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Propagational Factors in Short-wave Broadcasting

by

L. J. PRECHNER, B.Sc.
(External Broadcasting Department, BBC Engineering Division)

BRITISH BROADCASTING CORPORATION

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FOREWORD

THIS is one of a series of Engineering Monographs published by the British Broadcasting Corporation. About six are produced every year, each dealing with a technical subject within the field of television and sound broadcasting. Each Monograph describes work that has been done by the Engineering Division of the BBC and includes, where appropriate, a survey of earlier work on the same subject. From time to time the series may include selected reprints of articles by BBC authors that have appeared in technical journals. Papers dealing with general engineering developments in broadcasting may also be included occasionally.

This series should be of interest and value to engineers engaged in the fields of broadcasting and of telecommunications generally.

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PREVIOUS ISSUES IN THIS SERIES

PROPAGATIONAL FACTORS IN SHORT-WAVE BROADCAST RECEPTION

SUMMARY

This monograph deals primarily with problems associated with the operation of the short-wave transmissions which provide the major part of the BBC external service coverage. The factors involved include seasonal wavelength changes, increasing congestion in the short-wave broadcasting bands, and various types of propagational disturbances. The incidence of some of the latter, including tropical sunset fading effects, ionospheric storms, and sudden ionospheric disturbances, has been analysed over a number of years and the results are discussed. Finally, reception results obtained during the maximum and minimum periods of the current sunspot cycle are compared with the theoretical predictions for BBC transmissions over three typical long-distance paths.

1. The BBC External Broadcasting Services

The BBC short-wave broadcasting service commenced on 19 December 1932 with a single programme in English called 'The Empire Service'. From this modest beginning a very considerable expansion took place immediately prior to and during the Second World War, so that, by the end of 1945, the BBC short-wave output had increased to about 550 transmitter-hours daily in over forty languages. Since the war, the daily output in terms of transmitter-hours and languages has fluctuated somewhat, dependent on economic and political circumstances.

By mid 1962 the BBC External Services either operated or made use of thirteen transmitting stations in all, with a grand total of sixty transmitters in service. Of these, seven transmitting stations are located in the United Kingdom, comprising forty short- and four medium- and long-wave transmitters. (Plate 1 shows two short-wave aerial arrays at Daventry.) The other six transmitting stations, which are used mainly for relays, comprise: a short-wave station at Tebrau in Malaya; a medium-wave and a VHF station in Berlin; a medium- and short-wave station in Cyprus; a medium-wave station in Malta; and a medium-wave station at Berbera in the Somali Republic.

As some of the original transmitting equipment in the United Kingdom is now over twenty years old, a comprehensive plan for modernization has been evolved and work is well advanced. Higher transmitter powers and better aerials are being introduced to improve reception – particularly in those areas which have proved difficult to serve in the past.

2. Problems Peculiar to Short-wave Broadcasting

2.1 *General*

At the present time, short waves provide the only practical and economic means by which broadcast coverage on a world-wide basis can be achieved.

On the other hand, their use is subject to certain inherent disadvantages, for example:

1. Frequencies have to be changed in accordance with ionospheric variations,[1] in contrast to domestic broadcasts on long and medium waves and the VHF bands, which normally remain on fixed frequencies.
2. The ionosphere is not a constant reflecting medium, but is subject to many irregularities.[1] For instance, the quality of reception of short-wave transmissions may be adversely affected by different types of fading, tropical sunset effects, ionospheric storms, sudden ionospheric disturbances, etc.
3. The increasing congestion in the short-wave broadcasting bands, which is also greatly aggravated by deliberate jamming, often seriously degrades the general quality of reception in these bands.

Some aspects of these difficulties are discussed in greater detail below.

2.2 *Seasonal Wavelength Changes*

Short-wave radio transmissions are propagated via the ionosphere; hence, the choice of the best operational frequency for a given service area depends upon the ionospheric characteristics which vary in a complex manner with locality, time of day, season, and sunspot cycle.[1]

Different frequencies have to be selected for each specific service area, according to the time, season, and solar activity. For example, Fig. 6 shows the predictions for the U.K./Teheran path for June, with marked diurnal and sunspot cycle variations, and Fig. 15 shows the predicted and observed seasonal variations in reception on the U.K./Wellington path in 1960.

The Administrative Radio Conference at Geneva in 1959[2] decided that at least four major schedules would be required each year, to be introduced on the first Sundays in March, May, September, and November. The first schedule of this pattern was that for September 1960. In accordance with the 'Frequency Management Procedure'[2] the United Kingdom and other administrations forward their projected seasonal broadcasting schedules to the International Frequency Registration Board (IFRB) in Geneva. The IFRB collate and publish all these schedules in a single document called the 'Tentative High Fre-

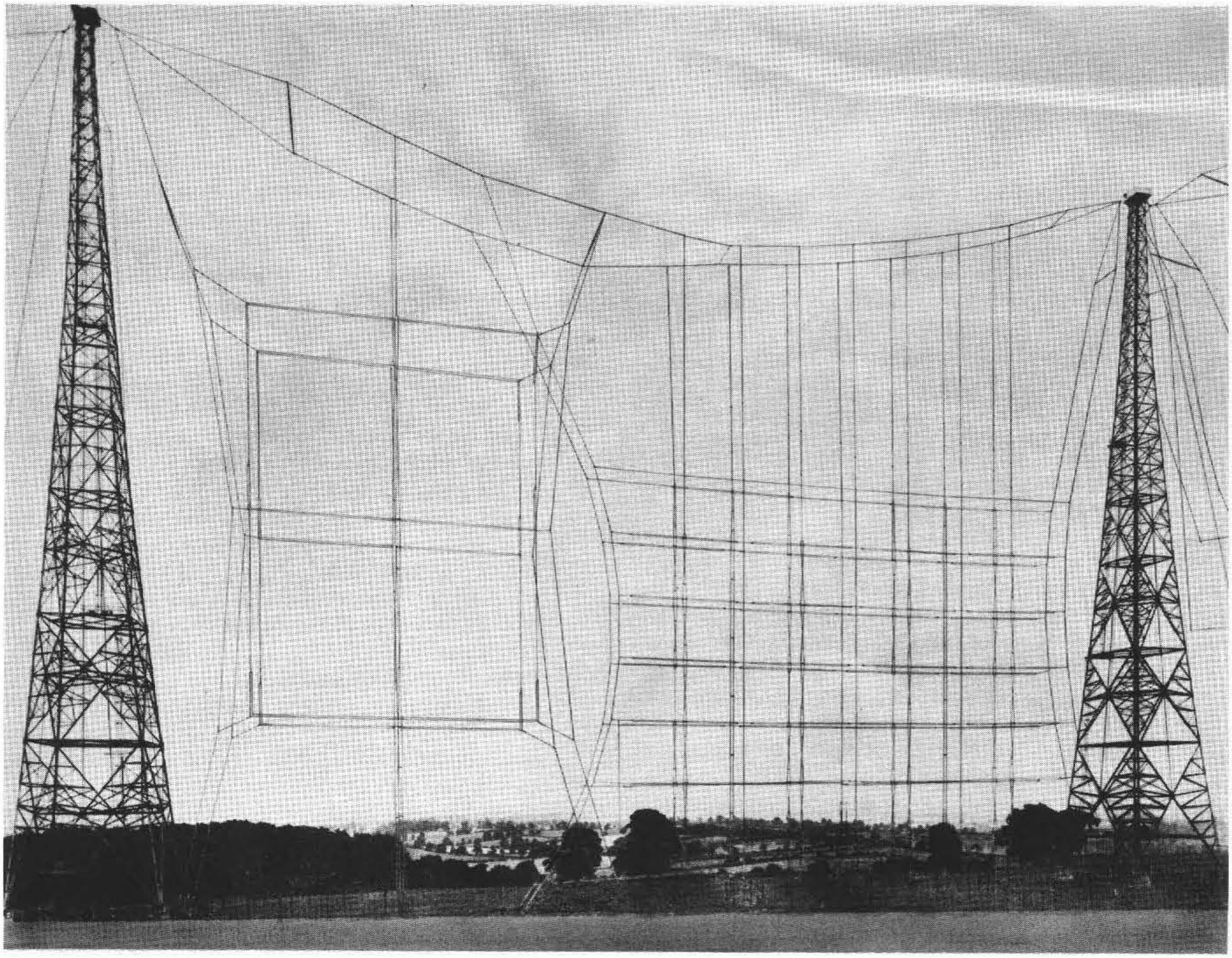


Plate 1 — *Short-wave aerial arrays at Daventry.*

6 *Mc/s Band* (49 *m*). *Array one wavelength wide.* *HRR* 2/3/0·5

17 *Mc/s Band* (16 *m*). *Array four wavelengths wide.* *HR* 8/6/0·5

quency Broadcasting Schedule', which is usually revised before the operational date.

To prepare transmission schedules early enough for the IFRB and for publicity on a world-wide scale, it is necessary to know several months ahead what operational frequencies will be required. As the ionospheric prediction charts[3] which were issued monthly by the Radio Research Station of the Department of Scientific and Industrial Research, near Slough, were not available so far in advance, recourse was had to other means of prediction, as discussed in Paragraph 3.1.

2.3 *Congestion in the Short-wave Broadcasting Bands*

The block allocations for the international high-frequency broadcasting bands[4] within the frequency spectrum have remained substantially unchanged since 1947. These allocations amount to only 11·7 per cent of the frequency range between 5,950 kc/s and 26,100 kc/s, that is, between the lower and upper limits of the bands assigned to international short-wave broadcasting.

On the other hand the total number of short-wave broadcasting stations and transmitters in the world is rapidly increasing; this is due partly to the steady expansion of existing short-wave services, and partly to the growth in the number of countries using short waves for domestic and external broadcasting. Thus, according to a BBC estimate, the number of transmitters operating in the short-wave broadcasting bands has more than doubled between 1947 and 1960. Also, according to United States estimates,[5] during 1960 alone the world total for short-wave broadcasting increased by 13 per cent in terms of transmitter-hours per week.

This high rate of increase in the amount of broadcasting has already caused considerable frequency congestion, resulting at times in serious interference inside the broadcasting bands. Hence, the IFRB recommend revisions to each Tentative High Frequency Broadcasting Schedule, involving adjustment of frequencies, not only for propagational reasons, but also to minimize possible interference. Furthermore, in accordance with the variation of the ionosphere with the sunspot cycle, the higher frequency bands will become less and less useful with the approach of the next sunspot minimum (around 1964), and more and more transmissions will be crowded into the lower frequency bands. Consequently, the overall congestion in the short-wave broadcasting bands is likely to continue to increase during the next few years.

Unless an increased allocation of frequencies for broadcasting in the international high-frequency bands is made, there will be a tendency for individual countries to try to counteract the adverse effects of this congestion by increasing the effective radiated power of their transmitters, which will force other countries to follow suit.

2.4 *Fading on Short Waves*

Short-wave reception is usually subject to some fading, even when propagation conditions are not affected by ionospheric disturbances. This fading may be caused by interference between waves arriving by different paths, by changes in the state of polarization of the downcoming sky-wave, or by variations in ionospheric absorption, etc.[6] The resulting adverse effects on reception may include short- and long-term variations in the intensity of the received signal (Fig. 1), and selective fading causing serious distortion.

The depth and rate of fading of field strength may vary considerably with factors such as circuit location, distance, time, ionospheric storminess, etc. Continuous pen recordings provide data for the statistical analysis of such variations, and Fig. 1 is a sample of this type of recording. An analysis was recently made of pen recordings of field strength at Singapore, on a normal BBC service transmission from the United Kingdom. This analysis was based upon one-minute median values as recorded during the same one-hour period for nine consecutive days in May 1961. The result showed that the fading range between the upper and lower deciles was about 12 dB, equivalent to a field intensity variation of 4 to 1.

2.5 *Tropical Sunset Fading Effects*

Fading of this type occurs frequently on paths which lie partly or wholly in the low latitudes, and is probably due to 'Spread-F' and/or 'Equatorial Sporadic-E'.

In the tropics after local sunset, the F_2 layer often rises rapidly in height, and numerous separate clouds of ionization are then formed inside it. Ionograms* taken locally at such times show a pattern of diffused echoes reflected over a wide range of heights. Such a pattern is usually associated with spread-F in contrast to the more clearly defined F_2-layer reflections generally obtained under normal conditions. The spread-F zone probably extends from about 30°N to 30°S magnetic dip latitude,[7] and the approximate boundaries are shown in Fig. 2 for Africa and Asia.

The incidence of spread-F varies not only with locality but also with time, and it may affect short-wave reception for a few hours after local ground sunset, particularly during sunspot maximum years.

The equatorial sporadic-E zone is much narrower, as it probably extends only from about 10°N to 10°S magnetic dip latitude[8] (Fig. 2). This form of sporadic-E is characterized by its high density of ionization, and by its regular occurrence during daylight hours. It tends to break up shortly before local sunset, and this disintegration may cause fading to occur at that time for an hour or so.[9]

Very little is as yet known about equatorial sporadic-E fading, except that, when it occurs, it usually precedes spread-F fading.[9] It seems that its variation with solar activity is not likely to be the same as that for spread-F.

An analysis[10] has been made of the tropical sunset fading effects on the reception of BBC short-wave broadcast transmissions as observed at Singapore and Johannesburg during the equinoctial months of the current sunspot cycle. It was found that, whenever tropical sunset fading occurred, there was generally no significant variation of its effects with frequency. There were, however, considerable differences in the variations of fading on these two paths (see Fig. 3).

* Graphs showing the relation between the equivalent height of reflection and the frequency of the exploring radio signal.

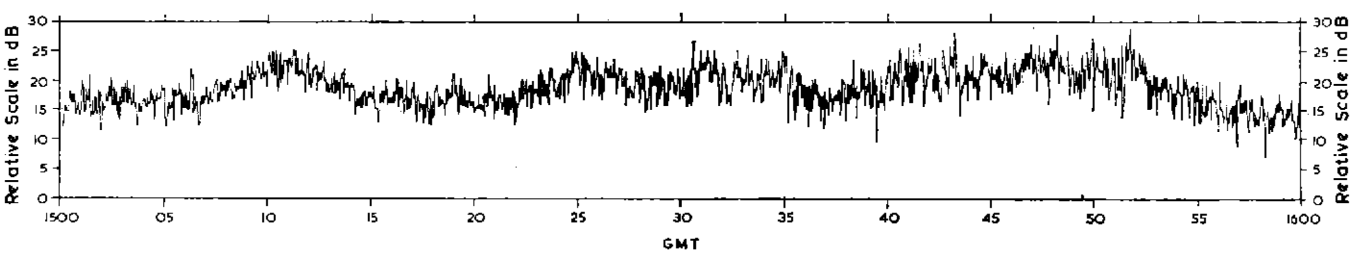


Fig. 1 — Pen recording of receiver input voltage on a BBC transmission from the U.K. at Singapore.

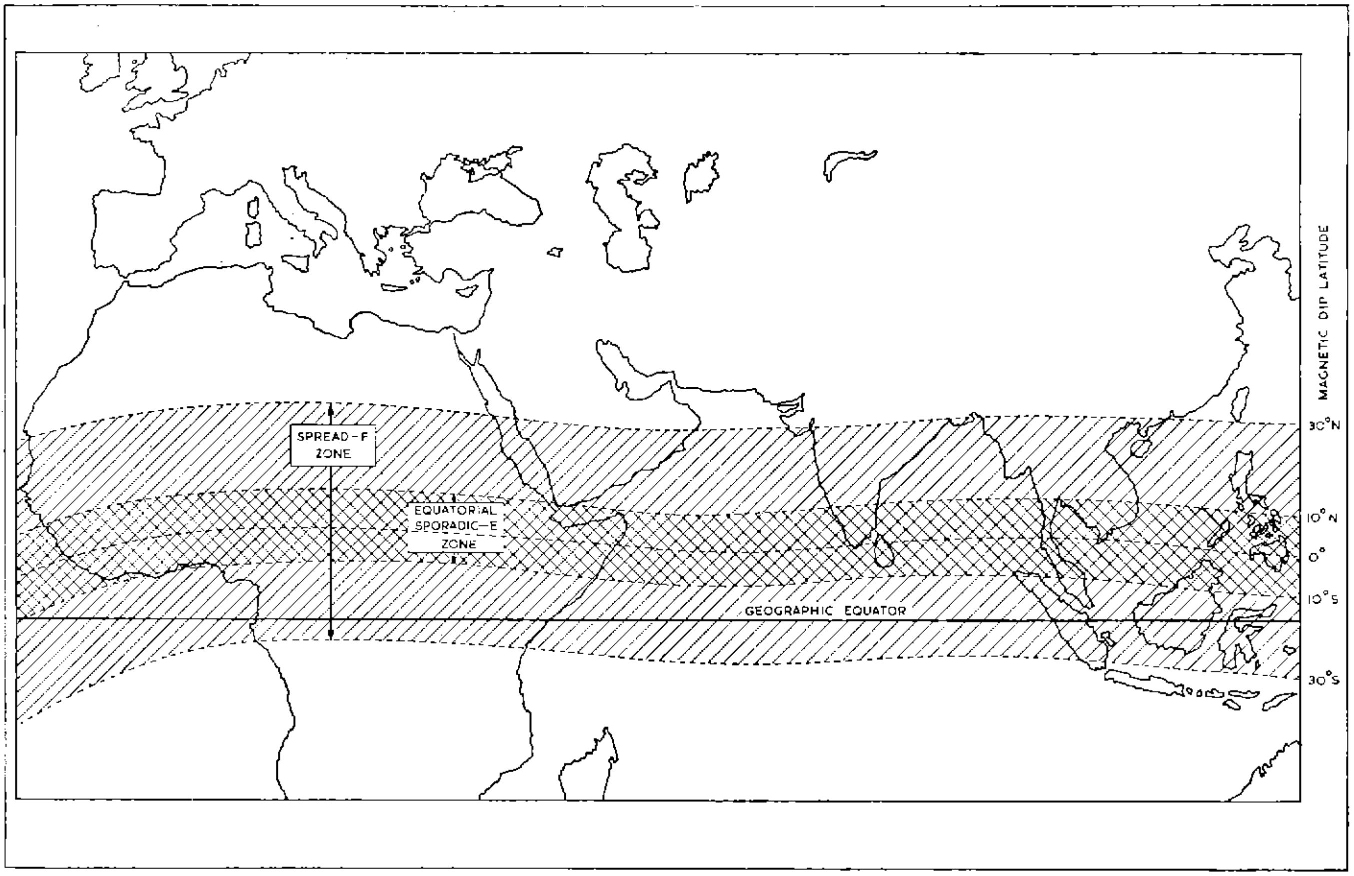


Fig. 2 — Spread-F and equatorial sporadic-E zones; approximate boundaries in Africa and Asia.

In the case of Singapore, the incidence of fading was almost negligible during sunspot minimum years and increased very considerably with solar activity. Such fading commenced shortly after the local ground sunset and lasted for as many as four hours on average, during equinoctial months at sunspot maximum. It is also worth noting that, during the period of tropical sunset fading, a consistent reduction in the field strength of the received signals was observed on the BBC U.K./Singapore path (Fig. 4). On the other hand, for the U.K./Johannesburg path fading commenced relatively much later than at Singapore, that is, about two hours after the local ground sunset, and it persisted much longer into the night. Also, fading was observed even during the sunspot minimum years.

These different reception results on the U.K./Singapore and U.K./Johannesburg paths may be connected with their location in relation to the spread-F and equatorial sporadic-E zones. Much more yet remains to be learnt about the incidence of tropical sunset fading and its variations with time, locality, and direction of the path.

As regards its effects on reception, the following facts are already known:

1. Broadcast transmissions can at times be much more seriously affected than certain other radio services, for example, radio telegraphy.
2. In broadcast transmissions, both speech and music are affected; although the intelligibility of speech is not usually seriously reduced, enjoyment of certain types of music is often completely spoiled by such fading.

The problem of counteracting these effects is a difficult one and no satisfactory solution has yet been found. If a choice of transmitting sites is possible, it is best to select the location which gives the least possibility of ionospheric reflections inside the spread-F and/or equatorial sporadic-E zones.

2.6 *Ionospheric Disturbances*

The reception of short-wave broadcast transmissions can be seriously affected by disturbed propagation conditions, due to occasional ionospheric irregularities. (Propagation conditions can also be disturbed by nuclear explosions, particularly those at high altitudes.) Two main types of such disturbances, i.e., ionospheric storms and sudden ionospheric disturbances (SIDs), are described below. Their incidence during the sunspot cycles No. 18 and No. 19 (1944–61) has been analysed and the results are shown in Fig. 5.

2.6.1 *Ionospheric Storms*

These storms are connected with many other solar/terrestrial phenomena such as magnetic storms, aurorae, earth currents, etc.[11] They are probably due to the effects of the impact of corpuscular radiation from the sun upon the earth's upper atmosphere, but recent research has shown that solar/terrestrial relations are very complex, and their nature is not yet fully understood. It is possible that the outer van Allen radiation belt may also be involved. Streams of corpuscles are at times ejected from the sun into space and are due to various causes, including solar flares (Plate 2) and solar M-regions (which as yet have not been visually identified). Some of these streams reach the earth from the sun in one to three or more days, and their impact on the ionosphere is usually followed by a decrease in the ionization of the F_2 layer in temperate and polar latitudes. Consequently, transmissions on frequencies propagated satisfactorily before the onset of a storm may be seriously affected and short-wave reception may therefore deteriorate—or even become impossible—particularly on the higher frequency bands.

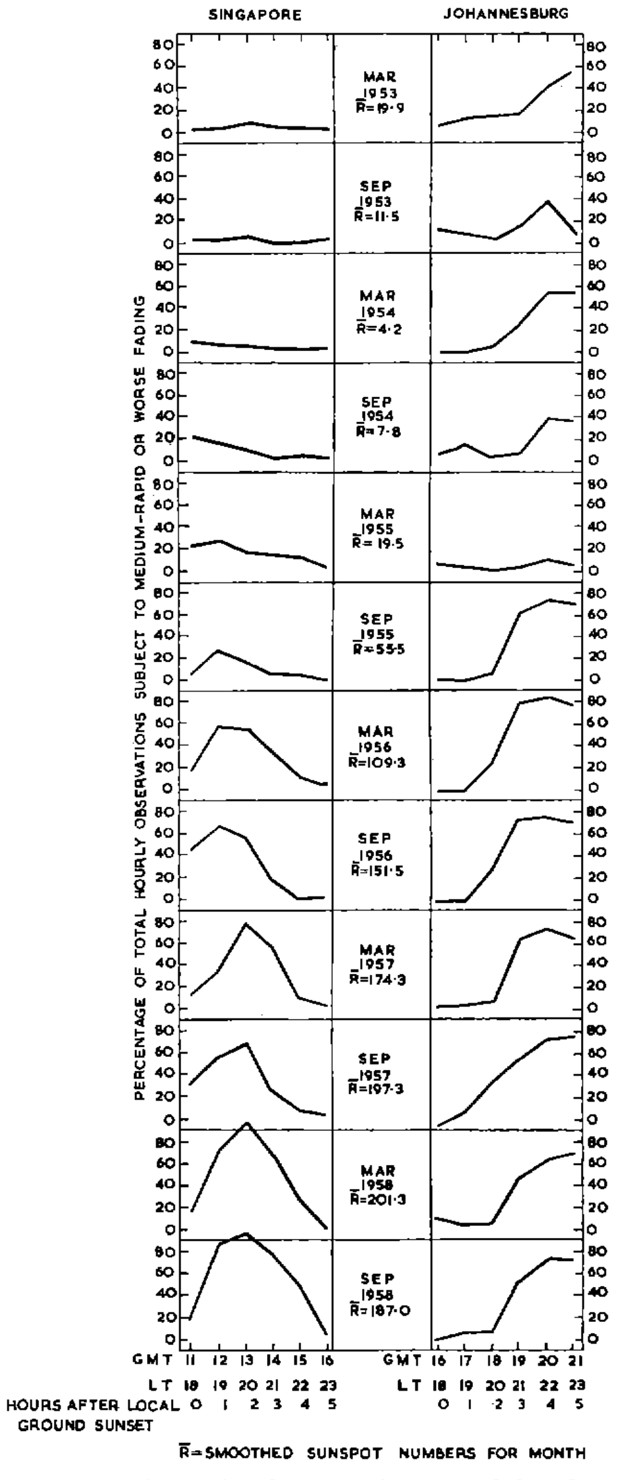


Fig. 3 — Incidence of medium–rapid or worse fading during the period 0 *to* 5 *hours after ground sunset during equinoctial months* 1953–8.

Storms attributed to flares are particularly prevalent during the years of high solar activity and can reach at times very great intensity; however, they do not often tend to recur. On the other hand, storms attributed to M-regions occur mainly during the years of median and low solar activity. They can be very troublesome, as they can last for many days at a time; also, they tend to recur because the M-regions may remain active for a very long period, continuously emitting corpuscular radiation. Therefore, such storms will tend to be repeated after intervals of about twenty-seven days, corresponding to the average synodic rotation period of the sun, and they have been known to recur regularly during periods of up to half a year.[12]

The effects of ionospheric storms vary considerably with latitude and longitude, being generally most severe near the northern and southern auroral zones, towards which solar corpuscles tend to be deflected by the earth's magnetic field.[11] Therefore, during ionospheric storms, the deterioration in short-wave reception is most likely to occur on paths crossing or passing near these zones.

An analysis of the ionospheric vertical incidence measurements taken during the period 1944–61 at the Radio Research Station, Slough, showed the following characteristics of ionospheric storms as observed in Southern England:

1. The diurnal variation was such that there was a distinct tendency for storms to commence during the evenings, although they could occur at any time.
2. Seasonally, their incidence was generally greatest during the equinoctial months, probably due to the position of the earth in relation to the zones of the sun where spots occur.
3. Their annual incidence did not correspond exactly with the solar activity, probably due to the different variations with the sunspot cycle in the occurrence of storms attributed to flares and M-regions.

Thus, the annual variation of the number of stormy days (Fig. 5) showed that maximum storminess during sunspot cycle No. 18 (1944–54), did not occur during the sunspot maximum year of 1947, but four and five years later, in 1951 and 1952, when about 50 per cent of all days were disturbed. Likewise, during the current sunspot

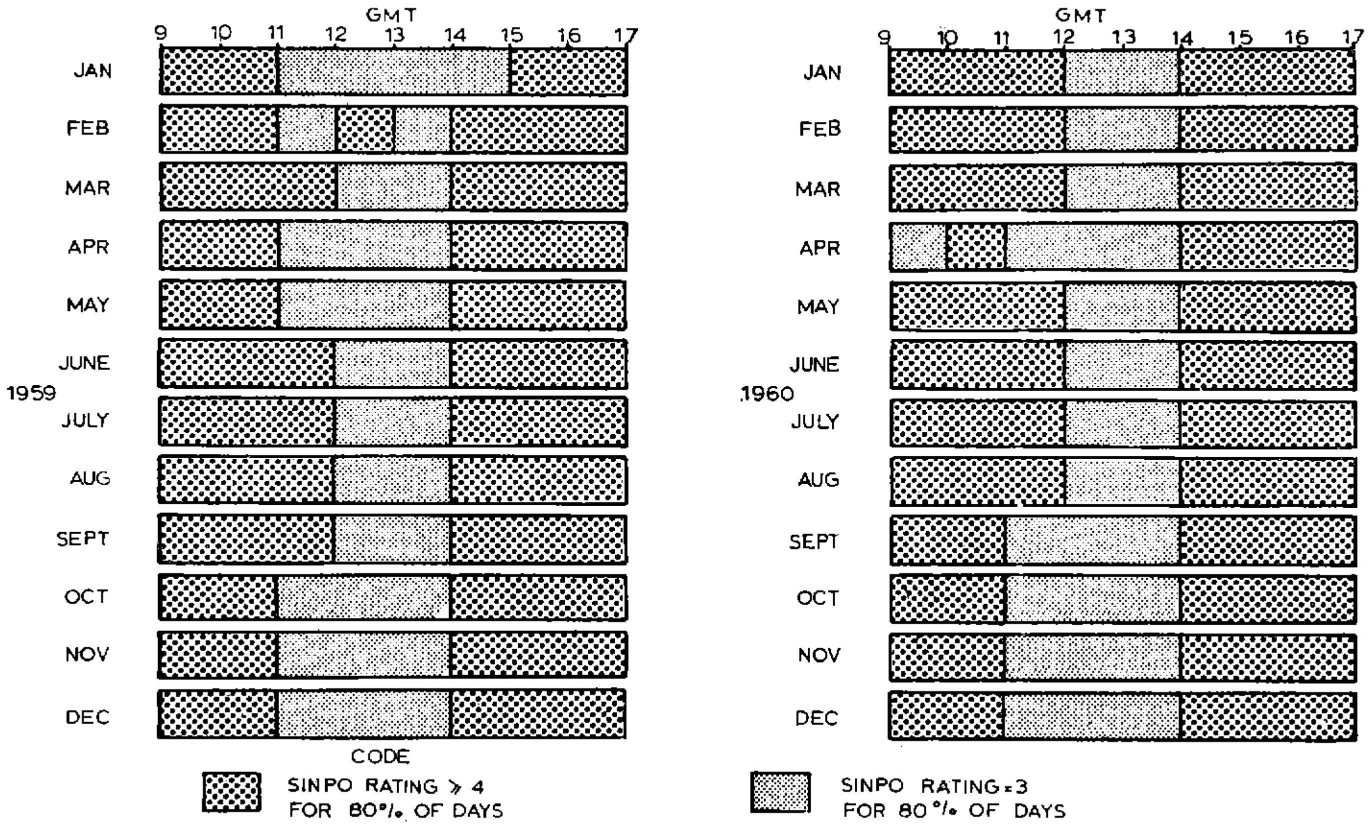


Fig. 4 — Reception at Singapore of strongest BBC transmissions in terms of signal strength (SINPO rating).

cycle, No. 19 (1954 onwards), the data available shows that maximum storminess so far occured in 1960 and not during the sunspot maximum epoch (1957–8). Minimum storminess occurred during 1944 and 1954 (17 per cent and 21 per cent of days), i.e., during the sunspot minimum years. The incidence of magnetically stormy days (as deduced from the measurements made in Southern England by the Royal Greenwich Observatory) is also shown in Fig. 5 for the purpose of comparison.

2.6.2 *Tatsfield Warnings*

The BBC Receiving Station at Tatsfield, about seventeen miles south of London, issues notices called 'Warnings',[12] whenever ionospheric disturbances affect reception from the west and/or east in the United Kingdom.

An analysis based upon the number of days on which warnings were in operation on westerly paths (i.e., from North America) during the period 1944–61 revealed that:

1. There was a tendency for propagational disturbances to commence in the evenings, and 35 per cent of warnings were issued between 1930 and 2230 GMT. As in the case of ionospheric storms, the period during which a Tatsfield warning was in operation varied from a few hours to over a week at a time.
2. There was a distinct seasonal variation in the number of days during which warnings were in operation. Thus, on average, during the period analysed, the least disturbed months were June and July (12 per cent and 16 per cent of all days respectively), and the most disturbed months were November and December (37 per cent of all days each). The most disturbed individual month was December 1948 (74 per cent of all days); on the other hand, there were quite a few months during the sunspot minimum summer (for example, June and July, 1954) when no warnings were issued.
3. The annual variation in the incidence of warnings was similar to that recorded for the magnetic and ionospheric storms (Fig. 5). Thus the greatest incidence was observed a few years after the sunspot maximum years, that is, for sunspot cycle No. 18 in 1952, and, for sunspot cycle No. 19 so far in 1960 with 39 per cent and 42 per cent of all days respectively.
4. During the period analysed, Tatsfield warnings were in operation on westerly paths for about five times as many days as on easterly paths. This is because the paths of transmissions from North America to the United Kingdom pass closer to the northern auroral zone than those of transmissions from the east (see Paragraph 2.6.1). Since reciprocal effects are generally observed, the BBC short-wave services most frequently and most severely affected during ionospheric storms are those which are directed to North America.

ZÜRICH MEAN ANNUAL SUNSPOT NUMBER ($\bar{R}$)

SUDDEN IONOSPHERIC DISTURBANCES PERCENTAGE OF DAYS

Based on short-wave reception reports in southern England

TATSFIELD WARNINGS PERCENTAGE OF DAYS

Based on warnings issued for the westerly paths

IONOSPHERIC STORMS PERCENTAGE OF DAYS

Based on ionospheric measurements (foF_2) at Slough (Radio Research Station)

MAGNETIC STORMS PERCENTAGE OF DAYS

Based on magnetic measurements ($C > 1$) at Abinger, Surrey, and, since May 1957, at Hartland, Devon (Royal Greenwich Observatory)

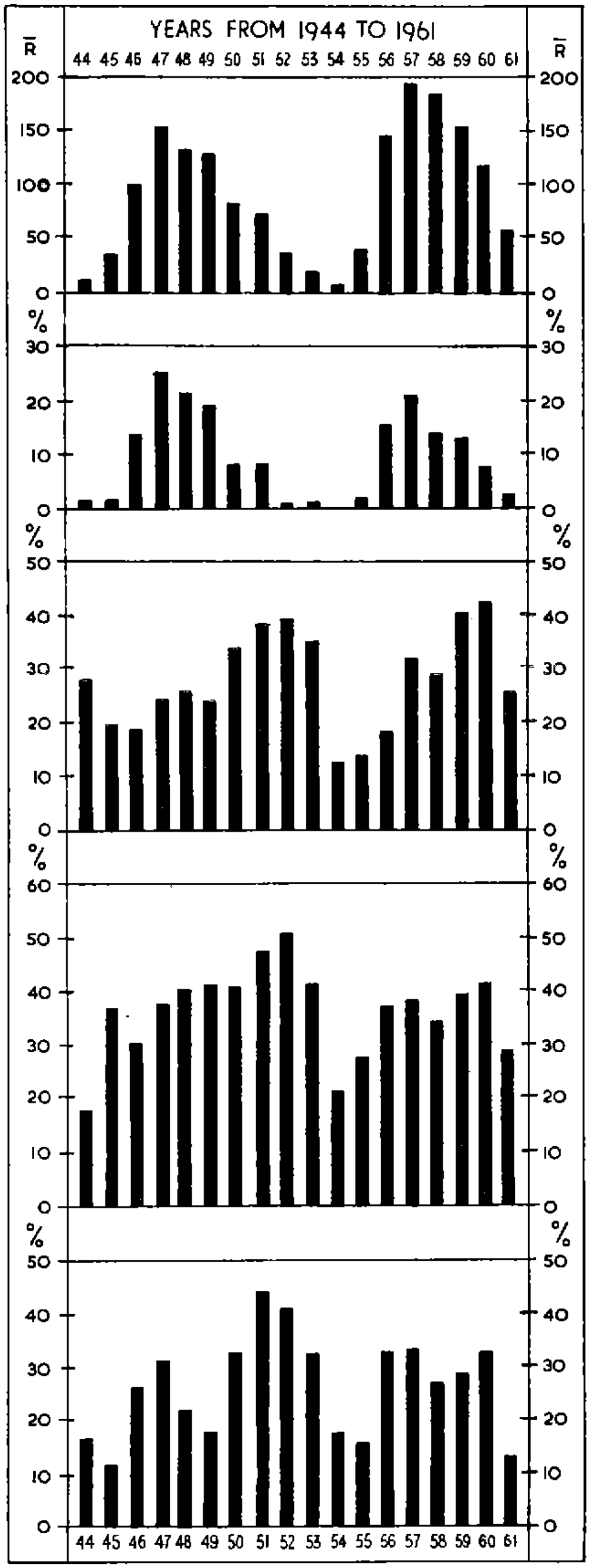
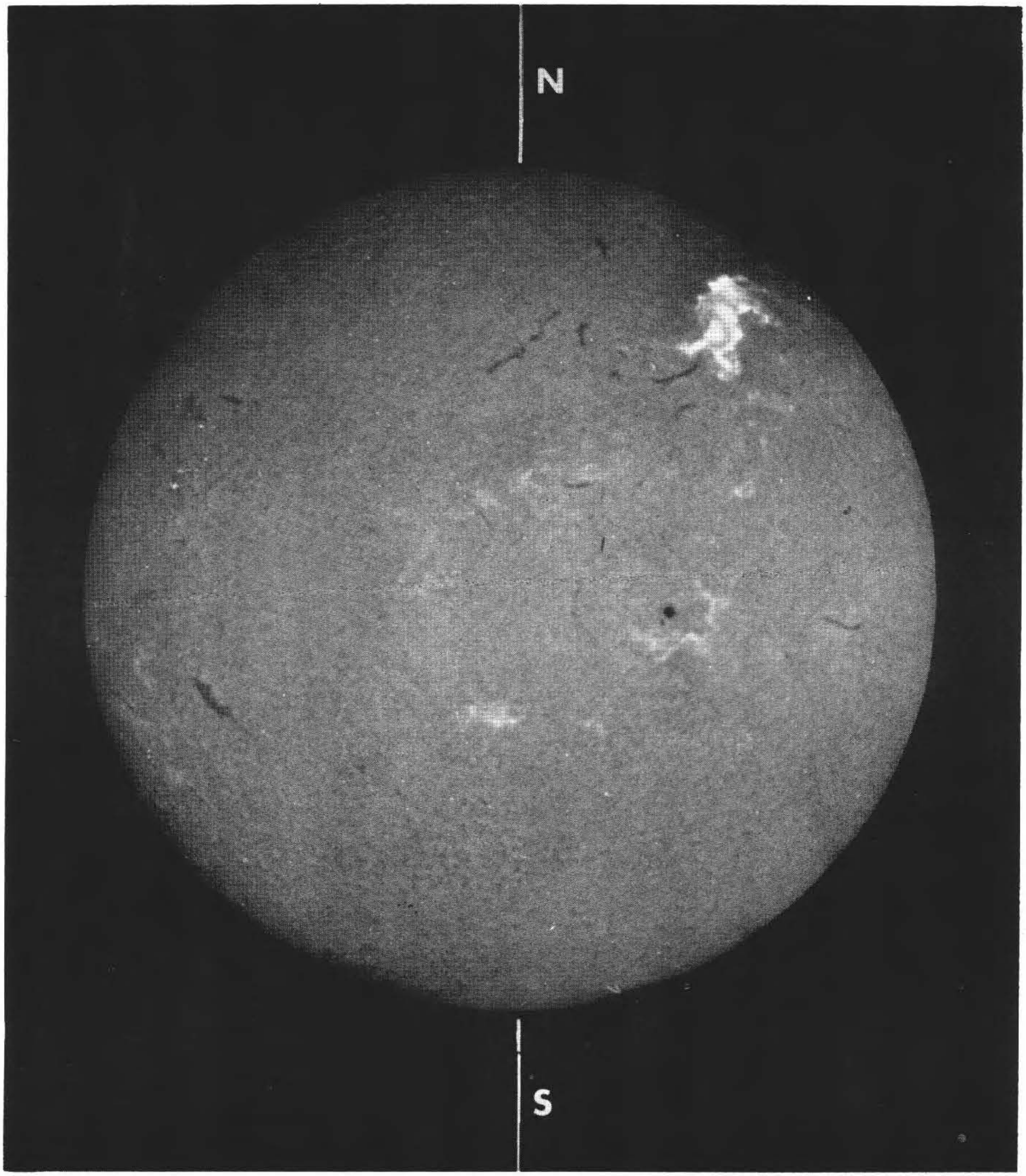


Fig. 5 — Variations of propagational disturbances in southern England with solar activity. Sunspot cycles Nos. 18 *and* 19 (1944–61).



By permission of the Astronomer Royal

Plate 2 — Solar flare. 1960 *June* 1 0908 *Universal Time*

The study of reception disturbances had to be based upon Tatsfield warnings, as these were the only BBC data available for the whole of the period analysed. Therefore, the above statistics are approximate and only show general trends in the effects of ionospheric storms on short-wave broadcast reception, for the following reasons:

1. The data on the incidence of warnings were not consistent throughout the period analysed, because many changes were successively introduced into the operation of the Tatsfield Warning System.
2. The sensitivity of a given transmission to warning depends largely upon the nearness of its operational frequency to the Maximum Usable Frequency (MUF) for its path, and it may thus vary with locality and time.
3. Many other factors can also play a part, for example, short-wave traffic variations, or monitoring procedures.

2.6.3 *Sudden Ionospheric Disturbances (SIDs)*

The propagational disturbance known as SID is due to a sudden increase in the absorptive properties of the D-layer of the ionosphere. This is probably caused by the effects of the occasional impact of hard X-ray radiation from the sun on the earth's upper atmosphere. Such radiation is emitted from very hot regions in the corona following the appearance of flares on the sun.[13] (A photograph of a flare is shown in Plate 2.) The time of travel from the sun to the earth is only about eight minutes, since X-rays are an electromagnetic radiation, and therefore have the velocity of light.

Most of the non-deviative absorption of short-wave transmissions reflected by the ionosphere usually takes place in its lowest layer, that is in the D layer, about fifty miles above the earth's surface. Solar hard X-ray radiation is very penetrating so that it tends to extend the D layer below its normal height. Due to the consequent increase in thickness and ionization density of this layer, and the high collision frequency of free electrons with gas molecules at these heights, the ionospheric absorption can increase considerably and cause SIDs. These can vary greatly in their intensity; usually reception on the lower frequency bands is most affected. On occasions all frequencies on certain paths may be rendered unusable, resulting in a total fade-out on certain services.

Fortunately, SIDs usually last for only a very short period, seldom exceeding two hours. However, they happen very suddenly and often without any prior warning. Their incidence would be expected to be highest during the sunspot maximum when solar flares occur most frequently.[14] Analysis of SIDs observed on short-wave reception in Southern England during the period 1944–61 has revealed the following:

1. SIDs were usually observed on those paths which were partially or wholly in daylight.
2. There was no obvious seasonal variation in their incidence.
3. The incidence of SIDs increased very markedly with solar activity (Fig. 5). Thus, the most disturbed years were the sunspot maximum years, 1947 and 1957, when SIDs were observed on respectively 26 per cent and 21 per cent of all days. On the other hand, during years of low solar activity, 1944 and 1945, and 1954, very few SIDs were observed.

The most disturbed individual month was September 1957, when SIDs were observed on 57 per cent of all days. In fact, not less than thirty-two SIDs were recorded during that month, more than one SID being observed on several days (for example, five on the 21st and four on the 18th). Conversely, not a single major SID was observed during the whole of 1954.

3. Comparison of Short-wave Predictions with Reception Data

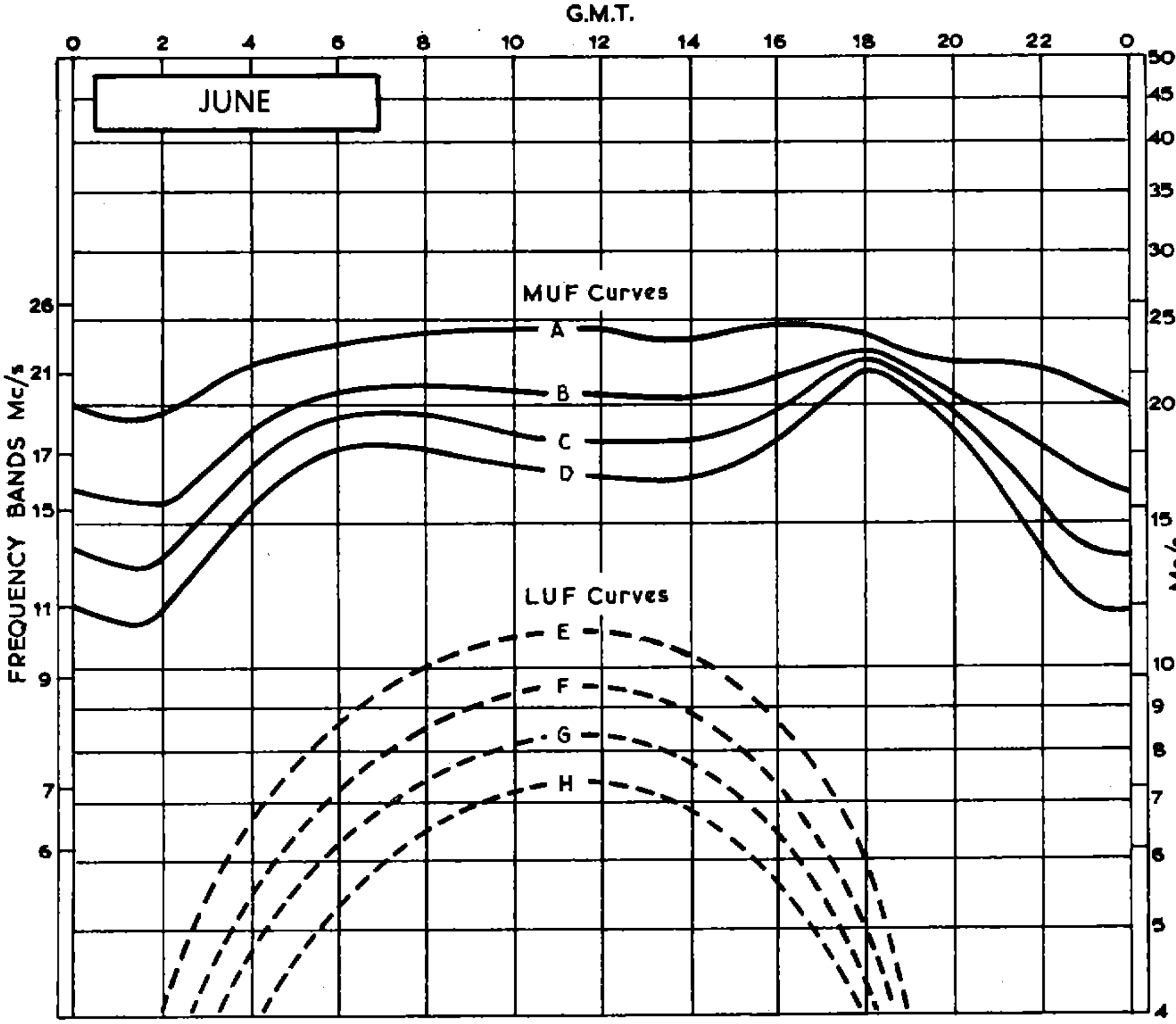
3.1 *Predictions for Short-wave Transmissions*

3.1.1 *Introduction*

For some twenty years up to 1962, short-term predictions were computed for a few months in advance, using the ionospheric prediction charts,[3] which were then prepared monthly by the Radio Research Station of the Department of Scientific and Industrial Research near Slough. However, the circulation of these charts has recently been discontinued, and in their place the RRS are issuing two sets of ionospheric charts for each month of the year, based upon years of high and low solar activity and derived from world-wide measured values. In addition, they are continuing to predict the monthly solar activity index IF_2[15] for a few months ahead. This index is derived from the F_2-layer ionization as recorded at ten stations throughout the world, and it gives a more accurate indication of the variation of the F_2-layer photon radiation with the solar cycle than the sunspot number, and consequently of the propagation characteristics of the F_2 layer. The predicted Maximum Usable Frequencies (as defined in paragraph 3.1.2) for any given month must now be obtained by linear interpolation—for the appropriate predicted IF_2—between the MUFs derived from the two sets of ionospheric charts for that particular month (Fig. 6).

In the past, the RRS charts[3] were not received early enough to allow for computation and advance notification of operational frequencies for the projected seasonal broadcasting schedules, as required under the latest frequency management procedure introduced in 1960.[2] For this purpose, 'once-for-all' long-term predictions of the complete sunspot cycle are required to provide the necessary guide for provisional advance planning. A book of long-term prediction curves for the BBC short-wave paths was therefore recently compiled, using the RRS ionospheric charts (Bulletin A—Special Issues Nos. 3 and 4) based upon world-wide measurements taken during the years of high and low solar activity in the current cycle, for the months of March, June, and December.

The number of paths for which predictions are computed has varied with the years; for example, during 1961



MUF Curves	LUF Curves (e.r.p. =7500kW)	I_{F_2} (Slough monthly solar activity index based upon F_2 layer)	$\overline{R}$ (Zürich smoothed monthly sunspot number)	
A	E	166	187·9	SUNSPOT MAXIMUM
B	F	80	100	
C	G	30	50	
D	H	−14	4·2	SUNSPOT MINIMUM

Fig. 6 — Long-term predictions; Path: U.K./Teheran.

some sixty paths were listed, of which about half were for distances greater than 4,000 km.

3.1.2 *Maximum Usable Frequencies and Lowest Useful Frequencies*

Predictions of Maximum Usable Frequencies[6] (MUFs) and of Lowest Useful Frequencies[6] (LUFs) are issued every month in terms of hourly median monthly values throughout twenty-four hours. They show those values which are likely to be exceeded on only half of the days of the month.

The MUF values refer to 'standard MUF',[16] that is, the highest predicted frequency for a given path at a given time which can be propagated by ionospheric refraction alone.

The LUF at a given time, for a given path and a given effective radiated power (e.r.p.), is taken as that frequency for which the ratio of the theoretical signal strength to local atmospheric noise level is 40 dB at the receiving point. Thus LUF differs from MUF in that it depends upon the e.r.p. For every 3 dB increase in e.r.p., the corresponding decrease in the LUF is about 0·5 Mc/s.

The BBC predictions of LUFs are made a few months in advance, using world-wide atmospheric noise data,[17] and the latest available predicted smoothed sunspot number issued by the Zürich observatory, on the basis of methods described in the *NBS Circular*, No. 462.[6] In the predictions for the overseas paths the e.r.p. is taken as 7,500 kW.

3.1.3 *Presentation of Short-wave Predictions*

The values of predicted frequencies for a service area from a given transmitter site may vary with distance, bearing, time of day, season, solar activity, etc. Hence, many methods of presentation are possible, according to which variations are to be displayed.

For the monthly predictions on individual paths, the most commonly used method of presentation is to plot, on special graph paper, predicted MUF and LUF curves against the time of day. Such presentation can be also used to display at-a-glance comparisons between many prediction curves, for example, for short-distance paths in the same direction, or for various months, or for various sunspot numbers for the same path (Fig. 6), or for different prediction methods for the same path and the same month, etc. Another method of presentation of predictions for many different paths is to construct MUF maps. These show how the predicted operational frequencies vary with direction and distance over a wide coverage area for transmissions from a given site at a given time. MUF maps of Europe for transmissions from the United Kingdom are prepared monthly by the BBC (Fig. 7), and, if necessary, similar MUF maps of the world can also be prepared. It should be noted, however, that such maps can only be used as an approximate guide, since they show a simplified representation of a very complex situation.

Other methods of presentation are possible, showing, for example, the variation of the predicted times of fade-in and fade-out of transmissions on a given path with the sunspot cycle.

3.1.4 *Future of Short-wave Prediction Methods*

Current short-wave prediction methods in general use are still much the same as those described in the NBS circular No. 462 of 1948.[6] More recent methods, which include the examination of differing modes of propagation and of their variations,[18] are also available, but they are so complex and laborious that to make full use of them a computer would be necessary for routine predictions. It may be added that the increasing use of rockets, satellites, computers, and other new techniques[19,20] is steadily contributing to a better understanding of the vertical distribution of electrons throughout the ionosphere,[21] and may well lead to further revision of short-wave prediction methods in the future.

3.2 *Description of the 'Post-mortem' Analysis of Short-wave Reception Data*

3.2.1 *Introduction*

Tape recordings and reception reports of BBC short-wave transmissions are regularly received from many sources abroad, ranging from specially equipped receiving stations to ordinary listeners. Many methods of reporting are used, including the SINPO and SINPFEMO[22] signal reporting codes, but there is an overall lack of standardization.

The SINPO signal reporting code was introduced on an international scale only about ten years ago,[23] and such reports on the BBC transmissions have been available from only a small number of stations. In view of this, and the limited space available in this report, it has been decided to concentrate on the SINPO reception reports on three typical long-distance BBC paths:

U.K./Ottawa (i.e., westwards)
U.K./Singapore (i.e., eastwards)
U.K./Johannesburg (i.e., southwards)

This reception analysis was carried out on the data obtained during the current sunspot cycle, No. 19. During this cycle solar activity reached the highest level ever recorded since 1749, which is the first year for which data is available. Plate 3 shows the sun as it appeared on a day during this period of high activity (1958), with a great number of spots clearly visible. In contrast, Plate 4 shows the sun as it appeared on a day during the period of low activity (1954), with practically no spots visible.

Thus the reception conditions observed during the sunspot minimum and sunspot maximum epochs of the current cycle correspond to the extreme limits of propagation so far encountered, and these are not likely to be exceeded in the foreseeable future. This study may therefore give a useful indication of the range of future propagation characteristics of short-wave transmissions in relation to the solar cycle.

3.2.2 *SINPO Signal Reporting Code and Statistical Analysis*

When reception of a given transmission is reported in

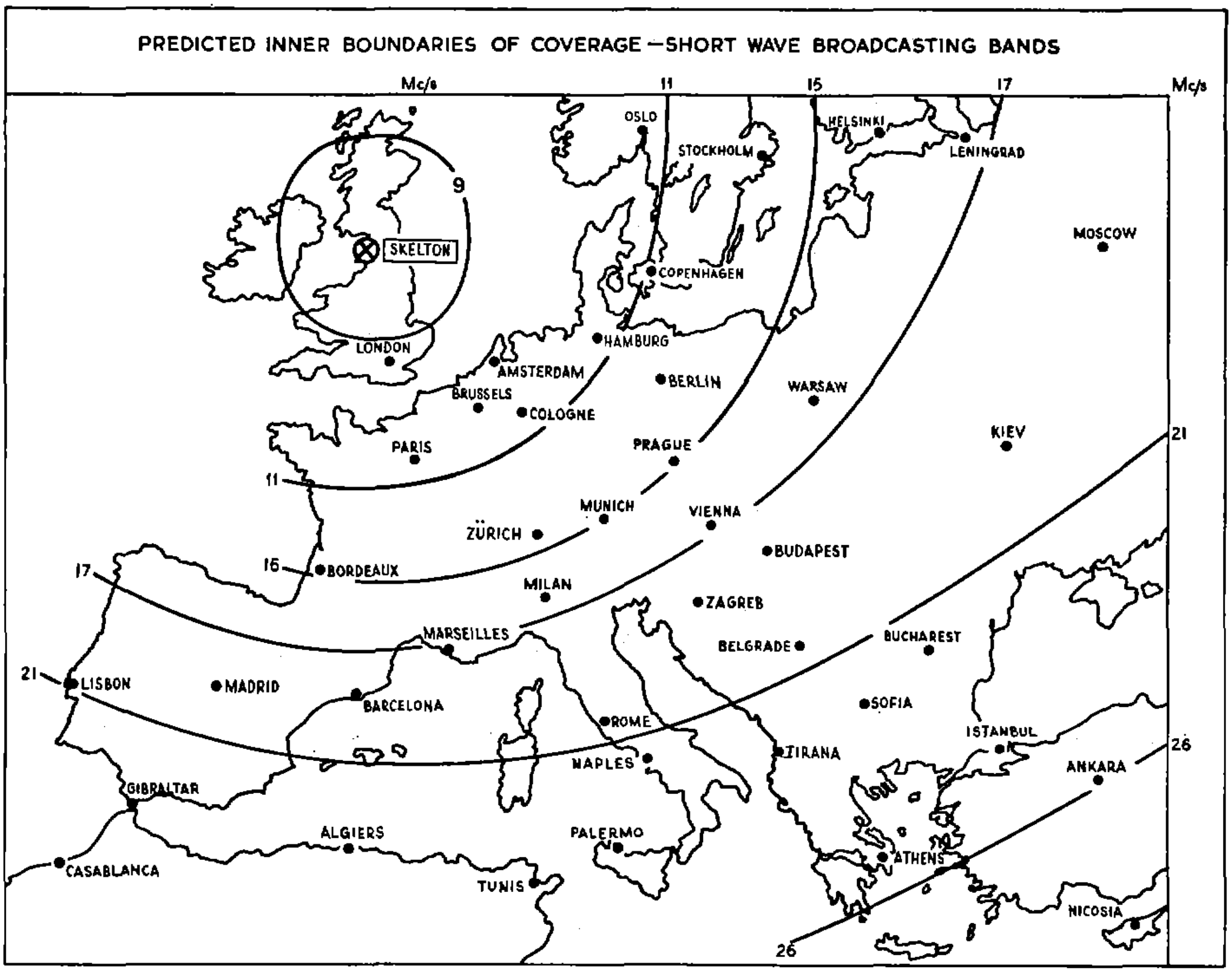


Fig. 7 — Map of Europe—predicted MUFs from Skelton. October 1961. 1600 *GMT*

this code, ratings are given on Signal Strength, Interference, Noise, Propagation Disturbance, and Overall Merit. The Overall Merit rating depends not only upon signal strength, but also upon the degrading effects of the other factors mentioned above. Reception results based upon Overall Merit ratings would not therefore provide a reliable guide to the future performance of short-wave transmissions under similar sunspot cycle conditions, owing to continually increasing congestion in the short-wave broadcasting bands, etc.; hence, as the SINPO reports were, in this case, mainly studied to find the effects of the solar cycle on short-wave propagation, only Signal-strength ratings were considered suitable for such a purpose. The SINPO rating scale for Signal Strength is as follows:

5—Excellent; 4—Good; 3—Fair; 2—Poor;
1—Barely Audible.[22]

It should be noted that the SINPO code generally relates to a subjective assessment which may be affected by personal and instrumental factors. Consequently, the same SINPO ratings may not always be equivalent at different receiving stations. In addition, analysis based upon the reception results on short-wave broadcast transmissions cannot be regarded as statistically complete. Operational frequencies are usually chosen on the basis of MUF predictions, and should these be too low the actual MUFs are not easily deduced from reception reports. Thus the amount by which the operational frequencies could have been raised above the predicted MUFs and yet still have provided satisfactory reception may often remain unknown. Another difficulty in testing the accuracy of predictions may be caused by the upper limit of the high frequency broadcasting bands. The highest band, 26 Mc/s, can be considerably lower than the predicted and actual MUFs for many long-distance circuits during periods of high solar activity. Also, if operational frequencies are

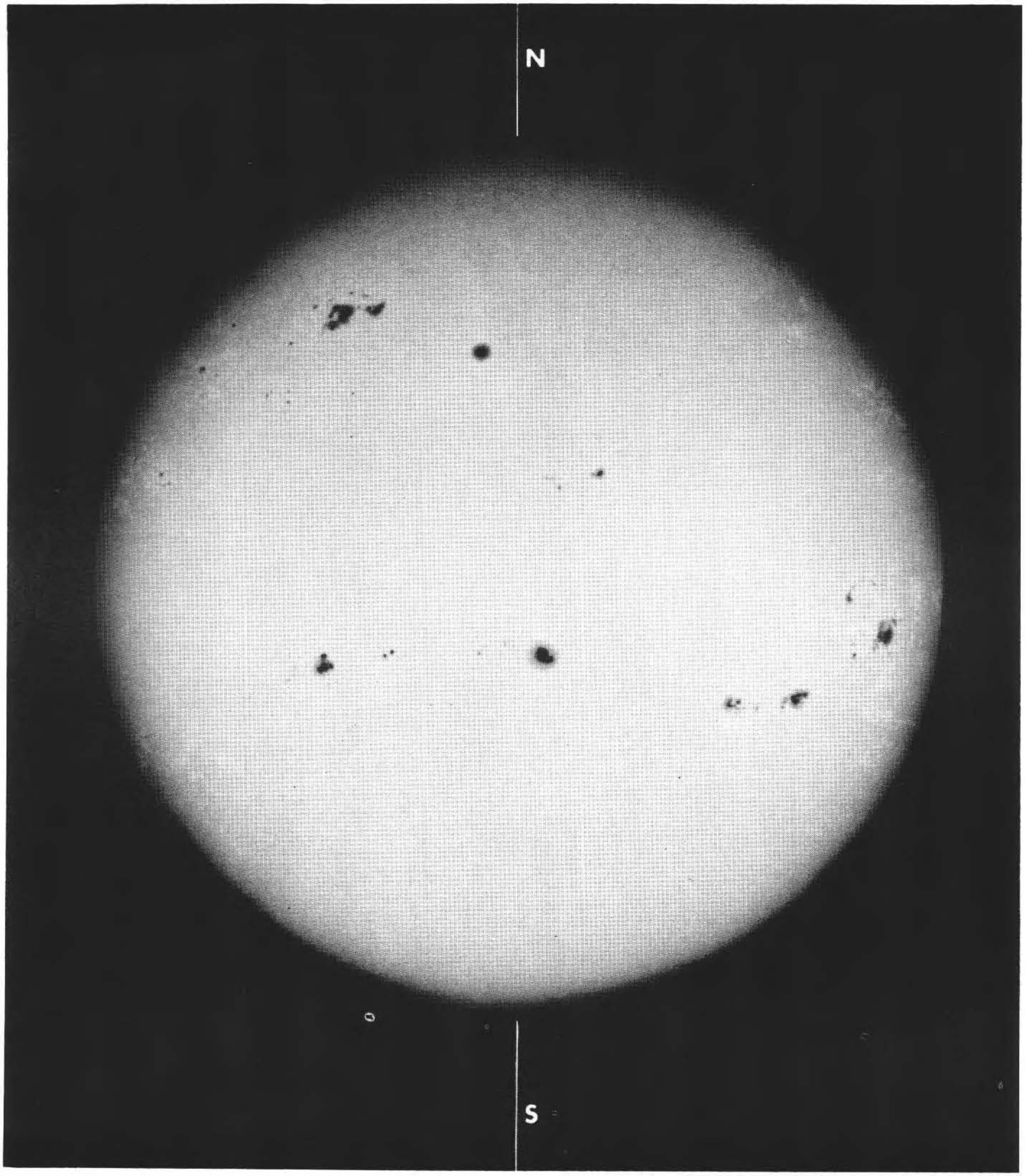


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Plate 3 — *Sun during the sunspot maximum epoch.* 1958 *April* 2.

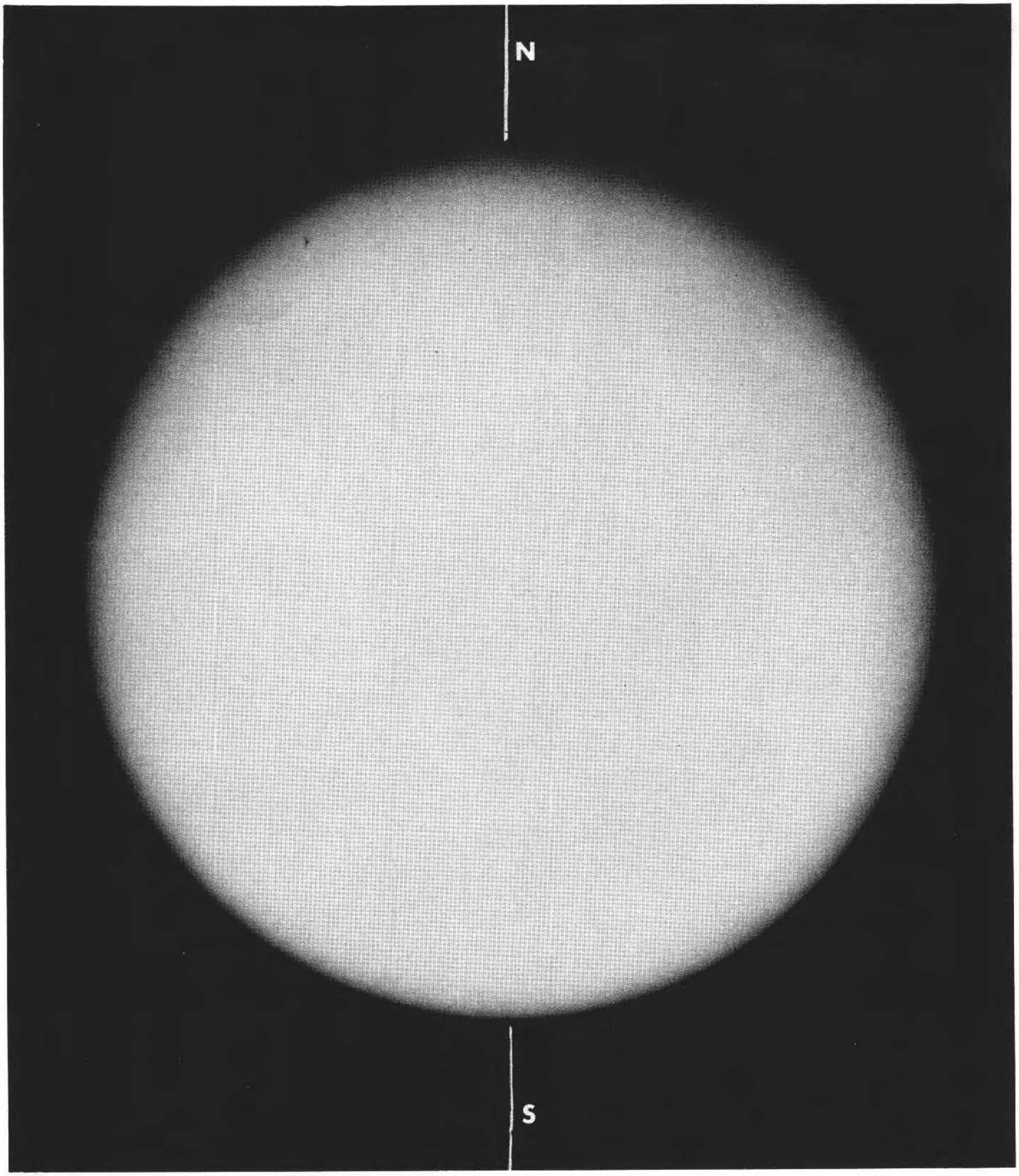

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Plate 4 — *Sun during the sunspot minimum epoch.* 1954 *February* 1.

chosen well below the predicted MUFs, the available reception reports cannot be used to check the predictions. Furthermore, as BBC short-wave transmissions are operational, they are radiated for only limited periods and on frequencies changing according to predictions. This means that there is no single BBC frequency which could be monitored, in a given service area, continuously throughout twenty-four hours every day.

A statistical analysis, to provide complete information,[24] should be based upon daily field-strength pen recordings of transmissions radiated continuously on many frequencies throughout twenty-four hours. In the case of the BBC transmissions, as this was not possible, some pen recordings have been obtained for limited periods (Fig. 1). It is too early yet to form any definite conclusions on the basis of available data, except to note the considerable variability of field-strength intensity (see Paragraph 2.4).

3.2.3 *Choice of Operational Frequencies for BBC Short-wave Transmissions*

The principal factors determining the choice of operational frequency for a given BBC short-wave path at a given time are:

1. The frequency should be inside one of the high-frequency broadcasting bands.
2. It should not exceed the predicted MUF, as transmissions on higher frequencies may penetrate the ionosphere instead of being reflected by it.
3. It should not be lower than the predicted LUF, as transmissions on lower frequencies may have an insufficient ratio of signal to local atmospheric noise, resulting in poor reception.
4. Past reception experience may provide useful information and may, at times, modify the above rules.
5. Operational conditions, such as availability of transmitters, aerials, time and duration of service period, listening habits, type of receivers, intensity of man-made noise in the reception area, etc., should also be considered.

3.2.4 *Presentation of Reception Data*

The data used were obtained from SINPO reception reports of BBC transmissions at the following receiving stations:

Britannia Heights, Ottawa (Canadian Broadcasting Corporation);

Panorama, near Johannesburg (South African Broadcasting Corporation);

Woodleigh, near Singapore (BBC Far Eastern Station).

The observations considered were those made on each hour throughout the periods of transmission in which the station reported receiving a signal. The reports on the frequency which gave the best reception in any broadcasting band were those used.

The method of statistical analysis adopted was that employed by T. W. Bennington.[25] The hourly readings for every day for each month were analysed in terms of the percentage of days when the signal strength equalled or exceeded a given rating. Signal strength 3 or more was considered to be capable of providing a service of programme value, if degrading factors were not too great.

3.3 *Discussion of Results obtained by 'Post-mortem' Analysis*

3.3.1 *Introduction*

The reception reports of the BBC short-wave transmissions can be analysed with many different objects in view. For example, prompt action can be taken, following reports of unsatisfactory reception, by changing operational frequencies of affected transmissions. Reception results obtained on a given circuit for a given sunspot number can be used as a guide to the choice of operational frequencies on that path, when a comparable phase of solar activity recurs in the future. As the various prediction methods in current use are still only approximate, it is of value to compare predictions with the observed reception results. It should be noted however, that:

(*a*) MUF predictions are based upon 'standard MUF',[16] whilst reception results may, at times, depend upon the 'operational MUF'.[16] The operational MUF for broadcast services occasionally exceeds the standard MUF due to effects such as ionospheric and/or ground scatter.

(*b*) The MUF predictions are given in terms of the hourly median monthly values. The day-to-day variability of the ionosphere is such that reception reports obtained on individual days may at times show discrepancies with one another and with the predictions.

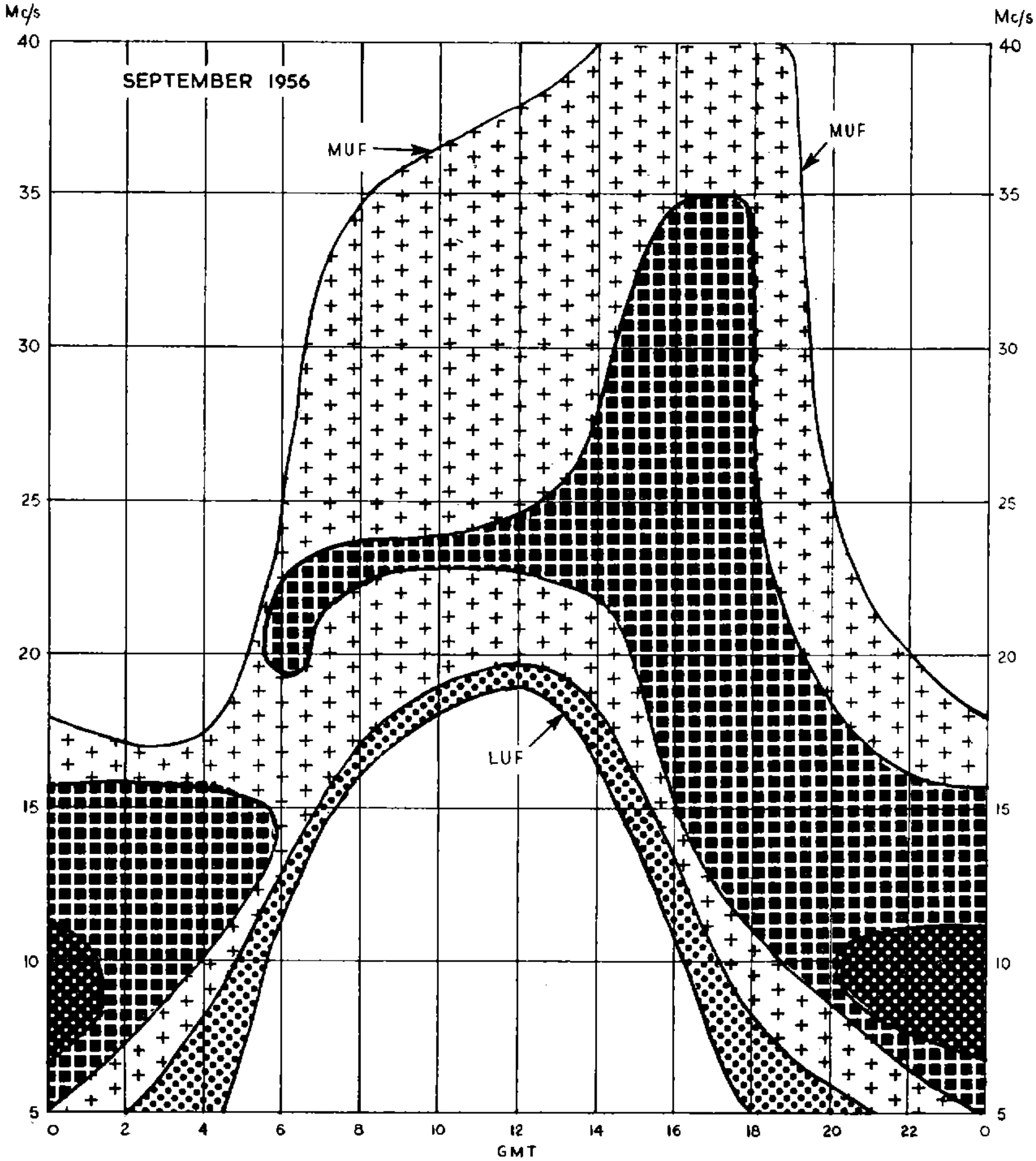
(*c*) The accuracy of each prediction method may also vary with distance, direction, and location of a given path, time of day, season, and phase of solar activity,[26, 27] etc.

A limited comparison of reception results with the short-term and long-term predictions has been made, and some of the results are discussed below.

3.3.2 *Accuracy of Short-term Predictions*

A comparison of short-term predictions with the reception results obtained on the BBC paths U.K./Ottawa,[28] U.K./Johannesburg,[25] and U.K./Singapore[29] has been made for every month in 1956.

During that year, the frequency usage based upon the short-term predictions gave generally satisfactory reception. Occasionally successful use of frequencies above the predicted MUF values was observed however, particularly on the U.K./Singapore path, showing that the predictions were at times too low. This 'underprediction' has also been observed on some short-distance paths, for example, on the U.K./Malta path during the summer of 1961, and Fig. 9 shows satisfactory reception on frequencies above the predicted MUFs. As MUFs computed by other methods were also too low, it is probable that sporadic-E



SINPO Signal Strength Rating	Percentage of Observation Days	Standard of Service	Code
3 or more	Less than 50%	Poor	
3 or more	Between 50% and 80%	Fair	
3 or more	More than 80%	Good	
4 or more	More than 80%	Very Good	
5	More than 80%	Excellent	

Fig. 8 — Estimated distribution of signal strength with frequency: Path: U.K./Johannesburg.

modes were involved in the propagation of higher frequency bands in this case.

An analysis was also made of the reception reports, obtained for many frequencies at Johannesburg in 1956 on BBC transmissions from the United Kingdom,[25] in order to study the distribution of signal strength with frequency and time. It has been found that the highest signal strength may not always occur on frequencies immediately below the predicted and actual MUFs and may vary considerably with frequency and time. For example, Fig. 8 shows that, during September 1956, the highest deduced signal strength on the U.K./Johannesburg path was restricted, between 0600 and 1400 GMT, to a relatively narrow frequency band well below the predicted MUF. Between 1400 and 1800 GMT, the highest signal strength extended over the greatest frequency range; later however, at its maximum, it was observed over a much more limited frequency range, still well below the predicted MUF. A similar analysis[30] of reception results of the standard frequency WWV transmissions from Washington, obtained during the last six months of 1953 at Tatsfield, also showed that the highest signal strength occured at times well below the actual and predicted MUFs.

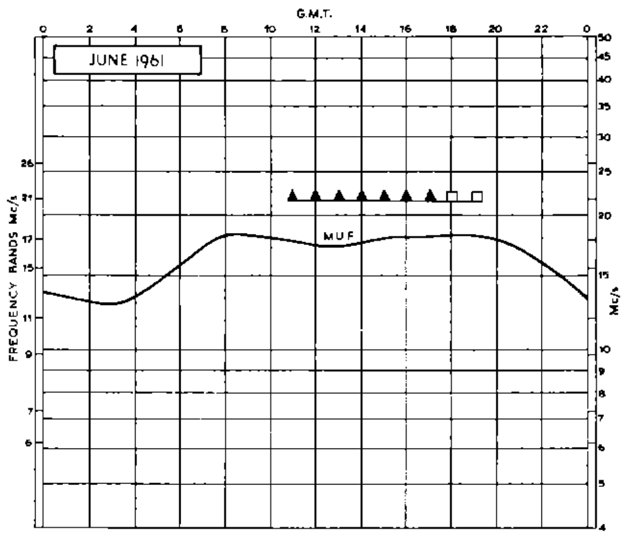


Fig. 9 — Comparison of short-term predictions with reception results; Path: U.K./Malta.

This observed distribution of signal strength with frequency and time probably varies with the propagation or non-propagation of different transmission modes, the signal being strongest when multiple modes are possible. It follows that, at a given time, the variation of signal strength with distance, for a given transmission in a given direction from a transmitter site, may also depend greatly upon the corresponding variation in the number and types of possible propagation modes; hence the variation of signal strength with increasing distance may show at times successive peaks and troughs.

3.3.3 *Accuracy of Long-term Predictions*

Whilst short-term predictions soon lose their actuality, long-term predictions are intended for continual reference, so that it is important to know the degree of accuracy to be expected. As a general guide, comparison of some of the long-term predictions with reception results are given below.

The paths chosen for this analysis were: U.K./Ottawa, U.K./Singapore, and U.K./Johannesburg, i.e., those which have been discussed in Paragraph 3.3.2. The comparisons are made only for those months during the sunspot minimum and maximum epochs for which the RRS special prediction charts were available (see Paragraph 3.1.1). The results are discussed below:

U.K./OTTAWA (See Figs. 10a – 10f)

Predicted frequencies and SINPO reception results were compared for the following months: March 1954, June 1954, and January 1955 (there was insufficient data for December 1954), for the sunspot minimum epoch; December 1956, March 1957, and June 1957, for the sunspot maximum epoch.

In general, frequency usage was according to the long-term predictions, and resulted in consistently good reception. At times, however, operational frequencies exceeded the predicted MUFs. This occurred in January 1955, and, as can be seen from Fig. 10c, fair to good reception was possible during the local evening on frequencies one band higher than predicted. On the other hand, during March 1954, when operational frequencies also exceeded the predicted MUFs during the local evening, reception was unsatisfactory (Fig. 10a).

Since there was no frequency usage below the long-term predictions of LUFs, no reception data were available to test their accuracy.

U.K./SINGAPORE (See Figs. 11a – 11d)

Predicted frequencies and SINPO reception results were compared for the following months: June 1954 and December 1954, for the sunspot minimum epoch; December 1956 and June 1957, for the sunspot maximum epoch. As reception during the equinoctial months can be affected by the tropical sunset fading effects, March 1954

Code	SINPO Signal Strength Rating	Percentage of Observation Days	Standard of Service
✕	3 or more	Less than 50%	Poor
△	3 or more	Between 50% & 80%	Fair
□	3 or more	More than 80%	Good
▲	4 or more	More than 80%	Very good
■	5	More than 80%	Excellent

Code for Figs. 9–12.

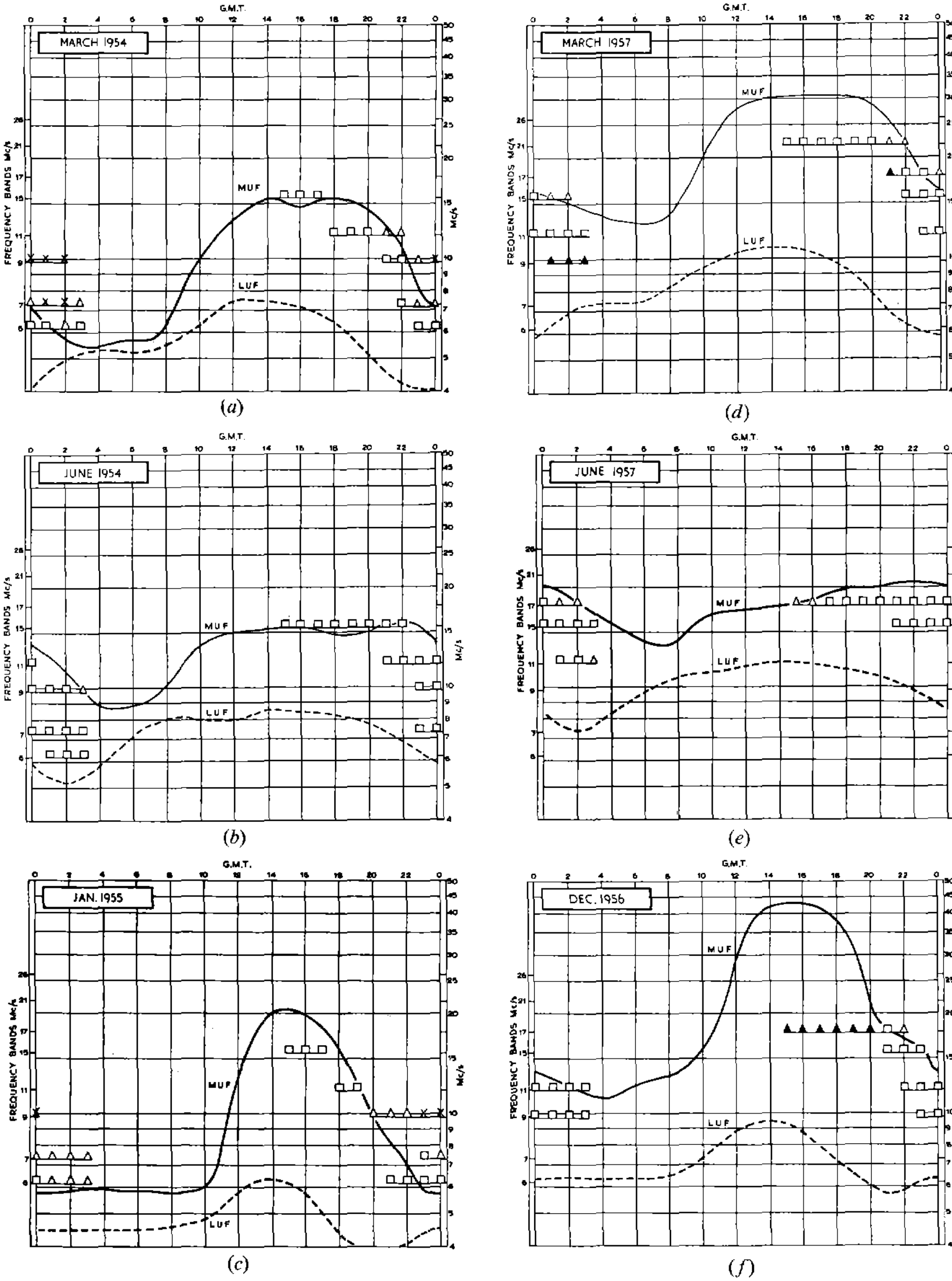


Fig. 10 — Comparison of long-term predictions with reception reports; Path: U.K./Ottawa.

and March 1957 have been omitted. These effects have been previously discussed in Paragraph 2.5.

In general, frequency usage according to long-term predictions gave consistently good reception, and on this path also operational frequencies at times exceed the predicted MUFs. This occurred in June 1954 and June 1957, and Figs. 11a and 11c show that operation on frequencies one band higher than the predicted MUFs gave good reception for long periods during the local evening. On the other hand, operation of frequencies above the predicted MUFs in December 1954 gave unsatisfactory reception at this time (Fig. 11b).

There was very little frequency usage below the predicted LUFs. Nevertheless, reception reports obtained during June 1954 and December 1956 indicate that the predicted LUFs for these months may have been too high, as good reception was obtained on somewhat lower frequencies (Figs. 11a and 11d).

U.K./JOHANNESBURG (See Figs. 12a – 12d)

Predicted frequencies and SINPO reception results were compared for the following months: June 1954 and December 1954, for the sunspot minimum epoch; December 1956 and June 1957, for the sunspot maximum epoch. Comparisons during equinoctial months were omitted for the reasons given for the U.K./Singapore path.

In general, frequency usage was according to the long-term predictions, and it gave consistently good reception. Again, operational frequencies at times exceeded the predicted MUFs. This occurred in June and December 1954 (Figs. 12a and 12b). Good reception was obtained in June 1954, for a long period during the local afternoon and

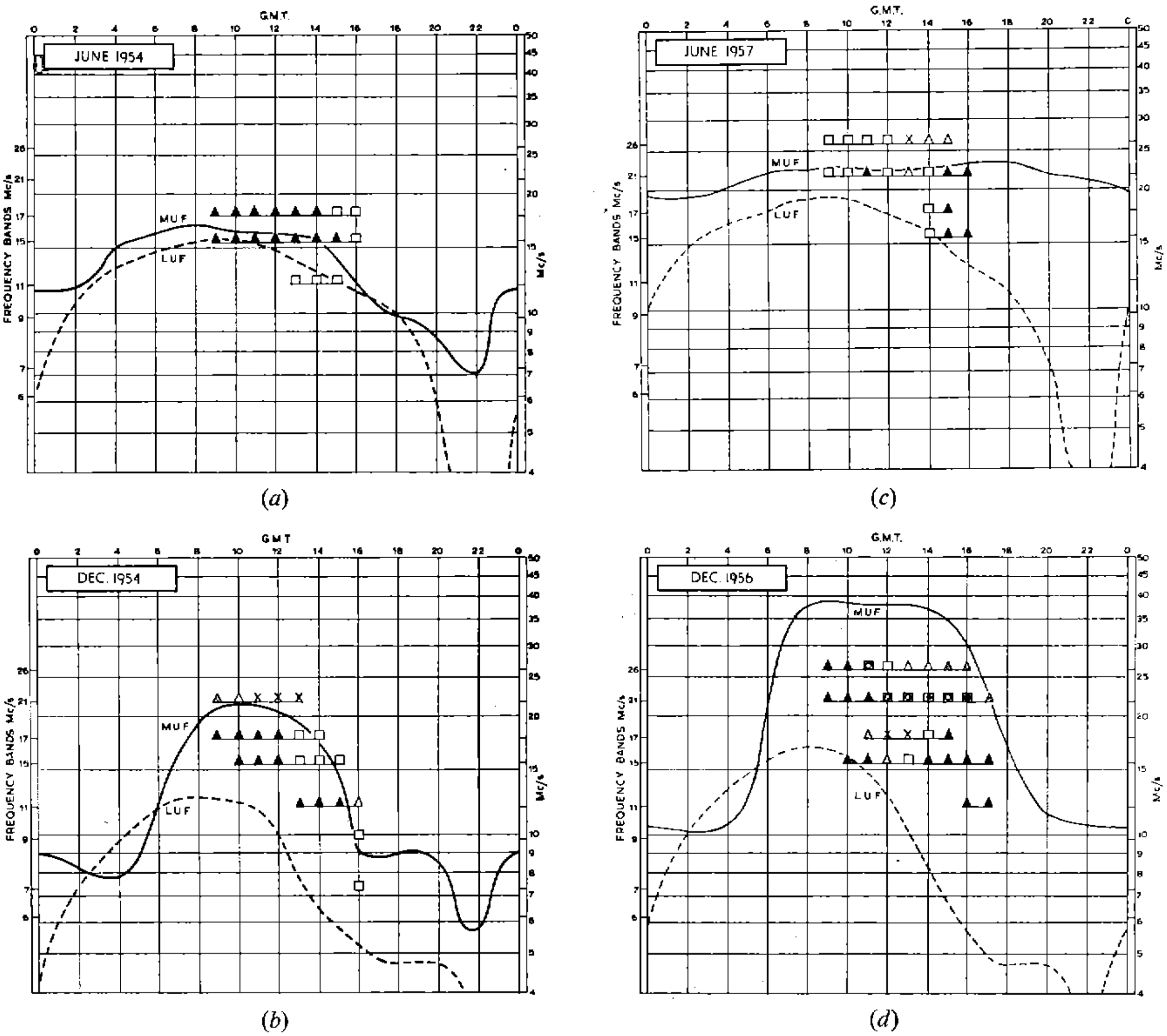


Fig. 11 — Comparison of long-term predictions with reception reports; Path: U.K./Singapore.

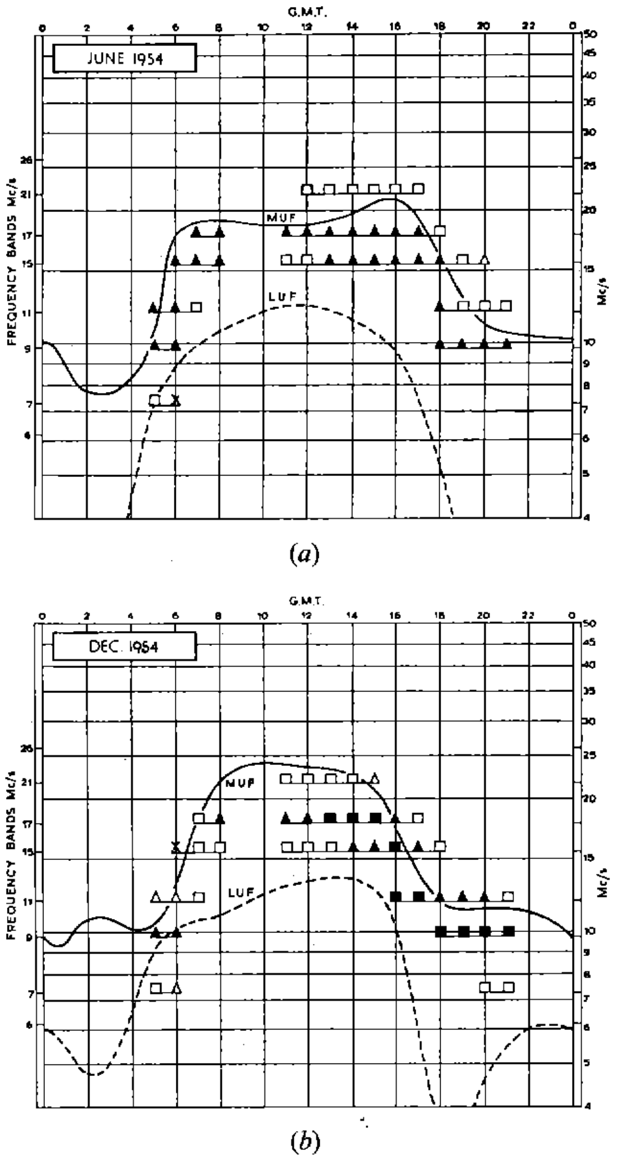


Fig. 12 — Comparison of long-term predictions with reception reports; Path: U.K./Johannesburg.

evening, on frequencies one band higher than those predicted. Also, during June and December 1954, the predicted fade-out times were too early on bands higher than 9 Mc/s.

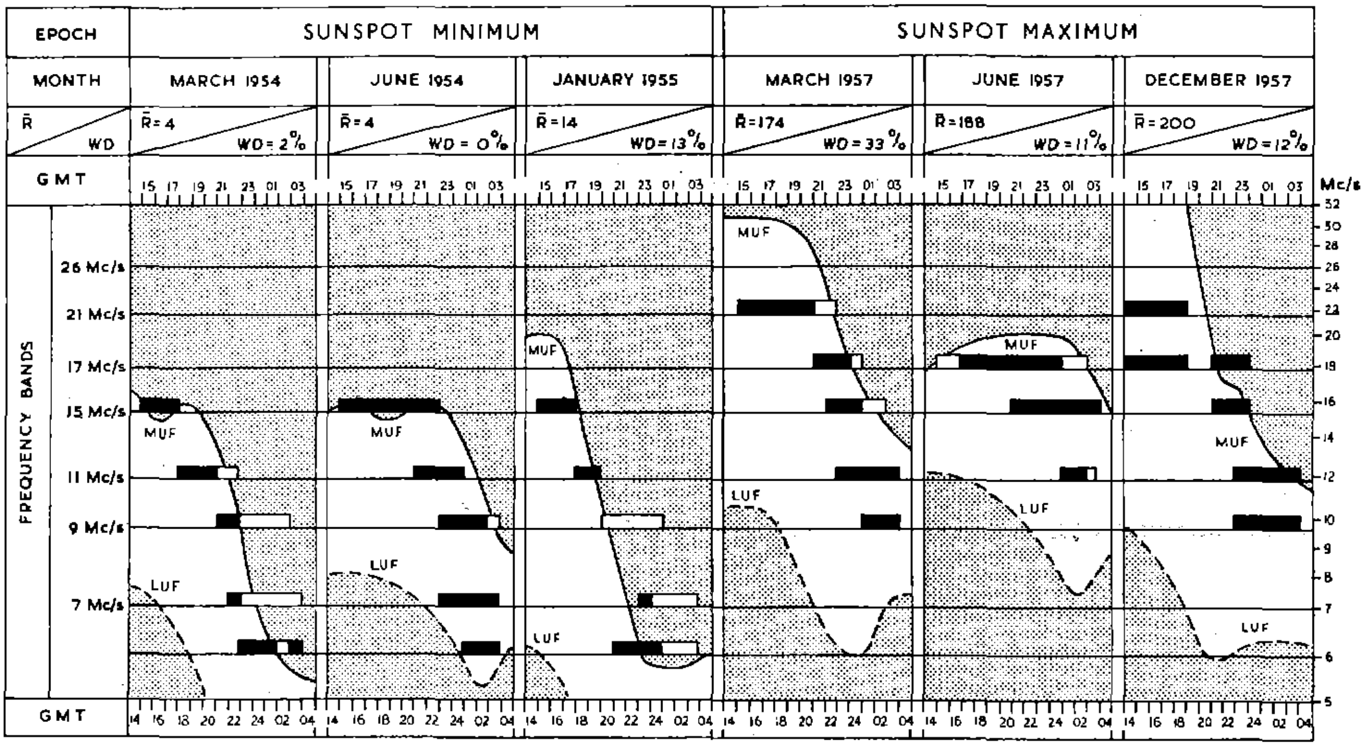
There was little frequency usage below the predicted LUFs. The reception results agree well with these predictions (Figs. 12a, 12c, and 12d), except that, during December 1954, good reception was obtained one band below the predicted LUFs (Fig. 12b).

NOTE: Reception results obtained for a given solar activity can be valuable, not only for the study of the accuracy of the short-term and long-term predictions, but also as a guide to the choice of suitable operational frequencies in future periods of similar solar activity. Some results for the U.K./Ottawa path are shown in Fig. 13. In this connection it is more accurate to use the F_2 index (IF_2) than the sunspot number (see Paragraph 3.1.4) as an indication of solar activity as it affects the propagation characteristics of the F_2 layer.

3.3.4 *Predictions for Antipodal Paths*

Propagation of transmissions from the United Kingdom to New Zealand is of special interest, because of their nearly antipodal situations and the considerable ionospheric absorption of radio waves over such great distances.

Firstly, it is found that certain BBC transmissions beamed in directions well removed from the great circle path, and not intended to serve New Zealand, are at times audible there. Secondly, there are also variations in the bearings which are satisfactorily received in New Zealand, probably due to the diurnal variations of ionospheric absorption over the different paths. Fig. 14 shows the



Code (based on hourly values) ■ Good service, i.e., Signal strength ⩾ 3 (SINPO Code) for more than 80% of days

□ Poor service, i.e., Signal strength ⩾ 3 (SINPO Code) for less than 80% of days

MUF = Maximum usable frequency (RRS Special predictions)

LUF = Lowest useful frequency (e.r.p. = 7500 kW)

N.B.: R̄ = Zürich smoothed monthly sunspot number. WD = Percentage of total time when Westdown Warnings were in operation at Tatsfield.

Fig. 13 — Summary of reception at Ottawa of BBC transmissions from the U.K.

diurnal variations in the bearings of the BBC transmissions which provided satisfactory reception at Wellington on 5 December 1960. Thirdly, owing to great ionospheric absorption at certain times, there are considerable periods during which it is not possible to provide a good service in New Zealand from the United Kingdom irrespective of the direction of the beam (Fig. 15). Fourthly, because certain great-circle paths from the United Kingdom to New Zealand traverse the northern or southern auroral zone, ionospheric absorption on these paths is increased still further, and propagation is made more sensitive to the effects of the ionospheric storms.

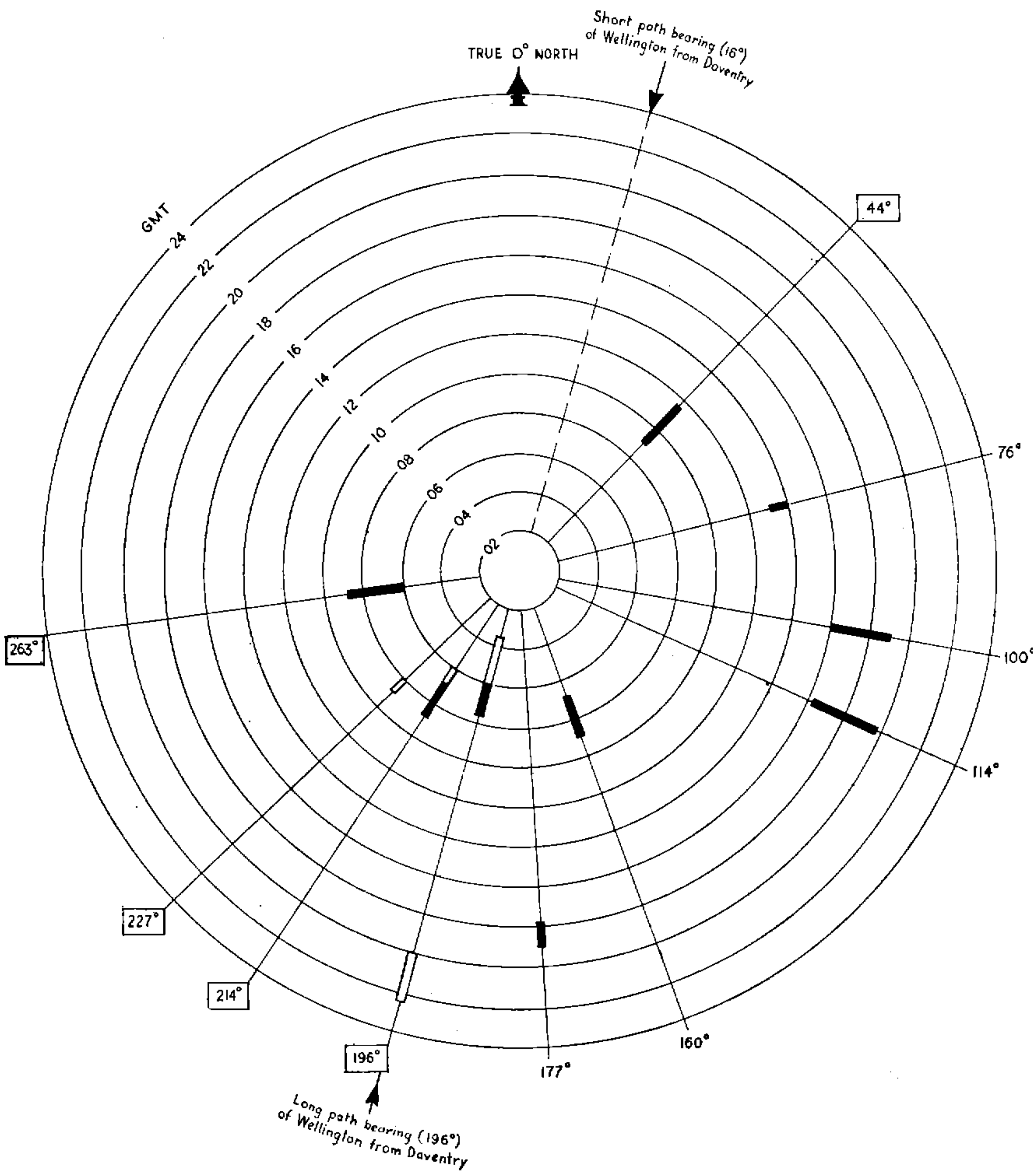
For these reasons, BBC transmissions are beamed to New Zealand in different directions at different times of the day, seldom using direct great-circle bearings. In 1960, for example, the General Overseas Service transmissions were beamed along bearings near to the great-circle long path between 0600 and 0800 GMT, and near to the great-circle short path between 0915 and 1130 GMT, etc.

As it is not always possible to assess the exact paths along which the radio wave energy can best be propagated at any time between the United Kingdom and New Zealand, empirical methods have to be used in predicting the MUFs and LUFs. Predictions are computed for the so-called composite short path and long path, i.e. for different hypothetical off great-circle paths at different times of the pay. Fig. 15 shows the periods of poor reception of BBC transmissions in New Zealand during 1960, according to the short-term predictions, irrespective of whether they were beamed along short-path or long-path bearings.

Fig. 15 also shows the actual periods during 1960 when any BBC transmissions from the United Kingdom, including these not intended for New Zealand, provided good service, as monitored in Wellington.

The diurnal pattern of reception shows a seasonal variation somewhat similar to that predicted. There were considerable periods when no satisfactory reception was possible, and these varied from summer to winter. For example, during New Zealand summer, between about 2030 and 0600 GMT and between 1130 and 1400 GMT, and during New Zealand winter, between about 0800 and 1700 GMT, no satisfactory service was available.

It follows that prediction techniques for these paths are of necessity empirical. Nevertheless, some measure of agreement between predictions and observed reception data is achieved.



Bearings from U.K. of array maxima with satisfactory reception (Beams ±17·5° wide to half-field strength)

44° — Bearing of transmission intended for New Zealand

114° — Bearing of transmission not intended for New Zealand

Periods of satisfactory reception: Signal strength ⩾ 3 (SINPO rating)

Periods of poor reception: Signal strength < 3 (SINPO Rating) (Shown only on transmissions intended for New Zealand)

Fig. 14 — Reception in Wellington, New Zealand, of BBC transmissions from the U.K. on 5 *December* 1960.

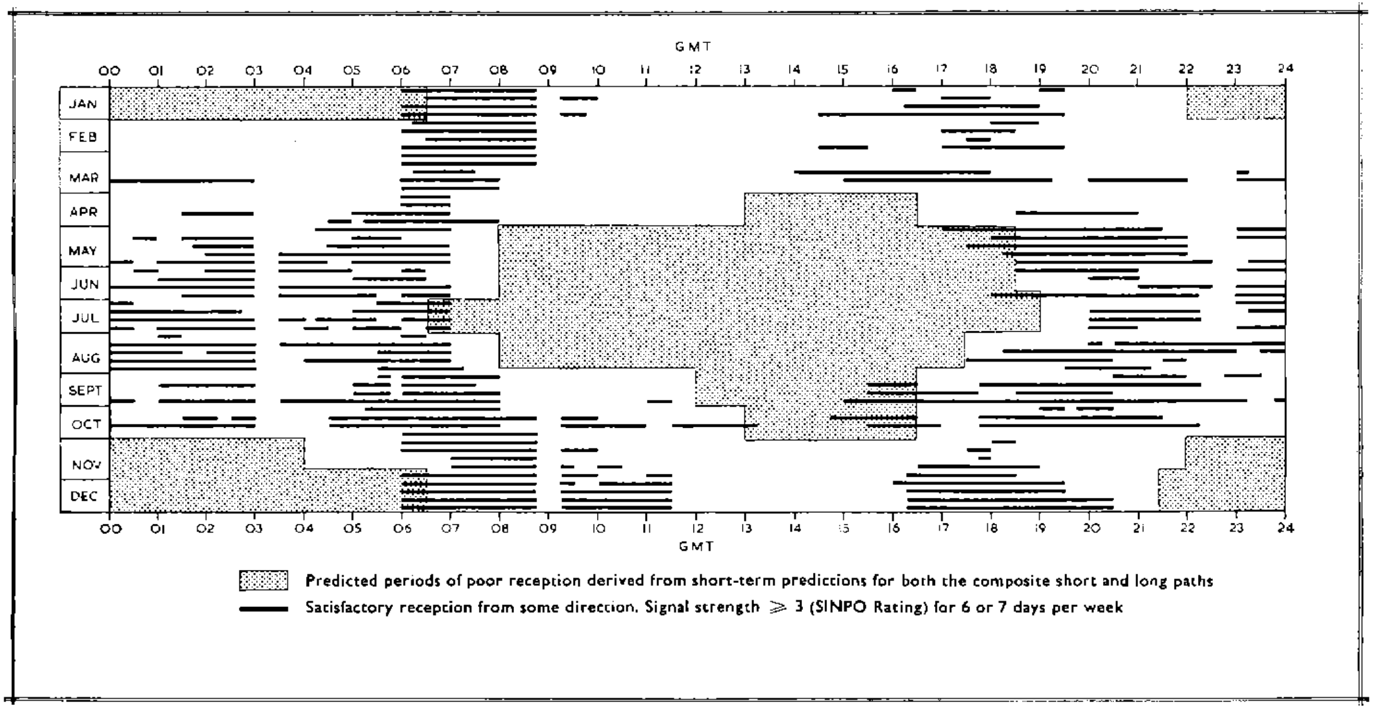


Fig. 15 — Predicted and observed reception of BBC transmissions from the U.K. in New Zealand during 1960.

4. Conclusions

The analysis of reception data on specific short-wave broadcast transmissions leads to the following conclusions:

1. Analysis of reception reports during the current sunspot cycle on the U.K./Singapore and the U.K./Johannesburg paths has revealed marked tropical sunset fading effects. Although the effects on these two paths were not identical, their incidence was generally greatest during the sunspot maximum years.
2. The effects of ionospheric storms on short-wave reception in the United Kingdom were analysed on the basis of Tatsfield warnings issued between 1944 and 1961. There was a marked tendency for peak storminess to occur a few years after the sunspot maximum. During each year, the incidence of warnings was greatest in autumn, winter, and spring, and least in summer. The effects of ionospheric storms on the westerly paths from the United Kingdom were very much more marked than on the easterly paths, due to the proximity of the U.K./North America paths to the Northern Auroral Zone.
3. From the study of their effects on short-wave reception in Southern England from 1944–61, it was found that the incidence of SIDs varied almost directly with solar activity, being greatest during the sunspot maximum, and least during the sunspot minimum years.
4. The performance of BBC transmissions during the current sunspot cycle on three selected long-distance paths indicates that the frequency usage for these transmissions, when chosen according to predictions, generally gave satisfactory reception in the target area.
5. Although there was little frequency usage outside the predictions, the results available on the U.K./Singapore and U.K./Johannesburg paths indicate that sometimes the predicted MUFs were too low, particularly in summer. There was also a less definite indication that the predicted LUFs may at times have been too high. However, if the considerable gain of the aerials at the receiving stations is taken into account, the predicted LUFs could be decreased by about 1 to 2 Mc/s.
6. The distribution of signal strength with frequency and time for the U.K./Johannesburg transmissions shows that, at times, strongest signals were recorded on frequencies well below the predicted MUFs for that path; this may be connected with the variation in the number and type of propagation modes.

5. Acknowledgments

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