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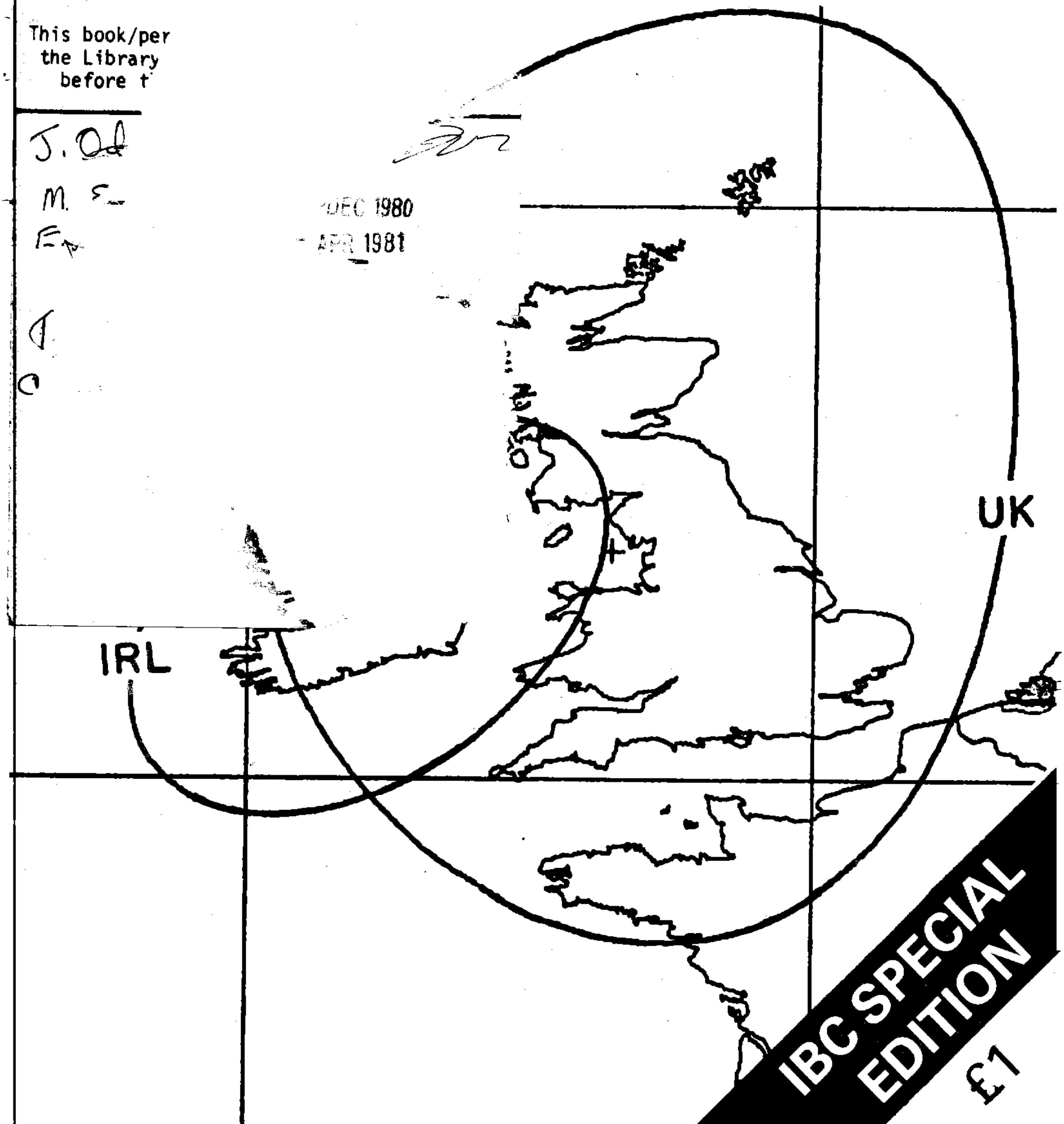

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Contents

The 1977 Broadcasting Satellite Conference in Geneva drew up a Plan for the development of satellite broadcasting in Regions 1 and 3. Under this plan geo-stationary satellites at 31°W would provide good reception in the areas indicated on the cover. Broadcasting direct from satellite to viewer is discussed in the article starting on page 3.

BBC Engineering: Final Edition

Foreword

I am sorry to have to say that this edition of BBC Engineering must be the last to be published for some time. Financial constraints have forced the BBC to cut back on many things which, although desirable and worthwhile, are not immediately essential in our prime business of making Radio and Television programmes.

I have certainly regarded BBC Engineering as a worthwhile effort and so, I believe, has its readership. We must look forward to the time when current austerity can be eased and some of our curtailed activities restored. In the meantime, I should like to thank our regular subscribers for their past support and, of course, the contributors and editors who made BBC Engineering worth supporting.

Director of Engineering

Direct Broadcasting by Satellite for the United Kingdom

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Summary: After giving details of the 1977 ITU Plan for direct broadcasting by satellite as it affects European countries, this article describes some of the technical requirements of satellites and receiving systems.

Work in other countries and future possibilities are considered next and, after a brief discussion of the types of programme which are envisaged in the United Kingdom, the BBC's proposals for establishing an introductory service are set out.

1 Introduction

We are in the decade of a new method of transmitting broadcast programmes – television and sound – into the home. The transmitter is placed in an orbit above the equator at a height of 36,000 km so that it moves round at the same rate as the Earth spins on its axis and thus remains at a fixed point in the sky. Doubts on the one hand and over-optimism on the other hand existed in the early seventies. Now, however, three points seem to be established: experiments have proved it works as expected; costs can be assessed and appear acceptable and, finally, it is increasingly appreciated that (whatever other methods of distribution, such as optical-fibre cable, may become available in the nineties or beyond) it is a method of distribution that comes closer to the ideal concept of broadcasting than any other method. There is surely an elegant simplicity in a transmitter of about 100 watts being able to provide a television programme to any home within a moderately-sized country provided there is access to a simple receiving system in line-of-sight from the satellite.

The cost of a broadcasting satellite is falling and by comparison the cost of terrestrial broadcasting is increasing, so if there is a need for a new national service, it should be provided by satellite. Unfortunately, the lead time necessary before a satellite broadcasting service can be launched is very long. Thus to make a decision today means that we must predict future trends and extrapolate existing evidence.

We see growing evidence of new opportunties and an awakening of public demand for new broadcasting services and it is clear that the more advanced nations of this world have already recognized this and made firm plans to provide a number of new broadcasting services.

It is the view of the British Broadcasting Corporation that plans should now be made to provide a national broadcasting service using a Direct Broadcasting Satellite (DBS) in the 12 GHz band and that the BBC has a vital role to play in such a service.

The BBC considers that there is both the opportunity and the potential demand for two new UK services. Satellite broadcasting has the inherent ability to provide national coverage, and it seems appropriate to take the first steps towards a consistent overall plan for television broadcasting by providing a new BBC national public broadcasting service using this medium. We believe there is a case for a second service, different in character, which we describe as Subscription Television. When established this would make a small but not insignificant profit which would help to support public service broadcasting.

We also believe that the possibility of new Radio services should not be neglected.

The opportunity to provide new services, the public demand, the potential to provide these services and the cost to the broadcaster and the public are all factors in the decision to provide a Direct Satellite Broadcasting Service.

There are already overseas plans for direct satellite broadcasting in France, Germany[1], Italy and the Scandinavian countries[2] (Norway, Sweden, Denmark, Finland and Iceland). Plans are also well advanced in Japan, Canada and the USA. The precise form of this broadcasting differs from nation to nation. In some it takes the form of public service broadcasting; in others there are plans for commercial television, Pay-TV or educational services. The possibility of new sound services is not ignored and both Germany and Scandinavia have made outline proposals.

There is also positive interest in satellite broadcasting in Luxembourg and there is awakening interest in Spain, Portugal and a number of other countries.

This article outlines the framework set by the 1977 ITU Plan for broadcasting in the 12 GHz microwave band and reviews, in a general way, the technology available and under development to implement satellite broadcasting systems. It concludes with the BBC's proposals for establishing satellite broadcasting services in the United Kingdom.

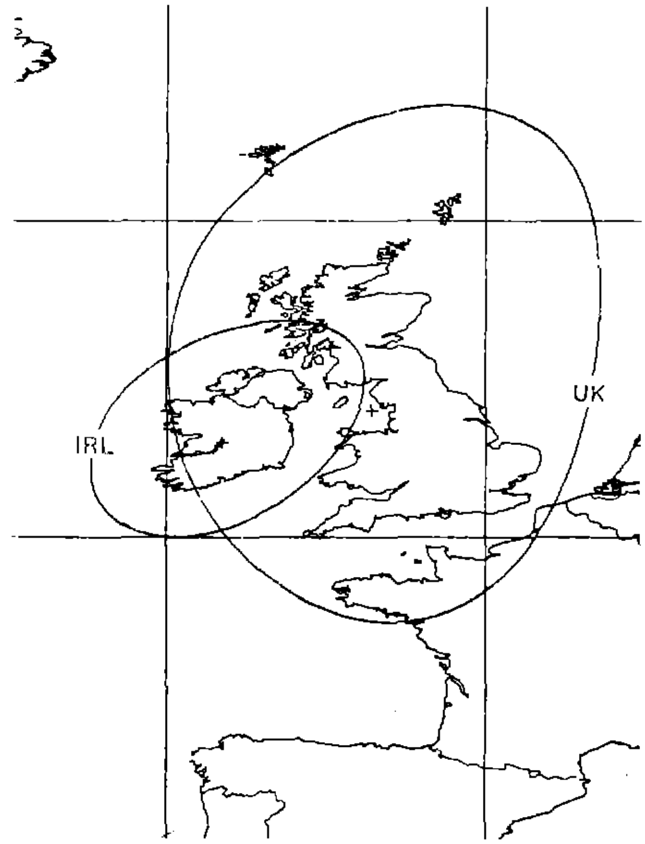

Fig. 1(a) Coverage areas for individual reception in the United Kingdom and Ireland.

2 ITU Plan for the 12 GHz band

The Broadcasting Satellite Conference, held in Geneva 1977, agreed a Plan for ITU Region 1 (Europe/USSR/Africa) and Region 3 (Asia/Australasia), in which orbit positions and frequencies were assigned to prescribed beams covering each country (or sub-division of a large country). This Plan will not only ensure the orderly development of satellite broadcasting itself, but will also help to avoid mutual interference problems with other services using the same frequency band, notably terrestrial microwave links. With a few exceptions, every country in Europe and Africa was assigned five frequency channels within the 11·7 to 12·5 GHz range. Polarisation (circular, clockwise or anticlockwise) was also specified. Each channel is suitable for a frequency-modulated television signal within a 27 MHz bandwidth; the actual channel spacing was about 19·2 MHz, giving 40 channels in all, but possible adjacent-channel as well as co-channel interference was allowed for in the Plan. A Regional Conference to conduct a similar assignment Plan for Region 2 (Americas) is scheduled to take place in 1983.

In the 1977 Plan, a power was also specified for each transmission derived on the basis of providing a flux of at least −103dB (W/m^2), sufficient for good reception with an individual 0·9 m diameter antenna, for 99% of time in the worst month. Figure 1(a) gives the areas of coverage to this standard for the UK and Ireland. Figure 1(b) gives some examples of coverage on the same basis for other cases: France, Germany, Luxembourg, Monaco and the large beam that was allowed on certain channels to cover the four Nordic countries as a group. These figures assume ideal pointing of the satellite antenna; it is seen the coverage areas allow some latitude for pointing error (0·1° maximum is assumed). Considerable overlaps occur: for example, the French beam covers southern England, Switzerland and northern Italy.

It may also be of interest to indicate over what area it is possible to receive a satisfactory signal with a somewhat larger receiving antenna. For convenience we can take the −111dB (W/m^2) limit corresponding to the level indicated at the 1977 Conference for reasonably noise-free community reception; this is illustrated in figures 2(a) and (b) for the same countries. In some areas this coverage may not extend to the limits shown because interference from other satellites, while planned to be negligible for individual reception within the country to which the transmissions are aimed, may be slightly disturbing near the limit shown for community reception.

A summary of the nature of the allocations for all countries in Western Europe is given in Table 1. Where possible, a definite request by a country to have the same orbit position as another country was met in the Plan; this facilitates individual reception of transmissions of two or more neighbouring countries in border areas, where there may be common interests, cultures or language.

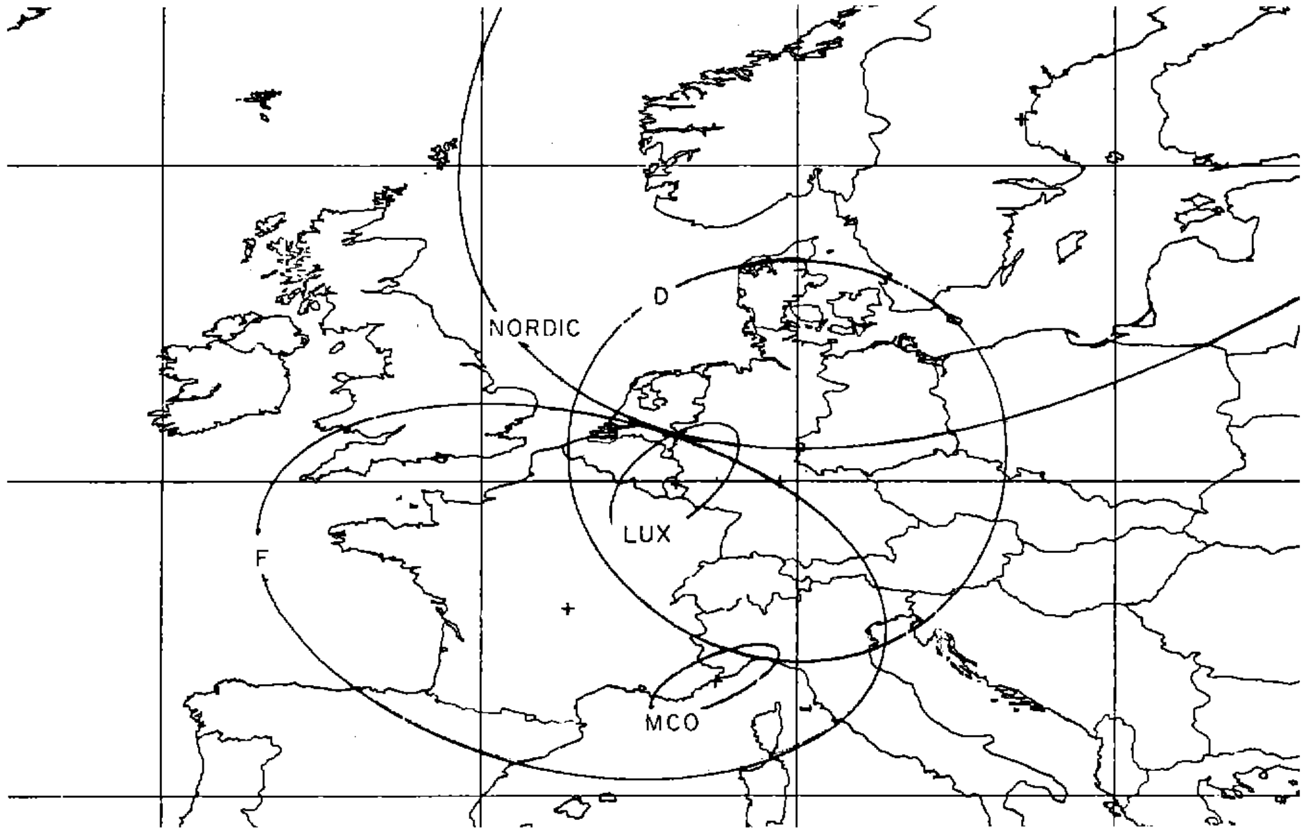

Fig. 1(b) Coverage areas for individual reception in France, Germany, Luxembourg, Monaco and the Nordic group.

TABLE 1
Channel assignments and orbit positions for countries of Western and Southern Europe

Orbit position	37° West	31° West	19° West	5° East
Lower half (11.7-12.1 GHz) Right-hand polarisation	San Marino 1, 5, 9, 13, 17 Lichtenstein 3, 7, 11, 15, 19	Ireland 2, 6, 10, 14, 18 United Kingdom 4, 8, 12, 16, 20	France 1, 5, 9, 13, 17 Luxembourg 3, 7, 11, 15, 19	Turkey 1, 5, 9, 13, 17 Greece 3, 7, 11, 15, 19
Upper half (12.1-12.5 GHz) Right-hand polarisation	Monaco 21, 25, 29, 33, 37 Vatican[1] 23, 27, 31, 35, 39		Belgium 21, 25, 29, 33, 37 Netherlands 23, 27, 31, 35, 39	Cyprus 21, 25, 29, 33, 37 Iceland[2] 23, 27, 31, 35, 39
Lower half (11.7-12.1 GHz) Left-hand polarisation	Andorra 4, 8, 12, 16, 20	Portugal[3] 3, 7, 11, 15, 19	West Germany 2, 6, 10, 14, 18 Austria 4, 8, 12, 16, 20	Finland 2, 6, 10 Norway 14, 18 Sweden 4, 8 Denmark 12, 16, 20
Upper half (12.1-12.5 GHz) Left-hand polarisation		Iceland 21, 25, 29, 33, 37 Spain[5] 23, 27, 31, 35, 39	Switzerland 22, 26, 30, 34, 38 Italy 24, 28, 32, 36, 40	Nordic[4] 22, 24, 26 28, 30, 32, 36, 40 Sweden 34 Norway 38

Notes:

(1) 0.6 degree beam except channel 23 which covers mainland Italy.
(2) Covers Iceland, Azores and part of Greenland. Channels 27 and 35 registered under Denmark.
(3) Same transmission channels also beamed to Azores (common programme).
(4) Eight channels in a wide beam covering Nordic countries; assigned to Finland (22, 26), Sweden (30, 40), Denmark (24, 36) and Norway (28, 32).
(5) Same transmission channels also beamed to Canary Islands (common programme).

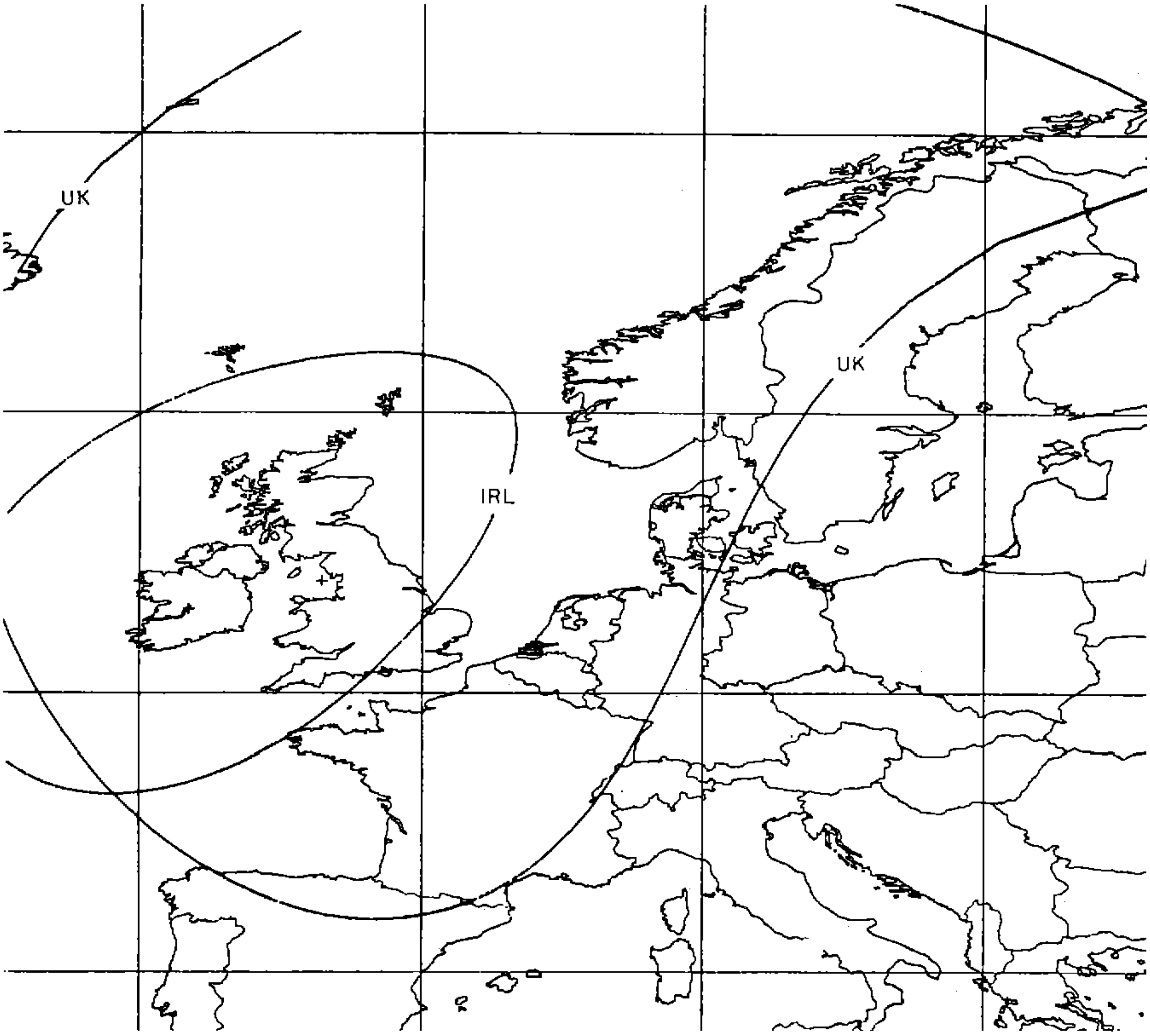

Fig. 2(a) Coverage for community reception in the United Kingdom and Ireland

In order to bring out the factors which affect the ease of reception in any country of transmissions other than those intended for that country, the table distinguishes groups of channels according to polarisation and whether they are in the upper or lower half of the 11·7 to 12·5 GHz band.

3 Satellites

Transmitters in the sky are no new thing. We have employed geo-stationary satellites for more than a decade to relay telephone traffic and television signals between continents. The powers of the transmitters on satellites for this purpose are generally below 20 watts; they also beam their signals over large areas. As a result a very large receiving antenna is required on the ground (e.g. a 30 m diameter reflector to receive 4 GHz signals) in such point-to-point links.

For broadcasting, the available transmitter power is concentrated by beaming over the limited coverage areas, typically with a beamwidth of one degree for many European countries. A power of the order of 100-200 W is then sufficient for individual reception with an antenna diameter of 0·9 m. The experiments in Canada and USA since 1976, with the CTS (Hermes satellite)[3], have come closest to this concept and successfully demonstrated television reception with small terminals. The satellite employs a 200 W repeater at 12 GHz and the beam is about 2·5 degrees wide.

Two important points govern the costs of satellite systems. Firstly the reliability should be as high as that from current terrestrial services and secondly, the satellite should remain accurately in its allocated position so that individual receiving antennae set up in fixed positions, pointing to the satellite, will remain effective. Because of orbit-perturbing forces, station-keeping requires fairly frequent correction by gas jets on the satellite, and the quantity of fuel to operate these is the critical factor which governs its life. A

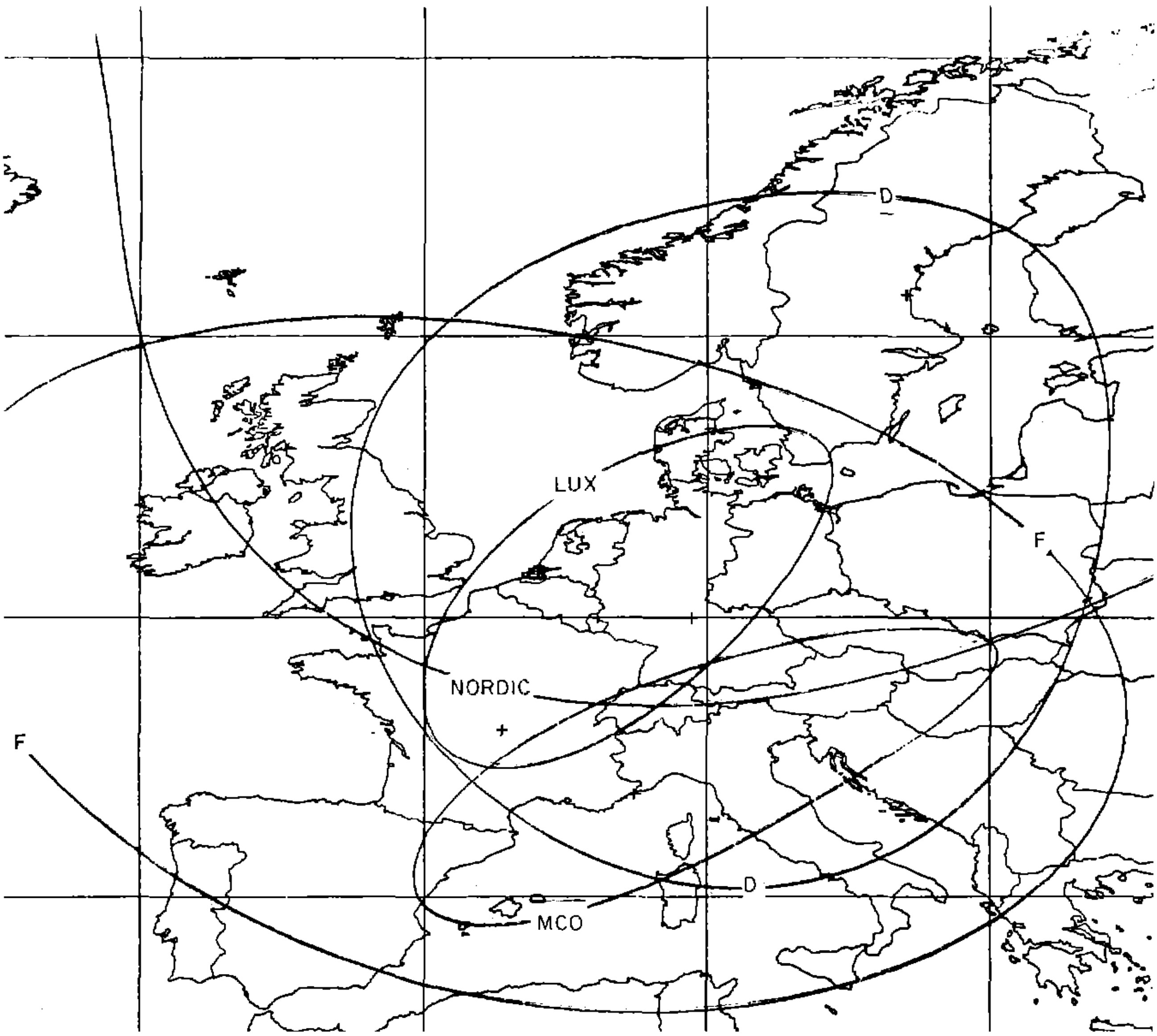

Fig. 2(b) Coverage for community reception in the same countries as in Fig. 1(b).

seven-year life is typical if a reasonable allocation of payload between the fuel and other essential items is made. Thus a service fully guaranteed at all times requires a spare satellite in orbit and a third ready to be launched at any time and it is evident that the cost of making and launching a single satellite is not sufficient investment to provide a service for 10 or 20 years. For example, for 10 years' reliable service, allowance must be made for the provision and launching of 5 satellites. However, at the opening of a new service it could be regarded as a secondary service where the occasional temporary break in transmission could be acceptable. This service could be provided using many less satellites.

Nevertheless the cost is actually less than total engineering cost to the broadcasters of providing a national service at UHF by terrestrial transmitters. Of course, an overall national picture, taking into account the receiver cost, would show a somewhat greater total cost for a satellite system. National decisions to implement satellite broadcasting will have to take into account total cost but, if broadcasters' costs are not prohibitive, it is reasonable to expect that steady development in receiver technology will provide receivers at a price acceptable to a steadily increasing proportion of the public.

4 The receiving system

4.1 Antenna position and size

For terrestrial television we are used to aerials which range from little more than the proverbial 'wet string' near transmitters to large Yagis at the fringe which usually need mounting high up to get good signals.

Receiving antennae for domestic reception of satellite broadcasting signals, however, are uniformly sized because everyone will get a flux within the narrow limits of −100 to

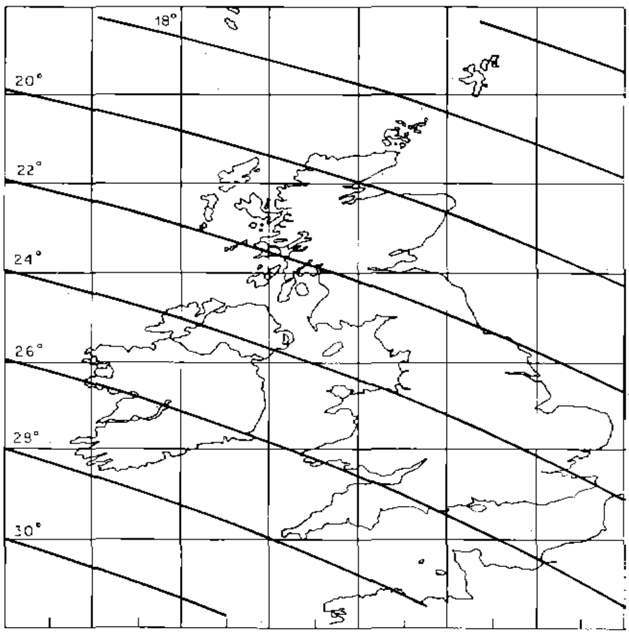

Fig. 3 Angle of elevation of UK satellite at 31°W (Geneva 1977 Plan).

−103dB(W/m²) according to the standard mentioned already. Also, the 12 GHz signals are such that a clear line-of-sight is usually essential, but with the angles of arrival of satellite signals for the UK as shown in figure 3, almost everyone can find somewhere on his premises that meets the requirement. This has in fact already been confirmed[4] by asking the occupiers of several hundred houses to observe shadows when the sun was shining at 3 pm British Summer Time in mid-October – this being a time when the sun has the same position in the sky for the UK as the assigned satellite position. The limited sample suggested that suitable sites for antennae could be found in 99·5% of cases. Furthermore, in many, but not all, cases the most suitable site is low on the side of the house or on the ground rather than at roof level.

The requirements of a 0·9 m diameter antenna is not a precise one. It depends on receiver noise performance, the available signal flux and the importance attached to a low-noise signal. As a guide, with the suggested antenna size, 8dB noise figure gives 14dB carrier-to-noise and a slightly noisy picture when the flux is just −103dB (W/m²). Manufacturers' developments now suggest that noise figures of 5dB with a mixer first stage, or 4dB with a FET amplifier, will be obtainable at modest cost. Some allowance for pointing error and reduced antenna efficiency should be borne in mind when considering the likely performance of domestic equipment over a period of several years.

4.2 Antenna beamwidth and satellite position

In order to exploit extensive frequency re-use in the 1977 Plan, advantage was taken of the directivity of receiving antennae, corresponding to a 2 degree beamwidth (at −3dB) for a 0·9 m dish. Antennae lined up on one satellite position have a poor response to signals from neighbouring positions. The Plan uses 6 degree spacing between adjacent allocated orbit positions, and at 6, 12 and 18 degrees respectively the antenna responses are assumed to be 20, 28 and 33 dB below the maximum. Furthermore it is assumed that in the direction of maximum response (i.e. for the same orbit position) the response to a signal with a polarisation opposite to that of the wanted signal is 20dB down. It is thus clear that an antenna, when set up for one orbit position, cannot be used by the viewer to receive from another. Receiver requirements are considered next, but clearly where a viewer in the UK wishes to receive transmissions planned for France or vice-versa, a first essential is either to have two antennae, or one that can be rocked between two carefully set-up aiming positions. Possibly, if there is a demand, some neater arrangement such as a single reflector with two feeds will be designed.

4.3 The receiver

It is a reasonable assumption that not many people will accept two television receivers in their living room. Equally, it appears to be a reasonable assumption that whatever the attraction of satellite broadcasting, people will wish to continue to receive terrestrial broadcasting. Thus, at the very least, the set will contain equipment which permits the reception of the 625-line PAL signal on the UK standard, System I. To save money many people will initially purchase converters for existing 625-line television receivers. In its most elementary form this converter will consist of an aerial unit with a frequency changer which feeds a signal down to the receiver in the conventional Band IV or V UHF form. This means that this signal must have the same radio frequency spectrum with the sound signal at the same point as that which occurs in our normal terrestrial broadcasting. If the assumptions made so far are correct, this basic form of converter will not permit 'off-air' domestic reception of sound and vision signals from any other station in Europe (regardless of the orbital position or the frequency or polarization assigned to the transmitting satellite) because the vision-to-sound carrier separation is different. Cable operators will, of course, have no such limitations and it is technically easy to have appropriate receivers which will provide audiences with compatible signals.

However, there are many proposals to introduce new television sound and radio services. Most of them describe a converter which has a separate sound output (either as a Band II or a baseband signal). If this type of converter is manufactured it will open the door to domestic reception of all PAL-system signals.

Alternatively, if we have multi-standard receivers similar to those available in Belgium today, reception of all overseas programmes will also be possible.

The Plan, as seen from Table 1, calls for a tuning range of 400 MHz to receive all channels of any one country, although it can be foreseen that, when several countries have begun using most of their channels, there will be some demand for means of receiving over the full 800 MHz band. Considering the basic 400 MHz receiving system first, it might well be as outlined in Fig. 4. A down-converter to 900-1300 MHz is placed on, or adjacent to, the aerial and employs a fixed-tuned oscillator, and avoids a microwave

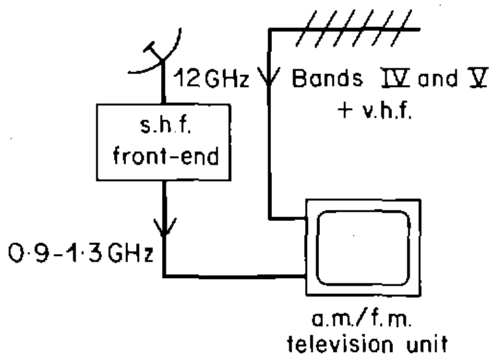

Fig. 4 Simple receiving system with an am/fm television receiving unit.

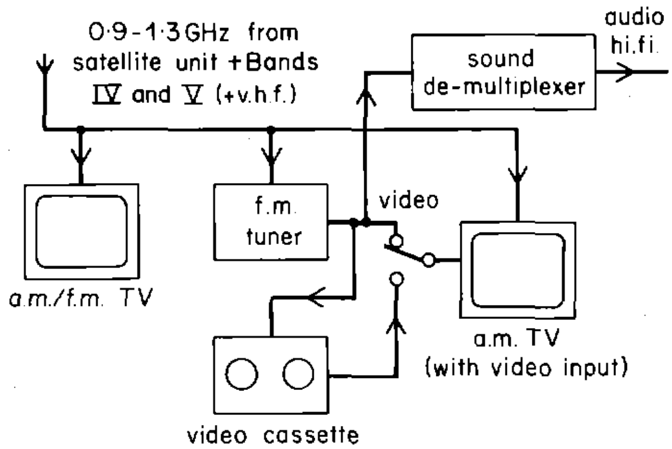

Fig. 5 Possible developments for unit video and unit audio in the home.

down-lead (which would be either lossy or expensive) but leaves the actual tuning in the room set. Secondly, terrestrial television must continue to be catered for since, in the foreseeable future, this would continue as the most practical system for television networks giving regional or local programme variations. Thirdly an fm/am converter is not featured. Rather, the early appearance of sets with dual tuners, (i.e. am/fm television receivers), is to be encouraged if the benefit from the picture quality with direct fm demodulation is to be obtained. (An fm/am unit demodulating and remodulating for feeding a conventional television receiver, would have three intermediate frequencies with a change to base-band, i.e. a quadruple superhet; this could be prone to interference and suffer am system distortion).

The basic set-up in the home of the future could well expand somewhat on this modest start as Fig 5 shows. The system now extends the distribution of the 900-1300 MHz signals to more than one room. The one containing audio hi-fi/radio equipment now uses an am television receiver with a video input facility, and a separate fm-to-video tuner so that interplay with the video cassette and television set is possible. The possibility of a digital sound multiplex in place of television on one of the satellite channels has also been anticipated. The assumption in this example is that the digital sound signal would be approximately within the normal video bandwidth and would frequency-modulate the transmission in the same way as for television.

A receiver for the international viewer can be considered with reference to Table 1. Here the situation may vary. Certain pairs of countries (UK and Ireland, France and Belgium, West Germany and Austria, for example) need no more than the basic receiver to see each other's programmes. In other cases the neighbour might have the other half of the 800 MHz band, different polarisation, or both. A receiver to tune over 800 MHz would be very convenient but could be difficult to design on the basis of a fixed oscillator and extending the range of the first intermediate frequency to 900-1700 MHz. A simple alternative is suggested. If the basic 400 MHz units have a wide market and therefore reasonable cost, two such units could be attached to the antenna with two down-leads, each carrying 900-1300 MHz, one for each half of the band. The receiver would have two input sockets and a two-way selector switch.

To change polarisation, a remotely-controlled, switched-polarisation feed could be fitted at the antenna. However, with more than one television set in the home, this solution could frustrate independent choice of viewing. An alternative would be an 'orthogonal feed' from which the left- and right-handed polarisations could be simultaneously connected to two basic first frequency-changers, again using two down-leads. Elaborating further, some 19°W satellite viewers in favourable locations might want to receive most or all of the eight European national services. They would require four 400 MHz units and four down-leads in order to cover both polarisations over an 800 MHz bandwidth.

To complete the picture on the receiver design the UHF tuner must be considered. This will select channels within the first i.f. range and the conventional approach would be to have a second, tunable, frequency-changer and a final i.f. in the region of 125 MHz. Image rejection would be necessary in this tuner. A surface-acoustic-wave filter could be a good choice for the i.f. filter in front of the fm discriminator which requires to operate over a 27 MHz bandwidth with low group-delay distortion. A less conventional approach, under study in France, is a phase-locked-loop fm demodulator which can operate directly on the required signal in the 900-1300 MHz band and provide a video output directly.

The method of transmitting the television sound component in satellite broadcasting is under active study by the European Broadcasting Union. Although the starting point in 1977 was to consider an fm subcarrier compatible with the terrestrial system (e.g. a 6 MHz subcarrier in the case of television Standard I, as used in the UK) serious consideration is being given to alternatives for enhancing the system to provide a pair of channels for stereo or second language. Digital modulation for the sound signal, which could give better quality and higher signal-to-noise ratio than is possible with analogue systems, is also being considered.

5 Feeder links (Up-links)

The system envisaged for a broadcasting satellite system is that a signal modulated to exactly the same standard as the downcoming transmission should be sent up to the satellite. This allows the satellite to be designed as a frequency-translating relay. The detailed assignments, or even the choice of the frequency band, for the up-links or feeder links were not dealt with at the 1977 Conference because priority was given to attaining an agreed down-link plan. Studies having established that a bandwidth at least as great as the down-link broadcasting band would be essential, the 1979 World Administrative Radio Conference was able to allocate for world-wide use the band 17·3 to 18·1 GHz for feeder links to broadcasting satellites transmitting in the 12 GHz band. In limited geographical areas, alternative frequencies have also been allocated for feeder link use, if required, including the 10·7 to 11·7 GHz band in the European area.

Although interim arrangements can easily be made at early stages when the band is relatively uncrowded, it is agreed that a detailed assignment plan for feeder links should be made and the expectation in the case of Regions 1 and 3 is that the frequency channelling and assignments could, as a starting point, be a carbon copy of the down-link plan translated from 11·7-12·5 GHz to 17·3-18·1 GHz. One advantage would be a constant frequency change of 5·6 GHz for all transponders, which would lead to some economies in design. If changes or adjustments had to be made to the assigned frequencies, they could be made without enormous repercussions (as would be the case in attempting to change the closely interwoven down-link plan). This is because up-link antennae at Earth stations are expected to be so directional that the choice of frequencies for transmissions aimed at one satellite would have little effect on the choice for transmissions aimed at other orbital positions. The main task is to agree on a series of mini-plans, each acceptable to a group of countries assigned to one orbit position, but with an overall check on the effect on other orbit positions. The ITU Conference to be held in 1983 for planning down-links in Region 2 will also be asked to consider detailed feeder link planning for the same region. It is not yet decided whether the conference needed for feeder link assignments in Regions 1 and 3 will take place at the same time or later.

6 Developments in Europe and elsewhere on satellite broadcasting

There are a number of satellite broadcasting projects under discussion in Europe. An outline of present proposals is given but details may, of course, be modified in the course of finalization.

6.1 European Space Agency 'L-SAT'

This project is for a large satellite, to be launched by Ariane-3 in the first quarter of 1984, to carry transponders for a number of different applications including two for pre-operational use in satellite broadcasting.[5] Other transponders will permit trials on business-system communications (up-link in 14 to 14·5 GHz band, down-link in 12·5 to 12·75 GHz Band) as well as propagation and wide-band data-link studies in the 30 GHz (up-link) and 20 GHz (down-link) bands. The precise details for the two 12 GHz broadcasting beams are still to be finalised but one beam is likely to be elliptical (approximately 1 by 2·4 degrees), carrying channel 24 with left-hand polarisation to correspond with one of the Italian assignments, and the other a circular beam (1·6 degrees wide) which may carry channel 20 or 28, probably with the opposite polarisation. The intention, for the first three years at least, is to take advantage of the fact that either beam can be independently steered to cover any European country, so that satellite broadcasting demonstrations and pre-operational experience can be obtained on a time-sharing basis. Most of the experiments are likely to take place with the satellite at the 19° West orbit position. Consideration is being given, however, to operation for extended periods at 31° West and 5° East as may be required to provide pre-operational test transmissions to match plans in the UK, Spain and Scandinavia for operating their own broadcasting satellites in the second half of the decade. The use of the satellite towards the end of its seven-year life is uncertain but Italy has made a strong bid to use it as a starting satellite for its service on two channels until replaced by a purpose-built operational satellite.

The UK has made the largest single contribution so far to the L-SAT project in terms of money and corresponding contracts. At least seven other countries are giving support, notably Italy and the Netherlands. British Aerospace has been selected as principal contractor. The decision in implementing L-SAT will be taken at the end of 1980 following completion of the definition/design stages now in progress.

6.2 French and German satellites

France and Germany withdrew their support for L-SAT in 1979 and agreed that they would co-operate in building two satellites, one for each country, each capable of transmitting on three channels. The satellites themselves would be built by Messerschmitt-Bölkow-Blohm in Germany in co-operation with Aerospatiale in France; they are intended to be launched by the Ariane launcher, which is largely a French development, though carried out within the framework of the ESA. Present plans are working towards a launch of the German satellite in December 1983 and the French one in June 1984. The German satellite will operate on channels 6, 10 and 14, and the intention is that two channels will carry television and the third a multiplex of sound programmes using digital modulation. The details for France are not finalised.

6.3 NORDSAT Project

As indicated earlier, the four Nordic countries are in the privileged position of having secured eight channels in the 1977 Plan within a beam whose coverage embraces Norway, Sweden, Denmark and Finland. NORDSAT is the joint body set up both to exploit this beam and to include transmissions for Iceland, Faroes and Greenland, the project being based on the use of a satellite at 5° East. The intention is to relay the various national television programmes throughout the whole group of countries. For the four major countries eight programmes could be relayed and for the Icelandic beam the assignments permit five. The participants wish to include sound programmes but are reluctant to forgo one television channel by dedicating one channel to a sound multiplex (as proposed in Germany). They wish to develop suitable means for adding several sound channels to the television channel to cater for a stereo pair for television, extra language channels connected with the television programme, and additional channels for sound programmes not associated with the television programme. While this is considered feasible, considerable experimentation and international discussion will be needed before the most practical and economic solution can be achieved, preferably with a common standard with other European countries, at least for the method of sending the main sound component of the television programme. Experiments with OTS (Orbital Test Satellite) have already shown that a digital subcarrier for 2, 4 or 6 audio channels may be one way of contributing to the needs and, as already mentioned in Section 4, there is interest in Europe generally in improving and extending television sound transmission methods. Another avenue to be explored is a digital sound signal in the video waveform within the line-blanking period (a development of the principle used in the Sound-in-Syncs system developed by the BBC for video links in the UK and for Eurovision) but the system would be dependent upon a practical decoder for domestic receivers.

6.4 Other countries

The only other European country that has been reported as actively investigating satellite broadcasting is Luxembourg which would clearly have a sizeable audience for commercial French, Dutch and German programmes in the area of good individual (domestic) reception extending some 200 to 300 km around Luxembourg. Transmissions from French and German satellites from the same assigned orbit position of 19° West would ensure the installation of suitable receivers; in particular, Table 1 shows that those equipped for the French satellite would already have the correct polarisation and half-band for Luxembourg's channels. The limited size of the Luxembourg beam makes direct broadcasting to any part of the UK impractical in terms of individual reception; even in the extreme south-east of England a 2 to 3 m diameter aerial would be required for reception, so a commercial audience is unlikely, unless re-distribution of programmes by cable becomes legally and economically acceptable.

Finally, in addition to the US/Canadian CTS experiments mentioned in Section 3, a demonstration of satellite broadcasting outside Europe has also been successfully accomplished in Japan with a 100 W transponder in the 12 GHz band[6].

7 Current investigations and future possibilities

Here we should perhaps air some of the uncertainties and some of the future developments on the subject of satellite broadcasting. One of the concerns has been possible interference. For example the image frequency or i.f. may correspond to radar or air radionavigation systems of significant power, and second thoughts may be needed on the preferred i.f. and whether to have the local oscillator frequency above or below the signal frequency. A more difficult problem may be harmonic radiation from microwave ovens since, by the end of the decade, both these and satellite receivers are likely to be in close proximity in residential areas. The fifth harmonic of ovens nominally on 2·45 GHz may be the main concern, and could affect reception in the upper half of the 11·7 to 12·5 GHz band. Of course, all the interference mechanisms mentioned have been studied theoretically but, as in many interference problems, practical experience will be necessary to see whether the assumptions are valid. First examination suggests that careful design of the receiving system will be needed to avoid problems with the known levels of signals from potential interfering sources.

Another topic not mentioned so far is that satellite television signals are required to have added to their video waveform, an 'energy dispersal' signal such as a 25 Hz triangular (symmetrical) sawtooth, corresponding to 600 kHz peak-to-peak deviation. The dispersal waveform assists in controlling interference to terrestrial systems carrying multichannel telephony and operating in the same band. Its removal from television signals will require additional clamp circuits to avoid picture flicker. The current satellite broadcasting standard for 625-line signals calls for CCIR pre-emphasis, a.c. coupling and the polarity convention used in terrestrial microwave links and satellite point-to-point vision links, but the fm deviation is about 14 MHz – a value higher than terrestrial link practice but below present satellite link video-deviation standards. It is possible that some aspects of these standards (e.g. the video pre-emphasis curve) may be revised to meet any difficulty in applying them for receivers in the home, although present opinion is that they are already close to the optimum.

For sound transmission it has been proposed for the French and German satellites that, besides an analogue subcarrier at 5·5 MHz for the main sound signal, a second analogue subcarrier at 5·746 MHz should be used, either for a second language or to provide a stereo difference signal. To ensure adequate sound quality there are proposals that each subcarrier should deviate the main carrier as much as 5·6 Mhz peak-to-peak and that the fm sound deviation should be increased above the present ±50 kHz value to ±65 kHz or even ultimately to ±100 kHz. Some engineers are concerned about the requirements for i.f. group delay accuracy, video linearity and the careful filtering of the video band that are called for in the domestic receiver to prevent any noticeable degradation (by patterning etc.) of the picture by the presence of the two analogue subcarriers at the proposed level. As a result there is a case for considering a digital sound system of some kind (a single digital subcarrier carrying two audio channels for example) to provide the sound for television from the start of satellite broadcasting. Those preferring this solution feel that, with a lower level of subcarrier, problems of sound or picture quality are more easily resolved and that large-scale-integration (LSI) circuits should ensure that digital demodulation will be cheap and will avoid analogue-circuit alignment problems.

Last, and by no means least in this part of the discussion a few comments should be made on expectations from satellite broadcasting. Some journalists and enthusiasts have pictured satellites as a means for anyone to 'drop in' and receive television programmes from other countries at will, so that when the 1977 Plan did not appear to provide for this, scorn or indignation was expressed at the apparent narrowmindedness of the planners[7]. What must be understood, however, is that there is nowhere near enough frequency spectrum to plan for interference-free direct reception of the 50 or 100 programmes implied. Furthermore there would be political, legal, copyright and advertising problems in widespread international coverage. Within the scope of the 1977 Plan there is nothing to stop shared programmes or joint productions, and pressure from the public should ensure that the broadcasting authorities provide them with what they want. The Plan is perhaps open to criticism because it is a compromise which allows a considerable degree of inevitable overspill between adjoining countries. Perhaps in the next band, at 40·5 to 42·5 GHz (apart from thinking of higher definition, digital video and maybe stereoscopy), we should use large aerial apertures and make sure that beams are tailored to fit each country or part of a country more precisely. This in turn would reduce interference to others, lead to more efficient use of the spectrum, and give more channels for each country.

8 Programme services

Having looked at the technical aspects of direct broadcasting by satellite, we can now consider what types of service could be introduced for the UK.

8.1 BBC and IBA services

Ultimately the total number of new broadcasting services would be limited by the number of broadcast frequencies which have been allotted to the UK. The recent WARC agreement allocated 5 channels to the UK for DBS purposes.

Satellite broadcasting has the inherent ability to provide a national coverage, and it seems appropriate to take the first steps towards a consistent overall plan for broadcasting by providing two BBC national broadcasting services using this medium. It would be a misuse of these resources to duplicate all the existing terrestrial national broadcasting services. On the other hand if satellite broadcasting is to fulfil its potential for national broadcasting there has to be a transition period.

The BBC would wish to devise new services to enrich the cultural life of the country by providing a wider choice of broadcast television, and would be looking for new styles of programming which give a reasonable speed of growth in the satellite receiver market but which also safeguard the existing viewer.

In support of these concepts the following two services are proposed.

A channel for *subscription television*, to include feature films, first runs of special BBC productions, opera, drama, music, and extensions of sporting events, offering a diet sufficiently attractive to promote growth of the service.

A national programme, UK 1, which would

- provide a service, to shift workers in particular but in fact to us all, by retransmitting the best of BBC-1 and BBC-2 in a new form. Television is a transient enough medium, particularly for people too busy to fit their viewing pattern into existing transmission schedules, and the option of alternative times for viewing the stronger programmes would have a very real appeal at relatively low cost.
- provide an alternative service to British Forces in Europe, and indeed to other expatriates, in overspill areas. It would also serve oil rigs and other remote sites.
- in addition it would provide a service to those people who, because of shortage of UHF frequencies, or because of unfortunate geographical location find themselves without a television service.

This service could then evolve into one of the channels relaying main network coverage when it becomes possible to consider deploying the terrestrial network on a more local and regional basis.

In the slightly longer term the IBA would probably wish to have its equivalent to UK 1 on which it would transmit a selection of the two channels under its control.

Regarding radio programme service, the position would clearly be altered significantly were portable and car radio reception ever to become practical. Meanwhile, assuming fixed receiver reception only, possible sound programme services might include high-quality music (utilising the most modern digital recording and transmission techniques), education, and specialised information services.

8.2 Other possibilities for satellite broadcasting

The proposals made so far only account for two of the five possible channels. Given four or five transponders, there are a number of further applications to explore. They include the continuation of prime-time broadcast education, both from the Open University and from the existing Schools and Continuing Education areas, as well as the possibility of more extensive coverage from Eurovision of events and programmes, which either have a limited-language requirement or can be adapted to a UK audience. It is worth noting that the existence of 'spillover' channels from Europe and of deliberate retransmission of European programmes, will promote a greater knowledge of foreign languages.

8.3 Responsibility for any additional programme services and sources from which they could be provided

This country already has two well respected and experienced bodies set up to regulate broadcasting – the BBC and the IBA. To introduce a third would quite possibly weaken the existence of these two and therefore the BBC strongly supports the Home Office view that programme services should be provided by, or under the supervision of, the existing broadcasting authorities. The opportunities of DBS do call for substantial co-operation between all the expert bodies involved and the BBC and the IBA have already been in close contact to establish such co-operation.

It does not follow that the final source of all programme material would necessarily come from these two bodies. We have already referred to Eurovision and to the Open University, and we would expect to draw increasingly on outside sources, freelance producers and other groupings, so that the widest range of talent is available to contribute to the growth of a new system.

Provided that the BBC and IBA operate any new services, then the effect will be largely one of national growth, which will be warmly welcomed. There are sufficient resources to ensure that the new programmes can be produced without impairing the quality of existing programmes.

It is inconceivable that this country will not ultimately fully utilize the frequency resource that is available to it. Past experience has shown that the pressure to entertain, inform and educate will force us to make good use of these new frequencies.

Equally, it is desirable that the BBC fully utilizes its production resources. It has the capacity to produce programmes of appeal to large audiences or small specialist groups. These programmes are sometimes inexpensive but, on other occasions, necessarily of high cost. It is clear that the full range of these programmes cannot be used in a public broadcasting service as currently financed. Increasingly occasions will arise in which a programme is too expensive to be reasonably provided for as part of our normal public service broadcasting or, alternatively, may attract too small an audience to justify inclusion in our programmes. The proposal to provide a subscription television service gives an opportunity to fully use our resources without depriving existing audiences.

National broadcasting is an essential role of the BBC who would not, however, wish to deprive minorities and small groups. Regional or area broadcasting is also an essential part of our output. In the long term, one would see the terrestrial services gradually reprogrammed to give more and more local coverage, and satellite broadcasting taking over the role of the national services. It should, however, be stressed that this process must be extremely slow, and the cessation of national coverage by terrestrial means must await the day when everyone can receive satellite broadcasting, either by their own aerial and receiver or, alternatively, as part of the output from a cable system.

9 Some alternatives for an introductory UK DBS

A UK direct broadcasting satellite service seems practicable by 1985-1987. No new opportunities will appear in 1990 and some of the financial, industrial and broadcasting opportunties will be lost at this later date. However, it may be that for financial reasons we have to introduce only a limited service in 1985-7 and wait until the early 1990s before the full services can be developed.

A direct broadcasting satellite service involves considerable investment by all concerned. At the start of such a service the income will be very small and it will run at a loss. The BBC would not wish this loss to be a charge on the general licence payer and in order to minimise this it is recommended that some of the undermentioned low-cost options should be pursued with vigour.

9.1 OTS

OTS, which was launched in 1978, has been provided essentially to serve as a vehicle for PTT tests preceding the ECS (European Communications Satellite), which is due to come into service as a working system at the beginning of 1983.

OTS, like ECS, is a communication satellite, and has, therefore, not been designed to provide a power flux density sufficient for good reception with an individual 0·9 m diameter antenna. It would probably be satisfactory in this respect, though, for community reception, including operation with cable systems. This could make it of some interest but other limitations are foreseen. It has not so far been possible to investigate all these fully, but they are discussed further below.

If OTS served a pre-operational role for, say, one year before the start of full service, this implies that it would be required some time in the period of, say, 1984-86. It would then be 6-8 years old, and doubt must be expressed about its reliability. However, it would appear to be economic in gas fuel (its limiting resource).

OTS and ECS use up- and down-link frequencies in the same bands. It would not be possible to continue to use OTS when ECS came into full service without moving it sufficiently from its present orbital location of 10°E (also planned for ECS) to obtain the necessary spatial discrimination to permit simultaneous operation.

Even with the spot-beam, OTS provides extensive European coverage and the extent of this 'footprint' would therefore make difficult its use for a service aimed specifically at the UK without international recognition.

9.2 L-SAT 1

L-SAT 1, due for launch in 1984, will carry (among other payloads) two broadcast channels, both of which are being funded by Italy. It is proposed to use one of these channels in conformity with the characteristics (Channel 24, left-hand circular polarisation) agreed for Italy in the 1977 Plan to provide a pre-operational service. The other, which will be used with a re-pointable antenna, would be available to EBU Members for general experimentation. At present, this transponder would also operate on a frequency and with a polarisation assigned to Italy (Channel 28, left-hand circular polarisation). The satellite would be located at the Italian position of 19°W.

The BBC has proposed to the Home Office that after two years of operation at 19°W (i.e. in 1986), the satellite should be moved to the UK-assigned orbital position of 31°W, and made available to the BBC for a Subscription-TV DBS experiment.

Other possibilities have been pursued with the Home Office on the assumption that L-SAT 1 may have to remain at 19°W. One is to change the second transponder to a frequency and polarisation suitable for the UK; and the other is to fund an additional broadcast transponder for UK use. But this could be provided only with changes to the existing payload. It would appear that the prospect of changing the payload should not be dismissed.

The Home Office is well aware of the problems which these proposals may bring but is doing all that it can to help to overcome them.

9.3 L-SAT 2

As part of the L-SAT programme, it is planned to provide a complete set of spare parts for a second satellite. If the first L-SAT is lost on launch, or fails relatively soon afterwards, then the spare satellite would be used as a substitute. If launch and use of the first satellite proceeds satisfactorily, a second satellite could be made available for further purposes. (80% probability of success has been quoted for insurance purposes). These uses might include a UHF sound broadcast experiment and maritime and aeronautical mobile uses. The latter would argue for the satellite's being located over the Atlantic at an orbital position possibly in the range 20°-30°W. All this is very provisional, but it offers the possibility of using the satellite at the correct orbital position for a UK pre-operational service. Launch could be in 1985 or 1986. The BBC has already recommended to the Home Office that the UK should declare an interest in using L-SAT 2 for this purpose. This could be done in a way which did not, as yet, commit us and leaves options open as to the precise form of DBS to be adopted.

Incidentally, the European Space Agency is currently investigating the possibility of including in the payload of L-SAT 2 two transponders operating at 1500 MHz which might be used for full-scale experimentation in sound broadcasting from satellites, and also for mobile and marine applications.

9.4 Conclusions

None of the options described in this Section would provide a full multi-channel DBS service. Nevertheless the economy offered during the early, difficult, years would be attractive.

10 Main conclusions

We have concentrated in this article on the engineering aspects of introducing satellite broadcasting services into the United Kingdom, as befits this journal, touching on the 'political' implications only where necessary, although these are, of course, under active consideration by the broadcasters and the Home Office. It is obvious that there are many problems yet to be solved but the BBC considers that it is vital to its viewers and listeners, the broadcasters, the industry, indeed to the country as a whole, that the various options be pursued vigorously towards an early solution.

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Digital Television

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Summary: This article looks at the way in which digital techniques have been introduced into BBC television studio equipment with particular reference to the choice of digital sampling structures. These are discussed further in the light of likely developments and the features of composite and component (YUV) coding of signals are compared. It is foreseen that all vision signals up to the network outputs will eventually be in YUV form throughout, with optimum sampling frequencies for studio use and bit-rate reduction on the distribution networks before transmission of analogue composite signals. It if forecast that within a year most new studio-quality digital equipment will be designed around a line-locked YUV structure with sampling frequencies somewhere between 14:7:7 amd 12:4:4.

1 The trend

In these days when electronics is making such a major impact on our lives, and mostly by means of devices based on digital circuits using signals in binary form, it may seem surprising that a large sector of electronics, namely the broadcast industry, is still based essentially on analogue equipment. However, one's surprise may evaporate when one realises that the whole of electronics had its roots in broadcasting based on thermionic valves; that semiconductor technology has only relatively recently become available in a form compatible with the requirements of television signal processing; that analogue electronics are producing very good results both at the transmission and receiving ends of the chain; and, above all, that, in broadcasting, change is inhibited by the need to be compatible with what has gone before and what is likely to happen next. Indeed, under these circumstances, it is remarkable that digital techniques are already being used quite extensively in broadcasting. This is because they are often the only practical and cost-effective way of providing some of the new processing which enhance the production of programmes. Awareness of an increasing trend to introduce digital techniques into broadcasting, though in a somewhat piecemeal manner, has encouraged the broadcasters to get together with each other and with the equipment manufacturing industry to try to establish an internationally co-ordinated transition to this new technology.

In Europe the EBU is working towards the recommendation of an interface standard for television which will allow the direct interconnection of digital studio equipment and the interchange of digitally recorded videotapes, for the 625-line system. In the USA the SMPTE is doing likewise for the 525-line system and both organisations are working together to get as close to an international standard as possible, bearing in mind the difference in the number of lines per picture and the difference in the field repetition rate. Although there are currently no plans for direct digital broadcasting of television signals, and the digital standards are concerned predominantly with equipment intended to be used within the confines of the broadcasting organisation, it is clearly in the interests of the broadcasters and the industry to have as much commonality as possible throughout the world.

2 Digital techniques in current use by the BBC

It is interesting to note that at present the entire BBC television programme output passes through digital noise reduction equipments at the network outputs of both BBC-1 and BBC-2. Further, most programmes will have been through at least one additional equipment involving A-D and D-A processes. In order to give an impression of the

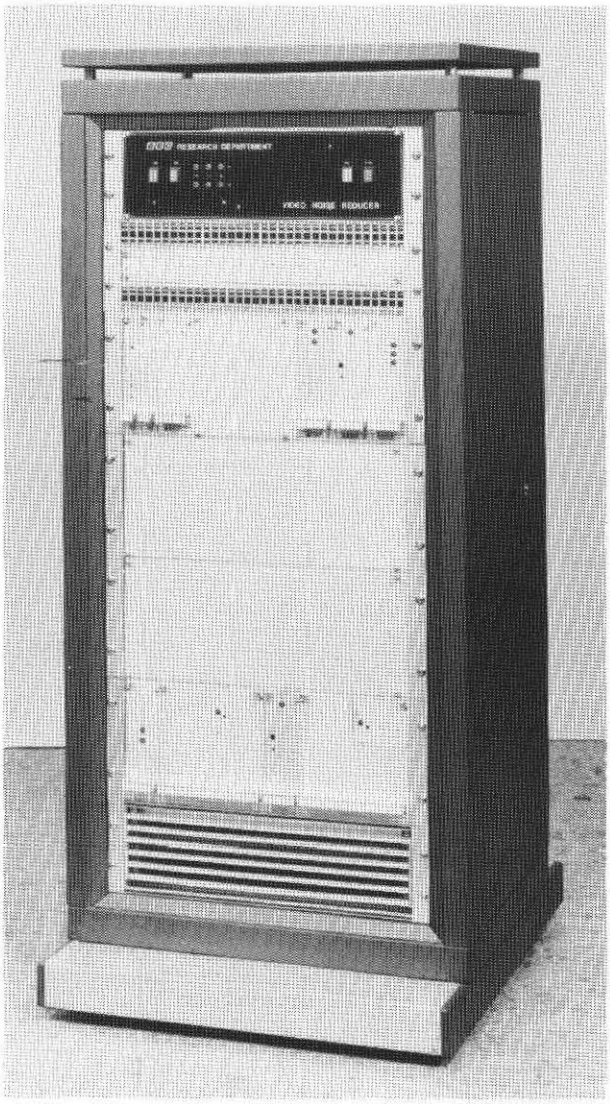

Fig. 1(a) Prototype noise reducer produced by BBC Research Department. This equipment has been in use at the network output of BBC-2 since September 1979. It uses composite coding sampled at a frequency of $3f_{sc}$.

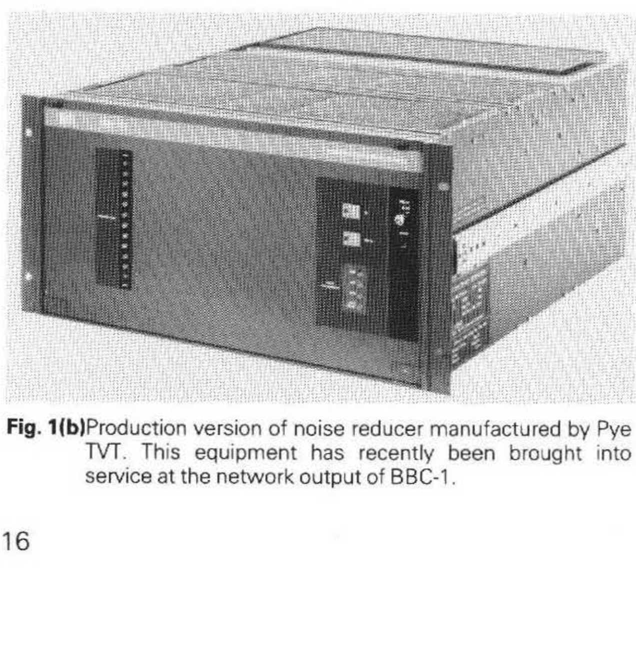

Fig. 1(b) Production version of noise reducer manufactured by Pye TVT. This equipment has recently been brought into service at the network output of BBC-1.

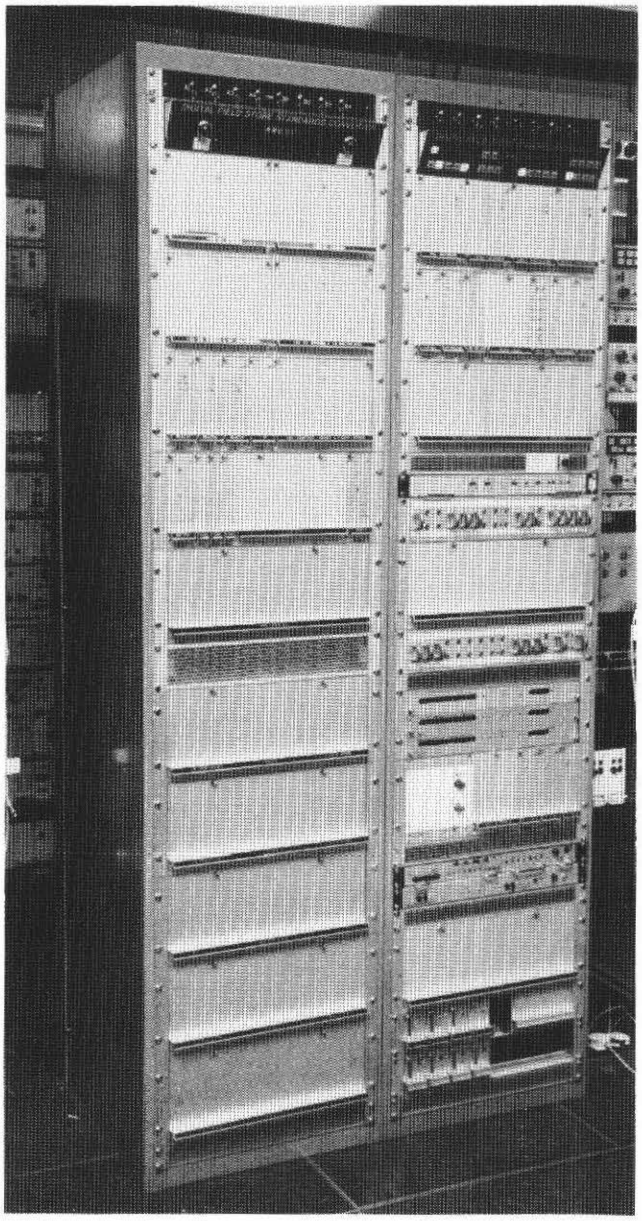

Fig. 2 Digital standards converter produced by BBC Designs Department in collaboration with BBC Research Department for conversion of signals between the European PAL and SECAM 625-line, 50-field systems and the NTSC 525-line, 60-field system. It can also be used as a SECAM to PAL transcoder and as a multi-standard synchroniser. It uses YUV component coding sampled at frequencies of 9·6:3·2:3·2 MHz for standards conversion and 16:4:4 MHz for synchronisation.

nature and extent of the application of digital techniques, some equipments in current use by the BBC are briefly reviewed.

2.1 The noise reducer

Noise reduction is effected by averaging successive pictures by recirculation in a picture store[1]. In the case of still pictures, the picture information is completely correlated from picture to picture, while noise is very much less correlated. Recirculation in a picture store results in the noise averaging to a low level, while the picture information is retained. In the case of moving pictures, this process would cause severe lag effects but these are avoided by examining successive pictures element by element with a movement detector which is used to inhibit the action of the recirculating filter.

This equipment is a good example of one whose success depends on the use of digital techniques and the improvements which have been made in semiconductor technology, notably the relative ease with which it is possible to store the information contained in one TV picture. The composite PAL signal is digitised using a sampling frequency which is approximately three times the colour subcarrier frequency (f_{sc}) giving 851 samples per line. Two field stores and ten line stores are used to hold the picture information on digital form.

At the time of writing the BBC Research Department's prototype equipment has been used almost continuously at the network output of BBC-2 for about one year, and one of the first production equipments (produced under licence by Pye TVT Ltd.) has recently come into operation at the network output of BBC-1.

2.2 Digital standards conversion

The new digital standards converter[2], produced by the BBC's Designs Department in collaboration with Research Department, has recently entered service. It converts television signals between the European PAL and SECAM 625-line, 50-field systems and the NTSC 525-line, 60-field system. Besides converting signals in both directions between these standards, the equipment can operate as a high-quality SECAM to PAL transcoder or as a multistandard synchroniser for locking non-synchronous contributions to the reference signal.

The converter operates by interpolating between the lines and fields of the input standard to produce lines of signal at the times and positions needed for the output standard. Four field periods of the input signal are stored in random access memories. The memories allow simultaneous access to sixteen lines of picture, consisting of four consecutive lines from each of four fields. These are multiplied by interpolation coefficients and the resulting products added together to form the output-standard signal.

In the conversion mode, the input-standard colour signals are decoded from the composite form to component form but as luminance (Y) and colour difference (U and V) chrominance signals, rather than RGB. A sampling frequency of 9·6 MHz is used for Y (the luminance having been limited to 4·2 MHz bandwidth) and 3·2 MHz for each chrominance signal with 8 bits per sample. The three signals are multiplexed together into a 16 MHz YUYVY package for interpolation.

For PAL synchroniser operation, the full 5·5 MHz luminance bandwidth is required. So, after decoding, the YUV signals are digitised using the 16 Mhz sampling rate for luminance and 4 MHz for each chrominance signal. To accommodate these higher data rates, the random access memories are reconfigured in this mode to form two high-capacity field stores. The digital Y, U and V signals are read out in parallel from different parts of the store and converted to analogue signals for PAL coding.

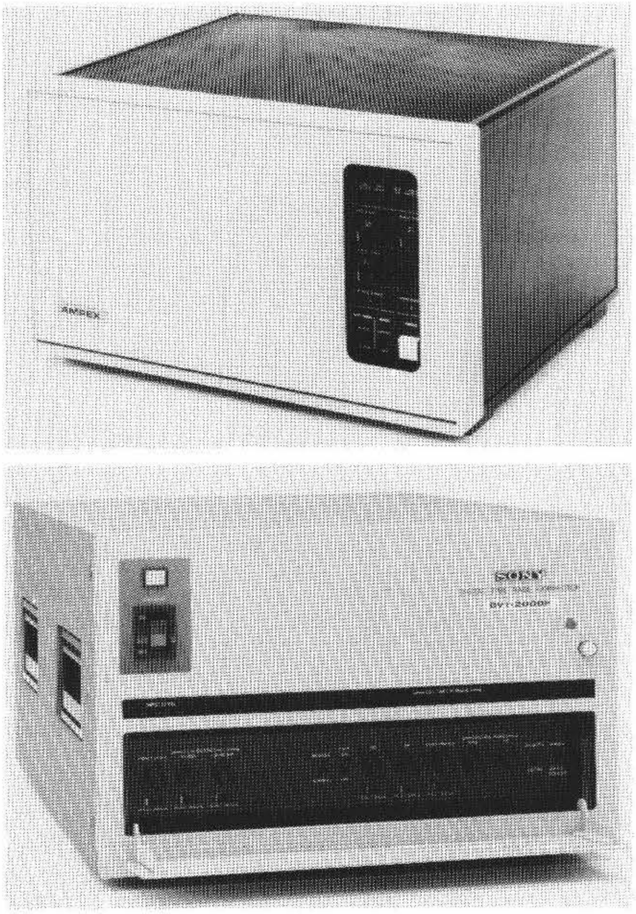

Fig. 3 Two examples of digital time-base correctors in current use by the BBC. The Ampex TBC-2B uses 16 lines of storage and the Sony Broadcast BVT-2000P has 24 lines of storage. The sampling frequencies are $3f_{sc}$ and $4f_{sc}$ respectively.

2.3 Time-base correctors[3]

The majority of our programme material will have been through at least one cycle of digital conversion for the purpose of time-base correction in association with video tape recording. Two equipments in current use by the BBC are the Ampex TBC-2B and the Sony Broadcast BVT-2000P. They correct timing instabilities ranging from coarse errors associated with ENG recorders to the slight velocity errors that are found in even the highest quality recorders. They also provide improved tape dropout compensation and make it possible to view the replayed picture over a wide range of tape-shuttle speeds, including slow, stop, and reverse motion. The digital video processing of the composite signal is carried out at a sampling frequency of $3f_{sc}$ in the Ampex equipment and $4f_{sc}$ in the Sony, both using 8 bits per sample. Digital storage of 16 and 24 lines respectively are used in these particular equipments.

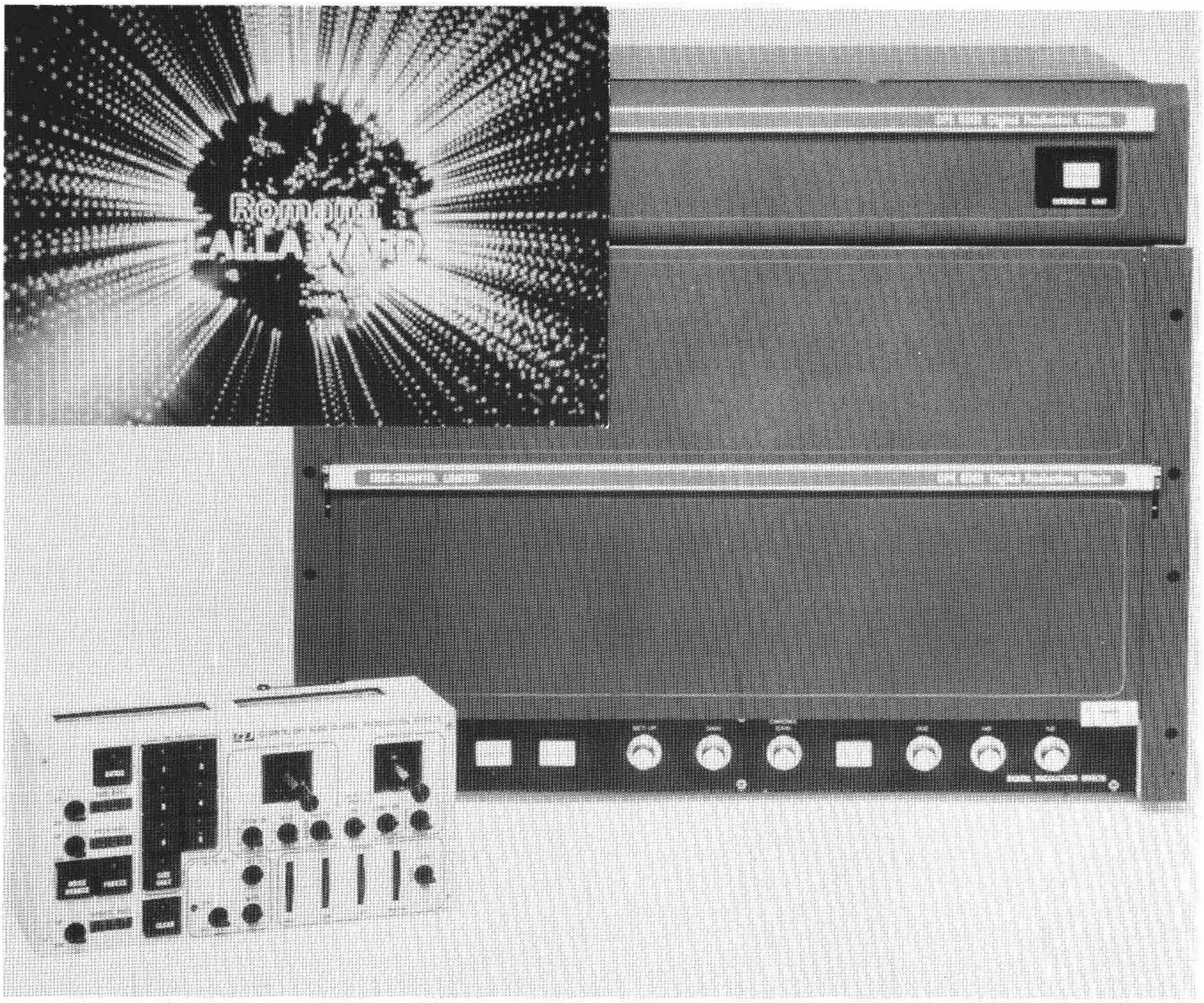

Fig. 4 The Quantel 5001 special-effects equipment produces changes in the size and shape of the picture by digital signal processing. It uses YUV component coding with sampling frequencies of 14:3½:3½ MHz. Inset: The shrinking head of 'Dr. Who' is one of the effects available.

2.4 Signal processing for special effects

The use of digital techniques has enabled the equivalent of optical processes such as changes in the size and shape of the picture to be produced by electronic means. An equipment currently in use by BBC producers to enhance the impact of their programmes is the Quantel DPE 5001[4]. This is based around a picture store and, like the standards converter, due to the complex nature of the algorithms used to change the size and shape of the picture, the digital processes are carried out with the signals in component form. A sampling frequency of 14 MHz is used for luminance and 3½ MHz for each of the colour difference signals.

DPE 3001 is an equipment capable of quarter-size picture compression, full-frame repositioning and freeze facilities as well as time-base correction. It is based essentially around a PAL picture store synchroniser. Since, in this case, no complex changes in picture geometry are involved, Quantel have used composite sampling at 3 times f_{sc} rather than component coding, with a corresponding economy in the required storage capacity.

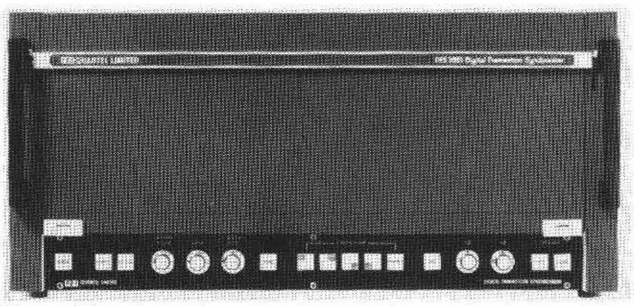

Fig. 5 The Quantel synchroniser which can also be used for quarter-size picture compression, full-frame repositioning and freeze facilities. It uses composite coding at a sampling frequency of $3f_{sc}$.

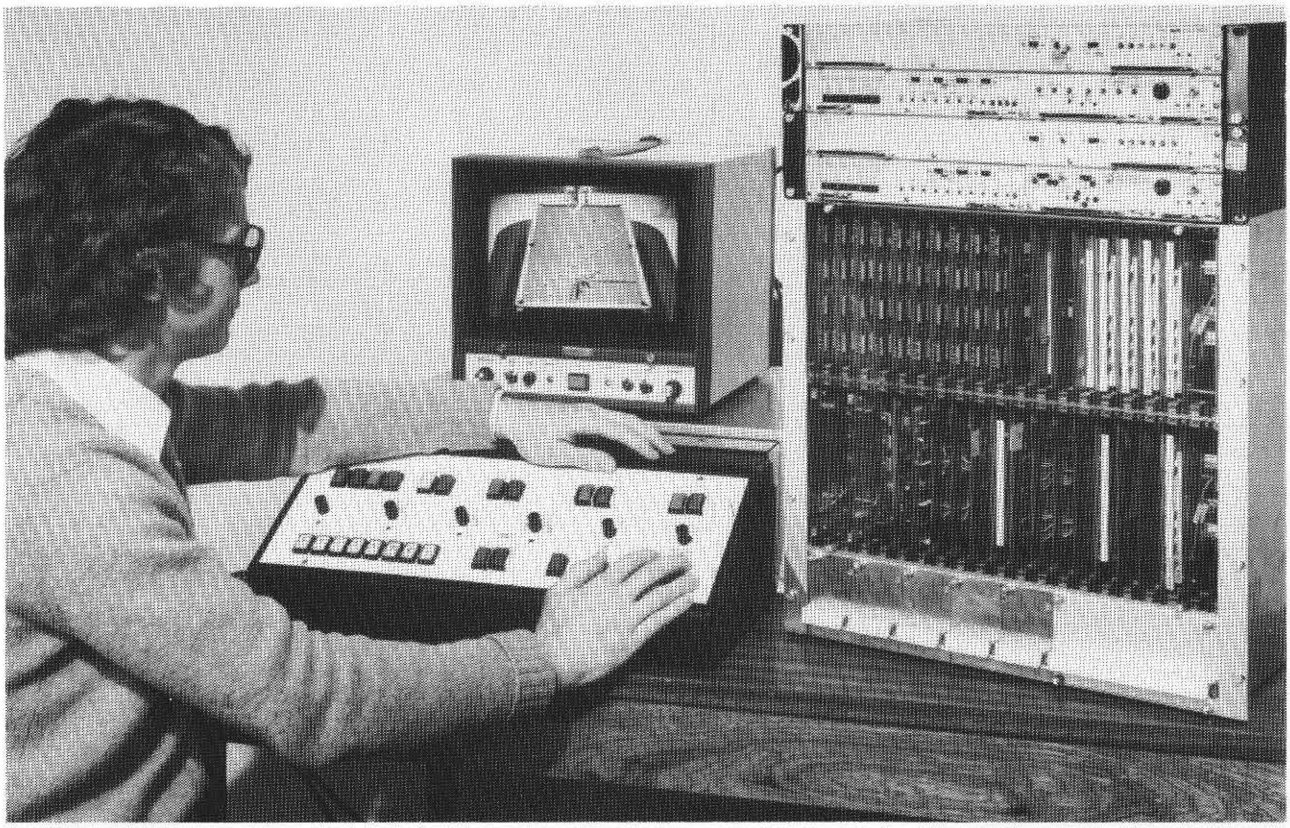

Fig. 6 The Teletrack special effects equipment produced by BBC Research Department which displays an object's trajectory. It uses composite coding at a sampling frequency of $3f_{sc}$.

2.5 Teletrack

Teletrack is a special effect system which periodically identifies and records the image of a moving object against a stationary background, creating a series of frozen images which display the object's trajectory[5].

The system detects the position of a moving object in any television field by comparing the signal from that field with a signal from a stored reference field. If the background remains stationary, any differences between the two signals correspond to the position of the object in each of the two fields. As the positions of the moving object are established, the corresponding images are written into a field store. The accumulated set of images can be displayed superimposed on the background.

This equipment, produced by BBC Research Department and recently commissioned for service, uses composite coding at a sampling frequency of 851 x line frequency like the noise reducer mentioned in section 2.1, i.e. approximately $3f_{sc}$. It uses 2½ field stores, and 18 line stores.

3 Further moves towards digital studio operations

It will be clear from the foregoing that the absence of a digital studio standard has not deterred the introduction of this technology into studio operations. However, even at this early stage, there is already concern that the various sampling structures which have in each case been chosen to be the best match between the available device technology and the requirements of the particular equipment, might interact to give undesirable aliasing effects, etc. if the introduction of digital techniques were to continue along these lines. Furthermore, perhaps the most important constituent of any broadcast studio complex, namely the VTR, is missing from the list of equipments described so far. The digital VTR is an equipment whose viability is critically dependent upon the establishment of a widely-accepted standard. Paradoxically, because of the current status of video tape recording technology, the digital standard itself is very sensitive to the predicted capability of this recording medium. It is this chicken and egg situation which is complicating the issues which need to be resolved in order to pave the way for a co-ordinated transition from analogue to digital studio operations. There are of course many other factors and constraints which complicate the establishment of a standard which will see us through at least to the start of the 21st century.

3.1 Composite coding

It will be seen from the review of equipments discussed in Section 2 that there is no common policy regarding the choice of digital sampling structure used by different manufacturers, or even by designers within one organisation like the BBC. If any common ground is to be found, it is that several equipments use composite PAL signals sampled at a frequency of $3f_{sc}$. For processes which did not need access to the components, composite coding was attractive because of the lower storage requirements. Early designs of codec produced beat patterns if the sampling frequency was not locked to that of the colour subcarrier, and $3f_{sc}$ was the lowest sampling frequency which met this requirement and comfortably exceeded the Nyquist sampling rate for a 5½ MHz PAL signal[6]. Thus is may seem that a studio standard based on composite PAL signals sampled at $3f_{sc}$ might have emerged. However, in the relatively short time which has elapsed since the equipments described in Section 2 were designed, rapid changes have been taking place in the technology and consequent application of digital techniques to broadcasting.

As processing became more sophisticated the fact that $3f_{sc}$ was not an exact multiple of the line frequency produced difficulties where line delays were involved ($3f_{sc}$ is approximately equal to 851¼ times the line frequency). At the same time semiconductor device speeds increased and the cost of the storage decreased. This led to the proposal of a digital standard based on composite signals sampled at a frequency of $4f_{sc}$ which was to all intents and purposes a multiple of the line frequency[7]. It is in fact 1135 times line frequency with a discrepancy of 2 samples per field which, with simple resynchronisation, enables a repetitive sampling structure to be achieved for consecutive pictures.

In 1979 a digital standard based on composite PAL signals, with samples taken at $4f_{sc}$, was comfortably within the state of the art of the semiconductor devices available for critical functions such as A-D conversion, and early models of digital tape recorders demonstrated that they were capable of handling the corresponding bit rates[8,9]. Thus everything seemed set fair for the establishment of a studio interface standard based on $4f_{sc}$ PAL in Europe. It had everything going for it including the feeling that since any digital equipment would have to co-exist with analogue equipment for a very long time, a standard based on composite PAL with the sampling frequency locked to the colour subcarrier would given the least problems at the analogue-digital interfaces. (Incidentally in the USA the SMPTE were putting the finishing touches on a studio interface based on the composite NTSC signal sampled at $4f_{sc}$.) Perhaps it was the very imminence of a standard in the middle of 1979 that made people at the BBC and other broadcasting organisations stand back and take a hard look at the possible growth of digital techniques in the studio. This exercise showed clearly that the main reasons why broadcasters would wish to change to digital signals are associated with an increased use of picture processing and the ability to survive many generations of recording with intermediate processing without the deterioration which would be found in multiple generations of analogue recordings. An examination of the nature of these processes showed that in many cases the digital signal in composite form would not allow the full benefits of digital processing to be realised e.g. the increasingly important technique of colour separation overlay, precision tape editing (hampered by the 8-field sequence), and changes in picture geometry. To some extent this trend can be seen from the discussion in Section 2 but as the use of digital processing in the studio becomes more extensive, side effects associated with the very efficiency of composite coding cause problems not present with component coding. Thus it became clear that whilst a composite digital standard might be useful it would not add all that much to the existing composite standard in analogue form. What was really required was a studio interface based on components.

3.2 Component coding

In addition to the advantages mentioned above the attraction of a component standard is that the degree of international commonality that can be achieved for equipment is of course much greater.

A component standard also has much more future growth potential since, almost by definition, it allows for the recovery of the original RGB signals much more cleanly than any composite signal. By the same token however, since one does not take advantage of the efficient manner in which a composite system like PAL enables the combined luminance and chrominance information to be conveyed with economical use of bandwidth the search for a standard had moved from a position well within the technological state of the art to a position hard up against the present limits of technology. To make decisions more difficult, the state of the art in the relevant technologies is a rapidly changing function of time, and although everyone agrees that the slope of the curve is positive, there are widely differing views about its magnitude.

Thus it was that the EBU sub-committee, chaired by Howard Jones of the BBC's Research Department and charged with recommending a standard, was faced with a seemingly impossible task. Because of the pressure to establish a standard quickly, and in phase with the CCIR timetable, it was asked to make its recommendation by the spring of this year. Yet a basic RGB signal, super-Nyquist-sampled to preserve the quality of the output of a present-day 625-line system camera would, for example, require a recorder capacity of over 300 Mbit/s. This was well beyond what manufacturers of digital tape recorders were predicting for tape consumptions comparable with analogue recorders. It was incidentally also thought beyond the capabilities of planned digital trunk networks which in Europe are likely to be limited to 140 Mbit/s. Although trunk transmission was not a primary consideration in the establishment of a studio interface, the transparency of such links to the digitised component signal would be a considerable advantage.

YUV component coding, as discussed in Section 2, enables most of the benefits of RGB to be retained for digital signal processing. Whilst more extravagant in the demands for storage and device speed, these demands can be substantially reduced from those required for the RGB signals by limiting the bandwidth of the chrominance signals U and V. The extent to which this can be done affects the gap between the requirements of the code and the available technology. However, before deciding on a studio interface based on YUV, two further questions have to be answered. Firstly, could all foreseeable studio functions be carried out in component coding? It would appear that whilst component coding is more or less essential for many processes, only the synchroniser is more readily instrumented in composite form and, as mentioned in Section 2.2, even this can be implemented in component form.

The second question concerns the protracted period during which analogue PAL signals and YUV signals will have to co-exist in the studio. Will it be possible to adequately decode PAL so that the benefits of YUV signal processing are retained? If the future YUV studio standard is to be superior to the present analogue interface (and there would be no point in changing to it if it were not) it is of course inevitable that a YUV signal derived from PAL may demonstrate certain deficiencies not shown by a signal which has remained in YUV throughout the production processes. What would not be acceptable, would be that by intermingling PAL and YUV processes, significant defects were introduced which would not be present in an all-analogue operation. This would be too high a price to pay for whatever benefits digital techniques may bring, and its introduction would have to be deferred, or limited, to applications where all-digital operation could be guaranteed. For the BBC this would mean delaying the transition to digital techniques for a long time. Although the answers to this question have not yet been fully resolved, it seems likely that application of digital techniques to the PAL decoding process itself will ease the problems of the transitional period.

Digital decoding provides high stability and accurately defined characteristics. This is particularly important when complicated comb filters are used to obtain improved separation of luminance and chrominance. Also, by using a digital demodulator designed to operate with line-locked sampled PAL signals, decoders can be made to produce line-locked YUV directly, in the form suitable for signal processing.

Preliminary experiments with digital PAL decoders carried out by BBC Research Department using picture-delay comb filters have produced encouraging results[10]. Performance benefits including complete freedom on still pictures from the cross-colour cross-luminance effects normally associated with the PAL system. In addition these decoders can retain full horizontal and vertical luminance and chrominance resolution. This approach to decoding offers the prospect of obtaining line-locked sampled YUV from PAL with quality similar to that of direct YUV signals.

In November 1979 the EBU sub-committee recommended that a YUV standard based on the sampling frequency of 12 MHz for luminance and 4 MHz for each of the chrominance signals be examined experimentally and if deemed satisfactory, be submitted to CCIR as a standard[11]. The sampling structure was of course line-locked with an orthogonal pattern for luminance and chrominance, there being 768 samples per line for Y and 256 samples per line for U and V. With all the various constraints placed on the choice of sampling structure, it was inevitable that some compromises were made. The attraction of 12:4:4 is that it does not make excessive demands on recorder bandwidth and that the multiplexed Y, U and V signals could be accommodated within the 140 Mbit/s digital trunk transmission standard adopted by the European PTTs without too much difficulty. The reservations about the standard lay with concern that the sampling rates may be a little too low to allow all the digital signal processing envisaged to be carried out with sufficient 'headroom'. Extensive tests were carried out and although many of these produced extremely good results, they did not completely allay the reservations about the adequacy of the bandwidth, particularly that allocated to the chrominance signals. Nevertheless, the EBU Technical Committee at its meeting in April 1980 following the demonstrations of equipment using the 12:4:4 sampling structure, accepted the key principles recommended by its sub-committee that the digital studio interface standard should be based on components, and use an orthogonal sampling structure (such as line-locked). This decision was communicated to CCIR with the comment that the precise sampling frequencies to be recommended for Y, U and V would be confirmed after some further study. The SMPTE also accepted these principles and experiments are currently being carried out on both sides of the Atlantic examining mainly luminance sampling frequencies between 12 and 14 MHz and chrominance sampling frequencies between 4 and 7 MHz in ratios producing orthogonal sampling structures, e.g. 12:6:6 and 14:7:7, etc. Although agreement has still to be reached on the precise sampling frequencies, it can be regarded as a considerable achievement that the essentials of a new digital standard have been accepted on a world-wide basis in a form very different from those which were under widespread discussion less than a year before.

4 Some ground rules for setting a standard

To sharpen the debate within the BBC on the choice of the sampling frequencies for luminance and chrominance, certain ground rules were established. It is envisaged that consistent with the requirements of the transitional period, all vision signals up to the network output will eventually be in YUV throughout. The choice of sampling frequencies should be the best for this operation, and should not be inhibited by possible bandwidth limitation of the links available for distribution to the transmitters. It is better to rely on bit-rate reduction techniques in the distribution network rather than choose a fundamentally inadequate standard for the studio.

It must be remembered that the signals will eventually be transmitted as an analogue composite signal, specifically in the UK a 5·5 MHz PAL signal. Thus if in the interests of providing adequate 'headroom' a standard is chosen which provides qualities which would be cut off by the 'window' defined by the transmission standard, then one runs the risk of incurring unjustified capital and running costs in programme production. In considering the 'window' one must take into account anticipated improvements in encoding for transmission, and future developments in receivers such as picture-store-based decoders which could be introduced in a manner compatible with existing practice.

Unfortunately, not even the discipline of a 'window' removes some of the dilemmas between adequacy and extravagance. Take, for example, the question of electronic

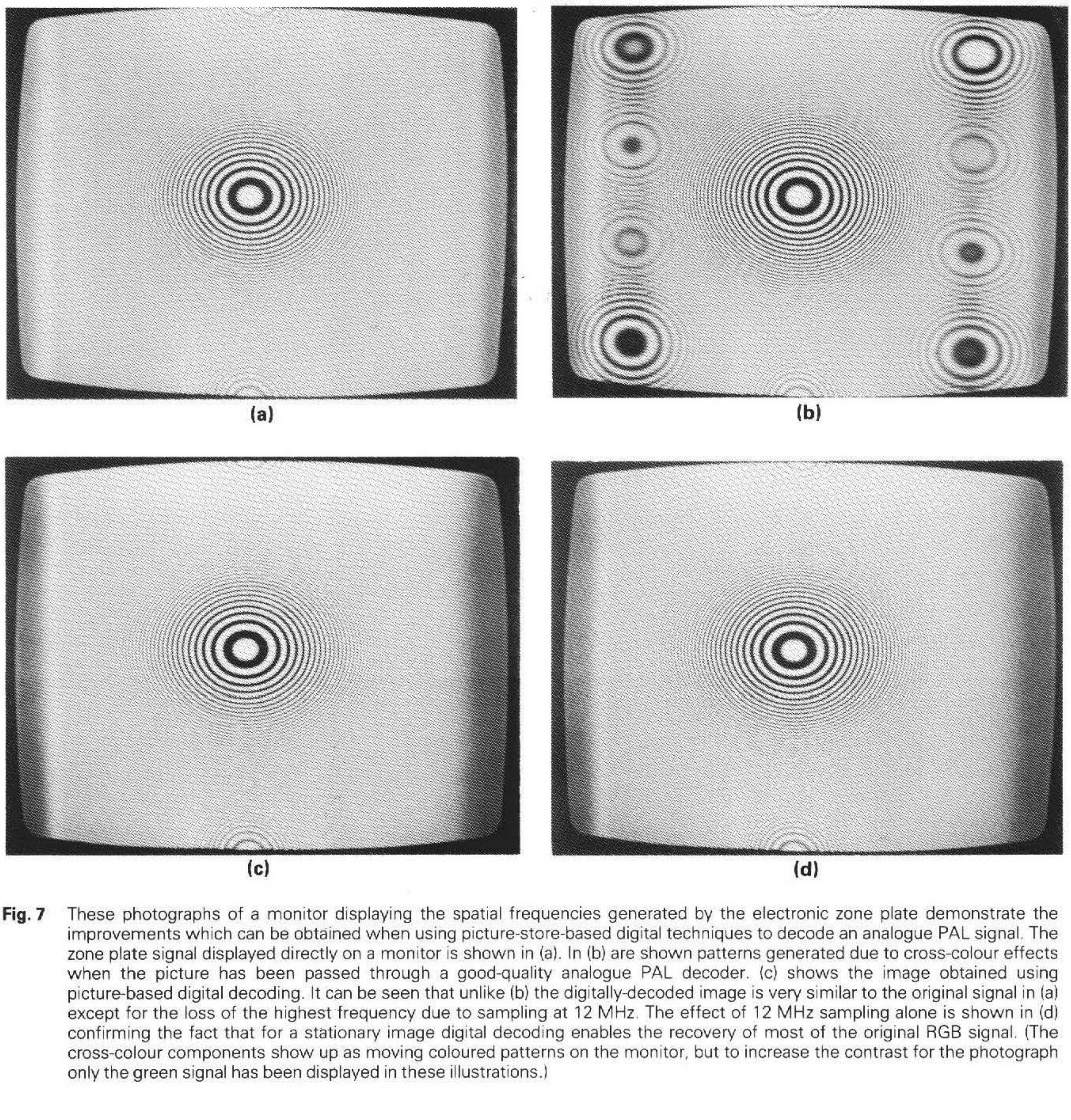

Fig. 7 These photographs of a monitor displaying the spatial frequencies generated by the electronic zone plate demonstrate the improvements which can be obtained when using picture-store-based digital techniques to decode an analogue PAL signal. The zone plate signal displayed directly on a monitor is shown in (a). In (b) are shown patterns generated due to cross-colour effects when the picture has been passed through a good-quality analogue PAL decoder. (c) shows the image obtained using picture-based digital decoding. It can be seen that unlike (b) the digitally-decoded image is very similar to the original signal in (a) except for the loss of the highest frequency due to sampling at 12 MHz. The effect of 12 MHz sampling alone is shown in (d) confirming the fact that for a stationary image digital decoding enables the recovery of most of the original RGB signal. (The cross-colour components show up as moving coloured patterns on the monitor, but to increase the contrast for the photograph only the green signal has been displayed in these illustrations.)

zoom. Programme makers might consider it very desirable to expand certain areas of the picture during post-processing by a factor of, say, 2 times. If a standard were chosen to ensure that there were no loss of resolution after such a process compared to the unexpanded original when viewed through the 'window', then a considerably higher sampling frequency would be required than for studio operations not requiring this particular process. The cost in additional tape consumption and studio equipment incurred if the standard made provision for this facility would have to be borne by all programmes not requiring a 2:1 expansion without loss of resolution. Similarly, in the case of colour separation overlay where the chrominance signal from one source is used to switch the complete image including the higher resolution luminance signal from another source, it may be necessary to use a greater chrominance bandwidth than that derived from the 'window' in order to finish up with sharp transitions during CSO.

These two examples show that, in formulating a policy, it is necessary to envisage the organisation and functions of the all-digital studio of the future and make a judgement about the relative importance of any processes which might affect the choice of standard. In the two particular cases discussed above, the view of the BBC is that it would be better to tolerate some degradation of resolution on the occasions when electronic zoom is required rather than load all productions with the cost of accommodating this facility in the choice of standard. On the other hand, the ability to

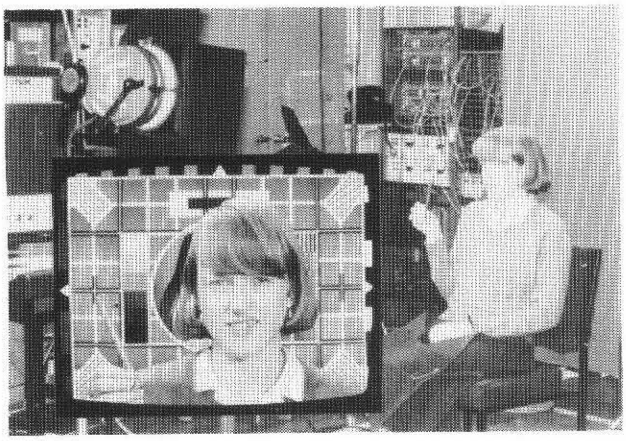

Fig. 8 One of the critical tests carried out at the comparative demonstrations organised by the EBU in the Spring of 1980, was colour separation overlay. Impairments observed when the image of the pen being rotated in the hand was overlaid on the test card stimulated some reservations about the adequacy of 4 MHz as a sampling frequency for the chrominance signal.

carry out colour separation overlay at any stage in programme production is considered so important that if, for example, additional chrominance bandwidth is required to accommodate this facility, then the BBC would wish the standard to reflect this requirement.

One of the concepts which may ease the accommodation of special, or future, requirements is the establishment of a 'hierarchy' of sampling structures related to the basic standard. Thus, if the choice of sampling structure were, say, 12:6:6 the establishment of a 'hierarchy' would ensure that, for example, anyone departing from the standard to produce an equipment using RGB, would use 12:12:12. Anyone deciding to use a low-bandwidth system, perhaps for ENG, might use, for example, 6:3:3 and so on. A disciplined application of such a 'hierarchy' in association with a basic standard could allow some growth potential and flexibility without losing the benefits of interoperability.

The broadcasting industry now seems very close to settling on an internationally accepted digital interface standard for television studios. It seems highly probable that within a year most new studio-quality digital equipment will be designed around a line-locked YUV structure with sampling frequencies somewhere between 14:7:7 and 12:4:4.

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Digital Coding of the Composite PAL Colour Television Signal for Transmission at 34 Mbit/s

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Summary: With the coming introduction of national and international digital telecommuncation networks, there are challenging incentives for compressing the digital television signal so that, compared with straightforward PCM coding, a reduced bit rate can be used for transmission between studio centres, and to broadcast transmitters. This article looks briefly at the history of television bandwidth compression, the incentives and constraints, and discusses the techniques required to achieve high-quality broadcast television transmission for composite PAL colour signals, at about 34 Mbit/s.

1 Introduction

Digital communication circuits offer the flexibility to combine, for example, data, telephone, and broadcast sound and vision signals on one digital multiplex highway. In Europe, the basic agreed building block for the data highway is a 2·048 Mbit/s unit (which can carry 30 PCM telephone signals), and a hierarchy of multiplex levels for access to and from the highway has been established at such levels as 8·448 Mbit/s, 34·368 Mbit/s and 139·264 Mbit/s (see figure 1). Additionally the British Post Office proposes to provide access at 68·736 Mbit/s specifically for television.

For the broadcaster, it is a prime concern that his signals should be tailored to make economic use of the data highway for contribution to, and distribution from, studio centres. In particular, this poses a most interesting challenge for television signals. A similar interest also applies in digital video recording, where economy of the recording medium can be a significant factor.

A digitally-coded colour television signal requires in excess of 100 Mbit/s channel capacity using conventional PCM. This is the major part of the fourth-order multiplex level (140 Mbit/s) and as such would make very inefficient use of the digital channel. However, if sufficient compression could be applied to squeeze the television signal in at the third-order multiplex level (34 Mbit/s), a considerable economy of channel utilisation would be effected (figure 1).

Additionally, digital modulation could provide improved performance on satellite communications links, where frequently only half the transponder bandwidth is available for analogue FM television transmission. This presently results in a degraded signal-to-noise performance, but the channel would alternatively support some 30 Mbit/s digital transmission capacity.

2 Nature of the problem

Compression of television signals is by no means a recent art, having a history dating back nearly thirty years. This is largely because, since its conception as a means of visual communication, television has been an embarrassment in its bandwidth requirements, especially when compared with other forms of communication.

Even so, as we know it today, the television image is somewhat akin to the image seen when peering through a small window onto the world outside, and rarely subtends more than 15° at the eye. Moreover, a three-dimensional scene is portrayed in a two-dimensional plane, wherein the incident light angles, the intensity, hue, and saturation have all been distorted. In no way does the television image attempt to reproduce the scene in every conceptual detail. Its purpose is merely to suggest the appearance of the original scene in a way that is psychologically satisfying to the viewer.

Yet even with these stringent limitations, the television signal uses many tens of Mbit/s channel capacity for so-called 'high-quality' image reproduction. On the other hand, it is known that the human visual system (i.e. the eye-brain combination) cannot absorb information at a rate greater than a few tens of bit/s (in terms of Shannon's theory of communication[1]). Thus, there appears to be an enormous lack of efficiency to be exploited. However, much is lost by the difficulty of defining what the human visual system is, and the fact that what information it chooses to absorb, and when, is not externally controllable (see for example the

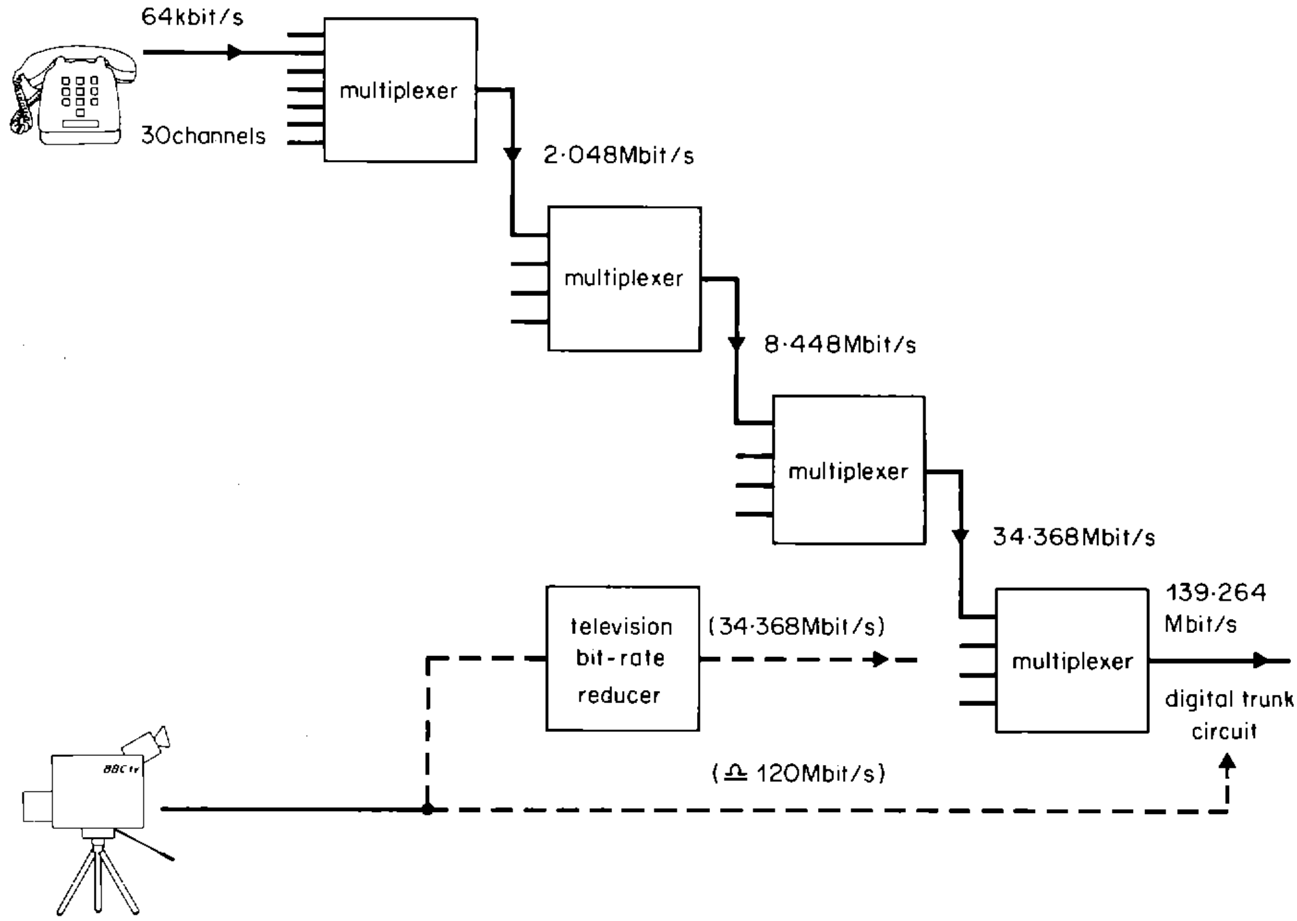


Fig. 1 Multiplex hierarchy in a digital communications network.

eye-trace patterns for different viewers and at different times when studying the same picture, as given in Kolers[2]). Thus, a model for all human observers has a much greater information-absorbing capacity than for just one, and most modelling has therefore been carried out more on an empirical basis, to determine physiological properties of the eye, rather than the psychological properties of the complete visual system.

3 History of television bandwidth compression

Television bandwidth compression began with an examination of the statistical redundancy in the signal (see for example Kretzmer[3]). It was quickly appreciated that in order to reduce the bandwidth, the information rate had to be smoothed, otherwise all that resulted from removing redundancy was a saving in power. Digital techniques held the key to such manipulation of the television signal and early investigations concentrated primarily on devising digital methods, in a predominantly analogue world, to remove statistical redundancy[4,5,6]. However, difficulty of digital implementation at video-signal frequencies restricted the rate of achievement.

At the end of the 1950s, Teer[7] and Seyler[8] reviewed the state of the art and considered systems which started to exploit the physiological aspects of the eye, in addition to statistical redundancy in the signal itself. During the 1960s a marked growth in the development of video bandwidth compression took place. This was largely precipitated by the advancement of device technology and the introduction of digital integrated circuits. Also the requirement for visual communications via satellite and from space probes was a great incentive to improve efficiency. In this field, bandwidth and signal power were at a premium right from the start. However, non real-time transmission was acceptable for space-probe pictures and complex slow-speed image processing was possible, creating a boom in the application of redundancy-reduction techniques.

Many interesting papers appeared in special issues on picture bandwidth compression and digital picture processing[9,10,11,12], presenting diverse approaches to the removal of statistical redundancy, and exploiting psycho-visual properties of the eye. A useful bibliography is given by Wilkins and Wintz[13]. The introduction of techniques such as differential pulse-code modulation (DPCM)[14] and transform coding[15] have spanned the literature ever since, and although much has been done towards applying Shannon's rate-distortion theory[1] in a more encompassing manner[16], the difficulty of modelling the human visual system sufficiently accurately remains the major limitation. What is clear is that a *reasonable* representation of an image is achievable by many different techniques giving high bandwidth-compression ratios, but that the high-quality requirements of broadcast signals not only defeat visual-system models but also require many times greater bandwidths.

Most of the early work on bandwidth compression discussed above was concerned with the monochrome television image, although in the field of broadcast television, much work was also done to establish methods of transmitting colour pictures in the same bandwidth as the monochrome signal. The well-known composite colour systems emerged, namely NTSC, PAL and SECAM, as efficient band-sharing systems with not too severe quality compromises, even though the division of the spectrum between luminance and chrominance components was not tightly controlled.

Work on digital coding of colour television signals did not blossom until the early 1970s, and much has been done in the last decade towards applying the basic techniques previously evolved for monochrome image-compression to colour signals. A good review of this work was given by Limb et al[17] and there are also other interesting papers in the same special issue on image bandwidth compression[18]. As device technology improves, particularly in terms of relatively cheap picture-storage elements, more complex processing is developed, making use of the large amount of temporal redundancy in the television image. However, this has also led to the growth of movement-adaptive techniques in order to overcome the lack of temporal redundancy in moving areas of the picture.

Papers presented at a recent Picture Coding Symposium[19] underline these modern trends and also that the gulf between intelligible images and high-quality broadcast television images remains wide. A creditable simulation of a moving head-and-shoulders picture, suitable for visual telephone applications, was demonstrated, theoretically requiring a transmission channel capacity of only 64 kbit/s, i.e. that of a sound telephone channel[20]! On the other hand there were no proposals for broadcast-quality colour television transmission in less than about 20 Mbit/s, and many of those described exhibited perceptible impairments under some conditions. Nevertheless, an increasing number of proposals for high-quality digital television transmission at around 30 Mbit/s have been made in recent years, and some of these are described in References 21 to 31.

4 Choice of techniques for efficient compression

There are two basic approaches to digital coding of colour television signals: either to code the composite colour signal directly or to code the individual separate components, usually the luminance and two colour-difference signals. For maintenance of the highest quality during production of the television programme, separate component coding is now favoured because of the flexibility that it affords, and the European Broadcasting Union (EBU) is currently working to establish a common digital-coding standard for Europe. However, bit-rate is not an overriding factor in the television studio and no attempt has been made to compress these signals. For distribution, on the other hand, efficient use of bandwidth is much more significant and importance must be placed on bit-rate reduction.

The choice of whether to code composite or separate component signals for efficient compression is not clear cut. PAL and NTSC composite colour signals are suited to direct digital processing because it is possible to take account of the modulated chrominance, but this is not the case for SECAM signals. Only limited attempts have been made to compress the digitised SECAM signal[31] (see Devereux[32], for example).

Many workers have opted for separate component coding methods since it ostensibly permits compression techniques to be better matched to the physiological properties of the eye. However, the digital PAL signal is particularly amenable to bit-rate reduction, and, given that the television signal has to be transmitted in PAL form to the general public in the United Kingdom, the best compromise between high quality and low bit rate may be obtained by processing the PAL signal directly. The chrominance information may be carried within the same bit rate required for the luminance information alone, and only one processing chain is required. In the separate component approach, three separate processes are required, and some workers have had to develop complex interactive techniques to minimise the combined effects of the distortion products of separate bit-rate reduction processes operating in parallel.

Over the last decade a considerable amount of work has been conducted at BBC Research Department into various techniques for bit-rate reduction of the composite PAL signal. Studies of the statistical redundancy in the signal[33,29] have shown that a significant saving in bit rate could be made using variable-length coding, of perhaps 50% or more, for many pictures. However, some picture sequences contain relatively little redundancy, and it would require an enormous buffer store to smooth out the transmission rate sufficiently to take advantage of the possible gains. Also, efficient variable-length codes have very poor immunity to transmission errors. On the other hand, removal of the highly-redundant television blanking intervals does not require variable-length coding. Moreover, this effects a significant bit-rate saving with good error immunity and does not impair the picture quality[34].

DPCM[35] and Hadamard Transform coding[36] methods have also been studied at length, and Clarke demonstrated that, for a given bit rate and using relatively simple implementation of each technique, DPCM was consistently better for high-quality pictures[37]. He concluded that, for a similar degree of equipment complexity, improved DPCM was likely to remain better than improved transform coding, and this has been subsequently confirmed by other workers[38]. More recently the development of the Cosine Transform[39] looks more promising[40], but workers in this field tend to favour it, in comparison with DPCM, at very low bit rates where the distortions of each approach have different subjective significance.

Additionally, it was found that the composite PAL signal could be sub-sampled, below the Nyquist rate, without serious problems arising from the mixing of the baseband and the sampling spectra[41].

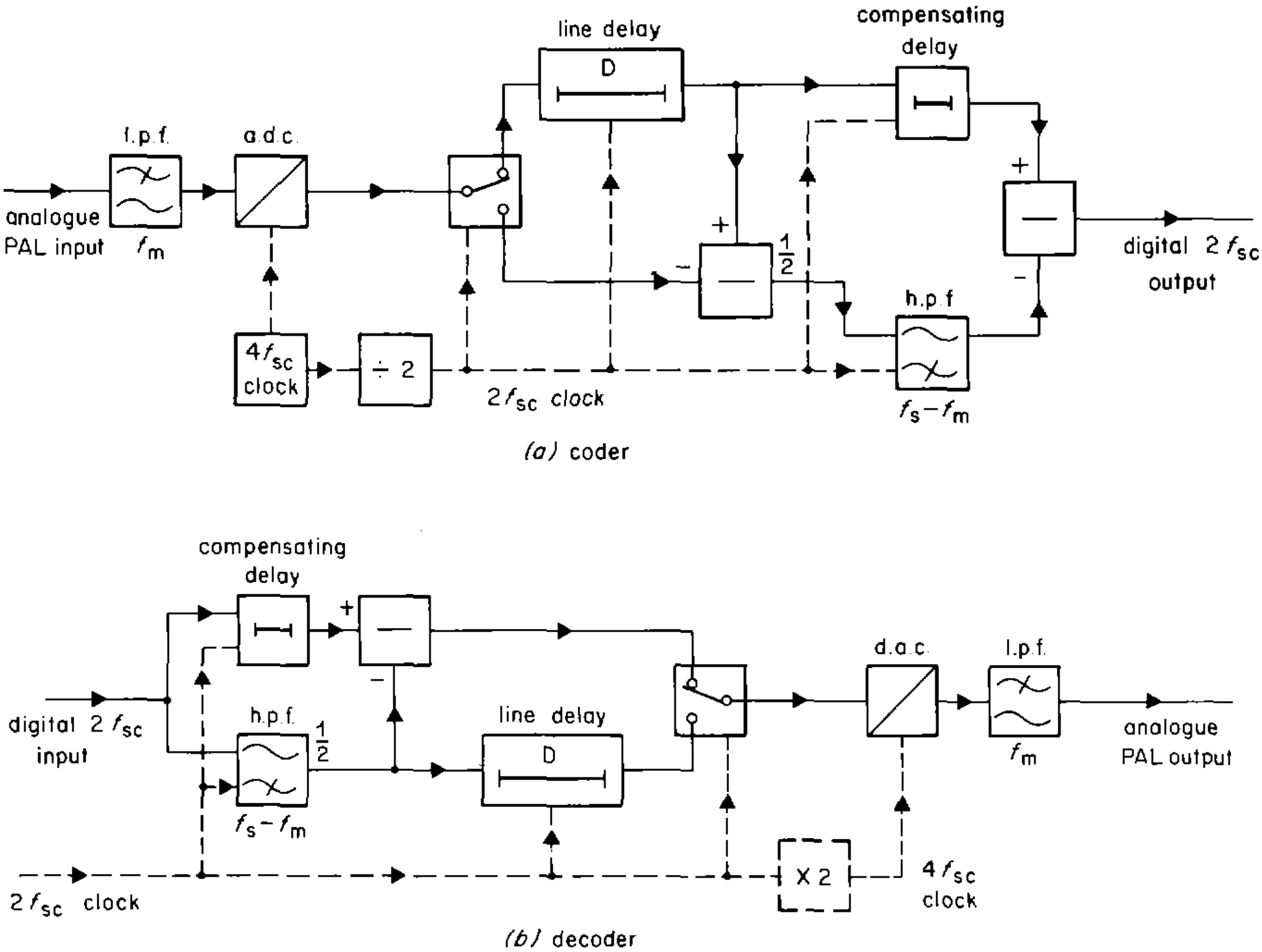


Fig. 2 Sub-Nyquist sampling codec

It became clear that a combination of three substantially independent techniques held the best chance of providing the substantial bit-rate savings necessary for efficient use of future digital communications networks. These are:

(a) Sub-Nyquist sampling,
(b) Blanking-interval suppression,
and (c) DPCM.

These techniques will be discussed in some detail, with an indication of the performance that can be expected of a transmission system using them, and operating at a bit rate in the region of 34 Mbit/s.

5 Sub-Nyquist sampling

Conventionally, the composite PAL colour signal is sampled at three times the colour subcarrier frequency, at about 13·3 MHz, which is slightly above the theoretically-required Nyquist rate of 11 MHz. The difference provides a margin for the finite roll-off of practical baseband filters, and the choice of a harmonic of subcarrier frequency minimises the visibility of any intermodulation products introduced in the analogue-to-digital converter (although with improvements in converter design the latter is becoming less of a problem). A total of 256 quantising levels, linearly disposed, is generally considered to be necessary to convey sufficient accuracy, and this gives rise to a bit-rate of about 106 Mbit/s. Similar methods applied to component coding require an even greater bit-rate; the coding systems presently being considered by the EBU require at least 160 Mbit/s.

However, it has been shown that with the composite PAL signal, the sampling rate can be substantially reduced, to the sub-Nyquist rate of only twice the colour subcarrier frequency ($2f_{sc}$), about 8·86 MHz, with minimal loss of picture quality[4]. The analogue signal is first sampled at the super-Nyquist rate of four times the colour subcarrier frequency ($4f_{sc}$). This is then halved by the action of an appropriate digital comb filter in the high-frequency part of the spectrum, to take account of the unwanted or alias components thus introduced (figure 2a). The filtering process consists of reducing the $4f_{sc}$ sampling structure to a $2f_{sc}$ structure by taking alternate ($4f_{sc}$) samples and averaging them with the alternate, but interleaved, samples from the previous television line. This has the effect of confining the high-frequency luminance to its predominant frequencies about multiples of line frequency, nf_H, such that its alias components interleave about odd multiples of half line frequency, $(n+½)f_H$

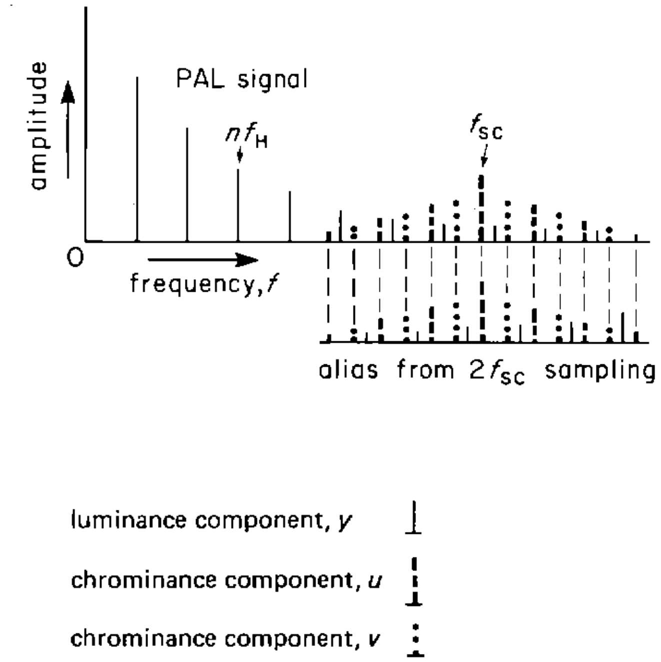


Fig. 3 Spectrum of composite PAL signal and its alias from $2f_{sc}$ sampling.

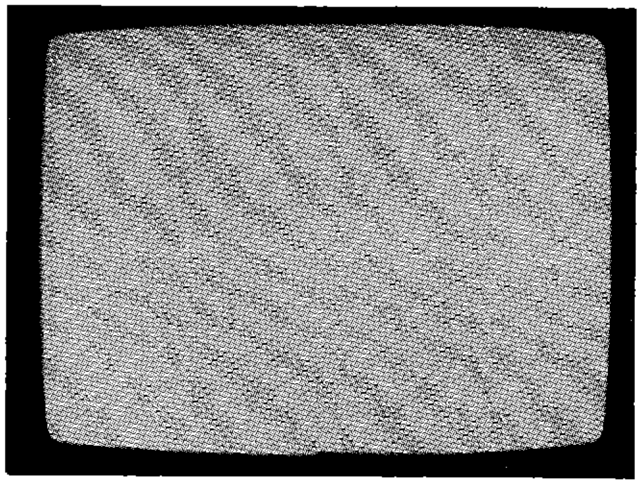


Fig. 4 'Coding loss' introduced by sub-Nyquist sampling. (Some of the 'loss' is the unwanted cross-colour in the original PAL signal and hence provides an improvement in picture quality, e.g. the patterns in the diagonal bars of the test-card picture).

(see figure 3). In addition, the phase of the initial $4f_{sc}$ sampling is chosen such that the chrominance alias components reinforce the modulated chrominance components (u,v) in the filter (figure 3). The chrominance is thus transformed into sum and difference modulation components ($u+v$, $u-v$) with unified phase on alternate television lines (as shown in figure 8).

At the decoder (figure 2b), a similar filter is employed prior to the digital-to-analogue converter to re-establish the conventional PAL signal. This filter separates the high-frequency luminance from its alias and combines the unified-phase chrominance components to reform the conventional (u,v) modulated PAL chrominance signal.

The main effects of sub-Nyquist sampling are to reduce luminance resolution on diagonal transitions and chrominance resolution on horizontal transitions. However, the latter is not normally significant, since the chrominance bandwidth of the normal PAL system restricts the resolution on vertical transitions to a greater extent.

These effects are best illustrated in the 'coding loss' picture of figure 4. The output of the sub-Nyquist sampling decoder has been subtracted from the input to the coder (for Test Card F signal) and the difference displayed on a television monitor, with mid-grey representing zero loss. However, it is interesting to note that some of the so-called 'loss' is, in fact, a reduction in the unwanted 'cross-colour' components present in the normal PAL signal!

It is seen that the loss is quite small, but nevertheless, it is possible to reduce it still further. Instead of averaging the $4f_{sc}$ samples across a line period, the delay, D in figure 2, can alternatively be a field period (313 lines)[42], or even a picture period (625 lines)[31]. In the latter case, no loss of resolution occurs on stationary pictures, but severe blurring occurs on moving transitions. The use of field delays halves the static resolution losses of the line-delays system and the movement blur of the picture-delays system. This gives perhaps the best match to the psycho-visual properties of the eye, unless a movement-adaptive system is employed. However, subjective assessments to date indicate that the simple line-delays system is adequate for high-quality broadcast use.

6 Blanking-interval suppression

The inclusion of considerable periods of waiting time in-between transmitting useful picture information seems a flagrant misuse of channel capacity, yet was largely determined by the requirement for cheap scanning circuits in domestic receivers and the inability to store a whole television field economically. Given the existence of such large overheads it is obvious that these blanking intervals should be suppressed as far as possible in point-to-point digital transmission, but be reinserted before broadcasting to the general public.

Figure 5a shows the essential elements of a blanking interval remover. After making measurements on the incoming video signal, the central controller reads the video signal into a buffer store only during active-picture periods. However it reads the video signal out of the buffer store at a continuous, but appropriately reduced rate. At the blanking reinserter (figure 5b), the reverse process occurs with the controller also operating the blanking waveform generator to fill in the gaps in the output picture signal, thus reconstructing a standard video signal.

The technique is, of course, applicable to all television coding systems with more or less equal effect, giving some 18% saving in bit rate if line-blanking intervals are suppressed, and about 24% saving if both line- and field-blanking intervals are suppressed. Figure 6a shows the blanking intervals in a normal video signal and figures 6b and 6c show the blanking-suppressed signal on a conventional monitor (6b) and on a specially-adapted monitor (6c), which shows

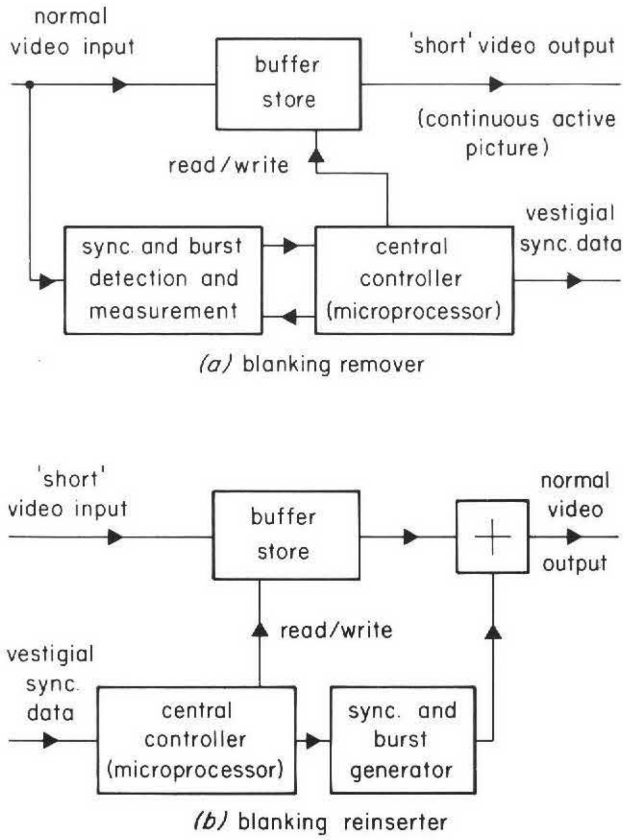


Fig. 5 Blanking interval suppression codec.

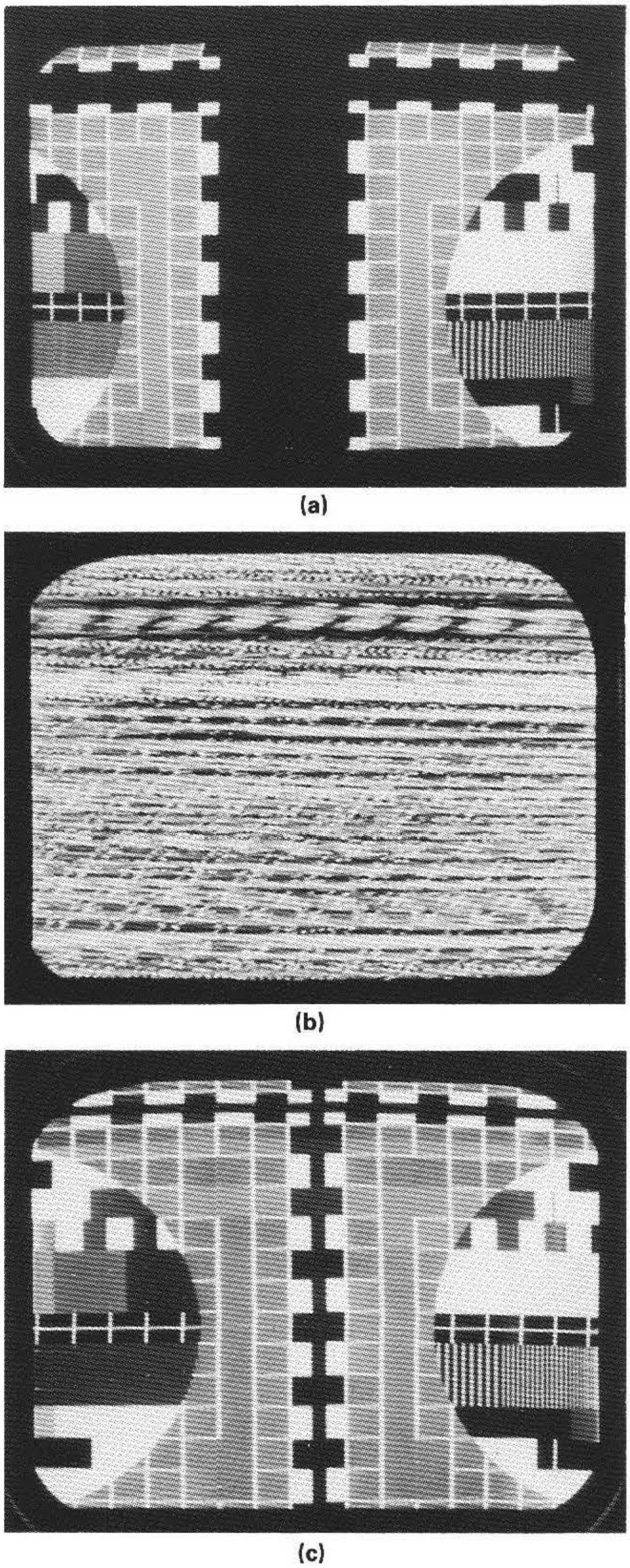


Fig. 6 Test-card pictures artificially displaced to show blanking intervals.

a) Normal picture signal.

b) Picture signal with blanking suppressed ('short' video).

c) Picture signal with blanking suppressed and viewed on a specially-adapted television monitor.

that only the active-picture information remains.

The blanking waveform regenerated at the digital receiving terminal is synchronised to the picture signal by the transmission of vestigial synchronising data. In the ideal digital world, with precisely-defined blanking intervals, a code transmitted only once per field or picture would be sufficient to maintain synchronisation. However, at present, the variation of analogue television-waveform generation and prior analogue signal processing make it necessary to ensure that the digital blanking-waveform regenerator reproduces a close replica of the blanking waveform removed at the digital transmitting terminal. Measurements of the input synchronising pulse and burst amplitudes, and their relative timings, are made and transmitted in a rugged manner, this occupying about 1% of the transmitted bit-rate. Hopefully, as digital technology spreads, the complexities of faithfully reproducing blanking waveforms distorted by previous analogue processes will disappear.

7 Differential pulse-code modulation (DPCM)

The number of quantising levels required for the video signal may be reduced by differential encoding. This is a very popular bit-rate reduction technique and relies on the considerable degree of redundancy within the television picture signal. A fairly good prediction of the signal can be made from previously transmitted information, and the

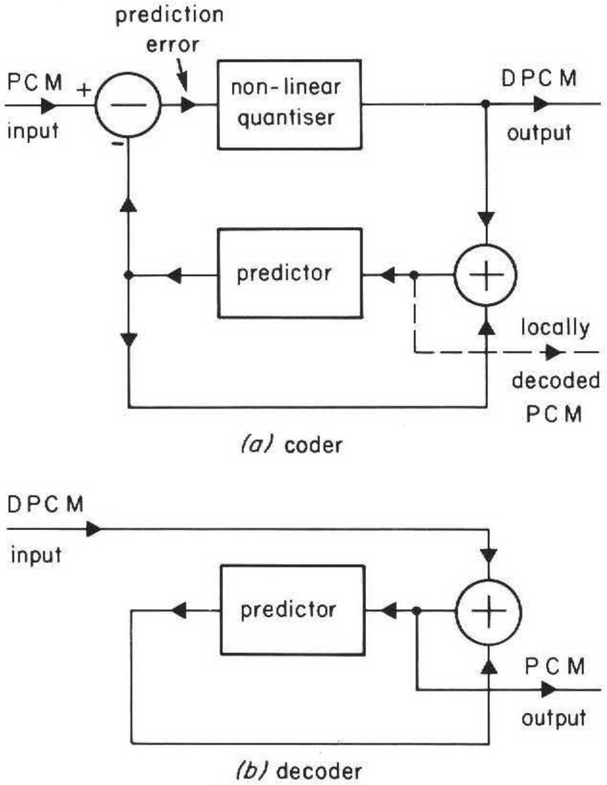


Fig. 7 DPCM codec.

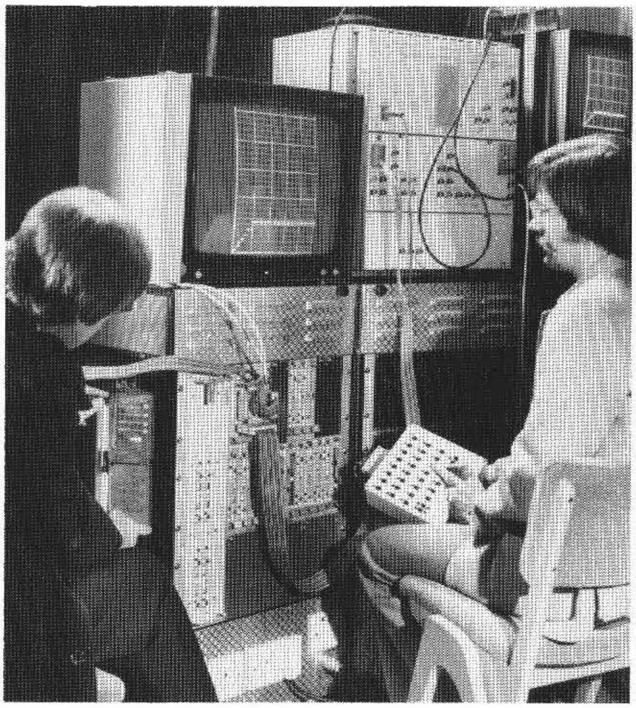


Fig. 9 Equipment for the study of video bit-rate reduction using sub-Nyquist sampling and complex DPCM. (The video monitor is displaying a 22-level, non-linear quantising law corresponding to the 4½ bits/sample available for 34 Mbit/s transmission).

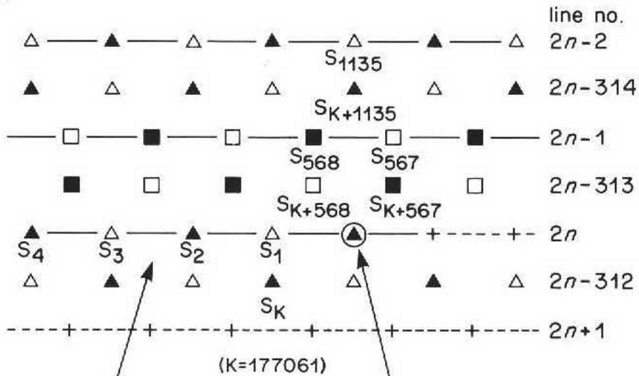


Fig. 8 $2f_{sc}$ sampling structure.

transmitted signal comprises the error between the predicted and the true signal. Figure 7 shows a block diagram of a DPCM codec. Statistically, the prediction error is small and can be substantially conveyed using a reduced number of quantising levels. Only when the picture is highly detailed does it become difficult to predict and give rise to large prediction errors. However, these large errors may be conveyed with reduced accuracy, since the eye is more tolerant to quantising inaccuracy in high-amplitude, fine-detail picture areas. The prediction-error signal is therefore subjected to non-linear quantisation before transmission, small differences being conveyed with full accuracy and larger differences with progressively reduced accuracy. Thereby, the total number of quantising levels required may be significantly reduced without introducing large subjective impairments.

With the composite PAL signal, the problem is how to apply the DPCM technique such that no loss of accuracy occurs in plain coloured areas. This is where the eye is most sensitive to contouring effects produced by insufficient quantising accuracy. The solution is to make a predictor which is good for steady-state chrominance modulation as well as DC. Figure 8 shows the $2f_{sc}$ sampling structure in a plain coloured area for one television picture. It can be seen that a simple prediction which satisfies this criterion is the second-previous sample value, S_2[41]. However its luminance frequency response is somewhat limited, and only a modest bit-rate saving can be made without generating perceptible impairments on critical pictures. A 6-bit non-linear quantising law has been used successfully in experimental digital-television transmission equipment operating at 60 Mbit/s[43].

For greater compression, a more highly-tapered quantising characteristic must be used. Television transmission at 34 Mbit/s requires that the video signal be reduced to about 31 Mbit/s to allow sufficient capacity for sound, ancillary signals and error-protection coding. Assuming sub-Nyquist

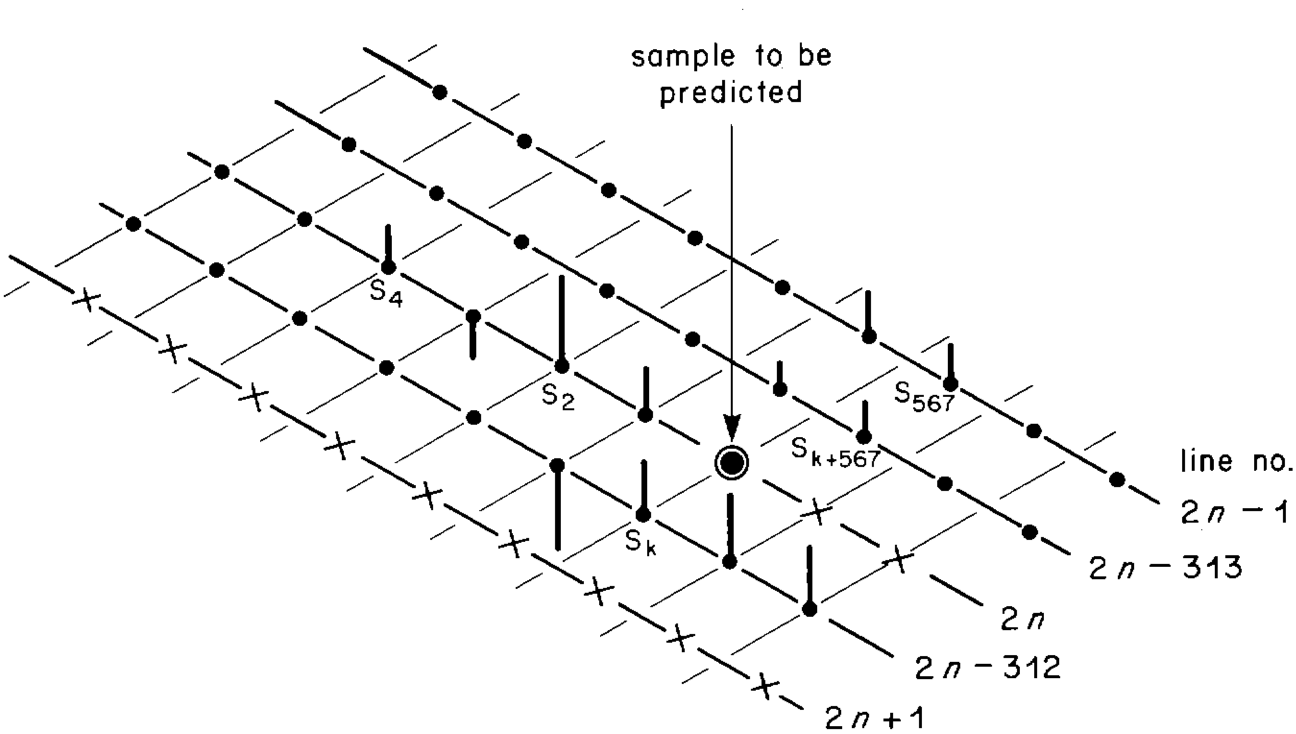


Fig. 10 Isometric diagram showing the sample weights of a complex prediction.

sampling and full blanking-interval suppression, this permits a mean of 4½-bits/sample to be transmitted (in practice, one 9-bit word represents two sample values). Thus the DPCM quantiser can have only 22 states, and such a characteristic may be seen displayed on the television monitor in figure 9, which also shows the experimental equipment.

It therefore follows that the prediction must be improved to provide a more highly-peaked distribution of the prediction error. An appropriately-weighted sum of the sample values back along the television line gives some improvement, but a prediction gain (the ratio of the mean-square prediction error for the predictor to that for the simple second-previous sample predictor) of only about 2 dB may be realised. Greater gains can be achieved by spreading the prediction into two dimensions, but normally the action of the v-axis switch, present in the PAL signal, complicates the use of samples in the previous line, necessitating the use of an adaptive predictor[35]. However, the sub-Nyquist sampling technique unifies the phase of colour subcarrier (in a plain coloured area, see figure 8) so that samples in the previous line can be used in a static predictor, although they do not contribute usefully to the chrominance prediction. Prediction gains of about 4 dB have been measured, but this is still not enough to provide broadcast-quality pictures with a 4½ bits/sample quantiser. However, if the previous-field samples are also stored, access to the interlace lines on both sides of the sample to be predicted is obtained. For stationary pictures a prediction gain of about 8 dB over the simple second-previous sample predictor may be achieved, by using the temporal dimension to improve the spatial resolution. Picture movement, however, may be expected to reduce this gain.

Initially, the sample weights were computed using a simple statistical model of the television signal[29], assuming it to be a first-order Markov source. However, because of the modulated chrominance of the PAL signal, an additional constraint was added in the computation of the sample weights of 'optimum' predictors, requiring steady-state colour to be predicted correctly. Thus the conditions which must be satisfied are:

(a) the sum of the predictor coefficients (sample weights, S_m) equals unity

(b) the sum of the even coefficients minus the sum of the odd coefficients on even lines equals unity

and (c) the sum of the even coefficients minus the sum of the odd coefficients on odd lines equals zero

where the sample to be predicted is considered to be even on an even-numbered line, $2n$.

A fixed temporal aperture was also assumed when computing complex predictors using both present- and previous-field sample values, and a previous-field correlation factor was determined empirically to be in the range of 0·8 to 0·9 for normal moving pictures. A typical complex-prediction algorithm is illustrated in figure 10.

The model gave quite good results on typical test pictures but was optimistic in its calculated prediction gains for pictures with large amounts of luminance detail and little chrominance.

Subsequently it became possible to transfer digital video signals to a computer for statistical analysis. 'Optimum' predictors were computed by minimising the mean-square prediction error, subject to the constraints listed above, for a range of standard test slides chosen to represent normal broadcast pictures. Subjectively these predictors give the

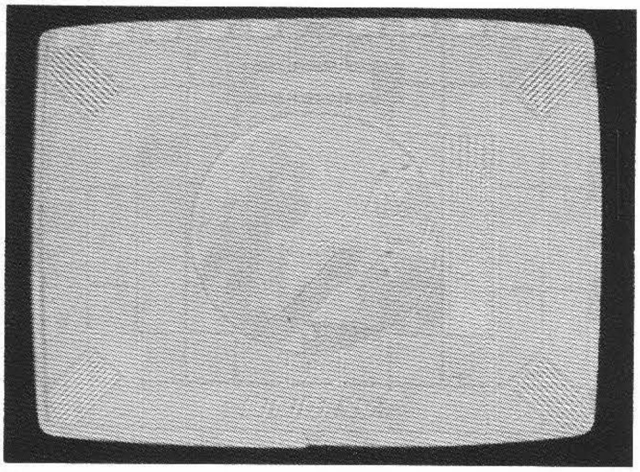


Fig. 11 Prediction error for complex, 14-coefficient, mixed-field prediction.

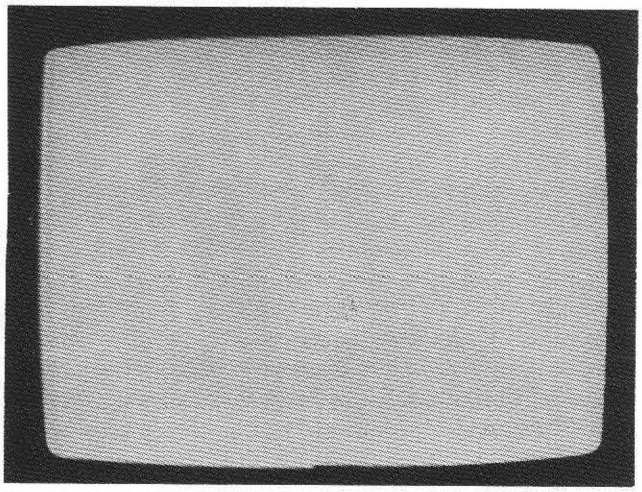


Fig. 12 Coding loss for 4½-bit, complex-prediction DPCM*.

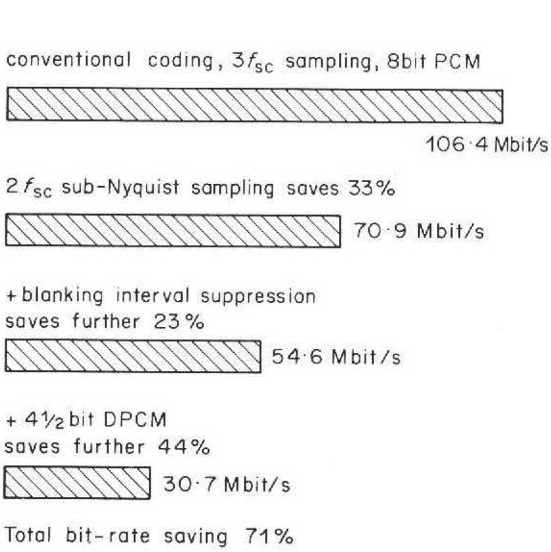


Fig. 13 Video bit-rate savings.

*Some loss is *just* apparent in the original photograph!

best results for the number of coefficients employed, and a 14-sample predictor, comprising samples from three lines in each field, gives remarkably good results. Figure 11 shows that the amplitude of the prediction error is small for the whole of the test card picture.

The non-linear quantising characteristics are initially derived by minimising the mean-square quantising error, but this gives a somewhat too-tapered shape, and final optimisation is achieved subjectively.

It has been found that a complex mixed-field predictor is admirably well suited to the characteristics of the human visual system. On stationary pictures and for slow movement, the prediction error remains small, such that the loss introduced by the non-linear quantiser is virtually imperceptible. In fact, it is only by subtracting the system output from its input and displaying the difference on a television monitor, as shown in figure 12, that we know where to look for any loss! As movement speed is increased, significant quantising errors appear on the loss pictures, but on the actual decoded pictures the movement is such that the eye is not able to resolve the loss of resolution of the moving transitions.

Many workers have used a spatially-coincident, previous-picture sample as a prediction for low bit-rate video systems, but, in contrast, we have found that use of previous-picture samples, either alone or in a mixed-picture predictor, gives rise to severe movement blurring and would require movement-adaptive techniques to be useful for high-quality broadcast pictures.

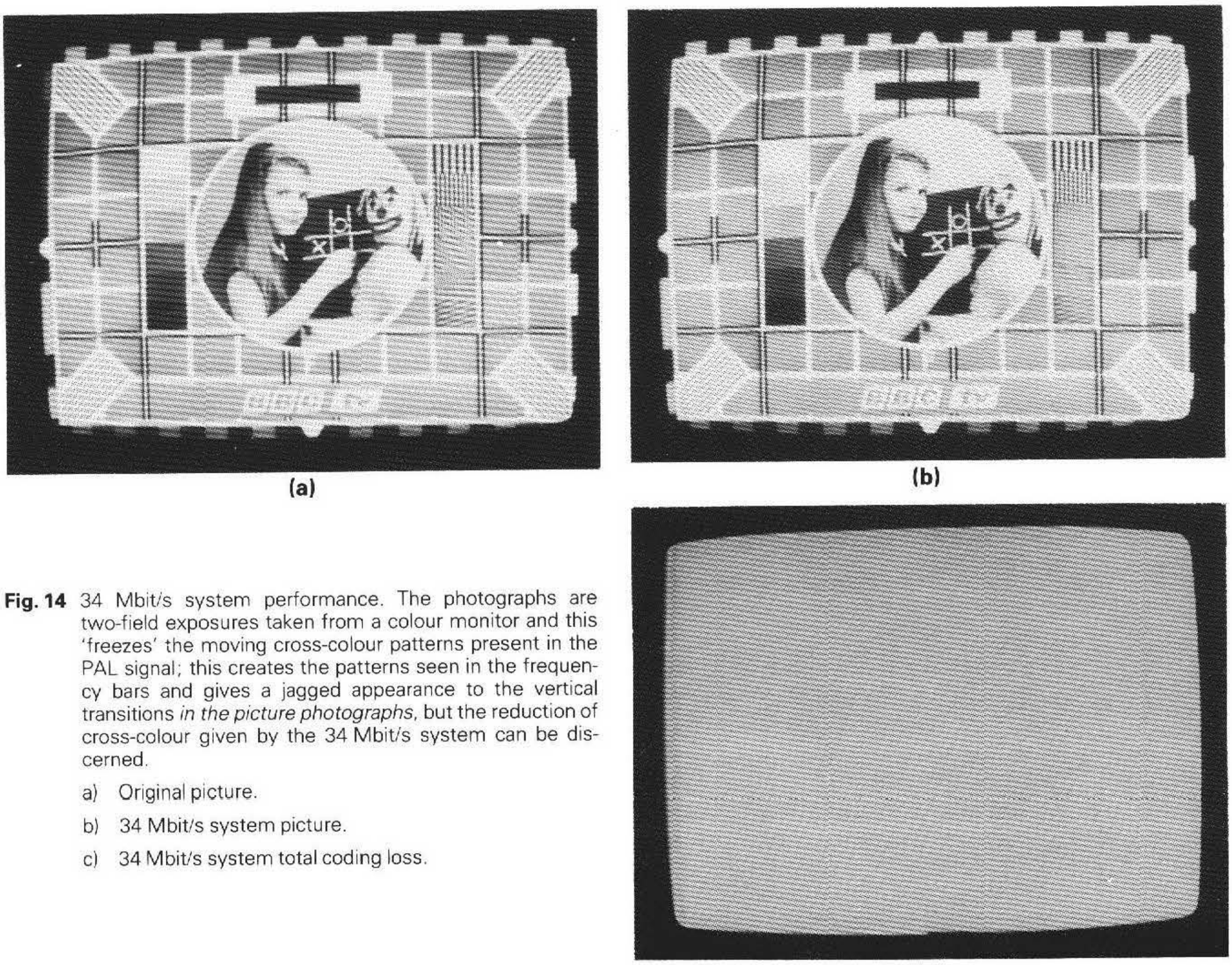
The necessity of using rather spread predictors, and in using previous-field samples rather than previous-picture samples, has proved a considerable advantage in designing a static three-dimensional predictor for the PAL signal. It provides sufficient gain to be able to reduce the number of quantising levels to 22 in the DPCM system, with negligible subjective loss in quality.

8 Transmission at 34 Mbit/s

Figure 13 shows that use of the three bit-rate reduction techniques described, namely sub-Nyquist sampling, line- and field-blanking interval suppression, and DPCM, make a total bit-rate saving of 71% possible when compared with conventional PCM coding of the composite PAL colour television signal. More importantly, such a system causes negligible subjective impairment to high-quality broadcast pictures, as can be seen in figure 14.

A complete television transmission system additionally requires to convey the associated sound signal(s) and the field-interval signals (e.g. CEEFAX, ICE), and figure 15 illustrates the composition of a system for transmission at the third-order multiplex rate of 34·368 Mbit/s.

About 7% of the total bit rate is reserved for error protection of the television signals, to overcome the deleterious effects of errors which can occur on the transmission path; this is discussed in the next section. A small margin also exists for ancillary signalling (for engineering purposes) and for multiplexing the various signals together asynchronously. This includes framing and justification data required by the receiving terminal to demultiplex the various signals



(a) (b) (c)

Fig. 14 34 Mbit/s system performance. The photographs are two-field exposures taken from a colour monitor and this 'freezes' the moving cross-colour patterns present in the PAL signal; this creates the patterns seen in the frequency bars and gives a jagged appearance to the vertical transitions *in the picture photographs*, but the reduction of cross-colour given by the 34 Mbit/s system can be discerned.

a) Original picture.

b) 34 Mbit/s system picture.

c) 34 Mbit/s system total coding loss.

into their separate bit streams again.

Thus a complete digital broadcast television signal can be conveyed with a transmission capacity equivalent to only 480 digital telephone channels. In contrast, a system using conventional coding would occupy a capacity equivalent to about 1650 telephone channels.

9 Transmission performance

In any proposed transmission system the effects of transmission errors must be carefully considered. A problem often encountered when redundancy-reduction techniques are employed is that the removal of signal redundancy also removes the ruggedness to transmission errors which may occur in a practical system. The deliberate addition of a little redundant information in the form of error-correction coding can be arranged to better match the channel characteristics to those required by the signal, but this is only a partial solution. There is a danger of removing redundancy to achieve maximum bit-rate reduction on the one hand, only to have to put it all back again in order to provide sufficient ruggedness to transmission errors.

In the system described here, the choice of DPCM predictor coefficients has been carefully controlled to minimise the subjective effects of transmission errors, whilst maintaining high prediction gain. A rapid decay of the impulse introduced by an error is required, rather than its integration at the decoder, as with simple DPCM systems. One solution is to introduce a 'leak' into the predictor by deliberately ensuring that its frequency response is less than

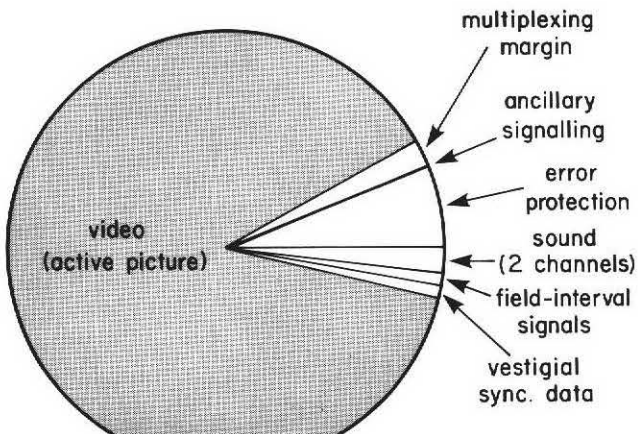
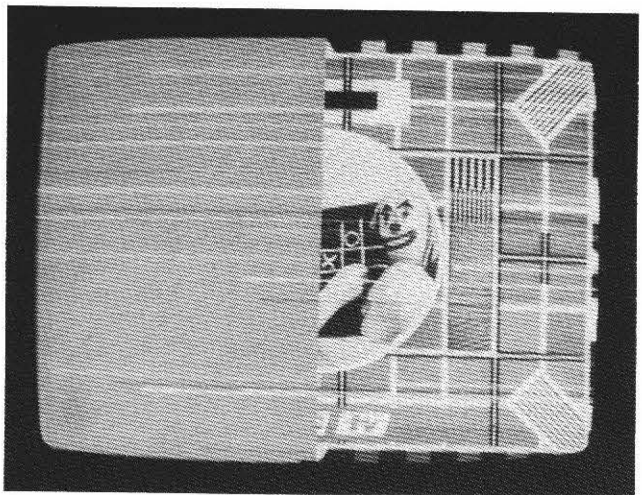
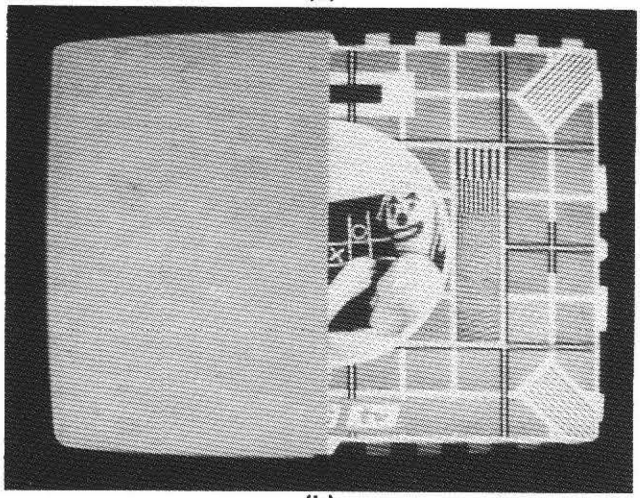


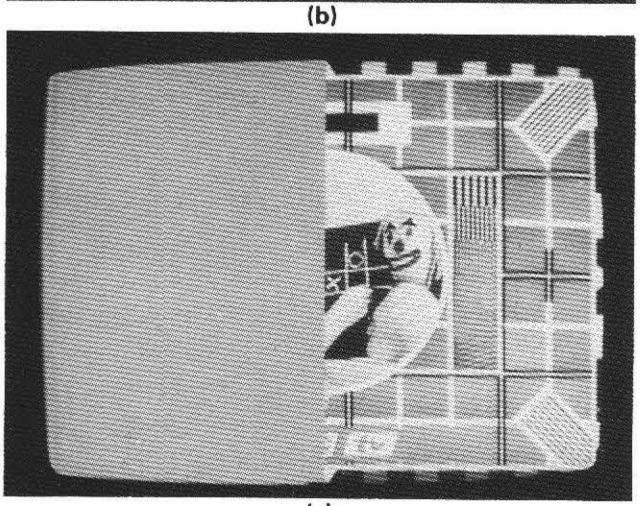
Fig. 15 Division of the bit rate in the 34 Mbit/s digital television transmission system.



(a)



(b)



(c)

Fig. 16 Effect of transmission errors at a bit error ratio of about 10^{-4} (a split screen shows the errors in isolation on the left and in the decoded picture on the right. Note that the two-field exposure of the photographs has the effect of making the PCM errors (c) appear relatively *less* annoying than in reality).

a) System using simple DPCM.

b) 34 Mbit/s system using complex DPCM.

c) PCM system.

unity at all frequencies. With simple predictors the prediction gain falls rapidly if the leak is sufficient to make the error decay short. However, with the complex mixed-field predictor described, greater control of its frequency response is possible and a very small leak may be introduced, having little effect on the prediction gain, but a dramatic effect on error-decay rate. Quantitatively, a good measure of the error performance of a DPCM system is gained from its stability margin, determined from a Nyquist plot of the open-loop frequency response of the decoder, i.e. that of the predictor. This is included in the computer optimisation procedure.

Figure 16 (view picture-side of photographs) shows that, in contrast to a simple DPCM system having second-previous sample prediction (figure 16a), the complex DPCM system with mixed-field prediction (figure 16b), is almost as tolerant to transmission errors as PCM (figure 16c). The bit-error ratio in the photographs is abnormally high, in excess of 10^{-4}, whereas the random bit-error ratio at which errors are just perceptible is about 10^{-8} for the 34 Mbit/s system.

In practice, it is expected that most terrestrial digital circuits (radio, line, and optical fibre) will be virtually error free most of the time, although some satellite circuits may exhibit a continuous bit-error ratio of the region of 10^{-8}. However, with suitable error-correction coding, requiring an additional 6-7% of the video bit rate, protection to bit-error ratios up to about 10^{-4} is quite feasible, even when the errors occur in short bursts, as is common with the digital modulation and scrambling techniques commonly used in digital transmission systems.

10 Conclusions

Television remains one of the most bandwidth-greedy forms of communication even in these modern times. It is not for the lack of effort over the last thirty years that the actual bit-rate requirements are still a million times greater than a single human observer can absorb. Nevertheless, considerable strides have been made with wide-spread use of digital techniques over the last twenty years, and for broadcast-quality colour television in particular, the last decade has seen some notable achievements and realisable systems. Many different compression techniques have been applied and there is no obvious universal solution. There will no doubt continue to be as many diverse systems as there are differing quality, bandwidth and cost factors to be met.

However, three complementary bit-rate reduction techniques have been presented here which are particularly tailored to take advantage of the attributes of the composite PAL colour television signal. It is thought that they offer the best picture quality yet obtained in the region of 30 Mbit/s for PAL colour television signals, and this is likely to be adequate for normal broadcast-signal distribution at the European third-order multiplex level of 34·368 Mbit/s. There is also a possible application in transmitting high-quality television pictures over a half-bandwidth satellite transponder.

Nevertheless, bandwidth compression, however elegant or satisfying in engineering terms, is not inexpensive, and how much compression is viable will inevitably be a complex economic question, no doubt favouring greater bandwidth compression with time, as channel capacity becomes ever more precious, and complex instrumentation more cheaply available.

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The Electronic Zone Plate and Related Test Patterns

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Research Department

Summary: Many television processes, such as noise reduction, improved colour coding and standards conversion, depend on combining nearby lines and fields of the source picture. Until recently, there has been no way of examining the fundamental properties of these systems. This article presents a new family of test patterns which enable the research engineer to investigate and optimise these systems methodically. They contain periodic (e.g. sine wave) gratings of all possible pitches, slopes and rates of movement. The patterns can be generated electronically and an indication of the method is given.

1 Introduction

In evaluating the characteristics of television systems, the familiar range of test signals used consists of stationary vertical gratings such as line sweep, multiburst, or test-card resolution bars. Although these can be used to reveal a great deal about simple one-dimensional television systems such as filters, cables and amplifiers, they cannot be used to determine the properties of more sophisticated systems which combine signals from different scan lines or pictures (e.g. vertical-aperture correctors, comb-filter coders, sub-Nyquist sampling systems, noise reducers and standards converters). These systems must be investigated using patterns which change from line to line and/or from picture to picture.

BBC Research Department first investigated such systems using electronically generated gratings, which could be adjusted to any pitch, slope and speed of motion. However, since only one pattern could be produced at a time, a thorough investigation of a complex system such as a standards converter was an extremely time-consuming process. This situation was eased for stationary patterns by the use of a two-dimensional frequency sweep called the circular zone plate[1]. This contains all possible spatial frequencies at all possible slopes but, until recently, it was only available as an optical test card from which inevitably imperfect signals were obtained by means of a television camera or slide scanner.

In order to provide more consistent test signals than those obtainable from a slide, an alternative two-dimensional frequency sweep pattern called the hyperbolic zone plate[1] (or Girard Grille)[2] was generated electronically (digitally). This pattern, although relatively easy to generate, is slightly less easy to interpret than the circular zone plate, and the lack of movement limits the usefulness of both patterns.

A new electronic (digital) pattern generator has now been developed[3], which can produce not only stationary patterns such as hyperbolic and circular zone plates, but also moving patterns; it thus enables the user to examine the temporal as well as the two spatial frequency characteristics of a system. This article illustrates some of the patterns which can be produced and describes briefly how they are generated.

2 Principles

It is convenient to describe periodic (e.g. sine-wave) gratings by specifying the phase of the signal waveform at each point in the picture. This article describes the set of patterns corresponding to a phase ϕ varying from point to point and from picture to picture according to the general second-degree equation in x, y and t (respectively, horizontal position, vertical position and time):

$$\begin{aligned}\phi = k_\phi &+ k_x.x &&+ k_y.y &&+ k_t.t \\ &+ k_{yt}.y.t &&+ k_{xt}.x.t &&+ k_{xy}.x.y \\ &+ \tfrac{1}{2}k_{x^2}.x^2 &&+ \tfrac{1}{2}k_{y^2}.y^2 &&+ \tfrac{1}{2}k_{t^2}.t^2 \end{aligned} \quad (1)$$

Any spatio-temporal frequency can be resolved into three frequency components, i.e. the horizontal, vertical and temporal. The horizontal component is the rate of change of phase in the horizontal direction:

$$\frac{\partial\phi}{\partial x} = k_x + k_{x^2}.x + k_{xy}.y + k_{xt}.t \quad (2)$$

Thus k_x controls the horizontal frequency component at the origin and k_{x^2}, k_{xy} and k_{xt} control the rates at which this

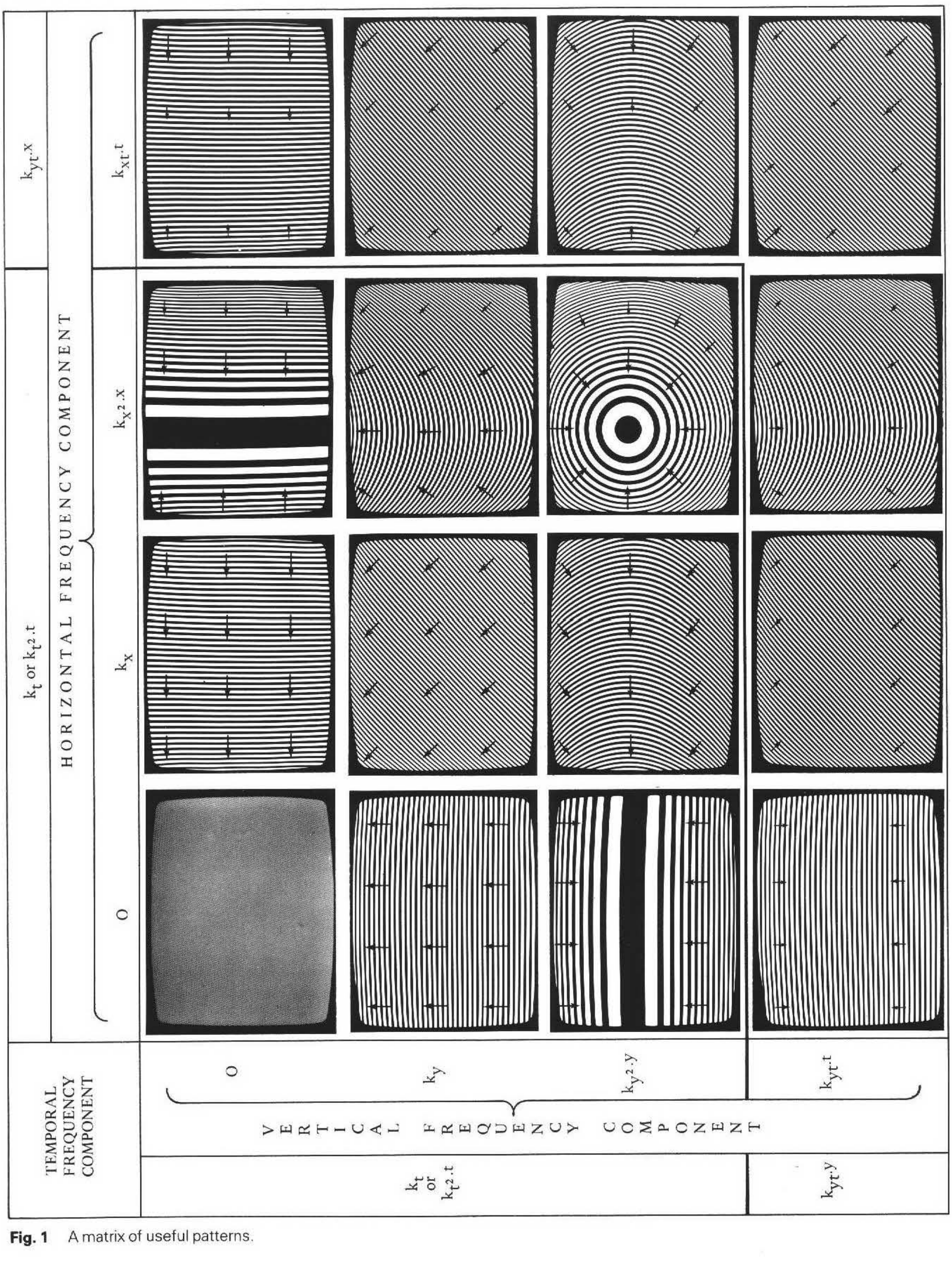


Fig. 1 A matrix of useful patterns.

component of the frequency varies with horizontal position, vertical position and time.

Similarly, the vertical frequency component is:

$$\frac{\partial \phi}{\partial y} = k_y + k_{xy}.x + k_{y^2}.y + k_{yt}.t \quad (3)$$

and the temporal frequency component is:

$$\frac{\partial \phi}{\partial t} = k_t + k_{xt}.x + k_{yt}.y + k_{t^2}.t \quad (4)$$

So vertical and temporal frequency components can also be made to vary with position and time.

3 Useful patterns

Full use of the ten coefficients in Equation (1) would produce an almost limitless range of possible patterns. In the prototype generator each of the coefficients is controlled by a sixteen position switch, which gives a total of more than 10^{12} possible combinations. Fortunately, the most useful patterns have most of the coefficients equal to zero, so that each of the three frequency components is either zero, fixed, or a function of only one of the three variables (x, y or t). Figure 1 illustrates 16 of these restricted patterns. They are arranged in a matrix in which the horizontal frequency components is zero for the left hand column of photographs, fixed for the next column, proportional to x for the third column and proportional to t for the right hand column. Similarly, the vertical frequency component is zero in the top row, fixed in the next row, proportional to y in the third row and proportional to t in the bottom row. Two very important patterns which do not fit into this matrix are illustrated in figure 2.

The patterns in the right hand column and in the bottom row are inherently moving since their properties are functions of t. The other nine patterns can be made to move by adding the time terms $k_t.t$ or $\frac{1}{2}k_{t^2}.t^2$. The direction and speed of movement is indicated by the arrows. For clarity, figures 1 and 2 are two-tone photographs of low-frequency patterns.

3.1 Spatial frequency sweeps

One of the most important patterns is the circular (or elliptical) zone plate (figure 1, third row, third column) in which the horizontal frequency component is proportional to horizontal displacement from the centre of the circles and the vertical frequency component is proportional to the vertical displacement. This pattern contains all possible slopes of pattern – horizontal, vertical and diagonal – with a range of pitches depending on the sweep rates of k_{x^2} and k_{y^2}. If k_{x^2} and k_{y^2} are not equal, an elliptical pattern is obtained.

The term $\frac{1}{2}k_{t^2}.t^2$ makes the temporal frequency proportional to time. Adding this to the circular zone plate gives a truly three-dimensional frequency sweep which has been named the 'spherical zone plate' (although the third dimension is time and not space).

Figure 2(a) shows a very closely related pattern produced by changing the sign of the $k_{y^2}.y^2$ term. This changes the circles into hyperbolas, but horizontal frequency is still proportional to horizontal displacement and vertical frequency to vertical displacement.

Rotating figure 2(a) by 45° gives figure 2(b) which is also a two-dimensional frequency sweep. In this case, the horizontal frequency component is proportional to vertical displacement and the vertical frequency component is proportional to horizontal displacement. Because of its very simple phase-function ($\phi = k_{xy}.xy$) this hyperbolic zone plate was the first two-dimensional frequency sweep to be generated electronically at BBC Research Department[1]. However, because of its more obvious symmetry the circular zone plate is much easier to interpret and tends to be preferred now that it too has been generated electronically.

3.2 Temporal frequency sweeps

Although patterns containing the term $k_{t^2}.t^2$ presents all possible temporal frequencies, they do so sequentially. In many applications in which temporal frequency is of interest it would be more useful to plot temporal frequencies along the x or y axis so that all temporal frequencies are simultaneously available for comparison. This may be achieved by using the terms $k_{xt}.xt$ or $k_{yt}.yt$ as illustrated in figure 1 by the moving patterns in the right hand column and bottom row respectively.

In particular, the third pattern in the right hand column combines a horizontal sweep of temporal frequency with a vertical sweep of the vertical frequency component. It thus plots vertical and temporal frequency components along the vertical and horizontal axes respectively. This is particularly useful for studying the vertical and temporal interpolation of field store standards converters.

4 Instrumentation

4.1 Phase computation

In order to generate the required patterns, the generator must calculate the phase ϕ according to Equation (1) for each sampling point in the picture. If the sampling frequency is line locked so that the sampling points are vertically aligned, then x can be defined as the number of samples from the left-hand side of the picture, y can be defined as the number of lines from the top of the picture and t as the number of fields since last reset by the operator. Because of interlace, y increases each line in steps of two so that for one of the two interlaced fields y is even and for the other field y is odd.

The number $k_t.t$ increases each field during field blanking by the amount k_t. It can thus be generated by an accumulation circuit (figure 3) which stores the present value of $k_t.t$ and adds k_t to it during each field blanking period.

Similarly, $k_y.y$ can be generated by an accumulator which stores the present value and adds $2.k_y$ to it during each line blanking period, the accumulator being reset at the top of each picture to values differing by k_y on odd and even fields. Similarly, $k_x.x$ is generated by an accumulator which adds k_x once per sample and is reset at the beginning of each line.

Generating the three 'cross-product' terms ($k_{xy}.x.y$, $k_{yt}.y.t$ and $k_{xt}.x.t$) is a two stage process. For example, $k_{xy}.x.y$ is a number which increases each sample by $k_{xy}.y$ which itself is a number which increases by $2k_{xy}$ for each line of the field. The term $k_{xy}.x.y$ can thus be generated by a sample rate accumulator which is reset at the beginning of each line and then, for each sample, adds the output of a line rate accumulator which is reset at the beginning of each field.

The 'squared' terms are also generated by a two stage process. For example $\frac{1}{2}k_{x^2}.x^2$ increases each sample by ($k_{x^2}.x$ - $\frac{1}{2}k_{x^2}$) which itself increases each sample by k_{x^2}. It is thus generated by two element-rate accumulators in tandem.

As the accumulations continue the phase will go through many complete cycles, but since only the fractional part is required, the accumulators need only count fractions of a cycle and can be allowed to over-flow after each complete cycle.

4.2 Waveform synthesis

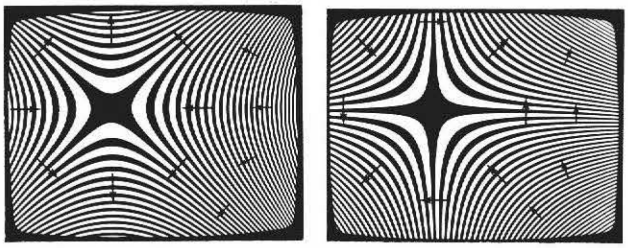
Having calculated the phase of each point it is then necessary to convert this to an output signal of the required waveshape. If the phase number were used directly as the video output (either as a digital signal or through a digital to analogue converter) then a sawtooth waveform would be produced. This waveform contains a large number of harmonics and is thus not suitable for measuring response/frequency characteristics. A better (although still not perfect) waveform is the triangular wave. This can be obtained from the sawtooth phase signal by doubling the gain and inverting the top half of the signal.

The only way to produce an output free of harmonics is to generate a sine wave. This can be achieved by a read only memory (ROM) programmed with the values of sin ø for each value of ø that the generator can produce. In practice, only half a cycle of sine wave is stored in the ROM and its input is addressed by the triangular wave.

A sine wave may eventually be distorted by the non-linearity of the display tube. So for some applications, it is useful to generate pre-corrected sine waves using another ROM. Other ROMs can be programmed to generate any other useful waveshapes.

5 Conclusions

The set of test patterns corresponding to phase varying according to the general second degree equation in x, y and t contains some extremely useful patterns for rapidly displaying the response/frequency characteristics of television systems in up to three dimensions. This paper has illustrated the most useful patterns and described how they may be generated digitally. It is now the subject of a licensing arrangement with a manufacturer.



(a) (b)

Fig. 2 Two other useful patterns (hyberbolic zone plates). (a) x^2, y^2 and time terms (x^2 and y^2 coefficients of opposite polarity). (b) x.y and time terms.

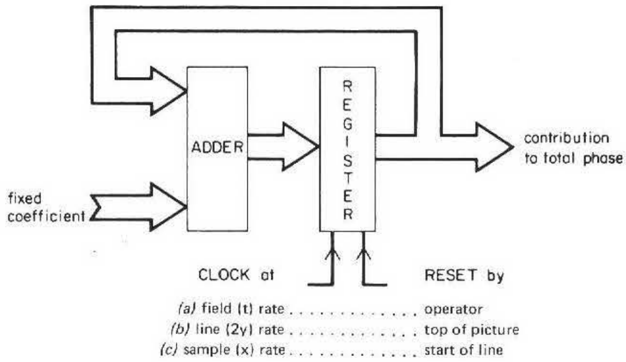


Fig. 3 A basic accumulator circuit.

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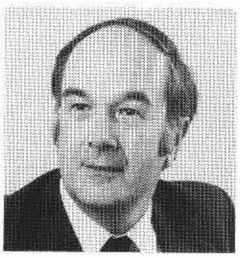
Contributors to this issue



Peter Rainger is the BBC's Deputy Director of Engineering.

After the war he took his degree in Electrical Engineering at Northampton Engineering College, London University. He joined the BBC as a graduate engineer in 1951 and worked on film equipment, later moving to the field of magnetic recording and then signal-processing equipment of various types. In 1969 he became Head of Designs Department and was appointed Head of Research Department in 1971 where he was responsible for work on many new developments. Subsequently, he was promoted to the post of Assistant Director of Engineering and then Deputy Director of Engineering where he has responsibility for all Research and Development and the other specialist departments involved in capital projects throughout the BBC.

In 1978 he was honoured with the CBE.

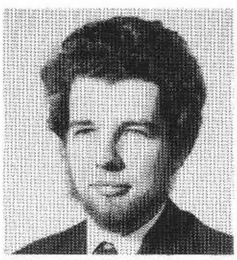
Charlie Sandbank joined the Brimar Valve Division of STC as a production engineer in 1953, after obtaining a degree in Physics at London University. In 1955 he obtained a post-graduate fellowship at Imperial College, where he spent a year under the supervision of Professor Denis Gabor and was awarded the DIC.

On his return to STC (at Footscray) he was engaged in valve development until 1959 when he transferred to the Transistor Division, and soon afterwards led the team which developed the first silicon-chip integrated circuits in Europe. In 1964 he joined STL to become Head of the Electron Devices Department. In addition to microelectronics research he took a particular interest in solid-state microwave generation and display.

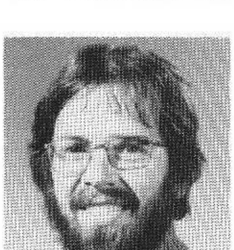
In 1969 he became Manager of the Communications Systems Division, where he placed particular emphasis on advances in communication by combining new technology with new systems concepts such as fibre-optic communication, micro-electronic radio systems, microwave navigational aids, and integrated local area systems. In 1976 he became Head of Advanced Technology and Defence at STL.

In September 1978 he joined the BBC as Head of Research Department at Kingswood.

Geoffrey Phillips read Natural Sciences at Cambridge University from 1942 to 1944, and again in 1947 after three years with the Admiralty. Following post-graduate work at Cambridge on movements in the ionosphere, he joined the BBC in 1951. He has worked most of the time in the Research Department on aerials, receivers and transmission systems. From 1972 to 1976 he was Head of Transmission Group of Research Department, and became involved in work on digital systems, as well as the use of satellites for broadcasting. His present position, held since 1976, is Head of Radio Frequency Group.



Paul Ratliff graduated from the University of Birmingham in 1969 with a first-class honours degree in electronic engineering. He was awarded a BBC Research Scholarship and remained at the University to study VHF multipath fading and diversity reception techniques for mobile radio, for which he gained his Ph.D in 1973. He joined BBC Research Department in 1972 where he has worked since, on both sound reproduction and digital video. In 1977 he became senior engineer to manage the digital video bit-rate reduction project and other digital transmission work, including experiments with the Orbital Test Satellite (OTS) and various terrestrial digital transmission circuits.



Martin Weston joined the BBC Research Department in 1970 after graduating in Electrical Sciences at Clare College, Cambridge. He has worked on television shot-change detection, digital telecine processing and aperture correction, noise and grain concealment, sub-Nyquist sampling of PAL television signals, the international distribution of digital colour television signals in YUV form, and complex decoding of PAL television signals. The Electronic Zone-Plate was developed to aid testing and to improve understanding of these systems.

He is at present working on computer graphics and colour separation overlay.