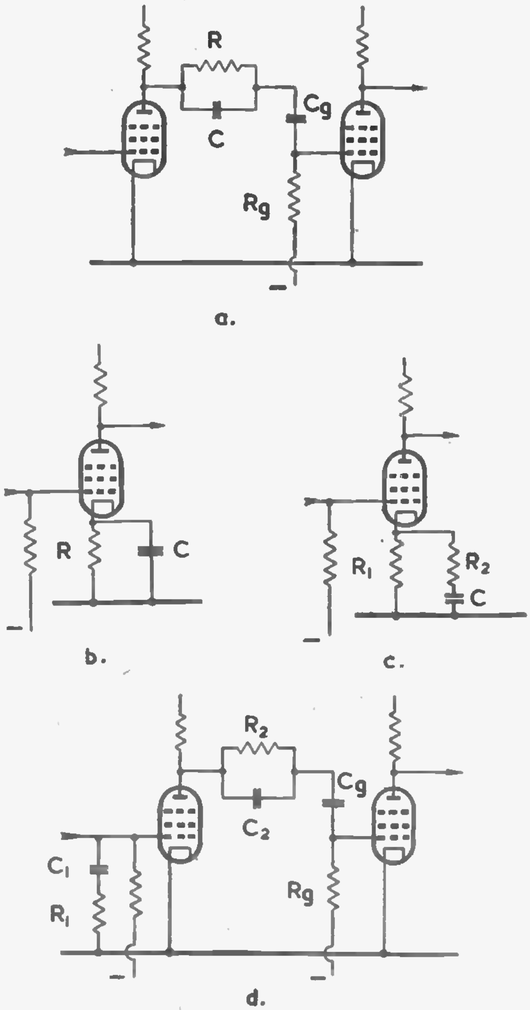


Fig. 12.—Examples of circuits effecting afterglow correction.

aperture of full transparency. The oscillogram exhibits the waveform along one line across this aperture and the picture shows the image, reproduced at the receiving tube, smeared by the afterglow effects.

In general, the screen decay characteristic is not a single exponential but contains several components of different time constant and the waveform is a superposition of the individual decay components.

Figures 10 and 11*a* illustrate the integrating effect of afterglow on the signal waveform, introducing similar distortions to those caused by shunt capacitances across load resistors in an amplifier. It suggests itself—and will be proved quantitatively later—that suitable differentiating circuits can compensate for the screen afterglow phenomena, and this is common practice. Fig. 12 shows a selection of useful correcting circuits. The schemes in Figs. 12*a* and 12*b* compensate a single time constant by a frequency-conscious potential divider R C with R_g (C_g large)[2] or frequency-dependent cathode feedback respectively.[13, 14] Closer approximation to the screen material decay characteristic results if a multiplicity of these circuits is used, if the basic circuits are modified[15] (Fig. 12*c*), or if additional integrators are included[16] (Fig. 12*d*) Group *b* in Fig. 11 gives an idea how the transparency η can be faithfully reproduced by including such compensating circuits in the amplifier. A stage as in Fig. 12*b*, followed by one of the type in Fig. 12*c*, was used to correct the signal in an experimental arrangement using a normal receiver viewing tube for scanning.

The application of negative feedback, in general, alters the influence of any time constant inside the feedback loop. It can be expected, therefore, that a flying spot scanner with feedback would show improvement with respect to the effects of afterglow. The first experiments confirmed that this is so; the streaking of the picture was considerably reduced, although the degree of improvement depended on the picture content. Slides with a general high transparency seemed to be better corrected than slides with large dark areas. The reason for this result is fairly obvious, since the degree of feedback and its effectiveness is controlled by the transmission factor η.

To analyse the effect of feedback on the screen afterglow, the feedback relation

$$i\,(t') = i\,[1 - \beta e_o\,(t')]$$

must be included in the equation (5) for the output signal.

$$e_o = c\,\epsilon^{-\frac{t}{\tau}} \int_{-\infty}^{t} \eta(t')[1-\beta e_o(t')]\,\epsilon^{\frac{t'}{\tau}}\,dt' \quad ..(6)$$

This is a rather complex expression. However, differentiation of (6) leads to a form which characterizes the signal and allows ready evaluation for the simple transition between black and white considered in Fig. 10. Differentiation of (6) with respect to t results in

$$e_o + \frac{\tau}{1+c\,\tau\,\beta\,\eta}\,\frac{de_o}{dt} = \frac{c\tau\eta}{1+c\,\tau\,\beta\,\eta} \quad ....(7)$$

Considering the non-feedback case, where $\beta = 0$, (7) reduces to

$$e_o + \tau\,\frac{de_o}{dt} = c\,\tau\,\eta\,(t)$$

i.e. signal plus τ times the derivative of the signal results in an output proportional to the local transparency. Thus the signal is corrected by the addition of its differential quotient as mentioned above.[17] The degree of differentiation is given by the coefficient of the derivative which is the time constant τ assumed for the screen decay. Equation (7) shows that with feedback applied the degree of differentiation is less as

$$\tau' = \frac{\tau}{1+c\,\tau\,\beta\,\eta} \leqq \tau$$

The flying spot scanner with feedback can be conceived as a non-feedback type but with a reduced screen afterglow time constant τ', the value of which changes with η.

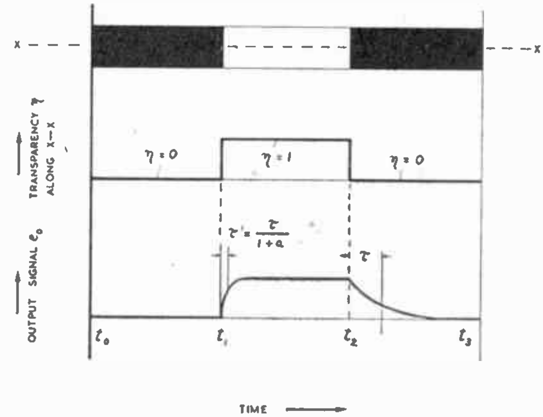


Fig. 13.—Example of Fig. 10, but with the application of feedback showing the decreased rise time in the black-white transition. $\alpha = c\,\tau\,\beta$

A solution of the differential equation (7) can easily be given for the assumption η = constant, which is suitable for the output signal analysis during a transition from one fixed level to another. Solving, we get

$$e_o = A\,\epsilon^{-\frac{1+c\tau\beta\eta}{\tau}t} + \frac{c\,\tau\,\eta}{1+c\,\tau\,\beta\,\eta} \quad ....(8)$$

where A is a constant depending on the initial conditions.

If again $\beta = 0$ (no feedback), e_o becomes

$$e_o = A\,\epsilon^{-\frac{t}{\tau}} + c\tau\eta$$

the output signal contains transients with the time constant τ in the non-feedback case while according to (8), if feedback is present, the transient time is reduced by the factor

$(1 + c\tau\beta\eta)$.

As an example the pattern used in Fig. 10 is reconsidered. In the first interval, $t_1 - t_0$, η is zero and no signal is generated, i.e. the transient at t_1 starts from zero. For the second period using (8) we obtain

$$e_o = \frac{c\tau}{1+c\tau\beta}\left[1 - \epsilon^{-\frac{1+c\tau\beta}{\tau}(t-t_1)}\right] \quad t_1 \leqq t \leqq t_2$$

e_o rises exponentially towards the final value of $\dfrac{c\tau}{1+c\tau\beta}$ with the reduced time constant

$$\tau' = \frac{\tau}{1+c\tau\beta}\;.$$

Assuming this value is reached before t_2, the return to black in the final period commences from that level and we have

$$e_o = \frac{c\tau}{1 + c\tau\beta}\,\epsilon^{-\frac{t - t_2}{\tau}} \qquad t \geqq t_2$$

The decay is also exponential but with the normal time constant τ.

The result, illustrated in Fig. 13, shows the manner in which feedback affects afterglow appearance: streaking in transition from black to white is reduced while that in the transition from white to black is not affected.

As another example a small transition from η_o to $\eta_o + \Delta\eta$ is considered (Fig. 14) where $\Delta\eta \ll \eta_o$

The rise in the signal generated by scanning the interval t_1 to t_2 is given by

$$e_o = \frac{c\tau\eta_o}{1 + c\tau\beta\eta_o} + \Delta\eta\,\frac{c\tau}{1 + c\tau\beta\eta_o}\left(1 - \epsilon^{-\frac{1 + c\tau\eta_o\beta}{\tau}(t - t_1)}\right)$$

and the decay of the signal after t_2 by

$$e_o = \frac{c\tau\eta_o}{1 + c\tau\beta\eta_o} + \Delta\eta\,\frac{c\tau}{1 + c\tau\beta\eta_o}\,\epsilon^{-\frac{1 + c\tau\beta\eta_o}{\tau}(t - t_2)}$$

Both transients are improved and reproduced with the shorter time constant

$$\tau' = \frac{\tau}{1 + c\tau\beta\eta_o}$$

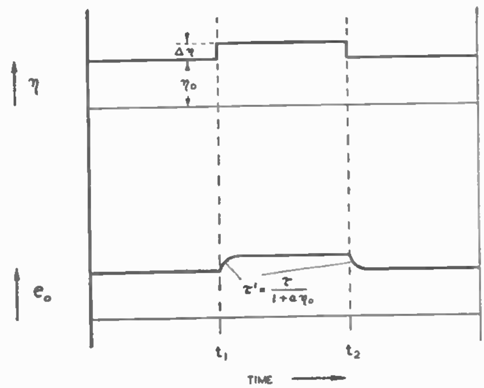
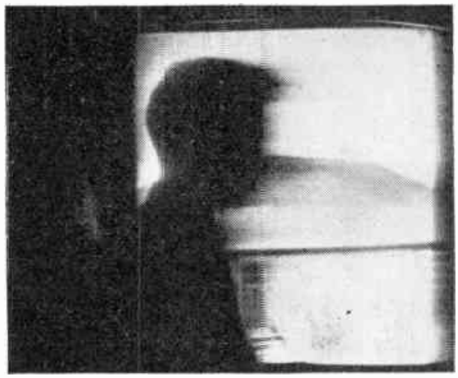
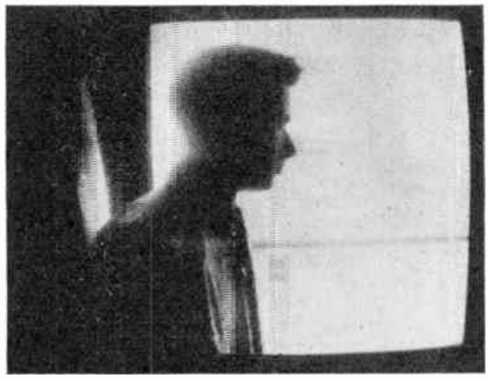


Fig. 14.—Waveform similar to Fig. 13, but with transparency changing from η_o to $\eta_o + \Delta\eta$ and back again along the scanning lines. $a = c\,\tau\,\beta$



(*a*)



(*b*)

Fig. 15.—The appearance of screen afterglow in the television picture (a), *and the "cleaning up" effect of overall negative feedback* (b).

The practical results were quite in accordance with these derived conclusions. This is illustrated by the television pictures in Fig. 15 without afterglow correction in the amplifier. The top picture (*a*) was taken under normal operation, and the picture below (*b*) was taken with feedback operative. It is evident that the application of feedback cleans up the picture, the correction being dependent on the sense of the transition in the picture shades, e.g., streaking from the profile disappears, the face becoming sharply outlined but, as expected, any transition from light to dark is not affected. (The apparent gradual change from white to black at the back of the head is, to a great extent, due to the gamma-reduction bringing up details in the dark areas.)

With the application of feedback, the screen afterglow causes exponential transients of variable time constants in the signal waveform, changing with the degree of feedback and transparency. One might think, therefore, that compensation by differentiation in the amplifier is not possible but, since the differentiator is within the feedback loop, its action is modified by the amount of feedback. It will be shown now that if the amplifier differentiator is adjusted to compensate for the screen decay time constant τ, the output signal remains corrected when feedback is applied. Referring to Fig. 16, in addition to the amplifier, which produces the output voltage e, a differentiator and mixer is included, giving a final output signal e_o where

$$e_o = e + \tau \frac{de}{dt}$$

Inserting this relation in equation (6) we obtain

$$e = c\epsilon^{-\frac{t}{\tau}} \int_{-\infty}^{t} \eta(t') \left[1 - \beta \left(e + \tau \frac{de}{dt} \right)_{t'} \right] \epsilon^{\frac{t'}{\tau}} dt'$$

differentiating e with respect to t leads to

$$e + \tau \frac{de}{dt} = e_o = \frac{c\tau\eta}{1 + c\tau\beta\eta} \quad \ldots\ldots\ldots\ldots\ldots (9)$$

This result confirms that the output signal e_o is free of transients introduced by screen afterglow and is, like equation (1), a function of the local transparency η only, i.e. only the transfer-characteristic is changed.

If the differentiator in the amplifier is not correctly adjusted to compensate τ, but is misadjusted to compensate a time constant τ^*

$$e_o = e + \tau^* \frac{de}{dt}$$

then the output signal e_o is given by

$$e_o = \frac{c\tau\eta}{1 + c\tau\beta\eta} + \frac{\tau^* - \tau}{1 + c\tau\beta\eta} \frac{de}{dt}$$

which, in addition to equation (9), contains the component $\frac{de}{dt}$ due to the incorrect adjustment of the differentiator. The magnitude of this spurious component is reduced by feedback from

$$\tau^* - \tau \quad \text{to} \quad \frac{\tau^* - \tau}{1 + c\tau\beta\eta}$$

This fact is an important advantage of the feedback application, as adjustment of the afterglow correction is less critical in the higher tone values.

It should be mentioned that the appearance of afterglow is also modified if the normal flying spot scanner is considered with gamma-correction by the usual method of non-linearity in the amplifier.[8]

It is obvious that a transition from black to white is reproduced with a faster rise time, similar to the feedback case (Fig. 10). However, the return to black is lengthened. This effect

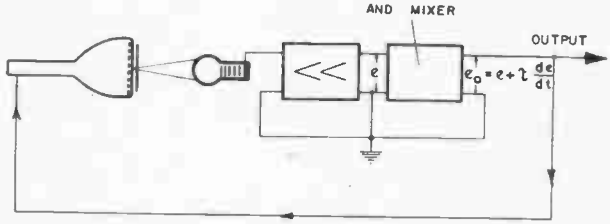
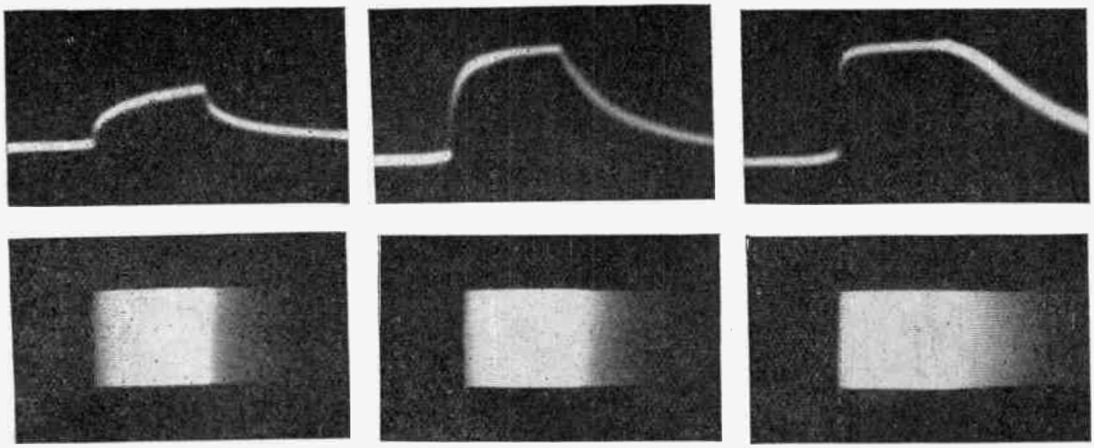


Fig. 16.—Schematic of a flying spot scanner with screen afterglow correction in the amplifier and overall feedback.

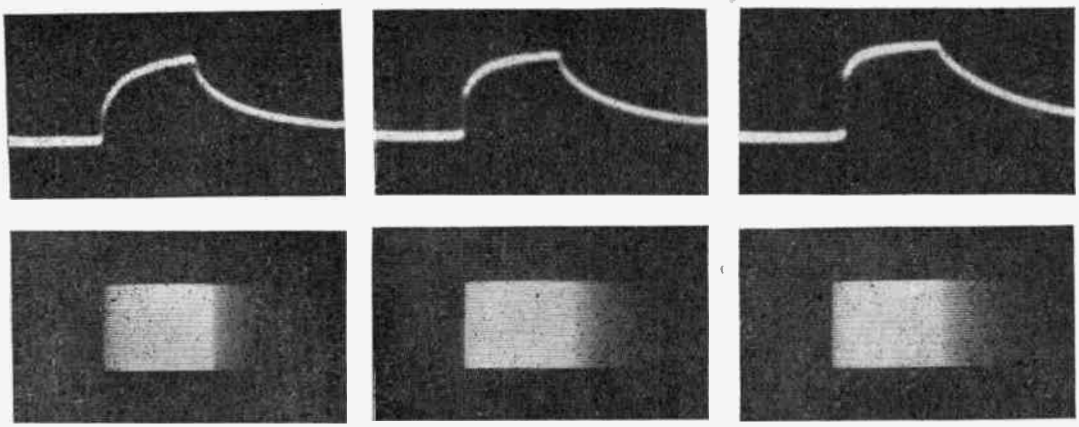
is illustrated in Fig. 17, where television pictures and line oscillograms are shown for a slide consisting of a white rectangle on a black field. The three groups of pictures are taken with different input amplitudes to the gamma-control circuit in order to demonstrate the change in waveshape depending on the degree of non-linearity involved. As the amplitude is small in Fig. 17*a*, the waveshape is little changed and similar to that in Fig. 11*a*. In Fig. 17*b*, where a larger extent of the non-linear characteristic is used, the change becomes evident, and, in the even higher degree of gamma-reduction (Fig. 17*c*) it is quite apparent that the return from white to black is much longer, the white streaking being emphasized.

For comparison Fig. 18 is the same group of pictures, but with gamma-control carried out by feedback, showing results as analysed in conjunction with Fig. 13. In contrast to Fig. 17, the time constant of the white-black transition is the same for all groups, the white streaking not being elongated with gamma-reduction.



(a) (b) (c)

Fig. 17.—The effect of gamma-reduction by amplifier non-linearity on the appearance of screen afterglow.



(a) (b) (c)

Fig. 18.—The effect of gamma-reduction by overall negative feedback on the appearance of screen afterglow.

4. The Influence of the Feedback Application on the Signal-to-Noise ratio

As a last point of interest the signal-to-noise ratio will be discussed. In a flying spot scanner with photo-multipliers, the noise level is solely determined by the photo-current shot noise (dark current may be ignored); thus the noise power is proportional to the brightness. There is no noise in true black ($\eta = 0$) and, as the light falling on the multiplier increases, both the signal and signal-to-noise ratio increase. The appearance of noise in the viewed picture depends on the overall transfer characteristic of the system. Since a flying spot scanner with a linear amplifier and a cathode ray tube receiver has a "gamma" greater than unity, noise in the darker tones is suppressed together with picture detail. The gamma-correction necessary changes the appearance of the noise in the picture because of the increased gain for small signals and the reduced differential gain in the highlight region.

In order to investigate the influence of "feedback gamma-reduction" on the signal-to-noise ratio, we have to compare two flying spot scanners producing the same tone scale, having gamma control by feedback in one case and by non-linear amplification in the other.

To be in agreement with equation (1), the non-linearity in the non-feedback case must be of the form

$$y = \frac{\eta}{1 + a\eta}$$

where a must equal the product of $c_3\beta$ in (1). This function operates on the signal with the factor

$$\frac{y}{\eta} = \frac{1}{1 + a\eta} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (10)$$

and has a differential amplification of

$$\frac{dy}{d\eta} = \frac{1}{(1 + a\eta)^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (11)$$

Signal and noise will now be considered for a given transparency η producing a photo-current i_1. The signal e_{01} is then according to (10)

$$e_{01} = i_1 \cdot \kappa \cdot \frac{1}{1 + a\eta}$$

where κ is a constant containing the gain of the multiplier and the amplifier. The associated noise in the output will be given according to (11)

$$\overline{e_{n1}} = p\sqrt{i_1}\,\kappa \frac{1}{(1+a\eta)^2}$$

with $p = \alpha\sqrt{2e\Delta f}$

e = electron charge

Δf = bandwidth

$\alpha \simeq 1{\cdot}5$ (noise increase due to secondary emission processes).

Thus the signal-to-noise ratio in the non-feedback case is

$$R_1 = \frac{1}{p}\sqrt{i_1}\,(1 + a\eta)$$

The transparency η produces in the feedback-type scanner a photo-current i_2, and with the same amplification, the signal is

$$e_{02} = i_2\,\kappa$$

and the associated noise

$$\overline{e_{n2}} = p\sqrt{i_2}\,\kappa \frac{1}{1 + a\eta}$$

because any noise pulse, i.e. any random fluctuation in the photo-current, is reduced by the instantaneous feedback $(1 + a\eta)$ times.

With feedback the signal-to-noise ratio is

$$R_2 = \frac{1}{p}\sqrt{i_2}\,(1 + a\eta)$$

A comparison factor F can be defined as the ratio of the signal/noise with feedback to the signal/noise without feedback

$$F = \frac{R_2}{R_1} = \sqrt{\frac{i_2}{i_1}}$$

If the screen brightness of the normal flying spot scanner is adjusted to be equal to the screen brightness of the feedback-type scanner, when the feedback is switched off (as happens when $\eta = 0$), the relation between i_1 and i_2 is given by

$$i_2 = i_1 \frac{1}{1 + a\eta}$$

and F becomes

$$F = \sqrt{\left(\frac{1}{1 + a\eta}\right)}$$

For the lower tone values, where $\eta \ll 1$, $F = 1$ and the two systems in comparison have the same signal/noise ratio. This is to be expected as the feedback is not active in dark shades, the screen brightness is the same and both scanners operate under identical conditions. With increasing transparency, however, the signal/noise ratio for the feedback type gets less and F reduces to the square root of the feedback factor. This result is a consequence of the difference in differential gain for the small noise fluctuation. In the non-feedback case the slope is given by the square of the "simulated feedback factor" (equation 11), while in the feedback case the small signal gain is determined by the feedback factor itself. This would infer a worsening of the signal-to-noise by the ratio of the feedback factor, but since the photo-current for $\eta > 0$ is reduced in the feedback case by the feedback factor, the noise generated will be less by the square root of this reduction; therefore the overall result is that feedback deteriorates the signal/noise ratio by the square root of the feedback factor.

The result is different if the comparison of the two systems is made assuming equal screen brightness at peak white, $\eta = 1$.

The relation between i_2 and i_1 then is

$$i_2 = \frac{1 + a}{1 + a\eta}\, i_1$$

and the factor F becomes

$$F = \sqrt{\frac{1 + a}{1 + a\eta}}$$

Under these circumstances, the feedback type produces a better signal-to-noise ratio in the low shades, F being $\sqrt{(1+a)}$ for $\eta \ll 1$ whilst the improvement lessens as "white" is approached in the tone scale, F being 1 for $\eta = 1$. Operation in this manner, however, involves higher values of scanning beam current at lower values of η and consequently higher screen load and loss of definition. Taking this into account, a fair comparison can be made by setting the screen brightness to be equal at a "grey" value, $\eta = \eta_0$

$$i_2 = \frac{1 + a\eta_0}{1 + a\eta} i_1 \text{ and } F = \sqrt{\frac{1 + a\eta_0}{1 + a\eta}}$$

The value of η_0 should be chosen so that the screen load is about equal in both scanners averaged over a lengthy period.

In this condition, the signal/noise ratio is the same for both systems at $\eta = \eta_0$; if $\eta > \eta_0$ (whiter tones) the non-feedback type is better, whilst for $\eta < \eta_0$ the feedback scanner gives superior results. As the spot size depends on the beam current the definition is improved in the high-lights of the picture on the feedback scanner, whilst it is less in the darker shades, and it is believed that the gain in the bright regions of the picture outweighs the poorer resolution in the dark areas.

Thus it can be said that the application of overall negative feedback in a flying spot scanner does not change the average picture quality with regard to noise and definition.

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6. References

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# of current interest . . . .

Commonwealth Broadcasting Conference

The second Commonwealth Broadcasting Conference (the first took place in 1945) will be held in London from June 23rd to July 4th. Between 30 and 40 delegates are to attend, representing the Australian Broadcasting Commission, All-India Radio, the British Broadcasting Corporation, the Canadian Broadcasting Corporation, the New Zealand Broadcasting Service, Radio Ceylon, Radio Pakistan, and the South African Broadcasting Corporation. Delegates will include Mr. Riaz Ahmad (Member), Director of Engineering, Radio Pakistan, and Mr. E. J. Middleton (Associate Member), Head of Transcription Service, South African Broadcasting Corporation.

The agenda for the Conference includes discussions on programme exchanges, technical problems, educational broadcasting, television development, and staff exchanges and training. An important feature will be visits by the delegates to B.B.C. establishments throughout the country.

Proposals for Television in India

The Scientific Advisory Committee for Broadcasting recently set up by the Government of India under the chairmanship of Mr. B. V. Baliga (Member), Chief Engineer of All-India Radio, has recommended that an experimental pilot station for television should be set up at an early date. This would enable the potentialities of television in India to be studied and provide an opportunity for training the necessary personnel.

Northern Radio Show

The first Northern Radio and Television Show organized by the Radio Industry Council was held in Manchester from April 23rd to May 3rd. Opened by Lord Brabazon of Tara, the show included displays by 47 exhibitors in addition to a B.B.C. studio erected specially for the show. The emphasis of the Exhibition was naturally on television and the interest aroused in the North following on the opening of Holme Moss last year was shown by the total attendance of 100,793.

There were comparatively few outstanding innovations, the trend being mostly in improvements to existing models. Many of the receivers on show were easily adaptable to any of the five television channels—a feature which will be of increasing importance with the opening of the B.B.C.'s Welsh television transmitter at Wenvoe in August.

The Sixth Congress of the International Scientific Film Association

The Council of the International Scientific Film Association has announced that this year's Congress will be held in Paris from Tuesday, September 23rd, until Wednesday, October 1st, 1952. During this period there will be meetings of the General Assembly of the International Scientific Film Association, meetings of the Permanent Committees dealing with Medical, Research, Technical and Industrial Films, as well as a Festival of Scientific Films.

A special Committee of the British Scientific Film Association will be set up to consider and recommend films for submission to this Scientific Film Festival. This Committee would be glad to have, as soon as possible, information about suitable films for this purpose. The Association's address is: 164 Shaftesbury Avenue, London, W.C.2.

Barnstaple Transmitting Station

In accordance with plans to improve reception of the Home Service programmes in certain areas, the B.B.C. is building a new low-power transmitting station at Fremington between Barnstaple and Bideford, Devon. As, however, the building and installation will take some considerable time to complete, a temporary transmitter installed in a caravan is being used on the site. The caravan transmitter, brought into service on March 9th, 1952, with a wavelength of 285 m (1,052 kc/s), radiates the West of England Home Service. The aerial system already erected for the permanent station is used for the temporary transmitter.

The station is intended to serve Barnstaple, Bideford and their immediate surroundings, but maximum coverage of the outlying areas will not be achieved until the permanent station is in operation. The temporary transmitting equipment consists of two 250-watt medium-wave transmitters, one normally being a reserve for use in the event of a breakdown, but provision is being made for paralleling the two outputs to give a total aerial power of 500 watts. Space has been left for the future installation of remote control gear.

THE APPLICATION OF TELECOMMUNICATIONS TO CIVIL "AIRWAYS"*

by

D. P. Taylor, M.B.E.†

A Paper presented at the Fourth Session of the 1951 *Radio Convention on July 27th at University College, Southampton.*

SUMMARY

Towards the end of 1948 the decision was taken by the Ministry of Civil Aviation to provide a system of "airways" over the United Kingdom as a means of promoting a high standard of safety and regularity in civil aviation operations.

These "airways" are now in operation and are in continuous use by aircraft of all types and nationalities, flying on both internal and external routes. Pilots of aircraft electing to fly along these "airways" are assured of free air-space and expeditious handling in the terminal area.

The purpose of this paper is to describe the work carried out during the last two-and-a-half years in planning, installing, and bringing into operation the telecommunications facilities which has made possible this control of aircraft in "airways."

1. Introduction

Towards the end of 1948 the decision was taken by the Ministry of Civil Aviation to set up a system of "Airways" over the United Kingdom as a means of promoting a high standard of safety and regularity in civil air operations.

To-day those "Airways" are in continuous operation and used by aircraft of all types and nationalities flying over this country. The use of these "Airways" is not mandatory, but pilots of aircraft electing to fly along them are assured of free air-space and expeditious handling in the terminal areas, and the high proportion of flights operated in this way is proof of the advantages offered.

Since the decision to set up "Airways" was taken, a great deal of effort has gone into the planning, setting up and bringing into operation telecommunications equipment essential to the system, and it is the purpose of this paper to deal in some detail with that work.

It will be noted that the word Telecommunications is used rather than Radio; this is deliberate since a very closely integrated system of radio and land-line facilities is used, and it is not possible to deal with either in isolation.

Before dealing with the technical aspects it is necessary to define what is meant by "Airways Flying," and a very brief description is given at Section 2 of this paper. It must be appreciated, however, that Air Traffic Control is in itself an extremely specialized and complex subject and it is not possible to dwell at any length upon the underlying philosophies and practices.

Sections 3, 4 and 5 deal with the Telecommunications aspects proper. Of these, Section 3 is necessarily brief, since it is concerned for the most part with standard G.P.O. practices, and a wealth of technical information has been published on this subject. Section 4 deals with the air-ground communications and occupies the bulk of the paper, since it is in this field that the greatest steps forward have been made during the past few years. The navigational aids covered by Section 5 are well established devices, although not perhaps well known in this country. It is, however, quite apparent that the newer systems developed during or since the war, in this country, have yet to make their impact on "Airways Flying," but when they do so there can be no doubt but that it will be considerable.

It should be noted that this paper is confined to a factual statement of engineering work of the period under review and does not attempt to cover future policy on Telecommunications or Air Traffic Control, or to deal with facilities not yet completed or still in the planning stage.

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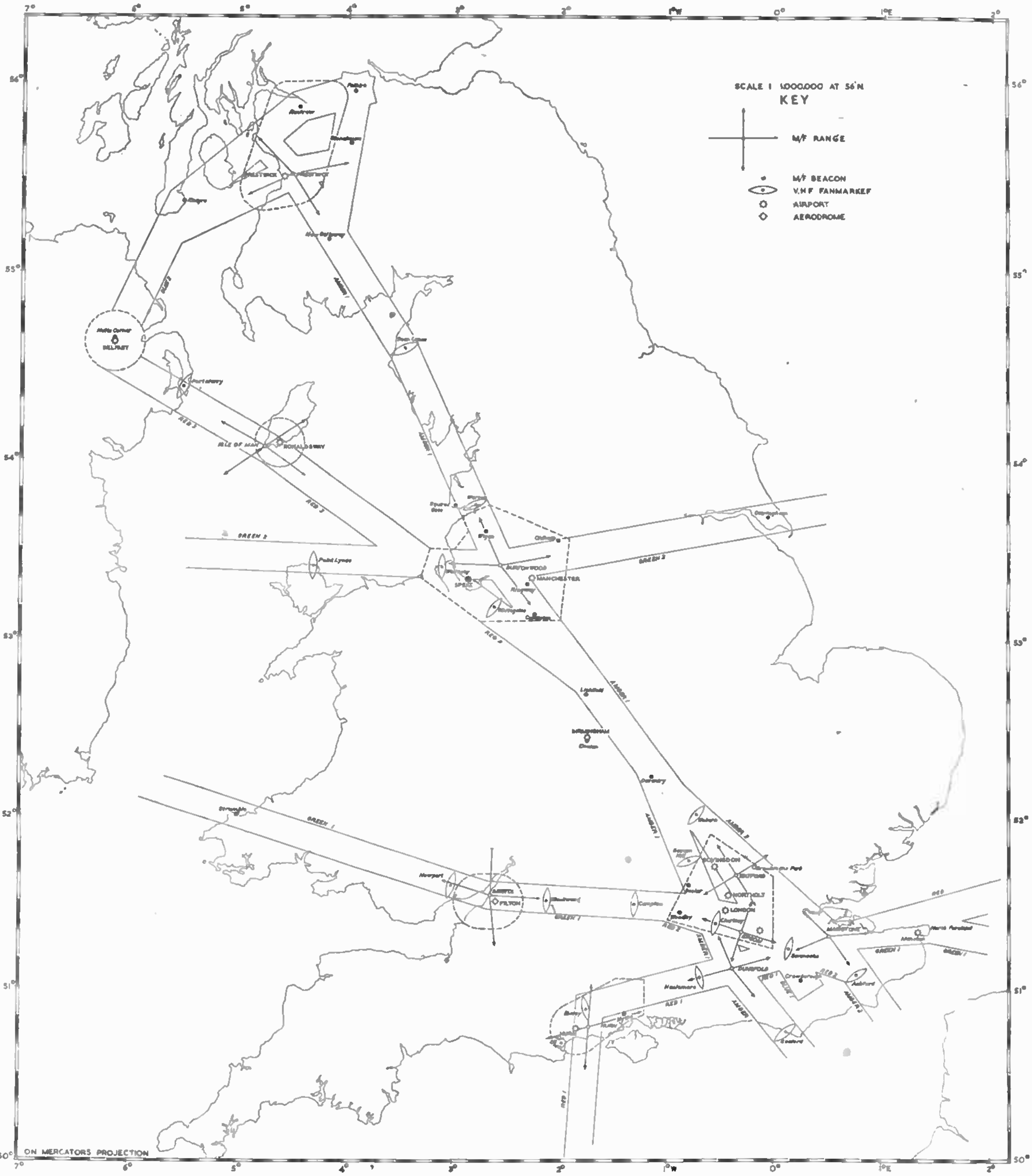

Fig. 1.—M.C.A. Airways Plan.

2. U.K. Airways Plan

In Fig. 1 is the basic U.K. Airways Plan, which was drawn up in agreement with the military authorities in 1948 and which has remained unchanged, apart from very minor details, a matter that reflects credit to those concerned with the early planning.

It will be seen that this comprises a series of Airways or corridors radiating outwards from three centres in Southern England, Northern England and Scotland respectively. In some cases the outer terminals extend beyond the coast to the boundary of the area coming under U.K. Air Traffic Control jurisdiction, in other cases they join up with an Airway from a different centre. It will also be noticed that the inner terminals of the Airways are terminated in Control Zones, and that other such Control Zones lie along the Airways.

The Airways themselves are 10 miles wide and extend from 5,000 to 11,000 ft. in altitude. Aircraft flying along the Airways come under the operational control of the appropriate Air Traffic Control Centre, these being located at Uxbridge, Preston and Prestwick, whilst those flying in the Control Zones are under the control of the local Zone authorities. Aircraft flying on the Airways are required to carry a certain minimum of radio and navigational equiment.

Aircraft entering an Airway whether at an outer terminal or from a Control Zone, require prior permission, and the permission specifies the point of entry and the altitude to be flown. The altitude is specified to ensure 1,000 ft. vertical separation between tracks, there being thus in effect a number of vertically displaced tracks available on the Airways. Once in the Airway the aircraft is required to remain continuously on the V.H.F. channel appropriate to that Airway, to give estimated time of arrival at certain specified "Reporting Points," and later, actual time of arrival at these points. To maintain adequate separation between aircraft the Air Traffic Control Centre may on occasions require an aircraft to "hold" at any of these Reporting Points.

The position of all aircraft in the Airways together with relevant information, i.e. altitude, estimated time of arrival at Reporting Points, etc., is continuously displayed at the Air Traffic Control Centre on Flight Progress Boards.

Similarly an aircraft is cleared from the Airway, and, when appropriate, handed over to the Control Zone Controller at a specified point and altitude; thereafter the Airways Control responsibility ceases.

It will be seen that to carry out such a control procedure the following essential facilities must be provided:—

(*a*) Rapid and reliable communication between Air Traffic Control Centres, and to the Air Traffic Control authorities at Control Zones and individual aerodromes.

(*b*) Radio communication channels that will enable the aircraft pilot to speak directly to the Air Traffic Control Officer at the appropriate Centre whilst flying at any point on the Airway.

(*c*) Radio navigational aids that will enable the pilot of the aircraft to fly a track in all weather conditions that will lie within the confines of the Airway.

(*d*) Radio navigational aids which will enable the pilot of the aircraft to locate the appropriate terminal, or joining point of the Airway.

(*e*) Radio navigational aids that will enable the pilot of the aircraft to ascertain the precise moment of arrival at a Reporting Point and, if necessary, enable him to "hold" at that point if required to do so by the Air Traffic Control Centre.

(*f*) A suitable altimeter to enable the aircraft to maintain specified height; this not being a Tels. facility, it will not be discussed, apart from noting the fact that a uniform correction for barometric pressure is given to all aircraft using a particular sector of the Airways by the Air Traffic Control Centre by means of the radio communication channel.

Details of the manner in which these requirements have been met will be given in succeeding parts of this paper.

3. Fixed Service Communications

It will be apparent from the foregoing description of the U.K. Airways Plan, that not only are radio communication channels to the aircraft essential, but in addition an elaborate system of ground communications is necessary. Not only must the three Air Traffic Control Centres in the U.K. be inter-connected, but communications must also be provided to Continental Air Traffic Control Centres, to Control Zone authorities, and to individual aerodromes.

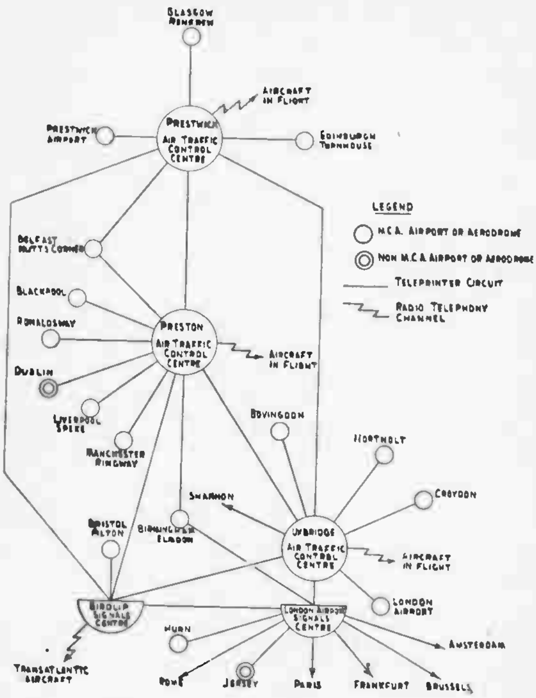

Fig. 2.—U.K. airways scheme: teleprinter and radio communications.

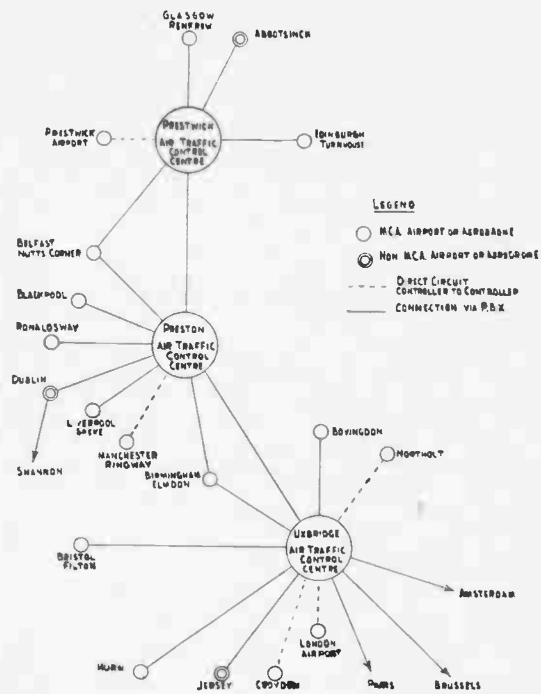

Fig. 3.—U.K. airways scheme: main telephone circuits.

In all cases the equipment used is of standard G.P.O. type so that it is not proposed to dwell on the technical aspects, but rather to provide a few facts and figures that will serve to show the magnitude of these communication networks.

Fixed service communications fall into three categories.

3.1. *Teleprinter Network*

The network of teleprinter circuits associated with Airways is shown at Fig. 2 where it will be seen that circuits are provided to 16 aerodromes in the U.K. and to seven centres outside the U.K. In all some 70 teleprinters are employed on this network which embraces approximately 6,000 route miles, of which about half are outside the U.K. At the Air Traffic Control Centres mechanical conveyors of the drag-belt and pneumatic tube type are used to ensure speedy transit between teleprinter operators and Air Traffic Control Officers.

3.2. *Telephone Network*

The operational telephone network is very similar to the teleprinter network already described, as will be seen from Fig. 3. Included in this network are both direct "Controller-to-Controller" circuits and also circuits via an Operational PBX. In this case some 6,000 route miles are employed of which about 2,000 miles are outside the U.K. To provide for flexibility, all external private lines into the Air Traffic Centres are common to a series of keyboards built into the Flight Progress Display Boards, but incoming calls are not received at a particular keyboard until a select key associated with the particular circuit is operated. By this means a Controller can select only the circuits that he requires for a particular tour of duty, up to a maximum of 20 circuits. This system has the additional advantage of permitting the collapsing of two or more Controller positions at times of low traffic density. Additional facilities provide for the "double-banking" of each Controller position during heavy traffic peaks. Adjacent to these keyboards are the control keys for the V.H.F. radio circuits which will be dealt with in a later part of this paper.

3.3. *Remote Control and Speech Channels for Remote Radio Stations*

In a later part of this paper mention will be made of the fact that certain of the radio navigational aid equipments are located at remote unattended sites and control and monitoring carried out by remote control. A technique akin to that used on automatic telephone systems meets this requirement, and some 250 route miles of circuit are provided for this purpose.

In the section of the paper dealing with Mobile Communications a system of Area Communications using remote V.H.F. transmitter/receiver sites is described, these remote stations in all cases being operated from the appropriate Air Traffic Centre. For this purpose 4,000 miles of land-line circuits are provided having a frequency response of 300 to 2,800 c/s within 1 db. Zero loss lines working at a level of negative 10 dbm are used.

4. Mobile Communications

In this case the requirement is to provide reliable communication on R/T between aircraft at any point on the Airways and the appropriate Air Traffic Control Centre.

Before the war, all communication between aircraft and the ground was conducted on Medium and High Frequencies, but with the rapid expansion of civil air operations the problem of congestion on these frequencies had already begun to be felt, particularly where R/T was used.

The acute need during the war for ultra-reliable air-ground communication on a scale far beyond anything previously envisaged accelerated the use of very high frequencies for this purpose, frequencies of the order of 100-150 Mc/s being finally adopted. By the end of the war, the use of these frequencies had reached a high state of development and post-war civil aviation found at its disposal an efficient means of carrying out reliable communication between aircraft and individual aerodromes. Furthermore, adequate supplies of surplus military equipment existed, sufficient to bridge the gap until civilian production could once more be got under way. By international agreement the frequency band 118-132 Mc/s was standardized for civil aviation communications.

However, the use of V.H.F. limited the range of communications to little more than the optical path between aircraft and ground stations, and the need for communication over much greater ranges to cater for Air Traffic Control on an Area basis was soon felt. At first, this requirement was met by the same means that had been used in the case of military aircraft during the war, namely, the use of W/T on M.F. and H.F. Thus two separate communication systems were in general use during flight, the pilot-operated V.H.F. channels used for communication with the terminal aerodromes, and the M.F./H.F. W/T channels operated by a wireless officer for "en route" communications. Apart from the necessity of carrying a multiplicity of radio equipment in the aircraft, and, of course, the M.F./H.F. frequency problem, the integration of these two systems on the ground presented considerable difficulties. Thus a requirement existed for a V.H.F. pilot-operated system for area communications even before the formulation of an Airways Plan, although the adoption of such a plan very considerably strengthened this need.

The development by the Ministry of Civil Aviation of Area Coverage Networks has been dealt with at some length elsewhere by the author,[2] but it is of interest to note the way in which these networks have been adapted to the Airways Plan.

A system was developed in this country to provide a means of communication with mobile police units operating over considerable areas, using V.H.F., and yet at the same time overcoming the optical-path limitations of these frequencies. This system has been described by J. R. Brinkley.[3,4,5] It depends upon the use of a number of V.H.F. transmitter/receiver stations suitably sited in the area concerned; these stations, whilst operating on the same nominal channel, are in fact slightly spaced in frequency; sufficient to raise any resultant "beat-notes" above audibility or the higher frequency limit of the receiver A.F. pass-band. This, of course, presupposes receivers having a R.F. and I.F. pass-band sufficiently wide to embrace all the individual stations in the network. If all the ground stations are simultaneously modulated, their radiations "flood-light" a considerable area, and by suitable siting, it is possible to ensure that the mobile unit is always in the field of radiation of at least one of the fixed stations. The important fact should be noted that it is not necessary for the operator of the

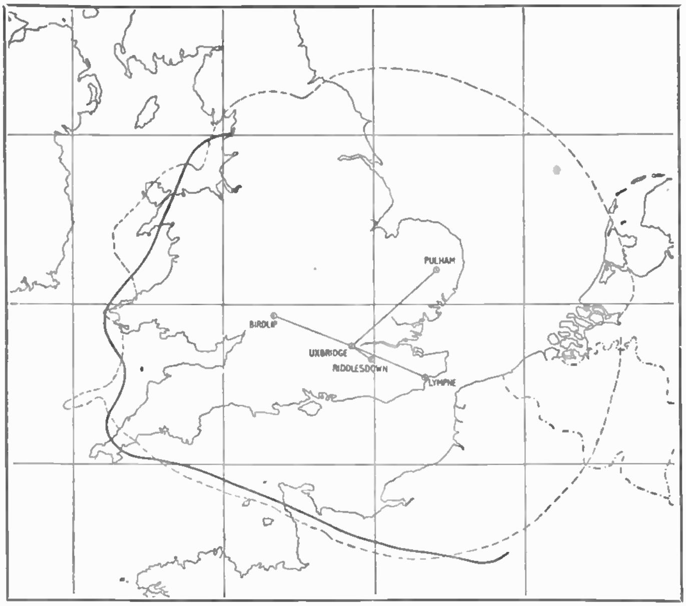

Fig. 4.—Location of stations in experimental scheme.
- - - - *Theoretical cover at 10,000 ft.*
——— *Limit of communication with aircraft flying at 5,000-10,000 ft.*

mobile unit to know his relationship to the fixed stations, since his receiver is sensitive to them all. It is thus unnecessary to change the frequency of the mobile unit receiver as this relationship changes. Thus, one single channel provides coverage throughout the area. Further, it is interesting to note that in practice the combinations of two or more signals in the mobile receiver produces an effect akin to diversity reception, materially reducing "fading" and "flutter."

Each ground station has in addition, of course, receivers, the outputs of which are conveyed back to the central control point where they are mixed.

The decision was taken by the Ministry of Civil Aviation in 1947 to set up such a network of stations for the purpose of investigating the possibility of its use for area-coverage in civil air communications. The stations of this network were all located in the South of England and connected to the Air Traffic Control Centre at Uxbridge. In view of the experimental nature of the network, existing Ministry stations were used, which were by no means ideally sited, the factor of immediate availability being over-riding.

The equipment used was for the most part ex-military, the transmitters being of the well-known T.1131 series having a power output of slightly less than 50 W, and the crystal-controlled R.1392B was used for reception. The individual stations were linked to the central point by G.P.O. land-lines having a frequency response of 300-2,500 c/s within 3 db, separate lines being used for the transmitters and receivers. One of the pairs carried, in addition, the d.c. switching circuit for the operation of the transmit/receive relays at the remote station. At the central point the combination of the incoming signals and the splitting of the outgoing signals was accomplished by means of transformers.

The transmitters used were designed for operation with simple quartz crystals of 0·01 per cent. frequency stability. Since this represents about ± 12 kc/s at the carrier frequency, it was obvious that a considerable improvement in stability would be necessary if excessive overall frequency spacing of individual transmitters was to be avoided. Although far from ideal, a simple ovened-crystal having a frequency stability of 0·005 per cent. was substituted and a spacing of 15 kc/s between stations was adopted, i.e., the three stations of the network were spread over 30 kc/s centred on the nominal channel frequency.

The layout of the stations of the network is shown at Fig. 4, which shows in addition the calculated coverage based on "line-of-sight," modified for refraction by the use of the well-known factor of 4/3 times earth diameter.

The success of the system was immediately apparent, and although brought into being in the first instance for experimental purposes only, it was, in June 1949, made available to certain airlines for operational use, and in July 1950 brought into general operational service using a frequency of 126·7 Mc/s.

Advantage was taken of the operational use of the system to collect practical data of coverage, by the systematic plotting of contacts with aircraft flying at heights of 5,000 to 10,000 ft.

It will be seen from Fig. 4 that these results agree closely with the calculated coverage, thus demonstrating that the use of the 4/3 correction factor provides a useful basis for V.H.F. coverage planning at these frequencies.

The successful results obtained with the experimental system led to the decision to cover the greater part of the U.K. with V.H.F. Area Control networks—these to comprise three independent networks centred on the main Air Traffic Control Centres at Uxbridge, Preston, and Prestwick.

The location of the stations of these networks and the calculated coverage is shown in Fig. 5.

It will be seen that the whole of the United Kingdom is served, except for the extreme North of Scotland. (Air routes passing over this area and those serving the Scottish Islands are catered for by a separate system of V.H.F. stations located at aerodromes and elsewhere.) Advantage was taken of the fact that the networks were planned from scratch to select sites almost ideal from the V.H.F. point of view; for example, it was possible to use such locations as Snaefell, the highest point in the Isle of Man, and Great Dunn Fell in the Pennines.

In planning the new networks it was desired to embody certain improvements over the earlier experimental system, the chief of these being:—

(1) Multi-Channel operation.
(2) Closer frequency spacing of transmitters.
(3) Improved audio-frequency characteristics.
(4) Use of audio-frequency for remote switching.

4.1. *Multi-Channel Operation*

It had been realized that a single V.H.F. channel would be insufficient to meet the needs of civil Air Traffic Control, in view of the rapid expansion of services that was taking place, and of the general tendency to replace M.F./H.F. W/T by V.H.F. pilot-operated R/T as the medium for Area Control. The new networks were, therefore, planned on the basis of a maximum of four channels, a fact that assumed importance later with the coming of Airways flying. This decision brought in its train technical problems.

It was obvious in planning the networks that the transmitters and receivers would have to be located on the same site; apart from economic considerations (which were formidable) in many cases it was not possible to find two separate comparable sites in the same locality (e.g., when a site existed at the summit of an isolated peak). Further, it was very desirable that one aerial tower only be erected on each site, to carry both transmitter and receiver aerials. With four channels on each site this would call for a total of eight aerials (excluding spares), and it was felt that such an arrangement, apart from its mechanical complexity, would make the attainment of substantially circular polar diagrams very difficult. It was, therefore, decided that some form of common-aerial working would be necessary. After a series of experiments a method of common-aerial working was adopted that had been developed during the war by the Admiralty. By the use of high-Q circuits comprising a tunable length of capacity-loaded silver-plated co-axial line it was found possible to operate four transmitters simultaneously into a single wide-band dipole with a loss of only 3-4 db. This system has been described fully elsewhere.[6]

When field tests were carried out to determine the feasibility of operating the receivers and transmitters on the same sites, results were at first very disappointing. Operation of two or more transmitters simultaneously made reception on the receivers of other channels impossible. This effect was not due to simple "blocking" since it did not occur when one transmitter only was radiating, even when the receiver was tuned to within 200 kc/s of the transmitter frequency. Fuller investigation showed that the effect was due to spurious frequencies generated by non-linear elements in the vicinity of the transmitter aerials, and in the earlier stages of the receivers; this has been described elsewhere by Blake.[7] The severity of this effect can be gauged from the fact that these spurious signals were troublesome when the transmitter and receiver sites were separated by as much as 20 miles. The effect was finally overcome after considerable experimental work which resulted in such measures as the use of a wooden tower to support the aerial system, the elimination of all unnecessary metal work from the immediate vicinity of the aerials, and by the use of the high-Q resonant units previously mentioned. The use of these latter items not only provided a degree of pre-selection ahead of the receiver inputs but also made possible common-aerial working for the receivers using the same methods as had been

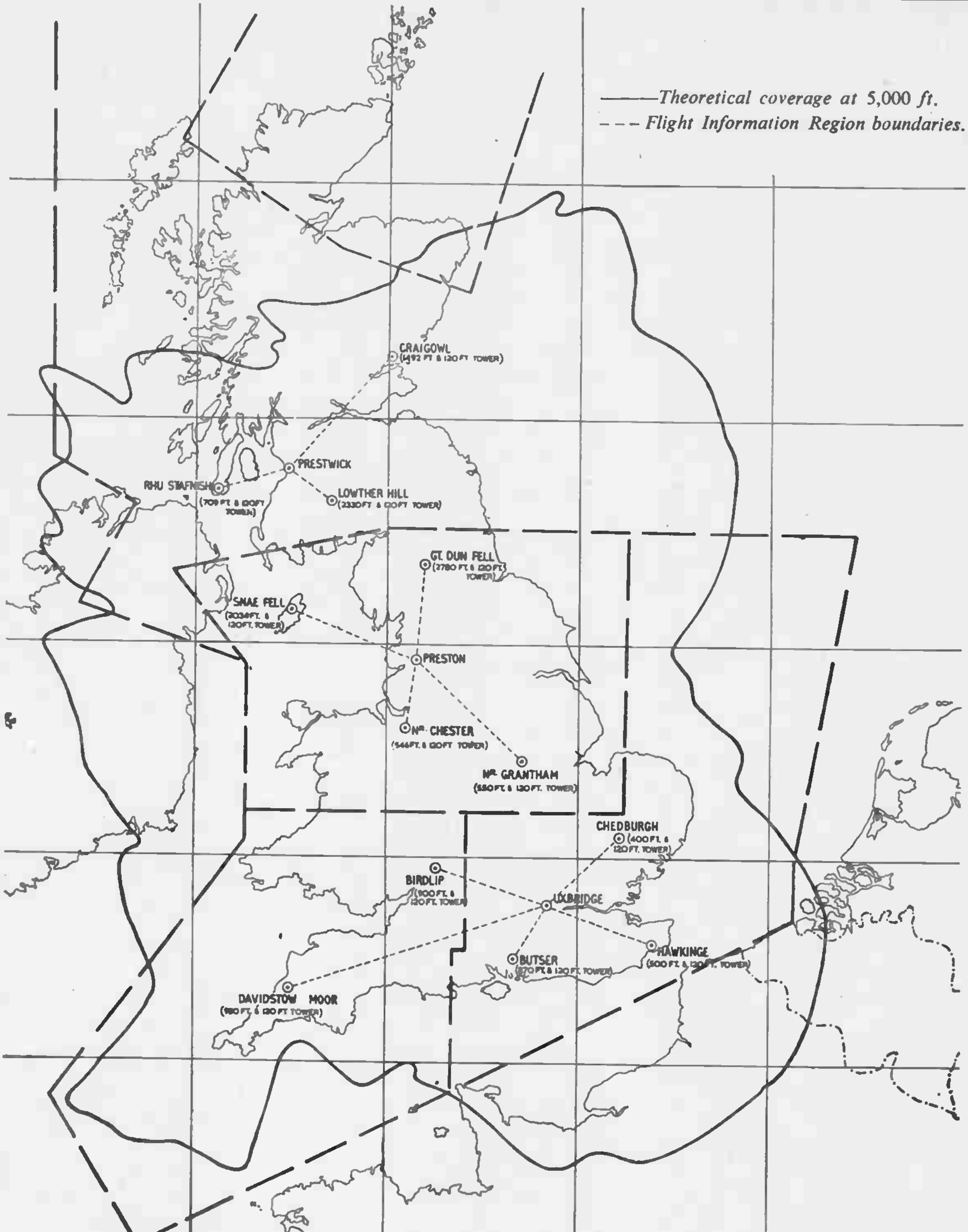

Fig. 5.—Layout of M.C.A. V.H.F. area coverage network.

adopted in the case of the transmitters. Experiments also showed that if the transmitter and receiver aerials were to be located on the same tower, it was desirable that they be mounted with their axes in line and separated by not less than 15 ft. At Fig. 6 is shown the aerial tower at one of the transmitter/receiver stations on which will be seen the four aerial systems, these being transmitter, receiver, transmitter spare, and receiver spare, respectively from the top of the tower downwards. The aerial systems used are of a wideband cage type having a balanced to unbalanced matching device in the supporting boom.[8] By attention to all these details it was found possible to operate four channels simultaneously from the same site, using two aerials only, mounted on the one tower. The only limitation that remained was one of frequency allocation, although it was found possible to operate with channel spacings as low as 200 kc/s (one channel in aeronautical allocations), nevertheless, it was found that care had to be taken in the relative spacing when a number of channels were in use on the same site. For example, it was found necessary to avoid the use of three or more channels having equal spacings; thus if two channels in use were x and $x + y$ then it was necessary to avoid the use of $x - y$ as an additional channel since a strong spurious signal would be found at this latter frequency carrying the modulation components of both the other channels.

In the design of the final transmitter/receiver stations the receivers were contained in a double screened-room to avoid any possibility of direct-pick-up from the transmitters in the same building.

4.2. *Closer Frequency Spacing*

It was felt that the spacing of 15 kc/s between individual transmitters used in the earlier system could be improved on, this being desirable for two reasons: firstly, it was necessary to use more than three transmitters to give full coverage over the Southern part of England, secondly, it was desired to avoid imposing limits on the design of airborne receivers from the point of view of selectivity.

A contract was placed for the development of a crystal oscillator of greatly improved stability to drive the transmitters. The specification called for a stability of ± 500 cycles at the carrier frequency, representing about 0·0003 per cent., this being a stability of more than 10 times that previously used.

The requirement was met by the use of a unit comprising a glass-enclosed B7G crystal having a temperature coefficient of the order of 1 part in 10^6 per 1°C, an oven having a thermal stability of the order of $\pm$ 1°C, and the maintaining valve with associated circuitry. The transmitters were modified to enable the high stability unit to be plugged into the driver panel and the original crystal oscillator valve used as a buffer amplifier.

A trimmer capacitor is also fitted in the oven to enable small adjustments to be made to the generated frequency. It has been found in practice that the specified frequency tolerance of ± 500 cycles at the carrier frequency is easily maintained over a wide range of ambient temperatures and mains voltages. It is of interest to note that the adoption of these high-stability units gave rise to another problem. Frequency measuring devices of a sufficiently high grade to measure deviations of the crystal oscillators are very expensive items and the cost of supplying such an instrument to all transmitter stations was prohibitive. It was decided, therefore, to adopt another approach to the maintenance problem. At each station there are three high-stability units for each channel in use, these being in the working transmitter, the standby transmitter, and a spare which is maintained with its oven at working temperature. A device was developed that would measure the difference frequency between the three units, and if one was found to be drifting away from the other two, to return that one to the M.C.A. sub-standard frequency unit for checking and readjustment. The technique has proved quite effective, and after the initial "settling-down" period it is rarely necessary to resort to this practice. The design of the Oscillator and Comparator Units has been dealt with elsewhere by Scholes.[9]

The use of these improved crystal-oscillator units has enabled the frequency spacing to be reduced to 10 kc/s.

4.3. *Audio-Frequency Characteristics*

The design of the audio-frequency equipment which was developed to a Ministry of Civil Aviation Specification has been described by J. L. French.[10]

The specification called for a frequency response to be within ± 3 db over a range of 100 to 4,000 c/s with a sharp cut-off above the higher frequency limit, since it was felt that this would provide a high degree of intelligibility for a commercial speech circuit. Audio expansion and compression is used in the amplifiers associated with the transmitter circuit, the compression to ensure a high constant level of modulation for all normal speech inputs, and the expansion to reduce the effect of background noise, since the operational layout of the Air Traffic Control Centres is such that a high acoustic background level is inevitable. The distribution of signals to the transmitter stations is effected by a resistance bridge network, and provision is made for the feeding of up to eight transmitter stations. A similar unit is also used to combine the incoming signals from the various receivers.

On each channel a Monitor Operator is employed, who is provided with the combined incoming signals (although indicating meters show the incoming level from each of the remote stations, and, if necessary, any of the incoming circuits can be switched out) and means of modulating the transmitters on the channel. It is the function of this operator to effect the initial contact with the aircraft, and then, if necessary, hand over the channel to the appropriate Air Traffic Control Officer, an intercommunication system being provided for this purpose.

If, however, the aircraft wishes to pass traffic to the airline operating company, this is passed direct by the Monitor Operator to the appropriate aerodrome by the Monitor operator on a teleprinter provided for that purpose.

4.4. *Remote Switching Facilities*

It has already been stated that the earlier experimental network used d.c. for the remote switching of the transmitters and receivers, this being possible in view of the fact that because of the comparatively short distances involved, it was possible to use physical pairs. The specification for the later networks called for the use of a.c. tones of 2,460 c/s for this purpose. Duplicated audio-oscillators with automatic changeover are provided at the Air Traffic Control Centres, and the switching tones are injected at the splitting networks previously mentioned. At the transmitter sites filter networks are used to separate the speech and switching frequencies for their respective functions.

4.5. *New V.H.F. Area Coverage Networks*

It has previously been stated that the new Area Coverage Networks were planned before the Airway conception had been fully accepted. The original planning called for four separate channels in Southern England, each using all five of the transmitter/receiver sites, to provide overall coverage. As the Airways plan took shape it was apparent that full geographical coverage would not be necessary for all these channels, since certain channels would be allocated exclusively to particular Airways. The final arrangement which was brought into service early this year is shown in the Table below.

It will be seen that although four channels are used, there are at present no more than two frequencies in use at any station. However, to maintain the flexibility of the system and to provide for future channel re-allocations, equipment sufficient for four channels has been installed at all the stations. Further, the transmitters and receivers, which are of the same T.1131 and R.1392 series used in the original tests, are installed in duplicate in order to minimize the possibility of loss of channels whilst servicing is taking place or in the event of faults occurring. Analysis of the coverage of the Southern Network is still incomplete, but preliminary results show that in all directions consistent communication can be maintained with aircraft well outside the boundaries of the calculated coverage shown at Fig. 5. Examina-

T.R. Stations	Channel 1 126·7 Mc/s	Channel 2 118·9 Mc/s	Channel 3 120·3 Mc/s	Channel 4 122·1 Mc/s
Chedburgh	×	—	—	×
Hawkinge	×	—	×	—
Butser..	×	×	—	—
Birdlip	×	—	—	×
Davidstowe	×	—	—	×
Serving	(All-round Non-Airways)	(Airways to South)	(Airways to East)	(Airways to West & North)

tion of the operating log at Uxbridge shows that frequently the Air Traffic Control Officer on the 126·7 Mc/s Channel is in communication during a short period of time with aircraft scattered as widely as the German border, over Eire, or south of Brest. It will be agreed that this represents a considerable stride forward from the days within our own memory when it was considered that V.H.F. was suitable only for communication "across rivers and estuaries." In the case of the other channels satisfactory communication can be maintained out to the limits of the Airways for all aircraft altitudes.

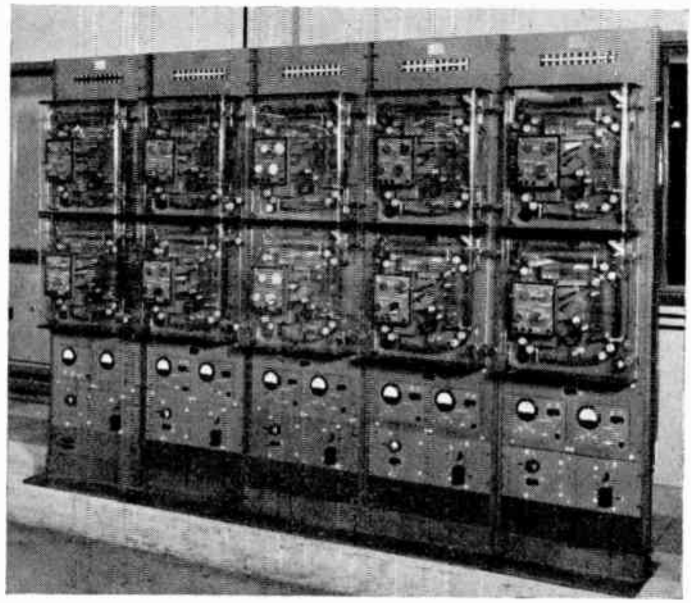

Fig. 7.—Long-duration film recorders installed at the Air Traffic Control Centre, Uxbridge. By the use of these equipments a permanent record is made of all R/T communications on the "Airways" channels.

(Photography by courtesy of Simon Sound Service)

In the case of the Northern and Scottish networks, due to the lower density of air traffic in these areas, equipment has been installed for two channels only, one for Airways and one for non-Airways communications, the coverage in the former case being obtained with four transmitter/receiver stations and the latter with three. The work of installing the equipment in these stations was carried out during the winter months and under the most severe climatic conditions. In some cases the equipment was dragged on to mountain summits on sledges, and staff were snowbound for days at a time.

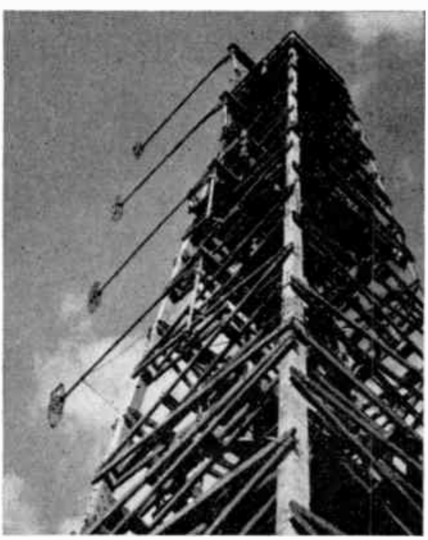

Fig. 6.—Aerial system of V.H.F. transmitter/receiver station

To safeguard against the possibility of V.H.F. equipment failure, either on the ground or in the aircraft, H.F. R/T transmitters have also been provided at each Air Traffic Control Centre.

To provide a permanent record of all communications carried on the Airways R/T channels, long-duration recorders have been installed at the Air Traffic Control Centres. These are of the type in which the sound track is embossed on a belt of standard 35-mm photographic film. The design of the units is such that 120 tracks are embossed on each side of a 80-ft belt, such a belt having a duration of eight hours continuous recording. The recording units are duplicated and automatic changeover occurs, a few minutes before the eight-hour period has elapsed, or at an earlier time in the event of an equipment failure. The combined unit is thus such that it can be run without attention for a period up to 16 hours. The time elapsed since start of recording is shown on Veeder counters and an essential feature of the equipment is that a "play-back" can be obtained of any part of the recording without interrupting the recording process; another Veeder counter is provided to enable the particular track required for "play-back" to be selected. A battery of these recorders can be seen in Fig. 7.

5. Navigational Aids

5.1. *M.F. Radio Ranges*

The requirement has been stated earlier in this paper for a radio navigational aid which will enable the pilot of the aircraft to fly a track within the confines of the Airway. This requirement is met by the use of M.F. Radio Ranges, which were adopted by reason of the fact that they were readily available in a fully developed and well-tried form. The main advantage of this type of aid is that nothing more than a medium frequency receiver is necessary in the aircraft, an important fact in view of the need to get Airways operating in the shortest possible time. A major disadvantage is, however, the need for further frequencies in an already over-crowded part of the spectrum.

For the benefit of those not fully conversant with this type of aid a brief description is given, although a more thorough treatment is available elsewhere.[11]

The Radio Range consists of an M.F. transmitter associated with an aerial system capable of radiating on either of two distinct and separate polar patterns. For simplicity these two patterns are shown at Fig. 8b as two similar "figure-of-eights" mutually at right-angles. The output of the transmitter is transferred alternately between these two patterns by means of R.F. relays. One pattern is keyed with the morse character "A" and the other character "N", and the timing of this keying is such that the spaces of the "A" characters interlock with the marks of the "N" characters, and vice versa; this is shown at Fig. 8a.

If an aircraft is flying in a particular sector where one of the patterns is predominant, the morse letter corresponding to that pattern will also be heard. Thus there are two "A" sectors and two "N" sectors. If, however, the aircraft is flying in a sector where equal signal strength is received from the two radiated patterns, then a continuous signal will be received, these sectors, of which there are four, are known as the "equi-signal zones" or range-legs, with typical aircraft equipment these sectors are about 3 deg. wide.

In the ideal case just stated the four range-legs are mutually at right-angles, a condition which would impose severe limitations on the planning of Airways. In practice it is possible, as will be seen later, to modify the patterns and so permit deviation from this ideal case.

There are two types of Radio Range in general use, these being the Bellini-Tosi and the Adcock (names very familiar to workers associated with marine D/F techniques). The difference between the two types lies in the aerial system used.

The Bellini-Tosi Range uses an aerial system consisting of two single-turn loop aerials fixed at right-angles, the transmitter being keyed alternately between the two loops. An aerial system of this type has the advantage of being both simple and inexpensive, but suffers from the disadvantage that an appreciable amount of horizontally polarized component is radiated, which reduces the effectiveness of the Range during night-time at appreciable distances. These equipments are anode-modulated at a frequency of 1,020 c/s to depth of 80 per cent. In the U.K. three Ranges only of this type are used, and the operational service limited to 30 nautical miles.

The Adcock aerial system comprises five self-supporting mast-radiators each 120 ft. high, and laid out such that four are at corners of a square of about 400-ft. side, and the fifth located at the centre. The radiators are fed by screened balanced-pair cable from the transmitter and impedance matching networks being located at the driving point. Diagonally opposite pairs of aerials are fed with "A" and "N" signals through a goniometer, and the central radiator being continuously energized. A raised counterpoise screen and radial earth wires are used around the base of each tower to lessen the effects of local variations of soil conductivity upon aerial characteristics.

If the size of one of the figure-of-eight patterns is varied with respect to the other, then the opposite angles of intersection, whilst remaining equal, will no longer be right-angles. This effect is known as "Course Squeezing" and is accomplished by the insertion of attenuator pads in the feed to one pair of aerials; this is illustrated at Fig. 8c.

On the other hand, if one lobe of a "figure-of-eight" is varied with respect to the opposite one, then opposite angles of intersection of range-legs are no longer equal. This is known as "Course Bending" and is accomplished by the insertion of electrical delay circuits in the R.F. feed to the radiators, which change the phase displacement

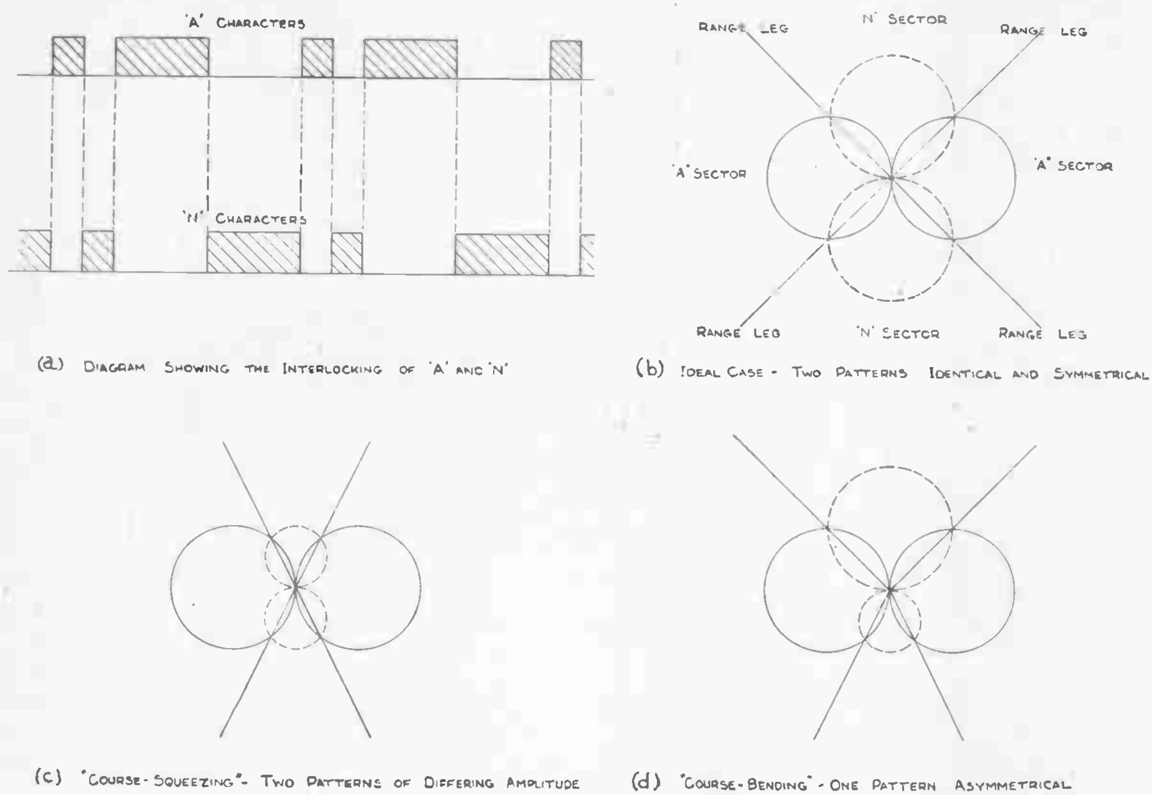

Fig. 8.—M.F. Adcock Radio Range

of currents in opposite towers to a value of other than 180 deg.; this is illustrated at Fig. 8d.

In practice, it is invariably necessary, for operational reasons, to resort to both "Course Squeezing" and "Course Bending" with the result that no two angles of range-leg intersection are similar. It should be noted that it is, however, not desirable to apply excessive "Squeeze" or "Bend" otherwise stability of course legs is liable to suffer.

Finally it is possible to rotate the combined patterns as a whole by means of the goniometer, thus permitting re-orientation of range-legs without the necessity of re-positioning the mast radiators.

It has been stated that the centre mast is continuously energized, the frequency of R.F. input to this differing from that radiated from the pattern aerials by 1,020 $\pm$15 c/s, thus providing an audio beat-note in the aircraft receiver, without the use of a local beat-frequency oscillator. Provision is made for the simultaneous modulation of the centre tower with speech signals if necessary, and by the use of 1,020 c/s "Band-Pass" and "Band-Stop" filters in the aircraft, to select at will either Range signals or speech. This facility for the transmission of speech by the Range station is not, however, used in the U.K., partly by reason of the increased frequency spectrum required and partly since an efficient V.H.F. communication channel has been provided for Airways flying—as described in Section 4 of this paper.

The transmitters themselves, which are shown at Fig. 9, are capable of supplying 400 W into the omni-directional aerial and 275 W into the Range pattern aerials, although in practice the radiated power is adjusted to give a field strength of 70 microvolts/metre at the limit of the service area. Duplicated transmitters are provided, and being normally unattended, provision is made for remote switching on/off, change-over and monitoring from the parent station using normal G.P.O. lines.

The unattended Radio Range stations are visited at weekly intervals for servicing and maintenance, and a continuous check is maintained on R.F. frequency, modulation frequency, and field strength by the Ministry of Civil Aviation Checking Station. To ensure that the correct orientation of range-legs is maintained, regular flight checks are carried out by aircraft of the Ministry of Civil Aviation Flying Unit.

It should be noted that the siting of Radio Range stations calls for great care, since stray reflections from topographical features can cause badly defined range-legs, or "Splits." In many cases it is necessary to carry out site trials, using a mobile equipment and conduct air checks before a decision can be taken as to the suitability of a site.

The Radio Ranges used in the U.K. Airways plan are listed in Table 1.

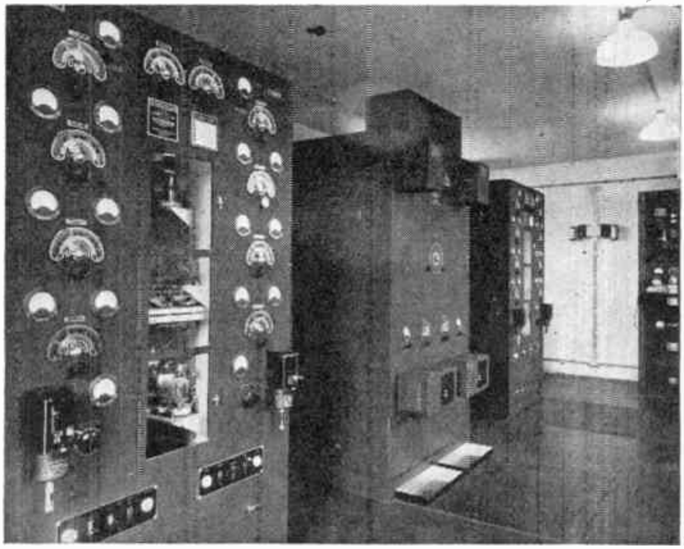

Fig. 9.—Medium Frequency Radio Range station showing duplicated transmitters. The R.F. keying equipment and coupling goniometer are housed in the unit between the two transmitters

5.2. *M.F. Beacons*

It has previously been stated that amongst the requirements for Airways flying are the following:—

(*a*) Provision of navigational aid to enable the pilot of the aircraft to locate the end or "joining point" of the Airway along which it is desired to fly.

Table 1

U.K. Radio Ranges

Location	Type	Callsign	Frequency	Operational Range Miles	QDM of Range legs			
Epsom	B/T	MYE	287·5	30	207	297	027	117
Filton	Adcock	MWA	279	100	193	284	005	118
Dunsfold	Adcock	MYD	357	100	263	329	084	166
Hurn*	B/T	MVH		30				
(Burtonwood) Liverpool	Adcock	MWB	383	100	271	334	103	167
Maidstone	Adcock	MVM	367·5	100	274	333	076	141
Prestwick	Adcock	GJR	374	100	076	148	271	339
Ronaldsway	Adcock	MYI	391	100	248	318	066	132
Watford	B/T	MYW	223	30	246	336	066	156

* Not yet in operation

(*b*) Provision of a navigational aid which will enable the pilot of the aircraft to "hold" at some particular point, when the section of Airway immediately ahead is occupied, or alternatively when the aircraft cannot be permitted to leave the inner end of the Airway for the terminal Control Zone.

Both of these functions can be met by the use of M.F. Beacons, since the carriage of M.F. D/F equipment by the aircraft is mandatory for Airways flying. In the first case, the aircraft radio compass is used to head the aircraft towards the beacon, sited at the end, or joining point of the Airway, arrival at this beacon being apparent by a reversal of the radio compass indicator. In the second case "holding" is performed by carrying out a prescribed orbit such that the aircraft passes over the beacon once during each "lap."

Ideally, M.F. Beacons would be sited at the ends of all Airways, at joining points, and at holding points, but due to the fact that insufficient frequencies are available in the bands allocated to aeronautical navigation this has not been possible, and as will be shown later, in certain cases use has to be made of another type of navigational aid.

The M.F. Beacons serving Airway functions are listed in Table 2, and their locations can be seen on the U.K. Airways Plan in Fig. 1. In all, 21 such beacons are used, of which the majority are operating between 255 and 405 kc/s, and these are set up for operational ranges of 10, 25, 50 or 100 nautical miles. It will also be seen, that in two cases B.B.C. transmitters are used as beacons, this being a measure made necessary by the acute shortage of M.F. channels; in these cases, when the B.B.C. transmitter closes down a low-power transmitter at the same location is brought into service.

Apart from the two B.B.C. stations referred to above, all beacons are located on remote, unattended sites and are visited at weekly intervals for maintenance; in some cases the parent station responsible for maintenance is as far as 100 miles away. It is of interest to note, that during experiments one of these beacons has operated without attention for four months during which time no operational failures have occurred.

It will be realized that reliability is of the utmost importance in the case of these beacons, and to this end two transmitters are installed together with an automatic changeover device, which brings the spare transmitter into operation in the event of a failure of the one in use. Means

Table 2
M.F. Beacons

Name	Identification	Frequency (kc/s)	Operational Range (nautical miles)
Burnham	MWM	362	50
Brookman's Park	London Home Service	908	(B.B.C. Station)
Congleton	MWG	361	25
Crowborough	MYC	343	25
Daventry	MVD	669·5	50
Falkirk	MZF	341	50
Hythe	MWE	322	25
Kintyre	MVR	355	50
Lichfield	MYA	543·5	25
New Galloway	MVG	723·5	50
Nutts Corner	MWC	343	50
Oldham	MYL	344	50
Ottringham	S	1295	(B.B.C. Station)
Renfrew	GER	325	50
Ringway	GFR	325	25
Speke	GJQ	340	25
Squires Gate	MVQ	286	25
Stonehouse	MVN	363	100
Strumble	MWL	352	100
Wigan	MWW	350	10
Woodley	MWZ	723·5	50

are provided whereby the parent station is made aware of the operation of the changeover device, and a special visit is made to ascertain the cause of the failure.

The transmitters themselves are crystal-controlled and capable of 100-W output, although in practice the power output of the transmitters is adjusted on installation to give a field strength of 60 ± 10 mV at the limit of the operational service area. Of the beacons listed in Table 2, the greatest power radiated is about 8 W and the least power about 0·01 W. The aerial systems used are for the most part of a simple "T" type having a top span of 140 ft. and a height of 70 ft., together with an 18-wire radial earth, the efficiency being of the order of 10 per cent. at the frequencies used. Identification of the beacons, which is carried out at 30-sec intervals, is effected by keying the modulation, the carrier remaining constant. This method of keying is adopted to eliminate disturbance to the radio-compass carried in the aircraft during the identification interval. The modulation frequency is $1{,}020 \pm 50$ c/s, and the modulation depth of the order of 90 per cent.

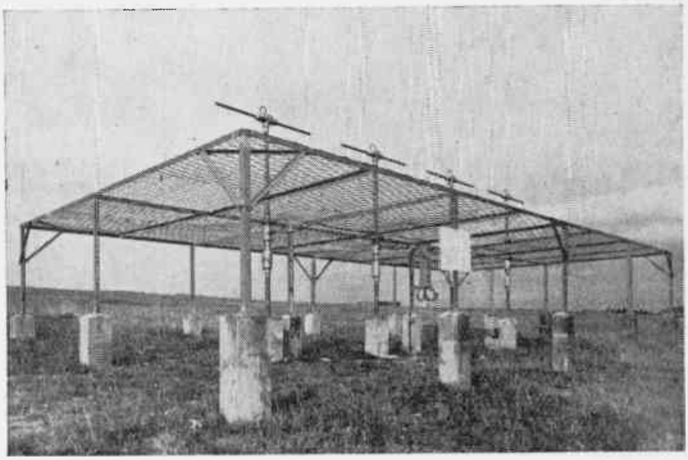

Fig. 10.—Fan-Marker aerial system. The four dipole aerials used to produce the vertical fan-shaped radiation pattern can be seen above the counterpoise screen.
(Photograph by courtesy of Ministry of Civil Aviation)

Apart from the continuous monitoring of the beacons by the parent station or Air Traffic Control Centre for operational purposes, the beacons are checked at regular intervals by the Ministry of Civil Aviation Checking Station to ensure that the radiated frequency and the power are within tolerance; the latter is of considerable importance since an essential feature of M.F. frequency allocation is the use of shared frequencies and compliance with laid-down "protection ratios."

5.3. *V.H.F. Fan Markers*

It has previously been stated that a requirement for Airways flying is a navigational aid that will enable the pilot of an aircraft to determine the precise moment that a "Reporting Point" is passed. This requirement is met by the use of V.H.F. Fan Markers.

A Fan Marker is a transmitter sited along the Airway and feeding into an aerial system that radiates vertically, the polar diagram being in the form of a fan laid across the Airway with the apex at the ground station, hence the name Fan Marker.

A fixed-tuned receiver is carried in the aircraft which causes a lamp to be illuminated in the cock-pit when the signal received from the Fan Marker exceeds a given value. Thus, an aircraft travelling along an Airway receives a visual signal that a Reporting Point has been reached, and the pilot is able to inform the Air Traffic Control Centre of this fact.

It has previously been stated when dealing with M.F. Beacons that owing to the acute shortage of these frequencies it is not always possible to provide such a beacon at "holding points." Where this is not possible then a Fan Marker is used instead, and the aircraft carries out a similar prescribed orbit which takes it over the Fan Marker.

The Fan Marker transmitters, which in all cases operate at 75 Mc/s, follow normal V.H.F. practice, being crystal controlled at a 1/18th fundamental frequency and have a maximum output unmodulated of 100 W, although if necessary the power output can be reduced down to 12 W. The final amplifier is anode modulated to 100 per cent. at a frequency of 3,000 c/s. As in the case of the M.F. Beacons the identification is effected by the keying of the modulation. The identification is repeated continuously and it is of interest to note that the usual three letter call-sign of a ground station is not used; instead a series

Table 3
Fan Markers

Name	Identification	Frequency	Located	Alignment of Minor Axis
Ashford	— — (continuously)	75 Mc/s	On S.E. leg of Maidstone Radio Range and S.E. leg of Epsom Radio Range	153°–330°
Beacon Hill	— — — — (continuously)	75 Mc/s	On N.W. leg of Dunsfold Radio Range	157°–337°
Chertsey	— — — — (continuously)	75 Mc/s	On N.W. leg of Dunsfold Range and N.W. leg of Epsom Radio Range	132°–312°
Compton (Hampstead Norris)	. . — — (continuously)	75 Mc/s	On E. leg of Filton Radio Range	093°–273°
Dean Cross (St. Bees Head)	. . — — — — (continuously)	75 Mc/s	On N.W. leg of Burtonwood Radio Range	151°–331°
Haslemere	— — — (continuously)	75 Mc/s	On S.W. leg of Dunsfold Radio Range	075°–255°
Ibsley	. . — — — (continuously)	75 Mc/s	On S.W. leg of Dunsfold Radio Range	033°–213°
Newport	— — — — (continuously)	75 Mc/s	On W. leg of Filton Radio Range	107°–287°
Point Lynas	— — — (continuously)	75 Mc/s	On W. leg of Burtonwood Radio Range	092°–272°
Portaferry	— — — — (continuously)	75 Mc/s	On N.W. leg of Isle of Man Radio Range	125°–305°
Seaford	— — (continuously)	75 Mc/s	On S.E. leg of Dunsfold Radio Range	140°–320°
Sevenoaks	— — (continuously)	75 Mc/s	On N.E. leg of Dunsfold Radio Range, S.E. leg of Epsom Radio Range, and S.E. leg of Watford Radio Range	144°–324°
Stockwood	— — (continuously)	75 Mc/s	On E. leg of Filton Radio Range	093°–273°
Wallasey	— — (continuously)	75 Mc/s	On S.E. leg of Isle of Man Radio Range	126°–306°
Warton	— — — — (continuously)	75 Mc/s	On N.W. leg of Burtonwood Radio Range	155°–335°
Whitegates (Tarporley)	. . — — (continuously)	75 Mc/s	On S.E. leg of Isle of Man Radio Range	138°–318°
Woburn	. . — — — — (continuously)	75 Mc/s	On N.W. leg of Maidstone Radio Range, and N.W. leg of Watford Range	132°–312°

of dots and dashes are sent in a sequence which indicates the particular leg of the radio-range along which the Fan Marker is sited, and its relative position where two or more are sited along the same range leg.

The aerial system used consists of four co-linear dipoles mounted $\frac{1}{4}$ wavelength above a metal counterpoise 20 ft. by 40 ft. The two outer dipoles are fed 180 deg. out of phase from the inner dipoles and the currents in the inner dipoles are three times those in the outer pair. The aerial system is fed by co-axial cable from the transmitter which is housed in a nearby building. The line sections to provide for impedance matching and adjustment of current ratios are housed in the columns supporting the dipoles. A view of a Fan Marker aerial system is given in Fig. 10.

By international agreement the aircraft receiver sensitivity is adjusted such that the lamp is illuminated when the input to the receiver terminals exceeds 3,000 μV and is extinguished when it falls below 2,500 μV. The aircraft aerial system, which consists of a dipole mounted under the fuselage, has also been standardized by international agreement. The duration of the lamp signal in the cockpit received by an aircraft flying along an Airway is clearly a function of both aircraft speed and aircraft altitude. The relationship between aircraft altitude and the distance over which the lamp is illuminated is shown at Fig. 11, from which it will be seen that it varies between 2 nautical miles at 3,000 ft. and 6 nautical miles at 11,000 ft.

Like the M.F. beacons previously described, the Fan Marker stations are at remote unattended sites, and duplicated transmitters are installed together with an automatic changeover device, and thus a high degree of reliability is assured. The performance of these Fan Markers is checked at regular intervals by specially equipped calibration aircraft of the Ministry of Civil Aviation Flight Unit.

The Fan Markers serving the U.K. Airways can be seen in Fig. 1, and are listed in Table 3. In all, 17 such markers are installed.

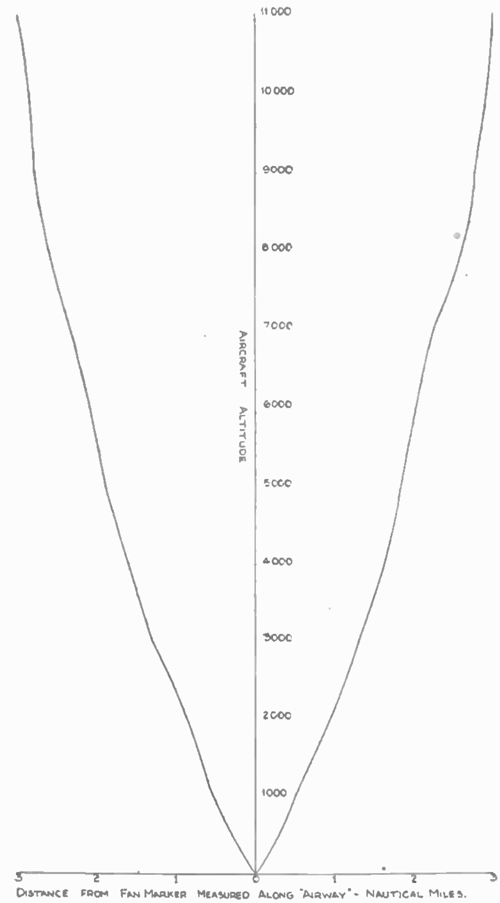

Fig. 11.—Graph showing relationship between aircraft altitude and the distance along airways that an indication is received from a V.H.F. fan marker.

6. Acknowledgments

The facilities described in this paper form part of the "Airways" programme of the Directorate-General of Navigational Services, Ministry of Civil Aviation.

A considerable number of colleagues took part in the original planning and experimental work, and later in the installation of the facilities described, and it is impossible to acknowledge their contributions individually.

The audio-frequency equipment for the V.H.F. networks and the high-stability oscillators used in the transmitters of these networks were developed by the Plessey Company to a Ministry of Civil Aviation Specification. All installation work was carried out by Ministry of Civil Aviation staff.

The author is grateful to the Director of Navigational Services (Telecommunications) for permission to publish this paper.

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THE STEREOPHONIC REPRODUCTION OF SPEECH AND MUSIC*

by

J. Moir and J. A. Leslie†

A Paper presented at the Sixth Session of the 1951 *Radio Convention on September 5th at Earls Court, London.*

SUMMARY

Monaural reproducer systems are probably nearing the limit of development and further improvement in the quality of reproduced sound is likely to be found in the application of stereophonic systems.

Methods of achieving true and pseudo stereophony are described.

Factors responsible for the stereophonic effect are discussed and it is shown that the loudness difference at the two ears makes no significant contribution to the accuracy of location.

1. Introduction

There can be little doubt that the best examples of monaural reproducer systems have reached a stage where further improvement in the quality of reproduction will be extremely difficult to obtain. A reasonably uniform frequency response up to 15 kc/s and a distortion level below 0·1 per cent. can be achieved, and there seems to be little justification for further development along those lines. It is not necessary to go into all the factors that are important for high-quality reproduction, for most of them are well known and in any case are equally important in both monaural and stereophonic reproducer systems. From the relatively small amount of work that has been done it would appear that further significant advances in quality will have to come from multi-channel systems of reproduction, and that further development effort should be directed towards finding engineering and economic solutions to the many problems that appear. This contribution is intended to direct attention to the fundamentals of stereophony and to discuss some of the solutions that have been suggested, and it seems reasonable to commence with an indication of the advantages of multi-channel reproduction. In view of the difficulty of conveying subjective impressions through the medium of the written word, it can hardly be expected to be completely conclusive.

2. Advantages of a Stereophonic System

In any monaural reproducer system the spatial co-ordinates are almost completely lost, only an impression of depth remains, and so all the action appears to take place in a tunnel with a microphone at its mouth. In a stereo system the acoustic characteristics of the studio can be faithfully reproduced and the long tunnel effect disappear. At first sight this and the concomitant advantage of being able to "place" the artiste or instrumentalist do not appear to be great advantages, but in practice they do produce a most remarkable improvement in the acoustic illusion.

A somewhat unsuspected result is the increase in clarity due to the spatial separation of the artistes, a result that is probably connected with the ear's ability to disregard sounds that approach the listener from directions other than that in which he desires to listen. Recent investigation has shown that there is an improvement of about 12 db in the signal/noise ratio due to the ear's steerable directivity pattern. The reproduction of a large orchestra through a small loudspeaker is unsatisfying even when all the usual performance criteria are satisfied; one misses the movement of the sound source and the interplay of the various sections of the orchestra with some slight revulsion at the idea of such a large sound source being confined to such a small hole. In fact a monaural reproducer gives much the same effect as listening with one ear at a hole in the wall of a concert hall.

A better idea of the relative merits of a multi-channel system may be gained by studying the comments of an audience after hearing a comparison. Such comparisons have been obtained in America by Bell Labs. and in Europe by Phillips. The American[1] tests indicated that a stereophonic reproduction flat to 3,750 c/s was considered to be equal to a single-channel system flat to 15 kc/s. J. P. Maxfield, of Bell Labs., has

* Manuscript received August 15th, 1951.
† British Thomson-Houston Co., Ltd.
U.D.C. No. 534.76:625.395.61.

stated, "I would rather hear 2-channel reproduction good to 6 kc/s than single-channel reproduction flat to 15 kc/s; it is more pleasing, more realistic, more dramatic." It should, perhaps, be emphasized that the improvement cannot be adequately expressed in terms of bandwidth, though this is convenient in the absence of any alternative index of æsthetic satisfaction.

3. Mechanism of the Stereophonic Effect

It is somewhat surprising that there is so little definite information and so much difference of opinion on the mechanism of the stereophonic effect. The possession of two ears spaced apart by the head permits the sound field to be sampled at two points and from the differences the ear-nervous system-brain combination is enabled to obtain the necessary clues to the location of the sound source. Sound from any source not in the median plane will arrive at the remote ear slightly later than at the near ear, and, because of diffraction round the head, it will also differ in frequency content. These differences, either singly or in combination, provide the clues to localization. The information available to the ear may be listed as follows:—

1. For impulsive or transient sounds the initial wavefront will strike the two ears with a time difference that is a function of the displacement of the source from the median plane. The maximum time difference will occur when the source is in line with the two ears and is approximately 0·00063 sec, corresponding to an ear separation of approximately 21 cm.
2. For a repetitive signal, such as a single musical note, the peaks in the wave will strike the two ears with the same time difference as in the case of a transient sound, but, if it is assumed that the ear cannot distinguish one peak from another, time differences corresponding to less than one cycle are the only ones that are significant. It is then conventional to refer to these as phase differences.
3. For any type of sound there will be a loudness difference at the two ears, this difference being due to the increased attenuation of the longer path to the further ear. It is generally small except where the sound source is close to the head.

While the loudness difference due to item 3 is generally small, significant differences do occur when the incident sound wave is a single tone of frequency above about 1,000 c/s or when it is a complex wave containing components above that frequency. The loudness difference arises because the two ears are separated by the mass of the head which introduces diffraction effects which are a function of frequency. Wiener[2] has recently measured the effect of diffraction, his results being shown in Fig. 1, from which it will be seen that there is a average difference of 7 db even at frequencies as low as 1,000 c/s. The

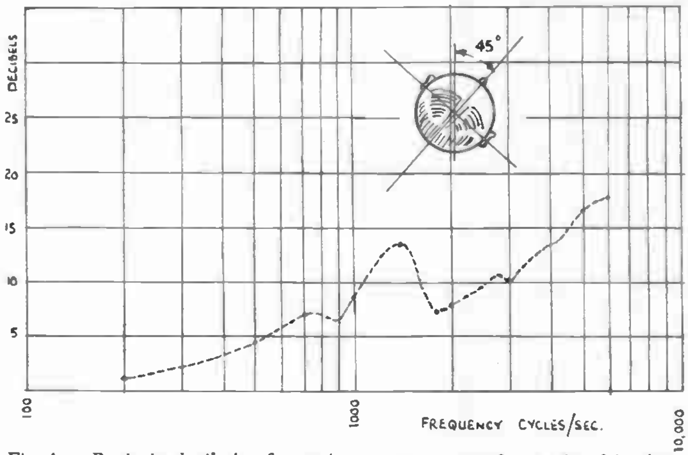


Fig. 1.—Ratio in decibels of sound pressure at ears for angle of 45 *deg. (After Wiener*[2].*)*

results on speech are of greater significance and Steinberg's calculated results are shown in Fig. 2, but too great reliance should not be placed on these calculations in view of the discrepancies that have appeared between calculated and measured diffraction patterns.

It will be appreciated that all these differences disappear for sound sources lying in the vertical median plane as all points in this plane are then equidistant from both ears. The precision of location in the vertical plane is, therefore, rather low. Discrimination between front and rear is also poor unless the head is free to make some exploratory movements. Without such freedom the brain apparently depends upon the frequency characteristic differences produced by the ear lobes, but, if the head is free to move, front and

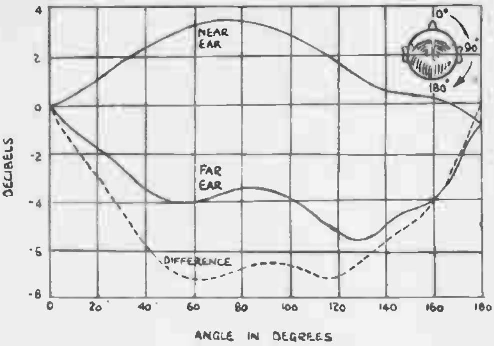


Fig. 2.—Variation in loudness as a speech source is rotated in a horizontal plane around the head.

rear can be more easily distinguished presumably as a result of the brain noting which ear receives the first wave front.

There is marked disagreement among world authorities as to which of the listed differences provides the clue to localization under ordinary conditions, the majority favouring loudness difference.[3] Stewart[4] favours phase difference, recognizing that this must fail somewhere in the region of 1,000 c/s where more than one cycle of the sound wave can be accommodated in the ear separation distance.

Shaxeby[5] favours time difference on the score that it is easier to locate a complex sound than it is to locate a simpler sound. The individual components of a complex wave all have different phase relations to the fundamental component, and at first sight it would appear that this should lead to confusion rather than to an increase in the accuracy of location but we have confirmed that the accuracy of location is higher on clicks than on speech.

Experience tends to suggest that the brain always takes note of all the evidence and, if this is the case, it would seem that phase might provide the clue below 1,000 c/s with intensity ratio effective between 1,000 c/s, and perhaps 3,000 c/s, and frequency characteristic difference effective above 3,000 c/s. This is a view that is fairly widely held.

4. Stereophony Indoors

Our prime interest is in the reproduction of sound inside buildings and it is essential that the introduction of stereophony should not demand any large-scale modification to buildings for acoustical reasons. Some of the factors commonly thought to be responsible for the stereophonic effect appear to be rather sensitive to acoustical conditions and some tests were, therefore, initiated to determine the loss of accuracy likely to result from the acoustical conditions in existing theatres, but early in the tests it was realized that the results being obtained had some significant bearing on the fundamentals of stereophony.

The first tests were intended to compare the accuracy of location of two types of sound source, (1) male speech, (2) sharp metallic clicks.

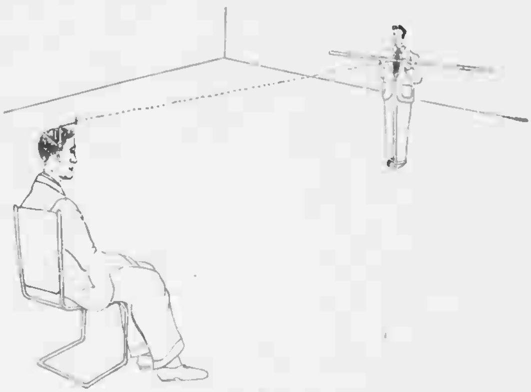


Fig. 3.—Method of error measurement in sound location tests.

The procedure was as follows. The reader and subject under test were spaced about 25 ft apart in the middle of an open field, the reader holding a horizontal stave scaled off in each direction from the centre, as shown by Fig. 3. The subject wore a light head band carrying a horizontal sighting rod initially lined up with the subject's head by asking him to look at the zero mark on the reader's stave and then adjusting the sighting rod to line up with the same target. The reader then took up 10 different positions on a 25-ft radius from the blindfolded subject, and for each position passages were read from a book until the subject indicated that he was "on target." A third assistant then read off the error on the reader's stave by means of the sighting rod. This was repeated with five different subjects and the results averaged. For the first series of indoor tests the same group of observers repeated the procedure in one of the works theatres, a room about 70 ft $\times$ 30 ft, the listening position being chosen as far from the speaker as could be managed, the spacing being about 55 ft. The two sets of results are set out in Table 1 and it is somewhat surprising that they show that the indoor accuracy is every bit as good as it is possible to achieve outdoors in free space. At this distance in this particular theatre it is computed that the reverberant sound energy exceeds the direct sound energy by a factor of approximately seven times. The majority of the reverberant sound arrives after multiple reflection from the boundary surfaces and cannot contain any information on the position of the point of origin of the sound.

Table 1

Comparison of the Accuracy of Location in Indoor and Outdoor Situations

Sound Source—Original Male Speech.

	Mean Error	*Standard Deviation*
Indoors at spacing of 55 ft.	1·04°	1·15°
Outdoors at spacing of 25 ft.	1·2°	2·7°

This result seems difficult to explain on any loudness difference theory of location, unless the combination of the ear, nervous system and brain is able to reject either wholly or in part the contribution of the generally reflected sound to the total loudness. A similar difficulty exists in the case of any time difference theory as the reflected sounds arrive with time spacings that are characteristic of the room rather than of the position of the source. Both difficulties are removed if it is postulated that the ear can, in fact, ignore the reflected sounds. Two inhibitory effects have recently been found in researches into the neural mechanism; the first a short-time effect in which the sense organ, once discharged, is unable to "fire" again for a time interval up to approximately two milliseconds, and a second effect, not so well established, in which the activity may be inhibited for much longer periods. It seems probable that the Haas effect results from the same inhibitory action, the long-time effect being the most likely cause.

Some indication of the factors that are important in providing the major clues to position localization might be obtained if the contribution of various regions of the spectrum were known. A first approach to this problem has been made by checking the accuracy of location of filtered male speech. Filters having the characteristics

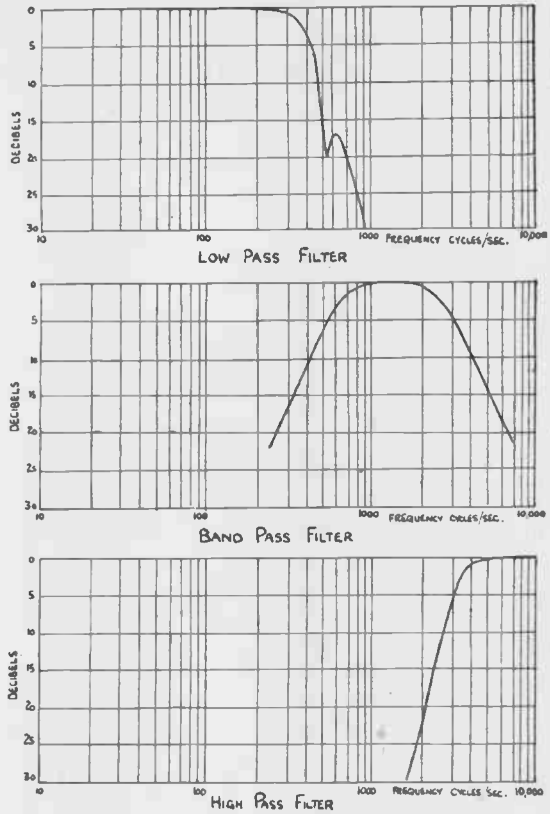


Fig. 4.—Filter characteristics.

shown in Fig. 4 enabled the frequency band to be divided into three bands, 0-500, 500-3,000 and 3,000-7,000 c/s, and the accuracy of location was checked on male speech. As some initial tests suggested that there might be difficulties with the 0-500 c/s band that were not revealed by error figures only, we also noted the time taken for each subject to get "on target," but, as will be seen, the time differences were never significant. As Table 2 shows there is sufficient information for the ear to give satisfactory location even when the band is restricted to the bottom 500 c/s, while above this frequency there appears to be slightly more information between 3,000 and 7,000 c/s than there is between 3,000 and 500 c/s. This is rather surprising in so far as there is little intelligibility in the signal that remains when everything below 3,000 c/s is removed from male speech. The figures do suggest, though not conclusively, that the ear relies on the information carried by the high-frequency end of the

Table 2

Accuracy of Location Using Bands of Filtered Male Speech.

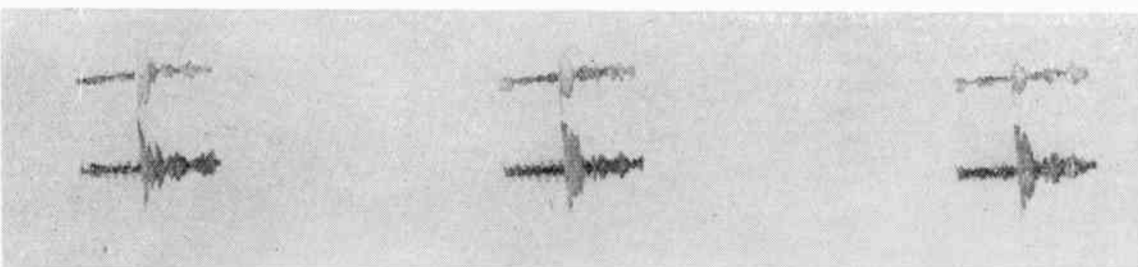
Frequency Range	*Average Error*	*Standard Deviation*	*Average time to Locate*
50-500 c/s ..	3·8°	3·55°	13·2 sec
500-3,000 c/s ..	·9°	3·8°	10·5 sec
3,000-7,000 s/c ..	·5°	3·4°	12·8 sec
50-7,000 c/s ..	·7°	4·7°	10·7 sec

spectrum and that the addition of the information in the lower end of the audio band only serves to confuse the ear in coming to any conclusion.

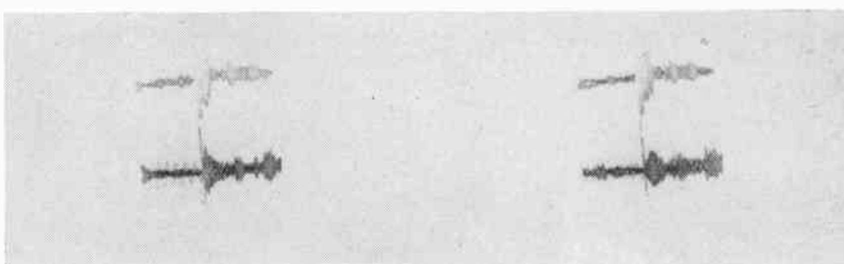
If the ear has some discrimination in this respect, localization may be due either to amplitude difference, or the time difference of the *direct* sound components at the two ears, or, as seems more probable, due to a combination of both factors with time difference playing the major part. The results of a further preliminary investigation are not yet conclusive, but are worth reporting.

Two Acos sound cell microphones were set up in a dummy head having reasonable resemblance to a real head, and time, direct amplitude difference and loudness difference at the two ears were measured as a function of the angular displacement of the head from the median plane. In order that we should be able to make simultaneous determinations of the relative amplitudes of the direct sound and of the loudness ratio, it was necessary to adopt a pulse technique as this makes it possible to separate direct and reverberant sound. The method has been described in a previous paper[8] and so it need not be repeated. A typical C.R.T. picture is shown in Fig. 5, the direct and reverberant sound pulses being indicated. For loudness measurements a standard type of sound level meter to the current American standard was used. Time of arrival differences were measured from the relative positions of the pulse fronts at the two ears, as shown on the C.R.T. 20-millisecond pulses of tone were used and the loudness and direct amplitude results quoted in Fig. 6 are the average values for five frequencies between 1 and 2·5 kc/s. As will be seen the rate of change of the direct amplitude ratio per degree is about five times higher than the rate of change of the loudness ratio. This is to be expected as the loudness is a function of the sound energy density at the ears and this is almost entirely reverberant sound energy when the speaker/ear spacing is more than a few feet.

Both the direct amplitude ratio and the time difference are seen to be capable of providing



(*a*) No rotation of head. (*b*) Head rotated 45° to left. (*c*) Head rotated 90° to left.



(*d*) Head rotated 45° to right. (*e* Head rotated 90° to right.

Fig. 5. C.R.T. pictures of pulses received by two ears. Frequency 2000 c/s.

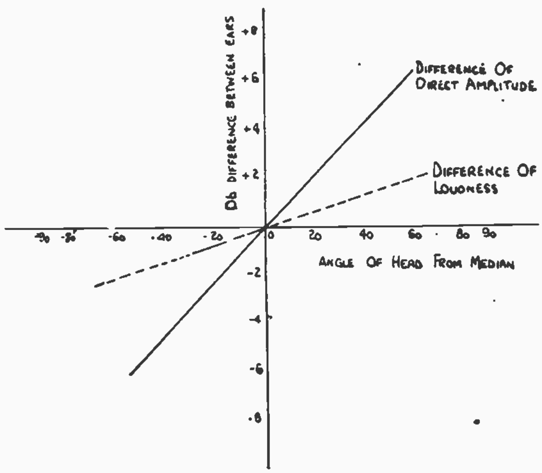


Fig. 6.—Difference in direct amplitude and loudness at the two ears.

satisfactory clues to localization and both are independent of the acoustic environment.

5. Methods of Producing Stereophony

There are two approaches to the practical problem of producing a stereophonic system and both have their exponents.

In the first a dummy head or some object having similar diffraction characteristics to the human head is provided with two microphones in positions equivalent to the ears, each microphone being connected through suitable amplifiers to headphones worn by each member of the audience, all left earpieces being connected to the left microphone and right earpieces to the right microphone. This is fairly effective in transferring the sound field at the pick-up point to each member of the audience, but is not completely effective if the dummy head is in one fixed position, the audience then being without any solid indication as to whether the sound source is in front or behind them. The brain appears to be sensitive to suggestion on this point and the appearance of a picture (sound film) provides all the suggestion necessary. Headphones are not considered a practical proposition in a theatre and this system will not be given further consideration.

The second system is equally simple in theory. If one considers a long hall having an audience at one end and an orchestra at the other, the acoustic conditions are not altered if one inserts a sound-proof partition across the centre, the partition being covered on the orchestra side by rows of microphones and on the audience side by similar rows of loudspeakers, each microphone being connected to its spatially equivalent loudspeaker. Though theoretically satisfactory, this scheme is not very practical unless some reduction in the number of separate speaker channels is possible, a particularly important point if a recording channel is to be used between microphone and speakers. It was noted earlier that localization in the vertical plane is rather poor and this suggests that the vertical rows of speakers might be dispensed with, without serious loss in performance. It is also obvious that the majority of stage action takes place at ground level, further justification for omitting the vertical rows of speakers. With present technique, two or three separate channels are all that can be accommodated in a recording link, and it is therefore fortunate that three channels are found to give a good performance that may be acceptable as an interim measure. Two- and three-channel systems have been compared by a number of investigators who have found that the performance of a three-channel system is generally superior to a two-channel system, but, as the comparison is available in recent publications, it need not be repeated here. A point that has not been made previously is that the dynamic localization of a source appears to be appreciably more accurate than is shown by the data obtained from localization tests on a stationary source. This applies to all the variations of two- and three-channel systems that we have compared.

Hybrid combinations of the dummy head and sound transparent wall techniques have been suggested, in which the sounds picked up by two microphones closely spaced or mounted in a head are then fed to two widely spaced loudspeakers. On referring to Fig. 7 it will be seen that this results in large amplitude and time differences due to the speaker separation being superimposed on the much smaller amplitude and time differences that exist at the microphones except for members of the audience sitting on a line symmetrically disposed about the loudspeakers. As one moves off the axis, the true time and differences due to the microphone spacing become increasingly diluted by the time and amplitude differences characteristic of the loudspeaker and audience positions. Experience indicates that this dilution of the true data

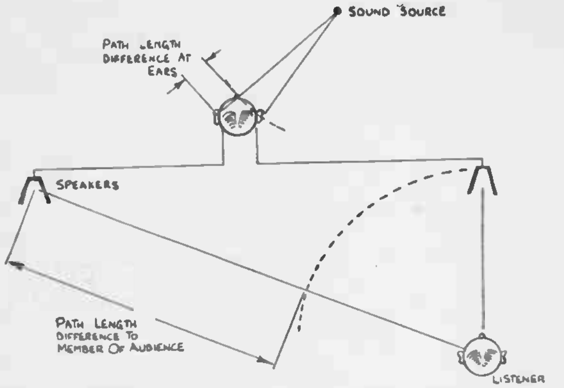


Fig. 7.—Path length discrepancy using closely spaced microphones and widely spaced speakers.

results in unsatisfactory localization for listeners off the loudspeaker axis, the sound source being confined to the loudspeaker on the listeners' side of the stage. This effect appears to exist up to a loudspeaker/listener spacing of about one and one-half times the loudspeaker spacing. On the centre line between the loudspeakers, the time differences due to the speaker spacing cancel and the performance can be very satisfactory.

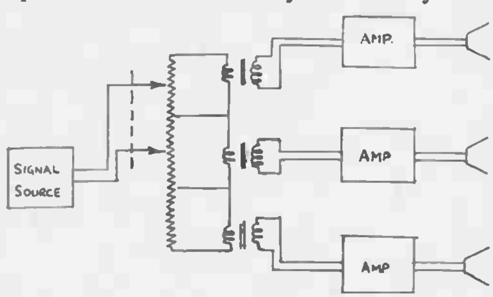


Fig. 8.—Simple panoramic sound reproduction system.

6. Pseudo Stereophony

Most of the recording organizations have built up large libraries of stock sound shots, train noises, birds, boats, aeroplanes, etc., and there are many occasions when it is convenient to work these into new recordings. Pseudo stereophonic effects can be produced by intensity changes only, the simple circuit of Fig. 8 changing the power distribution between loudspeakers while keeping the total power substantially constant. This is satisfactory for incidental effects, but is no substitute for a stereophonic recording. Room acoustic conditions are not transmitted and static localization is poor.

7. Conclusions

The real obstacle to the adoption of any stereophonic system is that of the multiplication of equipment and bandwidth. Equipment is not thought to be serious, but the bandwidth requirements for three channels does appear to require some thought. Earlier comment suggests that, where frequency space is restricted to ten or twelve thousand cycles, it may be better to use that band to transmit two or three stereo channels rather than one wide band monaural channel.

Other solutions are possible; Blumlein has demonstrated a two-channel system in which a disk recording with simultaneous lateral and vertical modulation is used. Quarter-inch tape recording systems have adequate space for two channels side by side and a further small increase in tape width would permit the use of three channels.

Woodyard has suggested the use of simultaneous amplitude and frequency modulation, and has verified that adequate separation can be obtained to allow the transmission of stereo signals.

This contribution is to be looked upon as an interim report which throws some further light on an interesting subject, but only serves to show that the ear is a long way from yielding up its secrets.

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MEMBERSHIP COMMITTEE

Arthur Frederick Bulgin was born in 1899 at Barry, Glamorganshire, where he received his general education. During the First World War he served in the Royal Flying Corps as a Wireless Operator/Observer and on demobilization studied electrical engineering at the Northampton Polytechnic.

After practical engineering training, he formed his own company, A. F. Bulgin & Co., in 1923. Mr. Bulgin is still managing director of the organization which became a public company in 1948.

Since 1941 Mr. Bulgin has been actively interested in the Air Training Corps, and he is Commanding Officer of the West Essex Wing of the Corps, holding the rank of Wing Commander. For his outstanding services he was appointed a M.B.E. in 1946.

Mr. Bulgin was elected a Member of the Institution in 1943, and was appointed to the Membership Committee in January, 1952. For very many years Mr. Bulgin has advocated closer collaboration between engineers engaged in the Services and engineers in industry. Toward this end he recently offered to endow an Institution Premium; the Council has accepted this offer and the Premium will from this year be awarded annually for the best paper received from a serving member of H.M. Forces.

Born in Plymouth in 1905, **Frank Walter Dawe** obtained an A.C.G.I. diploma at Finsbury Technical College in 1925 and his first company was the Edison Swan Electric Co., Ltd., at Ponders End.

Between 1930 and 1932 he was with the Gramophone Company's Test Gear Department, and subsequently joined E. K. Cole, Ltd. In 1937 he became Technical and Production Manager of Marconi Ekco Instruments and later Chief Engineer of E. K. Cole, Ltd. (Aylesbury Division).

For two years Mr. Dawe was Managing Director of R.F. Equipment, Ltd., and in 1945 he founded his own firm of Dawe Instruments, Ltd., of which he is Managing Director.

Mr. Dawe was elected a Member of the Institution in 1944 and he was appointed to the Membership Committee early this year.

William Philip Rowley was born in 1915 at Ealing where is received his general education. On completing his technical education at Regent Street Polytechnic, he joined the M-O Valve Co., Ltd., as a technical assistant in the Experimental Valve Department.

At the outbreak of war in 1939, Mr. Rowley joined the Royal Army Ordnance Corps, subsequently transferring to the Royal Corps of Signals and obtaining a commission in 1941. After a period as lecturer in radio at No. 1 Radio Mechanics School, he was appointed in 1942 Staff Officer (Wireless) to the Signal Officer-in-Chief, G.H.Q. Home Forces, later holding similar appointments with 21st Army Group and S.H.A.E.F. He was awarded the M.B.E. for his services in 1945 and demobilized in 1946 with the rank of Major. After joining the Radio Division of Edison Swan Electric Co., Ltd., Mr. Rowley became Manager of the Electronics and Industrial Valves Sales Department. Early in 1952 he joined Elliott Brothers (London), Ltd., as Sales Manager of the Electronics Division.

Mr. Rowley joined the Institution in 1941 as an Associate Member and was transferred to Full Member in 1944. He served on the Education and Examinations Committee from 1946 to 1950 when he was appointed to the Membership Committee. He has been an examiner in Electricity and Magnetism for Part I of the Graduateship examination since 1948.

APPLICANTS FOR MEMBERSHIP

New proposals were considered by the Membership Committee at a meeting held on May 14th, 1952 as follows: 21 proposals for direct election to Graduateship or higher grade and 27 proposals for transfer to Graduateship or higher grade; also 41 applications for Studentship registration.

The following are the names of those who have been properly proposed and appear qualified. In accordance with a resolution of Council and in the absence of any objections being lodged, these elections will be confirmed 14 days from the date of the circulation of this list. Any objections received will be submitted to the next meeting of the Council, with whom the final decision rests.

Direct Election to Full Member

BELL, Norman. *London, E.C.3.*
DUNCAN-SMITH, Edward. Colonel, D.Sc. *Bangalore, India.*

Transfer from Associate Member to Full Member

SKERREY, Cyril Ernest *Basrah, Iraq.*

Direct Election to Associate Member

BANFI, Alessandro. *Milan, Italy.*
BEAUMONT, Frank Halton. *Brighouse, Yorkshire.*
BOLTER, Douglas John. Flight Lieutenant. *Devizes, Wiltshire.*
DEIGHTON, Richard, B.Sc. *Gt. Malvern, Worcestershire.*
JANWEJA, Ram Krishan, B.Sc. *Lucknow, India.*
LALIT, Shankar Vishnu. *Bombay.*
MEHROTRA, Raja Ram, Ph.D., M.Sc. *Benares, India.*
POTTER, Stanley Arthur, Lieutenant Commander. *Wootton Bridge, Isle of Wight.*
RAJAGOPALAN, Kombur Srinivasa, B.Sc. *New Delhi.*
SIMMONS, Albert. *London, S.E.3.*

Transfer from Associate to Associate Member

GRANGER, Herbert James. *Calne, Wiltshire.*
HERSEE, George. *Littlehampton, Sussex.*
LACEY, John Howard. *Greenford, Middlesex.*
NORMAN, Geoffrey Percy Frederick. *Dumfries, Scotland.*
PHILLIPS, Graham. *Godstone Green, Surrey.*
REECE, Charles Norman William. *Wisterton, Cheshire.*
SHEAD, William Percival. *Hillingdon, Middlesex.*

Direct Election to Companion

SAWTELL, Leonard Alan. *Wembley, Middlesex.*

Transfer from Graduate to Associate Member

AMES, Gerald James, B.Sc. *St. Albans, Hertfordshire.*

Transfer from Student to Associate Member

WHITEMORE, Gerald. *Hayes, Middlesex.*

Direct Election to Associate

COLLINS, Aaron Dennis. *Bangalore, India.*
FRYDAS, Panos, B.Sc. *Athens.*

Direct Election to Graduate

MITCHELL, Donald Keith. *Greenford, Middlesex.*
SODHI, Jasjit Singh, B.A. *Simla, India.*

Transfer from Student to Graduate

DATE, Vishnu Purushottam, B.Sc. *Poona.*
GHOSH, Jyotirmay. *Benares, India.*
JACOBS, Frederick George. *London, N.1.*
MAHON, Vincent. *Coventry.*
STOKES, John Alfred. *Birmingham.*
TURVILLE, Denis Gregory. *London, E.6.*

Studentship Registrations

ANDERSON, Archibald Charles. *Netley, Hants.*
BAGDADLIAN, Jeraver Ardashes. *Southampton.*
BRIDGEMAN, James Neville. *Croydon, Surrey.*
BURKILL, Arthur Herbert. *London, N.W.10.*
CHALHON, Moise Oriel. *Beirut, Lebanon.*
CHANDRA, Kartik Chandra. *Calcutta.*
COOKE, Joseph James, B.Sc. *London, N.6.*
DOYLE, Martin Edward, Lieutenant. *Cork, Eire.*
D'SOUZA, Arthur. *East Croydon, Surrey.*
GREEN, Norman, B.Sc. *Bingley, Yorkshire.*
HARPER, Dennis George. *Farnborough, Hants.*
HATFULL, Terence James. *Dartford, Kent.*
JAMES, Brian Harry Laurence. *London, S.E.27.*
JORDON, Francis Joseph Patrick. *Dublin, Eire.*
KANWAR, Singh Randhir. *Roorkee, India.*
KHEIRI, M. Abdur Rahman, B.Sc. *London, W.11.*
KRISHNAMOORTHY, A., B.Sc. *Madras.*
KRISHNA RAO, Delapathyrao V. *Vijayavada, India.*
KULANTHAIVELM, Thampu, B.Sc. *Valvethitenai, Ceylon.*
LEWIN, John Ernest. *Bromley, Kent.*
LUETCHFORD, Leslie Walter. *Cochrane, Ontario, Canada.*
MANINDRA, Das, M.Sc. *Assam, India.*
MARTIN, Robin Fletcher. *London, N.3.*
MILLS, Arthur Frederick. *Southall, Middlesex.*
MURTY, Gudinaty Naravana. *Madras.*
NARAYANAN, Nambiath, B.A. *Madras.*
NEWMAN, Robert Hanmer. *Haywards Heath, Sussex.*
NICHOLSON, Michael David. *Guernsey, Channel Islands.*
OWENS, David Bernard Raymond. *Sanderstead, Surrey.*
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