BBC ENGINEERING

BBC Engineering

including Engineering Division Monographs

A record of BBC technical experience and developments
in radio and television broadcasting

Contents

The Cover Photograph shows the control desk
used in the assembly and routing of programme
networks at Bush House — the BBC's Overseas
Services studio centre

Editorial

The continuing search for economy

A glance at the Contents List for this issue would probably not reveal any common theme — apart, that is, from the one which we hope to present always — technological advance. There is, however, another common factor which, although implicit in many accounts of engineering developments, is tending to assume a more important role. We refer, of course, to the economic consideration. As broadcasting becomes more complex and inflation continues on its relentless way, so the broadcasting engineer has to concentrate more and more on finding cheaper ways of doing things better.

Automation represents one way of saving money, mainly because it can release expensive staff from the tedium of routine operational duties and allow their employment on more productive and interesting tasks. The first article describes how the automation of the programme assembly and routing operations for the BBC External Services has resulted in a more comprehensive technical performance with a saving in cost.

The second article describes an improved method of operating radio microphones at an acceptable cost. The description is related specifically to performers' microphones in a television studio but the techniques could, of course, be used in other multi-microphone operations.

The development of arrays of log-periodic aerials for use at low-power uhf transmitting stations, described in the third article, will result in a direct saving of money. The new arrays have lower wind loading than the types used hitherto and so permit lighter support structures. Thus a contribution is made toward keeping the costs of extending the uhf transmitter network within bounds.

A similar contribution could result from the work described in the final article. Success in solving the problems which tidal fading causes in uhf propagation and reception would mean, for example, that both shores of a tidal estuary could be served from one transmitting station, instead of requiring separate stations on both banks.

An apology

We should like to repeat the apology, already posted to all subscribers to 'BBC Engineering', about the serious delays in publication which have occurred during the past year. The editorial difficulties, caused by acute shortage of staff, are now being overcome and good progress is being made in recovering the lost ground.

Issue 102 is already well advanced toward publication as this Editorial is being prepared, and it will follow this present issue after only a few weeks. Its two major articles will describe the new Broadcasting House in Manchester, the latest stage in the development of improved facilities for non-metropolitan broadcasting.

An Automatic Control System for the Assembly and Routing of Programme Networks — External Services, BBC

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Summary: Following a general description of the BBC's External Services Operation, the authors examine the design philosophy of automated switching and the factors which led to the choice and installation of the present system in use at Bush House, the Headquarters of the BBC's External Services.

The system is described together with details of the staff necessary to both operate and maintain it to broadcasting standards. The cost in terms of capital and the savings which have been realised following its introduction are considered. The training necessary, together with the operational experience, is discussed following almost two years of use in service.

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2. Programme Structure
3. Changing requirements and difficulties in maintenance
4. Design philosophy
5. Choice of design
6. System description
7. Spare capacity and redundancy
8. Auxiliary functions
9. Staff training
10. Changeover to new system
11. Experience in use
12. Reliability in service
13. Savings
14. Conclusions

1 Historical survey

The External Services of the BBC now broadcast in 40 languages to all parts of the world, and are 'on the air' with one or more programme networks throughout the 24 hours. The service started in a more modest way in 1932 with experimental transmissions in English, when a single programme of 10 hours daily was radiated to parts of the Dominions and Colonies.

During those early years, arrangements for routing the studio output to the short wave transmitters were relatively straightforward. A single line from the studio to the transmitter was all that was needed and any complication was limited to changes of studio to permit alternative programme items to be produced. By the end of 1939, several different languages had been added and additional studio facilities provided.

The war years saw further changes with rapid expansion of Programme Services. This required the use of many more studios, music and control lines, and high frequency transmitting stations, each equipped with a number of transmitters. In order to deal with the greatly increased output, the contributions from studios were assembled into 'colour networks' or 'programme streams' where each item of programme followed a strict time discipline based on a quarter-hour unit. This provided a convenient method of routing programme packages from the studio to the transmitter via 'programme chains', although the original selection was still carried out manually by engineering staff on a Now/Next Event principle. Switching between transmitters was carried out independently at the transmitting stations and took place during a four second period set aside for this purpose between the finish of one programme item and the start of another.

In 1957, a major step forward took place when an electro-mechanical memory bank employing motorised uniselector switches was installed (as described by Axon and Barron)[1]. The unique use of this system enabled information on the routing of up to 24 programme networks between the studio centre and the transmitter site to be stored, and achieved automatic switching without the need for manual supervision. The assembly of the programme networks however was still carried out manually and required constant supervision of a number of different language programmes, monitored sequentially for long periods of time by staff unable to appreciate the programme content.

2 Programme structure

For operational convenience, it is the practice in External Services to standardise programme times to multiples of quarter-hour periods where each item starts at 28 seconds to the quarter-hour. Thus a single, half-hour programme may commence at 14.29^{32}GMT and finish at 14.59^{28}GMT. This gives a four-second blank period before the start of the next item at 14.59^{32}GMT and allows for the automatic switching of the networks at the studio centre and at the transmitter stations. Independent transmitter station switching is employed, but a common reference against Greenwich Time Signals is used to assist synchronization.

As separate switching takes place at the transmitter station, the continuity of programme streams has little meaning for overseas listeners. Consequently, the assembly of a number of studio sources dealing with different language programmes into a single network stream can be treated as an engineering convenience which permits the reduction of the many contribution sources into a smaller number of networks each designated by a colour for ease of handling. The importance of a strict time discipline is obvious where automatic switching is used and disregard of the junction gap by production or studio staff results in programme clipping or untidy presentation.

There is a limit however to the extent to which automation may be introduced. A single studio may require a number of miscellaneous broadcast sources to produce a complete programme item. This may involve an overseas contribution via landline set up only minutes before it is required, an outside broadcast commentary point where a contribution is taken on cue or an intake from a separate studio unit dealing with a news item which may be live or recorded. Full automation of this aspect of programme building is impracticable because the strict time discipline which would be required cannot be maintained.

3 Changing requirements and difficulties of maintenance

The basic 15-minute programme structure allowed the original development of the electro-mechanical switching system, but, by 1968, the system was becoming too small and additional channels were required. Also the replacement of the uniselectors which had been in continuous use for over 10 years was becoming necessary due to their increasing maintenance requirements and the difficulty in obtaining spares. As alternative methods of switching had become available it was decided to investigate new methods of programme assembly and routing control. A study group was therefore set up towards the end of 1968 to examine the switching requirements and to make recommendations on a technical solution, making use of modern techniques.

4 Design philosophy

As a result of the study it was decided that the main control room within Bush House should be reorganised so that it could be operated by fewer men during peak periods. As each member of the staff would be required to undertake a greater range of activities, particular attention was to be given to the layout of equipment and the procedures to be adopted. It was decided that complicated codes should be avoided and interrogation of any memory device associated with the assembly and routing of programmes should be made as simple as possible.

The basis of the system was to be a main memory store holding the scheduled repeating information needed for the assembly of the programme networks and the distribution of these networks to transmitter stations. Additional timing signals and the automatic injection of Greenwich Time

Signals would also be included and it was planned that this data would normally be held for up to 13 weeks. For each 24-hour period, the information would be transferred to a 'today' store — the executive device making the necessary switching operations required for the assembly and distribution of the daily programme material. A check between the main and the day stores would be available and 'change' indications given where a variation was detected. The 'memories' were to have expansion capacity from 60 studio sources to 120 sources on 15 networks, via 30 line inputs and 30 line outputs, and would deal with 15-minute programme modules with capability of easy conversion to 5-minute modules. Tape punches and tape readers for updating procedures were to be provided together with facilities for interrogation of either memory in plain language.

The continued use of the electro-mechanical uniselectors associated with miscellaneous source and destination selection of the original system was accepted since these items had not been in continuous use and therefore had useful life left. It was decided however to employ codebar switches for both the 'network' and 'chain' switching operations and a separate set of switches for the pre-transmission and transmission conditions, and for monitoring. As these switches had not been used within the United Kingdom for broadcast purposes, an accelerated life-test was undertaken to establish the performance and reliability for this particular application. It was decided that a small general purpose computer should be used as a processor controller and a magnetic drum as the main memory store coupled via an appropriate interface to the electro-mechanical switches employed in the selection, the usual line testing facilities were included.
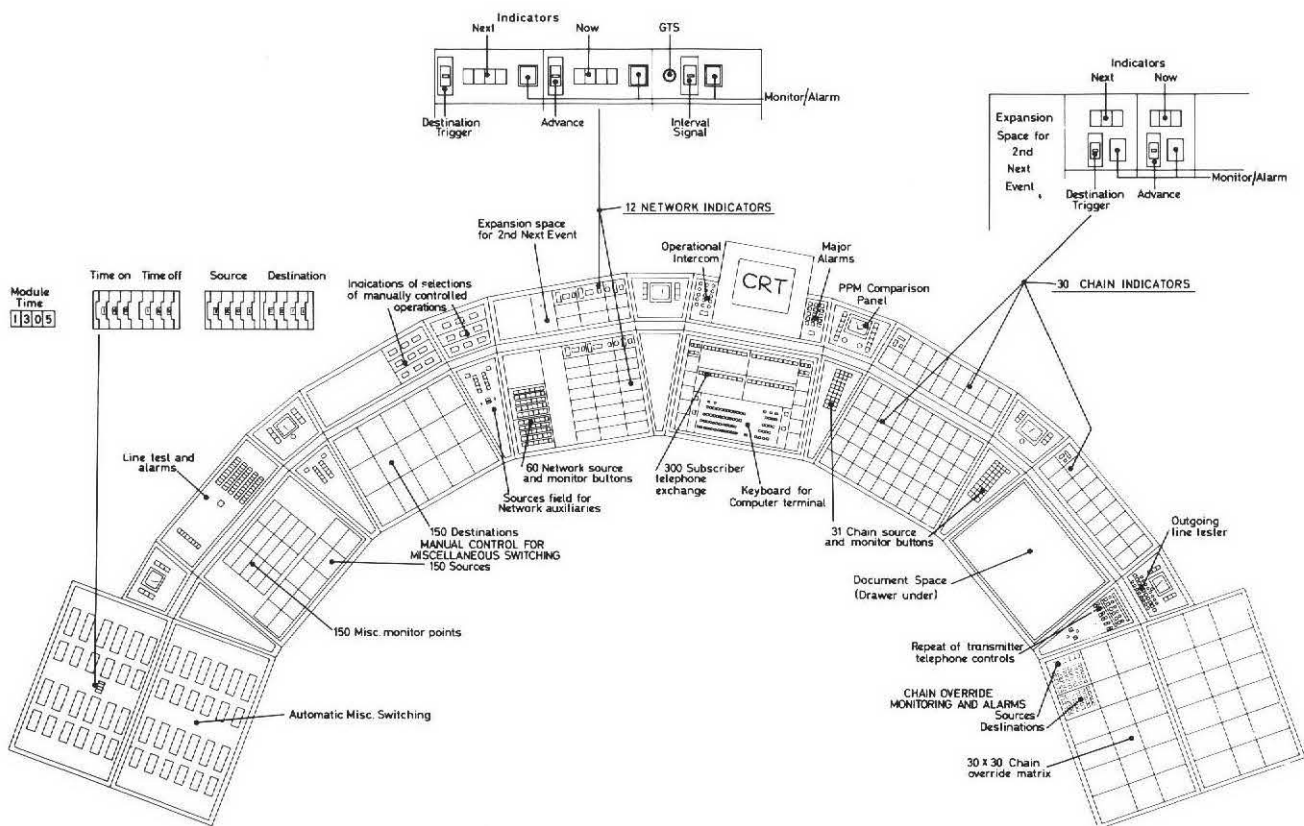
A new master control desk was to be provided which would contain all indications, manual override and communication facilities. The miscellaneous source and destination switches were to be connected to a mechanical memory bank based on thumb-wheel switches for easy selection of time and destination. Line-routing panels with easy override facilities would be provided on the main desk, so that in the event of external circuit failure, changes could be made from the desk position without the operator having to walk over to the apparatus racks.

The control desk position (Fig.1) would be constructed to allow standing operation during periods of high activity. The layout of the desk (Fig.2) was to follow a left to right distribution and the whole working area was to be illuminated with diffuse lighting to avoid high contrast areas, the panels being finished in a matt surface to avoid glare. The decision was taken that the control and display facilities should be fully integrated and not held separate as in previous designs, also that plain language indications were to be provided wherever possible, although abbreviations were acceptable.

It was proposed that a continuous automatic monitoring system should be provided on all lines and that pre-transmission tests should be made automatically between the control room and the contribution studios. The latter would prove the line performance and also verify that the studio operator was in attendance. An indication of the programme and network identity would also be available.

Fig. 1 The control desk position is designed for standing operation during periods of high activity. In the foreground can be seen the supervisory terminal

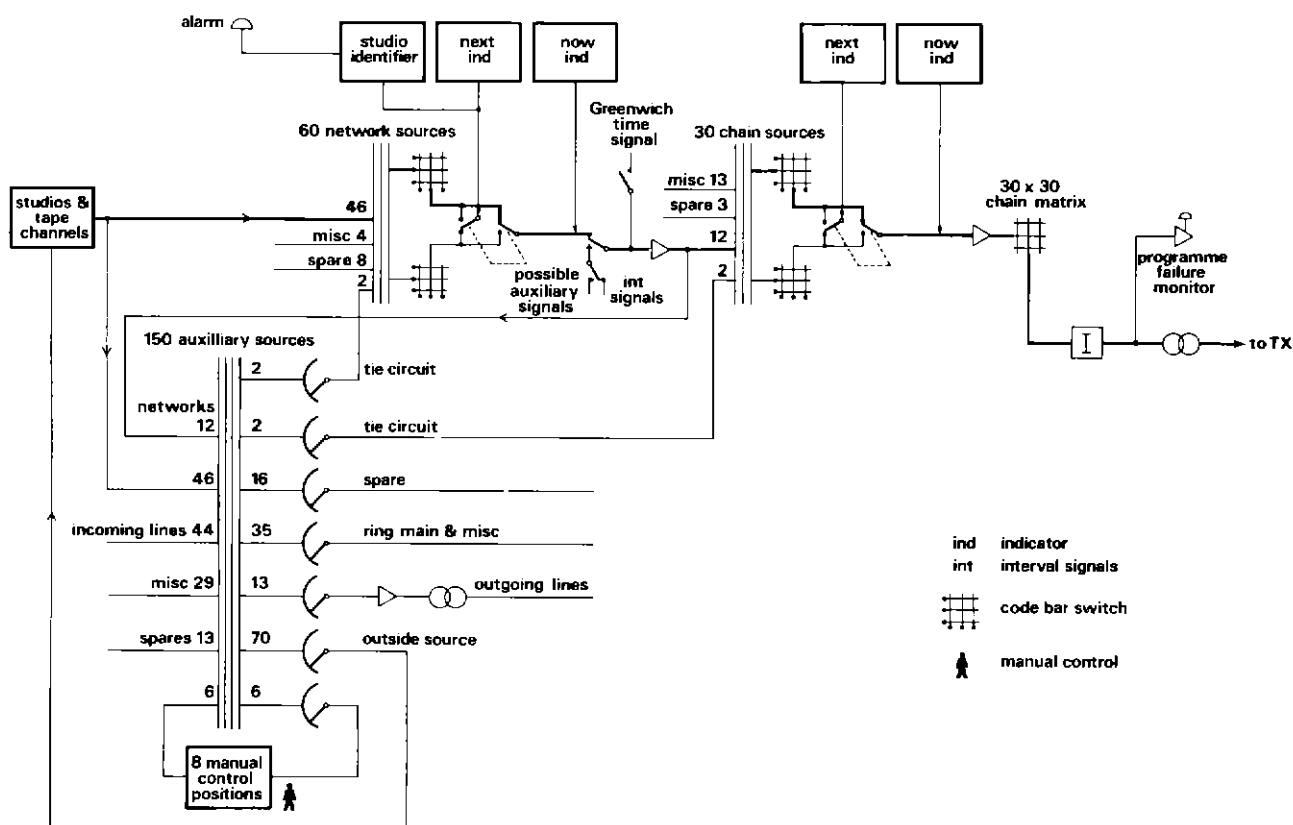**Fig. 2** Layout of the new control desk

alarm

| studio identifier | next ind | now ind | | next ind | now ind |

60 network sources

Greenwich time signal

30 chain sources

30 x 30 chain matrix

studios & tape channels

46
misc 4
spare 8
2

misc 13
spare 3
12
2

possible auxiliary signals

int signals

programme failure monitor

to TX

150 auxiliary sources

networks 12	2	tie circuit
	2	tie circuit
46	16	spare
incoming lines 44	35	ring main & misc
misc 29	13	outgoing lines
spares 13	70	outside source
6	6	

8 manual control positions

ind indicator
int interval signals
      code bar switch
      manual control

Fig. 3   Programme chain

5 Choice of design

Initial investigations at the time indicated that precious metal-plated contact, high-speed-motor uniselectors were no longer obtainable, so a survey of alternative programme switching apparatus was made with a view to selecting a suitable replacement. A codebar switch, type RVK3, was chosen on the ground of low cost and volume per crosspoint coupled with high reliability and ease of maintenance.

The method of using the switches was to be either the traditional two-step method of network assembly and distribution, or a single step process which would halve the number of components employed within the switching chain. The number of pre-transmission events was considered on a basis of one on-air with the next-event indicated, or one on-air with the next and second-events displayed.

The process controller could have taken any of several forms, e.g. a basic core store with hardwired programme and single data entry system with clock controlled output, or a small general purpose computer with back-up storage, software programme package and data entry by Teletype or Visual Display Unit (VDU). Similarly, the processor output could have been in any of several forms, e.g. a direct output to electro-mechanical switches, or in processor language with a translator to electro-mechanical type instructions. Various forms of memory were available, ranging from a simple peg-board system to commercially available magnetic core store, which could be employed for 15-minute programme modules and modified to deal with 5-minute units if required. It was decided that the system should comprise:

1. A small general purpose computer with extended option
2. A back-up storage, magnetic drum
3. A Teletype input equipment
4. A Visual Display Unit
5. A processor-to-drum interface unit
6. A dual clock control unit
7. An output interface unit
8. A software package
9. A switch interface unit
10. A transmission programme switching system
11. A main control desk
12. A miscellaneous source selection 'hopper' memory
13. A monitoring alarm system
14. An engineering telephone system

The first eight items were commercial units manufactured to a specification prepared by the BBC and the remaining items were designed and provided by the Engineering Division of the BBC.

The programme selection system using codebar switches was based on a studio-to-network router comprising two selection switches per network, alternating between the transmission and pre-transmission states with a time-controlled changeover. The network/chain router, for distribution of programmes to the transmitter stations, was engineered on a similar basis. A simple crossplugging line matrix between the chain output router and the line distribution system was adopted which enabled a rapid changeover to be achieved in the event of failure, without need to reprogramme the central processor. Programme failure detectors set to alarm at 40 seconds, were fitted to the programme distribution lines, selected and primed via the central processor. A schematic diagram of the programme chain is given at Fig. 3.

The existing 16-level miscellaneous switching system was retained, but converted from double rank to single rank selection and provided with a BBC-designed short term 'hopper' memory for regular commitments. A number of circuits however could be provided with restricted facilities and employ fewer levels of switches.

6 System description

A schematic of the system adopted is given at Fig. 4. Communication between the operator and the processor is via punched paper tape and alphanumeric VDU displays. The output signals are binary coded but the input data may be in the form of alphanumeric-mnemonic codes. The system includes a variety of self-check facilities which notify the operator of fault detection and is so designed that a mains break of up to 10-seconds duration will cause no error. The components parts are described as follows:

i) Magnetic storage drum

The heart of the system is the magnetic storage drum which acts as a long-term store for the whole system. All data transfers take place from or to the drum which has an effective storage capacity of just over half a million data bits. This storage is divided into a number of areas:

a) Schedule store — this holds the scheduled status of the broadcast programme routing switches, covering 24-hour periods in 5 minute modules, normally for 13 weeks duration;

b) Today store — the executive store which holds the current 24-hour period switch status is basically the same as the schedule store, but with daily variations included;

c) Buffer stores — these are temporary storage areas for use in data input/output transfers;

d) Reference data stores — these are employed to deal with code conversion tables and time of day required by the central processor operations;

e) System software store — this holds the system operating software and is frequently used for maintenance routines. With the reference data stores it facilitates maintenance and enables the system to be recovered in the event of failure;
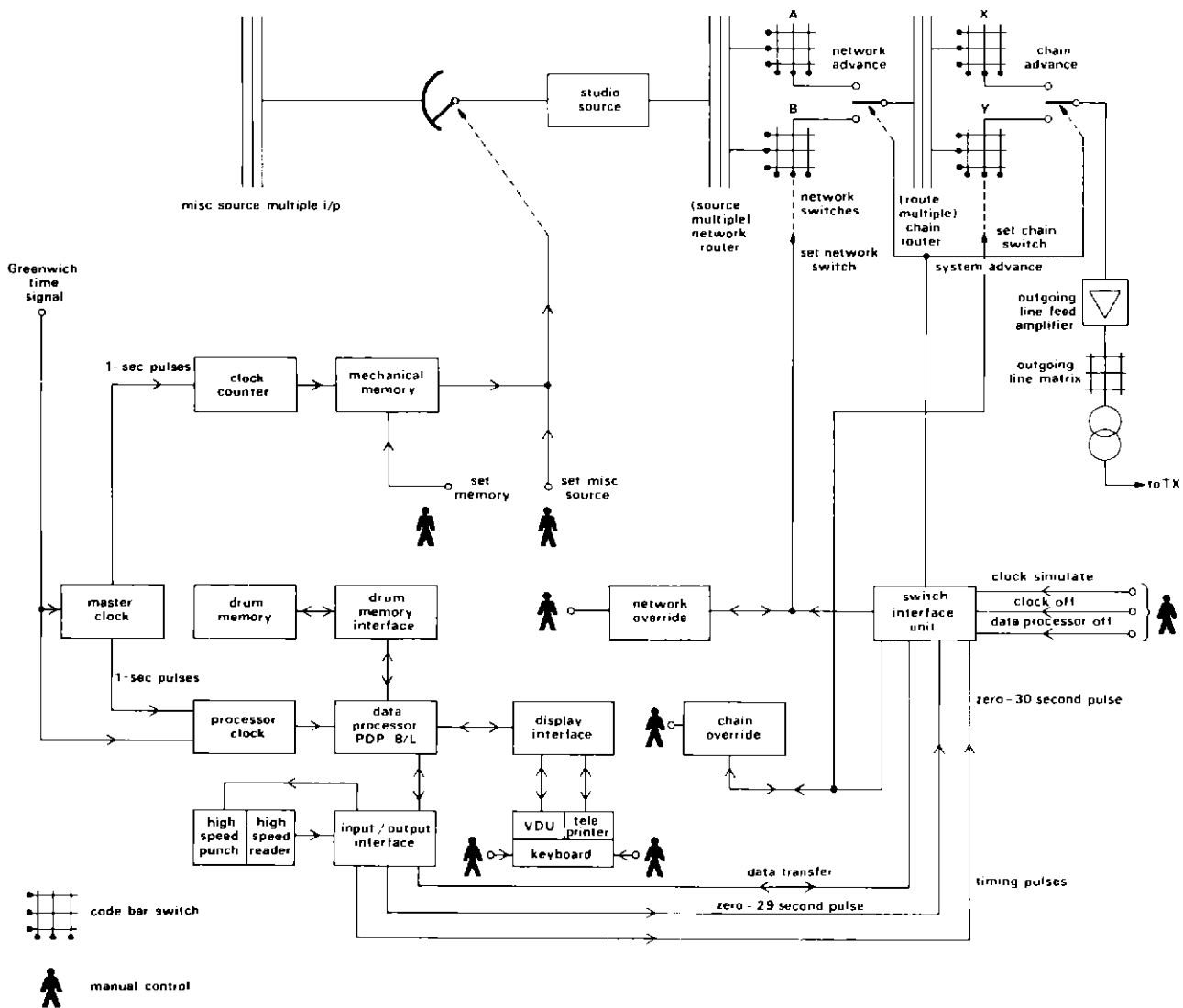

Fig. 4 Programme switching

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f) Emergency information store — this area is allocated to information on which the operator may call to obtain certain procedures to be used in the event of partial system failure.

ii) The central processor

This transfers data to and from the drum and the peripherals. This also organises code conversion, switch and service priorities, and includes a number of self-check and system check facilities. The capacity is 4096 twelve-bit words of core memory with parity check facilities and there is provision for expansion to a further 4096 words. This and any other hardware expansion can be achieved in a relatively short time.

iii) Visual display units (VDU's)

The system is supplied with a visual display unit and key board for communication with the processor. With minor hardware and software changes, additional units may be added and other serial line devices accommodated. The display contents may be entered or modified from the keyboard in an off-line condition, and only when the operator is satisfied with the display contents does he initiate the data transfer by operation of the transmit key. The processor only recognises a limited number of fixed display formats and in most cases the format skeleton will be written up by the processor at the request of the operator. In some information-only formats, the operator is unable to modify certain portions, except by clearing the entire display contents. The display is capable of 13 lines each of 80 characters and a normal format gives one hour of programme switching information excluding headings. A sample format is shown on the video screen at Fig. 5 and it will be seen that only change information is displayed.

iv) High speed paper tape reader and punch

Most of the input data can be prepared off-line on punched paper tape rather than on-line direct from the VDU's. A 300 character per second tape reader is provided to allow such tape to be read into the processor. Normally, this tape is presented to the operator on the VDU for approval before routing to the schedule or 'today' store. Associated with the reader is a 50 character per second punch which may be used off-line for the preparation of tapes or on-line as a logging device.

v) Teletype

The teletype is mainly intended for maintenance purposes, but also provides full stand-by facilities for the high speed punch/reader and the VDU equipment.

vi) Output interface

This device interfaces with the BBC translator, short-term store and timing device and provides in binary form the necessary signals for the presetting of the routing switching system. Signals cross on a 'handshake' basis through the exchange of Read and Ready signals. The BBC translator,
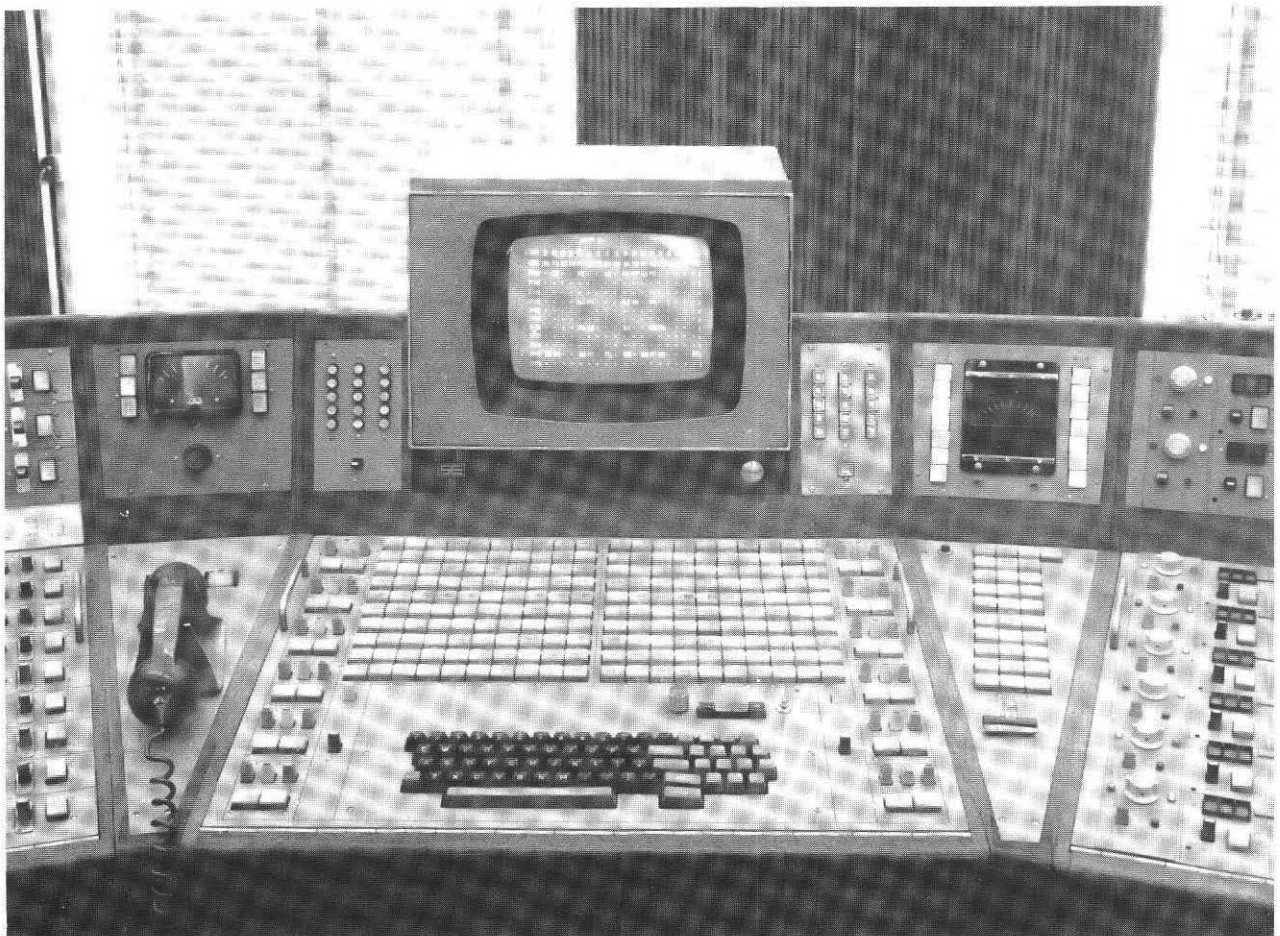

Fig. 5   A sample format showing change information on the communication VDU

or switch interface unit fulfils the following operational requirements:

a) it acts as the link between the process controller on the one hand, and the router bays and the pre-transmission tester on the other;

b) it acts as a link between the master clock and the digital clock in the processor bay;

c) it controls the 'advance' system of the auxiliary networks, networks and chains in accordance with the 5-minute clock pulse information or under manual control from the main desk.

vii) Timing device

Two identical clock units are provided for programme timing which recycle every 15 minutes. The clocks are driven from the seconds-pulses of the master clock system and a comparator constantly checks one clock against the other and against a Greenwich Time Signal reference, sounding an alarm when discrepancies of over half a second are observed. Thirty-two independent one-second output pulses are available, programmed to occur anywhere within the 15-minute clock cycle.

viii) Alarms

Most peripheral device faults are recognisable by the operator, but where the processor fails to recognise a character or format, or a data parity error is detected, the operator is warned by a blinking sequence on the display and/or ringing of the Teletype bell. The central processor continually checks its own functions and those of the drum, drum interface and output interface. If a malfunction occurs after a double check, a minor failure alarm signal is generated. The processor will then halt if the fault condition is within itself, but if present in another unit, data will continue to be given but must be regarded as suspect. A major failure alarm is given in the event of a mains power supply failure of more than 10 seconds to the drum or central processor. The processor then halts and further operation is impossible until the fault is repaired.

The BBC translator unit incorporates an advance control unit (ACU), which is interrogated at 5-minute intervals and causes a '5-minutes to go' warning lamp to appear in the preview windows and finally advances the selection 'on-air' 10 minutes after receiving instructions from the central processor.

With the introduction of the new system, a revised monitoring system and engineering manual telephone exchange was constructed and the full system is probably the first of its kind dealing with this volume of broadcast traffic.

7 Spare capacity and redundancy

As already indicated, expansion of the central processor core store and ability to deal with an increase in sources and network streams may be readily achieved. Limited redundancy is included in the equipment itself but since network modules are identical, fall-back position can be established relatively easily provided full networking is not in use at the time. Similarly, duplicate core storage in the advance control unit is provided and changeover can be

readily effected. Peripheral units for interrogation or display are provided and replacement is easily achieved. Although many circuit boards are employed in the system, a limited number of different types are in use and replacement necessary due to failure of any board may be achieved relatively quickly. Spare source/network and network/chain routers are provided and wired to enable changeover to be achieved relatively easily.

8 Auxiliary functions

A number of auxiliary signals, eg Greenwich Time Signal, interval signal, tape inserts etc, may be provided on instruction from the central processor and can be wired to achieve remote start of tape recordings or reproducing units.

Included in the system is a pre-transmission tester which operates automatically between the control room and the studio source on processor instructions. An indication of the network stream on transmission, the presence of a studio operator and a performance check proving the continuity of the studio to the Control Room circuit is provided and failure to satisfy any of the tests prior to transmission time causes an alarm to be raised in the control room. This system is relatively simple, consisting of a sender located within the control room and a receiver in each of the studios operating on a pulse tone signal with different counts representing one of each of the networks in use. The presence or absence of the operator within the studio is indicated by acceptance of the signal arriving at the studio.

9 Staff training

From the early stages of the design, it was accepted that the staff associated with the operation of the equipment would find the work more rewarding if they were involved in all stages of operation and maintenance of the new system.

Some 75 operational/maintenance engineering staff, who had previously been concerned with a completely analogue system, were re-trained in digital technqiues and the diagnosis of system failure where integrated circuits are used. Specialised instructional sessions and comprehensive manuals with flow charts of the system were prepared and descriptive leaflets dealing with individual parts of the system were produced for circulation to staff.

The training programme extended over a period of 9 to 12 months. This was conducted on a part-time release basis and it soon became apparent that the re-training required was appropriate to that of a systems engineer. Check programmes were produced to test the system and maintain familiarity with the entire range of complex equipment so that in the event of a failure, little time is lost in restoring the system to full service.

10 Changeover to new system

The new control desk comprises two main sections, a source-to-network assembly section dealing with miscellaneous changes which follow a daily booking schedule notified by the programme units, and a routing section dealing with

onward distribution of programme streams to the transmitter stations. The latter routings are less likely to change as they are fixed by the long-term schedule and changes would only arise in the event of plant failure external to the control area.

Two engineer positions are provided to deal with queries which may arise from the broadcasting source or destination, updating of store data and remedial action in the event of systems failure. When the long-term schedule changes are to be placed in store, the memory is updated by a supervisory engineer as part of his normal duties, at a position remote from the main desk area.

Operational staff are available for spot check monitoring but continuous aural monitoring is not carried out once the programme material has left the studio. Much reliance is placed on programme failure monitors associated with the distribution, the inevitable short delay in detecting failure of output being accepted. Incorrect programme resulting from misoperation following the studio is however not detected by this style of monitoring.

A major consideration in replacing the electro-mechanical system was based on the requirement to preserve without interruption the full broadcasting service throughout the 24-hour period. It was not possible due to economic or space restrictions to duplicate the system, although extensive use was made of parallel operation of the routing sections during the changeover from the old to the new system.

Much of the new system could only be checked when in use, and once satisfactory performance was achieved a cutover to on-line operation was made. Extensive use of normal break jack facilities allowed fall-back arrangements to be made and for a short period both the magnetic memory system and the electro-mechanical memory bank were programmed with the current transmission information. Arrangements were also established to permit easy rollover to full manual operation of the system should the general purpose computer system fail.

11 Experience in use

Since the system was installed, it has become apparent that each stage of the process (controller, interface and main desk) requires to be withdrawn from service from time to time for maintenance purposes or for modification to improve some operational procedure. Manual override facilities are available to permit each stage of the process controller to be withdrawn in turn and the entire operation can be conducted manually. This however imposes a considerable load on the operational staff and could not be carried out for long periods.

Interrogation of the processor stores by VDU's and the updating of the quarterly information was found to take about 15 man hours. Normally, however, day-to-day editing or remedial action via the input/output console present few problems. Diagnosis of system failure by single-step operation is lengthy, and clearly duplication of the more sensitive parts of the system by a general purpose computer is a desirable feature when this can be achieved. Some difficulties were encountered initially with the automatic pre-transmission tests caused by external interference but have now been overcome.

Environmental conditions within the processor and apparatus rooms were found to be important factors in achieving an acceptable standard of reliability. Expansion arrangements for the line-routing matrix were quickly used by increasing services, and more working space for records and the communication links should be included in future designs. the concept of 'stand-up' attendance during busy periods is proving satisfactory and the ergonomic considerations in the colour finishes, layout of panels and display has proved to be very successful.

12 Reliability in service

The design features provided for a Mean Time Between Failure (MTBF) of the central processor and its associated equipments of 1340 hours. Limited redundancy is included and an indication of the MTBF achieved for the data processing equipment and the switch interface unit following the 'burn in' period is given in Figures 6 and 7.

The variation in fault incidence between the data processing equipment and the switch interface unit shown in Figures 6 and 7 reflects the difference in complexity and constructional methods used in the two units.

Comprehensive records on the performance of the system have enabled the level of reliability and overhaul times to be established for the various parts of the system. This is indicated at Figure 8. Failures experienced however, may be
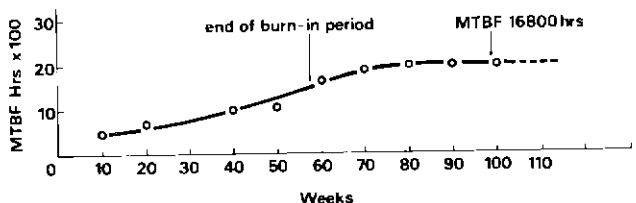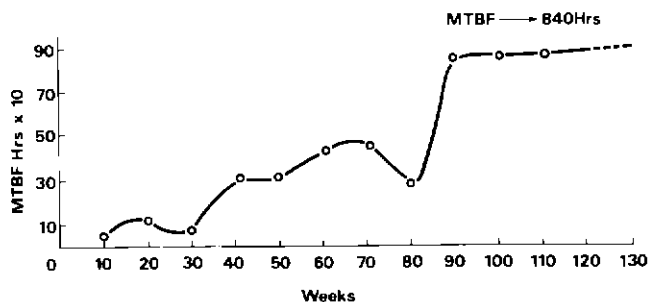

Fig. 6   Incidence of faults in data processing equipment

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Fig. 7   Incidence of faults in switch interface unit

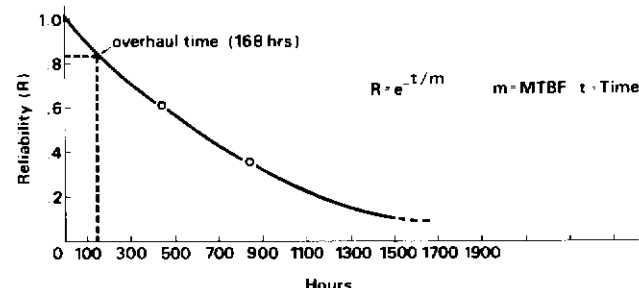$$R = e^{-t/m} \qquad m = MTBF \quad t = Time$$

Fig. 8   Equipment reliability

limited to errors revealed in the self-checking process requiring only simple remedial action by the staff supervising the operation. Since the introduction of the system an outage time of only 0.0017 per cent (actual programme loss) attributable to equipment failure has been achieved. This figure is expressed as a proportion of the total programme hours dealt with and is approximately half of that experienced prior to the system described becoming operational.

13 Savings

The decision to re-engineer the switching system at Bush House was based partly on the staff savings which would be realised and in the event it has been possible to make a saving of ten engineering posts which on current rates allows the capital cost of the installation to be recovered within a five-year period.

14 Conclusions

The system described has fully satisfied the design criteria cognisant with the allowable expenditure. Where many programme streams are to be assembled from studio or other sources and routed to various destinations for use in broadcast transmissions, and a strict time discipline in programme building is a requirement, as in external broadcasting, there is an obvious case for fully automated processes to be used. When full automation can be introduced, and repair in the event of failure can be arranged on a roving team principle, there is little doubt that the efficiency of the operation can be further improved. In complex systems, the ideal solution is provided by full redundancy of the plant hardware with automatic changeover in the event of failure, coupled with a complete feed-back system to include the control data processor, and alarm units which would alert maintenance attendance when necessary. Financial limitations do not at present allow this.

References

1 "Planning and Installation of the Sound Broadcasting Headquarters for the BBC's Overseas and European Services" Proceedings of the IEE November 1960. Axon, F., and Barron, O.H.

A Quadruple-Diversity Receiving System for Radio Microphones

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Summary: This article describes a radio-microphone receiver diversity unit intended for use in television studios. The unit utilises post-detection combination and achieves near-optimum signal-to-noise performance by way of a digitally-processed control signal.

In a television studio the efficacy of a radio microphone is impaired by the reflection of radio waves by the walls, roof, floor, scenery, lighting, etc. This causes the signal to vary as the user moves about; in some positions it can become noisy or even fail completely.

The purpose of the work was to develop a system in which up to four receivers are connected to separate aerials, which need not be repositioned for each production. The signals from the receivers are combined in proportions that are varied automatically to maintain best results as the performer moves. The system was found to be reliable and effective, requiring no adjustment before or during use. It gave good signals from a radio microphone whose wearer walked at random in a three-storey building.

1 Introduction

In many studio situations involving radio-microphone operation, the freedom of movement of the performer has been restricted by the uncertainty of the radio link between performer and control suite. The difficulties arising are a direct result of standing waves set up by reflection of the transmitted r.f. signal from the various surfaces encountered within the studio, e.g. walls, lighting gantries, cameras, scenery etc. The standing-wave pattern can cause the signal at the receiving point to fall to a level near or below that at which the receiver is muted.

An investigation into the propagation of r.f. signals in studios has shown that a great improvement in the reliability of the radio-microphone links would be obtained if diversity reception were to be employed. The report[1] describing this investigation considered the improvement obtainable by using dual-channel diversity reception. It also suggested that because propagation measurements were made under somewhat idealised conditions, the studios containing little or no equipment or scenery, a four-receiver diversity system should be employed to cover most eventualities which may occur under full operational conditions.* This article describes a prototype diversity system with digital control which can operate with up to four receiving aerials.

2 Choice of system

The report[1] showed that there was little statistical evidence for giving preference to any particular band of frequencies as far as studio use was concerned, so that the choice of frequency should be made on the ground of availability of equipment capable of providing both good performance and convenience in use. Generally, it appears that these requirements can be met by using frequencies near or in Band III: many commercial radio-microphone equipments are designed to operate near this Band.

It is common practice for radio-microphone systems to use frequency modulation, and the choice of system

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* The advantage for four-receiver diversity is illustrated further in Appendix II of this article.

considered to accomplish diversity reception was made from possible methods of combining receivers designed for use with this modulation system.

Diversity combining can be achieved in various ways; it can be performed either before or after detection. The signals can be switched, added linearly or in varying proportions.

Selection combining, which can be performed at r.f. or a.f., is a relatively simple method, requiring a receiver for each receiving aerial. This system tends to generate transient noise, and sudden changes in the level of random noise, when switching between channels occurs. Difficulties may arise with fast fluctuations of signal, if the switching is not carried out rapidly enough or if there is a time lag in the control signal. The signal-to-noise ratio is never better than that of the best channel.

Pre-detection linear addition of r.f. or i.f. signals can be achieved using phase adjustment between the various r.f. signal inputs. The system will produce optimal signal-to-noise ratio provided that both the relative phases and the relative amplitudes of the signal inputs are automatically kept adjusted to the optimum values. Most systems of this type require as many r.f. or i.f. channels as controlled inputs, although one proposed system[2] uses only one receiver; it uses external tone modulation of the input carriers to provide phase indication for control of the r.f. phasing networks. Using these systems phase control must be applied over the whole range of input r.f. voltages. If the control of phase is not rapid enough, zero input to the receiver is possible even when large r.f. signals are available at the reception points. In the studio the phase variation between receiving points can be expected to be rapid and very large so that design of the circuits for controlling the phases would be difficult.

Frequency diversity uses two or more frequency channels. It presents two main difficulties:

1) The need for two operating channels in the transmitter, possibly requiring two output stages with combining networks, so increasing transmitter size and battery consumption.

2) Increased use of valuable frequency spectrum.

The last system considered is post-detection combining, in which weighted contributions from several receivers operating on the same frequency are added together to give a composite audio output. In operation the output signal-to-noise ratio is almost the same as that obtained from the linear phase additions of r.f. signals. This is the system which has been adopted and is described in this article.

3 General arrangement of diversity system

The general arrangement of the diversity system using four receivers is shown in Fig.1. The aerials are distributed around the studio in well-separated locations and the connections between them and the receivers are by way of standard co-axial feeders.

The receivers are required to produce normal audio signals and, in addition, a signal which is proportional in magnitude to the input r.f. signal level. In the combiner the latter signals, shown as VC1, VC2, VC3, VC4, are fed to a
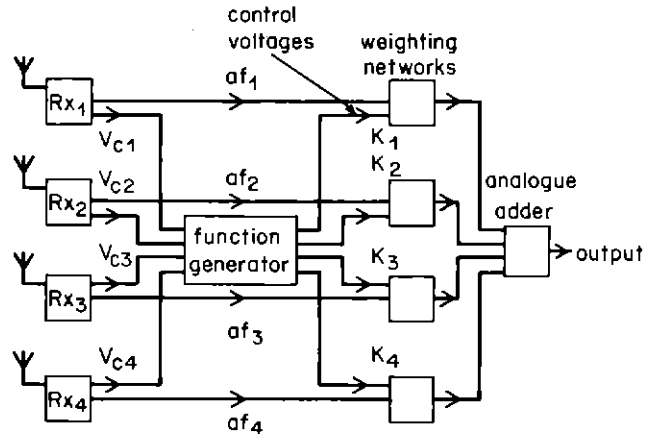

Fig. 1 Radio microphone diversity receiving system

function generator, where arithmetic processing is performed on them to produce control voltages for the audio weighting networks, which adjust the relative magnitudes of the contributions from the receivers. The separate audio signals are then summed in the analogue adder.

4 Design philosophy

4.1 Weighting coefficients

The audio weighting networks are required to control the amplitudes of the audio signal contributions from the receivers so as to ensure that the maximum signal-to-noise ratio is obtained when these contributions are summed.

Above the f.m. threshold the theoretical signal-to-noise ratio at the output of a f.m. receiver rises linearly with input r.f. signal level. In practice, however, the signal-to-noise ratio tends to a nearly constant value once the noise in the output of the demodulator becomes comparable with that generated in the audio stages of the receiver. The audio contributions from receivers fed with an input signal above this level, should preferably be combined with equal weights. A lower limit must also be placed on what can be considered a usable signal because of greatly increased noise due either to failure of limiting or to reaching the f.m. threshold.

The noise output from a receiver fed with input signal levels within the control range, is a direct function of the r.f. input amplitude. The addition of n unweighted receiver output signals gives a signal-to-noise ration R defined by the expression:

$$R = \frac{\sum_{y=1}^{n} S_y}{\sqrt{\sum_{y=1}^{n} (N_y)^2}} \tag{1}$$

where $S_1 \ldots S_n$ and $N_1^2 \ldots N_n^2$ are the signal voltages and noise powers respectively. The signal voltages are assumed

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to be coherent and can be added linearly, while the noise voltages are assumed to be random. In practice the a.f. signal voltages S_y at the outputs of the receivers are arranged to be equal, so that the weighted combination of signals gives a resultant signal-to-noise ratio,

$$R = \frac{S \sum_{y=1}^{n} k_y}{\sqrt{\sum_{y=1}^{n} (k_y)^2 (N_y)^2}} \qquad (2)$$

where $S_1 = S_2 ... S_n = S$,

$k_1, k_2 ... k_n$ being the weighting coefficients.
It is shown in the Appendix that optimum weighting occurs when

$$k_e = \frac{1}{(N_e)^2 \left(\sum_{y=1}^{n} (\frac{1}{N_y})^2 \right)} \qquad (3)$$

k_e and $(N_e)^2$ being the weighting coefficient and noise power of source e.

Since, within the range of control, the noise output from each receiver is inversely proportional to its input signal V_y:

$$k_e = \frac{(V_e)^2}{\sum_{y=1}^{n} (V_y)^2} \qquad (4)$$

or more generally where N_y is proportional to V_y^{-P}

$$k_e = \frac{(V_e)^{2P}}{\sum_{y=1}^{n} (V_y)^{2P}} \qquad (5)$$

Fig. 2 shows the improvement in signal-to-noise ratio resulting from the use of these coefficients, as compared with the use of the best signal only.
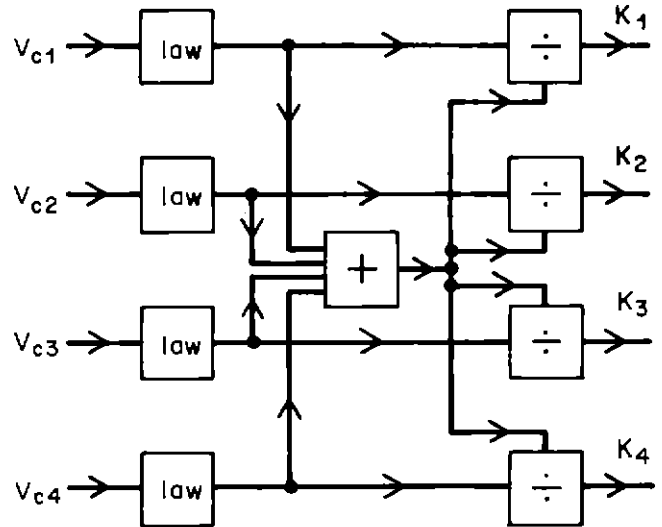
4.2 Processing of control voltages

Fig. 3 is a circuit for processing the control voltages in accordance with equation 5. The law function is dependent upon the receiver characteristics; in the special case where the output noise power is inversely proportional to the r.f. input signal power a square-law function is required.

The processing of control voltages before application to the weighting networks can be performed using either analogue or digital techniques. In an analogue system, where the processing is performed on varying d.c. voltages throughout, a large number of preset controls are required. Experience with this type of equipment has shown that difficulty occurs in maintaining alignment of the circuit
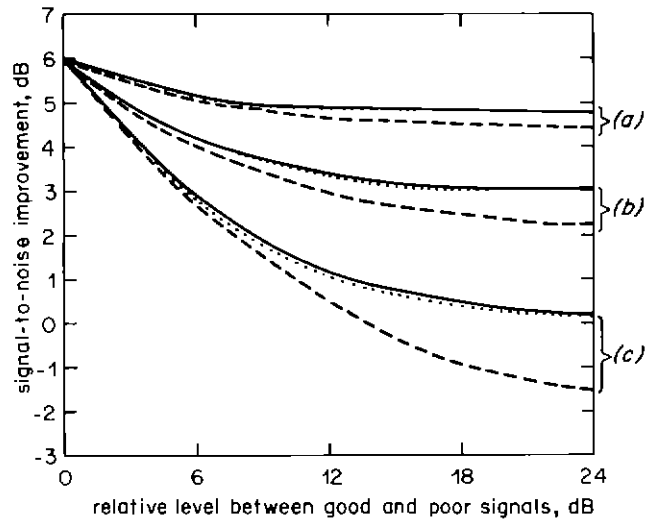
Fig. 2   Signal-to-noise improvement
(a) Three good signals and one poor signal
(b) Two good signals and two poor signals
(c) One good signal and three poor signals
————— optimum weighting
········ square index weighting
- - - - - unit index weighting

Fig. 3   Control voltage function generator

elements and the equipment is vulnerable to mechanical shock or disturbance. To ensure robust and accurate control of signals, digital processing is employed in the equipment described in this article.

4.3 Receiver characteristics

A requirement of the receivers for use with the combiner is that they should all have more or less equal characteristics, although some variation in performance can be met in the design of the combiner itself. Of particular importance are the receiver sensitivity and a.m.-suppression characteristics. Typical performance curves of a commercial radio-microphone receiver are shown in Figs. 4(a) and (b).

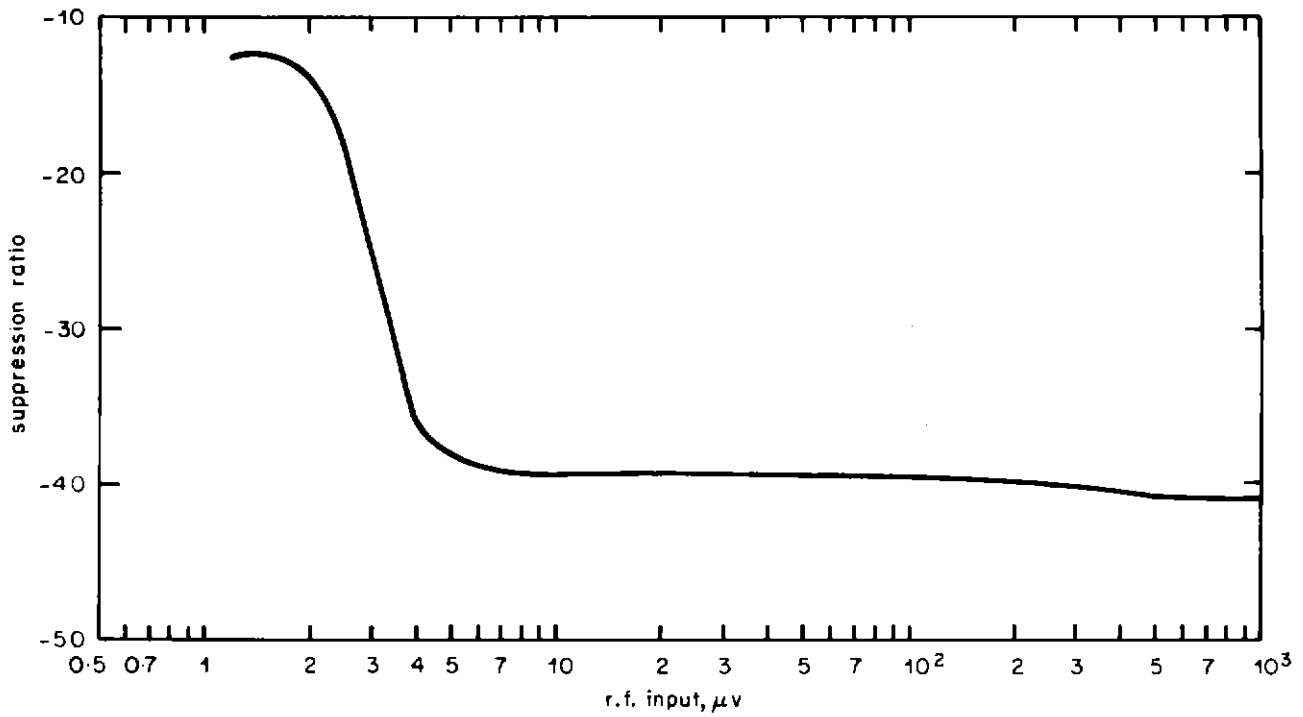The voltage made availabe for control purposes must be reasonably linear with respect to the r.f. input voltage and

Fig. 4   (a) Receiver a.m. suppression ratio characteristic

$$\text{suppression ratio} = \frac{\text{audio output due to 40\% a.m.}}{\text{audio output due to 22·5 MHz deviation frequency}}$$
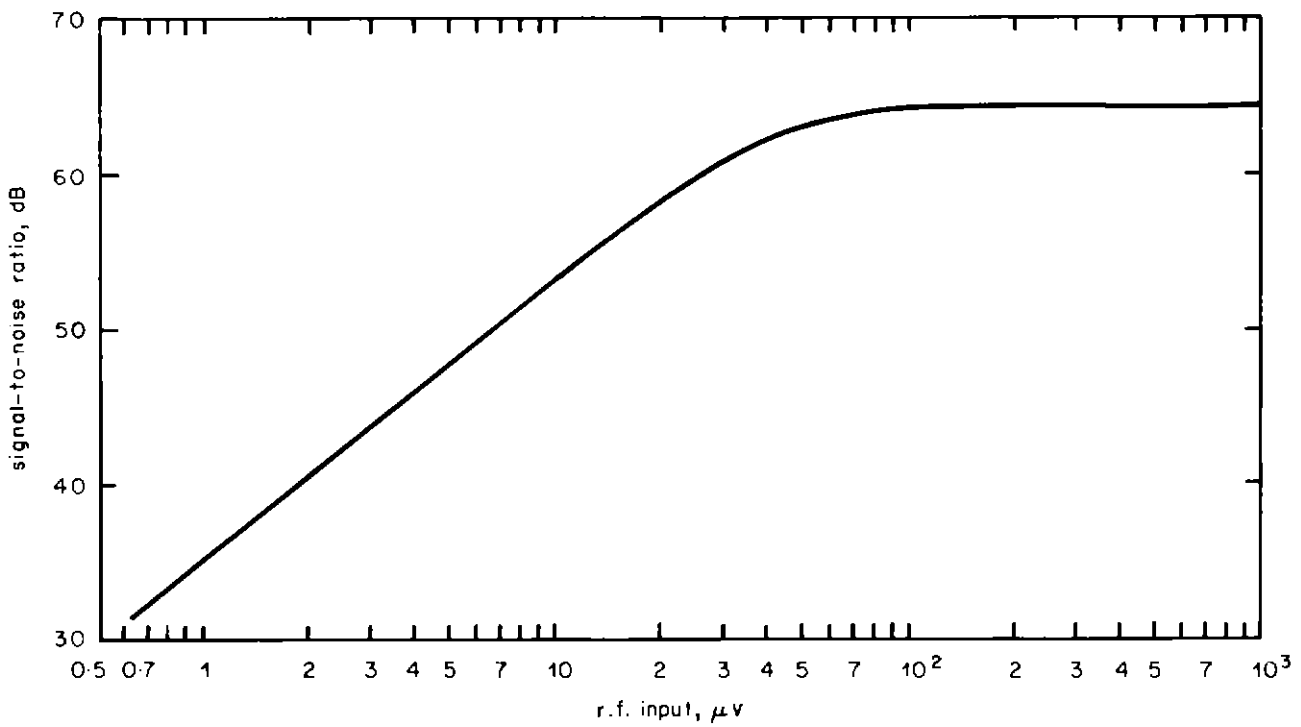

Fig. 4   (b) Receiver signal to noise ratio characteristic

must not be subject to limiting over the range of input voltages for which the combiner is intended to exercise control. By fitting a straight line to the curve in Fig. 4(b) the relationship between noise voltage N and control voltage Vc is found to be given approximately $N = kVc^{-0.85}$ over the range of input voltages for which control is to be applied. The required weighting function according to Equation 5 becomes:

$$K_e = \frac{(Vc_e)^{1.7}}{\sum_{y=1}^{n} (Vc_y)^{1.7}}$$

To realise the index 1.7 in the above equation would require complex digital circuits to perform log, multiplication and antilog operations. However, simpler circuits are involved if the index of 2 is used instead. The resulting loss in performance is small; the signal-to-noise ratio improvements using the optimum index and an index of 2 can be compared from Fig. 2.

The a.m. suppression characteristic of the receiver is important because incomplete limiting can lead to impairment of the output signal quality, giving a lower signal-to-noise ratio than that indicated in Fig. 4(b). In the combiner the use of a.f. outputs from receivers fed with input signals below the level where limiter action fails are not used. Reference to Fig. 4(a) shows that this point is reached when the r.f. input is approximately $4\mu V$.

5 The digitally controlled combiner

The prototype digitally controlled combiner unit contains four receivers, four digitally-controlled audio processing units and a digital function generator. It performs the following operations on the control voltages from the receivers; conversion from analogue to digital form, multiplication, addition and division of digital signals and the digital control of the analogue audio signal.

The combiner must be capable of following the variations of the r.f. signals applied to the receiver inputs without undue delay so that the effects of low signals are eliminated before they influence the audio output. At Band III frequencies, the maximum allowable time constant for the detector circuit is estimated at 2.3 ms, which was derived in the following way. Suppose that the mean r.f. voltage at the receiver input is 1 mv and that the user walks at 6 mph through the standing-wave pattern, crossing zeros at half-wave intervals. Approaching a zero, the r.f. voltage at the receiver input will fall from the maximum control value (approximately $100\mu V$) to zero in 6.4 ms. The detector output must fall to the minimum value in the control range corresponding to $6\mu V$ r.f. input to the receiver within this period. This is determined by the detector circuit discharge time constant T which satisfies the following relationship

$$T = \frac{t}{\log_e \dfrac{1}{.06}}$$

putting $t = 6.4$ ms, $T = 2.3$ ms.

The rate of change of field strength calculated in this manner is about four times faster than that obtained from propagation test results; the recordings, however, may have been limited by recorder response time.

Although considerable flexibility could be allowed in the choice of sampling rate for conversion of the control voltages to digital form, it was considered that the automatic adjustment to the audio channel should be made in small increments and a sampling rate of 16.6 kHz is used for each channel to achieve this. A frequency above the audio band is necessary to avoid coupling into audio stages.

To economise in components, sequential sampling of control voltages is used in the equipment. This is carried out during one cycle of the 16.6 kHz period. A commercially available analogue-to-digital convertor (a.d.c.) has been used in the combiner and most of the logic has been constructed from TTL integrated circuits. The digital/analogue multipliers (multiplying d.a.c.) used for the weighting networks are also available commercially and their performance is of particular importance to the operation of the combiner. Their characteristics include linearity to within one half of the least significant bit (l.s.b.), a small-signal bandwidth of 100 kHz and high attenuation when all control digits are at zero .One shortcoming of this device is that whenever the digital information at the inputs is changed, the analogue level change is accompanied by short duration (1 to $2\mu s$) glitch* and other transient pulses. The amplitude of these pulses is dependent on the magnitude of the change of digital information and if not removed they will produce intermodulation products which may fall within the wanted band of frequencies. The problem can be overcome by using signal blanking pulses which are of sufficient width and frequency to obscure the unwanted pulses on the analogue waveform. The blanking rate must be at more than twice the maximum audio frequency to avoid the lower sideband frequencies produced by the product of the fundamental and harmonic frequencies of the blanking waveform and the audio frequency, falling within the wanted audio-frequency band. The blanking rate used is four times the sampling rate so that aliasing does not occur.

A photograph of the prototype digital and analogue units is shown in Fig. 5. The audio and digital circuits have been kept, as far as possible, separate from each other; the receivers and audio processing boards are contained in one cabinet, the i.f. amplifiers and detectors and digital boards in the other. An audio output amplifier has also beeen included in the second cabinet. All interconnections between the units are via multi-core cables and coaxial feeders at the rear of the cabinets, except for the connection between the combined audio signal and output amplifier, which is made via a screened cord at the front of the cabinets. R.F. input to the receivers is via BNC sockets at the rear of the cabinet containing the receiver.

A schematic diagram of the combiner is shown in figure 6. The unit utilises sequential and simultaneous processing of signals. The first processes following the amplification and detection of i.f. signals are selection by a switching circuit

* Glitch — "A perturbation of a pulse waveform of relatively short duration and of uncertain origin" IEEE Standard Dictionary of Electrical and Electronic Terms
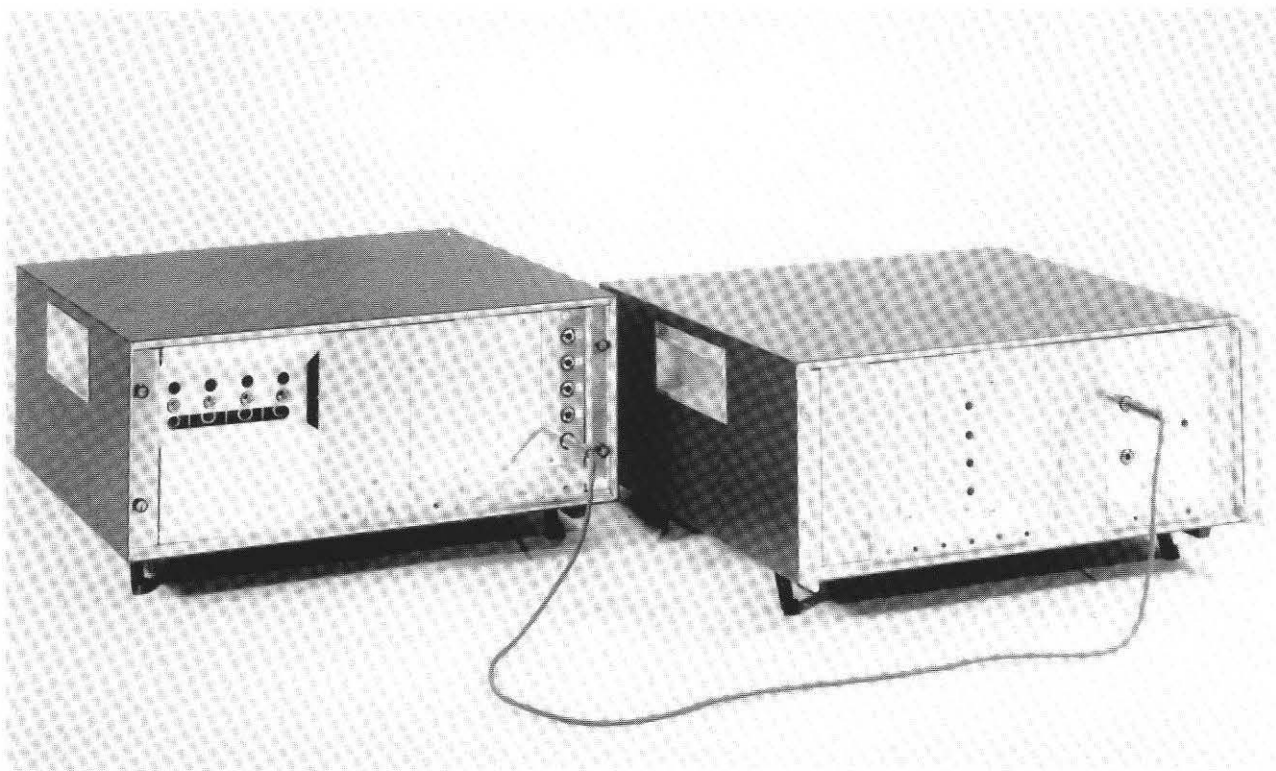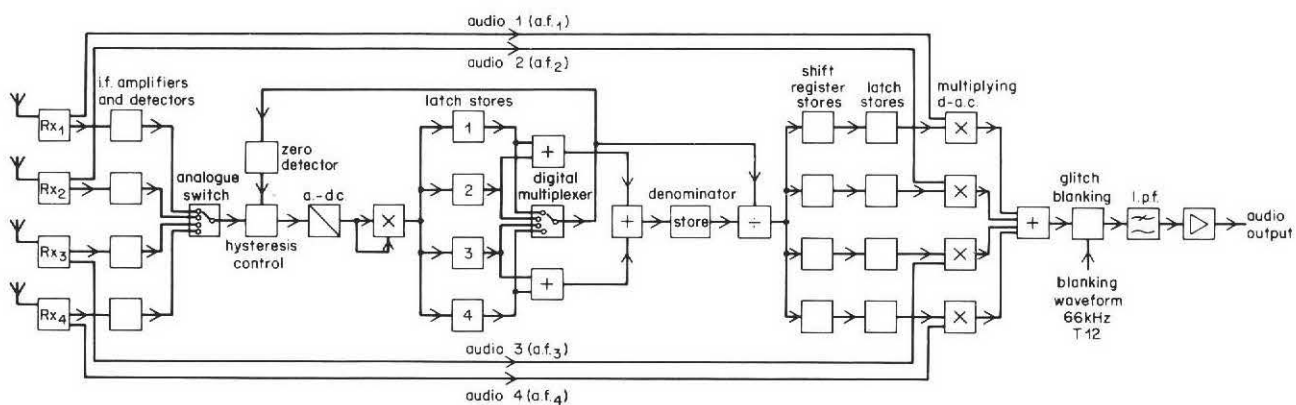
Fig. 5 Prototype combiner equipment

Fig. 6 General arrangement of digital combiner

and conversion to a parallel eight-bit binary code. This is followed by squaring in a multiplier stage and then storage. The process is repeated for each of the detected i.f. voltages, each squared output being put into its respective store. The outputs of the stores are summed and held to form the denominator for the divider unit.

The next stage is to read the unsummed stored outputs sequentially into the numerator position in the divider circuit. Once division of one numerator is completed a new numerator is loaded into the divider. The denominator, being held in a separate store, is retained until the sequence of division of all four numerators is completed. Each quotient is loaded into a separate shift-register store. While the division process has been in operation new data has been sampled by the a.d.c. and squared in the multiplier and is then held in the stores ready for the next division process. The existing data held in the shift registers is applied to the inputs of latch stores; a clock pulse applied simultaneously to all of these output latches transfers the data to their outputs, which in turn are connected directly to the digital inputs of the multiplying d.a.c.'s. Adjustment to the audio signal contribution from all receivers is effected in less than 2μs. Under low-signal conditions the logic circuits are arranged to eliminate the audio output from any receiver fed with a r.f. input signal of less than approximately 6μV. This is achieved by setting up the sensitivity of the a.d.c. circuit so that when this r.f. signal level is applied to the receiver

input terminals, a 1 appears in the l.s.b. position of the numerator, all other positions being zero. When the r.f. input is close to this level an unstable state could be reached whereby the logic circuits are not able to decide whether the input is above or below the drop-out value due to quantising uncertainty: this could give rise to noise at the output of the combiner. The problem is overcome by using a hysteresis circuit. Gates are used to detect the condition of all zeros appearing on the numerator output. When this occurs additional resistance is switched into the a.d.c. input before the conversion of the next sample of that particular channel is started. Once the input to that receiver rises 4 dB above the cut-off level, the added resistance is removed from the circuit.

The audio outputs from the receivers are combined in a virtual-earth adder circuit. The combined audio signal, which still has the glitch pulses superimposed on it, is passed through a blanking network and low-pass filter to an output amplifier.

5.1 Receivers

The receivers are of a commercial type designed for use with radio microphones at 174·1 MHz. These are standard receivers apart from the added facility of providing a sample voltage of the second i.f. at a nominal frequency of 300 kHz for control purposes.
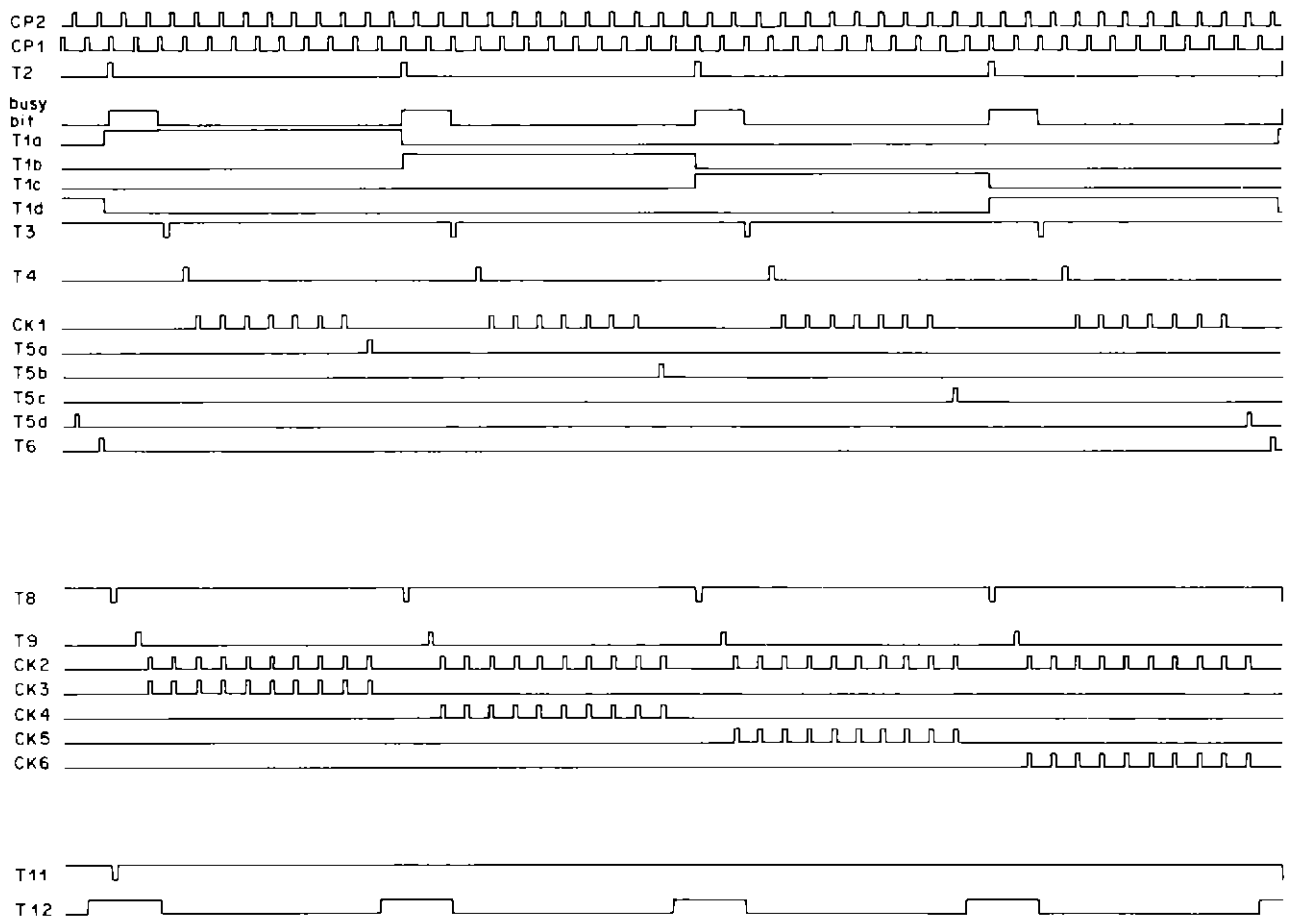

Fig. 7 Timing generator waveforms

Note: Inverters type SN7404N
      2 Input 'AND' gates type SN7408N
      2 Input 'NAND' gates type SN7400N
      2 Input 'NOR' gates type SN7402N
      3 Input 'NAND' gates type SN7410N
      4 Input 'NAND' gates type SN7440N

"AND" gate

"NAND" gate

"NOR" gate
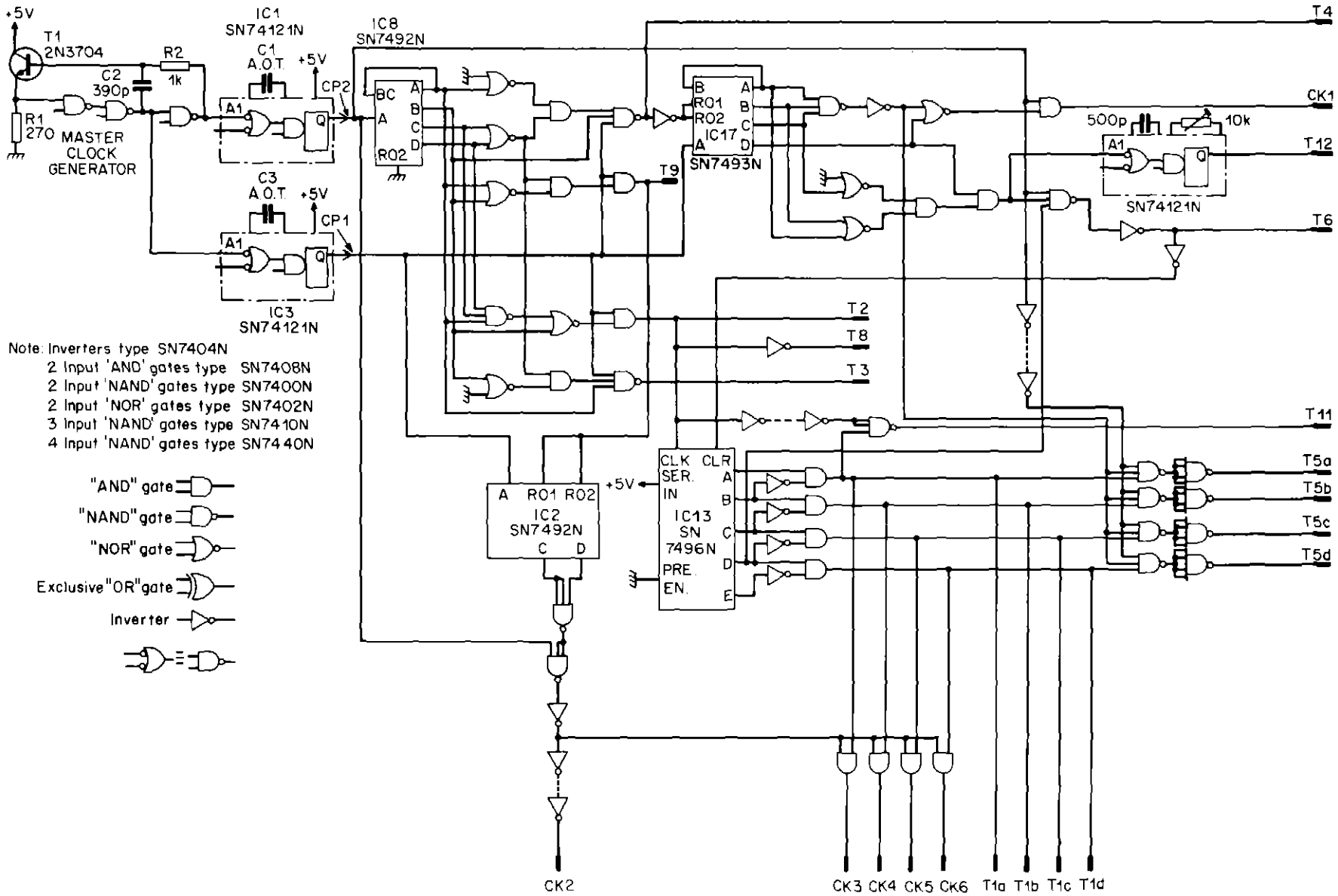
Exclusive "OR" gate

Inverter

Fig. 8. Timing generator circuit diagram

5.2 Timing generator

Fig. 7 shows the timing generator pulse waveform and Fig. 8 the generator circuit. The master clock generator produces a square wave and its complement at a rate of 800 kHz. The leading edges of these waveforms are used to trigger monostables IC1 and IC3 which in turn produce 200 ns wide clock pulses CP1 and CP2. All other timing pulses are produced from CP1 and CP2 using three counters and one five-bit shift register in conjunction with other logic elements.

5.3 Control signal amplifier and detector boards

The amplifiers have been developed as a standard card providing a gain of up to 60 dB with wideband characteristics (10 HZ—2 MHz). When used for i.f. amplification, the low-frequency response is reduced by using small valued coupling capacitors between feedback pairs of transistors and the gains are adjusted to compensate for differences in receiver i.f. output level. Four i.f. amplifiers, one for each channel, are mounted on a single board.

The detector circuits have been designed with a time constant of 2·3 ms. This is sufficiently fast to meet the signal variation requirements and slow enough to reduce the effect of amplitude modulation on the i.f waveform produced by the transmitter or by the selectivity characteristics of the receiver.

The d.c. voltages from the detectors are fed via emitter follower stages to an analogue multiplexer switch. The switch (CD 4016) is controlled by a SN7401AN gate, the latter forming a suitable interface between TTL and CMOS logic voltages. Sequential switching is provided with the timing waveforms T1a to T1d. The detectors and multiplexer switch are mounted on a single board which is separate from the i.f. amplifier board.

5.4 A.D.C. and multiplier board

A commercially available eight-bit a.d.c. having a maximum conversion time of 5μs is used. Input to the a.d.c. is from the detector board via a hysteresis switch on the zero detector and indicator board. The parallel outputs from the a.d.c. are applied directly to the multiplier inputs. The conversion is initiated by pulse T2, applied to the strobe input terminals
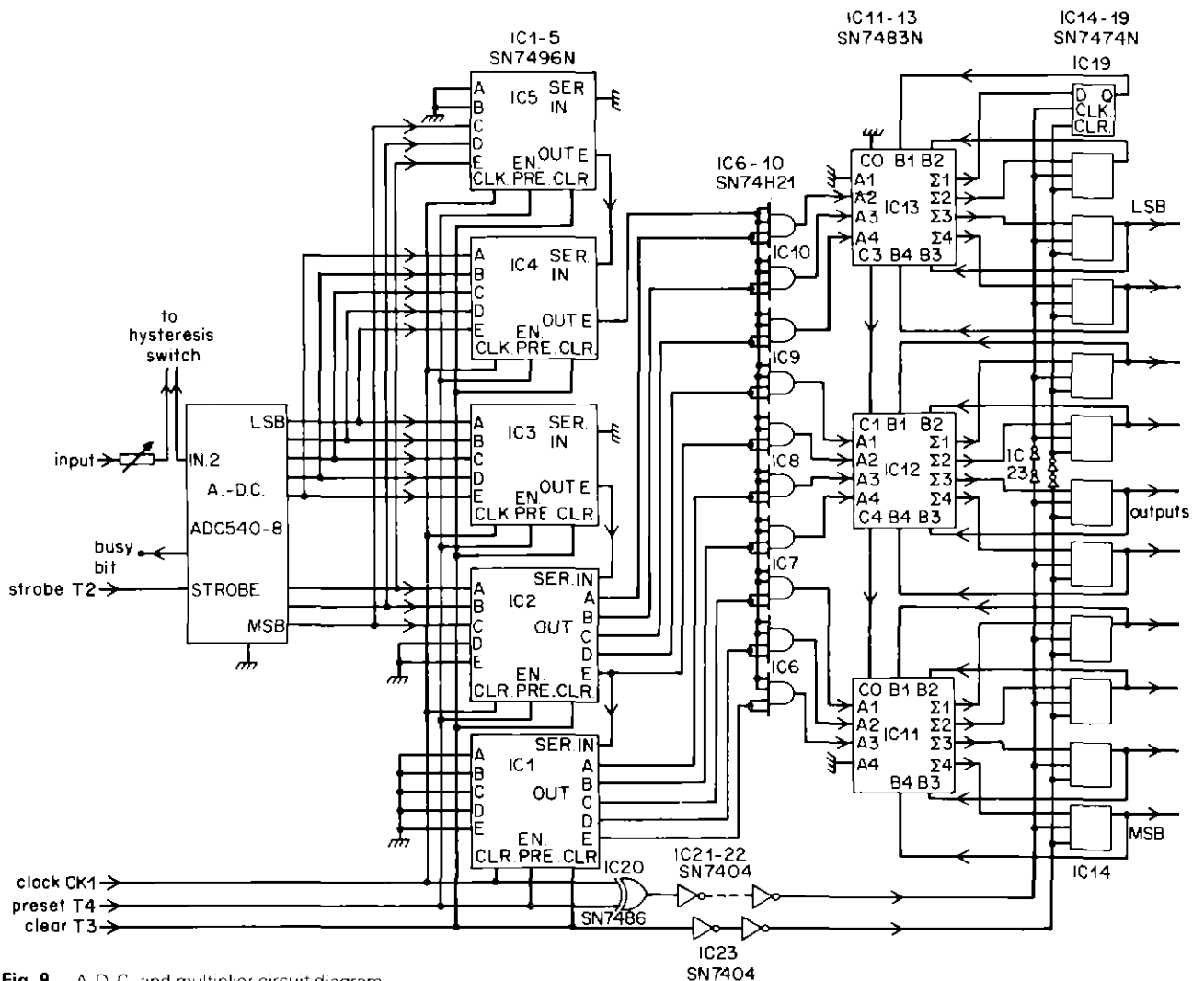

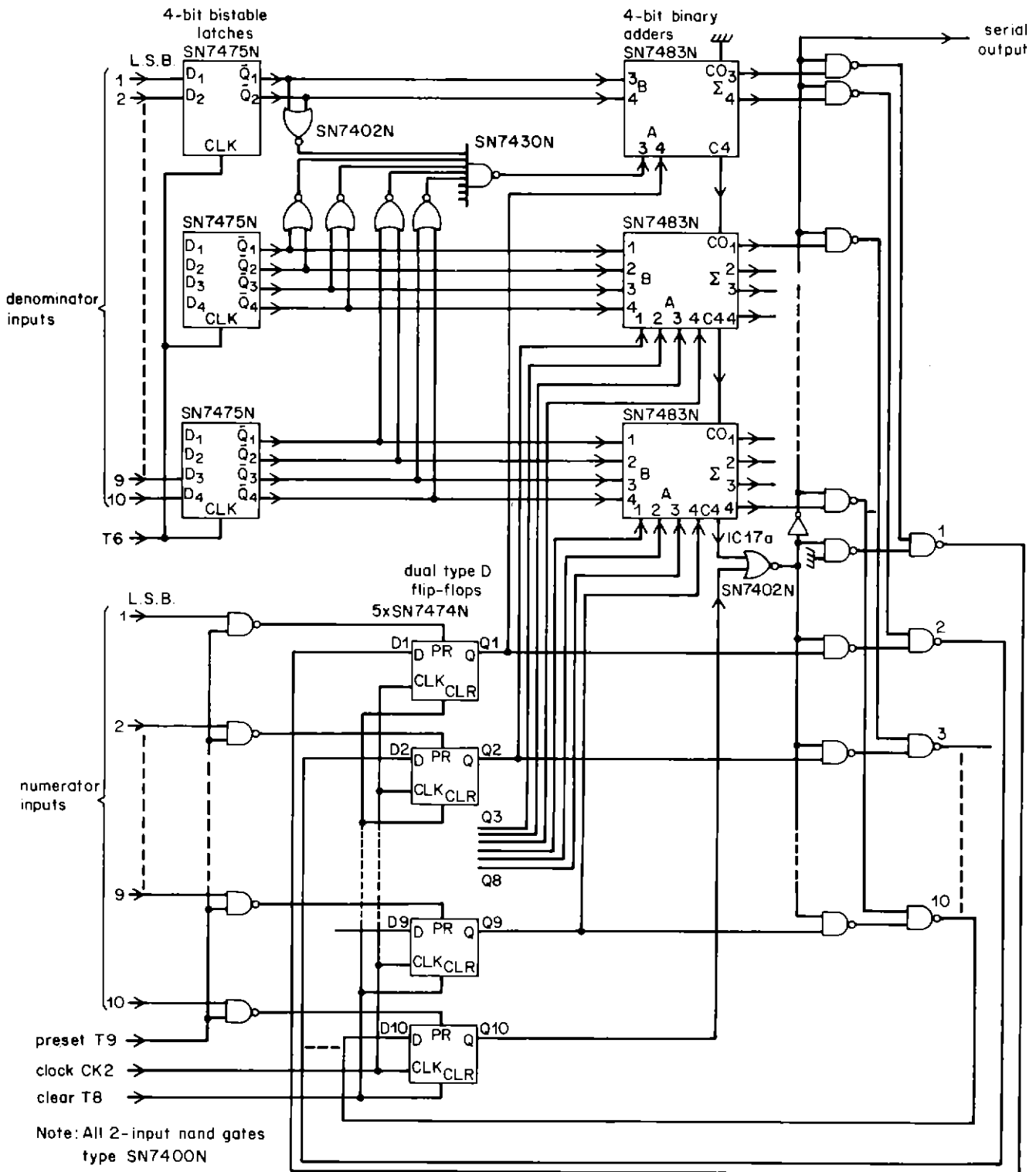**Fig. 9.** A.D.C. and multiplier circuit diagram

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Fig. 10 Divider circuit diagram

(A busy bit is available from the unit; this is not used except for test purposes). A circuit diagram of the multiplier stage is shown in Fig. 9. The basic operations for the multiplier are to shift and add. A clear pulse T3 is applied to the shift registers followed by a preset enable pulse T4, which loads in data applied to the register preset terminals. Data fed to shift registers IC1, IC2 and IC3 is loaded with the most significant bit (m.s.b.) last and to shift registers IC4 and IC5 with it first. Operation of the shift registers is shift down with clock pulse CK1. The serial output (l.s.b. first) from IC4 is used to gate the parallel outputs of IC1, IC2 and IC3, before application to the A inputs of the adder stages. The sum outputs of the adder stages are connected to SN7474 latches whose outputs form the output of the multiplier. During the interim period, before the final product is formed, the output from the latches is in partial product form and is fed back to the B inputs of the adder stages.

Delayed-clear, preset and clock pulses T3, T4 and CK1 are also used to control operation of the latches. Multiplication is completed following the seventh pulse of CK1. The circuit has been arranged to provide a ten-bit output.

5.5 Storage, adding and multiplex board

Storage of data input from the multiplier is accomplished in latch sets 1 to 4 (shown in Fig. 6). Selection of data entry into storage is by way of pulses T5a to T5d applied to the appropriate latch clock terminals. The latch outputs are summed in adder stages to form a ten bit denominator for the divider and are fed directly to the divider board. The unsummed outputs of the latches are gated to provide sequentially timed eight-bit numerators for the divider; gating pulses are provided by pulses T1a, T1b, T1c and T1d.
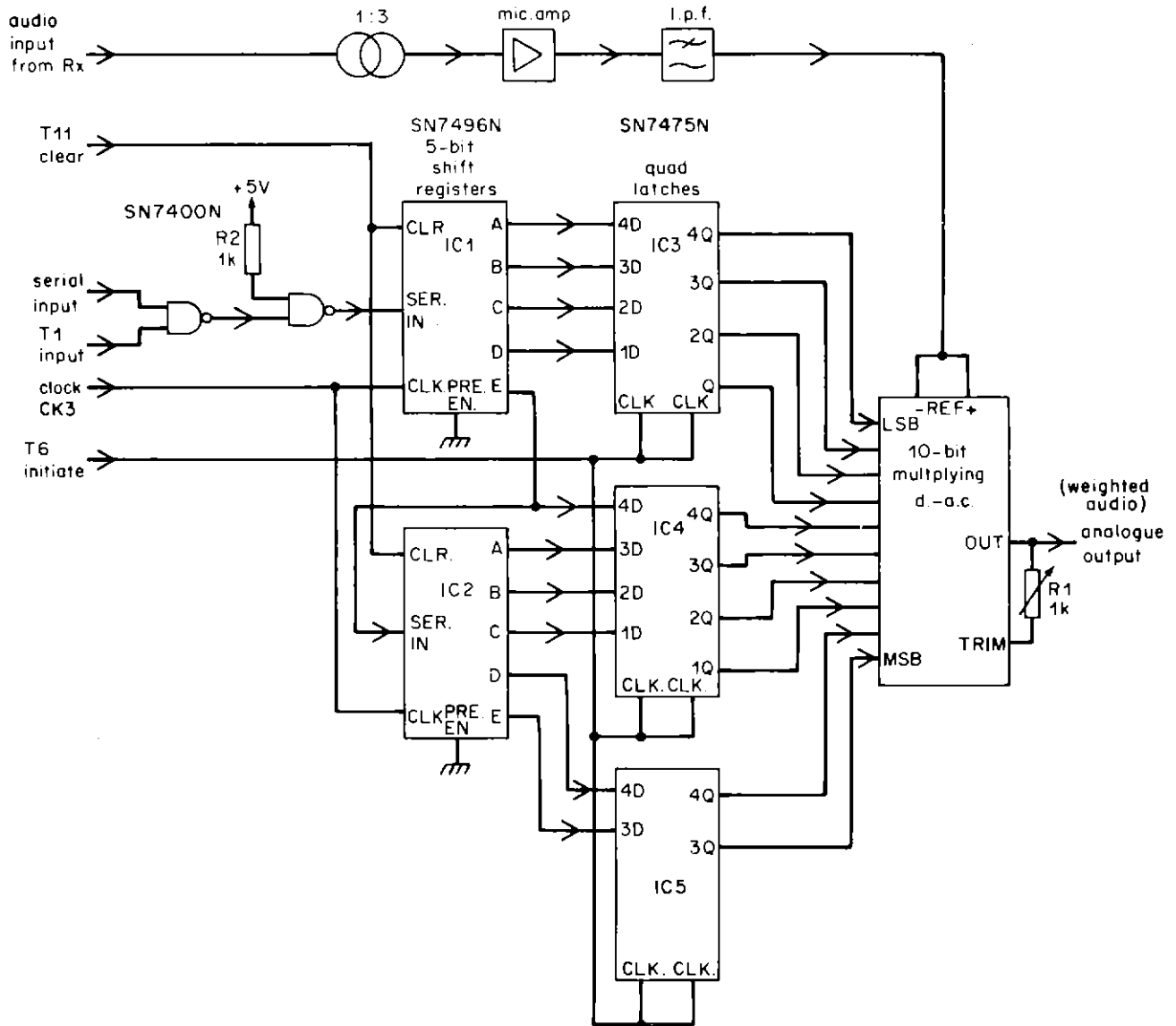

Fig. 11 Audio processing unit

5.6 Zero detector and indicator board

The input to the board is the sequentially-selected numerator from the storage, adding and multiplex board. An arrangement of nor and nand gates is used to detect a condition of all zeros occurring in a numerator. When this occurs the logic output is used to change the potential applied to the control input of the hysteresis switch. Operation of the switch causes extra source resistance to be added into the input circuit of the a.d.c. when the signal strength to a particular channel falls below a pre-determined level.

The zero detector logic output in conjunction with timing pulses T5a, T5b, T5c and T5d is also used to trigger 1-second monostables. The output pulses of the monostables are used to switch transistor circuits driving light-emitting diodes. The diodes are mounted on the front panel of this board; operation of a diode indicates that a particular channel has dropped out of use.

5.7 Divider board

The basic operation of the divider circuit is to compare and shift or to subtract and shift. A schematic diagram of the divider circuit is shown in Fig. 10.

Subtraction is performed by adding the two's complement of the denominator to the existing numerator at each stage of the division process. A sign bit is used to compare the magnitude of the numerator with that of the denominator. If the numerator plus complemented denominator produce a sign bit of 1 or the shifted numerator produces a sign bit of 1, the answer is 1 and the sum of numerator plus complemented denominator less the m.s.b. is shifted one place up to form a new numerator. If the result gives a sign bit of 0, the answer is 0 and the new numerator is the old numerator shifted one place up. In this divider the sign bit indicating the result of subtraction is the reverse of the usual convention for two's complement arithmetic; this is the result of not complementing the sign bit of the denominator.
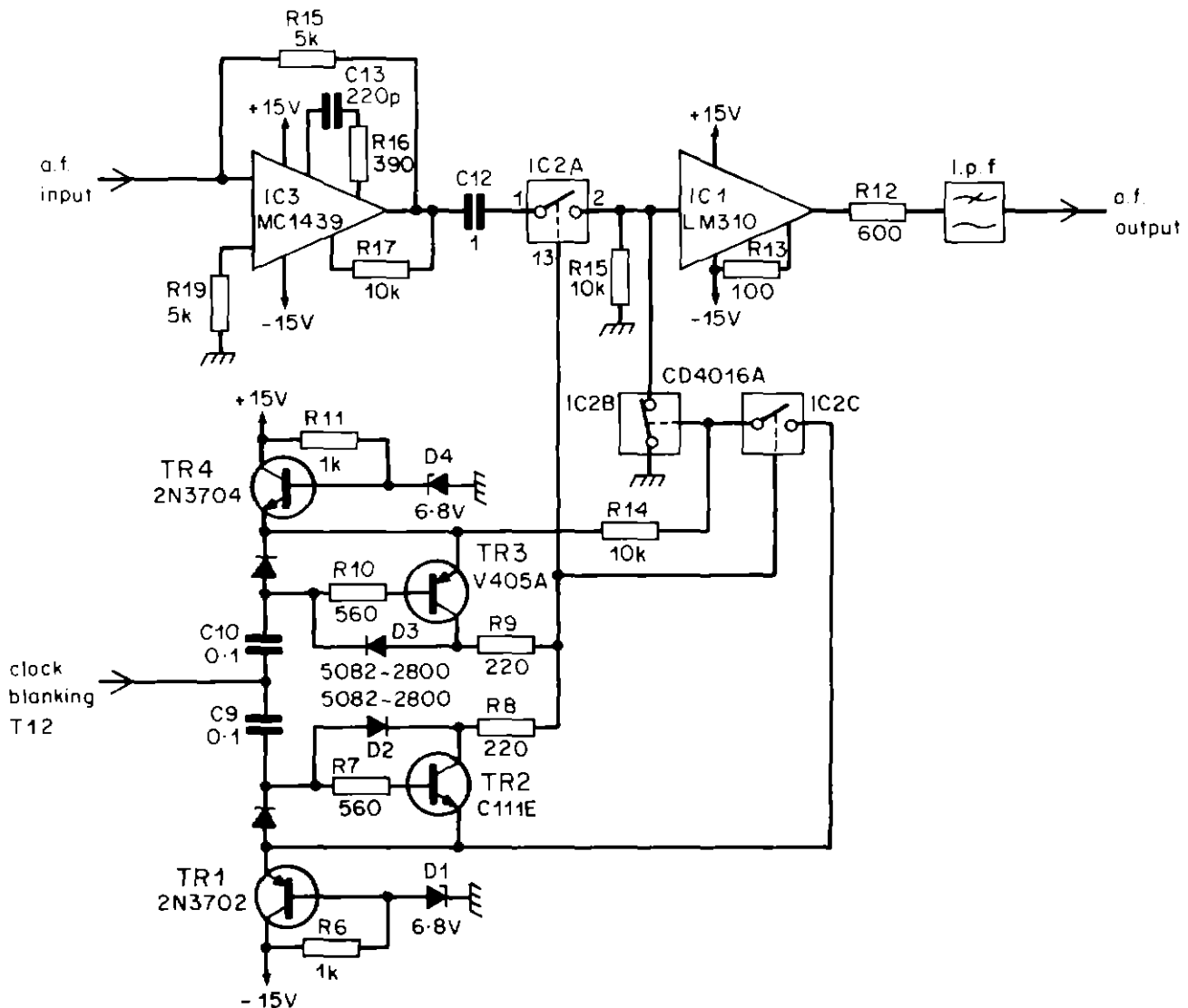

Fig. 12 Audio blanking circuit

The denominator is fed to latches SN7475 from the digital multiplex, add-and-store board and following application of pulse T6 to the latch clock terminals the denominator is stored for the whole period of division of all four channel numerators. The latch outputs are inverted and applied to the B inputs of the adder units; a 1 is added into the l.s.b. position on the adder stage to form the two's complement. The numerator is gated into flip-flop stages whose outputs less the m.s.b. are fed to the A inputs of the adder stages. Numerator inputs 9 and 10 are not used, but are earthed. The m.s.b. of the numerator output and the carry-out of the m.s.b. adder stage form the inputs to a dual input nor gate, (IC17a) controlling the nand gates which return and shift the numerator or the remainder from the adder stage outputs as a new numerator to the D inputs to the flip-flop stages. It is also provides the inverted data output from the divider. The logic system determining the new numerator is as follows:- if A represents the numerator held at the Q outputs of the flip-flop, B the remainder from the adder stages and C the output of IC17a, the logical expression for the output is:-

$$\overline{A \cdot C} \cdot \overline{\overline{C} \cdot B}$$ which simplifies to $A \cdot C + \overline{C} \cdot B$ by de Morgan's rule. It can be seen that if $C = 1$, the output is A or if $C = 0$, the output is B.

Clock pulses CK2 are applied to the flip-flops after each comparison or subtraction. The output from the divider is 10 bits in serial form. In the operation of the divider, the initial conditions are such that the numerator is never greater than the denominator. Under conditions where all four channels have very low input signals the numerators and denominator may be zero, and the complemented denominator will produce a sign bit of 1. This has the effect of raising the output of all channels by 6 dB when in fact, zero output is actually required because the audio output from the combiner would be of poor quality. Additional logic circuits have been included to overcome this problem. Following detection of all zeros in the denominator input, the 1 normally added into the l.s.b. position of the adder stage is removed.

5.8 The audio processing boards

The audio processing boards comprise: audio amplifier, low-pass filters, multiplying d.a.c. and digital stores. Four audio processing boards are used in the combiner unit, each board processing the audio signal from one receiver. The schematic diagram is shown in Fig. 11. The audio outputs from the receivers at microphone level are fed through 1:3 turns-ratio transformers and amplified to zero level; they are then passed through three-section low-pass filters having cut-off frequencies of 15 kHz and stop-band loss of greater than 60 dB, to the input of the multiplying d.a.c. units. Filtering at this stage is most important since out of band signals passed to later stages would produce intermodulation products falling within the audio bandwidth. The serial digital information from the divider is gated to the appropriate shift register input by timing waveform T1a to

T1d. The data is shifted into the shift registers with timing pulses CK3 to CK6. Once the sequence of loading shift registers on all four boards has been completed, the parallel output information is transferred to the final latch store output by timing pulse T6. The latch outputs are fed directly to the multiplying d.a.c. input terminals and the adjustment of audio levels completed in less than 2μs. This information is held until the whole sequence of processing of new data has been completed.

5.9 Analogue adder and signal blanking board

The audio outputs from the audio processing boards are fed into a virtual-earth integrated-circuit adder stage, the output of which is fed to a blanking switch (CD4016). The switch is arranged to provide series and shunt path switching so that, when in the blanking mode, negligible output is passed to the following circuits. The switch is supplied from +6v and −6v rails and the TTL to CMOS interface circuit used for controlling the switch is capable of producing a fast voltage swing between the two rail voltages. The circuit is shown in Fig. 12.

The output of the blanking switch is coupled to an emitter follower stage feeding the final low pass filter. The blanking pulse width is adjustable and set to approximately 3μs. Triggering of the blanking circuit is provided by pulse T12; the repetition rate is 66 kHz. The audio output is fed to a P.O. type socket and the level is at −10 dBm into an unbalanced 600Ω load.

5.10 Audio output amplifier

A MC1433G integrated circuit amplifier feeding LL/106SA transformer provides a gain of 10 dB and balanced output into a 600Ω load.

5.11 Power supplies

Regulated power supplies have been produced on a separate chassis mounted at the rear of the digital arithmetic processing cabinet. This provides +30v, +12v, +15v, −15v and five 5v supplies.

6 Performance

The overall signal-to-noise ratio of the whole system measured under the best conditions in the laboratory environment was 67 dB. The theoretical signal-to-noise improvement of 6 dB over a single receiver output has not been fully achieved due to some residual noise from the digital circuits; the actual improvement is about 4 dB. The audio frequency response is from 50 Hz to 15 kHz. The overall distortion is not greater than 0.6%.

7 Conclusions

Tests carried out in a three-storey building in which the radio-microphone transmitter was carried into many areas,

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along corridors, up and down staircases etc., illustrated the system working at its full extent. In this case, the availability of signals from four pick-up aerials placed at various points in the building was random and changes between usable received signals also occurred in an unpredictable fashion. In this circumstance, the high-speed and automatic operation of the combining system provided a continuous noise-free output.

The preceding sections have described in some detail the equipment associated with a quadruple diversity reception system specially designed for radio microphone applications in television studios.

Preliminary tests on the complete system have clearly shown the great advantage obtained from it when radio-microphone operation is required in a complex or extended area. Probably the most powerful attribute of the system is its ability to select and suppress the outputs from receivers at high speed without any audible indication of the change-overs.

8 References

1 Thoday, R.D.C. 1973. Radio microphones: propagation characteristics in television studios. BBC Research Department Report No. 1973/3.

2 Parsons, J.D. and Ratliff, P.A. 1971. Electronic Letters. Self-phasing array for f.m. communication links, 1971, 7, 13, pp.380—381.

Appendix I

Optimum Weighting

The signal/noise ratio after combination is given in Section 4 as:

$$R = S \cdot X \cdot Y^{-\frac{1}{2}}$$

when

$$X = \sum_{y=1}^{n} k_y \text{ and } Y = \sum_{y=1}^{n} K_y^2 N_y^2$$

Partial differentiation with respect to one of the weights, k_e, gives

$$\frac{\partial R}{\partial k_e} = S \left[\frac{\partial X}{\partial k_e} Y^{-\frac{1}{2}} - \frac{1}{2} X \cdot Y^{-3/2} \cdot \frac{\partial Y}{\partial k_e} \right]$$

Now

$$\frac{\partial X}{\partial k_e} = 1 \text{ and by constraint}$$

$$X = 1$$

$$\therefore \quad \frac{\partial R}{\partial k_e} \text{ equals zero when } \left(1 - \frac{1}{2} Y^{-1} \cdot \frac{\partial Y}{\partial k_e} \right) = 0$$

i.e. when

$$k_e N_e^2 = \sum_{y=1}^{n} k_y^2 N_y^2$$

For maximum signal-to-noise ratio all the partial derivations $\frac{\partial R}{\partial k_1}, \frac{\partial R}{\partial k_2}, \ldots\ldots\ldots, \frac{\partial R}{\partial k_n}$ must be zero so that

$$k_1 N_1^2 = k_2 N_2^2 = ,\ldots, = k_n N_n^2 = \sum_{y=1}^{n} k_y^2 N_y^2 = A, \text{ say}$$

Hence

$$k_e = A/N_e^2$$

Since

$$\sum_{y=1}^{n} k_e = 1 \quad , \quad A = \left(\sum_{y=1}^{n} \frac{1}{N_y^2} \right)^{-1}$$

and

$$k_e = \cfrac{1}{N_e^2 \sum_{y=1}^{n} \frac{1}{N_y^2}}$$

Appendix II

The propagation conditions in a television studio are such that the received field strength at a single fixed receiving point varies considerably as the transmitter is moved over the working area. Fig. 13 shows a typical example of the regions of a studio floor area where the density of poor positions for the transmitter in relation to two receiving aerials is greatest and where for either receiving aerial, signal drop-out is very likely to occur. The map (based on Band III field strength recordings) applies to a studio partially furnished with scenery and shows the situation with two aerials positioned approximately as indicated.

The map shows that two-aerial diversity can fail in certain areas but it has been demonstrated that a four fold system gives complete coverage. It should be remembered that the case depicted does not take account of the continuous variation of propagation conditions which occur during an actual studio production. This variability of conditions makes four fold diversity even more important if continuous operation is to be ensured.
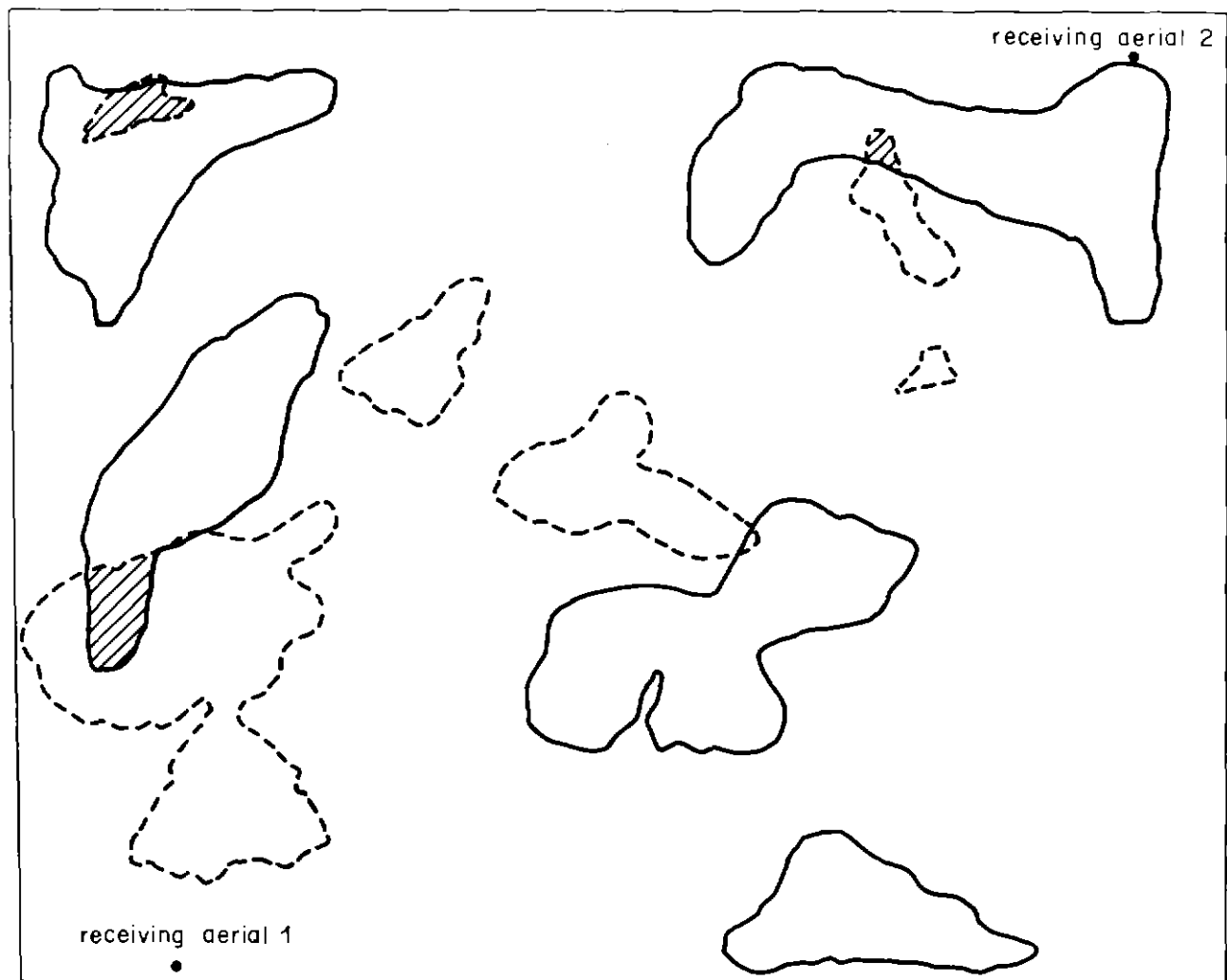
Fig. 13 The areas of a studio floor where drop-outs have a high probability of occurrence

———— contours relating to receiving aerial 1

---- contours relating to receiving aerial 2

//////   overlap of areas relating to receiving aerials 1 and 2

Ruggedised UHF Log-Periodic Aerials and their use in Transmitting Arrays

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Summary: A suggested uhf log-periodic aerial covering bands IV and V, suitable for both transmitting and receiving, was introduced in 1973. An early version with an air-spaced main feeder boom has been superseded by one with a polythene dielectric loading which provides a greater degree of weather protection.

Experience has shown the suitability of log-periodic aerials for use at low-power uhf relay stations and this aspect is described in detail.

1 Introduction

The log-periodic aerial has a wide bandwidth, with very good side- and back-lobe suppression and is capable of working in either the E or the H plane. The aerials described here have a gain of about 8 dB relative to that of a half-wave dipole[1] and side and back lobes are at least 23 dB lower than the main lobe.

The basic requirements of a receiving aerial and a transmitting aerial are different, the former being primarily concerned with directivity and low side- and back-lobe radiation levels and the latter being governed more by matching considerations. The intention has been to produce an aerial to fulfil both these requirements and to develop it for broadcast use.

In the receiving mode, log-periodic aerials have been used by field-strength measuring teams during the past two years and some experience of their use in service transmissions has been gained from a simple array of four stacked prototype aerials at the BBC's Ogmore Vale[2], South Wales, relay station. The log-periodic transmitting arrays described are intended for use at similar low-power uhf relay stations.[3]

The phase-centre of log-periodic aerials is an important characteristic, especially when a number of them are used in an array.

The reflection coefficient of an aerial array presents no problems with modern transposers. Measured horizontal and vertical radiation patterns of typical aerial installations are presented and, from these, their gain is computed. The radiation pattern performance can be predicted satisfactorily for planning purposes.

There are two main advantages of log-periodic transmitting arrays over panel arrays.[4] These are:

i) a saving in costs by having only one basic aerial unit to manufacture, store and erect;

ii) a saving in mast structure cost due to the decrease in wind resistance when compared with an equivalent panel array.

2 Initial design of a log-periodic aerial

The log-periodic aerial consists of a series of linear dipole elements of different lengths spaced along twin booms, the lengths and spacings between elements forming a geometric progression with common ratio $\tau (>1)$. Referring to figure 1, which shows the basic geometry,

$$\tau = \frac{l_{n-1}}{l_n} = \frac{r_{n-1}}{r_n} = \frac{a_{n-1}}{a_n} \qquad \text{(i)}$$

where l_{n-1}, l_n, r_{n-1} and r_n are lengths shown and a_{n-1} and a_n are the diameters of the corresponding elements.

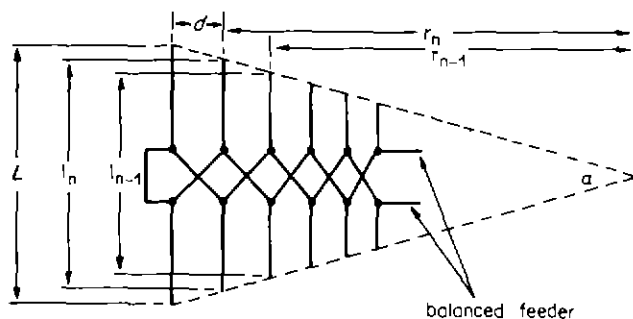**Fig.1**   Geometry of log-periodic aerial

A space factor, σ, is defined

$$\sigma = \frac{d}{2L} = \frac{r_n - r_{n-1}}{2l_n}$$ (ii)

and the characteristic angle α is related to τ and σ by

$$\tan\frac{\alpha}{2} = \frac{1-\tau}{4\sigma}$$ (iii)

The operation of the aerial is well documented.[5] Briefly, a coaxial feed input energises balanced feeder booms along which half-wavelength dipole elements are arrayed in an alternate manner. Power is radiated by those elements close to resonance and at a particular frequency this comprises a group of about three or four. This 'active' region of the aerial moves along the axis of the aerial booms as the frequency is varied. The booms are terminated in a short-circuit. The arrangement of coaxial feeder, balanced feeder booms and short-circuit termination provides a balun action. Because of the way in which the phase transition between elements is arranged, radiation from the elements is end-fire in the direction of the smaller elements.

The initial design was based on an early study of log-periodic aerials by Carrel[6], in which a number of nomograms are presented relating the aerial parameters for given conditions. Although the analysis is not exhaustive it is sufficient as a starting point from which a prototype aerial can be developed and optimised by experiment.

A combination of τ and σ was chosen to give optimum directivity over the band and to give an acceptable overall size by restricting the number of elements as necessary. The values arrived at are:

$$\tau = .93$$
$$\sigma = 0.18$$
$$N = 15$$

and these give a boom length of about 1m and longest element overall length of 300mm.

The designed frequency range of the aerial is made wider than the required transmission bandwidth in order to take account of the end-frequency effects which curtail the active operating range. Near the edges of the band, the 'active' region is reduced to fewer elements and log-periodic operation ceases. Accordingly, the lower frequency limit is made about 10 per cent lower than the lowest frequency of interest and this determines the length of the longest element in the array.

The element diameters are inter-related to the τ factor as seen in (i). It would be impracticable to use a different diameter for every element and three diameters have been chosen which satisfy (i) reasonably closely. The lengths of the elements are appropriately adjusted to compensate for the error by applying the King-Middleton formulae.[7]

The input impedance of the aerial is determined chiefly by the feeder boom impedance which, in turn, depends on the size and spacing of the feeder booms and the driving point impedances of the elements which load them. The terminating short-circuit of the booms is not very critical and has only a secondary effect on the pattern performance of the aerial at the lower end of the frequency range. Its optimum position was found by experiment.

The first version of the aerial was built with air-spaced

booms but a second version, based on polythene dielectric-spacing, has now been adopted because it does not suffer from the effects of icing between the booms. In the initial design an allowance was made for the lower velocity of propagation in the dielectric and this led to shorter booms but with a wider angle of boom taper.

3 Mechanical construction

The aerial booms are made of square aluminium tubing having a side length of 19mm (0.75 in.) and the elements are made of aluminium rod. The elements are attached to the booms by screws which are held tight with an anti-slip compound and so can be replaced easily if damaged. The mechanical dimensions of the aerial are listed in Table 1.

A mounting bracket incorporating the short-circuit termination holds the booms together at the back. The front is held and protected by encapsulation in moulded polythene and the booms are separated by a polythene dielectric insert.

TABLE 1

Aerial Dimensions

Element number	Element half-lengths (mm)	Element diameters (mm)	Element Spacings polythene (mm)
1	152	12.70	97
2	140.5	12.70	90.5
3	130	12.70	84
4	120	12.70	78
5	111	12.70	72.5
6	103	9.53	67.5
7	94.5	9.53	63
8	87.5	9.53	58.5
9	80.5	9.53	54.5
10	73.5	9.53	50.5
11	71	6.35	47
12	65.5	6.35	43.5
13	59.5	6.35	40.5
14	53.5	6.35	38
15	48	6.35	

The aerial feed input is a standard N-type connector mounted on a small metal block fitted into the end of one of the booms at the back of the aerial. The coaxial cable passes up the inside of one boom to protect it from mechanical damage and also to shield it electrically. The cable is made off onto the boom via a ferrule as shown in figure 2.

The booms are designed so that water may enter and leave freely. Weather protection is provided at the vital points by the encapsulation of the drive point and by sealing the cable where it enters the connector.

Arrays of log-periodic aerials are intended to be mounted on a standard 168mm (6.625 in) cantilevered pole in the same way as panels. Clamping plates bolt over and sandwich the back-plate of each aerial to a stiff arm protruding from a friction clamp fixed to the pole. The arms can be short if there is only a single aerial per tier but must be longer for the crossed arrangements. The arm lengths are approximately 0.45m for Band IV and 0.7m for Band V. Figure 3 shows an
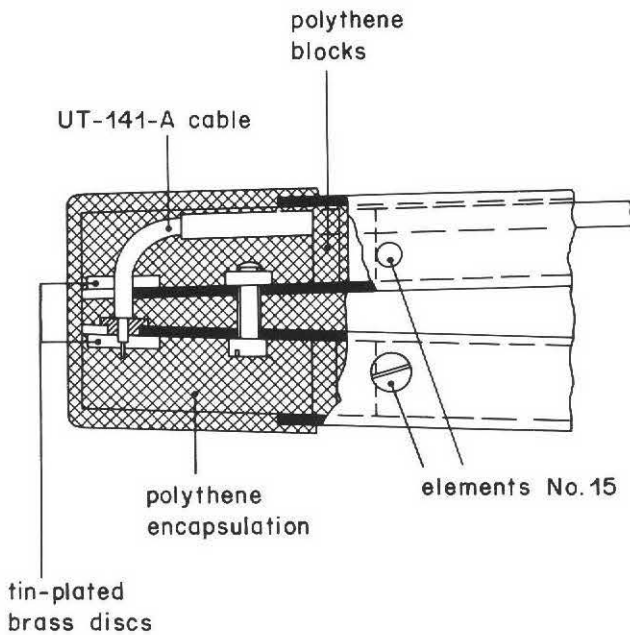
polythene
blocks

UT-141-A cable

polythene
encapsulation

elements No.15

tin-plated
brass discs

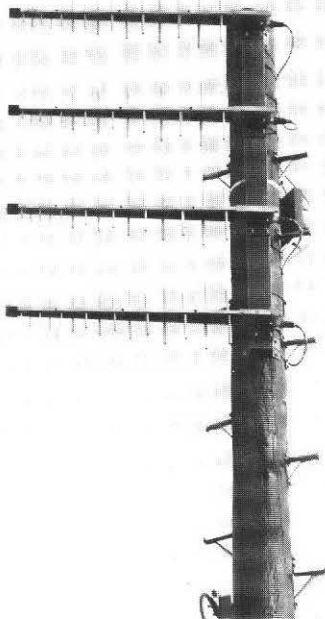**Fig. 2**   Driving point of aerial

Fig. 3   Polythene-spaced ruggedised uhf log-periodic aerials

array of four tiers of single aerials stacked vertically and mounted on a 'wooden pole' support.

3.1   Boom taper

The manner in which the dipole elements are attached to the booms inevitably means that there is a transverse displacement between them. If the feeder booms were parallel, the transverse displacement, expressed in terms of wavelengths appropriate to the frequency associated with a dipole element, would vary along the boom. By opening out the booms at the back of the aerial to maintain the transverse displacement constant in terms of wavelengths, a

better match of feeder-boom impedance to the driving-point impedance of the individual elements is achieved. This results in a better coupling of power into the elements.

Evans[8] has demonstrated the effects on log-periodic performance of excessively increasing the transverse displacement of the elements. The resistive part of the driving-point impedance of an element is shown to remain substantially unchanged until the displacement reaches 0.03λ. Because the aerial input impedance can be considered to be essentially dependent upon those elements comprising the active region at any one frequency and which are close to resonance, it will be little affected by displacements up to 0.03λ. The radiation pattern is also affected by the transverse displacement; the main beam tends to slew round and the sidelobes increase in amplitude.

The optimum degree of taper was found by experiment and the transverse displacement for this condition closely follows the τ relationship. The following result was obtained;

$$\frac{D}{\lambda \max} \approx 0.04$$

where 2D is the transverse displacement between elements.

The effect of the larger $D/\lambda\max$ is just noticeable in the pattern and match at 450 MHz but is not disturbing.

3.2   Element length compensation

In the initial design, the calculation of element lengths by applying the τ factor and the King-Middleton formulae takes no account of the mutual impedance between the elements in the array. Some compensation is required, especially at the high-frequency end of the aerial where dimensions are generally more critical.

3.3   Drive-point

If the input impedance characteristic as a function of frequency were represented on a Smith Chart, it would appear as a small group of points, lying within a circle, over the working frequency range. The impedance characteristic is optimised by the presence of the polythene in the region of the drive point which adds a small amount of shunt susceptance.

The drive-point also forms part of a balun arrangement whereby the unbalanced currents carried by the coaxial feeder are fed as balanced currents along the feeder boom. This transition is satisfactory provided the gap between the booms at the drive-point is small.

3.4   Dielectric loading

The introduction of a polythene dielectric medium into the gap between the feeder booms is designed to provide some degree of protection from the effects of icing because it effectively bridges the area where the electric field is strongest and where icing is most likely. The effect of the dielectric on the electrical performance of the aerial can be summarised as:

i) the increased dielectric constant of the feeder-boom dielectric lowers the characteristic impedance of the feeder-boom transmission line. To preserve the input impedance of the aerial, the boom taper must be increased;

ii) the velocity of wave propagation in the feeder-boom transmission line is reduced and the phase transition between the driving points of the dipole elements is altered. The spacings between the elements along the booms must be reduced to compensate. Although the driving points of the dipole elements lie on the feeder boom transmission line, the elements themselves radiate in air. The spacing of the elements along the boom has, therefore, to be reduced by a velocity factor which has a value between the relative velocity of propagation in the dielectric and unity.

A prototype aerial was constructed with a velocity factor of 0.80. Several polythene wedges with different tapers were tried between the feeder booms. An optimum wedge was found by examination of the aerial match and radiation patterns. The prototype was used to investigate the effect of varying the velocity factor by altering the spacing of the dipole elements along the booms and inserting extra elements of suitable length wherever necessary. In this way the velocity factor was varied between 0.67 and unity in five operations. A value of 0.85 was subsequently chosen because it gave the aerial a satisfactory match consistent with reasonably undistorted radiation patterns.

3.5 Weather-proofing

Complete protection of the aerial by means of a radome was not favoured because of the excessive increase in windloading area which would result.

The most vulnerable part of the aerial, the drive-point, is protected by a polythene moulding which encloses the whole of the end of the aerial beyond the last element. The booms are designed so that water can enter and leave freely although, if necessary, they could be filled with expanded polyurethane foam for complete weather protection.

Tests to simulate the effects of heavy rain revealed that the impedance match is worsened by only 1 to 2 per cent. It would be practicable to install a heater element in one of the hollow sections of the boom to give increased weather protection.

4 Arrangement of transmitter arrays

When transmitting, the arrangement of aerials which is likely to be most common is that of a single vertically polarised aerial or a number of tiers of single aerials stacked vertically to increase directivity. If a broader horizontal radiation pattern than that of a single aerial is desired, two aerials directed on different bearings can be used for each tier and the included angle chosen to suit the application. Beam-tilting to redirect the regions of maximum radiation to some small angle below the horizontal and gap-filling of the primary nulls in the vertical radiation pattern can be achieved by appropriate phasing of the distribution feeders.

When designing aerial arrays for optimum performance, an accurate knowledge of the electrical separation between them is important for computing the total radiation pattern. The reference point associated with an aerial and which is used for this purpose is the 'phase-centre' of the aerial. The concept of a phase-centre and its particular application to a log-periodic aerial has been discussed in another report.[9] Like the active region, the phase-centre is frequency-dependent. The location of the phase-centre measured from the front of the short-circuit plate of the aerial for different frequencies is given in Table 2.

TABLE 2

Phase–Centre Position of a Log-Periodic Aerial

f (MHz)	Distance of phase-centre from front of short circuit plate (mm)
450	365
500	460
550	548
600	618
650	678
700	729
750	775
800	812
850	847
900	875

In the case of a single aerial per tier there is no special problem with the movement of the phase-centre because the separation between individual phase-centres remains the same. When there are two aerials per tier the aerials must be positioned very carefully to avoid a large variation in separation of phase-centres. For example, an undistorted radiation pattern over a wide bandwidth cannot be achieved if the aerials are mounted radially from the mast. Instead, it is necessary that the aerials in a tier should cross over at a specified position along their axes. It is found that two cross-over points are sufficient to cover the Bands IV and V, one for each band. These were found by experiment and are;

Band IV: 250mm from front of short-circuit plate
Band V: 550mm from front of short-circuit plate

These arrangements allow the phase-centre separation to vary between about 0.25 λ and 1.5 λ. At wider separations than this the nulls in the forward lobe of the radiation patterns deepen and make the horizontal radiation pattern unsuitable for transmitter purposes.

The two aerials need to be staggered in height to effect the cross-over without the aerials interfering with one another. It is convenient that when the aerials are tiered in this fashion there is space in between two tiers for the other aerial of a tier pointing in another direction.

The aerials of the array are fed from conventional splitter transformers in the same way as for arrays of panel aerials. At smaller stations it may be appropriate to use the printed circuit type of splitter transformer.[10]
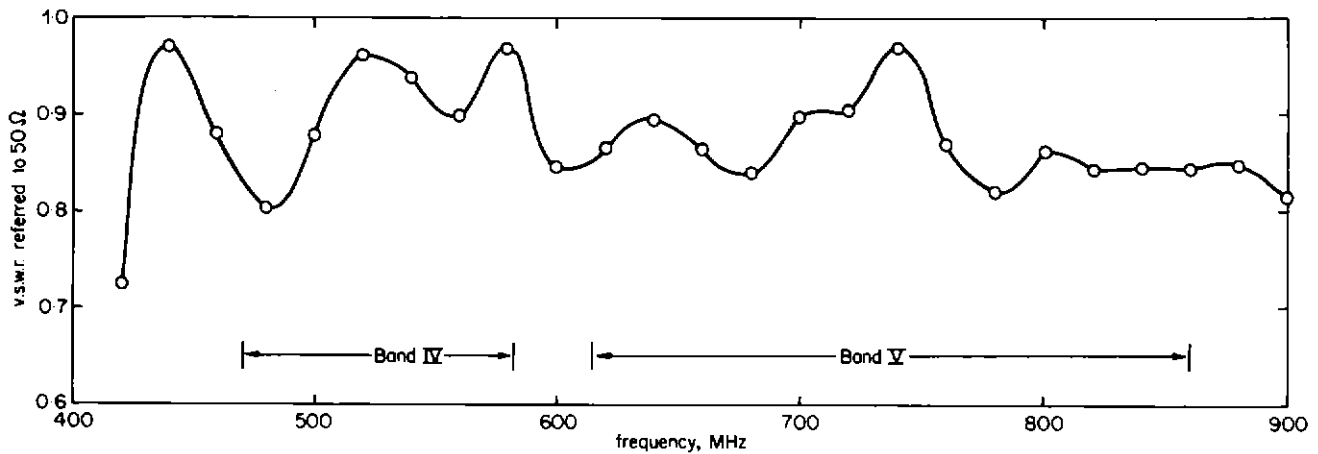
Fig. 4 Typical v.s.w.r. of polythene-spaced aerial referred to 50Ω

5 Measured performance

The performance of the aerials has been assessed in terms of the impedance match to 50 Ω, the radiation patterns in both E- and H-planes under normal and cross-polarised conditions and the gain relative to a half-wave dipole.

5.1 Impedance match

Impedance match measurements were made on a complex impedance bridge. The v.s.w.r. of the aerial is better than 0.8 over Bands IV and V. The results of measurements, in magnitude only, are reproduced in figure 4. The performance achieved is considered adequate for transmitting purposes at relay stations with present-day transposers and splitter transformers.

At a typical uhf low power relay station, where there may be 46m (150ft.) of feeder between transposer and aerial, the relative amplitude of a radiated delayed signal resulting from the mismatch at the aerial should be kept below −34dB.[11] Assuming that the reflection loss at the transposer is unlikely to be less than 12dB, the maximum reflection loss which can be tolerated at the aerials is 18 per cent in Band IV and 22 per cent in Band V. The maximum reflection coefficient of a single log-periodic aerial is 11 per cent. This may increase to 13 per cent in heavy rain. When a distribution transformer and feeders are taken into account, the maximum reflection coefficient of a log-periodic aerial array will rise above this. It is not likely, however, to exceed the figures arrived at above.

5.2 Horizontal radiation patterns

The radiation patterns were plotted on automatic equipment, the aerial under test being the transmit aerial, which was rotated and the received signal measured on a 'horn' aerial fixed some distance away. The beamwidths and worst minor lobe levels are tabulated in Table 3.

The CCIR templet for the recommended minimum directivity of a uhf receiving aerial[12] is largely met by the E-plane pattern but is transgressed by the H-plane pattern in

TABLE 3

Polythene-spaced Aerial Performance

| Frequency MHz	Half-power beamwidth degrees		Gain dB rel λ/2 dipole at aerial input	Minor lobe radiation dB below maximum field	
	E-plane	H-plane		E-plane	H-plane
450	±28	±35	8.0	24.0	25.0
500	±28	±35	8.1	33.0	31.0
550	±27	±35	8.2	29.0	30.0
600	±26	±35	8.2	32.0	27.0
650	±25	±34	8.3	31.0	33.0
700	±26	±35	8.3	27.0	28.0
750	±27	±36	7.8	27.0	23.5
800	±28	±34	7.8	26.0	22.5
850	±28	±37	7.8	30.0	22.5
900	±29	±41	7.3	23.0	22.0

the main lobe region. For field-strength measurement applications this is satisfactory and if for any reason a greater directivity were desired, two aerials side by side would suffice.

There is no transgression of the templet as far as minor lobe radiation is concerned.

Measurements have also been made to check the cross-polarisation performance when signals are received from aerials on the opposite polarisation. The CCIR recommendation is that there should be more than 20 dB protection, relative to the peak of the main lobe, on all angles of orientation.[13] This is substantially achieved.

The measured horizontal radiation patterns (h.r.p.'s) for the Band IV and Band V versions of two arrays with two aerials per tier are shown in figures 5 and 6. A typical included angle of 90° has been chosen for the examples and measurements were made at three frequencies in each band. The general pattern shape is somewhat similar to those of the panel aerials but there are two notable differences. In the case of two aerials set at 90°, the patterns are almost cardioidal at the lower end of the bands but with a more rapid fall-off of the side-lobes. As the diagrams show, there is very little backward radiation.
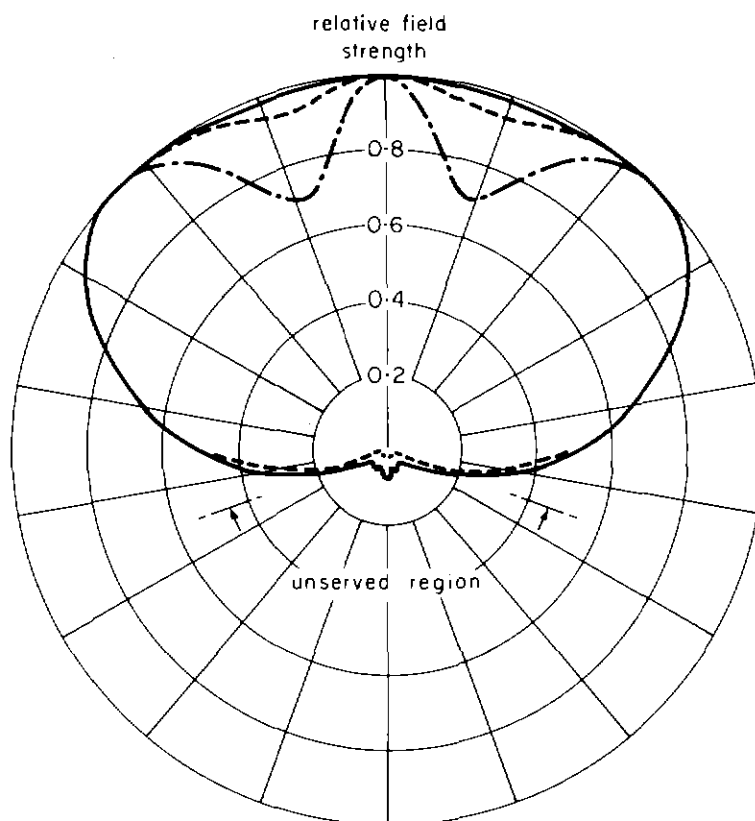
Fig. 5 Measured horizontal radiation pattern: 2 aerials set at 90°, Band IV
———470MHz — — — —530MHz —·—600MHz
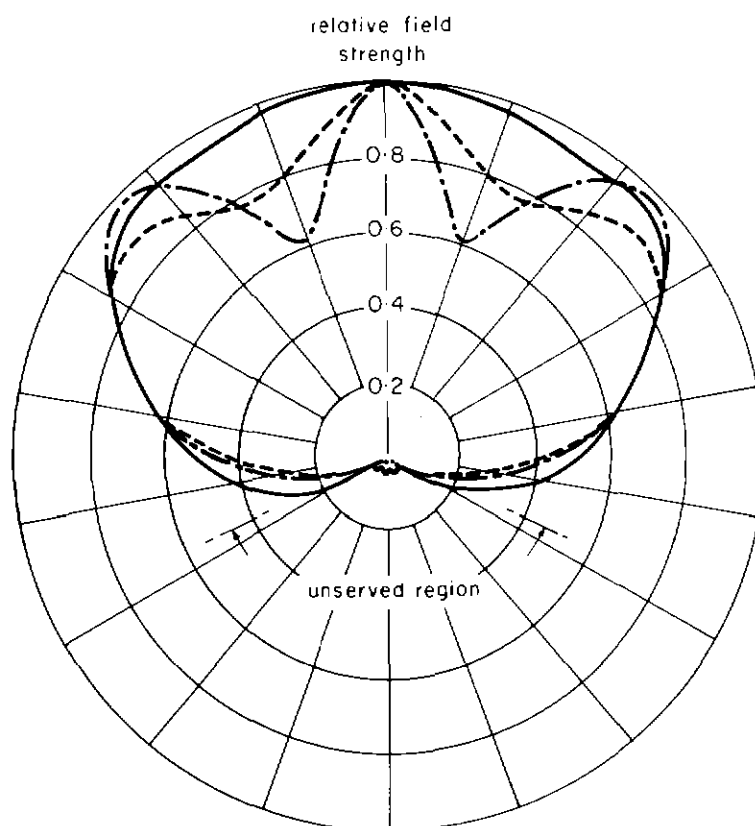
Fig. 6 Measured horizontal radiation pattern: 2 aerials set at 90°, Band V
———600MHz —·—·—720MHz —·—850MHz

5.3 Vertical radiation patterns

The measured vertical radiation patterns (v.r.p.'s) of 2 and 4 tiers of aerials at the h.r.p. maxima are shown in figures 7 and 8 respectively. The vertical separation of the aerials is
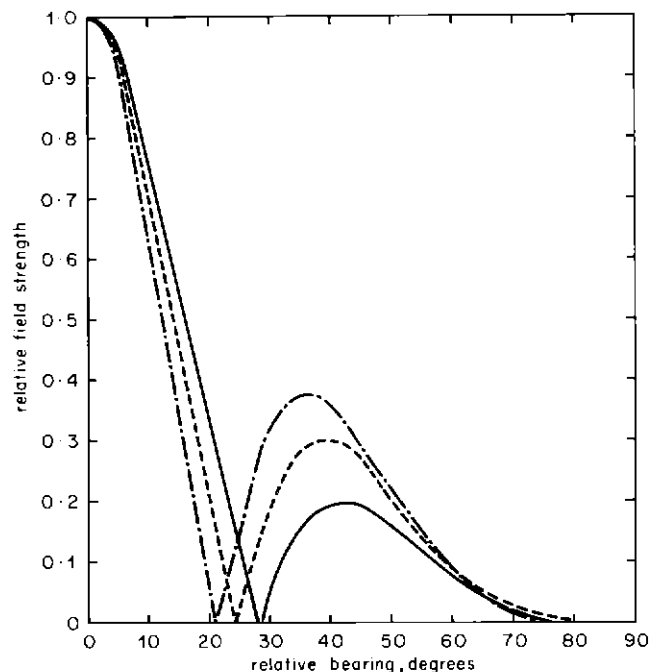

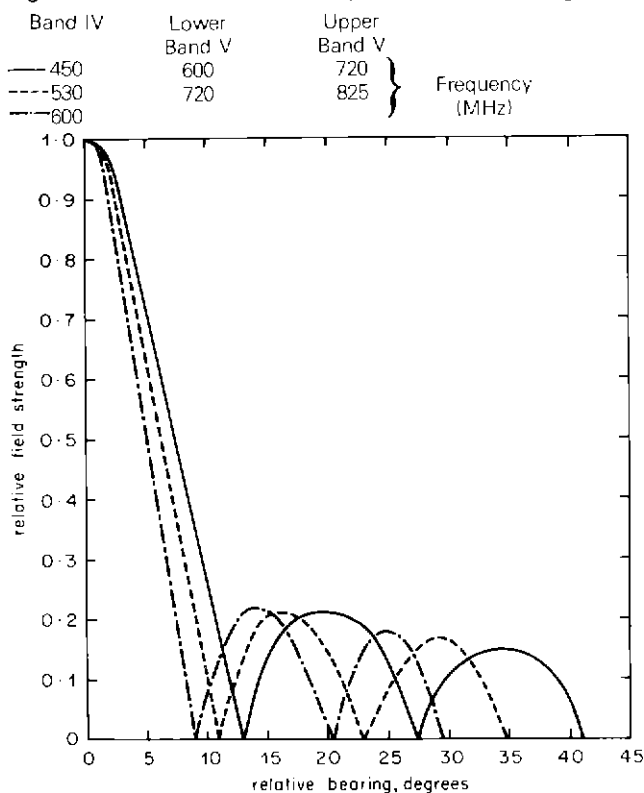**Fig. 7** Measured vertical radiation pattern: 2 tiers of a single aerial

Band IV	Lower Band V	Upper Band V	
——— 450	600	720	} Frequency
---- 530	720	825	(MHz)
—··— 600			

Fig. 8 Measured vertical radiation pattern: 4 tiers of a single aerial

Band IV	Lower Band V	Upper Band V	
——— 450	600	720	} Frequency
— — 530	660	780	(MHz)
——— 600	720	860	

chosen to maximise the gain over the band. In special cases there may be a requirement for larger vertical apertures. Because it is relatively easy to position aerials at different heights by adjustment of friction clamps, two settings are chosen to cover Band V and achieve a higher overall gain. The vertical separations of 2 and 4 tiers of aerials are given in Table 4.

TABLE 4

Vertical Aerial Separation for Multi-Tiers

	Vertical Separation (mm)	
	2 Tiers	4 Tiers
Band IV	680	750
Lower Band V	520	580
Upper Band V	440	500

5.4 Aerial gain

The gain has been calculated by integrating the measured v.r.p. and making an allowance for the maximum-mean radiation of the h.r.p.

The computed aerial gain of some typical arrangements of log-periodic aerials is shown in Tables 3, 5, 6 and 7.

TABLE 5

Gain of Single Tier of Aerials (dB)

Channel Number	21	33	53	65
Single aerial	8.1	8.2	8.1	7.7
2 aerials, set at 90°	4.7	5.3	5.2	5.2
2 aerials, set at 120°	4.8	5.0	5.1	

TABLE 6

Gain of Two Tiers of Aerials (dB)

Channel Number	21	33	53	65
Single Aerial/Tier	10.9	11.0	10.7	10.5
2 Aerials/Tier, set at 90°	7.5	8.0	7.9	8.0
2 Aerials/Tier, set at 120°	7.6	7.8	7.8	

TABLE 7

Gain of Four Tiers of Aerials (dB)

Channel Number	21	33	53	65
Single Aerial/Tier	13.8	14.0	13.8	13.6
2 Aerials/Tier, set at 90°	10.4	11.1	11.0	11.1
2 Aerials/Tier, set at 120°	10.5	10.9	10.9	

The values quoted are relative to a half-wave dipole and include the losses associated with the internal feeder of the log-periodic aerial and with the necessary distribution
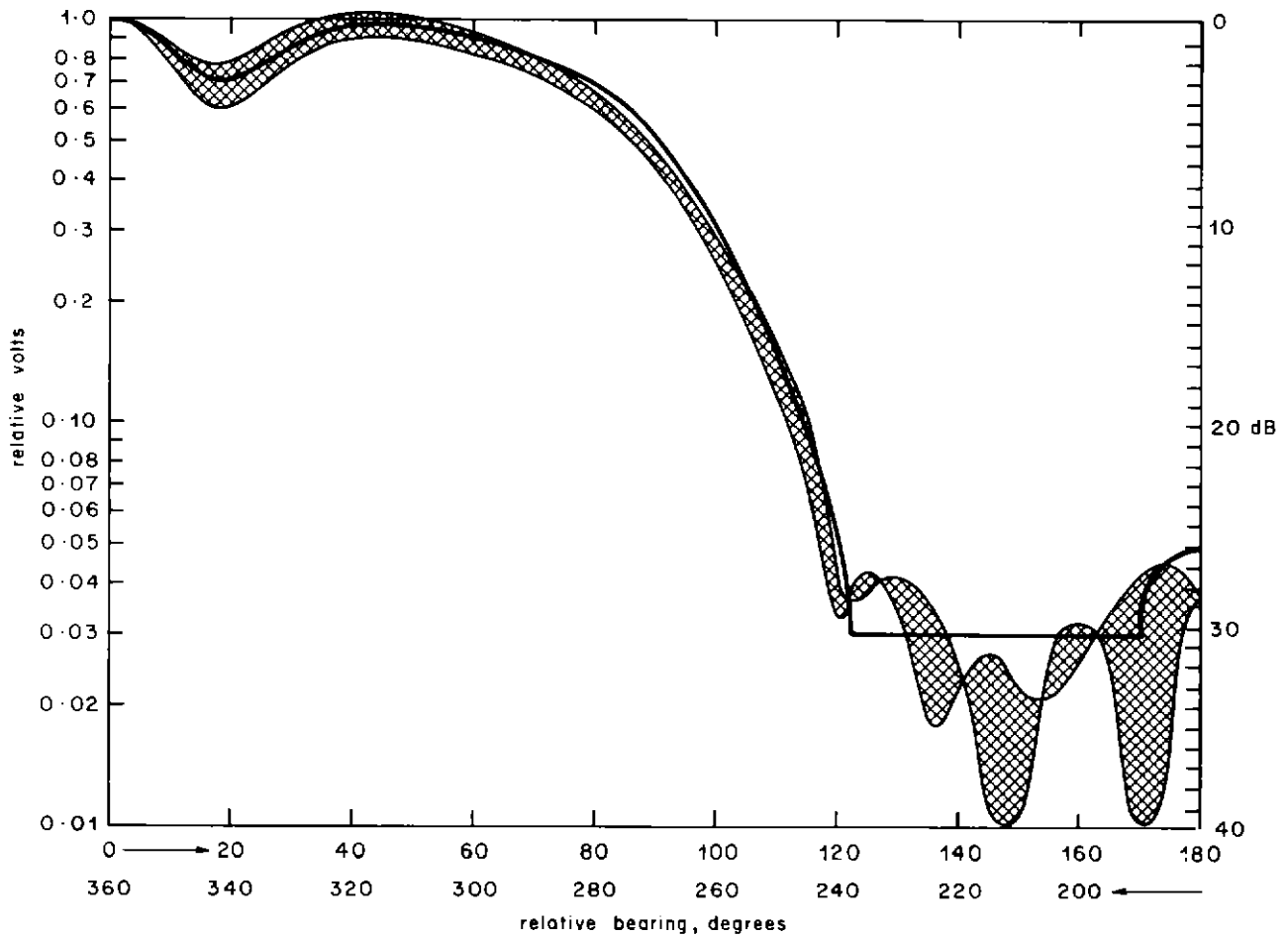
Fig. 9 Computed and measured horizontal radiation pattern, 2 aerials set at 90°, 600MHz, Band IV arrangement

Computed result ▨▨▨ Measured result

transformers and distribution feeders. The gain remains approximately constant throughout Bands IV and V.

Gap-filling of the v.r.p. and beam tilting of the main beam will tend to reduce these figures.

6 Computed results

For service planning purposes it has been found convenient to have a means of predicting the radiation pattern behaviour of a proposed transmitting aerial array. A computer program has been used for some time to provide this information for arrays of panel aerials, and it is possible to do the same for arrays of log-periodic aerials.

The data required by the computer are the frequency of operation, the locations of the individual aerials, their direction of fire and the complex radiation pattern of a single aerial in at least two planes. The complex radiation pattern of a log-periodic aerial is variable in the phase term because of the phase-centre movement with frequency. If the complex pattern data were used to produce an array pattern, a different set of pattern data would be required for each array.

If it is assumed that the phase-centre of the log-periodic aerial is valid for all angles of azimuth, the aerial can be thought of as one with a constant phase pattern at each frequency of operation, based on its phase-centre position. This assumption is valid in practice because the radiation

level outside the main beam region is more than −20 db below maximum radiation. Only the radiation pattern amplitude of a single aerial is now required and this is independent of frequency. The programme can be adapted to avoid the need of providing this data for each run. The aerial location data, however, now includes a factor dependent on frequency because, apart from the physical position of an aerial, the relative position of its phase-centre must be considered at each frequency. This method of working appears to be the most efficient way of overcoming the problem of a phase-centre moving with frequency.

The assumptions associated with this approach and the method of computation may be summarised:

i) the phase-centre concept is valid for a log-periodic aerial and may be assumed to hold for all angles of azimuth

ii) the back- and side-lobe radiation is very low outside the main beam region

iii) the h.r.p. of a single aerial remains substantially constant throughout the uhf Bands IV and V

iv) the pole and support structure do not influence the radiation pattern unduly

The computing method has been tested by producing the h.r.p.'s of typical arrays, set at 90° at a number of frequencies. In general there is a very close resemblance between the computed and measured results. Figure 9 shows
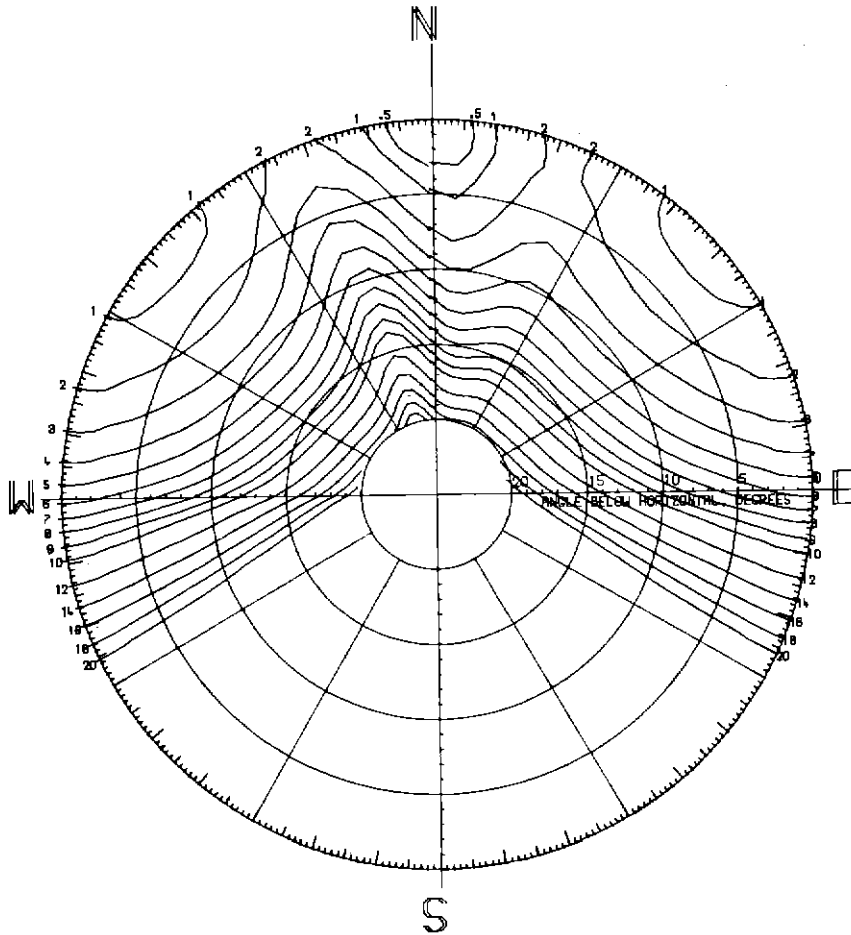
Fig. 10 Channel 33, computed radiation pattern plots: 2 tiers of 2 aerials set at 90°

a typical result for an array of two aerials set at 90° computed at the extreme frequencies in Band IV and V. Also shown are the envelopes of measured results taken from several sets of measurements. The biggest differences between computed and measured results can be estimated for the region of the patterns down to −10 dB relative to the maximum radiation level. They are ± 1.5 dB in Band IV and ± 2.0 dB in Band V.

An example of a computed contour plot embodying the h.r.p. and v.r.p. information is shown in figure 10. This is the form of presentation which is most convenient for service planning.

7 Conclusions

It has been shown that arrays of log-periodic aerials can produce suitable radiation patterns for low-power relay stations. The computed contour plots appear to give a satisfactory indication of the radiation pattern performance for planning purposes.

8 References

1 Riley, J.L. 1973. A uhf ruggedised log-periodic aerial. BBC Research Department Report No. 1973/24.

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The Effect of Polarisation on Television Reception on Oversea Paths

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Research Department

Summary: Details are given of a system using elliptical polarisation to reject sea-reflected signals, which is expected to offer a considerable improvement over horizontal or vertical polarisation.

Fading of u.h.f. signals on oversea paths within the horizon can occur because of interference between the direct and sea-reflected signals. Comparisons of transmissions using horizontal and vertical polarisation have been made on short oversea paths affected by fading. The results indicate that unacceptable fading can occur on either polarisation, although the fading with vertical polarisation is generally less serious.

1 Introduction

Severe fading of u.h.f. signals on oversea paths has been observed in various parts of the U.K.[1] The fading is due to interference between the direct and sea-reflected components of the received signal. The relative phase alters as the level of the sea varies with the tide; the amplitude of the received signal also changes and this can cause severe degradation of u.h.f. television reception.

In the earlier series of tests,[1] it was concluded that it would be advantageous to use vertical polarisation (v.p.) rather than horizontal polarisation (h.p.) To determine effects of polarisation over short paths, tests have been made from the Rosneath transmitting station. Most of the Rosneath u.h.f. service area will be exposed to sea reflections and fading is thus an important factor in determining the service area.

2 Horizontal and vertical polarisations: tests in the Rosneath service area

2.1 Measurement techniques

Two c.w. test transmitters were mounted on the Rosneath mast: one on h.p. on 666 MHz and the other on v.p. on 756 MHz. Continuous recordings of field strength were made during half-tide cycles (about 6¼ hours) at a number of locations in the Dunoon, Gourock and Port Glasgow areas. To supplement these measurements, field strength recordings were made as the receiving aerial height was reduced from 10 m to 2·8 m above ground level — this procedure was repeated at various states of the tide and by comparison of the recordings the fading range (maximum/minimum) for each location was derived. The latter method enables measurements to be taken more quickly and the results are similar to those obtained by continuous recordings over a half-tide cycle.

### 2.2 Results and discussion of results

Figs. 1(a) and (b) show the distribution of the measured fading ranges for h.p. and v.p. respectively. The median fading range was 15·5 dB for h.p. and 9·5 dB for v.p. Fading ranges of >10 dB were recorded at 72 per cent of locations for h.p. and 46 per cent of locations for v.p. Similarly, the percentage of locations affected by fading ranges of >20 dB was 41 per cent for h.p. and 8 per cent for v.p.

Figs. 2(a) and (b) show the theoretical variation of reflection coefficients (p) of sea water with grazing angle for both polarisations, and the individual values of the effective reflection coefficient* (p_{eff}) derived from the measurements. For v.p. the individual values of p_{eff} are spread around the theoretical curve, but for h.p. the values tend to be lower than theoretical. The discrepancies are due mainly to signals reflected by the ground near the receiving location. The effects of such ground reflected signals depend on the relative phase of the direct and ground-reflected

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* The reflection coefficient is the ratio between the amplitudes of the direct and the sea-reflected components. In practice the direct component is often modified by other components of constant phase, such as ground reflected signals. The fading range is determined by the relative amplitudes of the constant phase components (i.e. direct and ground reflections) and the variable phase components (i.e. sea reflections): hence the use of the term 'effective reflection coefficient' which implies the ratio between the amplitudes of the constant and variable components.
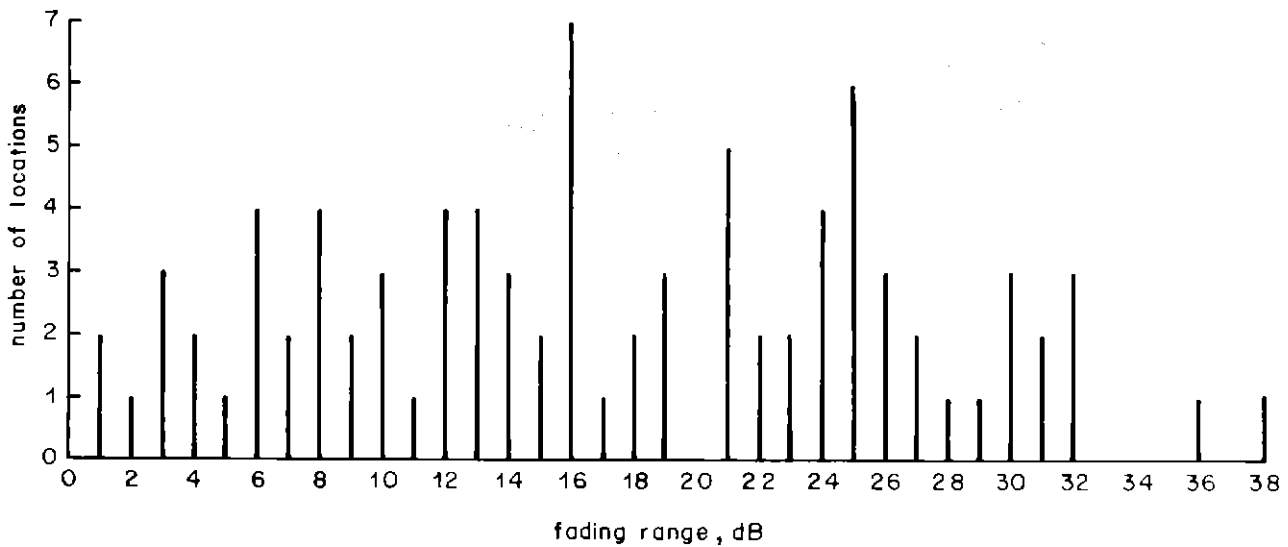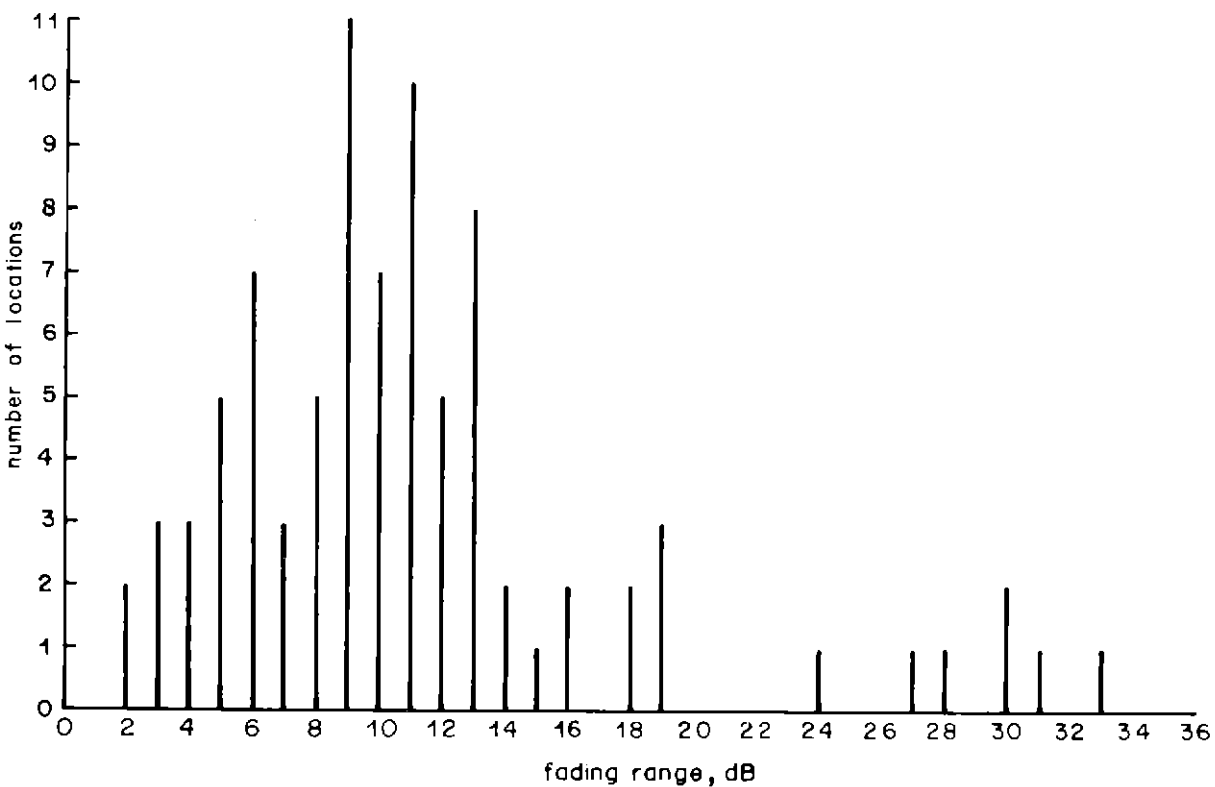
Fig. 1 Measured fading ranges (Maximum/minimum)
(a) Horizontal polarisation (b) Vertical polarisation

components; if they are in phase, the fading caused by the variable-phase sea reflected component will be reduced; if they are out of phase, the fading will be increased.

Diffuse reflection from the sea is caused by irregularities on the surface of the sea. As these irregularities move, the amplitude and phase of the reflected signal changes, causing a change in field strength.[2][3] Amplitude variations of more than 20 dB at a frequency of about 0·3 Hz were observed during these tests.

These fluctuations cause variations of the chrominance-luminance and vision-sound ratios of a television transmission. The tests at Rosneath used c.w. transmissions and thus no information was obtained about the subjective effects of such variations on television reception. A
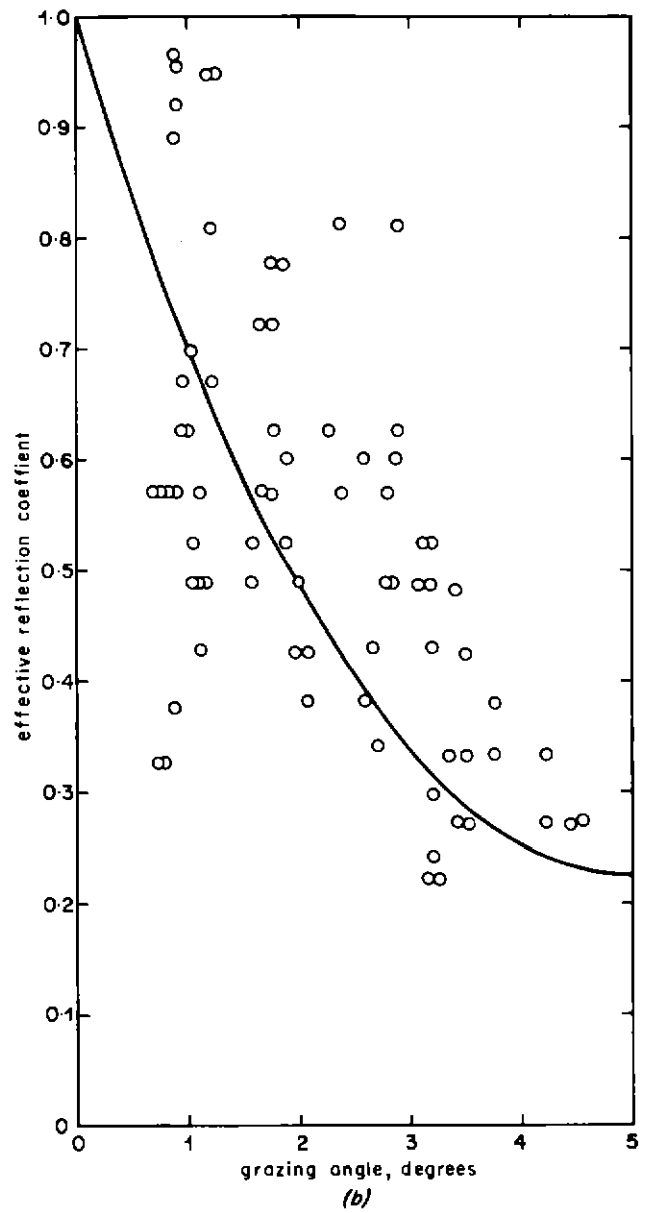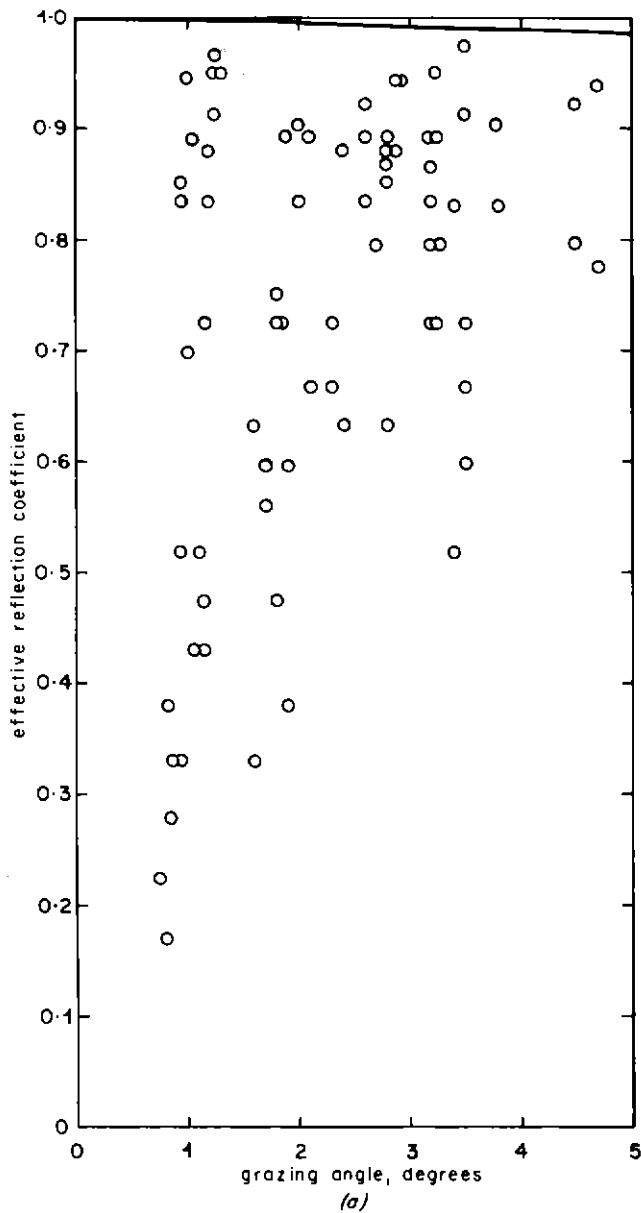
Fig. 2 Effective reflection coefficients
(a) Horizontal polarisation   (b) Vertical polarisation
——— theoretical   o measured

laboratory simulation of these variations using colour television receivers has been made and the results show that the subjective effects depend on a number of factors: the most important being the type of television receiver, the amplitude of the received signal, and the amplitude and frequency of the fluctuations.

During earlier tests at the Wenvoe[1] transmitting station the effects of diffuse reflections were less important because of two main factors:

(a) The measurements were made during fine weather when the sea was calm, and thus the amplitudes of the diffuse components were low (during the Rosneath tests, poor weather conditions caused rough seas and thus the amplitudes of the diffuse components were greater).

(b) It can be shown that for a given value of surface roughness the amplitude of the diffuse component

increases as the grazing angle ψ increases. For the Wenvoe transmissions across the Bristol Channel ψ is 1° or less; at Rosneath ψ can be as high as 4·5°, thus the diffuse component is more important at Rosneath.

It is probable that on short oversea paths, where ψ is large, the effects of the diffuse component on television reception may be more important than other types of picture degradation previously observed during tidal fading.

3 Elliptical polarisation

3.1. Theoretical considerations

For reflection from a plane surface, the incident and reflected waves differ in amplitude and phase as determined by the reflection coefficient. If the plane of polarisation of the incident wave is either parallel or perpendicular to the

reflecting surface (h.p. or v.p. in the case of reflection at the surface of the sea) the reflected wave will have the same polarisation as the incident wave. For more complex polarisations, which can all be resolved into h.p. and v.p. components, the polarisations of the incident and reflected waves will be identical if the reflection coefficients for h.p. and v.p. are equal. When these reflection coefficients are unequal, the amplitude and phase relationships of the h.p. and v.p. components change, thus altering the polarisation of the reflected wave.

If the polarisations of the incident and reflected waves are different it is possible to reject one of the components by using the polarisation discrimination of the receiving aerial. If the polarisation of the incident wave is chosen so that the reflected wave is linearly polarised, a standard receiving aerial will reject the reflected wave if it is tilted at $90°$ to the plane of polarisation of the reflected wave. Since the receiving aerial tilt required to reject the reflected wave is generally different from that required for maximum coupling with the direct wave, this implies a reduction in amplitude of the received signal in exchange for the rejection of the unwanted signal.

As the reflection coefficients vary with grazing angle, the system can only provide complete rejection of the reflected wave at a specific grazing angle. It will be shown later that useful suppression of the reflected wave may be obtained at grazing angles close to the nominal rejection angle.

The Appendix gives further details of theoretical aspects of this system.

3.2 Application to u.h.f. transmissions on short oversea paths

The principle described above can be applied to u.h.f. transmissions on short oversea paths to minimise fading due to sea reflections. The receiving aerial must respond to both h.p. and v.p. components of the transmitted signal, and it is suggested that receiving aerials could be tilted at $45°$, thus responding equally to h.p. and v.p. components.

Suppose it is required to reject components reflected from the sea at a grazing angle of $2°$ for a frequency of 756 Mhz; the required h.p./v.p. amplitude ratio is $0·491$ and the h.p. component is retarded in phase by $158·7°$ relative to the v.p. component.* For a grazing angle of $2°$ the reflected wave is plane-polarised at $45°$ from vertical and this may be rejected by a receiving aerial tilted at $135°$ from vertical. In this case, the amplitude of the direct wave is reduced by $8·8$ dB compared with the amplitude of the direct wave for h.p. or v.p. transmissions. This loss is probably acceptable at most locations where the rejection of the sea-reflected components is required because the most serious fading occurs at locations where the amplitude of the direct wave is close to the free-space value.

At locations where fading is not significant viewers could use vertical receiving aerials, which would increase the amplitude of the direct wave by $7·9$ dB, compared with that obtained with an aerial tilted at $135°$.

* The required h.p./v.p. amplitude and phase relationship is given by Equation (6) in the Appendix.

Fig. 3 shows the variation of apparent reflection coefficient with grazing angle; the apparent reflection coefficient is defined as the ratio of the amplitudes of the reflected and direct waves as observed on an aerial tilted to $135°$. For comparison, the reflection coefficients for h.p. and v.p. are also shown in Fig.3. It will be noted that for elliptical polarisation, designed for a rejection angle of $2°$, the apparent reflection coefficient is less than that for h.p. or v.p. for grazing angles up to about $3°$. For grazing angles above $3°$, the reflection coefficient is less if a v.p. receiving aerial is used.

This example shows that reduction of fading may be obtained by using elliptical polarisation and tilted receiving aerials. It is possible to choose different rejection angles depending on the requirements, and calculations of the performance of this system have been made for a range of grazing angles and frequencies; some examples are shown in the Appendix.

It has been shown from theoretical considerations that elliptical polarisation could be useful on oversea paths. This treatment neglects certain factors which may cause deviations from the calculated performance. The tests described in Section 2 showed that ground reflected components were an important factor in determining the fading range. The amplitude of these ground-reflected components may be reduced by the use of elliptical polarisation. Rapid fluctuations in amplitude of the received signal occur because of the roughness of the sea. For elliptical polarisation it is not known if these variations will be
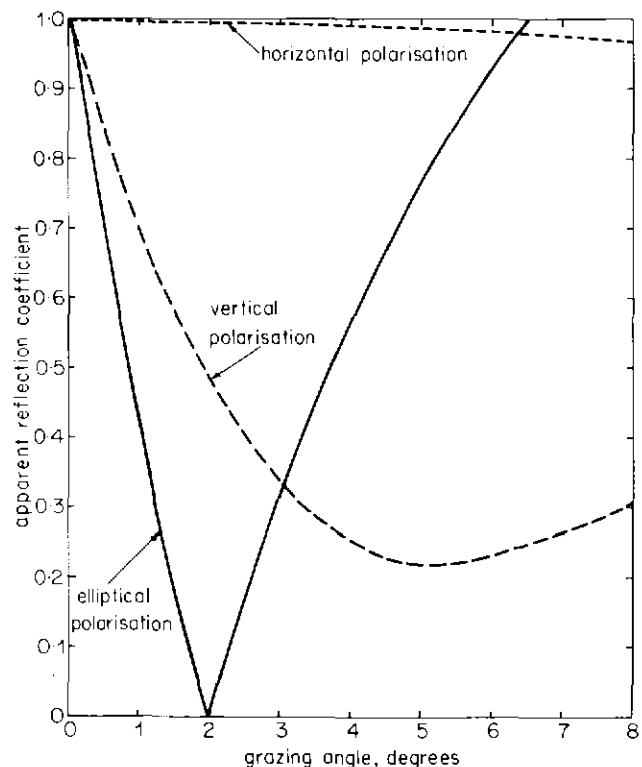

Fig. 3 Variation of apparent reflection coefficient at 756 MHz of sea water for horizontal, vertical and elliptical polarisations

Rejection angle for elliptical polarisation: $2°$

reduced or increased; this is dependent on the degree of correlation between the diffuse reflections for h.p. and v.p. Depolarisation of the h.p. and v.p. components is also expected to be important when the sea is rough.

4 Conclusions

The comparisons of horizontal and vertical polarisations indicate that if the Rosneath transmissions were horizontally polarised large parts of the service area would be severely affected by tidal fading. A change to vertical polarisation would alleviate the problem at most locations, but fading ranges (maximum/minimum) of more than 20 dB are still likely to occur at some locations. At locations where there were no significant ground reflections the theoretical values of fading range were confirmed. At the other locations ground reflections had the effect of either increasing or decreasing the fading ranges. It should be noted that these results apply to the Rosneath service area and that the effects of ground reflections may be either more or less important in other service areas.

When the sea was rough, rapid variations in amplitude of the received signal were observed. The frequency of these fluctuations was about 0·3 Hz and their amplitudes were dependent on the roughness of the sea. These fluctuations may be more serious on short paths affected by tidal fading than the other types of picture degradation observed previously; i.e. delayed image interference and frequency selective fading.

Details have been given of a system using elliptical polarisation to reject sea-reflected signals. Theoretical considerations show that this system could reduce fading but its performance may be adversely affected by the roughness of the sea.

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Appendix:

Calculation of amplitudes of direct and reflected components for elliptical polarisation

Propagation on oversea paths within the horizon can be considered as the resultant of a direct and a sea-reflected component.* The amplitude of the received signal is:

$$E = E_o(1 + \rho e^{-j\phi}) \qquad (1)$$

where E_o is the free-space field strength

ρ is the complex reflection coefficient

ϕ is the phase delay due to the path difference between direct and reflected components.

For horizontal polarisation

$$E_h = E_{oh}(1 - \rho_h e^{-j\phi}) \qquad (2)$$

For vertical polarisation

$$E_v = E_{ov}(1 - \rho_v e^{-j\phi}) \qquad (3)$$

With a linearly polarised receiving aerial inclined at α from the vertical, the amplitude of the received signal is

$E\alpha = E_v \cos\alpha + E_h \sin\alpha$

$= E_{ov} \cos\alpha + E_{oh} \sin\alpha - e^{-j\phi}(\rho_v E_{ov} \cos\alpha + \rho_h E_{oh} \sin\alpha)$

$\underbrace{\qquad\qquad\qquad}_{\text{direct component}} \qquad \underbrace{\qquad\qquad\qquad}_{\text{reflected component}}$ (4)

If it is required to reject components reflected at a grazing angle ψ_o (i.e. where $\rho_v = \rho_{vo}$ and $\rho_h = \rho_{ho}$) with a receiving aerial tilted at α_o the h.p./v.p. ratio E_{oh}/E_{ov} must be chosen so that

$$\rho_{vo} E_{ov} \cos\alpha_o + \rho_{ho} E_{oh} \sin\alpha_o = 0 \qquad (5)$$

$$\therefore \quad \frac{E_{oh}}{E_{ov}} = \frac{-\rho_{vo}}{\rho_{ho}} \cot\alpha_o \qquad (6)$$

From (5) $\qquad E_{oh} \sin\alpha_o = \frac{-\rho_{vo}}{\rho_{ho}} E_{ov} \cos\alpha_o \qquad (7)$

Substituting (7) in (4), the amplitude of the received signal is

$$E\alpha_o = E_{ov} \cos\alpha_o \left[1 - \frac{\rho_{vo}}{\rho_{ho}} + e^{-j\phi}\left(\rho_v - \frac{\rho_h \rho_{vo}}{\rho_{ho}}\right)\right] \qquad (8)$$

The apparent reflection coefficient (ρa) is the ratio of the amplitudes of the reflected and direct components as observed on an aerial tilted at the required value of α_o, and

$$\rho a = \frac{\rho_v - \rho_h \frac{\rho_{vo}}{\rho_{ho}}}{1 - \frac{\rho_{vo}}{\rho_{ho}}} \qquad (9)$$

Fig. 4 shows the variation of apparent reflection coefficient ρa against grazing angle ψ at the surface of the sea for various values of rejection angle ψ_o.

If E_o is the free-space field strength due to a linearly polarised transmission of radiated power equal to the total radiated power of an elliptically polarised transmission

$$E_o^2 = E_{ov}^2 + E_{oh}^2 = E_{ov}^2\left(1 + \frac{E_{oh}^2}{E_{ov}^2}\right)$$

$$\therefore \quad \frac{E_{ov}^2}{E_o^2} = \frac{1}{1 + \frac{E_{oh}^2}{E_{ov}^2}} \text{ and } \frac{E_{ov}}{E_o} = \left(\frac{1}{1 + \frac{E_{oh}^2}{E_{ov}^2}}\right)^{\frac{1}{2}} \qquad (10)$$

From (8) the amplitude of the direct component, E_d, as observed with a receiving aerial tilted at α_o is given by

* All the examples of use of elliptical polarisation given in this Appendix relate to the rejection of sea-reflected components at a frequency of 756 MHz. It is assumed that for sea water $\epsilon r = 80$ and $\sigma = 4$ S/m.

$$E_d = E_{ov}\cos\alpha_o\left(1 - \frac{\rho_{vo}}{\rho_{ho}}\right)$$

$$\frac{E_d}{E_o} = \frac{E_d}{E_{ov}} \times \frac{E_{ov}}{E_o} = \cos\alpha_o\left(1 - \frac{\rho_{vo}}{\rho_{ho}}\right)\left(\frac{1}{1 + \frac{E_{oh}^2}{E_{ov}^2}}\right)^{\frac{1}{2}} \quad (11)$$

$$= \cos\alpha_o\left(1 - \frac{\rho_{vo}}{\rho_{ho}}\right)\left(\frac{1}{1 + \frac{\rho_{vo}^2}{\rho_{ho}^2}\cot^2\alpha_o}\right)^{\frac{1}{2}} \quad (12)$$

From (6) it will be noted that to reject the reflected component of a v.p. transmission the receiving aerial must be horizontally polarised ($\alpha_o = 90°$), and that for h.p. transmissions the required value of α_o is $0°$ (v.p.). Equation (12) shows that when $\alpha_o = 0°$ or $90°$ the amplitude of the direct component E_d is zero, this implies that a vertical or horizontal receiving aerial would reject both direct and reflected components, as there is no change in polarisation after reflection for v.p. or h.p. signals.

From (11)

$$\frac{E_d}{E_o} = \cos\alpha_o\left(1 + \frac{E_{oh}}{E_{ov}}\tan\alpha_o\right)\left(\frac{1}{1 - \frac{E_{oh}^2}{E_{ov}^2}}\right)^{\frac{1}{2}} \quad (13)$$

$$= \frac{\cos\alpha_o + \frac{E_{oh}}{E_{ov}}\sin\alpha_o}{\left(1 + \frac{E_{oh}^2}{E_{ov}^2}\right)^{\frac{1}{2}}}$$

E_d/E_o has a maximum value when $\dfrac{\mathrm{d}(E_d/E_o)}{\mathrm{d}\alpha} = 0$

$$\mathrm{d}\frac{E_d}{E_o} = -\frac{-\sin\alpha_o + \frac{E_{oh}}{E_{ov}}\cos\alpha_o = 0}{\left(1 + \frac{E_{oh}^2}{E_{ov}^2}\right)^{\frac{1}{2}}} \quad \text{i.e. when } \frac{E_{oh}}{E_{ov}} = \tan\alpha_o \quad (14)$$

It will be noted that E_d/E_o has a maximum value when $E_{oh}/E_{ov} = \tan\alpha_o$ and this implies that the optimum value for α_o occurs when $\tan^2\alpha_o = \rho_{vo}/\rho_{ho}$.

For use in a broadcasting system with its requirement for a simple aerial installation, the value of $\alpha_o = 135°$ is proposed. The change in amplitude of the direct component E_d for $\alpha_o = 135°$ compared with the optimum value is generally small; for the example given in Section 3.2 E_d/E_o is -8.8 dB for $\alpha_o = 135°$ compared with the maximum value for E_d/E_o of -8.3 dB when $\alpha_o = 145°$. Fig. 5
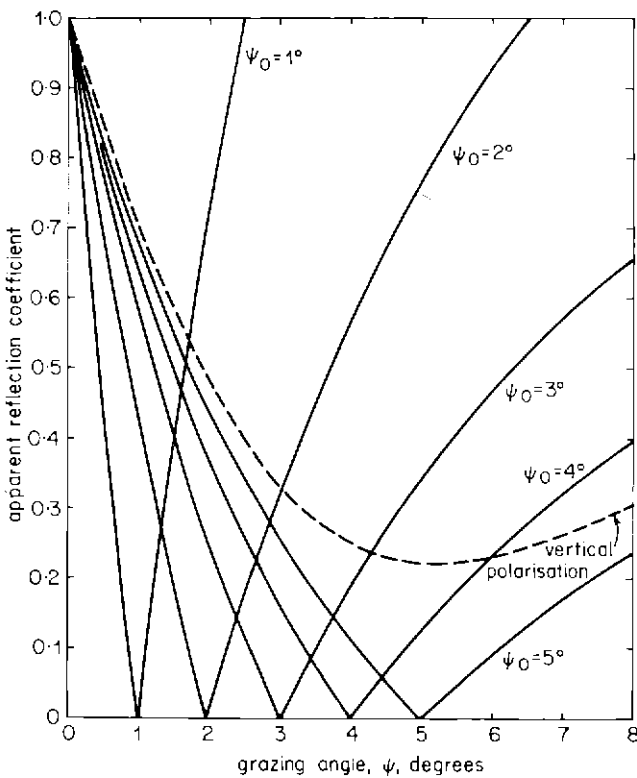

Fig. 4 Elliptical polarisation: variation of apparent reflection coefficient at 756 MHz of sea water with grazing angle ψ for various values of rejection angle ψ_o
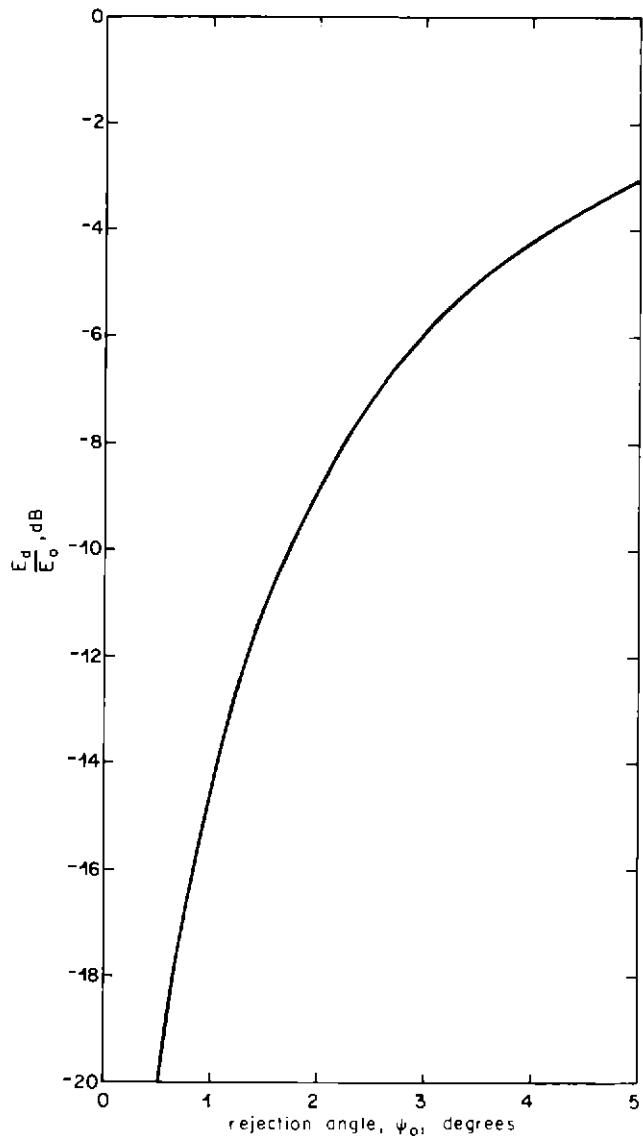

Fig. 5 Elliptical polarisation: variation of E_d/E_o with rejection angle ψ_o where E_d is the free-space field strength of an elliptically-polarised transmission as observed with a receiving angle tilted at $\alpha_o = 135°$

E_o is the free-space field strength of a linearly polarised transmission of radiated power equal to the total radiated power of the elliptically polarised transmission
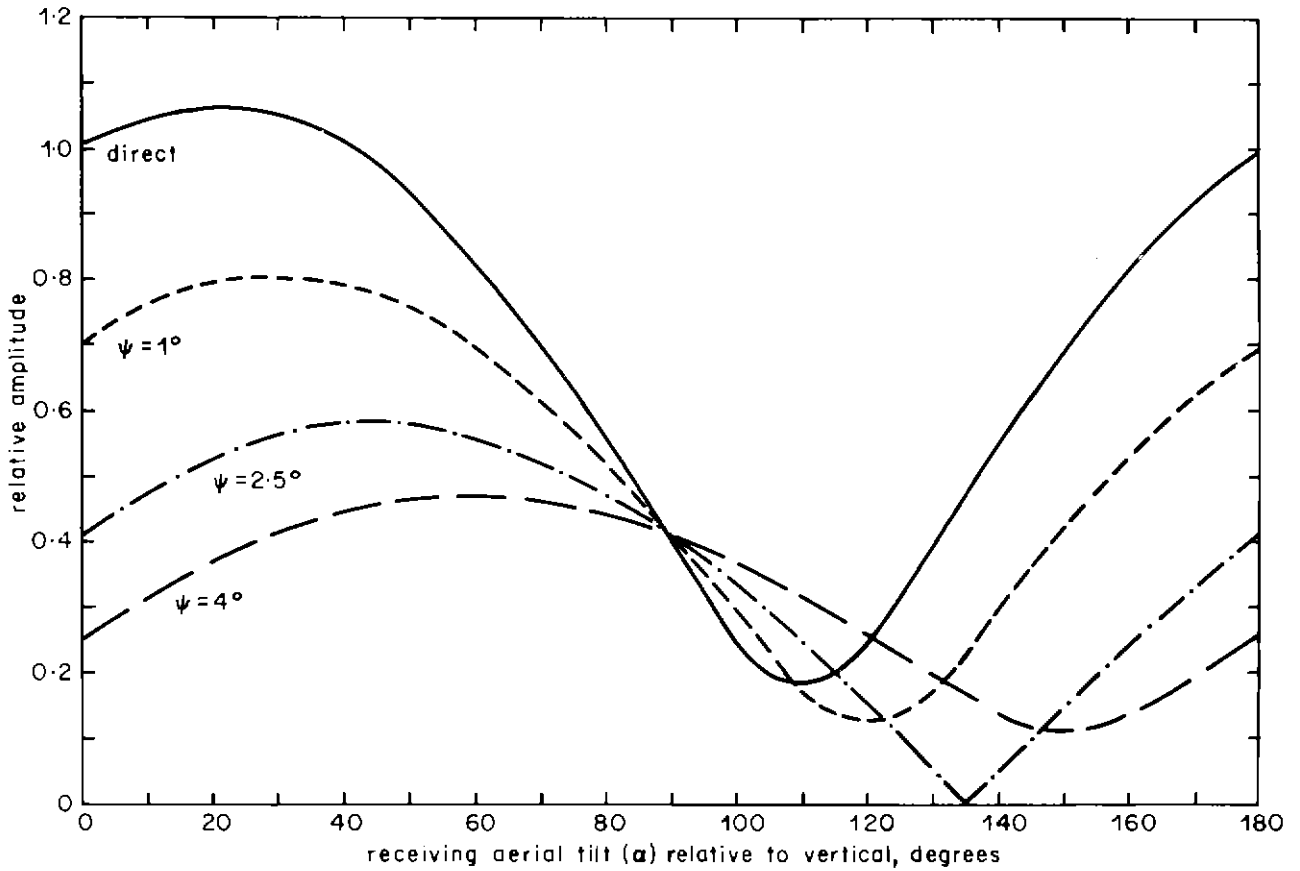
Fig. 6 Elliptical polarisation: variation of amplitudes of direct and sea-reflected components with receiving aerial tilt (α) relative to vertical for various values of grazing angle (ψ). Rejection angle $(\psi_o) = 2.5°$
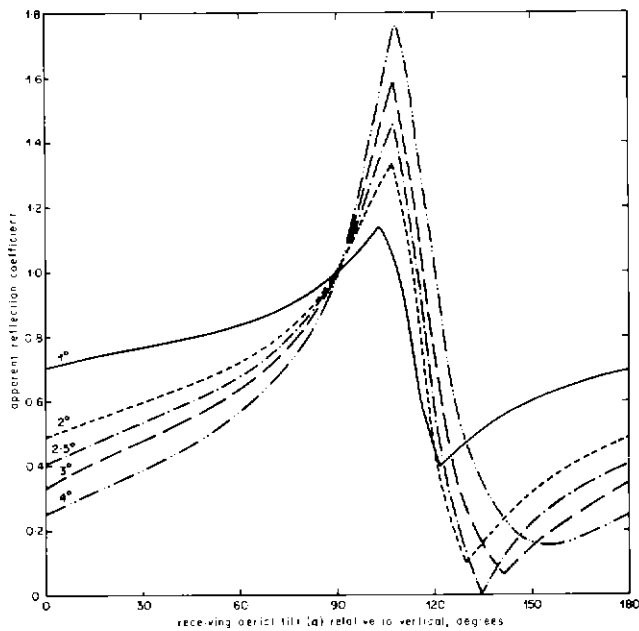

Fig. 7 Elliptical polarisation: variation of apparent reflection coefficient of sea water with receiving aerial tilt (α) relative to vertical for various values of grazing angle (ψ) Rejection angle $(\psi_o) \, 2.5°$

shows the variation of E_d/E_o with $\alpha_o = 135°$ for values of ψ between $0.5°$ and $5°$.

It should be noted that if a phase reversal of one component occurs, the value of α_o changes from $135°$ to $45°$. A phase reversal could be caused by physical inversion of a radiating element and it would be necessary to resolve this ambiguity by measuring the radiated h.p./v.p. amplitude and phase relationships.

Fig. 6 shows the variation of amplitude of the direct and reflected components against receiving aerial tilt (α) for $\psi_o = 2.5$ and $\alpha_o = 135°$. Fig. 7 shows the variation of apparent reflection coefficient against α for the same conditions as Fig. 6. It will be noted that for $\psi \neq \psi_o$, the minimum apparent reflection coefficient occurs at angles other than α_o. For example, if $\psi = 4°$ the value of the apparent reflection coefficient is 0.16 at $\alpha = 155°$ compared with 0.35 at $\alpha = 135°$; a further advantage obtained by using $\alpha = 155°$ is an increase of 4.1 dB in the amplitude of the direct component. For broadcasting purposes, viewers could not be expected to tilt their receiving aerials to the optimum angle for rejection of sea-reflected components, but for more specialised purposes such as re-broadcast links the use of tilted receiving aerials at angles other than α_o could be advantageous.

Contributors to this issue

John Gregory joined Brimar Valves as a trainee process engineer upon leaving Chislehurst and Sidcup Grammar School. He served in the Royal Air Force as a wireless operator and later joined Thermionic Products Limited as a magnetic recording engineer. He joined the BBC in 1951 as a technical assistant in the Recording Department where, a year later, he became a recording maintenance engineer. Since 1957 he has been in the Studio Capital Projects Department, where he has been mainly concerned with the design, installation and commissioning of studio control rooms.

Philip Laven joined the BBC in 1966, working at the Skelton h.f. transmitting station. Since 1968 he has been with the Service Planning Section of Research Department, where he has been involved in v.h.f. and u.h.f. transmitter-site tests and service area measurements. He has also been concerned with the problems of u.h.f. reception where his work has included investigations of fading on short sea paths and the use of elliptical polarisation to reduce this fading. Recently his work has been concerned with preparations for the l.f./m.f. broadcasting conference held in October/November 1975. He has also been involved in the development of computer programs for the production of digital maps of the world and their application to planning broadcasting services.

L. Richardson joined the BBC in 1943 and served at a number of transmitting stations. He moved to the Research Department in 1949 and was involved in the early experimental work which preceded the adoption of the present-day television line standards and the origination of video signals from studio and film sources for subsequent transmission in colour using the present-day television standards. He was appointed to the post of Engineer-in-Charge of the BBC's External Services Studio Centre at Bush House, London, in 1964 and to his present post in 1970. In this capacity he is responsible for the operations and maintenance of the studio centre dealing with the origination, assembly and distribution of network programme material for transmission overseas via the h.f., m.f. and v.h.f. transmitters of the BBC External Services.
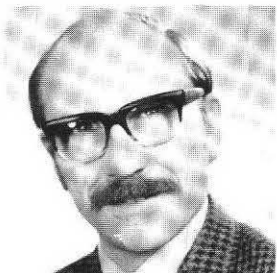
John Riley graduated in Electrical Engineering at Leeds University and a year later took an M.Sc. in microelectronics at Southampton University. After a 2-year teaching appointment overseas, Mr Riley joined Research Department in 1970 and has spent most of his time with Transmitters and Propagation Section of Radio Frequency Group. He has been chiefly concerned with u.h.f. aerial design and the development of the u.h.f. relay station programme.

Robert Thoday joined the BBC in 1952 and after working for a period in Operations & Maintenance (Transmitters) he transferred to Research Department in 1955. Since then he has been mainly concerned with the design and development of v.h.f. Television and F.M. sound transmitting aerials. Other activities in which he has been involved are the design of aerials and measuring equipment meeting special requirements in broadcasting.