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

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The Presidential Address of

Percy A. Allaway, C.B.E., D.Tech., C.Eng., F.I.E.R.E.*

Presented after the Annual General Meeting of the Institution in London on 6th October 1976

It is exactly 44 years ago that our Institution became an incorporated body and elected its first President. A glance at the list of members who have succeeded to that high office is, for me, daunting; all of them have been leaders who have added lustre to our profession and to the office of President by their contribution to our status as a Chartered Institution.

As an ordinary member I was in awe of my predecessors and it is with deep feeling that I express my thanks to so many of our Past-Presidents and Vice-Presidents, for their nomination and to our Council and all our Corporate Members for their kindness in electing me to this office.

Our Institution has been fortunate in establishing the tradition of Past-Presidents continuing to give help. I was heartened, therefore, to hear Your Royal Highness say at the end of our Annual General Meeting that you will continue to assist the Council in its deliberations. We welcome this statement because of your contributions to our work in recent years and your help in what has been a momentous yet difficult Golden Jubilee Year.

Even more, however, we in the Institution are delighted that Your Royal Highness will continue, as the Vice-Chairman of the National Electronics Council, to play such an important part in guiding the future of the British electronics industry. We shall rejoice if you follow another Past-President, Lord Mountbatten, as the Chairman of the National Electronics Council.

Against the background of all our Past-Presidents I have given much thought for the theme of my Presidential Address. I came to the conclusion that our members might prefer to hear my views as an engineer who has been more concerned with design and production than research and who has been distressed to hear criticism of the engineer because of the faults found in goods and projects of his creation. I do not wish to apportion blame but unreliability also extends to human beings. I wish later on to examine the whole chain of human endeavour so that we can all know the weakest links in the chain of the design and manufacturing processes.

The Engineer and Quality.

For many years I have been associated with the search for better quality products. My intense interest was stimulated by 18 months of association with George Raby—a Past-President—when I was included in his team to make a study for the Ministry of Defence and the then Ministry of Technology on the Government's nine Defence Inspectorates; we were asked to see what could be done to rationalize and improve those nine systems.

May I remind you of those nine Inspectorates that have done so much for engineering over many years: E.I.D., A.I.D., D.I.Arm., I.N.O., N.W.P.O., S.D.O.S., I.F.V., C.I. and I.S.C.†

Out of this study (which was presented in 1969 and approved by the Government in its entirety) has emerged a new series of Defence Standards for an integrated system to achieve quality and its assurance. This system is now controlled by the Defence Quality Assurance Board of the Ministry of Defence Procurement Executive and is known as the 05–20 series of documents. As a matter of interest it is the first common system we have had for all three Services and equates to the NATO 'AQAPS' system.

One of the most important points which emerged during the Raby Study was the realization that the specifications and design information available for many products studied left much to be desired; this being so, no amount of highly skilled inspection can possibly make good design deficiencies. In other words,

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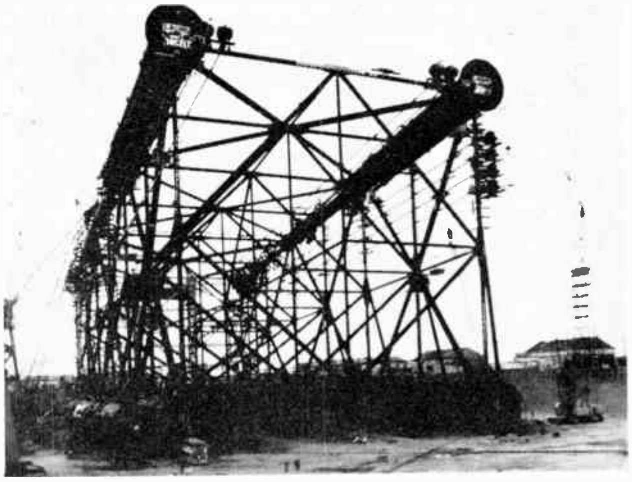
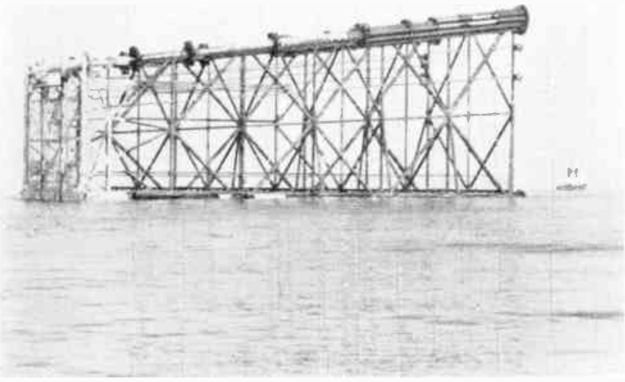
* EMI Electronics Limited, Hayes, Middlesex.

† See Appendix.

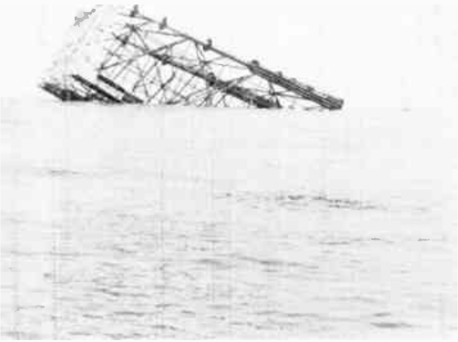
1. Double decker bus compared with foot of structure



2. Bus compared with whole structure



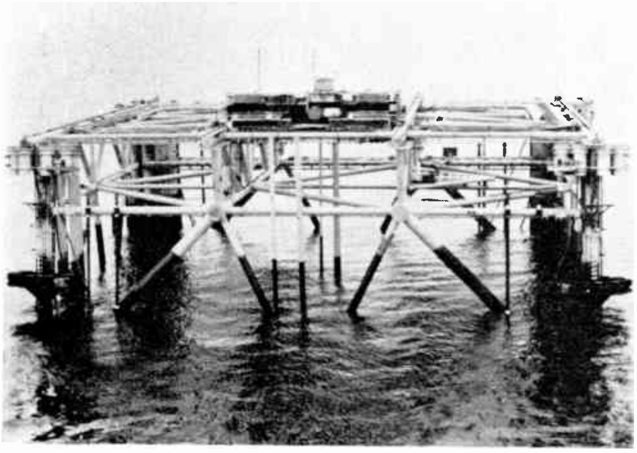
3. Structure in tow-out mode



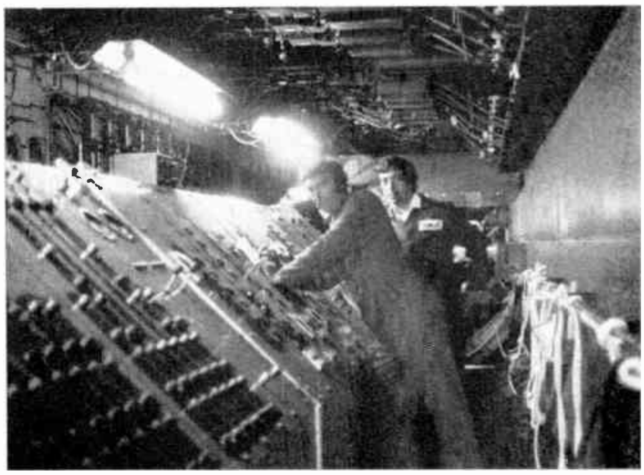
4. Long shot of 1st stage tilt

5. 1st stage tilt showing roll

6. 2nd stage tilt



7. Structure on sea bed



8. Remote control consoles on the control ship

Fig. 1. Placement of the Burmah *Thistle 'A'* platform.

we have a worry on our hands. A worry, incidentally, that is getting publicity in a lot of places at the moment. Let me quote from *The Times* of 13th September:

'In its monthly economic report published today the London Chamber of Commerce and Industry states:—"Without dramatic improvement in design—delivery—quality—performance and reliability, we seem doomed to live with the same economic problems which have proved so intractable in the past".'

How then do we set about putting this matter right for the future?

As Researchers, Designers and Manufacturers of all types of electronic equipment I recommend all our members to note the lessons of the Raby Study and introduce into our work adequate disciplines and procedures and a better method of communication of our design information to the makers to ensure that we design and make our products to the satisfaction of the market or the customer.

If engineers are to play a bigger part in improving this Country's image and if we are to increase our export business, we must design and produce goods of quality and reliability that are attractive. If we can do this, then we shall do a great job for Britain. I agree that to achieve this objective we must also improve other disciplines, Financial, Administration and Training. In short, we need to introduce Quality into everything we do.

Do not misunderstand me, 'Quality' is not a new-fangled and dignified term for old-fashioned 'Inspection'. Quality starts with the drafting of specifications to ensure that they include all the necessary parameters, that the designer understands the parameters, and that reliability is emphasized right through the manufacturing processes, right down to adequate packaging for delivery of the product to the customer.

To establish a reputation we must remember our duty to our customers to ensure that when they buy from us, off the shelf, or to their own specific need, that they really know what they want or clearly understand what they are going to get.

In the modern electronics industry, our designers and manufacturers have to cover a much wider range of disciplines than just electronics. So many projects use electronic techniques in association with other engineering disciplines, e.g. mechanical, structural, civil, marine, electrical power, chemical technology, and so on, and indeed, human engineering. Thus, as electronic engineers, we find ourselves involved with turnkey projects such as broadcast and television stations—computer installations—military installations—power stations, and automated factories. 'Systems engineering' is the name of the game!

One such project was recently successfully completed by my Company and our team included several members of this Institution. I am referring to the massive project that caught all our imaginations on August 10th last when all three television channels showed films of the crucial up-ending of the 35,000 ton—580 ft. long (or high) steel structure of the Burmah *Thistle 'A'* platform from the horizontal tow-out mode to the vertical deployment mode and the accurate and successful placement of the structure on the sea bed. (Fig. 1).

EMI engineers, who managed the project together with its sub-contractors, engineered the exercise and brought together the many other disciplines, such as structural, mechanical, marine, electrical, pneumatic, hydraulic, engineering, etc. Three electronic engineers controlled the operation and lopped 5½ hours off the planned time cycle for tilting over and placement of that massive tower in the right position on the sea bed. It was a real Quality job carried out by Quality-conscious companies with Quality-conscious staff who planned and specified every happening and forecast every risk with great accuracy. All British too.

The prime element of the system was a two-way data link which was used to transmit 200 platform status indications—60 analogue indications and 150 control signals. On the platform the control equipment was housed in a 120-ton 80 ft long tower placement control module. This equipment continuously monitored the status of tank levels, control valves, pressure switches and platform attitude.

From the remote control consoles on the control ship the deployment controller directed the entire up-ending operation. This was achieved by controlled flooding of the ballast tanks in the main legs of the platform to turn it through 90°, and to control its descent to the sea bed. Acoustic sensors were fitted to the platform structure to measure the water depth under each leg.

Duration of design and manufacture of the system—about 18 months—cost about £1·5M on a fixed price basis and the date *had* to be met to ensure getting the tower to its destination during a forecast slot in the weather pattern.

Quite a job, and a very good illustration of my point that quality in the true sense of the word matters. It all had to be right—there was no second chance. If ever a project threw up the importance of clear systems thinking it was this one—just think of the final checking that had to be carried out on the tower before tilting. Just one slip and a long drop into the sea was inevitable. But all went well—just another part of my interpretation of 'Quality' in action.

After this successful performance, and in view of the importance of electronic systems engineering and equipment in all walks of life, and the fact that we range over such a wide variety of other skills and technologies, perhaps we should take some of the other Institutions over and merge them with ourselves! But to be serious, these cross-disciplinary activities justify the creation of the CEI as a federal body promoting co-operation between all engineering.

I am sure that there are opportunities for many projects, such as the example I have talked about, presenting themselves continuously. To ensure that Britain gets its fair share of these 'electronic systems' we have an obligation to persuade others around us that there is a need for the raising of our standards and that there is a necessity for a better quality of understanding from everybody we work with including our financiers and administrators.

How many times over the years have we engineers designed a product to a high standard and had it sacrificed to meet a date or meet a price or to meet some other commercial consideration which completely overlooked the basic requirements of good engineering. Or when a money spinner has not been recognized and adequately supported or, indeed, when a business had been bought or sold or closed without advice from a Chartered Engineer having been sought before the decision was made.

The Chartered Accountant and the Chartered Engineer can make a very good team. The Accountant on his own can occasionally be disastrous.

An improvement in the quality of design and of manufacture brings an improvement in the product and maybe a reduction in price which can lead to improvements in our export performance and balance of payments, thus providing a boost to our aim to improve the quality of life.

As I have said before, I am using the word Quality in its widest sense which starts with the Company's system and the raising of appropriate specifications including quality plans and of course contractual documents to meet the overall customer requirements (home or overseas) through the design and all manufacturing processes, right down to ensuring the delivery of the product to the customer, at the right time and the right price, in the certain knowledge that what the customer requires is going to be met in its entirety.

What we now need to see is a swing of the pendulum back from a period of carelessness and poor and incomplete training and, dare I say it, a period of the use of cheap labour, until we again have responsibility with the designer for a specification and quality plan which will give our customers what they really want, and a responsibility with the production people for carrying out the designer's wishes, and to make the product, using materials and components of known and proven quality, to produce the value which is inherent in the design.

During my membership of the Raby Committee the theme which I stressed most strongly was this. It is nonsense to design and make a lot of things without proper control and then put a lot of Inspectors at the end of a line to pass out some and send the rest round again for repair or remaking. If many get rejected you can be sure that many of those which got through will soon fail to give service. The right way to carry on a business is to use procedures and disciplines that establish control such that the design and the resulting product are automatically right.

I appeal to all of you, whether you are in Industry or Education, Engineering or otherwise, to use your efforts and influence towards the time when nothing that is made subsequently proves to be inadequate.

Now with this realization that it is necessary for the specifications to be right and the importance of meeting them, due regard must be paid to many facets and conditions, such as performance, price, weight, environment, reliability, shelf life and life-cycle requirements. These facets and conditions are really not new but they are certainly some of the things that get forgotten. Perhaps those of us who are matured by years and experience may help improve the situation by getting involved and ensuring that these requirements don't get overlooked and by laying down some precise educational aims for industry and for the up and coming generation of design and production engineers. We have to add to the highly satisfactory academic training that is provided by the Universities, the hard lesson of practical experience which can only be gained by close assocation with the industrial environment. A recent review in the *Sunday Times* showed that, from a survey with 200 top executives, there were 25 main attributes, over and above the University degree, that were required by candidates for top jobs. Only six of these were developed in the University. The other 19 had to be developed on the job. Enough said.

We must, of course, always bear in mind that the duty of training our newcomers has to be planned and implemented with thoroughness and imagination, so that concern with quality in all the work they do becomes as natural to them as breathing. We have to train them so that quality does not mean some busybody peering over their shoulder and finding fault with their work when they have finished it—it means that they have to be contortionists and look over their own shoulders all the time they are working. It means also that they have to think down the line so that the engineer on project definition never forgets the concern with quality which will be displayed in five years' time by the contractor's mechanic or the ship's artificer or aircraft fitter who is engaged on maintenance and repair.

So to sum up my message on Quality of the product, if we are to use our total technology and design effectively we must start in the right environment and from the proper range of product specifications and ensure that they meet the requirements of the customer or the market and do not overlook the National and International regulations of that market. Here I include design specifications, manufacturing specifications, test specifications, sales specifications and package specifications. We must ensure that our designers are given every opportunity to become competent to work to the necessary disciplines and to choose appropriate materials, components, finishes, and processes, to B.S. Specifications when appropriate, and that they are knowledgeable of the packaging necessary to the specified needs. We must ensure that our production is carried out under disciplines and procedures (including all testing and packaging) to ensure the resulting product is fit for purpose and arrives with the customer safely, and, with the legislation of Health and Safety in mind, is safe for the customer to use.

Inventiveness, research and development are all carried out to a very high standard of efficiency in the UK and second to none in the world, but we must ensure that resulting engineered-products also become second to none and that our sales forces sell to the appropriate sales specifications, thus ensuring that the customer knows what he is going to get, or gets what he specified. After all, by tradition the customer is always right, and we have to protect him from the old cliché, 'after you pay the money you pay the price'.

Quality and Training.

We must persuade our financiers and our masters that these procedures are necessary to the well-being of our Companies and the Nation just as much as are corporate matters. We must use our influence on the educational authorities to ensure that all incoming staff entrants clearly understand what the commercial and industrial world is all about and what is wanted of them, and persuade young people entering industry that to compete and operate in the world markets it is not the University degree or equivalent which is the hall-mark of proficiency, it is the academic training plus the appropriate grade of membership of a Chartered Professional Institution which proves that a man is properly trained for his chosen career and is adequately supported by practical training and experience.

You will note that I refer to alternative academic standards to a University degree. Whilst we can no longer complain that radio and electronic engineering is ignored by Universities, as in my youth, the fact is that the output of graduates in radio, telecommunications and electronics falls far short of the needs of industry. Indeed, it is now the student who rejects opportunities in science and technology; some thousands of vacancies in science and technology now exist in British Universities. This is a problem I am currently discussing with my academic colleagues in the IERE and it may well be that we should press for more and up-to-date industrial experience and professional qualification when appointing professors and lecturers in our Universities.

However that may be, let us not prejudice the future of our industry by falling prey to demagogic cries to make entry to our profession so exclusive that we end up with undermanned and inefficient public and private services and a multitude of frustrated engineers. Let us remember that engineers cannot be put into one pigeon hole; engineering is a varied business which will always resist the 1984 concept of broad classification of citizens.

Every one of our 15 Chartered Engineering Institutions was founded and has survived because of the dedication of the members to the objects of their Institution. Dictatorship of the majority for squalid reasons of economy or ease of administration has never, in the whole history of man, finally succeeded.

Let us, therefore, be watchful. We must continue to press for better standards of academic ability and of teaching. Let us, however, keep our feet on the ground and preserve the British tradition of giving opportunity to the man who makes the best use of the opportunities open to him. Let us do away with restricting opportunity to the privileged few and remember that technology is studded with pioneers who have equalled the efforts of the University-trained in innovation and turning science into technology. Quality in the man is as important as the quality of the materials he fashions. This applies not only to the professional engineer but also to the technician and craftsman and I hope that during my Presidency our Institution will do more to help the technician and craftsman to join the professional in achieving quality in production and servicing.

Ruskin said 'Quality is never an accident, it is always the result of intelligent effort, there must always be a will to produce a superior thing'.

I believe young people have the will if they are given help and not frustrated by too many rules and regulations.

I have emphasized the importance of quality in promoting sales. Let us not forget, however, that scientific discovery has an international imprint, and as shown in our Clerk Maxwell Lectures, this especially applies to the development of radio and electronics.

Exploitation of technology is not the prerogative of any one country. The race goes to the fastest in being the first to capture a scientific principle and turning it into a service for all mankind. What an example that Body Scanner (Fig. 2) is of this philosophy! Usually this requires large-scale investment and the understanding of the corporate, financial and other interests that I have mentioned. Retention of a sales market will depend on the quality of the product.

Even so we cannot expect any one country to dominate the entire electronics scene. We, in Great Britain for example, have to decide those areas in electronics in which we excel in Quality—at a competitive price. I am pleased that the National Electronics Council is considering those areas in which Great Britain excels so that we can concentrate our electronics effort in the direction of a Rolls-Royce or a *Concorde* quality.

But technology, as with science, is international and we in Great Britain have much to contribute to the common weal of knowledge as, indeed, have many other countries. There is mutual benefit in engineers having international understanding and such Institutions as our own provide the necessary common platform—without, I may add, any cost to the taxpayer! In my mind the quality of the product of engineering contributes more to international understanding, peace and economic salvation than the prattling of theories of the less exact sciences!

But, in the UK, engineers do need more recognition. It seems to me a great shame that as far as I know no one has been able to identify any area in which the Engineer could have statutory privileges (excluding perhaps aircraft ground engineers) as the Accountant does in certifying the company accounts, as the Barrister has in pleading in Court, as the Doctor has in being protected when he gives treatment. If, for example, it were a legal requirement that an Engineer certify on the safety of a plant or a machine or even the design of a piece of domestic equipment, this would stress his importance in society and would immediately raise the status of the whole profession.

If we can get some recognition of status, our Engineers would then be on a par with their counterparts in certain other countries and, indeed, with Accountants, Lawyers, etc. Let's hope the CEI will make some progress in this direction. I'm sure our Board member will be pushing this matter.

The Engineer and the State

And now, having passed through my message on the Quality attitude towards our engineering and our products, I will now develop my thoughts on other matters equally important that will arise and worry the more senior of us who have to administer organizations, large and small, during the coming months. I refer to the new legislative requirements that are now with us and impinge upon everything we do.

It is a fact that when new legislation gets enacted and becomes law there are always penalties for those unfortunate ones who transgress. Since it is professional people like us who have to direct, employ and account for our businesses we will be busy for many months to come trying to cope with new laws and new problems that arise—and this over and above the very necessary tasks of creating employment and subscribing to the Gross National Product.

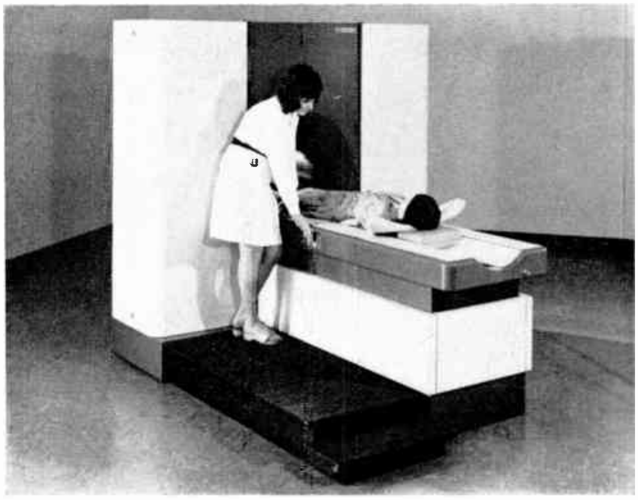


Fig. 2. The EMI Body Scanner.

Never before in my lifetime have there been so many new Bills and new Parliamentary Acts published in such a short space of time. A time of crisis—high inflation and high unemployment. Acts of Parliament to cover Industrial Relations—Equal Pay—Protection of Employment—Race Relations—Industrial Strategy—Health and Safety, to say nothing of new Company Acts and so on. Just think of the army of new and inexperienced Inspectors that will be calling upon us to ensure we all toe the line—and all interpreting the Acts differently. What will all this do to our overheads and our tempers? All this activity will not add to the productivity of the Nation.

But we, as engineers, are nothing if not resilient and we are not going to let this Government 'New Look' get us down and neither are we going to let our professional images get tarnished by shirking our increased responsibilities

It is all going to mean a greater effort to ensure that we cope and this brings me back to my quality theory. We have to be bigger people and to see that our young members learn from us and become not only accomplished engineers, but also people who can succeed in engineering and manage, despite the legal tangle which is growing around industry.

Now, in the short term, all this new know-how is not going to be developed in the Universities and Technical Colleges and it will be a long time before Consultants can help. It will have to be learned quickly, on the job. So, it is back to us—the Quality people—to show the way. I am sure we will do it through our daily contacts and by getting together at Bedford Square and through the opportunities that our Institution gives to enable us to lecture and be lectured at on the many interpretations and pitfalls of the new legislations.

This means we must encourage more young people to become professional through membership and learn from us about these new requirements. There is an awful lot that will have to be added to their formal engineering training that will not appear in text books for some time.

So as we pass from our Golden Jubilee Year with its pleasant memories and reminders of past achievements and with that all too brief look into the future by His Royal Highness just one year ago, may I propose that we move into Her Majesty's Year of Silver Jubilee by making a very special effort to improve the quality of so many things and work for greater recognition of the Engineering professions. What a step forward that would be! After all, any scheme to achieve this would have to be based on the Chartered Institutions and their grades of Corporate Membership, in this way using the principles that professional experience on the job is an essential quality that has to be vetted by 'on-the-job Chartered Engineers' before the coveted post-nominal letters can be awarded.

If we each encourage one or two young persons to achieve membership, our membership could treble in the year—and that would be an important addition to our national pool of professional Engineers. I'm sure it will have to be done in the long term, so why not now. Another point worth noting is this—I believe that of Engineers in top management approximately 10% only have the professional qualification of Corporate Membership of a Chartered Engineering Institution. There is scope here for improvement, I think.

On that note—may I conclude my address by saying: I view my Presidency of this important Institution as an opportunity to play a part, however small, in improving the quality of living. Like all our members my life has been spent in radio and electronics. I hope that every member, present and future, will join me in believing in the words of Francis Bacon

> I hold every man a debtor to his Profession.

In this spirit we shall all contribute toward improving the quality of living for all people.

Appendix: The Defence Inspectorates

Electrical Inspection Directorate (E.I.D.)—now Electrical Quality Assurance Directorate (E.Q.A.D.)

Aeronautical Inspection Directorate (A.I.D.)—now Aeronautical Quality Assurance Directorate (A.Q.A.D.)

Directorate of Inspection of Armaments (D.I.Arm.)—now Quality Assurance Directorate (Weapons) (Q.A.D.(W.))

Inspectorate of Naval Ordnance (I.N.O.)—now Naval Ordnance and Supply Department (N.Ord.S.Dept.)

Naval Weapons Production Overseer (N.W.P.O.)

Ship Department—Overseeing Ships (S.D.O.S.)—now Directorate of Naval Ships Production (D.N.S.P.)

Inspectorate of Fighting Vehicles (I.F.V.)—now Quality Assurance Directorate (Fighting Vehicles Establishment) (Q.A.D.(F.V.E.))

Chemical Inspectorate (C.I.)—now Quality Assurance Directorate (Materials) (Q.A.D.(Mat.))

Inspectorate of Stores and Clothing (I.S.C.)—now Quality Assurance Directorate (Stores and Clothing) (Q.A.D.(S. & C.))

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Contributors to this issue*

Adam Schneider obtained his B.Sc. in mathematics and M.Sc. in electrical engineering, and joined the Decca Navigator Company in 1945. He has subsequently been responsible for all aerial design for marine and harbour radars with Decca Radar Ltd. as well as various large antennae for defence purposes. In 1951, while with Decca Navigator, he read a paper on propagation of m.f. transmissions at the Institution's Festival of Britain Convention.

Philip Williams served in the Radar Branch of the Royal Navy from 1943 to 1947, and subsequently studied electrical engineering at University College, Nottingham.

He joined the Electronic Switching Laboratories of Ericsson Telephones, Beeston, in 1950, and two years later went to the Development Laboratories of Decca Radar. Since then he has had varied experience within the Company on marine radar, meteorological radar and low cost p.a.r. equipment and from 1960 to 1964 he was Group Leader of microwave heating.

During the next five years Mr. Williams was Design Authority and Team Leader for a pulse Doppler automatic search radar, and in 1969 he became Head of Future Projects, where his major interest is the relationship of theory to real results on working equipment.

Mr. Williams received the Institution's Brabazon Premium in 1975 for his paper entitled 'Limitations of radar techniques for the detection of small surface targets in clutter.'

Anagnostis Hadjifotiou graduated with a B.Sc. in electronics, specializing in communications, from the Department of Electronics at the University of Southampton in 1969. He obtained an M.Sc. on control systems from UMIST in 1970 and then returned to Southampton to work for a Ph.D., which was awarded in July 1975 following research on digital signal processing for radar. Since April 1974 Dr. Hadjifotiou has been employed as a Research Engineer working on p.c.m. systems with Standard Telecommunication Laboratories, Harlow, Essex.

J. C. Lim obtained the B.E. (Hons.) and Ph.D. in 1965 and 1968 respectively, from the University of Auckland, New Zealand. His Ph.D. dissertation was on 'Non-uniformly spaced arrays of directional elements'. From 1968 to 1970 he was with the Telecommunications Department of Malaysia involved with the commissioning of the Malaysian satellite communications earth station at Kuantan. In 1970 he received an appointment as lecturer in the Faculty of Engineering, University of Malaya, teaching electronics and communications. Following six months in 1973–74 as a Research Assistant on a Ministry of Defence funded contract at University College, London, Dr. Lim has now returned to the University of Malaysia.

J. P. McGeehan received the B.Eng. and Ph.D. degrees in electrical engineering from the University of Liverpool in 1967 and 1972 respectively. From 1970 to 1972 he held the position of Senior Scientist at the Allen Clark Research Centre, Plessey Co. Ltd., where he was primarily concerned with research into solid-state microwave devices and their applications. In September 1972, Dr. McGeehan was appointed Lecturer in the School of Electrical Engineering at the University of Bath, and he is currently conducting research in mobile communications.

Ralph Benjamin gained his B.Sc. in electrical engineering at the Imperial College of Science and Technology in 1944 and then joined the Royal Naval Scientific Service. In 1961 he was appointed Head of Research and Deputy Chief Scientist of the Admiralty Surface Weapons Establishment and in 1964 he went to the Admiralty Underwater Weapons Establishment as Director and Chief Scientist, also becoming a qualified Naval Diving Officer. From 1965 to 1971 he combined these appointments with the further one of Director of Underwater Weapons R & D at the Ministry of Defence. Since 1971 he has been Chief Scientist of the Government Communications Headquarters.

In 1964 London University awarded Dr. Benjamin the Ph.D. degree for a thesis on signal processing, and in 1970 it awarded him the D.Sc. for his contributions to general electronics. He is currently Visiting Professor in the Department of Electrical and Electronic Engineering of the University of Surrey. He published a book on 'Modulation, Resolution and Signal Processing in Radar, Sonar and Related Systems' in 1966 and is author of numerous papers in the proceedings of various learned societies, symposia, etc.

Dr. Benjamin has been a council member of the British Acoustical Society and has served on a number of official committees, advisory bodies and working parties in the United Kingdom, NATO and the USA.

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*See also page 48.

UDC 621.396.96:621.391.812.61

Circular polarization in radars

An Assessment of Rain Clutter Reduction and Likely Loss of Target Performance

A. B. SCHNEIDER, Dipl.Ing.*

and

P. D. L. WILLIAMS, M.R.I.N., C.Eng., F.I.E.E.*

SUMMARY

Fixed circular polarization has been used for rain clutter reduction for over thirty years,[1–3] but a proper understanding of the inter-relationship of radar propagation path and target parameters is still not widely known. The paper sets out to provide a basic analysis, together with a set of 'universal curves' from which expected rain clutter reduction and target loss may be obtained for any particular set of circumstances.

The paper then provides a guide to current literature from which the nearest reported results may be used to provide realistic performance estimates. These are supported with a limited number of experimental results obtained with an X-band radar fitted with dual aerials.

Comments on the use of the propagation factor F for rain in the special case of surface search radars are offered for criticism.

An alternative method of rain rejection using orthogonal linear polarization for transmission and reception is also covered in less detail.

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List of Symbols

E	maximum magnitude of electric field of a linearly polarized signal
$E \exp[j\omega t]$	instantaneous amplitude of electric field E
E_h and E_v	horizontal and vertical components of E on two orthogonal axes
$E_{h(av)}$	electric field on the h axis available as signal returned from the target to the aerial in the front of linearly polarized resolver
$E_{h(rec)}$	electric field resolved in the linearly polarized receiver following the square waveguide
k m n	modulus or magnitude of attenuation coefficient (smaller than 1) aerial prop. path target
K	overall ratio of horizontal to vertical system moduli of attenuation coefficient as defined in equation (8)
k_h	resolved magnitude of attenuation on horizontal axis, etc.
α β γ	corresponding argument or phase angle aerial prop. path target
Δ	overall (2-way) differential phase shift of vertical and horizontal vector components for complete radar–propagation path–target reflection system as defined in equation (9)
λ	operating wavelength
σ	general value of radar cross-section (r.c.s.) or radar equivalent area (r.e.a.)
$\begin{pmatrix}\sigma_{hh} & \sigma_{hv}\\ \sigma_{vh} & \sigma_{vv}\end{pmatrix}$	matrix or tensor description of r.c.s. value of a static or 'frozen' target (for a given λ, aspect and free space condition)
σ_{rain}	rain radar cross-section (m^2)
σ_0	rain coefficient of proportionality (m^2/m^3)
$P_{(av)}$	power available in the front of linearly polarized resolver
$P_{r(n)}$	normalized received power resulting from the electric fields $E_{h(rec)}$ and $E_{v(rec)}$
F	propagation factor due to multi-path
S	signal power received in any system from a wanted target $\equiv P_{r(n)}$
C	clutter signal received from unwanted rain or sea clutter
C_r	rain clutter return
C_{sc}	sea clutter return
c	velocity of electromagnetic waves
θ	horizontal aerial beamwidth
ϕ	vertical aerial beamwidth
ξ	angle between the linearly polarized resolver and the horizontal or X axis (Fig. 4)
t_p	radar pulse length
N	number of lobes in an aerial–sea vertical interference pattern

1 Introduction

Rain clutter has been recognized as a source of wanted target obscuration since radar first became widely used in the 1940s.[1–3] The backscatter from small spheres increases as the fourth power of the radar frequency increase, as shown in the normalized backscatter curves for a single sphere, e.g. Fig. 1 from Kerr.[4]

For many years this powerful relationship in the Rayleigh region made the use of metric radars very popular, even taking into account the enormous array needed to produce reasonable angular resolution. For example, for a wavelength of 1 m and a 2° × 2° beam, an array some 36 m × 36 m has to be built which is only suitable for slow rotation speeds.

For shipborne use such arrays are prohibitive and centimetric radar was quickly established enabling high angular resolution to be obtained with smaller aerials. Even so the volume of water illuminated by a modestly sized marine radar is very large. For example, with the following parameters:

Range to rain obscuration: $R = 10$ km
Aerial horizontal beamwidth (θ): 2° or 0·035 rad
Aerial vertical beamwidth (ϕ): 20° or 0·35 rad
Pulse length (t_p): 1 μs

the volume given is:

$$\text{Vol} = R^2\theta\phi\,\frac{t_p c}{2} = 1{\cdot}8\times10^8\ \text{m}^3$$

An accepted backscatter coefficient for 16 mm/h of rain at X-band is -53 dB m^2/m^3, thus to a first order a radar resolution cell full of 16 mm/h rain will appear on the p.p.i. the same as a target of 900 m^2, i.e. a medium ship.

If the distribution of rain is not homogeneous then the use of a log receiver and 'fast time-constant' (f.t.c.) video coupling will break up the rain into its intense parts, which will still show, and gaps in the rainstorm in which targets may be seen. Figures 2 and 3 illustrate a rain-cluttered special p.p.i. with the beneficial f.t.c. shown in Fig. 3. The photographs also illustrate the superior performance of a log receiver over a linear one. (The split display is covered in Refs. 40 and 41.)

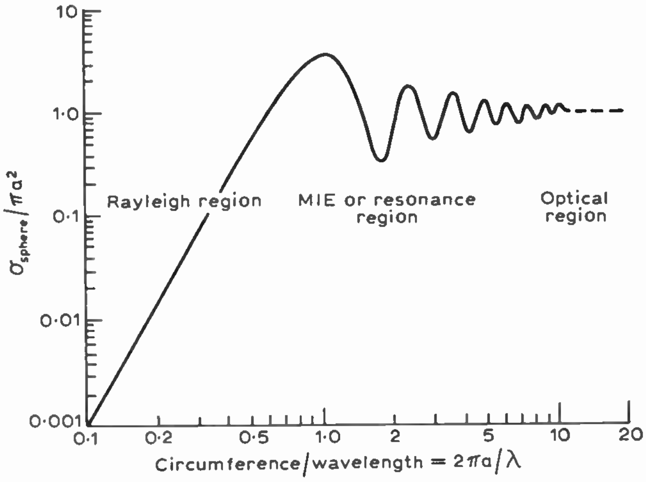
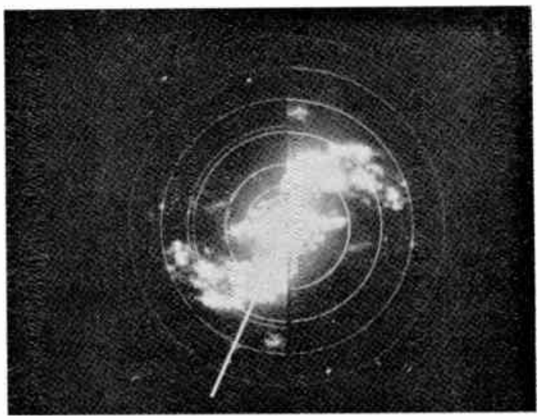


Fig. 1. Normalized r.c.s. of a sphere in terms of circumference to wavelength ratio.



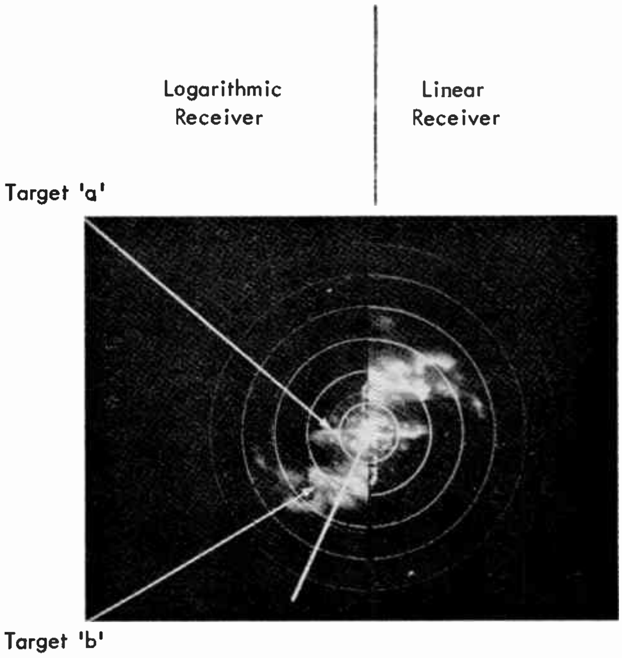


Fig. 2. (upper picture) No f.t.c. in either receiver.
Exposure: 4 revs. Time: 10.15.

Fig. 3. (lower picture) Equal f.t.c. in both receivers. Exposure: 6 revs. Time: 10.16. Targets (a) and (b) are arrowed as they appear on the log-f.t.c. or c.f.a.r. receiver and not on the linear one with f.t.c. on the right-hand side.

System parameters: $\lambda = 3{\cdot}2$ cm
$\theta = 0{\cdot}8°$
$t_p = 0{\cdot}5$ μs.
Range rings = 2 n.m. Split display presentation.

However, such techniques, whilst minimizing the rain shown on the p.p.i. do not allow true 'sub-clutter visibility' by a selective suppression of rain clutter only, whilst leaving the desired targets unchanged.

Thus, the need for a target selection system has been established and this paper considers the problems of using circular polarization which uses the different backscatter or radar reflection polarization properties of man-made targets, e.g. ships and harbours, compared to raindrops which are either spherical or bun-shaped.[5]

The frequent non-spherical nature of raindrops plus cross-polarization distortion (x.p.d.) of propagation paths:

at the aerial radome,
through rain,
due to multipath from depolarizing surfaces,

is currently being studied$^{6-13}$ for communication purposes and accounts for the often disappointing behaviour of old fixed circular-polarization aerial systems using quarter-wave plates over feed horns.[14] Nevertheless, fixed circular-polarization systems often gave 10 to 15 dB of clutter reduction with varying degrees of target loss.

2 Analysis

Thus the need for an effective circularly-polarized system and also the need for flexibility of operation has now been established, and a practical system designed and built to these principles has been developed and will now be described.

A parabolic mirror aerial is arranged to be fed with a square feed horn at its focal point. The horn may, of course, be flared to provide the optimum illumination to the reflector, but basically stems from a square guide capable of supporting an electric field at the operating frequency in either plane. A linearly-polarized signal is launched into this square guide at any chosen and continuously variable angle ξ as in Fig. 4.

A linearly polarized signal $E \exp[-j\omega t]$ as in Fig. 4 is launched at an angle ξ into a square guide, where it resolves into two mutually perpendicular components E_h and E_v, where

$$E_h = E \cos \xi . \exp[-j\omega t] \tag{1a}$$

$$E_v = E \sin \xi . \exp[-j\omega t] \tag{1b}$$

This arrangement forms a simple power divider, dividing available power between two mutually perpendicular components E_h and E_v. If these two components are obtained by any other means then

$$\tan \xi = \frac{E \sin \xi}{E \cos \xi} = \frac{E_v}{E_h}$$

and the following analysis is still valid.

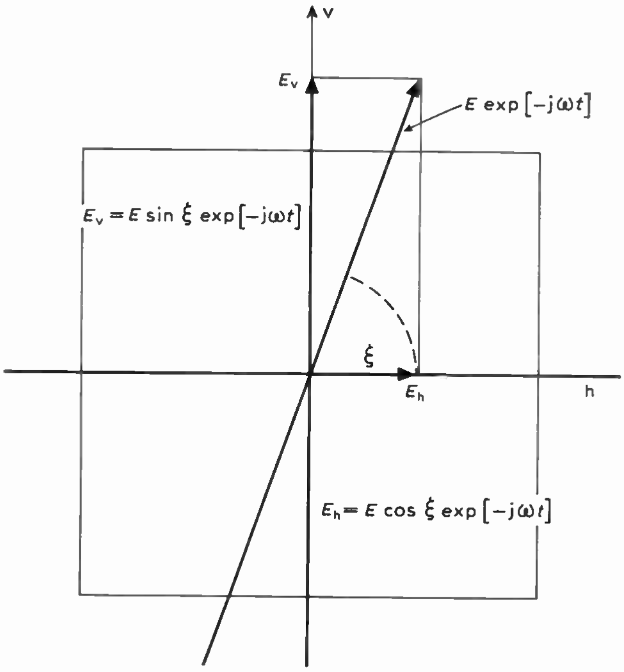


Fig. 4. Basic vector diagram.

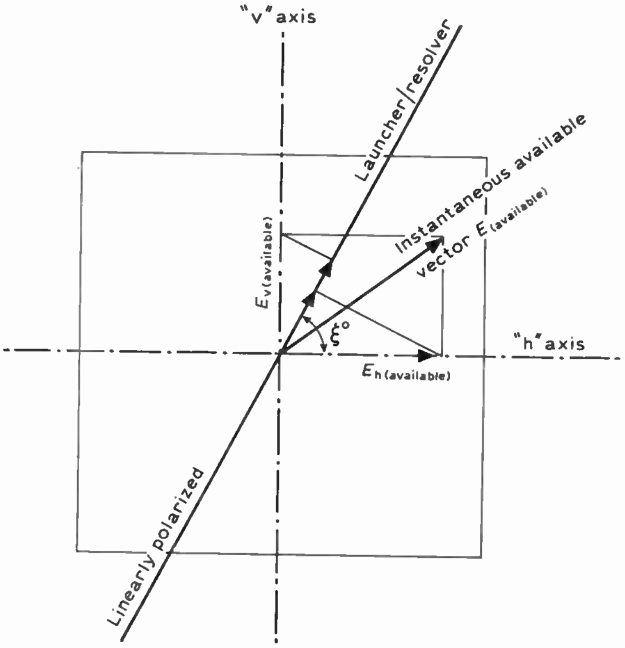


Fig. 5. Vector resolution diagram.

Both these components E_h and E_v are propagated through a waveguide system into the aerial, where they are eventually radiated. Let $k_h \exp[j\alpha_h]$ and $k_v \exp[j\alpha_v]$ be the complex attenuation coefficients of the waveguide-cum-aerial system for the E_h and E_v components respectively.

Then, emerging from the aerial:

$$E_{h(\text{transmitted})} = Ek_h \cos \xi . \exp[j(\alpha_h - \omega t)] \tag{2a}$$

$$E_{v(\text{transmitted})} = Ek_v \sin \xi . \exp[j(\alpha_v - \omega t)] \tag{2b}$$

Let us now denote by $m_h \exp[j\beta_h]$ and $m_v \exp[j\beta_v]$ the complex attenuation coefficients of propagation for the E_h and E_v components respectively. These coefficients comprise the apparent attenuation and phase shift which the E_h and E_v components will undergo when travelling from the aerial to the target and back, taking into account the dual path due to the ground/sea reflections.

It is obvious that the m and β are varying continuously in space and in time and form the most elusive part of this simple analysis; in fact the m and β are constant only for one instance of time and one direction of the aerial and one range element at one height.

If the target is characterized by the reflection coefficients $n_h \exp[j\gamma_h]$ and $n_v \exp[j\gamma_v]$, then the $E_h(t)$ and $E_v(t)$ components arriving after reflection at the end of the square guide in the front of the linearly polarized system as in Fig. 5 are in the form:

$$E_{h(\text{available})} = Ek_h^2 m_h n_h \cos \xi . \exp[j(2\alpha_h + \beta_h + \gamma_h - \omega t)] \tag{3a}$$

$$E_{\mathrm{v(available)}} = Ek_{\mathrm{v}}^2 m_{\mathrm{v}} n_{\mathrm{v}} \sin\xi . \exp[\mathrm{j}(2\alpha_{\mathrm{v}}+\beta_{\mathrm{v}}+\gamma_{\mathrm{v}}-\omega t)] \quad (3b)$$

and because the two components $E_{\mathrm{h(av)}}$ and $E_{\mathrm{v(av)}}$ are mutually perpendicular the available power at that point is equal to

$$\begin{aligned} P_{\mathrm{(available)}} &= |E_{\mathrm{h(av)}}|^2 + |E_{\mathrm{v(av)}}|^2 \\ &= E^2(k_{\mathrm{h}}^4 m_{\mathrm{h}}^2 n_{\mathrm{h}}^2 \cos^2\xi + k_{\mathrm{v}}^4 m_{\mathrm{v}}^2 n_{\mathrm{v}}^2 \sin^2\xi) \quad (4) \end{aligned}$$

The $E_{\mathrm{h(av)}}$ and $E_{\mathrm{v(av)}}$ components projected in the direction of the linearly polarized resolver are of the form:

$$E_{\mathrm{h(rec)}} = Ek_{\mathrm{h}}^2 m_{\mathrm{h}} n_{\mathrm{h}} \cos^2\xi . \exp[\mathrm{j}(2\alpha_{\mathrm{h}}+\beta_{\mathrm{h}}+\gamma_{\mathrm{h}}-\omega t)] \quad (5a)$$

$$E_{\mathrm{v(rec)}} = Ek_{\mathrm{v}}^2 m_{\mathrm{v}} n_{\mathrm{v}} \sin^2\xi . \exp[\mathrm{j}(2\alpha_{\mathrm{v}}+\beta_{\mathrm{v}}+\gamma_{\mathrm{v}}-\omega t)] \quad (5b)$$

Remembering that because the two components $E_{\mathrm{h(rec)}}$ and $E_{\mathrm{v(rec)}}$ are co-linear; the received power P_{r} is equal to:

$$\begin{aligned} &|A \exp[\mathrm{j}\alpha] + B \exp[\mathrm{j}\beta]|^2 \\ &\qquad = A^2+B^2+2AB\cos(\alpha-\beta) \quad (6) \end{aligned}$$

(here A and B are introduced to clarify the point) and the normalized received power $P_{\mathrm{r(n)}}$ is then:

$$P_{\mathrm{r(n)}} = \frac{|E_{\mathrm{h(r)}}+E_{\mathrm{v(r)}}|^2}{P_{\mathrm{(available)}}}$$

$$= \frac{\begin{array}{c} k_{\mathrm{h}}^4 m_{\mathrm{h}}^2 n_{\mathrm{h}}^2 \cos^4\xi + k_{\mathrm{v}}^4 m_{\mathrm{v}}^2 n_{\mathrm{v}}^2 \sin^4\xi + \\ + 2k_{\mathrm{h}}^2 k_{\mathrm{v}}^2 m_{\mathrm{h}} m_{\mathrm{v}} n_{\mathrm{h}} n_{\mathrm{v}} \sin^2\xi \cos^2\xi \times \\ \times \cos[2(\alpha_{\mathrm{h}}-\alpha_{\mathrm{v}})+(\beta_{\mathrm{h}}-\beta_{\mathrm{v}})+(\gamma_{\mathrm{h}}-\gamma_{\mathrm{v}})] \end{array}}{k_{\mathrm{h}}^4 m_{\mathrm{h}}^2 n_{\mathrm{h}}^2 \cos^2\xi + k_{\mathrm{v}}^4 m_{\mathrm{v}}^2 n_{\mathrm{v}}^2 \sin^2\xi} \quad (7)$$

Taking

$$K = \frac{k_{\mathrm{h}}^2 m_{\mathrm{h}} n_{\mathrm{h}}}{k_{\mathrm{v}}^2 m_{\mathrm{v}} n_{\mathrm{v}}} \quad (8)$$

and

$$\Delta = [2(\alpha_{\mathrm{h}}-\alpha_{\mathrm{v}})+(\beta_{\mathrm{h}}-\beta_{\mathrm{v}})+(\gamma_{\mathrm{h}}-\gamma_{\mathrm{v}})] \quad (9)$$

and substituting (8) and (9) into (7) then:

$$P_{\mathrm{r(n)}} = \frac{K^2\cos^4\xi + \sin^4\xi + 2K\sin^2\xi\cos^2\xi\cos\Delta}{K^2\cos^2\xi+\sin^2\xi} \quad (10)$$

A program for evaluating $P_{\mathrm{r(n)}}$ is given in the Appendix and a graphical solution is shown in Fig. 8.

2.1 Theoretical Examples

For a complete rejection of a target characterized by parameters $n \exp[\mathrm{j}\gamma]$ when the propagation parameters are in the form of $m \exp[\mathrm{j}\beta]$ and the aerial-cum-waveguide system is given by parameters ξ and $k_{\mathrm{h}} \exp[\mathrm{j}\alpha_{\mathrm{h}}]$ and $k_{\mathrm{v}} \exp[\mathrm{j}\alpha_{\mathrm{v}}]$ the normalized received power is equal to zero:

$$K^2\cos^4\xi + \sin^4\xi + 2K\sin^2\xi\cos^2\xi\cos\Delta = 0 \quad (11)$$

The only real solution is

$$\cos\Delta = -1$$

or

$$2(\alpha_{\mathrm{h}}-\alpha_{\mathrm{v}})+(\beta_{\mathrm{h}}-\beta_{\mathrm{v}})+(\gamma_{\mathrm{h}}-\gamma_{\mathrm{v}}) = 180° \pm (n360°)$$

where n is an integer,

$$(\alpha_{\mathrm{h}}-\alpha_{\mathrm{v}}) = 90° - \frac{(\beta_{\mathrm{h}}-\beta_{\mathrm{v}})+(\gamma_{\mathrm{h}}-\gamma_{\mathrm{v}})}{2} \pm n180° \quad (12a)$$

when

$$(K\cos^2\xi - \sin^2\xi)^2 = 0$$

$$\tan\xi = \sqrt{K} = \frac{k_{\mathrm{h}}}{k_{\mathrm{v}}}\sqrt{\frac{m_{\mathrm{h}} n_{\mathrm{h}}}{m_{\mathrm{v}} n_{\mathrm{v}}}} \quad (12b)$$

In general then, if one has a control over the phase difference $(\alpha_{\mathrm{h}}-\alpha_{\mathrm{v}})$ and the launching angle ξ, to reject a target, the phase difference $(\alpha_{\mathrm{h}}-\alpha_{\mathrm{v}})$ and the launching angle ξ must be set to satisfy equations (12a) and (12b); the radiated signal is in general elliptically polarized. For the classical case when:

$$\begin{aligned} k_{\mathrm{h}} &= k_{\mathrm{v}} \\ m_{\mathrm{h}} &= m_{\mathrm{v}} \qquad \beta_{\mathrm{h}} = \beta_{\mathrm{v}} \\ n_{\mathrm{h}} &= n_{\mathrm{v}} \qquad \gamma_{\mathrm{h}} = \gamma_{\mathrm{v}} \end{aligned}$$

the phase shifter $(\alpha_{\mathrm{h}}-\alpha_{\mathrm{v}})$ must be set to 90° and the launching angle ξ to 45°; the transmitted signal is then circularly polarized.

For a complete acceptance of a target the normalized received power $P_{\mathrm{r(n)}}$ is to be equal to unity:

$$\begin{aligned} P_{\mathrm{r(n)}} &= \frac{K^2\cos^4\xi + \sin^4\xi + 2K\sin^2\xi\cos^2\xi\cos\Delta}{K^2\cos^2\xi+\sin^2\xi} \\ &= 1 \qquad (13) \end{aligned}$$

Equation (13) has two basic solutions which do not depend on the setting of the variable phase shifter, namely:

$\xi = 0°$ Horizontal polarization (13a)

$\xi = 90°$ Vertical polarization (13b)

For launching angles $0° < \xi < 90°$, equation (13) can be solved only in one particular case when

$$\cos\Delta = 1$$

or

$$(\alpha_{\mathrm{h}}-\alpha_{\mathrm{v}}) = \frac{(\beta_{\mathrm{v}}-\beta_{\mathrm{h}})+(\gamma_{\mathrm{v}}-\gamma_{\mathrm{h}})}{2} \pm 2n\pi \quad (13c)$$

when

$$K = 1 \quad (13d)$$

If conditions (13c) and (13d) are fulfilled simultaneously the normalized received power $P_{\mathrm{r(n)}}$ given by equation (13) is equal to unity for any launching angle ξ between 0° and 90°.

For all other conditions, when $K \neq 1$ and $0° < \xi < 90°$ there will be always some loss of the normalized received power $P_{\mathrm{r(n)}}$.

If the case of an isolated spherical raindrop is now considered we have what was the classical case stated at the beginning of this Section. As the raindrop backscatter is $\sigma_{\mathrm{vv}} = \sigma_{\mathrm{hh}}$, i.e. $n_{\mathrm{v}} = n_{\mathrm{h}}$, and as the ideal raindrop presents a symmetrical surface to the incident radar energy, the differential phase shift is 0° and so $\gamma_{\mathrm{v}} - \gamma_{\mathrm{h}} = 0$. Thus if the transmitted radiation is right-handed circularly polarized as seen from the back of the radar aerial, the condition in Fig. 6 applies.

Due to the direction of motion of the wave on reflection from a spherical raindrop a left-hand circularly-polarized wave returns to the aerial and is, of course, rejected by the linearly-polarized resolver and has to be absorbed in the load provided for orthogonal components.

In the case of a non-spherical raindrop where it is of elliptical form then

$$\sigma_{vv} \neq \sigma_{hh} \quad \text{or} \quad \frac{n_v}{n_h} \neq 1$$

Then, for complete cancellation the launching angle ξ in the aerial has to be set to the appropriate value different from 45°, and the differential phase shifter (α) readjusted to give an overall value $\Delta = 180° \pm n360°$ (as before in equation (12a), etc.).

Now, once the radar beam penetrates the rain cloud, differential phase shift as well as differential attenuation will take place and to achieve ideal rain rejection both ξ and $\alpha_h - \alpha_v$, the differential phase shift in the aerial, needs to be continuously adjusted. Although Hendry and McCormick's work is discussed later in the paper, to the authors' knowledge no one has yet built a fully adaptive rain cancellation radar carrying out dynamic adjustments in real time, using what in radar terms would be 'swept ellipticity'. (Since this manuscript was accepted Nathanson's suggestions have been published.[45])

To consider another simple case, if the target were a single vertical wire, then the radar could achieve maximum return by setting the launching angle ξ to 90°; conversely, the target would give minimum return if ξ were set to 0°.

In practice, man-made objects such as aircraft and ships tend to be made up of one, two or three bounce reflections formed by dihedral and trihedral corners. In such cases, for a given aspect of a given target, if the number of odd bounce reflectors equals the number of even bounce reflectors, then a r.h. c.p. wave tends to reflect approximately even amounts of r.h. and l.h. c.p. This gives rise to the rule-of-thumb that 'most practical targets suffer a 3 dB loss when circular polarization is used', but our later results show this is not always the case and in some circumstances c.p. gives a greater value of apparent radar cross-section than linear polarization.[47]

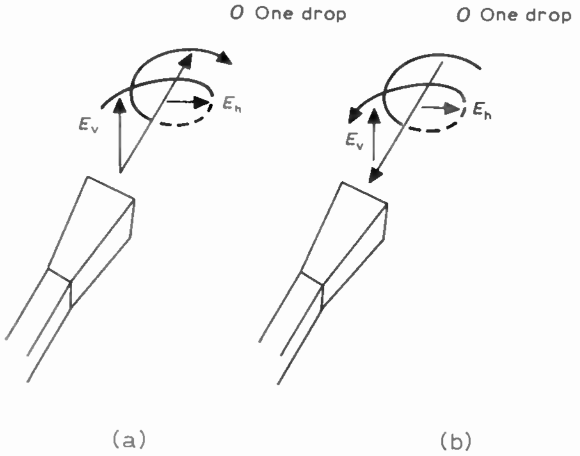


Fig. 6.

(a) R.h.c.p. emerging from radar aerial.

(b) L.h.c.p. being reflected back to radar aerial for rejection.

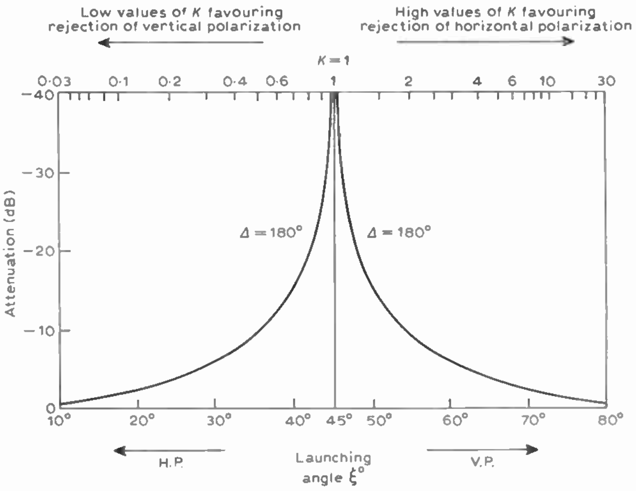


Fig. 7. Basic sphere rejection curve.

2.2 Universal Curves

Figure 7 gives the result of evaluating equation (10) for the usual case of c.p. when the launching angle $\xi = 45°$ and $K = 1$. Here the true sphere has rejection of infinity, limited by cross-talk in a practical system to some 40 dB. If the radar resolution cell contains a single sphere then the two aerial controls behave as the real and reactive arms of an impedance bridge, allowing a good null to be obtained. However, if the sphere is replaced by a real rainstorm the situation becomes dynamic and rejection will ultimately be set by the bandwidth of any control loop used to track the non-sphericity. This particular case leads on to the full set of universal curves shown in Fig. 8(a) from which target loss may be read off, providing the overall differential attenuation K and differential phase shift Δ are known or can be estimated. It is important to note that these are instantaneous exact values with no regard to the statistics of K and Δ from all their many contributors which will be discussed later (see also Refs. 15–17).

A shortcoming of equation (10) is the fact that it cannot recognize depolarization of reflected signals. If, for instance, a horizontally polarized signal is depolarized on reflection to contain half of the reflected power vertically and the other half horizontally polarized, then, according to equation (13a) there is no loss on reception when, in fact, there is a 3 dB loss.

To overcome this difficulty another set of complementary universal curves is presented in Fig. 8(b) for assessing what amount of power will be accepted by an arbitrarily polarized aerial receiving an arbitrarily polarized signal.

Let us suppose that an elliptically polarized signal given by

$$E_h = A_h \exp[j(\phi_h - \omega t)] \qquad (14a)$$

$$E_v = A_v \exp[j(\phi_v - \omega t)] \qquad (14b)$$

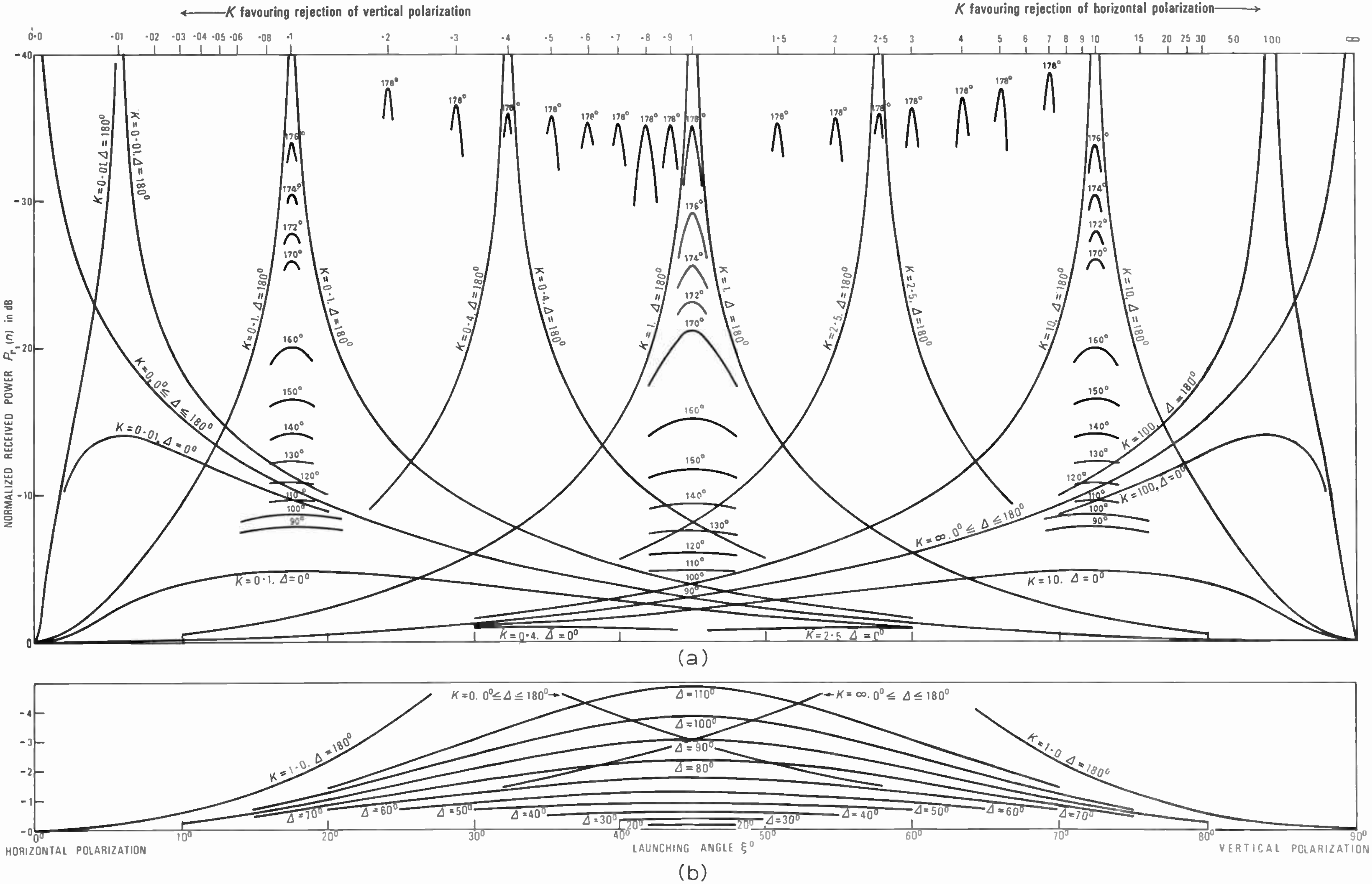


Fig. 8. Universal curves for various conditions—radar case, two-way path.

arrives at the receiving antenna characterized by complex impedances $k_h \exp[j\alpha_h]$, $k_v \exp[j\alpha_v]$ and that the angle between the horizontal component E_h and the linear discriminator is ξ.

Then the normalized, absorbed power $P_{n(abs)}$ may be expressed by:

$$P_{n(abs)} = \frac{(KA)^2 \cos^2 \xi + \sin^2 \xi + 2(KA) \sin \xi \cos \xi \cos \Delta}{(KA)^2 + 1} \qquad (15)$$

with

$$\frac{k_h}{k_v} = K \qquad (15a)$$

$$\frac{A_h}{A_v} = A \qquad (15b)$$

and

$$\Delta = [(\alpha_h - \alpha_v) + (\phi_h - \phi_v)] \qquad (15c)$$

The derivation of equation (15) follows similar steps as for the derivation of equation (10) and only the final conclusions are given. (See Appendix and Fig. 16.)

(a) For a complete absorption of the impinging signal given by equations (14a) and (14b) the phase shifter must be set to

$$\left.\begin{array}{l}(\alpha_h - \alpha_v) = \pm n360° - (\phi_h - \phi_v), \text{ where } n = 0, 1, 2, 3 \\ \text{and simultaneously the power divider set to} \\ \xi = \tan^{-1}\left(\dfrac{1}{KA}\right)\end{array}\right\} \qquad (16a)$$

or

$$\left.\begin{array}{l}(\alpha_h - \alpha_v) = \pm(1 \pm 2n)180° - (\phi_h - \phi_v) \\ \text{and simultaneously} \\ \xi = \tan^{-1}\left(-\dfrac{1}{KA}\right)\end{array}\right\} \qquad (16b)$$

(b) For a complete rejection of the impinging signal, given by equations (14a) and (14b) the phase shifter must be set to

$$\left.\begin{array}{l}(\alpha_h - \alpha_v) = \pm(1 \pm 2n)180° - (\phi_h - \phi_v) \\ \text{and simultaneously} \\ \xi = \tan^{-1}(KA)\end{array}\right\} \qquad (17a)$$

or

$$\left.\begin{array}{l}(\alpha_h - \alpha_v) = \pm n360° - (\phi_h - \phi_v) \\ \text{and simultaneously} \\ \xi = \tan^{-1}(-KA)\end{array}\right\} \qquad (17b)$$

By examining now Fig. 8(b) it is clear that for the case given above when, for instance, a horizontally polarized transmitted signal comes back depolarized with half the energy vertically polarized and the other half horizontal, then $K = 1$ and there is a 3 dB loss of the available received power irrespective of the phase relationship between them.

Equation (15) can also be used to evaluate the amount of power which will be received by an arbitrarily polarized receiving aerial from an arbitrarily polarized transmitting aerial when the transmission is over a sea/land path.

If $k_{th} \exp[j\alpha_{th}]$, $k_{tv} \exp[j\alpha_{tv}]$ and ξ_t are the complex impedances and the angle between the horizontal transmitted component and the linear launcher respectively for the transmitting aerial, and $m_{th} \exp[j\beta_{th}]$ and $m_{tv} \exp[j\beta_{tv}]$ are the complex attenuation coefficients of propagation comprising the apparent attenuation and phase shift which the horizontal and vertical transmitted components will undergo when travelling from the transmitting aerial to the receiving one, taking into account dual paths due to the ground/sea reflections, then parameters in equations (15a, b and c) have to be modified by substituting in them:

$$A_h = E_{(transmitted)} k_{th} m_{th} \cos \xi_t \qquad (18a)$$

$$A_v = E_{(transmitted)} k_{tv} m_{tv} \sin \xi_t \qquad (18b)$$

$$\Delta = [(\alpha_h - \alpha_v) + (\alpha_{th} - \alpha_{tv}) + (\beta_{th} - \beta_{tv})] \qquad (18c)$$

3 Target Parameter Evaluation

A simple radar basically cannot tell when a reflection from an object is wanted or unwanted.

Various current equipments attempt to use some target feature to achieve this classification, e.g. m.t.i. for all target suppression except those having a minimum radial speed. Such systems, however, suffer from rejecting all vehicles moving on near tangential courses (except areal or stationary plot m.t.i.).

The difference in the scattering matrix for raindrops and non-symmetric man-made targets is used for rain clutter rejection without the target speed limitation imposed by m.t.i. equipments.

Crispin and Siegal[18] deal with the general problem of scattering matrices, but this Section sets out to answer the question 'How do targets of interest differ from raindrops or other forms of precipitation clutter, e.g. snow, hail, rain and sea spray?'.

3.1 Wanted Targets

Shipping represents the bulk of interest for marine radars, and Nathanson[19] tabulates median r.c.s. values of a mine-sweeper as a function of:

(a) depression angle,

(b) aspect viewed,

(c) radar wavelength λ,

(d) radar polarization, v or h.

These results, which were taken by Daly of N.R.L.,[20] are of particular interest as the low grazing angle (1·3°) row at C- and X-band was:

$$\left.\begin{array}{ll}\sigma_{vv} & +19{\cdot}5 \text{ dB m}^2 \\ \sigma_{hh} & +18 \text{ dB m}^2\end{array}\right\}\text{X-band}$$

$$\left.\begin{array}{ll}\sigma_{vv} & +17{\cdot}5 \text{ dB m}^2 \\ \sigma_{hh} & +19{\cdot}5 \text{ dB m}^2\end{array}\right\}\text{C-band}$$

The complete table lists 19 sets of measurements taken from depression angles of 1·3° to 8·7° and the maximum 'median' value of r.c.s. was:

$$\left.\begin{array}{ll}\sigma_{vv} & +23 \text{ dB m}^2 \\ \sigma_{hh} & +27 \text{ dB m}^2\end{array}\right\}\text{X-band}$$

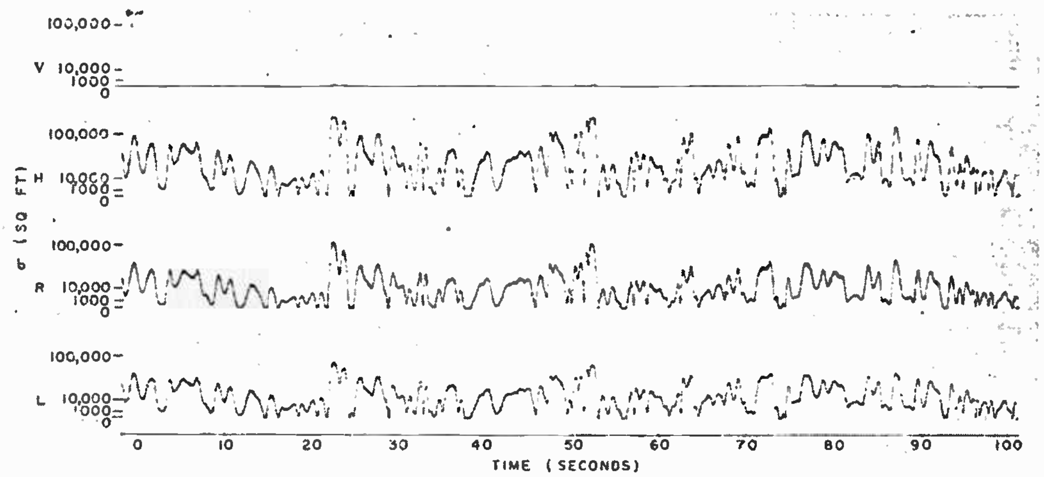


Fig. 9. Sample runs on test buoy No. 2. Showing very low cross- polarized returns. Horizontal X-band illumination[21].

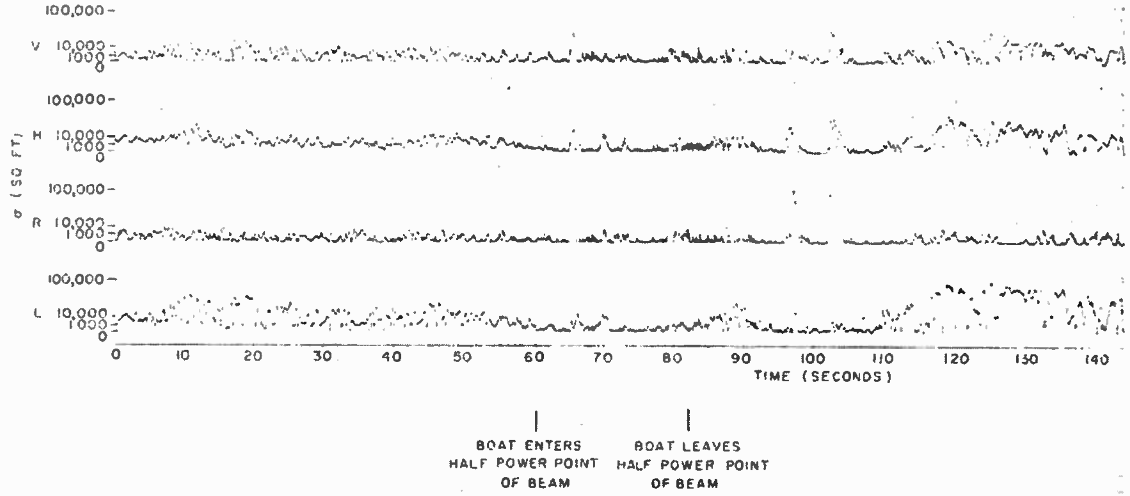


Fig. 10. Further sample runs on test buoy No. 2. Strong cross-polarized return on vertical receive[21].

$$\left.\begin{array}{ll}\sigma_{\text{vv}} & +24\text{ dB m}^2\\ \sigma_{\text{hh}} & +27\text{ dB m}^2\end{array}\right\}\text{C-band}$$

Thus, even before cross-polarization is considered giving the full scattering matrix description of a target σ, it will be seen how practical targets of dimension many times greater than the wavelength in use are very far removed from long thin wire models which are so polarization and frequency conscious.

Data on the cross-polarization characteristic of targets are not as plentiful as non-orthogonal data. However, Olin and Queen[21] carried out extensive trials on three types of radar reflector buoy. These, at first sight, would not appear to be ideal targets for examination, but in their sea environment a fair amount of cross-polarized return is experienced and two runs are reproduced of instantaneous or peak values of σ, varying with time over a 100-second period.

Figure 9 illustrates a 100-second run of an X-band instrumentation radar analysing the four types of return from a buoy at sea when illuminated with horizontal polarization, where the amount of cross-polarization entering the vertical channel is nearly zero. Figure 10 is another run against the same buoy but in a different sea state, showing a fair amount of cross-polarized return from the horizontal illumination.

The run also shows some partial blockage due to a passing boat. For these trials at Chesapeake Bay the instrumentation radar had its aerial assembly kept continuously on the target by means of an optical tracker.

In his paper Olin notes that one of the first references to scattering matrices on a circular basis is by G. Sinclair[22] in 1948; he then remarks that whilst some targets in particular environments do not show significant depolarization or cross-polarization using linear transmission and orthogonal resolving vectors on the vertical and horizontal axes, the same is not true for other orthogonal axes off-set from the vertical.

Thus it can be seen that all but the simplest of geometrical shapes have a degree of cross-polarization in themselves, without considering the further cross-

Table 1

Median values for σ for 3 navigation buoys fitted with essentially 2 bounce reflectors[21]

Buoy No.	Echo area (ft²)						$\frac{\sigma_{RR}}{\sigma_{RL}}$ dB	$\frac{\sigma_{RR}}{\sigma_{hh}}$ dB
	σ_{vv}	σ_{hh}	σ_{RR}	σ_{LL}	σ_{LR}	σ_{RL}		
1	4 000	5 900	7 300	2 100	420	1 750	+6·2	+0·9
2	7 200	13 000	7 000	9 700	900	3 600	+2·88	−2·6
3	700	300	100	200	150	370	−5·68	−4·7

polarization corruption due to multipath and propagation through polarized media, e.g. non-spherical raindrops or through trees. The last two columns in Table 1 show the change of r.c.s. in using a rain reject mode over opposite sense circular polarization or linear operation. Buoy 1 shows a gain in the rain reject mode over the linear one whilst the other two buoys show a loss.

Nathanson[19] deals with the polarization scattering matrix (Ref. 19, p. 145) and states in general terms that if the reflector has circular symmetry (as a raindrop or 3-bounce reflector) along the sight line, then the matrices have the properties:

$$\left.\begin{array}{l}\sigma_{hv}=\sigma_{vh}=0\\ \sigma_{RR}=\sigma_{LL}=0\end{array}\right\}\text{the mechanism of rain rejection}$$

and also, regardless of symmetry

$$\left.\begin{array}{l}\sigma_{hv}=\sigma_{vh}\neq 0\\ \sigma_{RL}=\sigma_{LR}\neq 0\end{array}\right\}\text{for asymmetrical practical targets}$$

but Olin's corner reflector results (Table 1) emphasize how surface targets do not have this second property, which a free space vehicle may well have.

Some actual marine shipping results in Section 5 illustrate how different our measured circular polarization losses are from the pessimistic results of Table 5-1 in Nathanson which gives shipping as being 6 dB down at X-band when using circular polarization for rain rejection, and even worse results for cross-polarized linear polarization operation, except for one C-band result admitting a 2 to 8 improvement using linear cross-polarization.

3.2 Target Parameters Estimation: Rain Clutter

Ridenour[1] was one of the earliest authors on rain cancellation using circular polarization. Skolnik (Ref. 14, Section 12-5) discusses precipitation clutter as it was understood in the 1960s, and records the performance generally expected using fixed c.p., i.e. cancellation of spherical raindrops by over 30 dB when everything is helping, to 15 dB on wet snowflakes. The split p.p.i. display shown is from an AIL experimental set-up. Skolnik draws attention to the contamination of results from ground reflections, quoting White,[2] McFee and Maher[23] and Beasley's forecast[17] of the limits of cancellation obtained using fixed c.p. when the radar is also illuminating the Earth's surface. These are reproduced for convenience in Table 2, which is based on McFee's analysis.[23]

Table 2[23]

Reflection surface for multipath	Maximum cancellation ratio (dB)
Sea	−20·20
Marsh	−23·60
Average land	−27·23
Desert	−34·12

Although the non-sphericity of raindrops has been mentioned in the earliest of references, Dunlop and Stachera[5] have gathered together much of the data which supports Oguchi's theory.[10, 11]

Stachera's work showed little cross-polarization on each of their 72 individual water drops studied in their laboratory vertical wind tunnel, but was mainly interested in the drop's peristaltic action. This drop vibration is one cause of rain clutter spectra broadening and limits the low-speed cover of m.t.i. sets if good rain clutter rejection is to be obtained.

The 15 sets of Proceedings of the Radar Meteorology Conferences held every two years in the USA are perhaps the most fruitful source of rain backscatter measurement with a recent emphasis on cross-polarized backscatter and also forward scatter x.p.d. For example, in Canada, McCormick of the N.R.C. with Hendry *et al.* have recorded and analysed a great deal of precipitation backscatter with their polarization diversity radar. The equipment is described in Refs. 24–26 and 29, and various sets of results are given (Refs. 25–28). The whole subject is reviewed in Ref. 37.

Initially,[24] McCormick's equipment was commissioned in 1968 and gave improvements ranging from 6 to 32 dB. The best results were obtained in light rain at the shortest ranges, coinciding with the leading edge of the rain from the radar (see Tables 3 and 4).

Table 3

Selection of results of rain cancellation measured by McCormick[24] on 16·5 GHz

Date (1968)	Time	Precipitation	Average cancellation (dB)	Notes
19th July	10.03	rain	18·7	c.p.
11th September	13.44	rain	25·4	c.p.
7th October	09.10	rain	22·5	c.p.
7th October	09.20	rain	28·5	o.p.
18th November	08.28	freezing drizzle	32·2	c.p.
28th December	10.17 to 10.32	freezing rain, snow, ice pellets	24·7	c.p.

c.p. circular polarization. o.p. optimum polarization.

It is emphasized that the search for 'true circular polarization' so sought after by radar specification writers is a fruitless objective and only variable polarization with freedom to adjust ξ and $(\alpha_h-\alpha_v)$ can bring

Table 4

Rain cancellation (in dB) measured by McCormick.[25] The equipment has an ellipticity set to optimum performance in Trials Nos. 3–4

Trial no.	Range (km)											
	0·5	1	1·5	2	2·5	3	3·5	4	4·5	5	5·5	6
1	28	28	29	29	27	21	21	21	22	23	22	23
2	28	28	29	29	27	21	22	21	22	23	22	23
3	25	26	27	27	28	27	28	27	28	29	28	28
4	25	26	26	27	28	27	27	27	27	29	28	28

any real benefit even before Section 4 of this paper is considered. This means that best rain rejection is obtained by adjusting ξ and $(\alpha_h - \alpha_v)$ for any particular area when using elliptical polarization aerials.

4 Propagation Path Considerations

4.1 Free Space

For a tracking radar with a vertical elevation of two beamwidths or more, and good side-lobes, ground reflections and multipath are not significant. In this essentially simple case the cancellation of the drops in the leading edge of a rain cloud or storm, providing they are not viewed through the 'bright band' or melting layer, is controlled simply by the radar aerial and raindrop sphericity.

Perhaps the first contamination of results is by the aerial radome itself, particularly if it is wet. In this area, either the scanning motion or an air blast has been found useful in reducing the x.p.d. occasioned by rain or snow on an aerial radome. McCormick uses an umbrella.[24] Detailed measurements at 11 GHz have been made by Evans[6] and Turner.[8]

Thus for best precipitation rejection, control of ξ the amplitude ratio (itself a function of the actual or conceptual launching angle ξ) and α the aerial differential phase shift, has to be continuously varied to minimize rain clutter as a continuous function of range and bearing, even in free space.

4.2 Propagation Over Water, etc.

The first paper pointing out multi-path as a source of x.p.d. due to differential attenuation and phase shift appears to have been by McFee and Maher,[23] possibly preceded in the classified literature by Hunter, whose later papers deal with the low-angle target problem.[3]

The calculations of Beasley have already been given in Section 3 (Fig. 12 from Ref. 17) and made a forecast of 20 dB rejection for radars with their aerials putting appreciable power on the sea. At this point the 'universal curves' may only be used to consider the cancellation of one raindrop in space, as even in a radar resolution cell there will be a finite distribution of raindrop ellipticity and canting angle, as well as a given amount of x.p.d. spread from the ground or sea reflecting surface.

The excellent cancellation results given by McCormick *et al.*[24–29] were obtained using optimum ellipticity and a pencil beam dish aerial elevated above the corrupting ground clutter. In this particular set of circumstances using auto-extraction of rain backscatter data, the aerial must of course be elevated above clutter not only to avoid multi-path but to remove land backscatter results from the computer read-out.

For radars engaged solely on high aircraft detection, multi-path can be virtually ignored, but for those seeking surface targets a more serious effect has to be considered.

4.3 Propagation Path, Consideration of Possible Rain Echo Enhancement Due to Multi-path

Blake, in his radar propagation forecasting reports,[30–32] emphasizes the need to use the correct multi-path propagation factor F (also complex) appropriate to the target being considered and also the competing clutter (rain or sea) around the target as appropriate.

Clearly, in the limit, a small rowing boat 15 or 25 km away from an X-band radar with a 10 m scanner height, is well below the lowest lobe in the multi-path vertical lobe diagram. But rain at these moderate ranges will nearly always fill the vertical beam. Consider a marine radar having a 20° vertical beam with its nose set on the horizon. Then over a calm sea the fingers of the lobe pattern will heavily modulate the upper 10°, extending the maximum coverage on a point target by 12 dB with narrow nulls in between these fingers. The angular spacing of the Lloyd's mirror pattern is given in equation (19) where $\theta_{\max}$ is the elevation from the horizontal of the lobe maxima:

$$\sin\theta_{\max} = \frac{2n-1}{f h_a} \qquad (19)$$

Thus for X-band where $f = 9375$ MHz, the aerial h_a is 15 m high and n here represents integers 1, 2, 3, etc., the angles come out at approximately 0·03°, 0·09°, etc. Then at 10 km the vertical lobe spacing is quite close at 10 m intervals above the sea. Thus in the 10° vertical aerial beam there are some 166 lobe fingers.

The Blake treatment[30–31] does not seem to represent observed results properly and a reason is offered in Fig. 11. Here the lobe fingers are seen extending 12 dB beyond the free space coverage diagram for the frequency and aerial height chosen. The question is, if the original 20° aerial beam is now 10° and there is no power absorbed at the sea surface, how is the radar performance in rain affected? The performance on a point target will depend on that target's position in the lobe pattern (at any one instant). For rain it has been suggested to the authors that there is a significant increase in rain clutter returns over water. This has never been observed to date as the problems of rain clutter and ground clutter confuse any p.p.i. as in Fig. 12, but the straight theory is briefly as follows.

Let the propagation or F factor be given as in equation (16) from Blake[30, 31] (or Kerr[4]):

$$F = 16\sin^4\left(\frac{2\pi h_a h_{\text{rain}}}{\lambda R}\right) = 16\sin^4[T] \qquad (20)$$

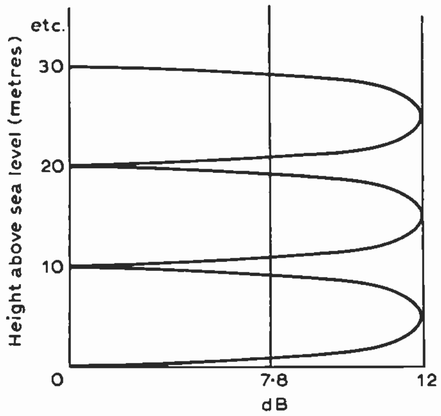


Fig. 11. Relative performance as a function of rain height above sea level.

Now the F factor requires integrating all up the lobe pattern so that its effect on the rain can be compared with the straight unmodulated aerial vertical pattern. There are 166 or N lobes to be integrated (a few more or less is trivial) in the example chosen. Thus the integral of F over the N lobes is equal to:

$$\int_0^N 16 \sin^4 T \, dT = [6T - 4 \sin 2T + 2 \sin 4T]_0^N \quad (21)$$

Now when the number of lobes T is a whole number multiple of 2π the integral of equation (20) becomes

$$\int_0^N 16 \sin^4 T \, dT = 6T \quad (22)$$

The final result required is the average performance change on the rain cell in the whole beam, thus the final value of F becomes

$$F = 6T : T = 6 \text{ or } 7{\cdot}8 \text{ dB} \quad (23)$$

which is shown for the bottom three lobes of Fig. 11. This, of course, follows the aerial polar diagram at greater heights above the water, but gives the impression that rain reflections will be much stronger over water.

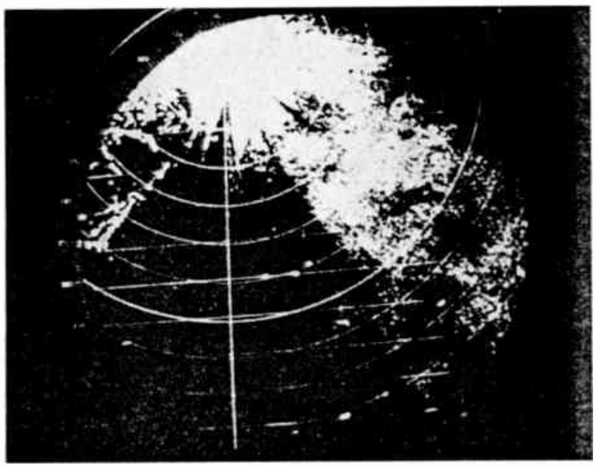


Fig. 12. Rain and sea clutter at a coastal radar site.
Notes: (i) No anti-clutter measures employed.
(ii) 0·5 n.m. range rings.
(iii) Three buoys shown SSE at 3 n.m.
(iv) At around 1 mile rain and sea clutter merge. 19th April 1970.

The radar resolved volume is half the free space one as the 20° vertical coverage has dropped to 10°, i.e. a 3 dB change, but this still leaves a significant increase of rain clutter over the sea of some 4·8 dB. Now, this has never been observed to the authors' knowledge and the reason postulated is that the coherent integration process carried out in equations (20) to (23) is not suitable for noise-like signals, the integration should be more in line with the treatment of thermal noise using an r.m.s. summation of the total power reflected in all the lobes. Confirmation of this can only be obtained if a conical beam radar in a height finder scans down through the rain over a smooth sea, the rain return would appear constant as the beam came from free space down to lie on the horizon, then dip into the sea for all the rain to be illuminated from the water reflection. Experimental evidence of this effect would be of great value in confirming this theory. At sea, of course, this happens all the time with an unstabilized aerial on a rolling ship, but to the authors' knowledge reports of rain clutter modulation synchronous with a ship's roll have never been made.

The discussion does not include the very serious lobe losses encountered in looking for small surface targets, so it can be seen that the shipborne marine radar has a much greater problem looking for surface targets than a ground-based radar searching the sky for normal air traffic, particularly in rain.[41]

The validity of the analysis just carried out is hard to check as so often rain conditions vary as rain crosses the coast; measurements to date have not revealed a sharp discontinuity in rain clutter as observed over land and sea, and the situation is bedevilled by the addition of land and sea clutter to rain over the coast as in Fig. 12. Kerr[4] reviews the low incidence of multi-path effects of microwaves over countryside with only serious effects taking place over really flat countryside or an airport runway.

4.4 Propagation Path Consideration Through Precipitation

The need for varying degrees of ellipticity to cancel rain as the radar waves propagate through a rain storm has been adequately shown by many workers interested both in c.p. corruption, e.g. McCormick *et al.*,[24–28] and in satellite to earth communications using orthogonal linear polarization for co-channel working to conserve the electromagnetic spectrum frequency usage (e.g. Bell, British Post Office, Bradford and Essex Universities). Reference 6 includes a good reference list up to 1972, and the basic calculations on x.p.d. have been carried out by Oguchi.[10, 11]

McCormick's earliest work[24] describes his 16·5 GHz instrumentation radar and then the first 6 months of observations from which preliminary rain cancellation results of around 20 dB are reported using true c.p., and up to 30 dB using optimum ellipticity. A feature of his equipment is the polarization symmetry of the offset 'Potter-fed' dish which has an integrated cancellation ratio over the significant part of its beamwidth of over 30 dB.

Hendry and McCormick then go on in Refs. 25 and 26 to give and discuss further results, particularly the likelihood of a significant number of raindrops within the radar resolution cell having a preferred orientation as has been previously noted by visual means, explaining the mechanism of progressive depolarization of propagation through rain which can be compared to Oguchi's theoretical work.

For light rainfall very good cancellation results are obtained but for heavier rainfall the variation of drop size and, more important, distribution of preferred drop orientation becomes greater. However, McCormick has measured cancellation ratios of approximately 13 dB, even with rates up to 100 mm per hour, if the storm is viewed over a clear free space path, and this point is made in Ref. 25 (Fig. 3).

A set of results for fixed c.p. through 5 km is shown in Table 5 and the correction to progressive x.p.d. is illustrated in the next set of figures, again from the same Ref. 25, shown here as Table 6.

Separately, in the 14th Radar Meteorological Conference, McCormick and Hendry[27] give results of cancellation in light and heavy rain—the melting layer and for snow, and are reproduced here with their permission; nine sets of range gates were used and for each type of rain four sets of results were taken spaced at one-second intervals (see Table 7).

The data in Table 6 were selected by McCormick for presentation in Ref. 2 and are reproduced to illustrate the improvement in trimming the ellipticity to suit as 3 and 4 in Table 6. Later McCormick[37] has suggested that the translation from Ku (J) to X-band of his extensive free space results could be approached by relating the differential complex propagation constant to the attenuation. These show that whilst light rain is very effectively dealt with and dry snow is less of a problem than was believed to be the case, the progressive cross-polarization through heavy rain reduces the value of circular polarization beyond a few kilometres, but James[38] has dealt with the low probability of heavy rain extending for very far, except in tropical storms.

Considerable measurements have been made of rainfall attenuation and theory and measurements do not agree. Nathanson (Ref. 19, page 195) suggests this is due to (i) higher atmospheric attenuation close to the actual storm due to a general rise in humidity and (ii) lack of knowledge of raindrop size. If the ratio of attenuation at 16·5 GHz and 9·375 GHz varies as the square of the frequency ratio, then at X-band the attenuation will be one-third that at J-band. However, at these wavelengths the normal Rayleigh λ^4 relationship no longer holds, hence the reduced power relationship as shown on Nathanson's Fig. 6.3.[19]

It is convenient for certain terms to be redefined for this analysis:

Let $\Delta\gamma$ = differential propagation constant through rain,
$\gamma = \alpha + j\beta$,
α = real attenuation in rain,
β = phase shift in rain,
χ = the argument of $\Delta\gamma$.

McCormick has shown that for three rainfall rates the data in Table 8 are applicable. Thus, although the values of the term $\Delta\gamma/\alpha_V$ are comparable at the two

Table 5

Rain cancellation in dB for heavy rain at 16·5 GHz.[25]

Trial spacings	Range (km)										
	0·5	1	1·5	2	2·5	3	3·5	4	4·5	5	5·5
0 s	18	14	15	13	11	9	7	7	6	7	5
2 s	18	15	15	13	11	9	7	7	6	7	5
4 s	17	15	15	13	10	9	7	7	6	7	5
6 s	17	16	15	12	10	9	7	7	5	7	5

Table 6[25]

Trial no.	Range (km)											
	0·5	1	1·5	2	2·5	3	3·5	4	4·5	5	5·5	6
1	28	28	29	29	27	21	21	21	22	23	22	23†
2	28	28	29	29	27	21	22	21	22	23	22	23†
3	25	26	27	27	28	27	28	27	28	29	28	28‡
4	25	26	26	27	28	27	27	27	27	29	28	28‡

† Fixed c.p.

‡ Ellipticity set for best rejection in last 6 gates.

Table 7[27]

Precipitation description	Range gates →									T (s)↓
	1	2	3	4	5	6	7	8	9	
Light rain	32	32	30	28	30	32	29	27	25	1
	31	31	30	28	30	32	29	27	26	2
	32	31	30	28	30	32	29	27	26	3
	31	32	30	29	31	32	29	27	26	4
Heavy rain	19	18	15	14	12	10	8	6	5	1
	19	19	15	14	12	10	8	6	4	2
	18	19	15	14	12	10	7	5	3	3
	19	18	15	14	13	10	7	5	2	4
						ML				
Melting layer (ML)	25	25	25	24	23	10	19	29	29	1
	27	26	26	25	24	10	19	29	29	2
	27	27	27	26	24	9	19	28	28	3
	26	26	26	26	23	9	19	27	28	4
Dry snow	32	31	32	32	33	33	33	33	32	1
	31	32	32	33	33	33	33	33	33	2
	32	32	32	33	33	33	33	32	33	3
	32	32	32	33	33	33	33	32	33	4

frequencies, as the α_V terms vary by three to one it is expected that the differential phase shift at X-band will be three times less severe than at J-band for a given rainfall rate and range. Thus, referring back to Table 7, it would appear that a much greater extent of rain can be tolerated, say, 18 km before a progressive change of ellipticity is required to ensure best results for a large rain mass during heavy precipitation when using X-band.

Table 8

Rain rate (mm/hr)	Frequency	χ (rad.)	$\frac{\Delta\gamma}{\alpha_V}$
2·5	15 GHz	1·320	0·513
12·5	,,	1·198	0·440
25·0	,,	1·136	0·430
2·5	11 GHz	1·408	0·893
12·5	,,	1·310	0·676
25·0	,,	1·263	0·606

5 Other Forms of Rain Rejection Using Multi-polarization

An alternative method is to transmit any linear polarization and receive orthogonally to it. Then any symmetrical target will have a target r.c.s. $\sigma_{HV} = 0$ as discussed in Section 3.1. Clearly, spherical raindrops will give zero return in the orthogonal channel if no cross-polarization distortion takes place in the radar–radome–propagation medium or at the target.

Semplak[28] has reported results over a 2·6 km propagation path at Holmdel. The operating frequencies were 18·65 GHz for c.p. and 18·35 GHz for horizontal linear polarization. In clear conditions x.p.d. in both channels was better than 32 dB. During rain storms in the summer of 1972 results indicated a superior x.p.d. performance on linear than c.p.; these are summarized for one moment of storm in Table 9.

Table 9

Relative performance at 18 GHz

Performance		System C.P.	 Linear
Attenuation	dB	36	38·5
Cross-polarization distortion	dB	8	13·5

For another moment later in the storm the analysis is given in Table 10.

Table 10

Relative performance at 18 GHz

Performance		System C.P.	 Linear
Attenuation	dB	18·5	19
Cross-polarization distortion	dB	18·5	28

Thus with regard to the aerial and propagation path parts of a whole radar system operating around 18 GHz, it would seem that a crossed polarization, linear aerial system would give better rain rejection results than the more conventional circular polarization systems, even when perfectly engineered.

It must be noted that these are extrapolated views taken from measurements on a propagation path and do not represent real rain clutter cancellation measurements.

6 Results

Our initial work on circular polarization was carried out around 1960 using a 4·27 m × 1·22 m (14 ft × 4 ft) parabolic section mirror aerial. The equipment operated at 3·2 cm and had a remote-controlled feed capable of transmitting c.p. and by varying the integral phase shifter various degrees of ellipticity to enable the best cancellation of any raindrops to be obtained. Its limitation was that the two limits of adjustment of c.p., i.e. linear polarization, lay on an orthogonal pair of vectors ±45° to the vertical, and did not allow best cancellation of elliptical raindrops having their major axis near the horizontal, as measured and discussed by Watson and Arbabi,[9, 39] Semplak,[13] Jones[42] and Pruppacher and Beard.[43]

In spite of this many equipments have been operating for over fifteen years as approach aids at airfields on aircraft final approaches at ranges up to 40 km (25 miles). Reports indicate that the circular polarization mode always gives substantial rain rejection with some loss of target strength, but on busy airfields quantitative measurements are not easy to arrange.

A second generation of equipment has been operating at an experimental radar site on Dungeness beach in Kent for a year. This equipment consists of two 1·22 m slotted waveguide aerials facing the same way, both mounted on a common turning gear with twin microwave rotating joints; one is conventional with horizontal polarization whilst the other can be varied from linear at 45° to c.p. with various degrees of ellipticity in between. The two aerials are fed from similar 3·2 cm transmitter receivers of the following parameters:

TRANSMITTER

Peak power	25 kW
P.r.f.	1000 p/s interlaced
Pulse lengths	0·05 or 0·25 or 1 μs

RECEIVER

Linear superhet with i.f. of	60 MHz
B_0	4 or 20 MHz
Noise factor	12 dB

Attenuators are fitted between the receiver pre-amplifiers and linear main i.f. strips to enable relative and absolute target strength measurements to be made.

The p.p.i. display is a very special one. It features twin video and time base circuits, enabling each r.f. head and aerial system to present its own display continuously interlaced at p.r.i. intervals, i.e. every milli-

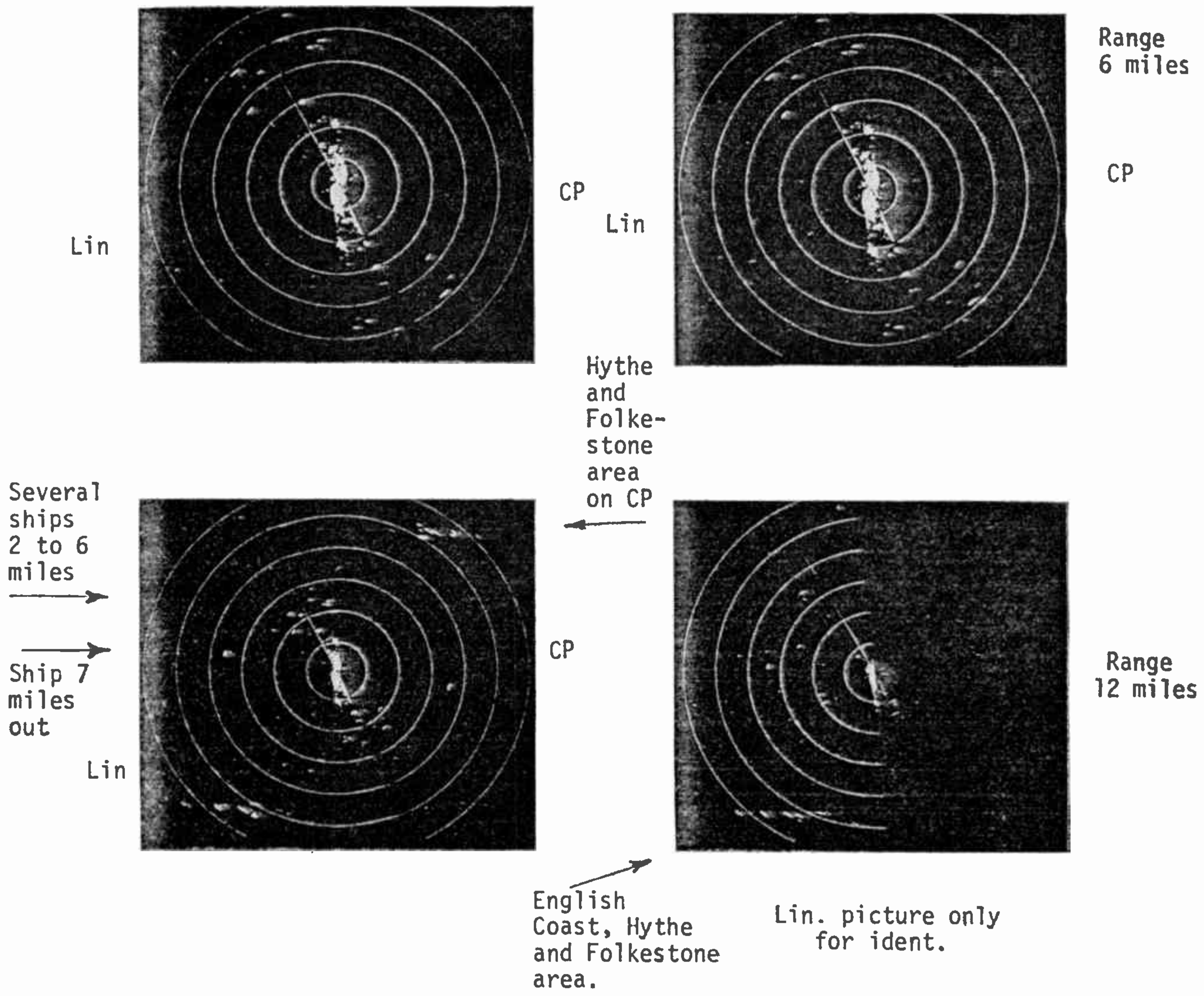


Fig. 13. Three comparisons of linear polarization on l.h.s. and circular polarization on r.h.s. in clear weather with performance set for equality on general overall picture. Aerial $\theta = 2^c$. $t_p = 0{\cdot}5$ μs.

second there is a fresh piece of radar data about a common set of targets. For clarity of presentation only, 180° of any 360° of area scanned is presented to give two half pictures of the same section facing each other.[40, 41] Thus the probability of a target fade occurring whilst being inspected by two types of polarization is minimized.

Figure 13 presents a split radar p.p.i. picture of the area around Dungeness Point with parameters as shown.

With the radars operating, the receiver noise backgrounds are balanced using their gain controls and marginal clipping in one or other of the two display video amplifiers. By general examination of the land echoes, differential i.f. attenuation can be applied to balance any one, or a cluster, of the many land echoes. Then, specific targets may be examined.

(a) In general the horizontal linearly polarized set (referred to as h.p. in text) requires about a 5 dB attenuation to achieve a general balance. This does not reflect a general c.p. loss but difference in waveguide loss, etc.

(b) At Dungeness the high voltage pylon line running North from the site 'Point' is extremely polarization conscious. Film strips have been taken on various days and with various conditions to illustrate ground, ship and sea clutter differentials due to c.p.–h.p. and h.p.–45° l.p., where the c.p. set is adjusted to give a linearly polarized performance which occurs at 45° to the normal h.p.–v.p. axis.

(c) A corner reflector of nominal 1000 m^2 set up some 100 yards away in a convenient spot on the beach, showed an overall reduction of σ of 20 dB. This can be taken as a rejection of from 15 to 20 dB depending on how one defines the parity of performance of the two sets.

(d) The bulk of the power pylons suffered a 15 dB effective reduction on c.p., but the chain contained some elements giving 20 dB rejection on c.p. and some as little as 10 dB, i.e. varying degrees of 'corner accuracy' or bounce asymmetry.

(e) Special targets: Within a 6-mile scan of Dungeness one target ¾ mile out amongst the pylon chain was enhanced using c.p. over the l.p. set by 17 dB. Otherwise most land targets tend to be detected more easily using the linear horizontal polarization.

(f) Shipping: Half a dozen ships were observed for several minutes and relative values of σ estimated. These are given in Table 11.

(g) At a later time the coastal targets at 20 miles from the site were balanced on the two sets, and in this condition some of the power pylons around 1·5 miles showed a 35 dB rejection on c.p. to h.p., but the average differential on these multi-corner reflectors remained about 20 dB.

(h) Large steel erection—power station rig: This target is interesting as it perhaps approximates to one of the new North Sea oil or gas rigs. On the h.p. set at 0·3 mile there is some 63 dB of spare performance. On c.p. the spare performance drops to 54 dB, giving a differential due to polarization of 9 dB from the particular aspect viewed.

Table 11

Comparison of ship signal returns in clear weather

Ship No.	Range	Spare performance	Ratio $\frac{\sigma_{\text{Lin}}}{\sigma_{\text{c.p.}}}$
1	10 miles	None	0 dB
2	6 miles	+20 dB	+1 dB
3	10 miles	+10 dB	+2 dB
4	8 miles	0	0
5	18 miles	Very marginal	+3 to +5 dB
6	5·5 miles	Marginal	+4 dB on lin No return on c.p.
6 later	5 miles	Marginal	+4 dB i.e. c.p. performance rose more quickly than lin at 5 miles

Table 12

Ship No.	Range (n.m.)	Excess perf. on lin. (dB)	Excess perf. on c.p. (dB)	Ratio $\frac{\sigma_{\text{Lin}}}{\sigma_{\text{c.p.}}}$ (dB)
1	5	10	10	0
2	6	20	20	0
3	5·5	15	15	0
4	5	30	30	0
5	7	23	20	+3
6	9	10	10	0
7	9	0	0	0
8	4	20	15	+5
9	7	30	30	0
10	8	15	15	0
11	10·5	0	0	0

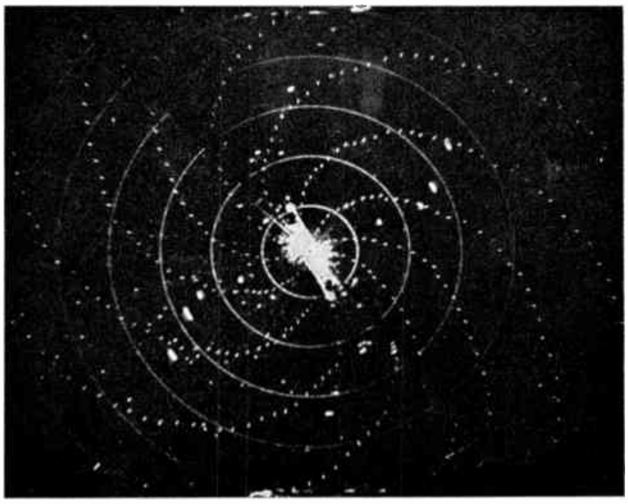


Fig. 14. Split image display comparing h.p. linear radar with c.p. set. (The catherine wheel interference is from other radars in the channel.) 10th July 1973. Range: 12 miles. Rings: 2 miles. Both radars operating at full gain. Transmitters on 0·5 μs pulse, 1000 p/s.

The interesting point is the definite change of shape of echo on c.p. and h.p. as the c.p. picture is not only weaker, but fatter, as though there is a single dominant linearly polarized part of the rig which is no longer dominant on c.p.

Further shipping in the clear was measured on the c.p. and h.p. linear system, and the results are shown in Table 12. Visibility was down to 2 miles, so no recognition was possible.

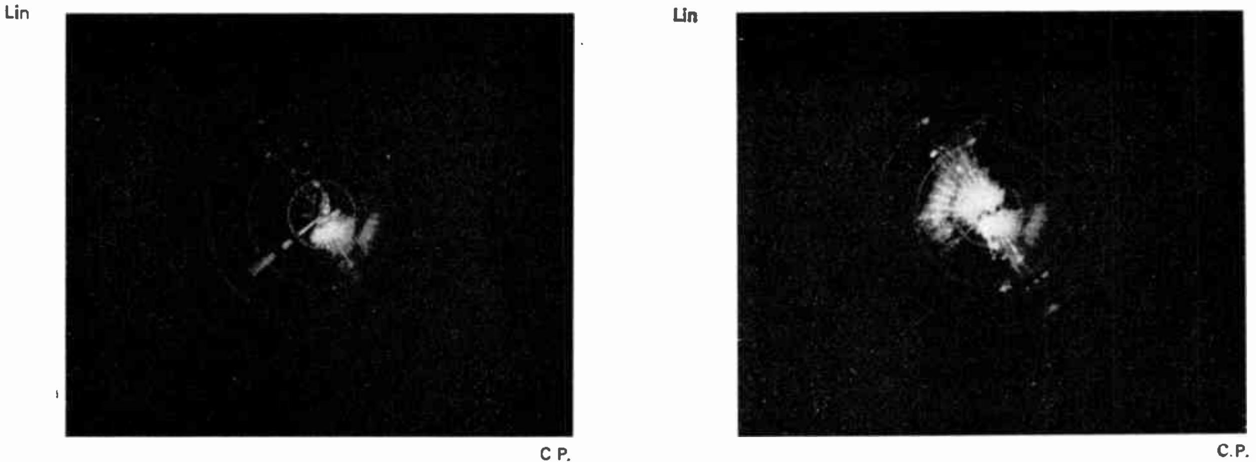
The Table shows a very slight advantage to linear h.p. of 3 to 5 dB in two cases.

For the 18 cases considered in Tables 11 and 12 there appears to be an advantage on linear h.p. of just over 2 dB, an insignificant loss of performance on shipping over the range to 18 miles.

Typical photographs comparing c.p. and linear h.p. are reproduced as three of the four photographs in Fig. 13 and Fig. 14 under clear conditions.

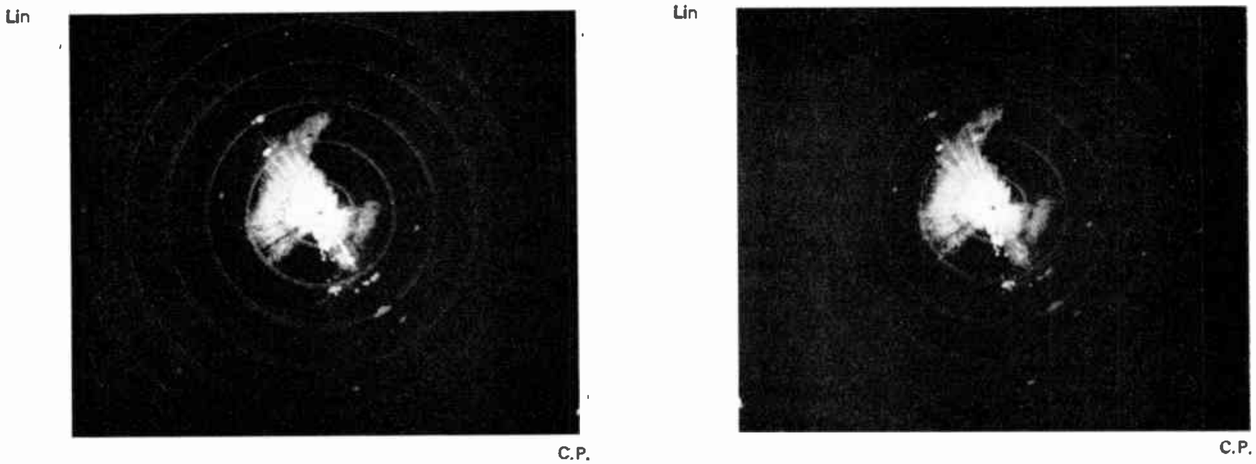
The results in rain are shown as Fig. 15 where of the four photographs the one with 15 dB of attenuation in the left-hand or linear system gives the best parity, showing an effective reduction of rain echoes of over 15 dB using c.p. over the linear system; the last photograph shows echoes on the 2- and 3-mile range rings at about equal strength, with severer rain returns on the linear channel.

The very quick transit of local rain makes these last four photographs rather confusing as the rain intensity and wetting of the two aerials is changing from shot to shot at the same time as the attenuation is varied in the linear system channel. For a search radar looking at quickly moving local rainstorms with manual adjustment of radar parameters, the accuracy of a fully instrumented tracking radar is not obtained, particularly over more than one azimuth.



(a) Linear attenuation 20 dB.

(b) Linear attenuation 15 dB. Nearest rain parity in sequence.



(c) Linear attenuation 10 dB.

(d) Linear attenuation 5 dB.

Fig. 15. Split image photographs with increasing gain in linear channel to estimate rain rejection at 15 dB on c.p. channel in (b).

Circular polarization compared to linear h.p. in a rain storm. Equipment details:

Range:	6 miles.	t_p:	0·5 µs.	Each set: 3·2 cm.	Peak power: 25 kW.
Cal. rings:	1 mile.	P.R.F.:	1000s interlaced between twin r.f. heads.		Aerial: θ: 2°.
Site:	Dungeness coast.				ϕ: 20°.

7 Conclusions

This paper has set out the relative merits of using special aerial polarization for maximizing rain rejection whilst presenting likely penalties of target reduction, and enables the true improvement of target to rain signal ratios to be understood. Many papers are published dealing with methods of rain clutter rejection without attempting to assess the true gain (or loss) of wanted target to unwanted clutter ratio. The work at Boeing by Jonsen and Friedland[44] is one of the few examples of showing rain rejection by cross-polarized linear transmission and reception with adequate detection of a fishing boat at 2·5 miles, and barge at 1·5 miles, on Lake Washington in a medium rainstorm. The use of circular polarization instead of linear orthogonal operation is, perhaps, fortuitous in that the earliest c.p. hardware took the form of a set of quarter-wave plates placed in front of early horn feeds to mirror-type aerials in a manner analogous to optical linear-to-circularly-polarized overlays. Orthogonal linear operation already shows considerable promise with far less practical shipping loss than earlier references indicate, but the hardware implementation is less easy to retrofit on older equipments.

8 Acknowledgments

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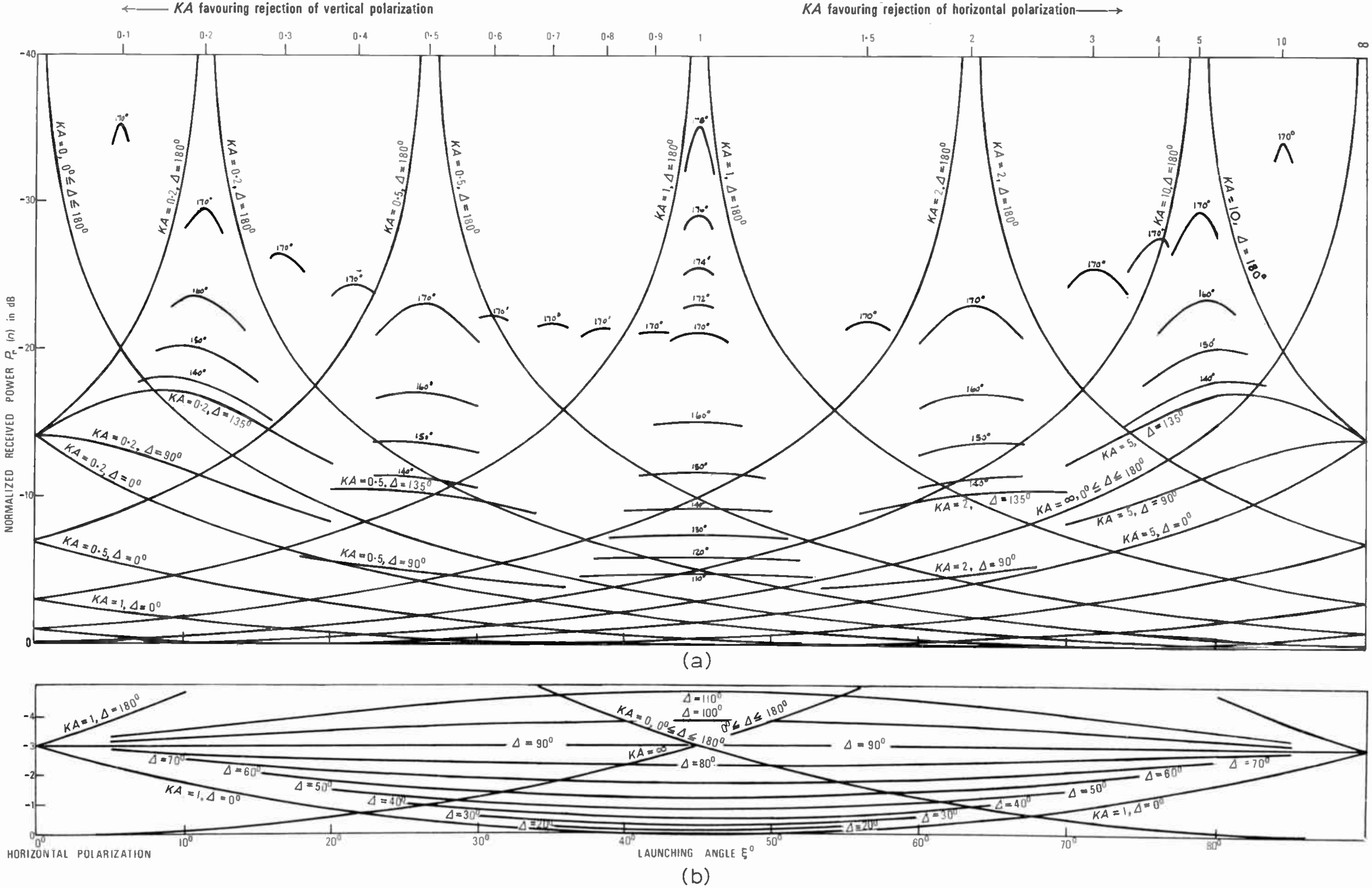

Fig. 16. Universal curves for various conditions—communication case, one-way path.

10 Appendix: Programs for Sumlock 322G (Scientist)

10.1 Two-way Path (Radar)

```
1.  Load
2.  Start/Stop
    Set ξ  (say 50)
3.  Store
4.  0 (ξ)
5.  Sin/Cos
6.  aˣ
7.  4
8.  =
9.  Store
10. 1 (Sin⁴ ξ)
11. √‾‾
12. Store
13. 2 (Sin² ξ)
14. Recall
15. 0 (ξ)
16. Sin/Cos
17. 2nd func.
18. aˣ
19. 4
20. =
21. Store
22. 3 (Cos⁴ ξ)
23. √‾‾
24. Store
25. 4 (Cos² ξ)
26. Recall
27. 6 (K²)
28. x
29. Recall
30. 3 (Cos⁴ ξ)
31. +
32. Recall
33. 1 (Sin⁴ ξ)
34. +
35. [
36. 2
37. x
38. Recall
39. 5 (K)
40. x
41. Recall
42. 2 (Sin² ξ)
43. x
44. Recall
45. 4 (Cos² ξ)
46. x
47. [
48. Recall
49. 7 (Δ)
50. Sin/Cos
51. 2nd func.
52. ]
53. ]
54. ÷
55. [
56. Recall
57. 6 (K²)
58. x
59. Recall
60. 4 (Cos² ξ)
61. +
62. Recall
63. 2 (Sin² ξ)
64. ]
65. =
66. Ln/Log
67. 2nd func.
68. x
69. 1
70. 0
71. =
72. Start/Stop
73. Run
```

As a check the result
reads now -6.78

<u>Constants</u>

Set K (say 0.5)
Store (K)
5
aˣ
2
=
Store
6 (K²)
Set Δ (say 180)
Store
7(Δ)

<u>Check Calculation</u>

Set 40
Press Start/Stop twice
the result reads -15.91

10.2 One-way Path (Communication)

```
1.  Load
2.  Start/Stop
    Set ξ (say 50)
3.  Store
4.  0 (ξ)
5.  Sin/Cos
6.  Store
7.  1 (Sin ξ)
8.  aˣ
9.  2
10. =
11. Store
12. 2 (Sin² ξ)
13. Recall
14. 0 (ξ)
15. Sin/Cos
16. 2nd func.
17. Store
18. 3 (Cos ξ)
19. aˣ
20. 2
21. =
22. x
23. Recall
24. 6 (K)²
25. +
26. Recall
27. 2 (Sin² ξ)
28. +
29. [
30. 2
31. x
32. Recall
33. 5 (K)
34. x
35. Recall
36. 1 (Sin² ξ)
37. x
38. Recall
39. 3 (Cos ξ)
40. x
41. [
42. Recall
43. 7 (Δ)
44. Sin/Cos
45. 2nd func.
46. ]
47. ]
48. =
49. ÷
50. [
51. Recall
52. 6 (K)²
53. +
54. 1
55. ]
56. =
57. Ln/Log
58. 2nd func.
59. x
60. 1
61. 0
62. =
63. Start/Stop
64. Run
```

As a check the result
reads now -8.00

<u>Constants</u>

Set (K) (say 0.5)
Store
5 (K)
aˣ
2
=
Store
6 (K)²
Set Δ (say 180)
Store
7 (Δ)

Check calculation
Set 40
Press Start/Stop twice

The result reads
now -12.67

The results of this computation are given in Fig. 16.

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UDC 621.396.677

Introduction of a sharp steerable null response in an otherwise omni-directional pattern using a circular array

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SUMMARY

A method of generating a single sharp null response in an otherwise omni-directional pattern using a circular array is discussed. The null width is reduced by the introduction of an abrupt phase reversal in the pattern function in the direction of the null. The null is also electronically steerable in the azimuth and in the elevation plane. Mutual coupling effect on the depth of the null is minimized through the use of sequence excitation components in the feed.

List of Symbols

θ	zenith angle of the direction of radiation
ϕ	azimuth angle of the direction of radiation
a	radius of the array
k	free space propagation constant
m	number indicating the position of the element
N	total number of elements in the array
v_m	angular location of the mth element with reference to the x-axis, i.e. $v_m = m(2\pi/N)$
ϕ_0	azimuth angle at which the null occurs
I_n	excitation coefficient for the nth sequence excitation

1 Introduction

An antenna system which will provide an omnidirectional coverage plus a single steerable null in the horizontal plane has been presented in an earlier paper.[1] This discussed an extremely simple and practical array configuration which will generate a sharp zero-crossing null in an otherwise omnidirectional pattern in the horizontal plane. The method had the additional advantage, in the case of the 4-element array, of utilizing a completely matched feed system, thus allowing the array to be used as a transmit antenna as well as a receive antenna. However, electronic null steering, although possible, is difficult to realize as it involves the adjustment of too many phase shifters.

In the present paper, another method is discussed which will produce a sharp zero-crossing null response in a certain direction while maintaining the radiation pattern away from the null essentially constant. The characteristic feature of this array is that the null is steerable electronically over 360° without significant change in the pattern characteristics using a Butler matrix network.[2, 3] Null steering can then be effected in the same way as the beam is steered in a linear array of equal inter-element spacings. Also, for a given feed configuration, by changing the operating frequency or a/λ ratio, the null is steerable in the elevation plane. In other words, it is possible to design a feed system so as to produce a null in any direction in the visible space. However, since attenuators are used in the feed to provide the proper excitations to the elements, this method is essentially suited for use in a receiving array.

2 Method of Synthesis

As was discussed in the earlier paper, the null width for a given array diameter will be narrowest if the null is a zero-crossing null, in which there is an abrupt phase reversal in the pattern function in the direction of the null. By so doing, it is possible to get a null width which is approximately half the beam width of the same array when the feed is designed to give a single co-phasal beam pattern. However, in order not to generate another null at some other direction, it is then necessary for the pattern function to be complex. One method of eliminating the second null is to allow the pattern function to change in phase progressively at half the rate of change

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of the azimuth angle. An idealized pattern which satisfies the above condition is

$$D(\phi) = \exp\left[j(\phi - \phi_0)/2\right] \tag{1}$$

An attempt is made to synthesize the above pattern by generating the appropriate spatial harmonics in the pattern function using a circular array. It is known[4, 5] that each spatial harmonic pattern can be generated by an appropriate sequence excitation in the array. The nth sequence excitation is a constant amplitude excitation with a constant phase change between adjacent elements such that the total phase shift upon completion of a complete circle around the array is $2\pi n$ radians. Hence for a circular array with uniformly spaced elements on the horizontal plane, the nth sequence excitation to the mth element will be

$$i_m = \frac{I_n}{N}\exp\left[jnv_m\right] \tag{2}$$

When the inter-element spacings are smaller than $\lambda/2$, the radiation pattern for the nth sequence excitation is approximated by

$$D_n(\phi) = j^n I_n J_n(ka)\exp\left[jn\phi\right] \tag{3}$$

By the superposition of a number of sequence excitations, the resultant directional pattern is

$$D(\phi) = \sum_{n=-M}^{M} j^n I_n J_n(ka)\exp\left[jn\phi\right] \tag{4}$$

It is obvious that for an array of a given number of elements, there is a limit to the highest sequence which can be used. As dictated by the sampling theorem where each sequence must at least be sampled at two points per phase cycle, the maximum value for M can be shown to be $N/2$.

From equations (1) and (4), and using the standard method for the calculation of Fourier components

$$I_n = \frac{\exp\{-j[(n+1)\pi/2 + n\phi_0]\}}{\pi . J_n(ka).(n-\frac{1}{2})} \tag{5}$$

Using the relation $J_{-n}(ka) = (-1)^n J_n(ka)$, the excitation coefficient for the negative nth sequence is

$$I_{-n} = \frac{\exp\{-j[(n+1)\pi/2 - n\phi_0]\}}{\pi . J_n(ka)(n+\frac{1}{2})} \tag{6}$$

The required excitation to the mth element is, therefore,

$$i_m = \sum_{n=0}^{M} \varepsilon_n\{I_{-n}\exp\left[-jnv_m\right] + I_n\exp\left[jnv_m\right]\} \tag{7}$$

where $\varepsilon_n = \frac{1}{2}$ when $n = 0$ and $\varepsilon_n = 1$ otherwise.

The radiation pattern due to the excitations as given by equation (7) can now be calculated using the exact pattern equation

$$\bar{D}(\phi) = \sum_{m=0}^{N-1} i_m \exp\left[jka\sin\theta.\cos(\phi - v_m)\right] \tag{8}$$

The depth of the null when computed may not be satisfactory in view of the approximations used in the computation of i_m. This can be easily resolved by making a small correction to the zero sequence excitation to null the response at $\phi = \phi_0$. The corrected zero sequence excitation is

$$\bar{I}_0 = I_0 - \bar{D}(\phi_0)/J_0(ka) \tag{9}$$

From equations (5) and (6), it is clear that there will be some frequencies at which $J_n(ka)$ is equal to or very close to zero. Consequently, it may not be practical to generate the desired spatial harmonics in the far field at these frequencies. It is therefore important to choose an appropriate frequency or radius such that this unfavourable condition does not exist. It can also be deduced from equation (8) that the effect of increasing the a/λ ratio of the array is to steer the null in the elevation plane. Thus with both frequency and excitation control, it is possible to steer the null to any arbitrary direction in space.

3 Results of Computations

To enable direct comparisons to be made with the patterns generated by the method used in Reference 1, computations are made for two arrays of similar sizes

Table 1. Sequence excitation coefficients

N	n	-3	-2	-1	0	1	2	3
4	Amplitude I_n	—	0·475	0·349	1·000	1·046	0·792	—
	Phase I_n	—	180°	−90°	0°	90°	0°	—
8	Amplitude I_n	0·168	0·193	0·957	1·000	2·871	0·312	0·235
	Phase I_n	−90°	0°	90°	0°	−90°	180°	90°

Table 2. Element excitation

N	m	0	1	2	3	4	5	6	7
4	Amplitude i_m	1·490	0·712	1·490	2·079				
	Phase i_m	0·487	3·142	−0·487	0·000				
8	Amplitude i_m	2·042	3·922	5·360	3·922	2·042	1·676	3·102	1·676
	Phase i_m	−1·130	−0·510	0·000	0·510	1·130	2·584	−3·142	−2·584

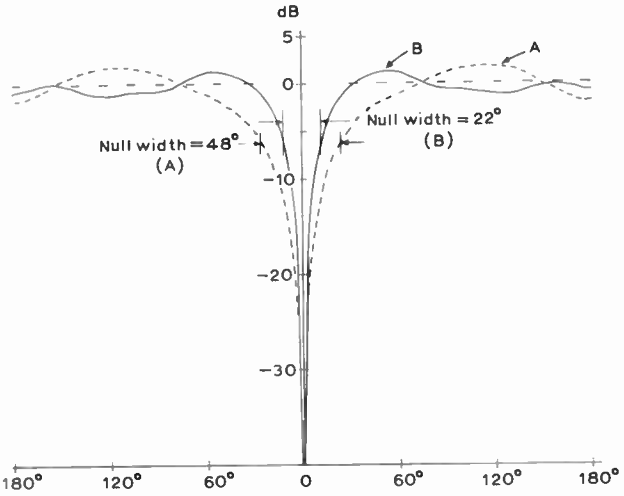

Fig. 1. Radiation patterns of the arrays.
A. 4-element. B. 8-element.

and number of elements. The radii for the 4-element and the 8-element arrays are respectively 0·25λ and 0·55λ. The computed sequence excitation coefficients for the two arrays are given in Table 1 and the resultant element-excitations are presented in Table 2. The sequence excitations are normalized with reference to the zero sequence which is assigned a unity amplitude and zero relative phase.

The computed far-field patterns for the arrays are shown in Fig. 1. Defining the null width, as in the earlier paper, to be the angle between two points 6 dB below the mean omni-level, it is found that the null width for the 4-element and the 8-element arrays are 48° and 22° respectively. For comparison, the corresponding null widths for the two arrays synthesized using the method in Reference 1 are 41° and 24° respectively. The gain ripple in the omni-region for the two arrays using the present method of synthesis are 1·8 dB and 1·2 dB respectively. The corresponding figures for the earlier arrays are 0·5 dB and 3·3 dB. It can be seen that the present method gives a superior pattern in the case of the 8-element array to that obtained through the earlier method. The reverse is true in the case of the 4-element array. It is only to be expected that the results obtained using the present method would be better for larger arrays in view of the availability of a greater number of spatial harmonic components.

For ease in null steerability, the various sequence excitations can be established in the array through the use of a Butler matrix network as shown in Fig. 2. The property of the Butler network is such that when the rth input port is excited with an excitation I_r, the $(r-1)$th sequence excitations with an excitation coefficient I_r/N appear at the output ports. Also when the $(N-r)$th input port is excited, the $-(r+1)$th sequence excitations will be established at the output ports. An important property of such a feed system is that the null can be easily steered by the introduction of a progressive phase shift to the excitations applied to the input ports of the network in the same manner as beam steering is effected in a linear array.

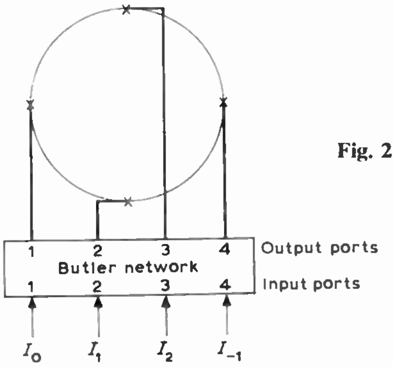

Fig. 2. A Butler feed network.

4 Conclusions

An effective and practical method of generating a sharp null in an otherwise omni-directional pattern is presented. The computed results show that the directional patterns so obtained have good characteristics in terms of the null width and the gain ripple in the omni-region. Mutual couplings between elements have little effect on the pattern function as all elements in the array have identical coupling environments since all components of excitations in the array have integral number of close cycle phase variations around the array. Rapid steering of the null can be effected electronically without any mechanical displacement of the elements in the array.

5 Acknowledgments

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Picture recognition and analysis

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SUMMARY

Picture recognition and analysis has numerous applications in all fields of technology, from medical diagnosis to document processing. This paper introduces some of the basic techniques of picture analysis: *correlation*, or matching of pictures; *transformations* and their uses, including their application to *normalization* for recognition purposes; *parametrization*, or property measurement, for picture classification; and *segmentation* of a picture into parts for purposes of description, with emphasis on segmentation based on region *connectivity*. Examples are given showing how each of these techniques is important in practical applications.

1 Applications of Picture Recognition

Steel generally includes small particles of non-metallic substances such as aluminates, silicates and sulphides, which may affect the quality of the steel (see Fig. 1). Automatic picture recognition techniques are used for measuring size and shape distributions of these non-metallic particles, for purposes of quality control in steel production. Analysis of dust particles in air, and sizing and counting of bacterial colonies, are further applications where thousands of particles per second must be examined, and the amount of visual data is too great for non-automatic techniques.[1, 2]

Blood contains cells generically known as white blood cells or leukocytes. There are five different categories of white blood cells (Fig. 2), and in normal human blood the percentage of blood cells belonging to these categories are typically[3]: neutrophil 65%, lymphocyte 25%, monocyte 7%, eosinophil 2%, basophil 1%. It is common clinical practice to examine 100 white cells of a patient's blood to determine how many are neutrophils, lymphocytes, etc., because abnormal numbers may be symptomatic of an illness such as leukemia. This clinical test is carried out hundreds of thousands of times per day in a country such as the USA, and until recently the various types of white blood cells were counted by hand by trained technicians. Equipment is now commercially available for recognizing and counting the five types of white blood cells automatically, at high speed. Whereas the quantitative analysis of non-metallic inclusions in steel can be done with black-and-white pictures, the differential white blood cell count requires colour data.[4, 5, 6]

Optical character recognition equipment has been in commercial use since the 1950s, and this is one of the oldest of the commercial applications of picture recognition, typically for reading account numbers and names and addresses.[7] Machines are available that recognize good quality print in several founts, including numerals, upper and lower case letters, and punctuation marks. If print quality is very poor, as on cash register rolls, it may be possible to achieve reliable automatic recognition only of numerals and special symbols. Hand-printed numeral recognition facilities have been commercially available since 1967, but currently available

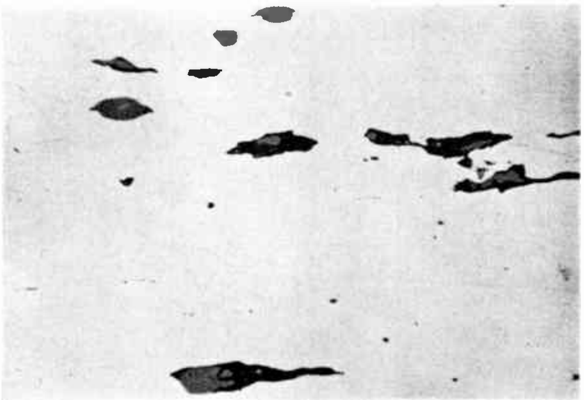

Fig. 1. Micrometallograph of oxide (darker) and sulphide (lighter) inclusions in steel. (By courtesy of Cambridge Instruments.)

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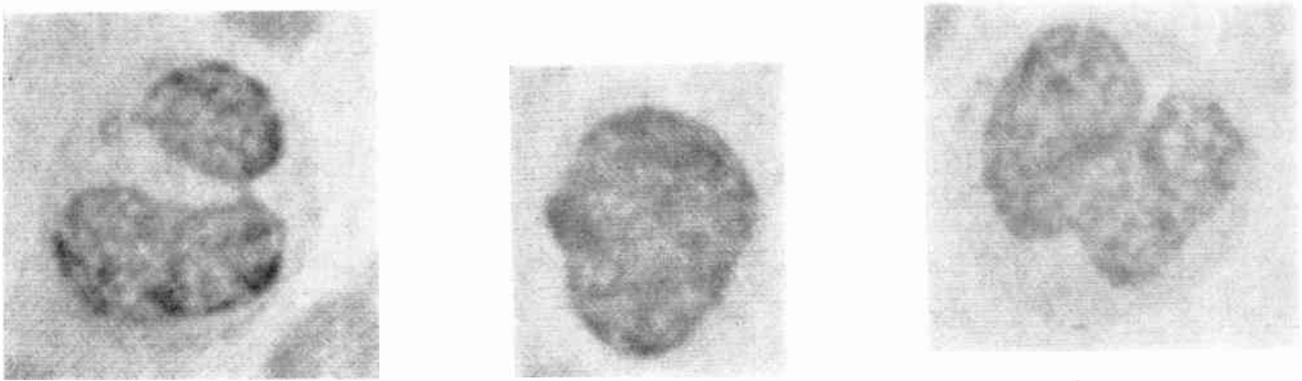
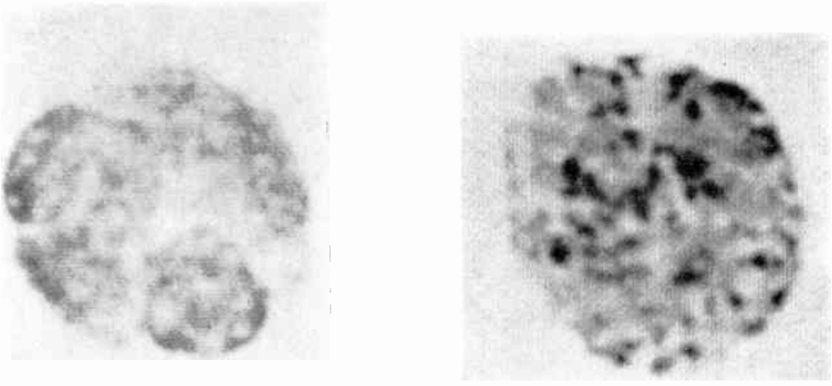


(a) Neutrophil. (b) Lymphocyte. (c) Monocyte.



(d) Eosinophil. (e) Basophil.

Fig. 2. The five types of white blood cells.

equipment for recognizing the 26 handprinted letters as well as the ten numerals is either very expensive or very limited in the number of trained writers that it can accept. In the automatic recognition of hand-printed characters a technical problem arises from the great differences among shapes of characters (see Fig. 3). From the point of view of shape recognition, character recognition is one of the more highly developed areas of the picture recognition field.

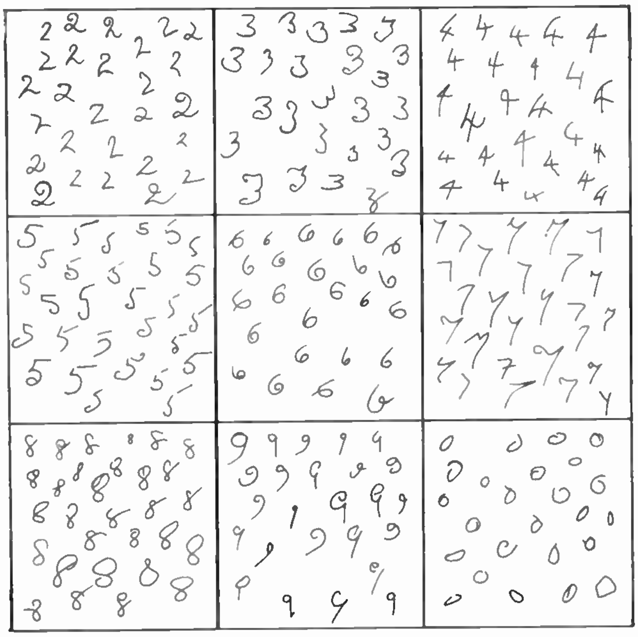


Fig. 3. Numerals hand-printed by different people.

The variability of shapes of handprinted characters means that we do not need to measure characters with great precision. An area of the picture recognition field where precise measurement is vital is in nuclear physics, in the automatic analysis of events visible in bubble and spark chambers (see Fig. 4). A charged particle moving in a known magnetic field through a superheated liquid leaves a helical track of bubbles, and measurements of the curvature of the track may reveal the charge-to-momentum ratio of the particle. As in the application mentioned previously, automatic techniques have become established in practice[8] because the quantity of visual data is too great for non-automatic techniques. Nuclear physics laboratories typically require analysis of hundreds of thousand of events per year, each involving detection and precise measurement of a collection of tracks.

Besides the established applications that we have mentioned, automatic picture recognition has many possible future applications. One of the most futuristic is for the robot control of a vehicle to drive on the surface of Mars[9] where a human driver might not survive. Less futuristic applications are in the automatic inspection of glass items such as bottles[10] and ampoules[11] to check for flaws, cracks and unwanted objects; and automatic inspection of printed circuits to check that there are no short circuits or accidentally open circuits.[12, 13] Further possible applications will be mentioned in the course of this paper.

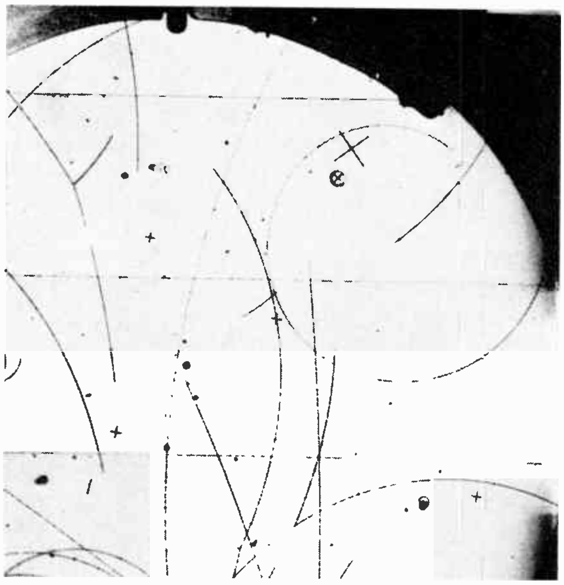


Fig. 4. Nuclear bubble chamber picture.

There are many different opto-electronic techniques for converting a visual pattern to a discrete array of values[14, 15] and it would not be possible for us to cover the rich literature on this topic in a few paragraphs. Instead we shall concentrate on the technical problems of picture recognition, starting with the probably familiar idea of correlation.

2 Correlation

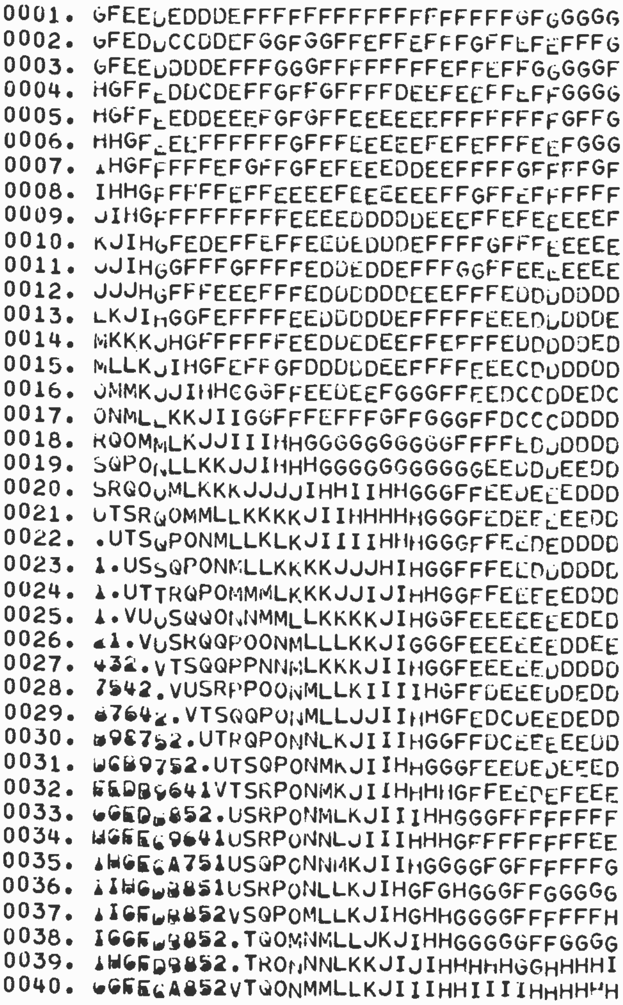
2.1 Methods of Correlation

A colourless black, white and grey picture can be represented by a function $f(x, y)$, and the value of this function at (x, y) is usually called the *grey level* at (x, y). A continuous picture is a continuous spatial distribution of grey levels, whereas a discrete picture is an array or matrix of discrete grey levels; in this paper we shall concentrate on the discrete case which is the more common in practice. When a scene is scanned with a television camera, flying spot scanner, scanning electron microscope, vidissector, etc., the result is usually a discrete picture comprising, say, $m \times n$ elements, each with an associated grey level. Figure 5 shows a picture (of some chromosomes) and a portion of a computer printout in which grey levels are represented by numbers and letters.

To introduce the principles of correlation, let us consider the problem of recognizing printed numerals. An $m \times n$-element picture of one of the ten numerals is presented to a machine, and the machine is required to decide which of the ten numerals this is. Making this decision is tantamount to recognizing the numeral. If the machine works by the simplest method of correlation, then one specimen of each numeral is stored permanently in the machine as an $m \times n$ array of values. Permanently associated with each of these ten specimens is a separate unique label, code word, or output channel, which signifies which numeral the specimen is. Let us represent a stored specimen by $X' = \{x_1', \ldots, x_i', \ldots, x_{m\times n}'\}$ and a pattern that is to be recognized by $X = \{x_1, \ldots, x_i, \ldots, x_{m\times n}\}$. To recognize X the machine compares it with each of the ten specimens, and outputs the label or codeword, or activates the output channel, associated with the X' to which X is most similar. The comparison of X with X' consists of comparing x_i with x_i' for all $i = 1, \ldots, m\times n$. This element-by-element comparison, which is the distinctive feature of correlation, can take various alternative forms.[16] One of these is

$$d^2 = \sum_{i=1}^{i=m\times n} (x_i - x_i')^2$$

(a) Picture of some chromosomes (128 by 128 digital array).



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0001. GFEEDEDDDEFFFFFFFFFFFFFFFFFFFGFGGGGG
0002. GFEDDCCDDEFGGFGGFFEFFEFFFGFFEFEFFFG
0003. GFEEDDDDEFFFGGGFFFFFFFFEFFEFFGGGGGF
0004. HGFFEDDCDEFFGFFGFFFFDEEFEEFFEFFGGGG
0005. HGFFEEDDEEEFGFGFFEEEEEEFFFFFFFFGFFG
0006. HHGFEELFFFFFFGFFFEEEEEFEFEFFFEEFGGG
0007. 1HGFFFFFEFGFFGFEFEEEDDEEFFFFGFFFFGF
0008. IHHGFFFFFEFFEEEEFEEEEEEFFGFFEFFFFFF
0009. JIHGFFFFFFFFFEEEEDDDDDEEEFFEFEEEEEF
0010. KJIHGFEDEFFEFFEEDEDDDEFFFFGFFFEEEEE
0011. JJIHGGFFFGFFFFEDDEDDEFFFGGFFEEEEEEE
0012. JJJHGFFFEEEFFFEDDDDDDEEEFFFEDDDDDD
0013. LKJIHGGFEFFFFFEEDDDDDEFFFFFEEEDDDDE
0014. MKKKJHGFFFFFFEEDDEDEEFFEFFFEDDDDDED
0015. MLLKJIHGFEFFGFDDDDDEEFFFFEEECDDDDD
0016. OMMKJJIHHGGGFFEEDEEFGGGFFFEDCCDDEDC
0017. ONMLLKKJIIGGFFFEFFFGFFGGGFFDCCCDDDD
0018. RQOMMLKJJIIIHHGGGGGGGGGFFFFEDJDDDD
0019. SQPONLLKKJJIHHHGGGGGGGGGGEEDDEEDD
0020. SRQOUMLKKKJJJJIHHIIHHGGGFFEEDEEEDDD
0021. UTSRQOMMLLKKKKJIIHHHHHGGGFEDEFEEEDD
0022. .UTSQPONMLLKLKJIIIIHHHGGGFFEEDEDDDD
0023. 1.USSQPONMLLKKKKJJJHIHGGFFFELDDDDDD
0024. 1.UTTRQPOMMMLKKKJJIJIHHGGFFEEFEEDDD
0025. 1.VUUSQQONNMMLLKKKKJIHGGFEEEEEEEDED
0026. 41.VUSRQQPOONMLLLKKJIGGGFEEEEEEDDEE
0027. 432.VTSQQPPNNMLKKKJIIHGGFEEEEEDDDDD
0028. 7542.VUSRPPOONMLLKIIIIHGFFDEEEDDEDD
0029. 87642.VTSQQPONMLLJJIIHHGFEDCDEEDEDD
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0034. MGFE99641USRPONNLJIIIHHHGFFFFFFFEE
0035. 4HGFCA751USQPONNMKJIIHGGGGFGFFFFFG
0036. 1IHG98851USRPONLLKJIHGFGHGGGFFGGGGG
0037. 1IGF98852VSQPOMLLKJIHGHHGGGGFFFFFFH
0038. IGGF99852.TQOMNMLLJKJIHHGGGGGFFGGGG
0039. 1HGFD9852.TRONNNLKKJIJIHHHHHGGHHHHI
0040. 6GFECA852VTQONMMLLKJIIIHHIIIIHHHHHH
```

(b) Computer print-out of upper left-hand corner (35 by 40 sub-array) of (a); symbols denote grey levels (blank, 1, . . ., 9, A, . . ., V = 0, . . ., 31; same characters overstruck with .'s denote 32, . . ., 63).

Fig. 5.

Patterns:

```
        1 1 1 1           1 1 1 1
        1                 1
        1 1 1             1 1 1
        1                 1
        1 1 1 1 1         1

              (blanks are 0's)
```

Correlation measures:

a) d^2 for the "F" matched with itself is zero; for the "F" matched with the "E" it is 4

b) $\Sigma x_i \cdot x_i'$ for the "F" matched with either itself or the "E" is 10

c) $\dfrac{\Sigma x_i \cdot x_i'}{(\Sigma x_i^2)^{1/2}(\Sigma x_i'^2)^{1/2}}$ for the "F" matched with itself is 1; matched with the "E", it is $\dfrac{10}{\sqrt{10}\cdot\sqrt{14}} \doteq 0.845$.

Fig. 6. Correlation measures for an 'E' and an 'F'.

and using this the machine recognizes X as the same as the X' for which d^2 is smallest. From a generalization of Pythagoras' theorem it can be seen that d^2 is the square of the distance between points X and X' in $m \times n$-dimensional space. The use of the d^2 measure is illustrated in Fig. 6(a).

Since

$$d^2 = \sum_{i=1}^{i=m\times n} (x_i^2 - 2x_i x_i' + x_i'^2)$$

and

$$\sum_{i=1}^{i=m\times n} x_i^2$$

is independent of X', the specimen X' for which d^2 is minimal is the same as that for which

$$\sum_{i=1}^{i=m\times n} x_i x_i' - \tfrac{1}{2} \sum_{i=1}^{i=m\times n} x_i'^2$$

is maximal. This may be of interest because the continuous counterpart of

$$\sum_{i=1}^{i=m\times n} x_i x_i'$$

can be evaluated† by holographic or non-holographic optical techniques.[17] Lohmann has described holographic techniques that do not require $f(x, y)$ to be in the form of a transparency and do not require coherent light.[18] The more usual holographic techniques[19] require very precise alignment of the hologram in the optical system, although this serious disadvantage is to some extent counterbalanced by the fact that holographic techniques are quite tolerant to scratches and blemishes of holograms.

Generally the value of d^2 depends on the position of X in its own plane with respect to X'. We may wish to evaluate d^2, or some other coefficient, for many different relative positions, so as to find a position of minimal value. X can then be recognized as the same as the reference pattern for which the overall minimal value is least. The evaluation of a correlation coefficient for many relative displacements involves a remarkably large amount of computation. For correlation by means of software, several short-cut methods have been devised to reduce the computational effort,[20, 21] and in some cases it may be worthwhile to use the fast Fourier transform and cross-correlation theorem.[21] Another short-cut is available on commercial array processors.[22] For correlation by hardware, particularly when X and X' are binary (i.e. composed of 0's and 1's), analogue and digital techniques are described in the literature.[7, 23]

2.2 Limitations of Correlation

Changing the level of illumination of a pattern X may be tantamount to multiplying all the elements $x_1, \ldots, x_i, \ldots, x_{m\times n}$ of X by a constant coefficient k. The squared distance d^2 between X' and kX depends strongly on the value of k, and therefore it is better not to use d^2 when we do not wish recognition to depend upon k. Instead we can recognize X as the same as the X' for which

$$\frac{\sum_{i=1}^{m\times n} k x_i x_i'}{\left(\sum_{i=1}^{m\times n} k^2 x_i^2\right)^{\frac{1}{2}} \left(\sum_{i=1}^{m\times n} x_i'^2\right)^{\frac{1}{2}}}$$

is maximal, since this[24] is independent of k, yet sensitive to other differences between X and X'. This match measure is illustrated in Fig. 6(c). In practice, however,

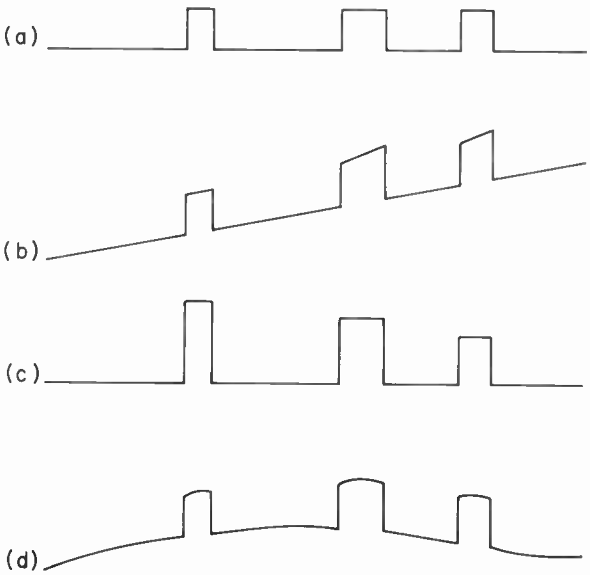

Fig. 7. Grey scale distortions: plots of grey level (vertical axis) versus position (horizontal axis).

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† However, $\Sigma x_i x_i$ itself is not a good match measure; see Fig. 6(b).

the value of k may not be constant across a picture, due for instance to uneven illumination, or due to uneven staining of a biological microscope-slide. When characters are printed on a document, the blackness of different characters may be different even though the background white is constant, so that different k's may be associated with black and white. The general problem is that the grey scale may be subject to distortion, and that this distortion may vary across a picture. To illustrate this, Fig. 7(a) shows the amplitude/time plot for one single line of a television scan of a picture. Figures 7(b), (c), (d) show similar plots for the corresponding line in three other pictures that a machine is required to recognize as the same as the first picture. Figures 7(b), (c), (d) can be regarded as vertically distorted versions of Fig. 7(a). Simple correlation scores such as d^2 are unwantedly sensitive to such distortions, and this is one reason why simple correlation of many-grey-level pictures is not a widely used picture recognition technique.

In normal human blood, lymphocytes are cells that do not all have precisely the same shape, and a machine may be required to recognize them as clinically normal despite their differences in shape.[25] On different occasions a fingerprint from the same finger may be differently distorted due to different distribution of pressure. A more obvious application where patterns are subject to distortion or shape-variation is in hand-printed character recognition. The character '2' written by different people is seldom the same shape. The correlation score for the two 2's shown in Fig. 8 is low although they are both immediately recognizable as '2'. Because pairs of similar-looking shapes may yield low correlation scores, simple correlation methods are inappropriate for the recognition of handprinted characters, finger prints, and lymphocytes, though correlation techniques have been studied for fingerprint recognition.[26]

Fig. 8. Two 2's that have low cross correlation.

Distortion of shape and of the grey scale are only two of the reasons why simple correlation is not much used in picture recognition. Another reason is that a pattern can only be recognized by simple correlation if a similar pattern has previously been stored to serve as a reference pattern. Cracks in glass bottles, fractures in bones in X-ray photographs, and certain non-metallic inclusions in steel can assume innumerable different shapes, and it would not be practical to store specimens of all of these. Therefore such items must be recognized by some principle other than that of simple correlation. For the same reason, simple correlation is not an appropriate technique for recognizing texture. Lungs damaged by coal dust may exhibit visual texture differing from that of normal lungs in an X-ray photograph.[27] Textures that seem very similar to a human technician may be different in fine detail and their correlation may be low. It would not be practical to store separate reference patterns for all the countless millions of textures that look alike.

2.3 Correlation of Small Regions

The effects of distortion of shape and of the greyscale are generally less over a small region than over an entire picture, and correlation of small regions may be useful even when correlation of complete pictures is not. For instance, to detect and determine the approximate direction of edges between regions of different grey level, we can use templates such as those shown in Fig. 9. Each of these can be seen to contain an edge between +'s and −'s, and will match a picture quite well wherever a similar edge occurs. We can use templates of different sizes and shapes, and determine which of all these matches the picture best at each position of alignment. The best-matching template gives the direction of the edge.[28]

```
                         + + + +
                         + + + +
                         + + + +
+ + + + - - - -          + + + +
+ + + + - - - -          - - - -
+ + + + - - - -          - - - -
+ + + + - - - -          - - - -
                         - - - -
```

Fig. 9. Edge-detecting templates (vertical and horizontal).

```
- + -
- + -
- + -
```

Fig. 10. A line-detecting template (vertical).

Figure 10 shows a template that detects vertical line-segments, or small segments of curves that look locally like vertical line-segments. For a dark curve on a light background, the template matching score depends on the blackness of the curve and the whiteness of the background. In particular, a faint grey line on a white background may not match the Fig. 10 template as well as a single very black point on a white background. There are two main approaches to remedying this type of difficulty. One is to check that each picture element aligned with the middle column of Fig. 10 is darker than both its horizontal neighbours.[29] The other is to attempt to normalize the grey scale so that all picture elements lying on the curve are at one grey level and all other elements are at another grey level, and we shall return to this later in Section 4. After normalization or binarization, the matching score for a template such as that shown in Fig. 10 depends only on the shape of the curve, not on the blackness of black and whiteness of white. Patterson[30] provides a practical example where binarization precedes edge detection.

Small regions have also been used in the matching of pairs of aerial photographs of the same ground-scene, for instance for the purpose of detecting changes.[31] One photograph may be distorted with respect to the other because of differences in viewing perspective and photographic and scanning distortion. To remedy this we can take a set of small regions of one photograph and find their positions of optimal correlation with the other photograph. If the small regions contain sufficient pictorial detail, then from their positions of optimal alignment it may be safe to determine by interpolation which point corresponds to which in the two photographs.[32] The pictures can then be correlated by comparing points that have been found to correspond.

Suppose now that we do not know which point in one picture corresponds to which point in the other, and furthermore we do not even know whether the two pictures are of the same scene or object. In order to determine whether the two pictures should be recognized as the same, it may be good enough merely to ascertain whether a prescribed set of small regions or features of one picture match the other picture tolerably well in some alignment. The positions of optimal alignment for the small regions need not all be the same: the relative positions of small regions may vary, so as to allow the pictures to be recognized as the same even though one is distorted with respect to the other. A Hitachi patent[33] discloses a character recognition machine in which various prescribed features are detected in an unknown character and the unknown character is recognized according to the features that it contains. The relative positions of features may vary (within limits) to allow an unknown pattern to be recognized despite distortion. This basic idea has been used in a less obvious form in recent character recognition systems.[7] One complication arises from the fact that the small regions must contain enough pictorial detail to prevent them matching an unknown pattern unwantedly in too many positions. This means that the regions must be made so large that in practice shape distortion prevents the use of simple correlation, and Boolean feature-detection techniques are used instead.

A system for recognizing the shapes of nuclei of white blood cells, or for recognizing hand-printed characters, is required to tolerate various complicated distortions, but not to tolerate distortions that could change a pattern into a pattern that should be differently recognized. In a particular practical application, *admissible distortions* are those that should be tolerated. To ensure tolerance only of admissible distortions, we could in principle compute correlation scores using all pairs of points that correspond in one admissible distortion, and then repeat this for all other admissible distortions in turn, and finally use the overall best match score in recognition. In practice the total number of admissible distortions would, however, be so large that we could not try them all out in turn. If, for economy, we use instead the technique mentioned in the previous paragraph, where features or small regions are allowed to move more or less independently, then various non-admissible distortions may be tolerated, so this technique may be too weak. There have been several attempts[34, 35] to find a practical compromise between this weak technique[36] and the technique of trying out all admissible distortions in turn,[37] but this remains an open area for research.

(a) Picture (satellite image of the Monterey area of California).

(b) Spatial Fourier power spectrum of (a).

(c) Edges extracted from (a) by spatial differentiation.

Fig. 11.

3 Transformation

Instead of applying a correlation technique, or some other recognition technique, directly to a digitized picture, it is sometimes useful to transform the picture into a further picture or array of values as a preliminary step in a multi-step process of recognition. The literature describes a wide range of transformation techniques. At one end of this range, a transformation changes a picture into an array of values that does not look similar to the original picture. Fourier,[38, 39] Walsh,[40] Karhunen Loève,[41] and higher moment[42] transformations belong to this end of the range. Figure 11(b) does not resemble Fig. 11(a), of which it is the spatial Fourier power spectrum. At the opposite end of the range, deblurring, denoising, and edge enhancement transformations can make a transformed picture look like an improved version of the original picture.[22] In the middle of the range are edge detection transformations, e.g. Fig. 11(c) shows only the edges in Fig. 11(a).

Spatial Fourier, Walsh and Karhunen Loève[43] transformations change a picture into a further array of values, each depending on many elements of the original picture. A few of these values (e.g. a few Fourier components,[39] or a few higher moments[42]) may be sufficient for the purposes of distinguishing between pictures that should be differently recognized, and by discarding unnecessary values (e.g. unnecessary Fourier coefficients) it may be possible to reduce the amount of data that has to be processed at subsequent stages of recognition. This data reduction may be particularly important in

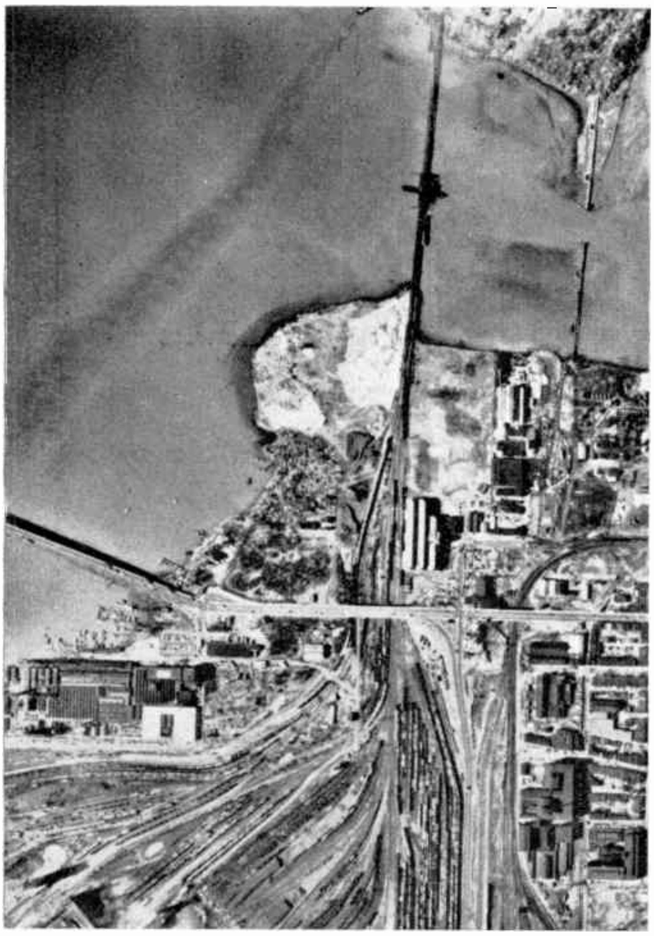


Fig. 12. Aerial photograph (of Baltimore harbour) showing texturally different regions.

the recognition of texture. The Fourier transform of a complicated texture may be very much simpler, or be more readily recognized,[44, 45] than the original texture.

An aerial photograph (e.g. Fig. 12) may include woodland, grassland, water, etc., each with its own texture, and to detect these textures separately we would be wrong to apply the Fourier transformation globally to the whole picture all at once. Small regions should be separately subjected to the Fourier transformation if their textures are to be separately recognized.[44, 45] A small region can be demarcated by means of a window that blanks out the rest of the picture. As in the short-time spectral analysis of speech,[41] the Fourier transform of the window aperture is convolved with the Fourier transform of the picture within the window, and this may be one of the reasons why simpler techniques of texture recognition appear experimentally to be more useful.[47]

Fourier power spectra and autocorrelation functions are invariant under shift of the original pattern.[48] In the recognition of fingerprints, blood cells,[49] etc., positional shifts constitute merely a small subclass of admissible distortions. Fourier transformation is not necessarily invariant under all admissible distortions. Functions of transformations that yield invariance under shift, rotation and dilation are catalogued elsewhere.[17] For instance, the autocorrelation function can be summed over each of a set of concentric rings (annuli) centred on the origin. The set of sums, comprising one sum per ring, is invariant under shift and rotation. This technique can be implemented in digital hardware,[50] but it does not necessarily provide invariance under all of the large number of complicated admissible distortions that elude simple mathematical formulation. This technique does, however, illustrate the principle of using a function of a transform, rather than the transform itself, to characterize pictorial data.

This principle is particularly useful in the recognition of texture. Over a small area of a picture we can count all pairs of points that are separated by a distance ∂ and have grey levels that differ by an amount $\pm k$. The counts $C_\partial(k)$ that correspond to different values of ∂ and k constitute a sort of transform of the small area of the picture, and functions of this transform can be used for classifying textures. One such function is computed by averaging the counts for each ∂, i.e. computing $\sum kC_\partial(k)/N$, where N is the total number of point pairs. The value of one of these averages is greater or smaller according as $|\partial|$ changes relative to the 'grain-size' of the texture in the direction of the displacement ∂ (see Fig. 13(a)). Unlike Fourier techniques, this technique does not suffer from problems of convolution with the window that surrounds the small area of the picture.[47]

Another useful descriptor for texture is a measure of the amount of edge, and in particular the amount of straight edge, within a small area.[52] To obtain this measure we can first apply a boundary-detecting transformation, and then sum the result of small areas. For instance the picture whose elements are

$$g(x, y) = \max\left(|f(x, y)-f(x+1, y+1)|, |f(x+1, y)-f(x, y+1)|\right)$$

is a transform of an original picture whose elements are $f(x, y)$. In this transform, $g(x, y)$ is relatively large only where (x, y) is on a boundary in the original picture. For example, the sum of all grey levels over a small area of Fig. 11(c) characterizes the texture over that area. This approach to texture analysis is illustrated in Fig. 13(b). Boundaries can also be obtained by spatial frequency filtering. High-pass filtering of a time-varying waveform increases the predominance of detail in the waveform.[53] Similarly, in the two-dimensional case, if low spatial frequencies in Fig. 11(a) are suppressed and only high frequencies remain unattenuated, then edges are obtained.

Noise in a picture can be mitigated by attenuating the high spatial frequencies, but we need not use the Fourier domain to achieve this. In a digitized picture, each element is usually some sort of average of grey levels over a small area of the original picture. By effectively increasing the size of this area we can reduce noise at the expense of losing detailed pictorial information.[54]

In Fig. 14 we have arrowed elements that are likely to have resulted from noise. To remedy this noise, we can change to white all black elements that have at least

Patterns:

```
        1  1  1  1 ...
(1)       1  1  1  1 ...
        1  1  1  1 ...
          1  1  1  1 ...
           ....


     1 1     1 1     1 1
(2)  1 1     1 1     1 1  ...
        1 1     1 1     1 1
        1 1     1 1     1 1  ...
     1 1     1 1     1 1
     1 1     1 1     1 1  ...

        (Blanks are 0's)
```

Busyness measures:

a) For distance $\partial = 1$ in the horizontal direction, all point pairs in pattern (1) have gray level difference ±1, whereas only half the point pairs in pattern (2) have difference ±1, and the other half have difference 0. Thus for pattern (1) we have $\Sigma k c_r(k)/N = 1$, while for pattern (2) $\Sigma k c_r(k)/N = \frac{1}{2}$.

b) In pattern (1), $g(x,y) = 1$ at every point, whereas $g(x,y) = 0$ at $\frac{1}{4}$ of the points in pattern (2). Thus the sum of the $g(x,y)$ values is greater for pattern (1) than for pattern (2).

Fig. 13. Texture 'busyness' measures.

one white neighbour, and then change to black all white elements that have at least one black neighbour.[13] Note that these operations remove isolated black and white elements. More elaborate conditions are required if the original picture contains lines that are only one element wide.

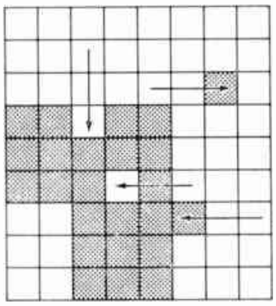


Fig. 14. Examples of noise points in a binary picture.

4 Normalization

Suppose that a picture $f(x, y)$ is transformed into a new picture $g(x, y) = b + cf(x, y)$, and that the texture of $g(x, y)$ is characterized by any of the methods mentioned above. The results will unwantedly depend on the values of b and c unless the grey scale is normalized. This can be done by dividing the entire grey scale into a number, h, of intervals, chosen so that $1/h$th of the picture elements lie within the first interval, $1/h$th of the picture elements lie within the second interval, and so on. The original picture $g(x, y)$ is transformed into a new picture whose grey scale has h discrete values, and this new picture is invariant under changes in b and c.[55] This grey scale transformation is illustrated in Fig. 15.

In steel non-metallic inclusions of a particular chemical composition[51] have approximately the same grey level and the background steel has a different grey level. For purposes of finding the size distribution of sulphide inclusions the grey-scale can be divided into just two levels such that all sulphide inclusions lie at one level and all else lies at the other level. Similarly in the automatic recognition of printed circuits it is only necessary to use two grey levels, one corresponding to the conductor and one to the insulator.[12, 13] A character on a document is essentially a distribution of black on white, or of one colour on another, and intermediate levels are accidental rather than essential. In a bubble-chamber photograph a picture element either does or does not belong to a bubble.

When it is not necessary to use more than two grey levels, there is no advantage in normalizing an original many-level grey scale into a new many-level grey scale that is invariant under distortions of the original grey scale. Instead it is usual to carry out normalization and reduction to two grey levels ('black' and 'white') in a single process that is called *binarization*. For instance, we can obtain a histogram of the number of elements at each grey level in the original picture. If the original picture $g(x, y) = b + cf(x, y)$ has elements mainly at two grey levels, then the histogram will have peaks corresponding to these two grey levels. We can choose a point in the valley between the two peaks to serve as a threshold. Each picture element is then deemed black or white according as its grey level does or does not exceed this threshold.[56] It is very important that the resulting binary picture is normalized in that it is invariant under changes of b and c. Binarization is illustrated in Fig. 16.

When characters are written on a document, the area covered by ink is generally far smaller than the area of background white, and therefore the 'black' peak in the histogram is far smaller than the 'white' peak, and may be indistinct and possibly lost in noise, so that valley-detection is difficult. To remedy this we can use a process of spatial differentiation to find which elements lie near

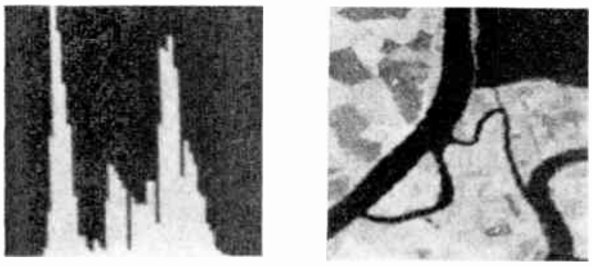


Fig. 15. (a) Grey level histogram of Fig. 11(a). (b) Result of transforming Fig. 11(a) to give it a flat grey level histogram.

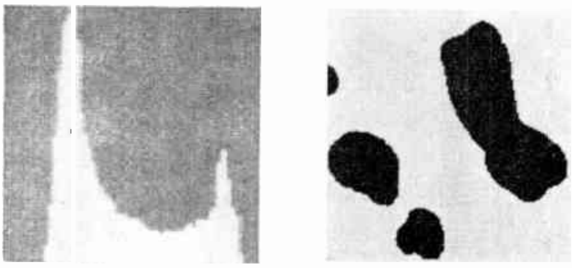


Fig. 16. (a) Grey level histogram of Fig. 5(a). (b) Result of thresholding Fig. 5(a) at the bottom of the valley between the peaks on its histogram.

black/white boundaries in the original picture, and we can use counts only of these elements in the histogram, which now has nearly equal humps corresponding to black and white, so that the valley is more distinct, and can be used more reliably to determine the binarizing threshold.[57]

In histogramming and related techniques[58] it is necessary to scan the picture twice, first to determine the histogram, and secondly to apply the threshold. In commercial equipment for fine particle analysis and character recognition it is economically undesirable to scan a picture twice, and instead the threshold is determined and applied in a single scan. A typical technique is to measure or track the grey level of background white, and set the binarizing threshold at a pre-set fraction of this level. If background white varies locally within a picture, the binarizing threshold varies with it, and the binarized picture is invariant under fairly local changes of b and c. Other commercial techniques are referenced elsewhere.[59]

Before correlation is used in commercial character recognition,[7] binarization is usually carried out as a preliminary step, in the hope of attaining invariance under local variations of the blackness of black and whiteness of white. One reason why optical correlation techniques are not much used is that they do not have this invariance.

The best-alignment correlation score for the two 2's in Fig. 8 would be higher if they were both the same size. Size normalization is a technique for standardizing the size of an object in a picture. Similarly, the effects of shift, rotation, shear[60] and perspective[61] distortion can be undone by appropriate normalization.

To normalize for position or shift, we first determine the position of some prescribed point on the object, e.g. the position of its left-most black point, or the position of its centre of gravity (taking blackness as mass). We then shift the object so as to bring the prescribed point to a prescribed standard position. Similarly, to normalize for size, we first measure a size-dependent property, for instance the height and breadth of an upright rectangular box into which the object just fits, and then adjust the height and breadth of the object so that for the normalized pattern these size-dependent properties will have prescribed standard values.[62, 63] To avoid relying entirely on the outermost black bits of an object to determine its size, we can find the average, $\bar{y}$, of the y (vertical) coordinates of all black points, then find the average of $|y-\bar{y}|$, and finally adjust the height of the object so as to bring the average of $|y-\bar{y}|$ to a standard value. Of course width can be normalized similarly.

In general, normalization consists of two steps, first a process of measurement, and secondly a transformation that is quantitatively determined by the first step. For instance, binarization may consist first of measuring the valley-position in the grey-level histogram, and secondly of using this position as the threshold in a binarizing transformation. Size normalization consists first of some sort of size measurement and secondly of a size-standardizing transformation. All normalization involves transformation, but the converse of this is not true.

We might use a histogramming method to find a threshold grey level between leukocyte cytoplasm and background. If part of a red blood cell is included in the area of the picture from which the histogram is obtained, then a wrong threshold may be selected. This illustrates a basic difficulty that can be further illustrated in terms of height-normalization of an object that has its bottom part accidentally missing. Because the height measurement does not include the missing bottom part, the height transformation will make the remainder of the object too tall. The basic difficulty is that normalization depends on a process of measurement that may give incorrect results.

Before pictures can sensibly be compared by simple correlation, their corresponding elements must be brought into mutual alignment, and normalization for size, shift, etc., is intended to do this. It is important to understand that normalization is not the only means of finding the correct alignment. For instance, if two patterns differ from each other only by positional shift, they can be brought into mutual alignment either by shift normalization or by correlating the patterns in all relative positions and finding the highest correlation score, and assuming that this score occurs at the position of optimal alignment.[64, 65] The latter method does not depend on an error-prone process of measurement such as that which is the first step in normalization. In general, to bring corresponding elements of two distorted patterns into mutual alignment, it would not be enough to try out all possible positional shifts, and instead we would need to try out all possible admissible distortions.

As we have remarked previously, this would be impractical because there are generally too many admissible distortions, and some sort of short-cut method would be required instead. The short-cut technique of Fischler and Elschlager[34] matches geometrically distorted patterns without prior normalization. Because Fischler and Elschlager do not normalize, they do not need to segment a picture into objects, prior to recognition, in order to measure the objects. The error-prone processes of segmentation and measurement are avoided, but at the cost of much computation.[34]

5 Parametrization

For distinguishing between nuclei of normal and abnormal lymphocytes, Bahr *et al.*[25] used parameters such as the area and perimeter of the nucleus, length of the longest straight-line segment contained in the nucleus, and area of a circle centred on the centre of mass and just enclosing, or just enclosed by, the nucleus. In order to measure such parameters it is necessary to determine which picture elements belong to the nucleus. For fine particle analysis, for instance analysis of non-metallic inclusions in steel, it may be useful to obtain a histogram showing the numbers of particles having each possible area, or each possible maximal horizontal chord length, or each possible perimeter^2/area, or some other parameter.[1, 66, 67, 74] Again it is necessary to determine which sets of picture elements belong to the same particle, because otherwise particles cannot be parametrized. Here we have a distinction between transformation and parametrization: a transformation is applied directly to a picture without the use of any knowledge as to which elements do or do not belong to objects (such as cell nuclei or fine particles), but parametrization necessarily depends on such knowledge.

There are three main reasons for parametrization. One is that the parameter values themselves are the required output, as in fine particle analysis, and also in bubble chamber analysis where track curvatures and lengths may be vital parameters. A second reason for parametrization is as a preliminary step in normalization, as explained previously. A third reason is that an object can be recognized by applying techniques, such as correlation, to parameters of the object.[25, 68, 70]

To illustrate the art of parametrization, let us consider the analysis of asbestos dust. In asbestos dust, particles longer than 5 μm, narrower than 3 μm, and with length/width greater than 3 are deemed harmful to human lungs.[71] To test whether air is dangerous to breathe, it is necessary to count the number of harmful particles per unit volume, and a particle can be recognized as harmful by its elongatedness. A commonly used parametrization of the extent to which a shape departs from a perfect circle is its perimeter^2/area, which should be high for elongated particles. In fact if the perimeter and area of a rectangular particle are known, then we can calculate its length, since

$$\text{area } (A) = \text{length} \times \text{width}$$

and

$$\text{perimeter } (P) = 2 \times (\text{length} + \text{width})$$

whence

$$\text{length} = \frac{P + \sqrt{P^2 - 16A}}{4}$$

The area of a black object is simply the total number of black elements in it. The perimeter of a black object can be approximately measured by counting the number of alignments in which various 4-bit templates match the binary picture. If b and w stand respectively for black and white, then the number of alignments in which any of the 4-bit templates

$$\begin{array}{cccc} \mathrm{b\,b}, & \mathrm{w\,w}, & \mathrm{b\,w}, & \mathrm{w\,b} \\ \mathrm{w\,w} & \mathrm{b\,b} & \mathrm{b\,w} & \mathrm{w\,b} \end{array}$$

match the picture is a rough measure of the total horizontal and vertical edge length. The number of alignments in which any of

$$\begin{array}{cccccccc} \mathrm{b\,w}, & \mathrm{w\,b}, & \mathrm{w\,w}, & \mathrm{w\,w}, & \mathrm{b\,b}, & \mathrm{w\,b}, & \mathrm{b\,w}, & \mathrm{b\,b} \\ \mathrm{w\,w} & \mathrm{w\,w} & \mathrm{w\,b} & \mathrm{b\,w} & \mathrm{w\,b} & \mathrm{b\,b} & \mathrm{b\,b} & \mathrm{b\,w} \end{array}$$

match the picture is roughly $\sqrt{2}$ times the total diagonal edge length,[72, 73] provided no configuration of adjacent bits

$$\begin{array}{c} \mathrm{b\,w} \\ \mathrm{w\,b} \end{array} \text{ or } \begin{array}{c} \mathrm{w\,b} \\ \mathrm{b\,w} \end{array}$$

occurs in the picture. Perimeter, area, and P^2/A for some simple objects are shown in Fig. 17.

If the perimeter of a digitized image is precisely measured, its length actually increases with the fineness of spatial sampling, because the perimeter contains more little corners. For this reason the value of P^2/A may be unwantedly high for a digitized circle. An alternative measure of elongatedness is the number of times we can do the following to a binary image successively before it disappears: construct a new image that consists only of those black elements that have no white neighbour.

Shapes:	bbb bbb bbb	bbbbbbbbb
	(Blanks are w's)	
Areas:	9	9
Perimeters:		
Horizontal and vertical edge length	8	16
Diagonal edge length x√2	4	4
Total	8 + (4/√2) ≐ 10.8	16 + (4/√2) ≐ 18.8
P^2/A	13.0	39.4

Fig. 17. Perimeter, area, and P^2/A for two rectangles.

```
Input pattern:

                bb   bb        bbbbb
                 bb bb         b   b
                  bbb          b   b
                 bb bb         b   b
                bb   bb        bbbbb

                   (Blanks are w's)


Result of assigning successive labels A, B, C to
the black  elements (see text):


                AA   BB        CCCCC
                 AA BB         C   C
                  AAA          C   C
                 AA AA         C   C
                AA   AA        CCCCC

           Note that labels A and B belong to the
           same object, but no label occurs on two
           different objects.
```

Fig. 18. Connected object labelling.

Obviously a thin line will disappear after fewer steps than will be needed to make a fat disk disappear.[16]

6 Connectivity

Before a black object can be parametrized we must determine which black elements belong to it. This determination may be based on prior knowledge, or on a hopeful assumption, that any connected set of black elements constitutes an object. Two black elements are said to be connected (by black) if it is possible to move from one of the elements to a black neighbour element, then to a black neighbour of the neighbour, and so on until the other one of the two elements is reached. In a connected region, all pairs of elements are connected. The theory of connectivity in digital pictures is presented elsewhere,[22, 67] and practical techniques for determining connectivity are well known. Amongst these techniques the following is usually the most efficient.

A picture that contains black objects on a white background is scanned from left to right, row by row, just like a television scan. When the scan first hits black the label '1' is assigned to the first black element and also to all subsequent black elements connected to this first black element in this horizontal row. If after returning to white the scan again encounters black, then the label '2' is assigned to this black element and also to all subsequent black elements connected to it in this horizontal row. If after returning to white the scan again encounters black, then the label '3' is assigned to this black element, and the procedure continues in this way until the end of the scan row. During the scanning of the next row each black element is assigned the same label as has already been assigned to any adjacent black element. A separate new label is assigned to each black element that is not adjacent to any black element that has been labelled previously. If an element would, according to these rules, be labelled with two different labels, then we record that these two labels are associated with the same object. When this procedure has been carried out for all rows, all elements labelled with the same label belong to the same object. Furthermore, all elements labelled with labels that have been recorded as being associated with the same object belong to the same object.[75, 76] An example of this process is shown in Fig. 18. To illustrate the usefulness of this determination of connectivity, consider the determination of a histogram that tells us how many black objects have what number of black elements.[67] This cannot be done unless we know which elements belong to which objects.

Another reason why connectivity is of central importance in picture recognition is that it is invariant under geometrical distortion. The connectivity of the character '3' is different from that of '8' because '8' contains two white regions enclosed by black, and '3' does not.[7] The fact that the black parts within '3' and within '8' are differently connected can be used for distinguishing between '3' and '8', however much these characters are distorted.[77, 78] Similarly the difference in connectivity between normal and dicentric chromosomes can be used for distinguishing between them regardless of distortion.[79]

A television picture of an electric circuit diagram can be transmitted over a communication channel, but this may make inefficient use of the channel in that the essential pictorial information can be transmitted in fewer bits. One idea is to locate all points in the diagram where straight lines meet, and transmit only the coordinates of each of these junction points, together with a statement as to which junction is connected to which.[73] Given a real-life circuit diagram, the first task is to locate the junctions. This can be tackled by thinning[77, 83] all lines down to single element width by a process designed not to change the connectivity of the picture, i.e. the statement as to which junction is connected to which. After thinning, a junction of, say, three lines can be recognized as a black element that is adjacent to three black elements, no two of which are mutually adjacent.[73] Junctions of limbs in characters can be recognized similarly,[77, 80] and so can junctions of ridges, i.e. bifurcations, in fingerprints.[81] A thinning process is illustrated in Fig. 19.

Ho and Lee[82] find bifurcations by centring a 12 × 12 element window on each picture element in turn. The perimeter of this window comprises 44 elements. If, scanning round this perimeter, we find a connected set of black elements followed by white followed by a second connected set of black elements followed by white followed by a third connected set of black elements followed by white followed by the first connected set of black elements, and if all of these black elements are connected by black to a black element at the centre of the window, then a bifurcation is present in the window. Here connectivity instead of correlation is used for recognizing bifurcations because their connectivity is constant while their shapes vary greatly.

In our discussion of connectivity we have so far assumed that a picture has already been binarized so as

```
Input pattern:

                    bbb
                    bbb
                    bbb
                    bbb
                    bbb
                    bbbbbbbbb
                    bbbbbbbbb
                    bbbbbbbbb   (Blanks are w's)
                    bbb   bbb
                    bbb   bbb
                    bbb   bbb
                    bbbbbbbbb
                    bbbbbbbbb
                    bbbbbbbbb

After removal of all "deletable" b's

                    b
                    b
                    b
                    b
                    b
                    bbbbbbb
                    b     b
                    b     b
                    b     b
                    b     b
                    b     b
                    bbbbbbb

Note that in this thinned pattern, no b's are
deletable
```

Fig. 19. Thinning.

to ensure that black elements belong to objects and white elements do not; and connectivity has been used in partitioning the set of all black elements into separate objects. Suppose now that we do not yet know whether any given element belongs to any object. If we know *a priori* that an object is connected, then we can use this knowledge in a sequential process that finds which elements belong to objects. For instance, after finding the beginning of a track in a bubble chamber we may search for a continuation only in the region where a connected track would be expected to continue. When we find a further piece of track, this narrows down our field of search for a still further piece of track, and so on.[8] In this process we decide irrevocably which elements belong to a track as we work along it, and an erroneous decision at an early stage may be disastrous. Instead of risking this we can in effect explore many tracks or curves at once, and postpone choosing any one of them until reaching the end.[84, 85] For instance, in a chest radiograph an image of a tumour may be partially obscured by ribs and blood vessels, and Ballard and Slansky have coped with this by evaluating globally the shape of an entire edge before deciding that this may possibly be the edge of a tumour.[86]

Sequential techniques have been used not only for detecting lines and edges but also for detecting connected regions of digitized pictures. Having ascertained that a particular element belongs to a particular region, for instance a lung in a radiograph, we can assign adjacent elements to the same regions if they do not differ too much in grey level from the original element. If any further elements are in this way assigned to the region, then elements adjacent to these can be processed in the same way, and so on.[87] This technique allows the grey level to vary gradually across a region. Having segmented a body into regions we can merge these into larger regions if they do not differ from each other too much in some prescribed property or set of properties.[16, 88]

7 Segmentation

In the literature on picture recognition, *segmentation* is the technical term for dividing up a picture into parts. In practice we choose segmentation techniques in accordance with our knowledge of a picture, which may be as follows.

7.1 Single Black Object

If we know *a priori*, or somehow arrange,[63] that a picture consists of a single black object on a white background, then we can segment the picture into object versus background by binarization. This is satisfactory even when the object is not connected.

7.2 Many Black Objects, not connected to each other, but each connected internally

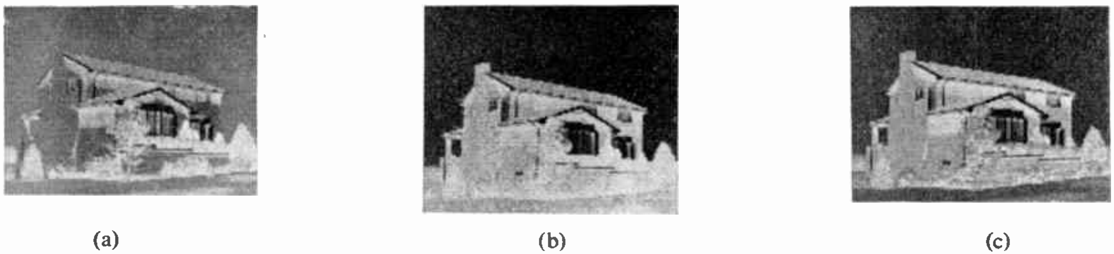
If we know *a priori* that a picture comprises many black objects, each of which is connected, then we can use this knowledge to segment the picture into objects,[66, 67] as explained previously in Section 6.

7.3 Objects with Distinct Colour or Texture

If we know *a priori* that each different object in a picture has its own distinct colour and texture, then we can segment the picture into objects by classifying the colour and texture of its elements or small regions. For instance, to segment an aerial photograph into copper-bearing and not-copper-bearing regions it may be sufficient to classify the spectra of light reflected from small areas of the ground.[89]

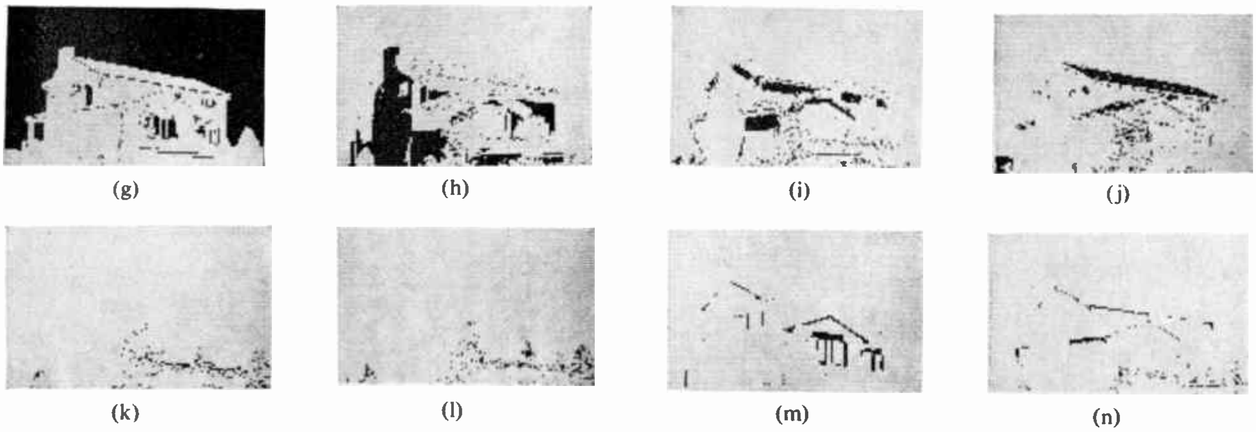
The airborne search for oil employs sideways-looking radar and infra-red photography as well as ordinary colour photography from aircraft and satellites.[90] Over each small area of the ground the reflectivity spectra, ranging from radar to visible, can be automatically classified. The ground is thereby partitioned into regions, such that all points in the same region have the same classification.[55]

The human eye and brain recognizes various different spectra as having the same colour,[91] and to recognize colours, for instance colours of stained cytoplasm of white blood cells, it is not necessary to determine full spectra. Instead it is usual to base colour recognition on grey levels obtained via only two or three different colour filters.[3, 5, 6] Figure 20 illustrates an approach to the segmentation of a colour image. Parts (a–c) show a house photographed through red, green and blue filters. Parts (d–f) show scatter diagrams of the frequencies with which the various pairs of grey levels occur in the three pairs of images (red, green), (green, blue) and (red, blue). The sets of points giving rise to the clusters in these scatter diagrams are shown in parts (g–n); they correspond roughly to meaningful parts of the image.



(a–c) Red, green and blue components of a photograph of a house.

(d–f) Scatter diagrams for pairs of colour values: (red, green), (red, blue), (blue, green).



(g–n) Regions corresponding to the clusters of colour values: sky, sunlit brick, shadowed brick, roof, shrubs (sunlit and shadowed), sunlit trim, shadowed trim.

Fig. 20. Segmentation of a colour photograph.

7.4 Objects not Distinguished by Colour, Texture or Connectivity

In a picture a human hand and arm may have the same colour and texture, and there may be no line or mark physically present in the picture to divide off the hand from the arm. In this case none of the previously mentioned segmentation techniques will segment the hand from the arm. In character recognition none of these techniques will segment a line of touching characters, nor segment an individual character into features such as junctions and ends of limbs. These techniques will not pick out events in bubble chamber photographs nor bifurcations in fingerprints, nor segment a picture such as Fig. 21 into individual polyhedra. To remedy this we must use *a priori* knowledge of shapes of objects, and this knowledge may either be incomplete or complete.

7.4.1 *Segmentation using incomplete* a priori *knowledge of shape*

In order to determine a size distribution of bacterial colonies it is necessary to segment the microscopic scene into individual colonies, even though they may overlap. To achieve this segmentation it is possible to use *a priori* knowledge that the colonies are roughly circular. Non-circular objects can be segmented so as to yield several circular objects.[92] Here the knowledge of shape is incomplete in that the radii of curvature are known only very approximately.

If we know *a priori* that Fig. 21 is composed of polyhedra, then we can segment Fig. 21 into individual polyhedra without knowing their detailed shapes. This can be done by taking the shapes of the vertices where lines meet in Fig. 21 as clues as to which face belongs to which polyhedron.[93]

If we know *a priori* the size of an object, and if we know the position of one side of it, then we may be able to calculate where to segment it at the other side

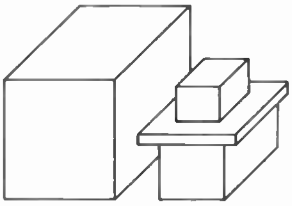


Fig. 21. Line drawing of a collection of blocks.

if it touches another object there.[94, 95] For this there is no need to know the detailed shape of the object beforehand.

7.4.2 *Segmentation into objects, using complete* a priori *knowledge of their shape*

For purposes of segmentation, incomplete knowledge of shape may not be good enough in all applications, and we may instead be obliged to use complete knowledge of shape. For instance, in character recognition a line of printed characters may have no white intercharacter gaps. In this case we can correlate templates for all possible characters with the line of text in all alignments, and segment the line into characters where they best match the templates.[65, 96] Lahart has described a similar technique for picking out targets in aerial photographs,[64] and we have previously referred to this in Section 5, where we also mentioned that a technique such as that of Fishler and Elschlager[34] should be used if shapes are subject to non-trivial distortion. Apart from the possibility of distortion, the shapes are completely known in that complete templates are available for them *a priori*. The basic idea here is that a scene is segmented into objects by recognizing them. Thus recognition does not take place after segmentation, but *at the same time*. Normalization and parametrization may be inappropriate techniques for recognition in this application because they have to be *preceded* by segmentation, as we have been careful to explain previously in Sections 4 and 5.

8 Concluding Remarks

This paper has introduced some of the basic principles and techniques of picture recognition and analysis, namely correlation, transformation, normalization, parametrization, and segmentation (including methods based on connectivity). References to various applications of these principles have been given.

For further reading on the subject, the reader is referred to a number of books and survey articles written by the present authors.[7, 16, 17, 22, 23, 20] Particular mention should be made of a series of survey papers by the second author, which now appear annually in the journal *Computer Graphics and Image Processing*;[97–101] these include extensive bibliographies comprising over 2000 references.

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The physical basis of signal theory

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SUMMARY

This paper reviews the basic physical principles behind:

the processing and combination of noisy signals;

the quantification of information and of channel capacity;

transformations and dualities in the representation of signals in frequency, time and space.

The treatment is largely non-mathematical, and is aimed at fostering an insight into the nature of these concepts and their interrelations. In each of its three parts, the paper outlines some of the basic principles and theorems, indicates—and in some instances extends—the limits of their application, and then relates them to real-life operating conditions and design objectives. It is hoped that this approach will assist readers to see the connection between systems they are analysing, assessing or designing, and the idealized models normally postulated for the development of formal theoretical methods.

Special emphasis is given to ways of looking at signal design and processing problems which have proved of particular value in system development in a wide field of applications.

1 Signal Processing for the Optimum Reception of Noisy Signals

Signal processing has a wide range of applications in such fields as communications, radar, sonar, navigational aids, acoustics, seismics, and industrial and medical ultrasonics. In many practical systems in these fields, information concerning each element of signal intelligence is received independently by a number of transducer or antenna members, receiver channels or transmission paths. Signal processing may then be employed with advantage wherever these signals are not in optimum alignment and are significantly degraded, or contaminated by uncorrelated noise.

'Signal processing' normally implies improving the 'order' in a signal which has been subjected to a degree of disorder. This disorder may have been introduced deliberately by the source for one or more of the following reasons:

(i) to spread a signal in time, and so overcome peak-power limitations, or to spread a test signal so that it can be injected without disturbance to the normal working of a system;

(ii) to disperse it in time, frequency, phase or polarization in order to minimize interference with other services;

(iii) to disperse it similarly in order to prevent *mutual* interference within an appropriately-designed group of communications channels.

Alternatively, the disorder may arise within a receiving system of multiple receiving channels and transmission paths, which may produce multiple signal outputs misaligned in frequency or phase or time, or the signals may be misaligned, within a transducer array or aerial system, in three-dimensional space or in polarization.

Yet another cause of disorder can be Doppler effects due to movement of the transmitter, the receiver or intermediate reflectors.

Indeed, Doppler effects, multi-path dispersion or other forms of disorder are introduced by almost any transmission geometry which is not both stationary and in an infinite homogeneous medium.

Finally, disorder is introduced by the environment, in the form of external interference or noise.

Signal processing is then concerned with

(a) *identifying a priori* potential signal elements,

(b) *transforming* their relative frequency, phase, amplitude, polarization and timing, to maximize the contrast between wanted signal and unwanted noise.

The noise may be thermal 'white noise' arising within the receiver itself, or external atmospheric, galactic or man-made noise. Usually we can identify some property or statistical characteristic of this noise. Frequently we can justify the assumption that it comprises several (not necessarily equal) orthogonal components, which are uncorrelated when the corresponding signal components are brought into coherence.

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The processing algorithm, to combine such multiple, noisy signals in an optimum manner, is described in the next Section.

1.1 The General Theorem

Assume we can estimate for any noisy signal element number i that its signal component is of amplitude s_i and phase ϕ_i, arriving at time t_i, and that it is contaminated by uncorrelated noise of amplitude n_i. The optimum procedure when combining the same intrinsic signal, is then as follows:

1. define a reference signal channel or element s_0, ϕ_0, t_0, n_0;
2. apply to each other signal element the time shift $t_0 - t_i$ and phase shift $\phi_0 - \phi_i$ required to align it with the reference;
3. scale up the amplitude of element i by the ratio s_i/s_0, thus further emphasizing the strong (though possibly noisy) signal channels and de-emphasizing the weak ones;
4. additionally multiply the resultant amplitude by n_0^2/n_i^2, thus discriminating strongly against the noisier signal components.

The application of these simple rules results in a composite signal-to-noise ratio which is equal to the sum of the signal-to-noise ratios of all the contributing elements or channels.

This is a theorem of great universality and power, which will be proved in the next Section.

1.2 Derivation of the Optimum Weighting

By Norton's theorem, we may represent each signal channel by a source of signal current s, in parallel with a source of noise current n and an impedance Z. This combination is further connected across the primary of an ideal transformer, whose secondary winding steps up the current in ratio $x : 1$ (see Fig. 1). The circuit also contains a phase shifter $-\phi$ to neutralize any phase difference ϕ between the channel signal and the reference, but this will not need to be explicitly referred to in subsequent discussion.

When the output terminals of a number of such channel circuits are connected in parallel, their (transformed) currents all feed into a common, composite impedance. Hence the signal power W_s, due to a number of coherently combined signal currents, is proportional to the square of their combined (scaled) magnitudes, i.e.

$$W_s \propto \left[\sum_{i=1}^{N} x_i s_i\right]^2$$

The noise currents, on the other hand, are postulated to be non-coherent.† Hence, their combined power is merely the sum of the powers generated by the individual noise currents, i.e.

$$W_n \propto \sum_{i=1}^{N} (x_i n_i)^2$$

The constant proportionality in both relations is the same—namely the composite impedance.

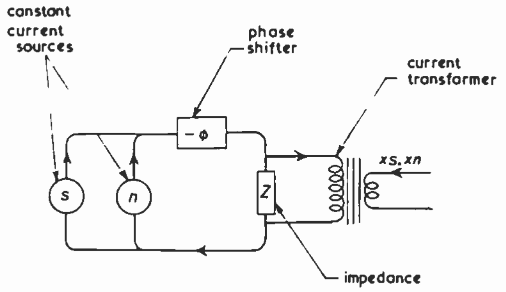

Fig. 1. Representation of 'noisy signal' element.

Hence the signal-to-noise power ratio for two such elements combined is

$$R = (s_1 + y s_2)^2 / [n_1^2 + (y n_2)^2]$$

where

$$y = x_2/x_1$$

Differentiating this we find that, for maximum R,

$$y \equiv \frac{x_2}{x_1} = \frac{s_2/n_2^2}{s_1/n_1^2}$$

Regarding the resulting 'optimum' combination of two channels as a single input, to be combined with a further one, etc., we can generalize and say that the optimum weight x_i for channel i is indeed proportional to s_i/n_i^2.

The condition for optimum combined signal/noise ratio, derived above, depends solely on scaling the individual signal currents in proportion to their s/n^2, and feeding them into a common impedance. Hence the same optimum signal-to-noise ratio will apply when using equivalent active circuits, in lieu of the passive transformers, to combine multiple signal sources or channels.

1.3 Derivation of the Optimum Composite Signal-to-Noise Ratio

Let us now look at the signal-to-noise ratio obtained with this optimum weighting. This is

$$R = \frac{W_s}{W_n} = \frac{\left[\sum_{i=1}^{N} x_i s_i\right]^2}{\sum_{i=1}^{N} (x_i n_i)^2}$$

Substituting the optimum values of x derived in the preceding Section, this becomes

$$R = \frac{\left[\sum_{i=1}^{N} \frac{s_i}{n_i^2} s_i\right]^2}{\sum_{i=1}^{N} \left(\frac{s_i}{n_i^2} n_i\right)^2} = \frac{\left[\sum_{i=1}^{N} \left(\frac{s_i}{n_i}\right)^2\right]^2}{\sum_{i=1}^{N} \left(\frac{s_i}{n_i}\right)^2} = \sum_{i=1}^{N} \left(\frac{s_i}{n_i}\right)^2 = \sum_{i=1}^{N} r_i$$

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† Internal thermal noise is almost invariably non-coherent and so is external noise if it is quasi-isotropic and if the relevant antenna elements are not much closer than half a wavelength. Closer spacings are likely to imply super-directivity involving deliberate coherent cancellation of off-axis external noise. The weightings of the element signals would then be determined by the requirements of super-directive beam-forming.

where r_i is the signal-to-noise ratio of the ith element. Thus we have proved that the optimum composite signal-to-noise ratio is equal to the sum of the individual signal-to-noise ratios, as stated in Section 1.1. (Note that these are arithmetic power ratios, *not* logarithmic ones in dB.)

1.4 The Combination of Noise Sources

Let us now make a small digression, whose relevance will soon become apparent. Consider two noise sources of equal power, namely

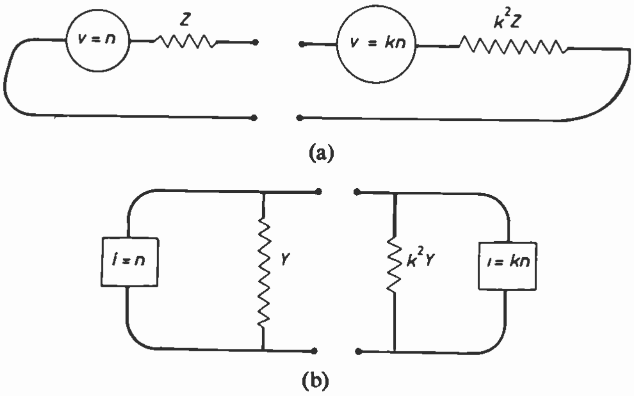
> a voltage source n in series with a resistance Z, and an uncorrelated voltage source kn in series with a resistance k^2Z, both giving a non-coherent noise power of n^2/Z (see Fig. 2(a)).

If we connect these in series, the mean square of their non-coherently combined voltages will be $n^2(1+k^2)$, and their series-combined resistances will be $(1+k^2)Z$. Hence their combined power is n^2/Z, like that of either by itself.

Similarly (or by duality), a noise current n in parallel with an admittance Y, and a noise current kn in parallel with an admittance k^2Y represent two sources of equal noise power (see Fig. 2(b)). Their non-coherent parallel combination produces a mean-square current $n^2(1+k^2)$ in parallel with a combined admittance $(1+k^2)Y$ and thus, once again, their combined power is n^2/Y, like that of either by itself. Clearly, we can generalize this result to say that any combination of passive components of similar type and equal noise power will give an equal resultant noise power. This incidentally also implies that the noise power across any two-terminal passive component or circuit can depend only on the material of the component and its temperature.

1.5 Maximum Signal vs. Optimum Signal-to-Noise Ratio

Reverting to the combination of noisy signals in a passive network, if the initial noise powers of all signal elements were equal, the noise power of the eventual output would thus still be the same. However, it was shown (in Sect. 1.3) that 'optimum' weighting produces an output signal-to-noise ratio equal to the sum of the input signal-to-noise ratios. With equal noise powers, the denominators of all these signal/noise power ratios would be the same. Hence the optimum weighting would then also produce an output signal power equal to the sum of the coherent input signal powers.



(a)

(b)

Fig. 2. Combination of noise sources.

Since, however, the resultant combined signal power depends only on the weighting applied to the constituent signal components, we can further conclude that the aggregate incoming signal power is preserved in full, if we weight the contributions of the various channels *as if for equal noise powers*. Since we cannot add to the available power in a passive circuit, this is the weighting for maximum output signal power. However, this will *not* also give the maximum signal-to-noise ratio, unless the noise powers in the individual channels were indeed equal.†

So now we have established how to scale the contributions from the various constituent signal elements to obtain the highest combined signal power or—more importantly—the best resultant signal-to-noise ratio. Before we can apply this, however, we must be clear what we mean by 'signal' and 'noise'.

1.6 What do we Mean by 'Noise'?

In practical systems, noise may arise from

- the receiver
- the propagation medium
- galactic sources
- atmospheric effects
- man-made interference
- reverberation/clutter
- inter-modulation.

Before applying the foregoing analysis, we must decide which of these is dominant, and confirm that it is uncorrelated from signal element to signal element, can be added on a mean square basis, and is shared between the signal elements in the postulated ratios.

1.7 What do we Mean by 'Signal'?

It is even harder to decide what we mean by 'signal', because the proper definition depends on the *use* to which the data will be put. Let us illustrate this with a few examples.

If our object is merely to detect the *presence* of a signal, we will seek to eliminate any intelligence-bearing modulation, and merely look for discontinuities in the energy distribution in the dimensions of time, frequency, direction of arrival, and polarization.

On the other hand, we might wish to determine the *frequency* of the signal, which we shall assume to be constant during the time of observation and equal to the rate of change of phase, $\Delta\phi/\Delta t$.

The signal parameter to be measured in each contributing observation is then the phase change $\Delta\phi$. Any

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† We may also note that, as all signal elements resolvable in frequency and time are combined coherently, the resultant represents the total signal energy. The non-coherent combination of the corresponding elements of noise, on the other hand, gives a resultant equal to the noise energy per unit area on the frequency/time plane. Hence, the optimum combined signal-to-noise ratio is equal to the ratio of the aggregate signal energy to the noise energy density.

practical measuring process will be analogous to a model in which the observed signal phase, at a number of sampling points in the 'observations-time window', is compared with the phase of a mid-band reference oscillator, the signal and reference phases being aligned in the centre of the time window (where $t = 0$). The quantity to be determined is then the frequency misalignment Δf, and this produces a phase misalignment $\Delta\phi = \Delta f.\Delta t$, at an observation time Δt relative to the centre of the time window. Thus the *a priori* magnitude of this 'signal' is proportional to Δt, the time over which the frequency was able to build up the phase change. The noise-induced phase error, on the other hand, is inversely proportional to the signal-to-noise *amplitude* ratio. Hence, the s, for s/n^2 weighting, is then proportional to Δt, and the n to (n/s). Thus optimum weighting entails scaling the measured phase increments $\Delta\phi$ to the form $[\Delta t(s/n)^2]\Delta\phi$. However, we require to derive the best assessment of frequency from the set of observations $(\Delta\phi_i, \Delta t_i)$. Assuming the time intervals are known without significant errors, the weighted phase terms will define the relative contributions to be made to the composite estimate. Hence the sum of the weighted phase increments should be divided by the sum of the similarly weighted time increments, thus giving the frequency as

$$\Delta f = \frac{\sum[\Delta t(s/n)^2]\Delta\phi}{\sum[\Delta t(s/n)^2]\Delta t} = \frac{\sum[(s/n)^2\Delta t\Delta\phi]}{\sum[(s/n)^2\Delta t^2]}$$

where $\Delta\phi$ and Δt are measured relative to the values of ϕ and t at the centre of the observation-time 'window'. (This would, in fact, also be the formula for the 'maximum likelihood' fit of a linear phase slope to a set of observed data.)

A closely analogous situation pertains in the measurement of the angle of arrival of a radio signal at a linear antenna array, i.e. the slope of plane phase front relative to the plane of the array, which we may visualize as the rate of change of phase *in space* across the antenna's aperture. If a given antenna element is at a distance x from the 'phase centre' of the total antenna array, then its 'true' phase, relative to that at the phase centre, will be proportional to x. Hence, by an argument exactly analogous to that of the preceding paragraph, the optimally weighted composite measurement of direction gives the angle of arrival as θ, defined by

$$\sin\theta = \frac{\lambda}{2\pi}\,\frac{\sum[(s/n)^2 x\Delta\phi]}{\sum[(s/n)^2 x^2]}$$

If, on the other hand, we require the maximum directional *discrimination* against isotropic noise from an array of equal elements,† the *a priori* signal amplitudes are likely to be equal in all the antenna elements, and so are the noise powers. Hence, all elements should then be phased to align them with the desired direction of maximum gain, but should *not* be weighted in any way.

As is well known, suitably tapered weighting could reduce side-lobe *peaks* in the radiation pattern of an antenna array; hence such weighting may well be desirable if we wish to reduce the *worst* interference likely to be encountered; however, the above universal formula shows that this could only be achieved at the expense of degrading the overall discrimination against isotropic noise—and the *average* discrimination against any interference of unknown angular distribution.

Note that we have concluded that the best use of a given aperture to provide information on the angle of arrival entails weighting proportional to x, i.e. a V-shaped amplitude taper, zero at the centre and increasing linearly from there outwards. A convenient approximation to this is the simple 2-element interferometer. (Combining the outputs from the two elements multiplicatively by cross-correlation, rather than additively, is incidental; it is a non-linear process which increases undesirable cross-modulation near the threshold of detectability, but is a convenient means of contrast expansion to produce an apparent improvement in any already high signal-to-noise ratio.)

As discussed in the next Section, the benefit from such a process depends mainly on its ability to segregate the incoming signal into multiple cells (in this instance directions), only one of which contains the wanted transmission. A spacing of D between the two antenna elements will spread the relative arrival time over $\pm D/c$ (where c is the speed of 'light'). Hence the benefit from interferometry depends on the time resolution of the signal compared with this. Since a bandwidth B is required to give a time resolution of $1/B$, the number of potential distinct directional resolution cells will be $2BD/c \equiv G$, say. However, this potential gain against wide-band isotropic external noise will be realized only if any G consecutive elements of wanted signal, of duration $1/B$ each, are uncorrelated in their modulation. The gain may be explained in terms of each signal sample from one element matching only one of G samples from the other. (Alternatively, G sets of filters could be used to generate G independent narrow-band interferometers, whose *patterns* are combined coherently according to the s/n^2 weighting rule, to give the optimum directional resolution.)

It is not uncommon for a noisy signal to pass through a circuit or a propagation medium equivalent to a filter, presenting unequal transfer 'gains' to different signal elements. Then each element of this signal may have *both* its signal and its noise constituents modified by a common ratio—differing from one element to the next. Assuming the signal-to-noise ratio in all the elements was originally the same, we can then state that the noise associated with each element finally received is proportional to the signal. Hence, optimum weighting by s/n^2 is then equivalent to weighting by $1/s$, so that it equalizes all signal elements. In the circumstances postulated—but only in these circumstances—this weighting, sometimes known as 'inverse filtering' or 'pre-whitening', gives the optimum combined signal-to-noise ratio.

Finally, if a given item of signal intelligence is carried redundantly by multiple elements resolvable at the receiver, all equally contaminated by local thermal noise, our weighting formula specifies the conventional

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† Even if unequally spaced.

'matched filter'. Indeed, we may now recognize that we have extended the concept of a matched filter to a much wider class of applications and operating conditions.

1.8 Processing Gain

Let there be k signal channels with an average signal voltage s_0 and individual signal voltages

$$s_i = s_0(1+\delta s_i)$$

Hence

$$\textstyle\sum_k s = ks_0 \quad \text{and} \quad \sum_k \delta s = 0$$

$$\frac{1}{k}\textstyle\sum_k (\delta s)^2 \equiv \Delta_s^2$$

i.e. the fractional variance of the signal.

$$\left(\textstyle\sum_k s \text{ denotes } \displaystyle\sum_{i=1}^{k} s_i, \text{ etc.}\right)$$

Equivalent notations and relations apply to the noise voltages n_i, etc., and to the signal/noise voltage ratio $\rho_i = s_i/n_i$.

Thus unweighted coherent addition produces a resultant signal/noise power ratio of

$$R' = s_0^2[\textstyle\sum_k (1+\delta s)]^2/n_0^2 \sum_k (1+\delta n)^2$$

i.e.

$$R' = \left(\frac{s_0}{n_0}\right)^2 [k + \textstyle\sum_k \delta s]^2/[k + 2\sum_k \delta n + \sum_k \delta n^2]$$

i.e.

$$R' = k\left(\frac{s_0}{n_0}\right)^2 \bigg/ (1+\Delta_n^2)$$

Hence the non-optimized coherent processing gain, relative to the signal/noise ratio of a hypothetical 'average' channel is

$$k/(1+\Delta_n^2)$$

This contrasts with the optimally-weighted coherent-processing signal/noise power ratio which, from Section 1.3, is

$$R = \textstyle\sum_k \rho^2 = k\rho_0^2(1+\Delta_\rho^2)$$

Thus the optimum processing gain, relative to a single 'average channel' is

$$k(1+\Delta_\rho^2)\rho_0^2 \bigg/ \left(\frac{s_0}{n_0}\right)^2$$

The significance of optimal weighting will be indicated by the ratio

$$R/R' = (1+\Delta^2\rho)(1+\Delta^2 n)\rho_0^2 \bigg/ \left(\frac{s_0}{n_0}\right)^2$$

Thus this extra processing gain increases with increasing fractional variance both of the set of signal/noise voltage ratios and of the set of noise voltages.

Shading (tapering) the aperture distribution of an antenna to reduce side lobes is evidently a departure from optimum (equally weighted) processing for maximum discrimination against isotropic external noise. The resultant loss is clearly the reciprocal of the gain realizable by restoring uniform weighting.

The misapprehension is sometimes encountered that a system which can *measure*, say, the location or velocity or frequency of an emitter, or the timing of a transmission, with high accuracy (given an adequate signal-to-noise ratio) must therefore offer a high processing gain. Only if a system can *resolve* some parameter into multiple, mutually-exclusive elements can it give a corresponding processing gain, due to concentrating the signal in one (or a few) of these resolution cells whilst leaving the noise more widely spread amongst them all. According to conservation law (i) of Section 3.2, the number of independently resolvable outputs is equal to the number of distinct measurements in the input (time-bandwidth-antenna) observation space. Some subtleness may be required, in system design, to endow the modulation with resolution in the dimension where it will be most profitable to separate the wanted emitter from undesired emissions.

The rules for the optimum combination of multiple signal channels or elements are as valid at video or audio frequencies as they are at radio or intermediate frequencies. However, a given processing gain G_2, subsequent to an incoherent detector (the 'second detector'), is equivalent to only, roughly, $\sqrt{G_2}$ prior to this incoherent detector. Hence, when a pre-detector processing gain G_1 is combined with, say, post-detector matching to some known variation of the signal envelope, given a processing gain G_2, the equivalent r.f. gain is $G \simeq G_1\sqrt{G_2}$.

2 The Information Capacity of Communications Systems

2.1 The Measure of Information in a 'Population' of Equi-probable Messages

So far we have discussed how best to combine a number of signal elements which, but for the effect of noise, carry essentially the same information. We now need to examine more quantitatively what information can be conveyed by a given signal structure, and how to match our information-rate requirements most effectively to the constraints of a known signal system environment. Let us therefore first of all establish our unit of measurement.

'Information' is that which enables us to make a valid choice between the members of a population of alternative messages. Since differences of probability would contribute to this choice, they must entail information. Hence, for minimum *a priori* information, all the available messages should be equi-probable. Since two is the smallest discrete number of messages (or sets of messages) between which a choice can be made, we may conclude that the 'natural' unit of information defines the choice between two equally probable sets of messages and hence is the binary digit or 'bit'.

The addition of a second bit doubles the information—and permits two equiprobable subsets to be defined *within each* of the two sets defined by the first bit. Clearly n data bits can convey a choice between 2^n combinations, and by our definition of the unit of information, n bits of information convey a choice between 2^n *equi-probable* messages. This implies that the information is equal to the logarithm (to base 2) of the 'population' of equi-probable messages.

2.2 The Effect of Unequal Message Probabilities

In practice, however, the messages are not necessarily equi-probable. Hence we must be a little more explicit in distinguishing between the bit as an element in the data structure and as a unit of information. A digit used for synchronization, and appearing in its proper known position in the data structure, conveys no information, and a 'parity' error-check digit conveys very little information if previous experience has taught us that the *probability* of an error is very low. We can take this varying *a priori* message probability into account, by treating each message M_i *as if* it were a member of a population of 2^{n_i} equi-probable messages. Hence, this message, when received, carries n_i 'bits' worth of information.

Furthermore, with a joint probability of unity, these messages would have an individual probability of 2^{-n_i} each. Hence the information content of any specific message M_i of probability $p_i = 2^{-n_i}$ is $n_i = -\log_2 p_i$. However, the proportion of the total stream of messages taking the form M_i is p_i by the definition of probability. Hence the average information per message is

$$I = -\Sigma p_i \log_2 p_i$$

and if we are dealing with 2^n discrete n-bit messages, the mean information per message is

$$I = -\sum_{i=1}^{2^n} p_i \log_2 p_i$$

When all p_i are equal, at $p_i = 2^{-n}$, I becomes equal to n, as required. When they are unequal, the mean p_i cannot change, since $\sum p_i \equiv 1$. However, $\log_2 p$ increases with p. Hence, the decrement in $-\sum p_i \log_2 p_i$, due to any p_i values above the mean must always exceed the countervailing increment due to the associated p_i values below the mean. Hence the information conveyed is maximum when all the messages are equi-probable, and it is then equal to the total number of data bits.

Indeed, one could argue that, if the messages are not equi-probable, the pattern of relative message probabilities, derived from a large sample of received signal, will itself convey some information—and hence absorb some of the potential information capacity of the channel. Hence unequal probabilities would divert useful information capacity from the sender to provide some unwanted information on the design of the system.

2.3 The Information Capacity of a Set of Noisy Multi-level Signals

So far we have discussed how to measure information in terms of binary digits and (briefly) how *messages* should be structured to make the best use of a given number of binary digits. We now must turn to the complementary aspect of how the *signals* are structured to provide this number of binary digits, and we shall then go on and consider how this signal structure is adapted to various signal-system constraints.

The choice of one member, from a set of 2^n possible messages, can be specified by n binary digits, or by one signal of 2^n discriminable values, or by any intermediate message structure—say n/a 'characters' of 2^a discriminable levels each. In order to understand the effect of noise on a multi-valued character, consider such a character which comprises a signal of amplitude range $\pm S$, 'polluted' by noise of amplitude range $\pm N$. The number of discrete amplitude levels distinguishable, from $+S$ via 0 to $-S$ is then $1+S/N$. Clearly this choice could alternatively be specified by d binary digits, where

$$d = \log_2 (1+S/N)$$

Note that $(1+S/N)$ covers one state where there is no recognizable signal present plus S/N discriminable levels of non-zero signal. (For $S = 0$, $d = \log_2 1 = 0$, as required.)

In practice we are more likely to be concerned with a signal of r.m.s. amplitude S, and with Gaussian noise ranging from $+\infty$ to $-\infty$ with a standard deviation of N. It can, however, be shown that the result, derived above in an illustrative way for a single character and a truncated noise-distribution, retains its validity if S and N are r.m.s. values and N is subject to a Gaussian distribution. The result must then, however, be interpreted on a statistical basis, and it defines the *limiting* information capacity of a message comprising a very large number of characters.

Hence a data set of multiple independent characters has a total information capacity

$$I = \sum \log_2 (1+S/N)$$

which is achieved if (and only if) all messages are equi-probable.

2.4 The Information Capacity of a Spectral 'Window'

Let us now examine how to maximize this information capacity, with given power, time and bandwidth constraints. For this purpose we only need to realize that the convexity of the log curve implies a 'law of diminishing returns'. This indicates that the capacity is maximized if the available signal power is spread equally between all the character sets which jointly comprise the message. Indeed, it is further maximized if the maximum number of such characters is accommodated within the available time/bandwidth product and signal energy. Hence the limiting information capacity is

$$I = 2BT \log_2 (1+S/N)$$

where B = bandwidth,
T = observation time available,
S^2 = probable signal power per frequency/time element (i.e. $S^2 = E/BT$) (E is the total signal energy received),
N^2 = noise power per frequency/time element, assumed to be uniform in the time and frequency dimensions.

(The factor 2 arises from Nyquist's theorem that two independent amplitude samples can be accommodated within one cycle time of the channel bandwidth.)

Thus we have derived Shannon's classical law in a simplified—and somewhat less rigorous—manner.

2.5 Coherent Replicated Messages

The foregoing arguments all applied to situations where the contributions of the separate characters to the specification of the message are totally independent (i.e. orthogonal). This case is important, both as an optimum limiting situation and as a first approximation to many practical systems in which linguistic single-letter probabilities are in fact neither equal nor independent of the preceding (and following) character values.

A good many other practical systems can be considered in terms of a common identical message being received via a number of separate data characters, polluted by separate, uncorrelated noise sources. These intrinsically identical signals can then be brought into coherence by appropriate compensation for their known separation in frequency, time, phase, propagation path, antenna space, etc. For this case Section 1.3 showed that optimum signal processing gives a resultant signal-to-noise power ratio equal to the sum of the constituent signal-to-noise power ratios.

$$\frac{W_s}{W_n} = S^2/N^2 = \sum \frac{s_i^2}{n_i^2}$$

Section 1.5 also showed that, if the noise-power density is uniform, this optimum coherent combination of multiple characters (or channels or elements) carrying the same signal intelligence will produce the same resultant as a single character comprising the total combined signal energy. Hence S/N, for assessing the information capacity, may then be derived, on this basis as $(W_s/W_n)^{\frac{1}{2}}$.

If x such channels are used to carry the same message each, with identical signal voltages s and (uncorrelated) noise voltages n, then, from the equation above, they give a joint information capacity per message element of

$$I_i = \log_2(1+S/N) = \log_2\left(1+\sqrt{x}\,\frac{s}{n}\right)$$

Such a system fails to distribute its information uniformly over the full time and bandwidth available. Hence it is non-optimum, compared with the same power and number of channels carrying independent signals, which provide an information capacity per element of

$$I_1 = x\log_2\left(1+\frac{s}{n}\right) = \log_2\left(1+\frac{s}{n}\right)^x$$

$$\left(\text{More generally, } I_1 = \log_2\left\{1+\left[\sum\left(\frac{s}{n}\right)^2\right]^{\frac{1}{2}}\right\}\right.$$

and

$$\left. I_2 = \sum\log_2\left(1+\frac{s}{n}\right) = \log_2\left\{\prod\left(1+\frac{s}{n}\right)\right\}.\right)$$

For the sake of completeness, it may also be worth mentioning the case when both the noise and the signal are fully correlated from one of the multiple elements to the next, although their relative power (i.e. s/n) may vary. This applies, for instance, when the dominant noise is of external origin and the aperture of the transducer array is insufficient to distinguish signal from noise by direction of arrival. The separate signal elements may then arise from multiple propagation paths or multiple transducer or antenna elements. The same conditions apply also to many cases of external-noise limited diversity reception or duplicate recording. We can then distinguish three situations:

(a) all s/n known to be equal: select any one channel;

(b) s/n unequal but known (or measurable): select the channel of biggest s/n;

(c) s/n unequal and totally unknown: sum all channels, so as to obtain the mean s/n.

Thus, in all such cases, the information capacity is reduced to that of one single channel of this type.

2.6 Orthogonally-structured Replicated Messages

Yet another class of practical problems is represented, for example, by the derivation of a fault diagnosis from multiple contrived measurements or multiple available clues. Other typical examples include 'optical' character recognition, or teleprinter signal regeneration, with decisions based on the relative strengths of various features of the received pattern. We shall discuss this class of problem below, referring to the measurements, clues or features as 'message elements' and to the discrete fault conditions or characters as 'messages'.

We may then receive a set of E separate noisy message elements, each having its own mapping function, relating its noise-free amplitude to the selection of the appropriate one from a set of M possible 'messages'. Here we should ideally apply Bayesian statistics which give

$$P_j = P_{j0}\prod_{i=1}^{E} P_{ji}$$

where P_j = resultant probability that the 'true' message is j,

P_{j0} = *a priori* probability that the message is j,

P_{ji} = probability ratio in favour of hypothesis derived from the received value of message element i.†

This general solution can be simplified somewhat if we have adequate freedom to design the desired combinations of diagnostic signals. It may be instructive to consider a simple special case of this type, as follows:

(a) each of E message elements, if noise free, identifies the same, correct one of the M possible messages by one of the M equally-spaced discrete amplitudes;

(b) the patterns of amplitude assignments are orthogonal from one message element to the next; (i.e. each message element has the assignment of the M meanings 'scrambled' in a different way over its M-point amplitude scale);

(c) noise 'smears' the signal level over m contiguous amplitude increments, and so causes each message element to define a subset of m messages with equal

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† $P_{ji} = \dfrac{\text{probability of } j \text{ (if present) giving rise to } i.}{\text{total probability of } i \text{ arising}}$

probability, where the magnitude of m is the same for all E message elements but the membership of the subset is different;

(d) all messages have equal *a priori* probability.

In this instance we can avoid the Bayesian approach and say that each message element contributes $\log_2 M/m$ bits of independent information.

If the total information from the E elements exceeds $\log_2 M$ bits, it should be possible to identify the message uniquely. (Otherwise the deficiency will define the residual ambiguity.) Thus the threshold of unique message identification is

$$E \log \frac{M}{m} \geqslant \log M$$

i.e.

$$(E-1) \log M \geqslant E \log m$$

This sort of simple analysis can be very valuable in assessing how close a given diagnostic facility or recognition device is to the requirement—and to the theoretical optimum—and how it might be most profitably improved.

2.7 Independently Fading Replicated Messages

Yet another instance of replicated messages arises when single-channel reception is limited primarily by random deep fades in the channel, rather than by lack of signal power. It pays then to share the available signal power between several such channels which are subject to independent fading. Analysis of this case[1] (assuming addition of the diversity outputs following linear detection) has shown that the probability of correct detection is maximized if the number of diversity channels is that giving individual mean signal-to-noise power ratios of approximately 7 dB. (Clearly, the number of such diversity elements should be reduced with increasing correlation of fading patterns.)

If any fluctuations in the carrier frequencies are known to be outside the signal modulation band, such multiple carriers can be brought into phase coherence. Due to such adaptive phase adjustment or otherwise, the signals in these 'diversity' channels may be coherent, and the dominant noise sources may be uncorrelated far-field sources, subject to the same fading as the signal. In these circumstances Section 1.7 shows that the optimum signal processing is inverse filtering, which equalizes all the signal contributions prior to coherent addition. In other noise conditions, the weightings have to be adjusted in accordance with Section 1.2, and if the diversity channels have no r.f. coherence (a common situation) similar optimally-weighted addition will have to be applied to the audio or video signals from the individual second detectors. This, of course, gives only the reduced processing gain appropriate to the *post*-detector signal-to-noise ratios (see Sect. 1.8).

3 Transformations

3.1 Transformed Measurements Viewed as Messages

So far we have discussed the number of discrete 'messages' which can be resolved from a number of discrete, multi-valued 'measurements' in quite general terms—although with special emphasis on mutually 'orthogonal' measurement axes. In an important class of practical cases, however, the 'messages' may be output quantities derived from the input or observational measurements. For instance, we may wish to distinguish between M alternative frequencies, directions or times of arrival. A convenient way of relating these outputs to an appropriate set of orthogonal observational measurements is to use a discrete Fourier (or other) transform to derive:

time from the phases of a number of frequency channels;

frequency from the amplitudes of a number of time samples;

direction from the phases at a number of space (antenna) elements.

3.2 The Conservation of Dimensionality and Information in Transformation

Such a transformation cannot add to the quantity of information available and should not take away from it. It is, however, important to distinguish between measurement and information:

(i) The number of distinct measurements (channels, samples or elements) in the observation plane should be preserved, to permit the resolution of the same number of distinct signal parameters (in the dimension of time, frequency or direction, as appropriate) in the object plane.

(ii) The number of 'bits' of data acquired in the observation (measurement) plane should be preserved, to produce the same number of bits in the object (transform) plane.

The first of these 'conservation laws' arises directly from the theory of simultaneous linear equations: each additional independent equation permits the definition of another independent variable. If, however, the sets of coefficients are closely similar (equivalent to the measurements being fairly highly coupled), the magnitudes of the constituent emission parameters will only be very imprecisely specified—by the differences of nearly equal quantities.

The second conservation law arises from the fact that every combination of distinguishable states of the 'input' set of message elements can be 'mapped' onto a corresponding combination of distinguishable states of the 'output' set of message elements. However, the actual number of bits of independent *information* available is determined by information theory, as indicated in Sections 2.1–2.4. It is small if the constituent observations are closely coupled or otherwise have high *a priori* probabilities.

3.3 The Sampling Theorem

Let us now turn to a very important special case of the law of conservation of the number of distinct measurements. We may accept that a frequency spectrum is defined by the amplitudes of two non-cophasal measurements at each of its distinct frequencies, and that a mono-chromatic radiation pattern may be defined by two non-cophasal amplitudes for each distinct direction. On this basis the foregoing 'conservation law' implies the 'sampling theorem', which states that a band-limited periodic signal is fully specified by any integral number of samples exceeding $2T/\tau$, where T is the period of the signal and τ the period of the highest frequency component. Similarly, a wave front periodic in space may be specified by any integral number of samples exceeding $2D/\lambda$, where the aperture D is the spatial period of the wave front and λ is the shortest constituent wavelength. In both cases the maximum information is derived, from measurements of given accuracy, if these samples are spread uniformly over the time or space period containing the signal.

These principles remain valid if we are concerned with a time-limited wave-form or aperture-limited wave front, and describe the signal by a Fourier transform in place of the Fourier series.

Provided the near-field of an antenna system is in fact fully established, it can be controlled, in transmission, or measured, in reception, by means of the above number of sample elements with (ideally) almost any distribution of these elements within the known near-field width. (Similarly, a periodic wave-form can be specified by the appropriate number of samples at any distribution within the known period.) However, closely spaced constituent observations provide less independent uncorrelated information than observations spaced uniformly over the full available aperture, and hence any uncorrelated noise is then more significant in relation to this reduced signal content. This is discussed more fully in a companion paper.[2]

3.4 The Relation of Matched Filters in the Antenna-space and Observation-time Domains to Normal Beam Formers and Frequency Filters

An understanding of the transformations available and of the analogies between them, and an insight into the implications of having at one's disposal a given number of discrete measurements of given S/N are crucial to the analysis and design of signal-processing systems, and can also offer a fertile basis for innovative thinking. Hence these aspects will be pursued a little further hereunder.

The relation of antenna beamwidth to the azimuthal distribution of signal—and noise—sources, is closely analogous to the relation of bandwidth to the spectral distribution of signal—and noise—sources, if we substitute observation time for aperture, wave periods for wave lengths, wave forms for aperture distributions, frequencies for sines of directions, and (subject to this sine term) bandwidths for beamwidths. Further substitutions, in this duality, include filters for antennas and selectivity for directivity.

In both cases, narrowing the band (or beam) width of a single receiving channel

(i) reduces the number of potential emitters covered, and

(ii) improves the signal-to-noise ratio by eliminating noise from non-selected frequencies (directions).

Let us examine the ability of a set of M measurements across a spatial aperture (or time window) to specify a given directional (or spectral) signal distribution. Any arbitrary set of weights, attached to the M measurements available over the spatial aperture (or time window), will specify a particular distribution of signal power in the direction (or frequency) dimension, and will constitute a filter matched to this distribution. Furthermore, the theory of simultaneous equations tells us that, if we have M such mutually independent sets of weights, we can specify any practical distribution in terms of its components in these M arbitrary matched filters, just as well as in terms of the M original measurements. Many of the directional (or frequency) patterns implied by these matched filters would, however, be likely to be 'freak' distributions of little practical meaning or value.

The most important special case of such matched filters is that represented by the simple single beam-former (or narrow-band filter). In this instance, each specific set of weights (and phase or delay adjustments) causes the M input measurements across the array aperture to be transformed into a single, maximum-discrimination beam. The processing-gain due to optimum combination implies that this beam covers only $1/M$ of the full available azimuthal spread. Hence it must be possible to form M such beams, which jointly just cover the full azimuthal spread. Finally, since the M outputs are thus independent of each other (covering a different azimuth each), the corresponding M sets of appropriately weighted input measurements must also be orthogonal to each other: a very important and convenient property of such beam formers. The same arguments apply of course, *mutatis mutandis*, to the relation between observations across a time window and the corresponding frequency filters.

Increasing the antenna aperture by the addition of one more element (or the time window by one more sample) clearly increases the total collected energy *pro rata*, and it also provides the additional degree of freedom to define one more independently resolvable beam (or frequency).

The total number of potential composite signal patterns which can be distinguished depends on the number of discrete amplitude levels which can be recognized in each of the M 'orthogonal' measured—or transformed—components. Adopting the conventions and assumptions of Sections 2.3 and 2.4, directional component i will be resolvable into $(1+S/N)_i$ potential amplitude levels. Hence the total number of resolvable combinations will be

$$C = \prod_{i=1}^{M} (1+S/N)_i$$

In practice we may not often need to handle continuously spread arbitrary distributions of emissions in azimuth, since most emitters can be treated as discrete point sources. In these conditions, a system of mutually 'orthogonal' beams may provide the information that given unique emitters are associated with particular azimuth (or frequency) resolution cells. Beyond this, we may also be able to measure the azimuth or frequency of an emission from the ratio of the amplitudes or difference in phase between the signals in adjacent resolution cells, with an accuracy depending on the signal-to-noise ratios concerned. However, such directional classification and, more particularly, any such measurement is contingent on *a priori* knowledge that we are dealing with azimuthally discrete signal sources, standing out over the background 'noise'.

Where the samples are separated sufficiently in the array space (or time window) to be mutually independent, the beams (or filters) of the appropriate resolution would be formed by coherent addition. At closer spacings, coherent cancellation can still be maintained, to generate the $(M-1)$ nulls, required for orthogonality to the other $M-1$ patterns, with least rejection by the antenna (or filter) at the wanted bearing (frequency), thus giving super-directivity (super-selectivity). These phenomena are discussed in a separate paper.[2]

4 Concluding Remarks

For some 30 years the author has been concerned—*inter alia*—with finding solutions, choosing between alternative solutions, assessing the potential of putative solutions, or optimizing 'trade-offs' between sub-systems of proposed solutions to the problems of varied signal-generating and processing systems. The fields involved have included primary and secondary radar, radio warfare, data processing, data links, noise and vibration problems, active and passive underwater acoustics, hydrodynamic turbulence, oceanography, line, radio and satellite communications, etc.

Most of this work has been at the 'policy' level, where the time available for the study of specific systems has been strictly limited. Hence there has been every incentive to develop and put to practical use a set of concepts and criteria—or ways of looking at established phenomena—which are of wide application, and which may reveal opportunities for cross-fertilization and assist in a quick appreciation of the capabilities of a proposed system, or of its limitations, and which may indicate how far short it may be of any theoretical limit.

In so far as these principles have been developed or presented in new ways, they have also provided new perspectives for looking at problems. Hence, like any new perspective, they have frequently yielded a new insight into problems, and so have helped the discovery of solutions—or the recognition of limitations. This paper contains those concepts which the author and his colleagues have found of the greatest interest and practical value, and he hopes they will similarly help some of the readers in their own practical problems.

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Round-off error analysis in digital m.t.i. processors for radar

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SUMMARY

Digital signal processing offers considerable advantages over analogue processing for video target extraction in moving target indication (m.t.i.) radars. These advantages include simplicity in the realization of delays, overall stability of the processor and the possibility of multiplexing. However, because of the finite resolution of the arithmetic unit, digital processing introduces a noise component which is a function of the resolution (register length), mode of arithmetic and filter configuration.

A theoretical and experimental evaluation of six representative digital filters, suitable for m.t.i. systems, is presented which shows that the simple model of round-off noise is a good approximation of the round-off process and good agreement is obtained between the theoretical and experimental estimates. The model partially fails in the case of recursive filters, because these filters do not satisfy the basic assumptions of the model.

Symbols

a_i	feed-forward filter coefficients
b_i	feed-back filter coefficients
C_i	mean square value of input clutter
C_o	mean square value of output clutter
e_q^2	mean square value of quantizer noise (error)
$E\{\cdot\}$	the expectation operator
$e_r(m)$	round-off noise (error) at instant m
f_c	filter cut-off frequency (Hz)
f_d	Doppler shift (Hz)
f_s	pulse repetition frequency (p.r.f. in Hz)
$H(\exp j\omega T)$	filter transfer function
$H_i(\exp j\omega T)$	transfer function of the i-th section
i.f.	intermediate frequency
IF	improvement factor
k_i	number of elementary noise sources in the input adder of the i-th section
l_i	number of elementary noise sources in the output adder of the i-th section
n	word length (register length) in bits (magnitude)
$p_r(e_r)$	probability density in round-off noise
$R_r(\tau)$	autocorrelation of round-off noise
$s(k)$	signal sample at instant k
$S_c(\omega)$	clutter spectral density
S_i	mean square value of input signal
S_o	mean square value of output signal
T	sampling period
v_r	target speed (radial)
$\delta(\tau)$	Dirac (impulse) function
λ	wavelength (metres)
σ_c^2	mean square value (variance) of clutter process
σ_ω	clutter spectral deviation (rad)
ω	angular frequency (rad/s)

1 Introduction

The moving target indication (m.t.i.) radar is the most widely used pulsed radar for the detection of moving targets. Its principle of operation uses the well-known Doppler effect according to which if either the source or the receiver of the radiation is in motion relative to the other, there results an apparent shift in frequency. Assuming that the target is in motion, the distance R and phase ϕ are continually changing. A change in ϕ with respect to time, is equal to frequency and the apparent frequency shift is given by[1]

$$f_d = \frac{1}{2\pi}\left(\pm\frac{\partial\phi}{dt}\right) = \pm\frac{2}{\lambda}v_r \qquad (1)$$

where the plus and minus correspond to closing and receding targets respectively. Similarly, back-scattering from non-targets such as precipitation, sea, forests, etc.,

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exhibits a Doppler shift as if it were a moving target and consequently additional signal processing is needed in order to extract the target from the back scattering of unwanted objects. The returns from unwanted objects are collectively known as clutter.

Clutter can be treated as a random process[1,2] and for the m.t.i. signal processor its most important characteristic is the spectral density. Although clutter from such objects as buildings, bare hills, or mountains is constant in both amplitude and phase, clutter returns from ensembles of elementary scatterers (precipitation, sea, forest), which are under a regime of internal fluctuations, after translation to baseband possess a narrow-band spectral density centred at about zero frequency or displaced from zero by a frequency corresponding to the average radial speed of the ensemble (equation (1)). If the average speed of clutter is zero, then the m.t.i. processor must function as a high-pass filter in order to separate the target returns from clutter. The assumption is made, of course, that the expected target Doppler shift and the significant part of the clutter spectrum do not occupy the same part of the spectrum and this assumption is essential for successful m.t.i. operation. In situations where the average ensemble speed is not zero, additional processing is required in order to remove the average shift and present the m.t.i. processor with a zero average speed clutter process. Because this paper is limited to the discussion of the m.t.i. performance with zero average speed clutter, it is assumed that such processing has taken place and the clutter process has zero average shift.

The high-pass filtering can be performed in either the i.f. or after coherent demodulation, in the video section of the receiver. Filtering in the i.f. section is superior to video filtering because it does not suffer from blind phases and improves the average target detectability by between 1·5 to 3·0 dB depending on the number of pulses processed.[1] However, because of the complexity in hardware, i.f. processing is not often used. On the other hand, target extraction in the video section has the advantage of relatively simple hardware and, as a result, is widely used. Blind phases in video processing can be avoided by operating two video channels in quadrature. A typical video processor with two channels for a coherent m.t.i. radar is shown in Fig. 1.

A pulsed radar is inherently a sampled data system and therefore the video processing in a m.t.i. radar can be performed digitally. The advantages to be gained from digital processing are the ease of realization of signal delay, the stability afforded by the digital system and the possibility of multiplexing. Referring again to Fig. 1, the elements of the processor which can be realized in digital form are the high-pass filter, the envelope detectors and the adder. In spite of the advantages of digital processing there are two sources of signal degradation; coefficient quantization and round-off noise. It is possible to design a digital processor with no coefficient quantization but there is no way of eradicating the round-off noise; it can be reduced to an acceptable level but not removed completely. The source of the round-off noise is the finite resolution of the arithmetic unit of the digital processor, and the effect it has on the quality of processing depends on the word length (number of bits in the register) and the mode of arithmetic.[3] The cost and speed of operation of a digital processor depend, to a large extent, on the word length and it is, therefore, very important to have an estimate of the round-off noise effect on the signal processor.

This paper presents a theoretical and experimental study of the round-off noise effect on the performance of typical video digital processors suitable for m.t.i. radars.

2 The Round-off Noise Model

In the realization of the linear digital filtering algorithm

$$y_k = \sum_{i=0}^{L} a_i x_{k-i} - \sum_{j=1}^{N} b_j y_{k-j} \tag{2}$$

only two arithmetic operations are involved, addition and multiplication. In fixed-point arithmetic (which is generally used in hardware realizations) addition, assuming no overflow occurs, is an exact operation, but multiplication is inherently non-exact. The reason for this is that the product of the two n-bit numbers is a $2n$-bit number and if the register length is to be kept constant to n-bits, the product should be reduced to n-bits. The approximation can be affected by truncation or rounding.[4] The error incurred is known as round-off error (or noise). Both approximations are, essentially, non-linear operations, but they can be linearized if the error is small compared to the actual number (product), and some other assumptions, to be discussed shortly, are made. In truncation, the error sign depends on the representation of the negative numbers, whereas in rounding (adding the $n+1$ bit to the n-th bit and discarding all bits after the n-th), it can be considered to be uncorrelated with the product. Restricting the discussion to rounding, the approximation of the $2n$-bit product by an n-bit number can be considered as a linear process if the following assumptions are made:

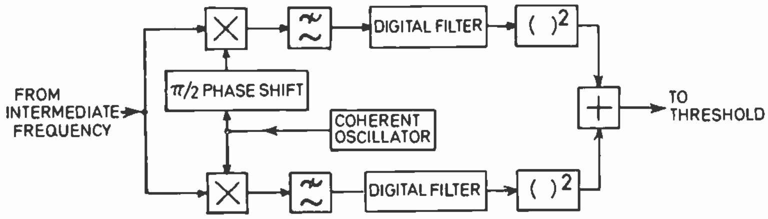


Fig. 1. Coherent m.t.i. video processor with two channels in quadrature.

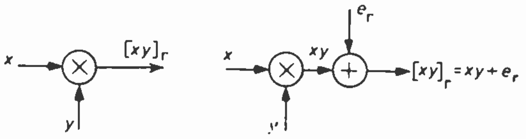


Fig. 2. Equivalent representation of multiplier with rounding.

(i) the word length is sufficiently long;

(ii) the round-off noise is uncorrelated from one iteration to the next of equation (2), i.e.

$$E\{e_r(m)e_r(k)\} = 0 \qquad m \neq k; \tag{3}$$

(iii) the round-off noise and the processed signal are uncorrelated, i.e.

$$E\{e_r(m)s(k)\} = 0 \qquad \text{all } m, k. \tag{4}$$

Under these assumptions the round-off noise is considered as being a random process with probability density

$$p_r(e_r) \begin{cases} |e_r| < \tfrac{1}{2}2^{-n} \\ 0 \text{ otherwise} \end{cases} \tag{5}$$

and

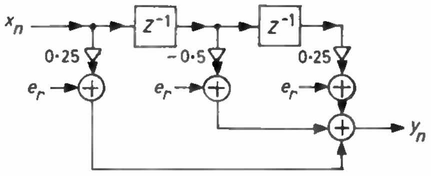
$$\begin{aligned} E\{e_r\} &= 0 \\ E\{e_r^2\} &= \tfrac{1}{12}2^{-2n} \\ R_r(m) &= \tfrac{1}{12}2^{-2n}\,\delta(m). \end{aligned} \tag{6}$$

Some explanations are clearly required. The concept of a sufficiently long word length is ultimately connected with the particular filter in question, but it was found that 6 bits can be considered as a lower bound for the sufficiently long word length. With regard to equation (4), there is a causal connection between the noise and the signal. The degree of this connection depends on the word length and the filter, and as a result the third assumption is a by-product of the first. The second assumption depends on whether or not the signal samples are uncorrelated; but if the first assumption is satisfied, equation (3) represents a first-order approximation if the signal is not strongly correlated.

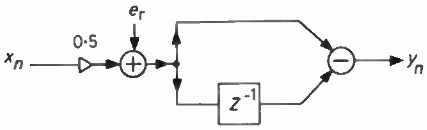
With the aforementioned assumptions we are led to a very simple model for the fixed point multiplier with rounding (Fig. 2). The assumptions made in the development of the multiplier model are similar to those made by Bennett in the analysis of the linearized quantizer.[5]

3 Theoretical Performance of Digital M.T.I. Filters

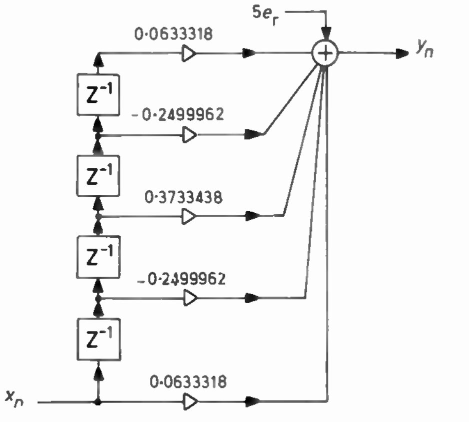
The performance evaluation of the digital m.t.i. filters was based on six representative filters: four non-recursive and two recursive. Of the four non-recursive, three belong to the binomial class $(1-z^{-1})^p$, with $p = 1, 2$ and 3, and the fourth is a five-pulse optimum filter.[6] The binomial filters were selected because they are popular with simple systems. Of the two recursive filters, the first, a 3rd-order 1-dB Chebyshev, was designed by



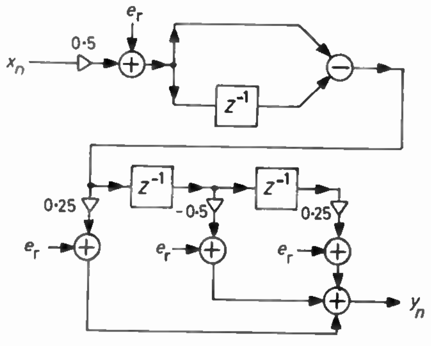
(b) THREE-PULSE CANCELLER



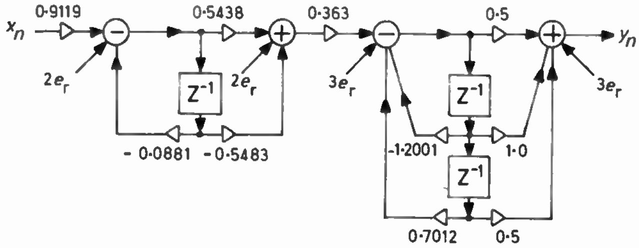
(a) TWO-PULSE CANCELLER



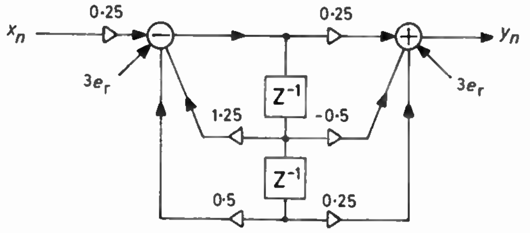
(d) FIVE-PULSE OPTIMUM FILTER



(c) FOUR-PULSE CANCELLER

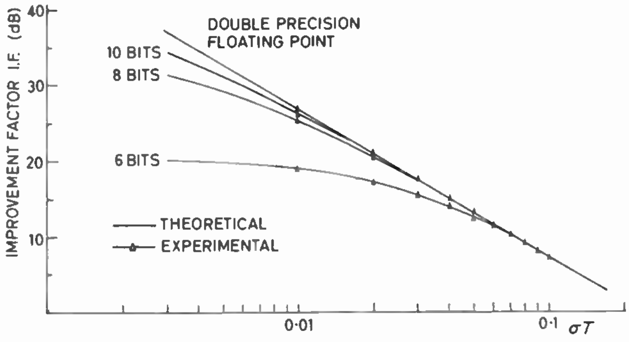


(e) THIRD-ORDER CHEBYSHEV FILTER

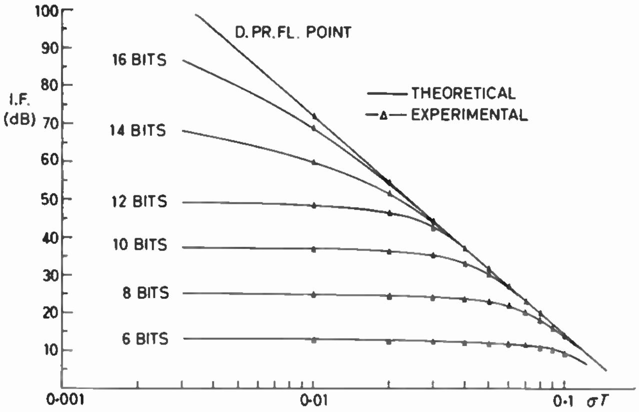


(f) SECOND-ORDER CHEBYSHEV FILTER

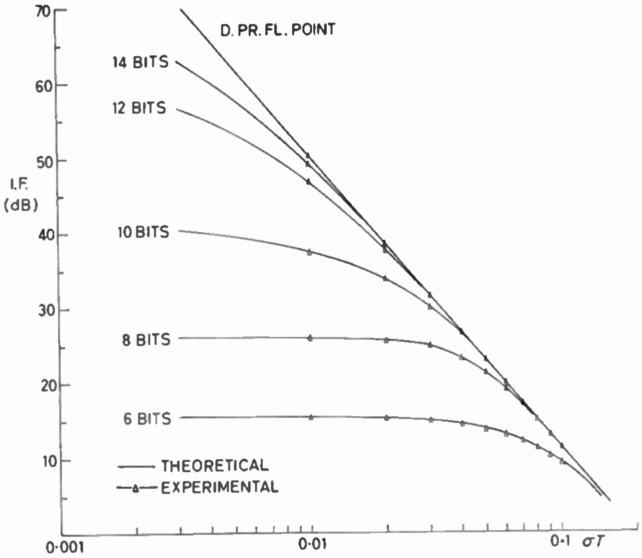
Fig. 3. The six filters which were tested with normalized coefficients and equivalent noise sources for rounding.



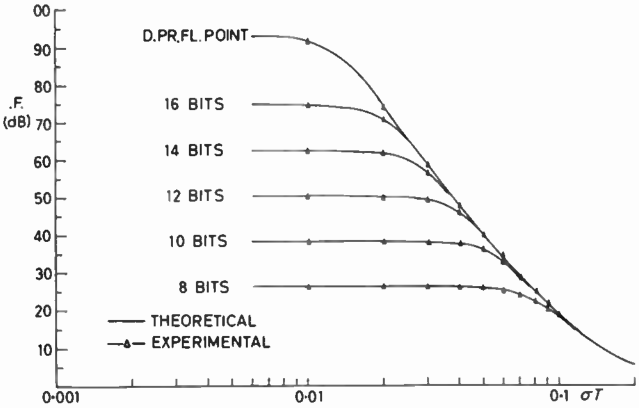
(a) Two-pulse non-recursive filter.



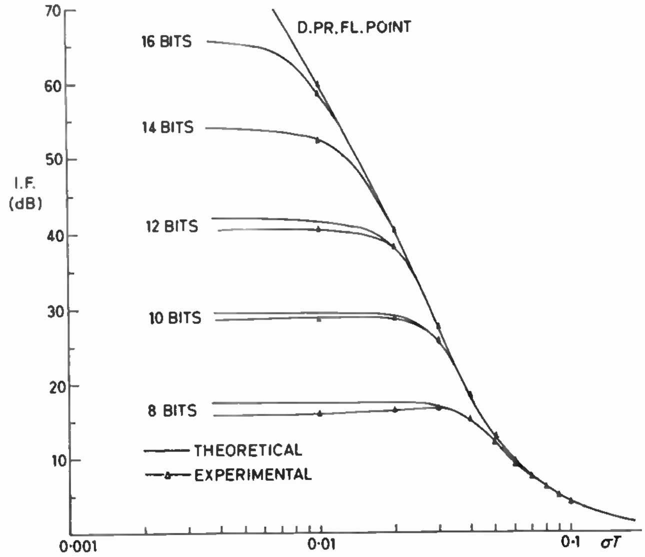
(c) Four-pulse non-recursive filter



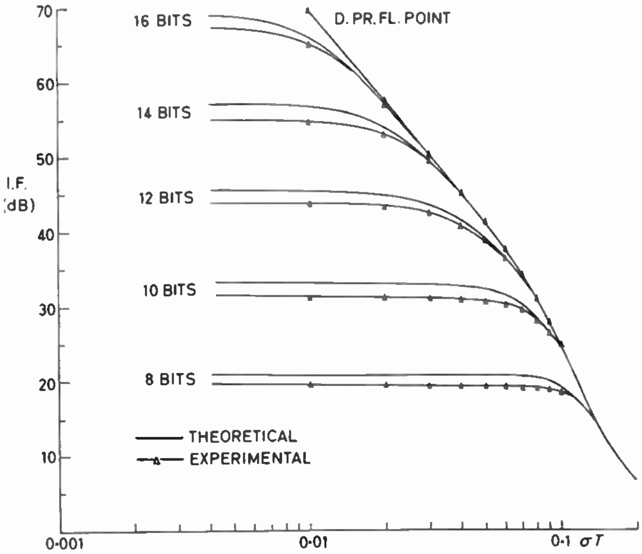
(b) Three-pulse non-recursive filter



(d) Five-pulse optimum non-recursive filter



(e) 3rd-order Chebyshev recursive filter.



(f) 2nd-order Chebyshev recursive filter.

Fig. 4. Improvement factor (IF) as function of word length and clutter spectral deviation.

White and Ruvin;[7] and the second, a 2nd-order 2-dB ripple Chebyshev, by the author. The difference between the two recursive filters is not only in the order but also in the fractional bandwidth. Defining the fractional bandwidth as

$$\mathrm{BW} = \frac{f_s - 2f_c}{f_s} \tag{7}$$

the 3rd- and 2nd-order Chebyshev filters have fractional bandwidths of 0·77 and 0·2 respectively. The six filters with scaled coefficients and round-off noise sources inserted after the multipliers are shown in Fig. 3.

There are a number of performance indices suitable for the evaluation of m.t.i. processors,[1] but in the work reported here only one of them, namely the improvement factor, (IF), was used because it is related directly to the filter. The IF is defined as

$$\mathrm{IF} \triangleq \left(\frac{S_o/S_i}{C_o/C_i}\right) = \left(\frac{S_o}{S_i}\right).\mathrm{CA} \tag{8}$$

where the clutter attenuation (CA) is defined as CA $\triangleq (C_i/C_o)$. The spectral density of the input signal (i.e. the expected Doppler shift) S_i, is taken to be uniform over $(-f_s/2, f_s/2)$.

The mean square output of a digital filter, operating on an analogue signal (clutter in this case), consists of three components.[8] The first is the input clutter breakthrough

$$C_{ob} = \frac{1}{\omega_s}\int_{-\omega_{2/s}}^{\omega_s/2} S_c(\omega)H(\exp \mathrm{j}\omega T)H(\exp - \mathrm{j}\omega T)\,\mathrm{d}\omega \tag{9}$$

and it is a measure of the inability of the filter to reject completely the clutter. The second is the contribution of the analogue-to-digital converter quantization noise to the output:[5]

$$C_{oq} = \frac{\overline{e_q^2}}{\omega_s}\int_{-\omega_s/2}^{\omega_s/2} H(\exp \mathrm{j}\omega T)H(\exp - \mathrm{j}\omega T)\,\mathrm{d}\omega. \tag{10}$$

The third is the contribution of the digital filter round-off noise, which, for a cascade configuration with the sections in canonic form (Fig. 3(e)) is given by

$$C_{or} = \frac{1}{\omega_s}\sum_{i=1}^{M-1}\int_{-\omega_s/2}^{\omega_s/2} \{l_i\overline{e_r^2} + k_i\overline{e_r^2}H_i(\exp \mathrm{j}\omega T)H_i(\exp - \mathrm{j}\omega T)\}\prod_{j=i+1}^{M} H_j(\exp \mathrm{j}\omega T)H_j(\exp - \mathrm{j}\omega T)\,\mathrm{d}\omega +$$

$$+\frac{1}{\omega_s}\int_{-\omega_s/2}^{\omega_s/2}\{l_M\overline{e_r^2} + k_M\overline{e_r^2}H_M(\exp \mathrm{j}\omega T)\ H_M(\exp - \mathrm{j}\omega T)\}\,\mathrm{d}\omega. \tag{11}$$

For non-recursive filters, realized as in Fig. 3(d), equation (11) reduces to

$$C_{or} = N\overline{e_r^2} \tag{12}$$

where N is the number of coefficients less than one. In deriving C_{ob}, C_{oq} and C_{or} it was assumed that the only source of performance degradation is the rounding-off of the data and that the filter coefficients are represented exactly.

Because the three noise components are uncorrelated

$$\mathrm{CA} = \frac{C_i}{C_o} = \frac{C_i}{C_{ob}+C_{oq}+C_{or}}. \tag{13}$$

The ratio (S_o/S_i) is computed from

$$\left(\frac{S_o}{S_i}\right) = \frac{1}{\omega_s}\int_{-\omega_s/2}^{\omega_s/2} H(\exp \mathrm{j}\omega T)H(\exp - \mathrm{j}\omega T)\,\mathrm{d}\omega \tag{14}$$

and finally the IF is obtained from equations (8), (13) and (14). The tacit assumption made in the derivation of the IF is that the round-off noise remains the same with clutter or clutter plus signal and that there is no interaction between clutter and signal because of rounding.

The IF for the six filters was computed using numerical integration and a Gaussian clutter spectral density

$$S_c(\omega) = \frac{\sigma_c^2}{\sqrt{2\pi}\sigma_\omega}\exp\{-\omega^2/2\sigma_\omega^2\} \tag{15}$$

where $\sigma_c^2 = C_i$. The results are shown in Figs. 4 (a) to (f) as function of $\sigma_f T$ ($\sigma_f = \sigma_\omega/2\pi$) and the filter word length (sign and magnitude). For all the curves the input quantizer word length equals that of the filter and $\sigma_c = 0{\cdot}2$.

As should be expected, the effect of the round-off noise is to degrade the performance of the m.t.i. filter. For low $\sigma_f T$, the dominant factor in determining the IF is the round-off noise but, as $\sigma_f T$ increases, the significance of the breakthrough clutter increases and eventually it becomes the dominant factor in determining the IF. Another interesting characteristic is that high-order filters with coarse quantization do not have any advantage over lower-order filters with finer quantization. For example, the three- and four-pulse binomial filters have a crossover point at approximately 10–12 bit word length. For less than 10–12 bits the improvement in performance by using a four-pulse filter instead of a three-pulse one is very small. However, for word lengths longer than 12 bits the four-pulse filter has a better performance. The performance evaluation, as presented here, deals with a linear system from the antenna to the output of the filter and does not include the effect of any non-linearity such as saturation in i.f., the signal quantizer or the filter.

4 Performance Estimation of Digital M.T.I. Filters

In order to assess the validity of the assumptions of the round-off noise model and estimate the performance of the m.t.i. filters, the clutter process and the digital processor were simulated in a general-purpose digital computer.

The clutter process was considered as normal with a Gaussian spectral density (equation (15)).[8, 10] By assuming that the clutter is a normal process it was tacitly accepted that the system has low resolution. It has been found recently that for high resolution systems

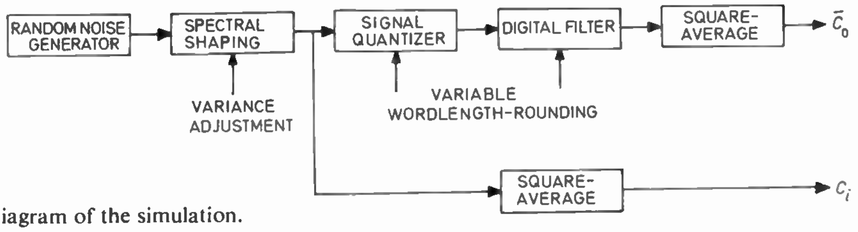


Fig. 5. Block diagram of the simulation.

the clutter is better represented by the log-normal distribution.[1,9] Nevertheless, the IF depends on the spectral density, not the probability density, and bearing in mind the difficulties in sampling a distribution, other than the Gaussian, with a specific spectral density, it is reasonable to use a Gaussian process as clutter. The details of the simulation are presented in Appendices 1 and 2, and a block diagram is shown in Fig. 5.

The IF estimates were obtained, as described in Section 3, by computing the ratio (S_0/S_i), estimating the CA and using equation (8). The results are shown in Figs. 4 (a) to (f), superimposed on the theoretical estimates. The CA estimates were based on 40 960 samples with $\sigma_c = 0{\cdot}2$. The 40 960 samples give 80 independent samples for a correlation coefficient 0·001 and $\sigma_f T = 0{\cdot}01$. The filter coefficients were realized using the maximum word length, 31 bits.

There is excellent agreement between the theoretically predicted and experimentally estimated IF for all non-recursive filters. For the recursive filters the agreement is partial. Comparing the IF for the two recursive filters it is evident that as the word length increases the experimental estimates converge to the theoretical ones, but not at the same rate; the convergence rate of the filter with the smaller fractional bandwidth is slower than that of the filter with the larger fractional bandwidth.

The difference between the theoretical and experimental estimates of IF for the recursive filters can be explained by re-examining the assumptions of the round-off noise model. For low values of $\sigma_f T$, the assumption that signal (in this case clutter) and round-off noise are uncorrelated is not satisfied because the signal is small and occupies the least significant part of the register; hence after rounding the error is an appreciable part of the register. The assumption that the error samples are uncorrelated is also not satisfied, because for low $\sigma_f T$ successive clutter samples are highly correlated and as a result the error samples are also correlated. Basically, the difference between the theoretical and experimental estimates demonstrates that the validity of the round-off noise model depends on the spectral composition of the signal and the word length. If the signal is within or near the filter passband the model works reasonably well, but for the signals outside the passband, where high levels of attenuation are sought, the model gives an optimistic expectation. For the non-recursive filters the situation is simpler because the round-off noise is not processed by the high-gain poles of the filter and the input signal is not attenuated in order to avoid overflow.

5 Conclusions

In this paper the performance of typical digital m.t.i. filters has been studied both theoretically and experimentally. The round-off noise model was introduced and discussed in some detail because of its importance in the theoretical performance evaluation. The theoretical estimates indicated that due to round-off noise an upper bound on the expected improvement factor exists. From the experimental results, it was found that for non-recursive filters the model represents the round-off process reasonably well. For the recursive filters the model proved successful with signals inside or near the passband, but not so successful with signals well outside the passband. This shows that the rounding process for short word length and small signal levels is highly non-linear and as a result the simple round-off model cannot represent it very accurately. The effects of saturation were not studied because, due to the feedback, it would be more satisfactory to study non-linear effects in the context of a particular design.

6 Acknowledgments

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8 Appendix 1: Simulation of the digital signal processor

The digital signal processor for the m.t.i. radar was simulated in a Honeywell DDP-516 digital computer. The processor consisted of a signal quantizer, a digital filter (recursive or non-recursive), detector (linear or quadratic), integrator (sub-optimal single or double loop), and threshold. The detector and integrator were not involved in the work reported here and consequently the discussion is limited to the quantizer and the digital filter.

The signal quantizer operates on a single precision floating point number (27-bit mantissa, 8-bit exponent) and produces a fixed point number between $(-1, 1-2^{-n})$ where $n; n = 1, 15$. The quantizer is uniform and saturates for $|\text{input}| \geqslant 1$. The digital filter (recursive and non-recursive) is simulated in fixed point 2's complement saturation arithmetic with variable word length (maximum 31 bits) and rounding. The recursive filter is simulated by connecting in parallel or cascade the basic second (first) order section in canonic form. The non-recursive filter is simulated with a separate sub-routine which realizes the structure of Fig. 3(d). The two-, three- and four-pulse cancellers were simulated using the recursive filter sub-routine but setting the feedback coefficients to zero. The quantizer and filter sub-routines were written in assembly language (DAP-16) and because of that no further information is given here. In spite of using low-level language for the fixed point simulation, high-level language (FORTRAN IV) was used for the input-output operations.

9 Appendix 2: Simulation of the clutter process

The main problem in the simulation of the clutter process for clutter attenuation measurements is the representation of the spectrum extremes (tails).

The general idea behind the sampling of a normal process with specific spectral density is to sample a white normal process and introduce spectral shaping by operating on the process with a linear operator (filter). The operator can be recursive or non-recursive and for the work reported here a non-recursive operator was used which simulated a scanning antenna.

It is well known that a scanning antenna broadens the spectral lines corresponding to non-moving objects, with the result that they appear as clutter sources. This property of the scanning antenna can be used as the operator to shape a white normal process because the processor has no way of distinguishing between the spectral spread due to scanning and one due to internal clutter fluctuations.

The spread caused by the antenna motion during scanning can be expressed in terms of an equivalent spectral deviation. For a Gaussian beam it is given by Ref. 11 as

$$\sigma_f = \frac{0{\cdot}265}{NT} \tag{16}$$

where N is the number of pulses in the beamwidth (-3 dB points). For the one-way Gaussian beam the voltage gain pattern is

$$g(\theta) = \exp\{-\theta^2/2\theta_1^2\} \tag{17}$$

where θ is the angle measured with respect to the beam centre and θ_1 the standard deviation. With a spectral density given by (15) the voltage is $[S_c(\omega)]^{\frac{1}{2}}$ and the time function $g(t)$ is the inverse Fourier transform of $[S_c(\omega)]^{\frac{1}{2}}$

$$g(t) = \sigma_c(2\pi)^{\frac{1}{4}}(2\sigma_\omega)^{\frac{1}{2}} \exp\left\{-\frac{t^2(\sqrt{2}\sigma_\omega)^2}{2}\right\}. \tag{18}$$

The deviation of the time function is $1/\sqrt{2}\sigma_\omega$ and as a result

$$\theta_1 = \frac{1}{\sqrt{2}\sigma_\omega} = \frac{NT}{2\pi\sqrt{2}\,0{\cdot}265} \tag{19}$$

using (16).

Thus, to generate one clutter sample, k returns from elementary scatterers are weighted by the antenna pattern (equation (17)) and then added. For simplicity, it was assumed that all scatterers give equal amplitude returns but the phase is uniform over $(0, 2\pi)$. Then the k-th complex clutter sample is given by

$$C_k = \sum_{j=1}^{k} \exp\left\{\frac{(90-j)^2}{2\theta_1^2}\right\} \exp\{\mathrm{j}2\pi r_{j+k}\} \tag{20}$$

where $T = 1$, the scanning rate is unity and $k = 180$. The rotation of the antenna is accomplished by dropping one and acquiring a new random number in equation (20). It is clear that if the sequence produced by (20) is sampled with a skipping scheme then the clutter spectral deviation σ_f, is multiplied by the appropriate factor. For example, if one sample is skipped then the product $\sigma_f T$ is doubled. The process, generated by (20) for various N, was tested by estimating the CA of a seven-pulse non-recursive filter simulated with double-precision floating point arithmetic.

Manuscript first received by the Institution on 21st January 1976 and in final form on 13th April 1976 (Paper No. 1751/AMMS 77).

Letters

From: **G. M. Smith,** B.E.M., C.Eng., M.I.E.R.E.
D. C. Price, B.Sc., A.R.C.S.

'Reliability in Avionic Systems'

The recent paper by Mr. D. C. Price* in which he reviews the techniques currently used in the design of aircraft flight control systems and the line that future developments may take, does not appear to consider all aspects of the problem. The need for increased performance requires a more complex solution with a higher reliability. The required performance can be achieved by the use of a digital system of adequate reliability and pulse pick-up can be eliminated by an optical link, leaving only the common failure hazards and the unpredictible to be contained.

Unfortunately, there would seem to be a penalty for each part of the proposed solution. Whilst the reliability of the digital system components may be adequate, there is a new requirement to establish the integrity of the programmes used. Similarly, the proposed use of an optical link raises a requirement to demonstrate its mechanical and electrical reliability—whilst the use of a special local environment to provide increased component reliability requires the reliability of the refrigeration plant to be established in turn.

With systems of this nature, safety must be assessed in terms of the probability that all possible causes of loss of the required performance (including spilt coffee!) have been recognized and effectively dealt with. The defence afforded by both the system designer and those responsible for certification, since it is based on experience, is neccessarily limited where such a jump in the application of technology takes place.

It could therefore be concluded that in order to make an effective assessment of safety, the system must first be fitted to a fleet of aircraft with a reversionary manual flying capability and operated over a number of years leaving the change of airframe and installation as the only remaining uncertainties.

G. M. Smith

6 Balmoral Road,
Salisbury, Wilts.

12th October 1976

Mr. Smith is quite right to point out that solutions of stringent problems by new technology create a requirement to establish a degree of confidence in such new techniques which is high enough to meet the exacting standards demanded. Because of the difficulty of foreseeing all possible causes of loss of performance, jumps in technology are limited. Evolutionary steps are necessary, backed by exhaustive appraisal of new techniques in both hardware and software, and their gradual introduction by teams of engineers of long experience in the art of high-integrity system design. May I assure Mr. Smith that in parallel with the flight experience now being obtained in digital flight control systems for the *Tornado* and the *YC*-14, very detailed practical examination of the engineering problems involved in the adoption of 'safe software' and optical data transmission are being carried out in close consultation with our customers. Because of the problems of the use of refrigeration systems in aircraft and the power load such systems would present, consideration of improved cooling techniques is going hand in hand with an examination of methods for reducing the power dissipation of computing circuitry, e.g. through the use of lower speed microprocessors operating in time parallelism.

For combat aircraft, the use of mechanical reversion, to which I think Mr. Smith is referring in his final paragraph, presents a fundamental problem. If we are to obtain the full advantages of manoeuvre potential by electronic stabilization, the aircraft may well have to use flight regimes where unaided manual flying is impossible. Hence the time at risk during which the aircraft is wholly dependent on electronics will increase. Experience now being built up, where the use of manual reversion is becoming very rare indeed, is a positive step towards its safe omission in future combat aircraft. Reversion capacity would then be provided within the electrical-hydraulic control system ensuring graceful degradation of performance.

D. C. Price

Technical Manager,
Marconi-Elliott Avionic Systems Limited,
Airport Works, Rochester, Kent ME1 2XX

1st November 1976

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* 'Failure survival techniques for avionic systems', *The Radio and Electronic Engineer*, **46**, No. 7, pp. 343–9, July 1976.

Ariel V Working Well Two Years after Launch

Launched on 15th October 1974, *Ariel V*, the British-built scientific satellite has surpassed all expectations by continuing to send back much valuable information about X-ray sources in deep space. At the present rate of propane gas consumption the satellite is expected to last a further year before its useful life comes to an end.

Ariel V was launched into a near-equatorial 550 km orbit from the Italian San Marco platform situated some 3 miles off the Kenya coast using as launch vehicle, a four-stage solid fuel *Scout* rocket, provided by the US National Aeronautics and Space Administration. Ground control is carried out from the Science Research Council's Appleton Laboratory at Slough, Bucks.

The satellite carries six cosmic X-ray experiments, five of them British and one American. The results obtained have thrown light on both pulsars (sources whose intensity varies repetitively with periods ranging from minutes to tens of milliseconds) and transient sources (which flare up to a high intensity and decay over several weeks). However, the most sensational observations have been those concerning so-called X-ray 'bursting sources'. These stars emit bursts of X-ray in a repetitive non-periodic manner and their existence was not previously known.

A brief description of the satellite and the experiments was published in the April 1975 issue of *The Radio and Electronic Engineer*. Known before launch as *UK*-5, *Ariel V* was built at Portsmouth by Marconi Space and Defence Systems Limited, under a £2.5M contract awarded by the Ministry of Defence on behalf of the Science Research Council.

UDC 621.396.62.029.62: 621.396.931

Design and characterization of a phase-locked v.h.f. land mobile receiver

J. P. McGEEHAN, B.Eng., Ph.D.*

Based on a paper presented at the IERE Conference on Civil Land Mobile Radio held at Teddington on 18th to 20th November 1975.

SUMMARY

A 'long loop' v.h.f. phase-locked a.m. receiver with synchronous detector is described. The effect of the narrow-band Chebyshev i.f. filter on receiver lock-in range, hold-in range and capture time is investigated as a function of carrier level, −60 to −120 dBV, for a range of low-pass filter time-constants. The transient response of the Chebyshev filter and instantaneous limiting in the i.f. strip are shown to play a crucial role in determining the time which the receiver takes to lock onto the carrier. The receiver is not significantly more complex or expensive than sets currently in use and has the advantage that it may also be used to demodulate double-sideband diminished carrier (d.s.b.d.c.) signals.

1 Introduction

In recent years, the almost insatiable demand for channel allocation at v.h.f. in the land mobile radio service has led to a considerable reduction in channel bandwidth, at present 12·5 kHz in the United Kingdom. At the same time there is a good deal of interest in applying other services simultaneously to speech channels, such as facsimile picture transmission and overlay paging. This does of course mean that the speech spectrum has to be limited in order to accommodate the additional service with the result that any receiver/transmitter drift will cause some loss of intelligibility. An obvious way of overcoming this problem is to use a receiver in which the locally generated carrier is phase-locked onto the carrier of the received a.m. signal, i.e. by using a phase-locked loop. The application of phase-locked loop techniques to receivers is not new, indeed NASA has used f.m. phase-locked tracking receivers in space exploration for some considerable time.[1] However, despite this work and the great amount of theoretical and experimental work published on basic loop configurations (reviewed extensively by Gardner,[2] Stiffler[3] and Lindsey[4]) very little information to the author's knowledge has been published on the application of phase-locked techniques to a.m. systems in the mobile environment. The advantages of such a receiver are immediately apparent; frequency variations due to either oscillator drift or Doppler shift can be tracked automatically, an important design principle in view of the general trend towards higher frequencies and narrower channel bandwidths.

It is the intention of this paper to describe the design and development of a phase-locked receiver with synchronous detector, suitable for use with amplitude modulation. Besides referring to the normal loop parameters of lock-in and hold-in range, particular attention will be paid to the transient response of the receiver during carrier acquisition. In this context, the effect of impulsive noise, the primary source of noise at v.h.f., on receiver performance will also be evaluated. These aspects of the receiver's characteristics are of particular significance during the reception of data.

It is clear that in developing a suitable phase-locked receiver, designs which are significantly more expensive or complex than the sets currently in use are not acceptable.

2 Design of A.M. Phase-locked Receiver

Mobile v.h.f. radio receivers in common usage are of the superheterodyne type shown in Fig. 1. This type of set is relatively simple and inexpensive and easy to maintain. A phase-locked receiver which is capable of demodulating an a.m. d.s.b.d.c. signal is shown in the block diagram of Fig. 2. It will be noted that this receiver does not differ radically from that shown in Fig. 1. In fact, the phase-locked receiver described here was constructed by modifying an existing piece of commercial equipment, namely the S.T.C. type AM681. Before discussing these modifications let us first consider the principles of operation of this phase-locked design.

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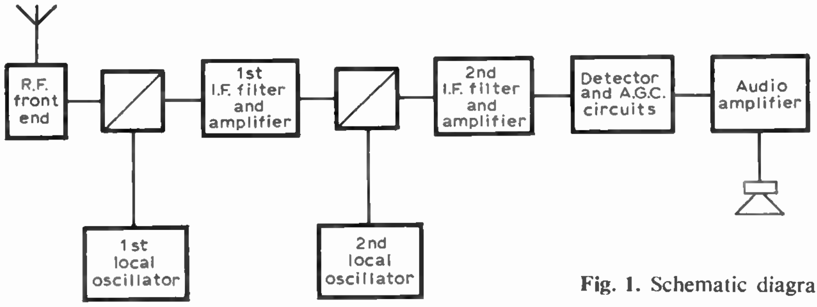


Fig. 1. Schematic diagram of a simple two-stage superheterodyne receiver.

The received signal, after passing through the front-end of the receiver, is mixed with the output from the crystal-controlled oscillator to produce an intermediate frequency of 10·7 MHz. In the i.f. strip the signal undergoes filtering and automatic-gain-controlled amplification before being passed into a phase-sensitive detector, PSD1, which is also fed with a 10·7 MHz reference. A low-pass filter, often called the loop filter, selects the d.c. component from the output of PSD1 which, after amplification, is used to 'pull' the voltage-controlled crystal oscillator (v.c.x.o.) into lock, i.e., the i.f. from the first mixer is equal to, but in phase quadrature with, the reference 10·7 MHz signal. Any phase or frequency variations of the received signal as a result of Doppler shift, or crystal oscillator drift of either the transmitter or receiver are automatically tracked out by the loop. The required modulation is then extracted by means of a synchronous demodulator. Here, the i.f. signal and a 90° phase-shifted version of the reference oscillator output are fed into a second phase-sensitive detector, PSD2. By low-pass filtering the output from PSD2 the desired audio-frequency modulation is obtained. This type of demodulator has several advantages over the conventional envelope detector. It has superior performance under poor signal-to-noise conditions[5] and may be used to demodulate both a.m. and d.s.b.d.c. types of modulation.

Extensive modifications were made to the i.f., a.g.c. and detector circuits of the AM681 set, but no alterations were made to the r.f. and audio stages. A block diagram of the complete receiver is shown in Fig. 3. The 10·7 MHz i.f. strip was modified by the insertion of a 12·5 kHz channelling filter (Chebyshev 6th-order band-pass filter) and by the insertion at the end of the i.f. of a Plessey SL612C i.c. amplifier so as to compensate for the decrease in gain brought about by the removal of the 450 kHz i.f. strip of the AM681.

For the case of the detector circuits, the original envelope detector was replaced for the reasons given above by the synchronous demodulator shown in Fig. 3. The principle of operation of this circuit has already been given although the following comments need to be made for a complete understanding. PSD1, which is fed with the i.f. signal and the 10·7 MHz reference signal directly, has an output which can easily be shown to be proportional to sin θ, where θ is the phase angle between the two signals. When the loop is in lock the angle θ is equal to zero so that the error signal sin θ is also equal to zero. If now for some reason the input frequency were to change slightly, the error signal is no longer equal to zero and is used to pull the v.c.x.o. until the frequency difference between the signals is again zero. The second phase-sensitive detector, PSD2, which is again fed with the same two synchronized signals, but with the 10·7 MHz reference oscillator phase shifted by 90° has an output which can be shown to be:

$$v_0 = \frac{k_D v_S v_R}{2}\cos(\theta_R - \theta_S) + \text{2nd harmonic components}$$

where k_D = constant of proportionality for PSD2
v_S = signal voltage from i.f.
v_R = reference oscillator voltage level (constant)
θ_R = phase of reference oscillator voltage
θ_S = phase of i.f. signal voltage.

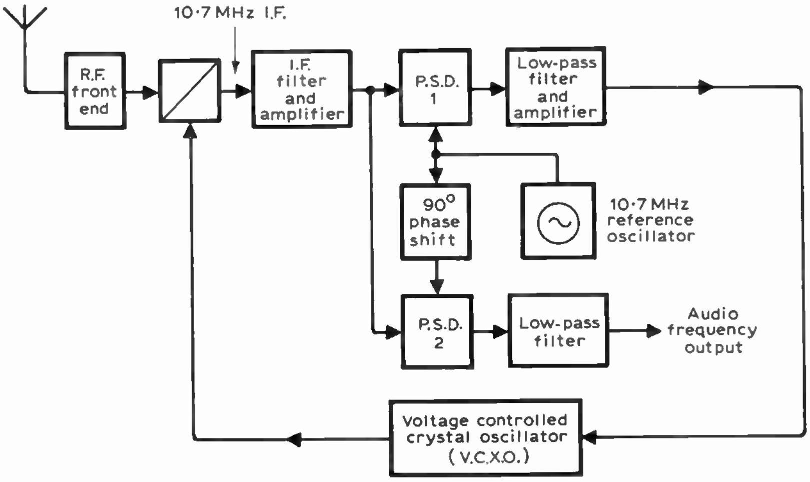


Fig. 2. Schematic diagram of a phase-locked receiver.

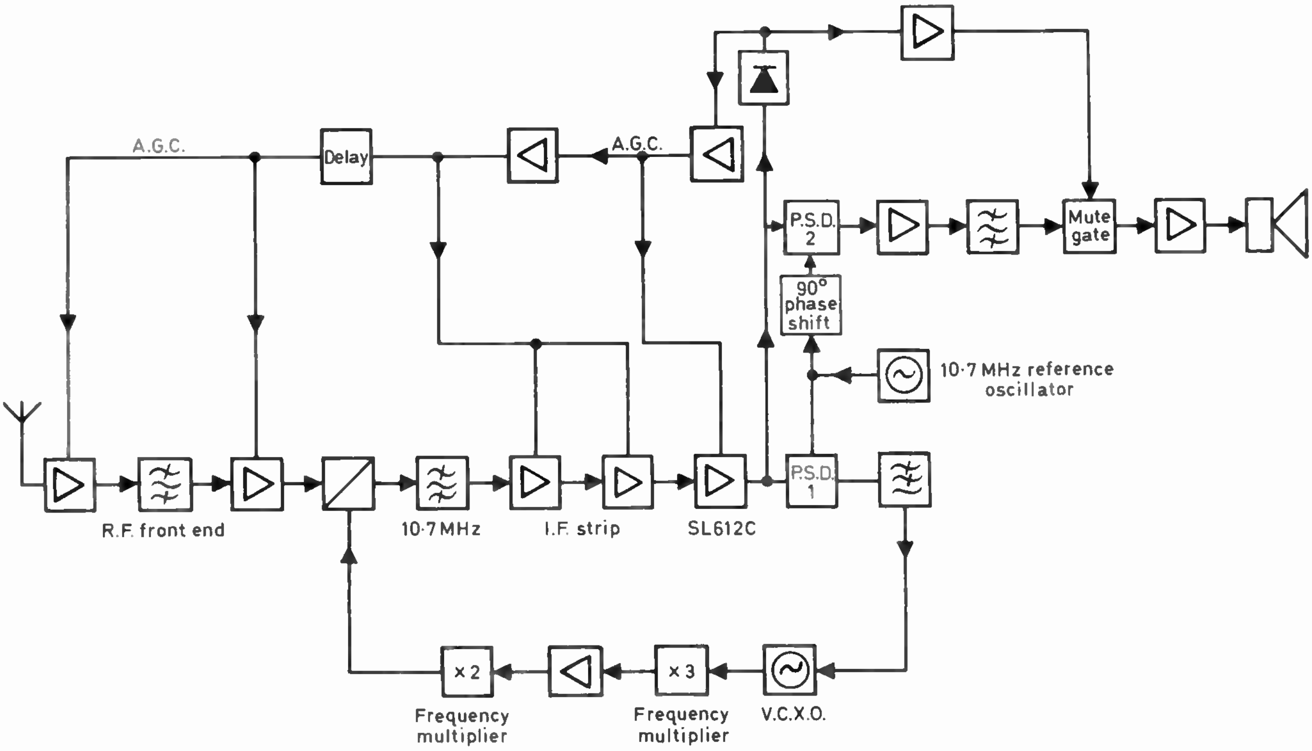


Fig. 3. Block diagram of modified AM681 phase-locked receiver.

Again when the loop is in lock, or phase synchronization, $\theta_R = \theta_S$ and the output of PSD2 is proportional to the required signal voltage. Second-order harmonic components produced in PSD2 are removed by means of a low-pass filter. The Texas Instruments SN76514 double balanced modulator i.c. was used for both PSD1 and PSD2. In the series of measurements presented here the SN76514 i.c.s were used in the single-ended output configuration and the loop filter was a simple lead-lag network shown in Fig. 4. This was primarily done for convenience since it enabled the time-constants of the loop filter τ_1 and τ_2 and the d.c. gain following the filter to be varied easily and independently. This arrangement has now been replaced with an active filter which is fed differentially from the SN76514. This mode of operation of the SN76514 is particularly advantageous in that it balances out the temperature drift of the d.c. output voltage level.

Incoherent a.g.c. was used throughout the receiver.

3 Receiver Characterization

3.1 SINAD Measurements for Receiver

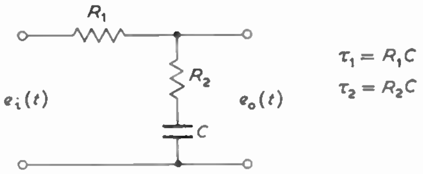
Of the techniques available for measuring receiver sensitivity[6] the SINAD method is now usually acknowledged as being the most meaningful. It has the advantage of evaluating the performance of the entire receiver, including the audio section. SINAD is defined as the ratio:

$$\frac{\text{measured signal + noise and distortion}}{\text{noise and distortion}}$$

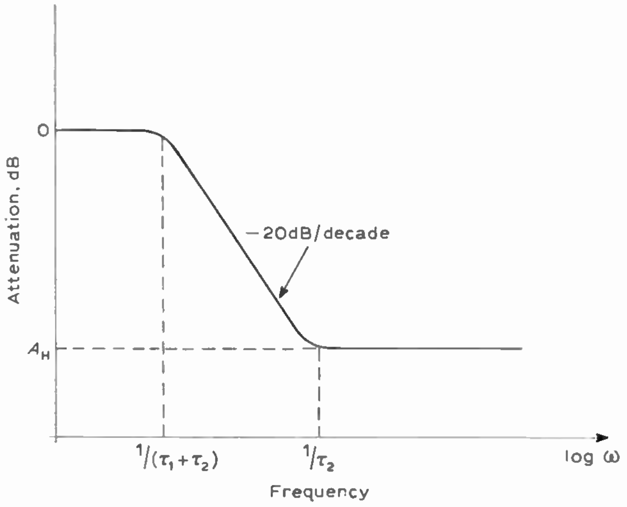
at the rated audio power level and is usually expressed in dB. The ratio provides an unambiguous measure of the receiver's ability to receive a modulating signal.

To measure sensitivity by the SINAD method, an a.m. signal-generator is connected to the receiver input terminals and an audio-distortion analyser with tunable notch filter connected to the audio output terminals. The modulating signal, a 1 kHz tone, is set to modulate the carrier to a depth of 50% and the receiver volume control adjusted to deliver the rated audio output power.

Fig. 4.



(a) Lead-lag network.



(b) Amplitude response of lead-lag network.

For each level of carrier input, the distortion analyser is first switched to read the total audio output—1 kHz signal plus noise and distortion. The frequency and null controls on the analyser are then adjusted to filter out the 1 kHz tone, the distortion meter reading the remaining audio output noise and distortion. By repeating these measurements for various carrier levels, the entire SINAD performance curve for the receiver can be obtained In production testing, however, the above measurement procedure is simplified to stating the SINAD figure at 1 μV input.

The SINAD curve for the phase-locked receiver described in this paper is shown in Fig. 5. With an input of 1 μV to the receiver (corresponding to −120 dBV) a SINAD figure of 11 dB was measured. For higher levels of input signal (> −80 dBV) a maximum figure of 38 dB is attained.

3.2 Effect of Impulsive Noise on Phase-locked Receiver Performance

As mentioned previously the effect of impulsive noise on receiver performance is of primary importance at v.h.f. Since this type of noise is generated by car ignition systems it is a necessary condition that the operation of the receiver is not affected adversely, i.e. it is important that the impulsive noise spike does not throw the loop out of lock. To simulate the effect of impulsive noise, an electro-mechanical relay was inserted into the receiver's input and the impulsive noise generated by the make and break of the relay's contacts. Contact noise frequencies chosen were representative of normal engine speeds, i.e., 4000, 2600 and 1000 rev/min. The impulsive noise spikes were typically 400 mV in amplitude and of 1·5 ms duration. The receiver was tested over a wide range of d.c. gains and low-pass filter time-constants. For carrier levels of between −60 dBV and −120 dBV loss of lock was never observed. SINAD measurements were also made using a 50% a.m. carrier (1 kHz test tone) and were only slightly different from those measured under impulsive-noise-free conditions for signal levels above −110 dBV. Below this level the measured SINAD figures fell off rapidly and were lower at the higher engine speeds.

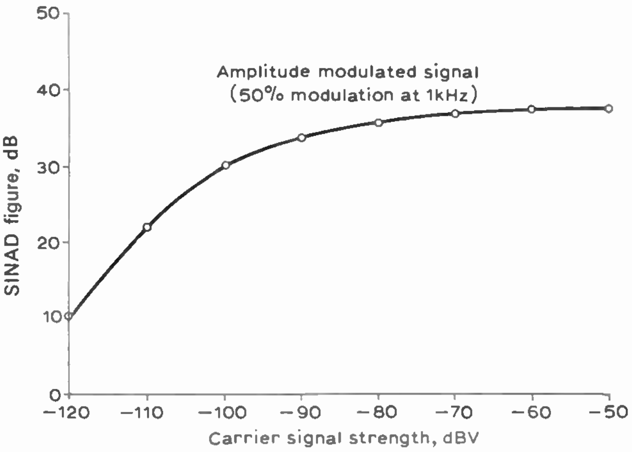


Fig. 5. SINAD curve for receiver as a function of carrier level.

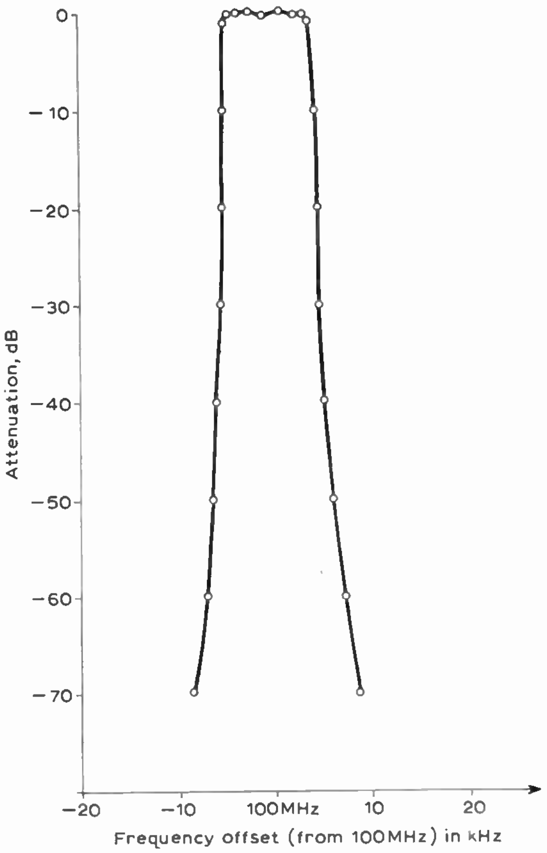


Fig. 6. Frequency response of receiver.

3.3 Receiver Selectivity

A selectivity curve for the receiver is shown in Fig. 6. At ±8 kHz deviation from the 100 MHz carrier frequency the receiver exhibits 70 dB rejection to adjacent channels.

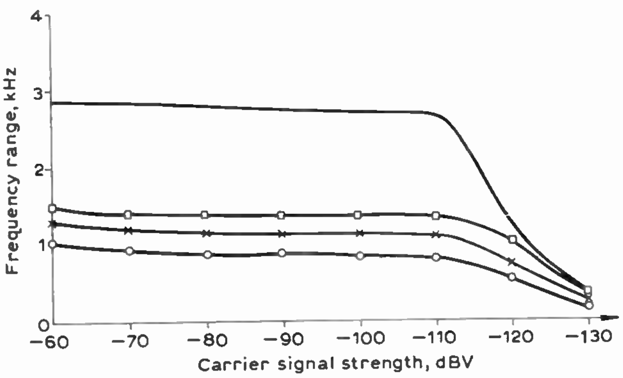
Spurious responses are determined by the front end of the AM681 receiver and are not affected by use of a p.l.l.

3.4 Measurement of Lock-in and Hold-in Ranges

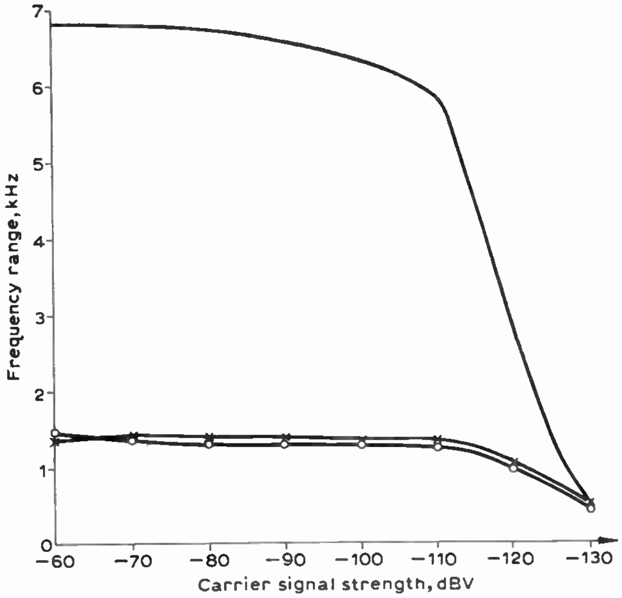
In order to obtain a rapid and overall assessment of the lock-in and hold-in performances of the receiver as a function of input signal strength, these parameters were measured over a wide range of low-pass filter time-constants and d.c. gains. The unmodulated carrier was obtained from a Schumandl 100 MHz frequency synthesizer and the results of these measurements are given in Figs. 7(a) and (b). These results represent the lock-in and hold-in range of the 'long loop' receiver with d.c. gains of 47 and 100 respectively. The lead-lag filter components were chosen such that the first break point, corresponding to an attenuation, A_L, and a frequency, $1/2\pi(\tau_1+\tau_2)$ Hz, occurs at approximately the same value of frequency in all cases and that the high-frequency turning point, $1/2\pi\tau_2$ Hz, occurs over a range of frequencies at a gain

$$A_H = 20 \log_{10} \frac{\tau_2}{\tau_1+\tau_2} \text{ dB.}$$

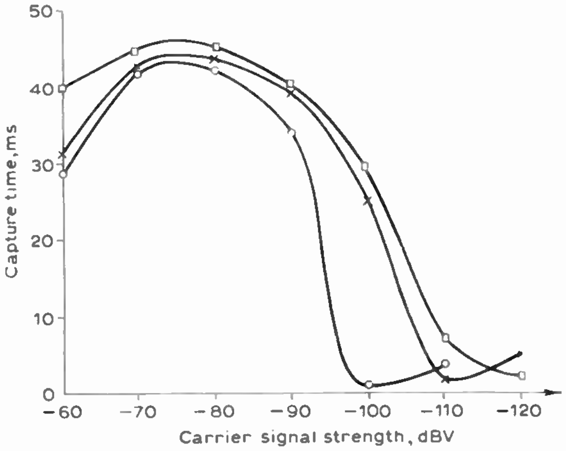
Consider first the results shown in Fig. 7(a). As τ_2 is increased, the lock-in range of the receiver increases,



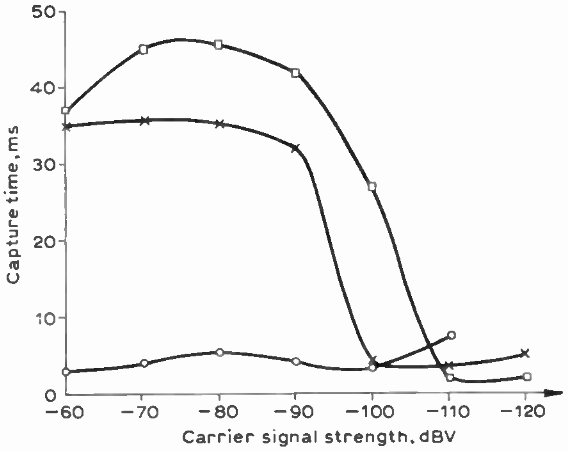
(a) Hold-in range and lock-in range as a function of carrier level, d.c. gain = 47.



(b) Hold-in range and lock-in range as a function of carrier level, d.c. gain = 100.



(c) Capture time as a function of carrier level, d.c. gain = 47.



(d) Capture time as a function of carrier level, d.c. gain = 22.

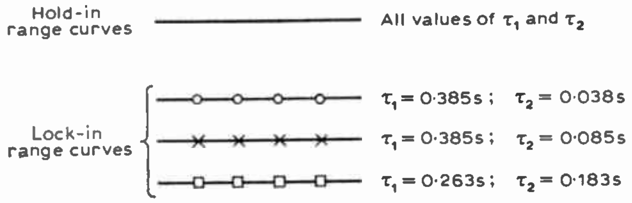


Fig. 7.

although not by the amount expected. The lock-in range for a loop employing a passive filter is given by[2]:

$$\Delta\omega_L = \frac{K\tau_2}{\tau_1+\tau_2}, \text{ where } K \text{ is the loop gain,}$$

and one would therefore expect a proportional increase in $\Delta\omega_L$ as τ_2 increases, the sum$(\tau_1+\tau_2)$ being held approximately constant. This saturation effect is shown more explicitly in Fig. 7(b) where a maximum of 1·5 kHz is recorded for all values of τ_2 barring $\tau_2 = 0{\cdot}18$ seconds. At this particular value of τ_2 the loop oscillates at a frequency of 830 Hz. This instability at high loop gain is not entirely unexpected. Gardner[2] has discussed in some detail the effect of narrow-band i.f. filter on loop stability and on the possibility of false-lock positions. No false-locking positions were observed in this series of measurements. It is apparent that some element in the loop is bringing about this saturation or limiting value in the lock-in range. Now Viterbi[7] has shown mathematically that the mixer band-pass filter arrangement can be replaced by a low-pass filter equivalent. Consequently, it would appear that the narrow-band Chebyshev filter is the limiting low-pass filter in the loop. As expected, the hold-in ranges measured were not affected by the low-pass filter time-constants, being solely determined by the loop gain. The fall in lock-in and hold-in ranges at input signals less than about −110 dBV is due to the fact that the receiver a.g.c. cannot maintain a constant input to the loop p.s.d. below this level.

3.5 Signal Acquisition Study

In land mobile radio the time required for the receiver to lock onto the carrier is quite often of the utmost importance. This is particularly so for data communication receivers and polling receivers. Gardner[2] and

Lindsey[4] have reviewed the considerable amount of work that has been carried out in p.l.l. acquisition although it must be stated that most of this work has concentrated on basic second-order loops and f.m. receivers. The phase-locked receiver described in this paper is of course considerably more complex. Besides having a narrow-band i.f. filter in the loop it has three stages of a.g.c. as shown in Fig. 3. One stage is applied to the r.f. front end whilst the remaining two stages are applied to amplifiers in the i.f. strip. The question which must therefore be asked is what effect, if any, have the i.f. filter and the a.g.c. got on the transient response of the loop?

Before describing the measurements taken it is first necessary to define precisely what we mean by acquisition or capture time. Here capture time will be defined as the time taken for the phase-sensitive detector to give a d.c. output. Unfortunately, this parameter is statistical in nature, due to the random phase relationship of the p.s.d. signals, so that we must therefore define some mean or average capture time. In the measurements presented here, carrier capture times were measured one hundred times and the mean value taken. The pulsed carrier signal was obtained from a HP 8640B signal generator and the capture transient at the output of the p.s.d. was observed on a Tektronix 485 oscilloscope with delay-expand facilities. Figures 7(c) and (d) show the effect of the input carrier strength on capture time using the same lead-lag filter time constants as in the previous set of measurements.

With a relatively low value of d.c. gain, i.e. 22, and with a high-frequency attenuation factor, A_H, of $-20{\cdot}8$ dB an approximately constant capture time of 4 ms is observed. However, by decreasing the high-frequency attenuation factor of the lead-lag filter and keeping the d.c. gain constant at 22, the capture time is seen to increase rapidly above an input signal strength of -105 dBV. Using a high-frequency attenuation factor of $-7{\cdot}6$ dB gives rise to a peak capture time of about 45 ms. Extreme care was taken in making these measurements to ensure that the input frequency of 100 MHz was always at the centre frequency of the phase-locked loop. By increasing the d.c. gain to 47, the rapid increase in acquisition time is observed for all values of low-pass filter time-constants. Again, as for the previous set of results, there is a definite threshold above which capture time increases rapidly. On comparing these curves more closely it is noteworthy that the threshold onset occurs at progressively lower input carrier strengths as the lead-lag filter high-frequency attenuation constant, A_H, is also decreased.

It is quite apparent from these results that the input signal strength, the d.c. gain and the high-frequency attenuation factor, A_H, of the low-pass filter are all contributory factors in bringing about this phenomenal increase in capture time.

At first it was felt that a possible factor in this phenomenon was the effect of changing a.g.c. voltage on the gain/phase relationship of the receiver by the following reasoning: prior to the detection of a carrier by the receiver, the a.g.c. voltages are such as to allow maximum gain through the receiver, the muting circuitry keeping the set quiet. When the receiver first sees the carrier, the a.g.c. voltages then change to a magnitude appropriate to the particular input signal level. In doing so the gain of the i.f. stages change and possibly their phase. The phase-locked receiver, which has to chase this changing phase, takes consequently a longer time to lock. By now inserting an unmodulated carrier of known amplitude and by fixing the a.g.c. voltages in turn from external d.c. supplies it was possible to identify the SL612C i.c. as the amplifier leading to the increased capture time. However, on measuring the phase change across this amplifier with a vector voltmeter, a negligible change in phase was recorded, thus indicating that the original hypothesis was incorrect.

On reassessing this information two important factors stand out:

(a) the i.f. amplifier (SL612C), which predominantly affects the capture-time, is at the end of the i.f. strip, and

(b) the rise-time of the a.g.c. voltages under normal operation is very long, being some 30–50 ms.

This means that when the receiver is subjected to an unmodulated carrier, virtually a step function, the a.g.c. voltages change far too slowly to lower the receiver gain thus allowing the high-gain amplifier at the end of the i.f. strip to saturate. On investigating this in much greater detail experimentally, the rapid increase in capture time was observed whenever the SL612C was limiting and provided the appropriate values of loop gain, etc. were being used, the limiting condition occurred when the input to the SL612C exceeded 25 mV, corresponding to a receiver input of about -105 dBV. Capture times were then measured under limiting and non-limiting conditions for a wide range of input signal strengths. In all cases, the receiver locked extremely rapidly (<2 ms) when the a.g.c. voltages were prefixed at levels appropriate to the input signal strength. When the receiver was operated without any a.g.c. acting at all, the capture times measured were only slightly worse than those measured under normal a.g.c. operation!

In taking these measurements it was noted that the i.f. filter caused the pulsed carrier to be severely modulated by a ringing waveform (i.e. the impulse response of filter). Now in a recent publication Blanchard[8] has shown that the presence of an unwanted signal at the input of a basic 2nd-order p.l.l. can lead, under certain conditions, to extremely long lock-in times. It is felt that the asymmetrical sets of sidebands produced in the limiting SL612C by the ringing modulation are giving rise to a similar effect. In the light of this hypothesis it is interesting to reconsider the results obtained.

The capture process is strongly dependent on both the d.c. gain used and the lead-lag filter time-constants, i.e. the filters differ basically in their high-frequency attenuation factor, all other factors being approximately the same. This is interesting since it is these loop parameters which determine the relative magnitude of the sidetones, the sidetones then modulating the v.c.x.o. to help produce the d.c. component which will eventually pull the loop into lock. It is believed here that the unequal sidebands caused by the SL612C exert unequal pulling forces on the v.c.x.o. and therefore tend to pull the oscillator off carrier. This will obviously lead to an increased capture time. It is clear that further investigation is required so as to establish the exact mechanism causing the increased lock-in time.

4 Conclusions

A phase-locked a.m. receiver for use in the land mobile radio service has been described. The receiver has a maximum lock-in range of 1·5 kHz and simulated ignition noise had no effect on loop lock over a wide range of operating conditions. The effects of the narrowband i.f. filter and loop parameters on receiver performance have been investigated and have been shown to effect quite considerably the lock-in range and acquisition time of the loop. In order to obtain the maximum lock-in range of 1·5 kHz a capture time of approximately 45 ms has to be tolerated. Although this time is acceptable for speech communication it is prohibitively long in data systems. Further investigations are being carried out to determine the exact mechanism causing the extension in lock-in time.

5 Acknowledgments

The author is grateful to Mr. D. Weston for his assistance with the many measurements taken and to Professor W. Gosling for helpful discussions on various aspects of this work.

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IERE News and Commentary

The Professional Engineer

In response to frequent inquiries by members, the description of the 'Professional Engineer' which was agreed at a meeting of EUSEC (Conference of the Engineering Societies of Western Europe and the United States of America) some years ago and which is regarded as an authoritative definition which the Institution follows is reproduced below.

'A professional engineer is competent by virtue of his fundamental education and training to apply the scientific method and outlook to the analysis and solution of engineering problems. He is able to assume personal responsibility for the development and application of engineering science and knowledge, notably in research, designing, construction, manufacturing, superintending, managing and in the education of the engineer. His work is predominantly intellectual and varied, and not of a routine mental or physical character. It requires the exercise of original thought and judgement and the ability to supervise the technical and administrative work of others.

'His education will have been such as to make him capable of closely and continuously following progress in his branch of engineering science by consulting newly published work on a worldwide basis, assimilating such information and applying it independently. He is thus placed in a position to make contributions to the development of engineering science or its applications.

'His education and training will have been such that he will have acquired a broad and general appreciation of the engineering sciences as well as a thorough insight into the special features of his own branch. In due time he will be able to give authoritative technical advice, and to assume responsibility for the direction of important tasks in his branch.'

New Executive Secretary of the Royal Society

The Council of the Royal Society has appointed Dr. R. W. J. Keay, O.B.E., as Executive Secretary in succession to the late Sir David Martin, C.B.E., who died suddenly on 16th December.

Dr. Keay has served the Society as Deputy Executive Secretary since 1962, his responsibilities being especially concerned with the Society's international relations. After graduating from Oxford, he joined the Colonial Forestry Service in 1942 and was Director of the Federal Department of Forest Research in Nigeria from 1960 to 1962.

Index to Volume 46

The Index for the 1976 volume of *The Radio and Electronic Engineer* (comprising title page and principal contents list, subject index and index of persons) is being published and copies will be sent automatically to all subscribers to the Journal with the March issue. Members wishing to obtain the Index for binding with their Journals or for reference will be sent a copy free of charge on application to the Publications Sales Department, IERE, 9 Bedford Square, London WC1B 3RG, by letter, or telephone 01-637 2771, extension 19.

Indexes are included in all bound volumes of the Journal and members who propose to send their 1976 issues for binding need not apply for a copy of the Index beforehand.

MacRobert Award withheld for 1976

The MacRobert Award Evaluation Committee, which assesses entries for Great Britain's major engineering award, has announced that no prize will be given for 1976. The Award, consisting of £25,000 and a gold medal, is intended to be made annually by the Council of Engineering Institutions on behalf of the MacRobert Trusts. It is presented in recognition of an outstanding contribution by way of innovation in engineering or the physical technologies or in the application of the physical sciences which has enhanced or will enhance the prestige and prosperity of the United Kingdom.

The MacRobert Trusts have made many contributions to agricultural research, education, medical research, youth and Services welfare work. In founding the MacRobert Award for engineering and technology the Trustees wished to honour individuals who contributed to the economic well-being of the United Kingdom.

A spokesman for the Committee—whose chairman is Lord Hinton of Bankside, CEI's President—said that in the present year the Committee had been unable to find a topic which matched the standards of the winners in earlier years. There had been many first-class developments to existing equipment as well as many marketing successes. What the Evaluation Committee had been unable to find was a real technological breakthrough, coupled with potential financial success. It had reluctantly concluded, therefore, that this important award should not be made in 1976.

The MacRobert Award was instituted in 1968 by the MacRobert Trusts and first awarded in 1969; this is the first time that the Award has been withheld. The rules allow the award to be made to any individual or independent team, or a team working for a firm, organization or laboratory. Last year, for only the second time in its history, the Award was split between two separate teams (five in each)—one from British Railways Board and one from Westland Helicopters. In 1972 Mr. Godfrey Hounsfield and EMI Ltd. won the Award for the invention of new X-ray techniques used as the basis of a new computerized system for diagnosing brain disease. This was the first time the Award had been won by a single individual.

It is the earnest wish of the Evaluation Committee that the 1977 Award should attract entries of high standard, comparable with those for which the Award was made in the years 1969 to 1975. There are almost certainly recent technological developments in electronics which merit consideration and the attention of IERE members is therefore particularly drawn to this prestigious honour. Rules and conditions of the Award for which submissions are to be made to CEI by 30th April for 1977 can be obtained from: The MacRobert Award Office, CEI, 2 Little Smith Street, London SW1 3DL (Telephone: 01-799 3912).

Corrections

The following corrections should be made to the paper 'Transformation for modifying the lumped-element equivalent circuit for metal-encapsulated crystals in unbalanced semi-lattice filters' in the December 1976 issue (Vol. 46, No. 12).

Page 615, Fig. 2(a): The value of the right-hand capacitor of the T equivalent circuit should be preceded by a minus sign.

Fig. 2(b): The value of the series capacitor in the right-hand equivalent circuit should be $\frac{C_{op}}{n_1 - 1}$

CEI News

Programme for Implementing Constitutional Changes in CEI

It was announced in the November Journal (page 565) that the Board of CEI, at its meeting on September 22nd, had formally agreed substantive changes to the CEI Charter and By-Laws, and authorized submission of a Petition to H.M. The Queen seeking approval to these changes.

An official announcement of the presentation of a Petition to Her Majesty in Council by the CEI for the grant of a Supplemental Charter was made in the London Gazette of 29th October, 1976 and this stated that all Petitions for or against the grant of the Supplemental Charter should be lodged with the Privy Council on or before November 18th. In addition to this public announcement, it is also the customary practice to circulate the Petition to departments of State as well as to the Law Officers, Charity Commissioners and any others the Privy Council feel should be consulted.

These consultations of necessity take considerable time since they involve a close scrutiny of the Supplemental Charter and By-Laws. It is to be expected that the views of the CEI will be sought by the Privy Council Office on any comments of substance that are received. Modifications to the changes in the Charter and By-Laws may be sought of the CEI, and if these are substantive it may well take time to clear them with the Chartered Institutions.

Informally the Board has been advised that a decision on the grant of a Supplemental Charter to effect the constitutional changes might not be taken until the latter part of 1977. Until the changes are approved the CEI must work under the present Charter and By-Laws which provide the constitutional framework in which the CEI carries out its activities. To allow for flexibility in the conduct of the business of the Council, the By-Laws provide for some of the activities to be controlled by regulations which can be modified by the Board to meet changing circumstances of the day without reference back to the Privy Council, subject to their not being at variance with the constitutions.

In anticipation that the modifications to the present Charter and By-Laws will be allowed, steps are now being taken to draft a new series of regulations compatible with the future needs of the CEI and its members, both institutions and individual Chartered Engineers.

A copy of the draft Supplemental Charter and By-Laws can be seen at the CEI Office at 2 Little Smith Street, London SW1P 3DL (near Westminster Abbey) or a copy will be sent to those who send a stamped, addressed envelope, A3 size, to that address.

CEI's Comments to ACAS on Draft Codes and to Minister on Pensions White Paper

CEI has recently replied to the invitation from the Advisory, Conciliation and Arbitration Service (ACAS) for comments on two draft Codes of Practice issued by the Service.

In the first letter, dated 1st September 1976, CEI comments in detail on the draft 'Code of Practice, Disciplinary Practice and Procedures in Employment'. The purpose of the draft Code is to help employers and trade unions as well as individual employees and give them practical guidance on how to draw up disciplinary rules and procedures and how to operate them effectively. The Council made detailed comments on working of the draft and emphasized the crucial importance of all employees being properly aware of the procedures.

The draft Code states that 'except in special circumstances breaches of disciplinary rules should be removed from an employee's record after an appropriate period of satisfactory conduct'. CEI recommended that it should be made clear what 'special circumstances' apply and what is deemed an 'appropriate period'.

In the second letter to ACAS, dated 14th October, CEI commented on the draft Code, 'Disclosure of Information to Trade Unions for Collective Bargaining'. The Council gave its support to the policy requiring employers to disclose to their employees information which will assist them in negotiations about pay and conditions of work. Nevertheless the Council made it clear in the letter that it remains critical of the assumption in legislation and Government pronouncements about industrial relations, that representation of the workforce can be left entirely to independent trade unions. The letter went on to say: 'The Council's view is that consultative arrangements should be extended to all in industry and not just members of trade unions and that the Codes guiding procedures should be so framed'.

More recently the Council has written to the Right Hon. Stanley Orme, MP, Minister for Social Security, commenting on the recent White Paper 'Occupational Pension Schemes—The Role of Members in the Running of Schemes'.

The Council made it clear that it believes that no reasonable employer will object to member representation on the management of pension schemes and that a 50/50 representation is also reasonable. However, the Council did object to the proposed legislation in that the White Paper equates member participation with trade union participation and ignores funds which have no trade union members or only a very small proportion of them.

The letter continued: 'There are many organizations where employees are not members of independent trade unions or where no trade union recognition agreement exists. Professional staff are not, in many cases, members of independent trade unions and where a recognition agreement exists, they are often not in the class of "worker" covered by the agreement . . . . . Professional staff are most likely to be covered by a contracted-out occupational pension scheme and it would seem that their pension provision might be at risk'.

Finally the Council recommended that where a recognition agreement exists in respect of a proportion only of the workers, then the representation of workers on the controlling bodies should be proportioned equitably between members and non-members of the trade union.

CEI Meeting with MPs

During November and December CEI extended invitations to some fifty Members of Parliament to meet its senior officers and Executive Committee. The purpose of the meeting was to establish closer links with those MPs who have an interest in engineering matters, to brief them on the new structure and role for CEI incorporated in its revised Charter (now with the Privy Council), and to discuss with them the needs of British manufacturing industry to attract sufficient engineers of the right calibre.

Other matters which concern both the professional engineer and the legislator were raised including professional engineers and trade unions; professional engineers and participation in industrial democracy; health and safety regulations and their application; and professional engineers overseas (especially in the EEC).

1976 General Assembly of EUREL

Report by Professor William Gosling (*IERE Representative*)

This year's General Assembly of EUREL was held during the Annual Congress of VDE (the German Electrical and Electronic Engineering Institution) which took place in Munich from October 12th to 14th, thus making it possible for those attending EUREL also to be present at the sessions of VDE. Some of these were of course concerned with heavy electrical engineering, but many were on topics of interest to members of this Institution.

VDE-Kongress '76

The preoccupations of electronic engineers in Germany seem to be very similar to those in Britain, in short microprocessors were on view and being discussed everywhere. A number of distinguished people spoke at the opening of the VDE conference, most significantly Mr. Anton Jaumann who is the Minister of Economics in the Bavarian State Government. He made very clear the significance attached to the electrical and electronics industries in German government circles but also drew attention to the problems and challenges as well as the opportunities of our present situation. The future well-being of Germans, and by extension no doubt of all Europeans, is much tied up with a series of critical decisions in the economic and technical spheres and very many of these bear upon electronics. An important speech was also made by Mr. R. Dingeldey who is President of VDE and President for this year of EUREL.

The VDE sessions opened in the famous Deutsches Museum, which might be described as the German equivalent of the Science Museum, and in which there is a particularly good electronics collection. When I visited the Museum, between sessions, it seemed to be full of schoolchildren and young people, who were obviously fascinated by the many electronics exhibits. Most of these were of the working type and demonstrated everything from the elementary principles of circuit theory to the construction of a computer, in a way which must have been challenging and exciting to electronic engineers of the next generation.

Executive Committee's Report

Turning to the sessions of EUREL itself, these were introduced by Mr. Dingeldey, and subsequently Dr. R. Richard of Switzerland talked about the growth of EUREL and the need for it to continue to be flexible in its attitude to its future and to review continuously the purposes for which it has been established and which it serves. The growth of EUREL was all too obvious in that thirteen Western European countries were represented at the meeting, with guest observers from three Eastern European countries (Yugoslavia, Poland and Hungary). Dr. Richard defined the policies of EUREL as aiding study and research in our discipline, promoting the exchange of information, developing a spirit of collaboration between the different national electrical and electronics engineering societies or institutions, to try to universalize that collaboration by links outside Europe, to develop ties of collegiality and friendship between electrical and electronics engineers practising in Western Europe and at all times to promote discussion without the intrusion of politics or sectarianism. He felt that a good deal of progress along these lines had already been made and expressed the thanks of the electrical engineers of Western Europe to those who had given so generously of their time already to bring this about.

EUROCON and other Conferences

The longest report of the formal session was given by Dr. H. Fleischer, Chairman of the Executive Committee, which carries out most of the detailed work of EUREL and reports to the General Assembly on an annual basis. An important activity over the last year has been the organization of EUROCON which will be held in Venice on 3rd–6th May 1977 under the presidency of Professor Gigli, EUREL Representative of Italy. This very significant international conference is being organized primarily by EUREL on behalf of its member institutions, of which the IERE is one of the larger, but the IEEE (Region 8) and URSI have also participated in the organization of the conference from the beginning. More recently the International Telecommunications Union has expressed its strong support for the conference and the General Secretary of the ITU will act as a session chairman. The success of the conference is obviously guaranteed and already 300 papers of high standard have been received although only 200 can be presented. (For details of the arrangements see facing page). The complete text of conference papers will be published as a Proceedings volume, and will in due course be available through IERE.

Another developing EUREL activity is to give support to conferences having an international character which are organized by the individual electrical engineering societies in Europe. Dr. Fleischer emphasized that the executive committee would be delighted to consider requests for this kind of support, although of course each one is considered on its merits. At each conference so supported arrangements will be made for the President of EUREL or a nominee to be present.

Cooperation between Member Societies

During the year EUREL has published a handbook describing its functions and giving a summary of material relevant to the member institutions. This booklet was published under the auspices of VDE and is available to members of the IERE from Institution headquarters.* The book has also gone to a variety of outside bodies and particularly to East European societies, and it may be that it was as a consequence of this that our East European guests were present at the recent General Assembly. Informal feelers about the possibility of membership of EUREL from East European societies have been received but at present the constitution of EUREL prevents any progress being made in this area, although the question is still a lively one and progress may be made in future. EUREL membership cards (also available from IERE†) are now in fairly wide circulation and any members of the Institution contemplating visits to other West European countries are advised to obtain membership cards which will serve as an introduction to the national societies. Most national societies will accord temporary rights of membership to visitors on production of a EUREL card.

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* Price 50p. post free—see October Journal, page 505.

† See October Journal.

The Executive Committee of EUREL also intends to distribute information on events, conferences and meetings to the individual institutions on a monthly basis. Already of course *The Radio and Electronic Engineer* publishes monthly a list of such events.

Future EUREL Work

A series of working groups have been set up under the Executive Committee dealing, for example, with problems of young engineers, of ethics, professional matters (possibly including comparative income survey for engineers in the different European countries), exchange of journals, and relationships with outside organizations. There has been also a development of regional activities within EUREL, promoting links across national borders between electrical and electronic engineering societies where these seem to be relevant, for example in the Benelux area. The question of engineering education is also being looked at, particularly in relationship to need for cooperation between governments and the institutions.

The need for governments to take account of the views of electrical and electronic engineering institutions in the various countries was the theme of a resolution passed at the General Assembly which urges governments to take account of the highly qualified specialist advice that they could obtain from this quarter. It was felt that this resolution would be particularly helpful to some European countries where relationships between government and the institutions were less close than in the UK.

Presidential Speeches

The next business of the meeting was to elect the President for the year 1977. This is Mr. H. W. F. van't Groenewout of Holland who has had a varied career in electronic engineering and is now President of the electrical branch of the Royal Engineering Institute of Holland (K.I.v.I.). The new President in his inaugural speech referred again to the relationships between EUREL and the societies of Eastern Europe which he said must be cautious but positive. Perhaps at first they might only be on a person to person relationship but later could develop in the direction of institutional relationship. He too was very pleased to report the development of contacts between member societies of EUREL in neighbouring countries and although this had started between Belgium and the Netherlands, contacts between Germany and the Netherlands were likely to develop. Where questions of language do not make it impossible, joint meetings in border areas and the presentation of technical papers from one society in the area of another seemed to be the sort of approach that looked attractive. Environmental problems in particular might well lend themselves to consideration on an international basis. Expressing general satisfaction with the development of EUREL, and particularly the advances recorded by Dr. Fleischer, Mr. Groenewout looked forward to the next General Assembly which is to be held in the third week of September 1977 at The Hague.

As retiring President, Mr. Dingeldey said that he had no doubt at all that the electrical and electronic institutions of Western Europe had been strengthened already by the cooperation that it had been possible to establish, and that he was sure that the problems of East–West cooperation were not insuperable. He felt that it was particularly important that individual engineers in Western Europe should become aware of the existence of EUREL and of its functions and he hoped that the provision of individual identity cards would be a useful step in this direction.

A British Proposal

Finally EUREL decided that in the coming year, in addition to existing activities, the Executive Committee should look into the problem of radio frequency spectrum congestion in Western Europe. This matter was raised by the IERE delegate, who pointed out that spectrum congestion was likely to be more severe in Western Europe than in the United States, due to the greater aggregation of the population. The matter will be taken under consideration by the Executive Committee and is likely to issue in a statement or resolution of EUREL at a later General Assembly.

European Conference on Communications: EUROCON 77

The papers to be presented at EUROCON 77, to be held in Venice, Italy, from 3rd to 6th May 1977, cover the state of the art and future developments in virtually the whole field of Communications. One hundred and ninety-five papers from 26 countries have been selected; of these, 83 are concerned with new developments in communications, and the future will be examined further in a whole-day session on market research and technological forecasting.

EUROCON 77 is organized by the Institute of Electrical and Electronics Engineers (IEEE) and the Convention of National Societies of Electrical Engineers of Western Europe (EUREL), and has the special support of the International Union of Radio Science (URSI).

The programme is divided into five main sections:
Communications in large power systems
New developments in communications
Communications and computers
Communications and signal processing in medicine;
Communications in the developing countries.

A complete day is to be devoted to market research and technological forecasting, and the relationship between technical developments and future market requirements.

A special session has been arranged at which students and young engineers can discuss topics of their choice with senior engineers. Many of the review papers in the programme will be of especial interest to students.

Those interested in attending are urged to send for a Preliminary Programme and Registration Form immediately, since the Conference fee is lower for registrations received before 1st March—$96 compared with $108 for members of IEEE and EUREL Societies, and $120 compared with $131 for non-members. There is a special fee for students, $25, irrespective of the date of registration. Write to EUROCON 77 Office, c/o AEI, Viale Monza 259, I-20126 Milano, Italy, or to the IERE.

Of Current Interest

Britain's Export Prospects

'It is certainly the impression of those of us who talk to exporters that overseas demand is rising, that British exports are competitive and profitable, and that home demand is unlikely to pre-empt the available capacity. Although this is not yet reflected in the trade figures we can be reasonably optimistic for this coming 12 months about the trend in exports, as we were a year ago about the trend in inflation' states Sir Frederick Catherwood in his Foreword to the British Overseas Trade Board's 1976 Report which has just been published.

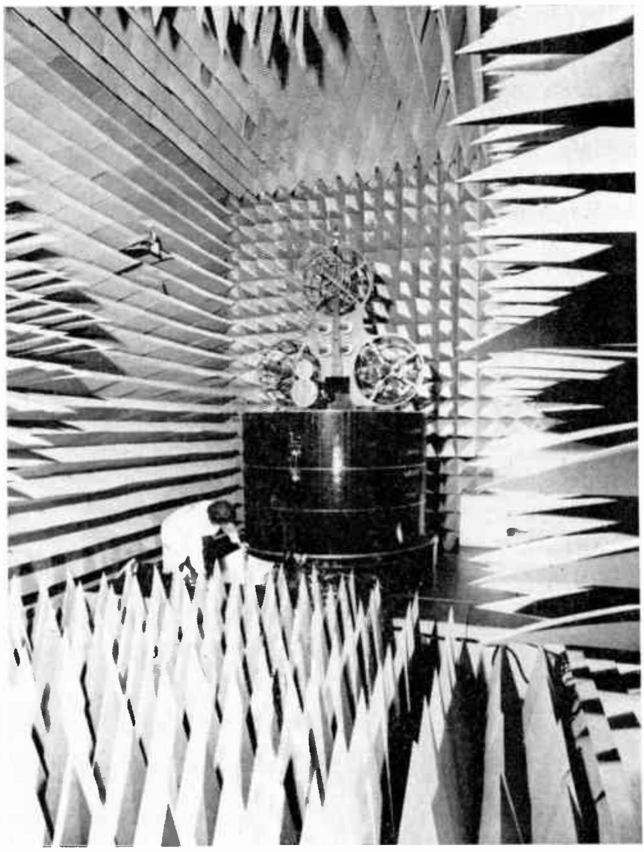
Sir Frederick stresses the need for a reallocation of national resources into industrial capacity in the export industries and says that at present 'It is extremely depressing to those promoting British exports, time and again to meet the problems caused by inability to supply the goods customers want: goods which could be manufactured profitably in a high productivity, high wage economy but which British sources cannot currently supply.'

The Report covers the activities of the Board—including details of expenditure amounting to £48.1M in the financial year ending March 1976 on export promotion. The work of the Board's Area Advisory Groups and of the British Overseas Trade Council are also summarized.

Copies of the Report are available from the Publicity Unit, British Overseas Trade Board, 1 Victoria Street, London SW1H 0ET (Tel. 01-215 5492)

Satellites for Mariners

A third *Marisat* communications satellite to carry ship-to-shore communications for owners and crews of vessels on the high seas was launched from NASA's Kennedy Space Center, Cape Canaveral, Florida, on October 14th. The new satellite joined similar *Marisats*, launched in February and June this year, which are now in commercial service above the Atlantic and Pacific Oceans. The latest *Marisat*, designed and built by Hughes Aircraft Company for Comsat General Corporation, is stationed in a synchronous orbit 22,300 miles above the Indian Ocean to augment the present system. The satellite is shown in the accompanying photograph during a radio frequency test in an anechoic chamber at the Hughes space facility in California.



NEW BRITISH STANDARDS

Primary Cells and Batteries

Appliances using non-rechargeable batteries have proliferated since 1960, when the British Standard BS 397 *Primary cells and batteries* was last revised. Demands made on the power source vary widely from high-current short duration to very small current drains continuously over long periods and the latest edition of BS397 incorporates five of the new electro-chemical systems.

In order to simplify the specification it is now in loose-leaf form and is divided into sections. Section one gives the system of designation and the general requirement for all batteries and for connectors, while sections two to six consist of individual sheets relating to battery sizes in each electrochemical system. One sheet for each battery size gives full details of dimensions and test parameters with performance requirements related to the type of usage.

The specification is substantially in agreement with international publications thus ensuring interchangeability of size.

Copies of BS 397 are available from BSI Sales Department, 101 Pentonville Road, London N1 9ND. Price £8.20.

School Television Receivers

A supplement to BS 4958 *School television receivers and stands* has just been published. It is supplement No. 1 *Colour television receivers*, and it invokes relevant clauses of BS 4958 for the construction and performance requirements of monochrome television receivers, amended as necessary to apply to colour receivers. Additional performance requirements applicable only to colour television receivers for use in schools are also specified.

This supplement has been necessary because there is no comprehensive British or International standard for domestic colour television receivers and it is intended as an interim document to provide general guidance in the assessment of suitable parameters for colour receivers.

Work is currently in progress within the International Electrotechnical Commission (IEC) to produce a standard covering methods of measurement and performance of television receivers, including colour receivers.

Copies of Supplement No. 1 to BS 4958 are available from BSI Sales Department. Price £1.50.

Electrically switched optical 'prism' using liquid crystals[*]

An electrically switched optical 'prism' that uses liquid crystals to deflect a laser beam has been devised by Dr. D. Jones and Mr. A. Fray of the Royal Signals and Radar Establishment, Malvern. Large angular deflections of up to ± 20° have been obtained using a layer of liquid crystal only 1mm thick.

Basic concept. Conventional refractive devices such as lenses and prisms deflect radiation by presenting the wavefront with a spatially varying path length. However the molecular orientation of liquid crystals can be controlled electrically so as to produce a variation in refractive index that results in deflection of an optical beam. In some respects such a device acts as a conventional prism, except that it is polarization dependent and the light follows a curved path through the cell.

A simple form of cell for deflection in a single plane is shown in Fig. 1. The device consists of a cell, typically 1–2 mm thick and 3–4 mm wide, containing a positive nematic liquid crystal. The crystal molecules can be aligned parallel to the cell walls by applying a transverse alternating electrical field[†] using four electrodes. In this state the device behaves as a uniaxial crystal with its optic axis parallel to the cell wall and a normal polarized beam will pass through undeflected.

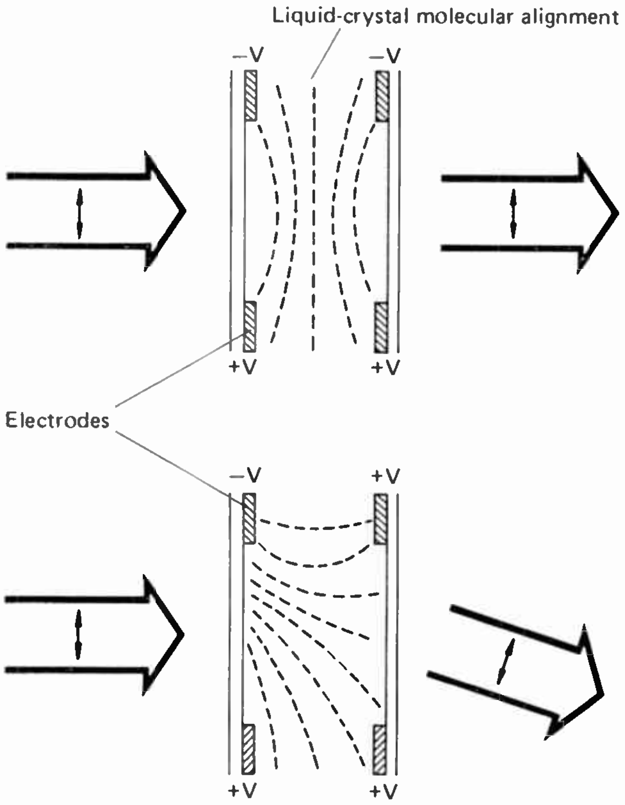


Fig. 1. Basic mechanism by which optical beam is deflected.

If, now, the ratio of the electrode potentials is varied, the molecular alignment is modified and defines a new spatially varying optical axis. The light follows a curved path through the cell. The angle through which the beam is deflected depends on the cell dimensions, the optical anisotropy of the liquid crystal, and the ratio of the electrode potentials. The absolute values of the electrode potentials determine the speed of deflection only. The optical path length does not vary linearly across the cell and therefore the angle of deflection varies with position.

Possible applications. The possibility arises of using the device for scanning applications. Unfortunately the region producing maximum deflection is also one in which switching produces turbulence in the crystals so that continuous scanning is not compatible with maximum deflection. Nevertheless, the device will still perform as an optical switch in this region, and continuous scanning can be achieved if the beam is focused a little way off the turbid region. At 1 kV the beam can deflect full scale and return in less than 1 ms (return is faster than deflection). At present the transmission loss due to absorption and scattering is typically greater than 50%; scattering is combated by special treatment of the cell walls and operating the device at high fields.

Electrically switched optical modulation cells could offer advantages over a number of existing devices. The main competitor is the Kerr cell, but it only gives deflections of a fraction of a degree; rotating mirrors are fast and inexpensive but involve moving parts; acousto-optic methods also give less than 1° deflection.

A number of eventual uses could be envisaged, and these might include the following:

laser-beam deflection for computer storage applications
image modulation for pyroelectric devices
a coherent or incoherent light torch for hazardous environments
an artificial horizon for instrumentation
a flying-spot scanner
an optical waveguide switch
a zoom Fresnel lens
orientation of solar panels
addressing of holographic photographs
optical signal processing and Fourier analysis.

An 8-electrode device which is capable of deflecting a beam in two dimensions has already been constructed. This offers the possibility of x-y addressing.

Companies interested in the possibilities offered by these optical modulation devices are invited to contact Dr. M. J. Knight, Electrical Engineering and Electronics Group, National Research Development Corporation, 66–74 Victoria Street, London SW1E 6SL. Tel 01-828 3400

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[*] UK Patent Application 27180/75.

[†] The device only works with an alternating field owing to electromigration effects.

Letters to the Editor

From: **B. Summers**, C.Eng., M.I.E.R.E.
K. L. Finney

Life Expectancy of Members

Whilst reading the March issue of the Journal my attention was drawn to the Obituary section. Of the seven deceased members listed therein six of them were evenly distributed in the age range of 38–57 years.

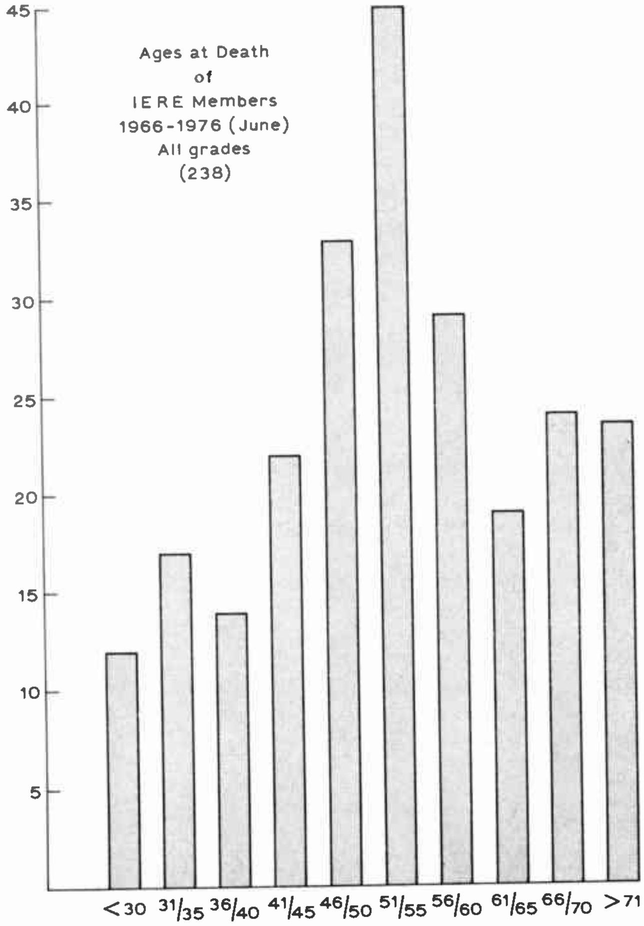
I am not sure if this is statistically significant for professional engineers as a group, or perhaps some quirk in the manner in which obituaries are published.

Any information which the Institution could provide concerning the life expectancy of its members should surely be published, as I personally may wish to replan my current pension contributions (or alternatively my career).

Brian Summers

2384 Rondel Street,
Ottawa, Ontario, K1B 4M2,
Canada.
15th June 1976.

An analysis of the ages at death of 238 members of whom obituary notices were published in the Journal from January 1966 to August/September 1976 inclusive shows that the average age at death was in fact 52 years. The accompanying histogram shows the distribution over the age ranges. In analysis by grade the following figures are obtained (the number of members is shown in brackets):



	Average age
Fellows (49):	62 years
Honorary Fellows (4):	81 ,,
Members (111):	52 ,,
Companions (2):	50 ,,
Graduates (35):	40 ,,
Associate Members (14):	51 ,,
Associates (19):	53 ,,
Students (4):	25 ,,

The statistical significance of such figures based on a relatively small sample, which admittedly does not include *every* member whose death occurred in the period (altogether about 260), might be questioned in so far as professional engineers are concerned. Nevertheless, the ages for the higher grades are fairly consistent, although one can only note with some amazement the comparative longevity of our Honorary Fellows! Editor

'New Academic Qualifications in Australia'

I have been directed by the Council of this Institution to write to you in relation to your news item 'New Academic Qualifications in Australia', which appeared in *The Radio and Electronic Engineer* of March 1976 (page 136).

Our Council has expressed disappointment that the item carried no reference to the Institution of Radio and Electronic Engineers Australia. By virtue of its Royal Charter granted in 1967, the highest distinction that can be awarded a professional and learned body, this Institution is regarded as the pre-eminent body in Australia catering exclusively for engineering professionals in the Science of Radio and Electronics. In addition, the I.R.E.E. caters for sub-professional members in the field such as the technician engineers, most important members of the scientific community, who are ignored by our fellow Engineering Institution.

I would draw your attention to the fact that the I.R.E.E.'s academic requirements for membership are at least equivalent to those of the Institution of Engineers (Australia) and are more stringent in some areas, in regard to minimum ages and years of experience. In addition, no person is eligible for Corporate Membership unless professionally employed as an Engineer.

It is worthy of note that neither the Institution of Radio and Electronics Engineers Australia nor the Institution of Engineers (Australia) has any connection with the Association of Professional Engineers of Australia, which is purely an industrial body, representing its members, who may also be IREE or IEA members, in matters relating to industrial awards under the Australian Arbitration Commission system.

Our Council considers that perhaps some statement of the foregoing facts in an issue of your Journal may be worth presenting to your members and other readers, who might otherwise have gained an incomplete or inaccurate picture of the professional engineering situation in Australia.

Keith L. Finney
General Secretary

The Institution of Radio and Electronics Engineers
Australia,
157 Gloucester Street,
Sydney, New South Wales 2000, Australia.
27th October 1976 (Delayed in post.)

Colloquium Report

Technicians and Technician Engineers in the Electronics Industry

Held in London on 17th November 1976

The recent IERE Colloquium on the above topic posed four questions: What do Technicians *do* in the Electronics industry? What is a Technician Engineer? Will TEC bring Technical Education nearer to the needs of Industry? and Will ERB Registration of Technicians and Technician Engineers improve their status? Despite the fact that the speakers were all experts on their particular subjects, and the lively and uninhibited discussion which took place, at least one delegate was left with the feeling that none of the questions had been fully answered.

Mr. W. W. Smith, of the EITB, opened the proceedings by giving statistics, based on a survey made in 1973, of the kinds of work undertaken by Technicians and Technician Engineers, and of the academic qualifications which they held. His first basic statistics are worth quoting:

27% of all engineering employees are in the electronics industry and of these 10% are technicians and technician engineers. The broad areas of technician work are in commerce, R & D, production and services.

Draughtsmen form about 33% of all technicians and half of these are in R & D, and one quarter in production.

Of the remaining 66% or so—non-draughtsmen—30% work on production, 21% are in R & D, 9% in services, and 7% on commercial activities.

Throughout the engineering industry, technicians and technician engineers are roughly equal in terms of numbers employed. Employers who provided this information did so after assessing their staff in respect of the jobs they undertake, rather than academic qualifications.

The startling feature of the statistics on work and qualifications was that, despite the fact that over 50% of the individuals in the two categories under investigation had either no 'paper qualifications' at all, or none relevant to engineering, the total range of their activities covered almost the entire spectrum of employment in the industry. It was also apparent that there was little, if any, correlation between the level of the individual's academic qualifications and the type or standard of the work undertaken: in the speaker's words, 'Industry is full of educational failures who are doing very good jobs'.

Mr. A. C. Gingell, of the IEETE, gave a clear picture of his Institution's answer to the question 'What is a Technician Engineer?' but one was left wondering whether, if the Technician Engineer is indeed the man 'of many parts' (and abilities) envisaged, industry needs any other kind of employee. One could hardly, however, dispute his claim that we have tended in recent years to produce too many mediocre graduates, and that such people are 'misfits' in the industry. They lack the breadth and depth of vision which a Chartered Engineer should possess, and have not the practicality of outlook essential to a good Technician Engineer. (Was his concept of the Chartered Engineer perhaps a little too Olympian? He seemed to think that they should almost have more in them than mortal knowledge.) Nevertheless, there was food for thought in his comment that the span of academic qualifications which contained the entire range of CEI/ERB registrants—that is, from an ONC to a first degree—may be too small to accommodate a 3-tier registration structure comfortably. His suggested remedy—increasing the standard required at the top—would no doubt be highly unpopular with those 'trendy' educationalists who appear to think that the remedy for all ills lies in lowering the standard demanded at the bottom, or abolishing standards altogether.

In the discussion which followed the attempt by Mr. A. J. Kenward, in his capacity as Chairman of TEC Programme Committee A2, to answer the question 'Will TEC bring Technical Education closer to Industry's needs?' it was apparent that there are still many who fear that TEC may be prepared to accept lower standards, not just at the bottom, but all the way up, and that this may have dire consequences for those whose engineering careers begin at the lowest level. While Mr. Kenward left the audience in no doubt that TEC was aware of the need to maintain standards, and was striving to meet the needs of both industry and the individual, the question 'Would it succeed?' remained poised. It was agreed that, regrettable though it might be, a temporary hiatus was an almost inevitable consequence of the introduction of a new qualification system: 'the proof of the pudding is in the eating' and the quality of the TEC pattern, and its relation to the pattern which it will replace, cannot be assessed until its products have been sampled.

Mr. P. G. South ('Mr. ERB', as the Chairman described him) spent some time in describing the origins and aims of the ERB, and detailing the progress which it had made to date, before turning to the question 'Will Registration improve the status of Technicians and Technician Engineers?'. To this, his answer was, in short, that status cannot be conferred; it must be earned. At present, all that the ERB could do was to say, in effect, 'Mr. A. has been investigated on behalf of the Board by its member Institution X, and found to conform in all respects with the Board's specification for a Technician (or Technician Engineer as the case may be)'. Again, an element of 'proof of the pudding' will be involved. The potential employer can study the Board's specification and, if it appears to meet his needs, sample the product, but not until many employers have done this, and found the product better than those they have used before, will Registration improve status.

No doubt much that was said both by the principal speakers and in the discussion would have alarmed academics and formalists; no doubt the failure to produce pocket-sized definitions of Technicians or Technician Engineers will have disappointed some of those present. Perhaps the reason for these things, and for the inability to compartmentalize the functions of the people under discussion, lies in the fact that, while the pundits can compile lists of the qualities and qualifications which they should have, the one which they *must* have if they are to be successful engineers, and the lack of which will doom academic and non-academic alike to mediocrity or total failure, has still not been identified, let alone measured.

K. J. COPPIN

Members' Appointments

NEW YEAR HONOURS

The Council has sent its congratulations to the following member whose name appeared in Her Majesty's New Year Honours List:

MOST EXCELLENT ORDER OF THE BRITISH EMPIRE

To be an Ordinary Officer of the Military Division (O.B.E.)

Wing Commander Gareth Huw Rees, M.Tech., B.Sc., Dip.El., RAF (Fellow 1974, Member 1961). (Wing Commander Rees was at the RAF College, Cranwell, from June 1969 to June 1976, latterly as Officer Commanding Basic Sciences Squadron, and the Award recognizes his contribution to the life and work of the College. He is now Officer Commanding Education Wing at RAF Cosford.)

CORPORATE MEMBERS

Sir Ieuan Maddock, C.B., O.B.E., D.Sc., F.R.S. (Past President 1973–75) gives up his appointment as Chief Scientist of the Department of Industry on 31st March 1977. He will be succeeded by Dr. Duncan Davies, currently General Manager, Research and Development with Imperial Chemical Industries. Sir Ieuan has been Chief Scientist since 1974 and from 1971 to 1974 was Chief Scientist to the former Department of Trade and Industry. He will continue to be in charge of the National Physical Laboratory for a period after Dr. Davies takes up his appointment.

Mr. A. E. Green, B.Sc. (Fellow 1966, Member 1956, Graduate 1953) who is General Manager of the National Centre of Systems Reliability of the UKAEA at Culcheth, has received the 1975 Annual Reliability Group Award of the IEEE. The citation of the Award read 'for outstanding contributions and international leadership in the field of nuclear reactor safety and reliability'. This was the first time that a British engineer has received this notable US award.

Mr. Green has been with the UKAEA in the Safety and Reliability Directorate and its predecessor, the Authority Health and Safety Branch since 1969. He was previously a Senior Engineer concerned with industrial process control in the Electronic Engineering Department of Metropolitan Vickers Electrical Company Ltd.

Brigadier R. A. King, R.Sigs (Fellow 1976, Member 1961) has taken up an Honorary Visiting Fellowship at the University of Bath to carry out research into aspects of speech and signal processing. Since 1974 he has been Commander, Training Brigade, Royal Signals, at Catterick Garrison, North Yorkshire. His service appointments included two years at the Royal Military College of Science, Shrivenham, as Director of Studies (Telecommunication 2) as a Lieutenant Colonel concerned with the planning and organization of courses in telecommunications.

Professor D. R. Towill, M.Sc. (Fellow 1970) has recently spent some weeks in India as a member of a United Kingdom delegation helping to organize the Indo-British Conference on Engineering Production to be held in New Delhi in August 1977. He has also been concerned with running two short courses in advanced control engineering design techniques for the staff of the Indian Institute of Technology, Delhi. Professor Towill was the founder of the Dynamic Analysis Group in the Department of Mechanical Engineering and Engineering Production at the University of Wales Institute of Science and Technology, Cardiff. He is chairman of the IERE Automation and Control Systems Group Committee.

Dr. W. G. Burrows, Ph.D., D.I.C. (Member 1958) has recently taken up the appointment of Head of the Department of Marine Electronics at Brunel Technical College, Bristol. For the past ten years he has been on the staff of the Department of Electrical Engineering of Imperial College, London, latterly as Senior Tutor. Dr. Burrows has served on the Institution's Papers Committee since 1970.

Major P. C. Coderre, C.D., B.Eng. (Member 1971, Graduate 1967) has been appointed Sub-Section Head, Land Radio Systems, with the Directorate of Land Armament Electronics Engineering and Maintenance, Canadian Forces. He was previously with the Electrical Engineering Department of the Royal Military College of Canada, Kingston, Ontario, after a staff appointment at the Headquarters of Canadian Forces Communication Command, Ottawa, from 1973 to 1974.

Mr. W. R. Crooks, B.S. (Member 1973, Graduate 1963) who is on the staff of the North East Liverpool Technical College, has been promoted to Senior Lecturer in Electrical Engineering and Electronics.

Mr. I. G. Frith (Member 1971, Graduate 1968) who joined Senior Service, Ltd., Hyde, Cheshire, as Electronic Process Control Supervisor in 1974, has been promoted to Departmental Engineer (Electrical) with the company.

Dr. S. Ganguly, Ph.D. (Member 1974) is now a Research Associate with the National Astronomy and Ionosphere Center, Arecibo, Puerto Rico. Dr. Ganguly came to England in 1974 as a Leverhulme Visting Fellow in the Department of Environmental Sciences at the University of Lancaster; he had previously been for two years a Senior Research Fellow at the Institute of Radiophysics and Electronics, Calcutta.

Mr. C. H. Garnett, B.Sc. (Member 1964, Graduate 1958) has moved from the Defence Quality Assurance Board Executive to the Computers, Systems and Electronics Division of the Department of Industry, where he is concerned with electronic components and microelectronics.

Mr. A. C. Hayward, B. Eng. (Member 1971), formerly head of the Department of Electronics and Radio Engineering at the Charles Trevelyan College, Newcastle-upon-Tyne, has been appointed Vice-Principal at the St. Helens College of Technology, St. Helens, Lancashire.

Grp. Capt. R. H. J. Hence, RAF (Member 1966, Graduate 1955) who until recently was at RAF Biggin Hill, Kent, has been appointed Assistant Chief of Staff Communications and Electronics at Headquarters, Allied Forces Baltic Approaches, Karup, Denmark. From 1966 until 1970 Grp. Capt. Hence was on the RAF Staff at the British Embassy in Washington, U.S.A.

Mr. J. R. D. Holmes (Member 1970, Graduate 1967) has moved from Marconi Space and Defence Systems Ltd., where he was a Principal Project Engineer in the Space Division, to become Senior Project Control Engineer with EASAMS Ltd., Frimley.

Wing Commander R. J. A. McGuigan, RAF (Member 1971, Graduate 1968) has transferred from the posting of Officer Commanding Engineering Wing, RAF West Drayton, to the staff appointment of Electrical Engineering (Radar) at Headquarters Strike Command, RAF High Wycombe.

Capt. R. G. W. Maltby, REME (Ret.) (Member 1973, Graduate 1969) who until August of this year was Project Officer, *Rapier* Support Group, with the Radar Branch Technical Group, REME at RRE Malvern, has taken up the appointment of Senior Customer Training Engineer with Racal-Tacticom, Reading.

Mr. A. S. Omosule, A.R.G.I.T. (Member 1972, Graduate 1971) has now completed a two-year period of study in the UK supported by the Petroleum Technology Department Fund of the Nigerian Federal Ministry of Mines and Power, during which he took a postgraduate course in Electronics at UWIST, Cardiff, followed by a period with the Department of Physics, Portsmouth Polytechnic. He has now returned to Nigeria to take up again his post as a Lecturer in Electrical Engineering at the Ibadan Polytechnic.

Mr. T. L. Pearce (Member 1966, Graduate 1962) a Principal Professional and Technology Officer with the Ministry of Defence (PE) has transferred from London to a similar post with the Weapons and Fighting Vehicles Headquarters, ROF, Leeds.

Mr. C. O. Peck (Member 1956) is now in Riyadh, Saudi Arabia, where he is Chief Engineer (Broadcasting) with the Beta Company. In recent years Mr. Peck has held a number of senior appointments with broadcasting organizations in various parts of the world.

Mr. D. C. Reeves (Member 1973, Graduate 1969) who was with Data Dynamics from 1969 to 1976, latterly as Senior Engineer, has taken up the post of Chief Electronics Engineer with De La Rue Crosfield Ltd., Watford.

Mr. K. C. S. Richardson, Dip.E.E., M.Sc. (Member 1969, Graduate 1962) who is a Lecturer in the Department of Electrical and Engineering, Glasgow College of Technology, has been awarded the degree of Master of Science from the University of Strathclyde for his thesis on Control Engineering.

Flt. Lt. D. H. Rycroft, RAF (Member 1973, Graduate 1968) has taken up a staff appointment concerned with the installation of airfield navigation aids and radars at Support Command Signals Headquarters, RAF Medmenham. From 1973 to 1976 he was with the RAF Central Servicing and Development Establishment as Project Officer based at the Royal Signals and Radar Establishment, Malvern.

Lt. J. B. Sadler, RN (Member 1973, Graduate 1970) has completed a tour of duty as a Weapon Systems Training Officer at the Submarine School, Portsmouth and is now a Tactical Systems Weapon Engineering Officer in HMS *Sceptre*.

Flt. Lt. P. E. Sharp, RAF (Member 1973, Graduate 1969) has been transferred on promotion to the posting of Officer Commanding *Hawk* Command Engineering Development and Investigation Team, RAF Valley. He was previously *Hawk* Project Officer Resident at Hawker Siddeley Aviation's factory at Kingston-on-Thames.

Sqdn. Ldr. P. J. Smith, RAF (Member 1974) has taken up an appointment with the Ministry of Defence Air Force Department in Support Engineering 4d. He was previously at RAF Medmenham.

Mr. M. Steele (Member 1961, Graduate 1960), previously a senior member of the engineering staff of the RCA Company, New York, is now with the Jones & Lamson Division of Waterbury Farrel, Textron, of Springfield, Vermont, as Chief Engineer, Automatic Image Analysis. Before going to the United States in 1964 Mr. Steele was with the Decca Navigaor Company.

Mr. D. L. Stevenson (Member 1971, Graduate 1969) is now Head of the Radio, Television and Line Transmission Group in the Service Division at Scottish Telecommunications Board Headquarters at Edinburgh.

Mr. K. Thiagarajah, B.Sc. (Member 1975, Graduate 1971) who is with the Sri Lanka Overseas Telecommunication Service, is now Engineer (Radio, Training & Planning) in charge of two radio stations. For the past four years he has been involved with the recruitment and training of technical staff.

Mr. A. R. Tizzard (Member 1973, Graduate 1968) has left his post as Deputy Quality Assurance Manager with the Signetics Corporation to take up a similar appointment with SGS-ATES Ltd. (UK).

Wing Cdr. R. C. Travis, M.B.E., B.Sc., RAF (Member 1962, Graduate 1958) has been appointed to RAF Strike Command Headquarters, High Wycombe, as Education 2. From 1971 to 1974 he was on the directing staff of the RAF College of Air Warfare, followed by two years as a Staff Officer in the Ministry of Defence. For a number of years he was a member of the Institution's Panel of Examiners.

Mr. G. Turton (Member 1972, Graduate 1967) is now Branch Manager with Digital Equipment Co. Ltd., Leeds. In 1968 he joined Pilkington Brothers Ltd., St. Helens, Lancashire, as a Development Engineer, ultimately becoming in 1972 Section Head, Control Systems Analysis & Development Department (Computer Hardware Section).

Mr. M. E. Walker (Member 1969, Graduate 1962) has been appointed Senior Consultant with Messrs Rex, Thompson & Partners, of Farnborough, Hants. For the past six years he has been with Hawker Siddeley Dynamics Ltd., Hatfield, Herts, as a Senior Reliability Engineer, and latterly as Technical Adviser on Reliability.

Mr. D. L. Webb (Member 1968, Graduate 1964) who was previously Quality Manager/Staff Manager with GEC Semiconductors Ltd., Wembley, has joined the Principal Directorate of Technical Costs, Ministry of Defence Procurement Executive, in London.

Mr. D. M. Whitaker (Member 1973, Graduate 1971) has been appointed Principal Engineer responsible for Medical Electronics and X-Ray with the South Western Regional Health Authority, based at Bristol. He was previously a Technical Officer with the Institute of Cancer Research, Sutton, Surrey, concerned with the design, development and commissioning of projects for nuclear medical investigations.

Mr. J. A. Willcox (Member 1969, Graduate 1965) is now Senior Missile Systems Engineer on the staff of the UK Senior *Polaris* Representative in Washington; he was formerly Head of Systems Development, Royal Naval Armament Depot, Coulport.

NON-CORPORATE MEMBERS

Sir John Read (Companion 1974) has been appointed Chairman of the Electronics EDC ('Little Neddie'). Sir John, who was elected a member of the Institution's Council in 1975, has been with the EMI Group since 1965 and became Chairman in 1974.

Sub-Lt. I. F. Crawford, B.Sc., RN (Graduate 1976) has recently been commissioned in the Royal Navy. He had previously been with Marconi Elliott Avionic Systems Ltd., Rochester, as a Development Engineer.

Mr. L. F. Jackson, B.Sc. (Associate Member 1973) has been appointed a Documentation Officer with NATO in Luxembourg.

Mr. E. P. Rodney (Associate Member 1973, Graduate 1970) is Service Manager with Commodex Electronics Ltd., London. He was previously Assistant to the Chief Electrical Engineer, Bookers Sugar Estate, Ltd., Georgetown, Guyana.

Mr. A. M. Solomonidis, B.A. (Associate Member 1973), formerly Force Communications Officer with the Cyprus Police, has moved to Dubai as Telecommunications Engineer with J & P Overseas Ltd.

Lt.-Cdr. J. Stafferton, RN (Graduate 1967) who was formerly Weapons Engineer Officer in HMS *Diomede* has received a similar posting in HMS *Juno*.

Recent Accessions to the Library

This list of additions to the Library covers the period June to November 1976. With the exception of titles marked* 'REF', *which are for reference in the Library only, these books may be borrowed by members in the British Isles by personal call or by post. Information on loan conditions can be obtained from the Librarian, Miss E. J. Keeley.*

Amplifiers

Wait, John *et al.*
'Introduction to operational amplifier theory and applications'. *McGraw-Hill*, New York, 1975.

Electronics

Bell, David A.
'Fundamentals of electronics devices.' *Reston Pub. Co.*, Virginia, 1975.

Meiskin, Z. H.
'Thin and thick films for hybrid microelectronics.' *Lexington Books*, Massachusetts, 1976.

Millman, Jacob
'Integrated electronics: analog and digital circuits and systems.' *McGraw-Hill*, Tokyo, 1972.

Shepherd, W.
'Thyristor control of AC circuits.' *Granada*, London, 1976.

Ionospheric research

Beynon, W. J. C. and Ratcliffe, J. A.
'A discussion of the early days of ionospheric research and the theory of electric and magnetic waves in the ionosphere and magnetosphere.' Philosophical Transactions of the Royal Society. Vol. 280., No. 1293, *The Royal Society*, London, 1975.

Linear systems

Gabel, Robert A. and Roberts, Richard A.
'Signals and linear systems.' *Wiley*, New York, 1973.

Microprocessors

Altman, Laurence (Editor)
'Microprocessors', *McGraw-Hill*, New York, 1975.

McGlynn, Daniel R.
'Microprocessors technology architecture and applications.' *Wiley*, London, 1976.

Motorola Semiconductor Products Inc.
'Microprocessor applications manual.' *McGraw-Hill*, New York, 1975.

Soucek, Branko
'Microprocessors and Microcomputers', *Wiley Interscience*, New York, 1976

Radar

Bird, G. J. A.
'Radar precision and resolution.' *Pentech Press*, London, 1974.

Recording

Kirk, David
'Audio and video recording.' *Faber and Faber*, London, 1975.

Telecommunications

Bussey, Gordon
'Vintage crystal sets 1922–1927.' *I.P.C. Electrical-Electronic Press Ltd.*, London, 1976.

C.C.I.T.T.
'Economic and technical aspects of the choice of transmission systems.' *I.T.U.*, Geneva, 1972. (3 folders and an appendix to section BIV.3 titled 'Propagation', in book form 1971).

Freeman, Roger L.
'Telecommunication transmission handbook' *Wiley*, New York, 1975.

Smol, G.
'Telecommunications: a system approach.' *Allen & Unwin*, London, 1976.

Sunde, Erling D.
'Communication systems engineering theory.' *Wiley*, New York, 1969.

Television

Grob, Bernard
'Basic television, principles and servicing.' *McGraw-Hill*, New York, 1975, 4th edition.

History of technology

Goldstine, Herman
'The Computer from Pascal to Von Neumann.' *Princeton University Press*, Princeton, 1972.

Conference Proceedings

Charged Coupled Devices, International Conference on Technology and Applications. University of Edinburgh, 1974.

Society of Electronic and Radio Technicians
Symposium on Microprocessors at Work, University of Sussex, September 1976.

International Joint Conference on Artificial Intelligence. Advance papers. Tbilisi, Georgia, USSR, 1975.

Reference works

International Telecommunications Union
Final acts of the regional administrative LF/MF broadcasting conference (Regions 1 and 3), Geneva, 1975. REF.

Radio regulations 1: radio regulations. Additional radio regulations. Radio regulations 2. appendices to the above. Geneva, 1976. REF.

Turner, L. W.
Electronics engineer's reference book. 4th ed., *Newnes*, London, 1976. REF.

The library receives the D.A.T.A. series of publications produced by Derivation and Tabulation Associates Inc., which are for reference.

The following issues are available.

Digital integrated circuits (Spring '76) 22nd ed.
Discontinued thyristors (1975–76)
Discontinued transistors (1975–76) 11th ed.
Linear integrated circuits (Spring '76) 15th ed.
Microwave tube data book (Autumn '75) 35th ed. (Spring '76) 36th ed.
Power semiconductors (Autumn '75) 3rd ed. (Spring '76) 4th ed.
Thyristor data book (Autumn '75) 5th ed. (Spring '76) 6th ed.
Transistor data book (Autumn '75) 39th ed. (Spring '76) 40th ed.

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* Reviewed books are not included. See 'New Books Received' in July 1976 and November 1976.

Applicants for Election and Transfer

THE MEMBERSHIP COMMITTEE at its meetings on 8th December 1976 and 20th January 1977 recommended to the Council the election and transfer of the following candidates. In accordance with Bye-law 23, the Council has directed that the names of the following candidates shall be published under the grade of membership to which election or transfer is proposed by the Council. Any communication from Corporate Members concerning the proposed elections must be addressed by letter to the Secretary within twenty-eight days after publication of these details.

Meeting: 8th December 1976 (Membership Approval List No. 228)

GREAT BRITAIN AND IRELAND

CORPORATE MEMBERS

Transfer from Graduate to Member

ASHWORTH, Martyn Keith. *Sheffield.*
HURRELL, Ian Edward. *Tattershall, Lincoln.*
STEED, Julian James. *Bellinge, Northampton.*

Direct Election to Member

FINN, Michael John. *Langbaurgh, Cleveland.*
PARISH, Clive. *Southampton, Hampshire.*
PILGRIM, David. *Christchurch, Dorset.*

NON-CORPORATE MEMBERS

Transfer from Student to Graduate

FLAVIN, Philip Graeme. *Felixstowe, Suffolk.*

Direct Election to Associate Member

BUCKBERRY, George Charles. *Welling, Kent.*
CUBLEY, Leonard David. *Newcastle upon Tyne.*

Direct Election to Associate

FUTCHER, Richard George. *Cheshunt, Hertfordshire.*
LAVELLE, Brian Joseph. *Whitley Bay, Tyne and Wear.*

STUDENTS REGISTERED

AVERY, Robert John. *Orpington, Kent.*
CROFTS, Joe Nigel. *Maidenhead, Berkshire.*
GERMER, Robert Ian. *Doncaster, South Yorkshire.*
LUMBY, Simon John. *Cottingham, North Humberside.*
MOBBS, Donald Peter. *Bristol.*

OVERSEAS

CORPORATE MEMBERS

Transfer from Graduate to Member

KUMARAPATHIRANA, Ranbana. *Kurunegala, Sri Lanka.*
SIBBONS, Michael Edward. *B.F.P.O. 15.*

Direct Election to Member

GALEA, Daniel. *Zejtun, Malta.*
ONOLAJA, Babatunde. *Lagos, Nigeria.*
SYED, Rashid Husain. *Riyadh, Saudi Arabia.*

NON-CORPORATE MEMBERS

Transfer from Student to Graduate

KWAN, Yuk Tak. *Hong Kong.*

Transfer from Student to Associate Member

DE JONG, Josephus Theodorus. *Soest, Netherlands.*
TAN, Kai Ching. *Kuala Lumpur, Malaysia.*

Direct Election to Associate Member

KHAN, Masroor Hasan. *Ndola, Zambia.*
TEO, King Hock. *Singapore.*

STUDENTS REGISTERED

CHAN, Charm Fung. *Hong Kong.*
CHAN, Chi Ming. *Hong Kong.*
CHAN, Leung Ting. *Hong Kong.*
CHEUNG, Kwok Keung. *Hong Kong.*
CHEUNG, Lin-Sang. *Hong Kong.*
CHU, Wing Pong. *Hong Kong.*
FUNG, Yat Tong. *Hong Kong.*
GOH, Seng Khim. *Singapore.*
IP, Yan Ling. *Hong Kong.*
KOH, Liang Tee. *Penang, West Malaysia.*
LAM, Ka-Fai. *Hong Kong.*
LAU, Chi Wai. *Hong Kong.*
LAU, Wing Fat. *Hong Kong.*
LEE, Chi Keung. *Hong Kong.*
LIM, Chee Chein. *Singapore.*
NG, Chi Hung. *Hong Kong.*
POON, Chiu Hung. *Hong Kong.*
TANG, Chai Chung. *Hong Kong.*
VALASUBRAMANINADAR, Nagaraj Perumal. *Madras, India.*
WONG, Kim Chung. *Hong Kong.*
YU, Shu Pui. *Hong Kong.*

Meeting: 20th January 1977 (Membership Approval List No. 229)

GREAT BRITAIN AND IRELAND

CORPORATE MEMBERS

Transfer from Member to Fellow

CLEMENTS, Arthur John Baskett. *Chorleywood, Hertfordshire.*
HARRISON, Anthony Frederick. *Galashiels, Selkirkshire.*
MALSTER, John. *Ross-On-Wye, Herefordshire.*
STONE, Geoffrey Malcolm Cecil. *London.*

Transfer from Graduate to Member

BABER, Bryan. *Emsworth, Hampshire.*
KING, John Patrick. *Malvern, Worcestershire.*
MARSLAND, David. *Royton, Lancashire.*
WYLES, Gordon. *Crowthorne, Berkshire.*

Transfer from Student to Member

BUTTIMER, Malcolm Douglas. *Romsey, Hampshire.*

Direct Election to Member

CHAIMOWICZ, Jean-Claude Adam. *Greenford, Middlesex.*

NON-CORPORATE MEMBERS

Transfer from Student to Graduate

AGGARWAL, Om Prakash. *Manchester.*
AKINWALE, Isaac Adeladun. *London.*
GETHING, David Bernard. *Slough, Buckinghamshire.*
KHAN, Mahmood Ahmad. *Putnoe, Bedford.*
PUDNER, Anthony Richard Gordon. *Glasgow.*
TULLY, Michael Francis. *Dublin.*
ZAURO, Mohammed Umar. *London.*

Direct Election to Graduate

BARLEY, Michael. *Keston, Kent.*
GUY, John Reginald Francis. *Wimborne, Dorset.*
THOMAS, Christopher Ian. *Canterbury, Kent.*

Transfer from Student to Associate Member

GARA, Michael C. *Dublin.*

Direct Election to Associate Member

JAKOMIN, Vincent. *Richmond, Surrey.*
MAIRIS, Michael Edward. *Portsmouth, Hampshire.*
MOTT, Robert James. *Epsom, Surrey.*
SUTHERLAND, George Henderson. *Glasgow.*

Transfer from Student to Associate

AKHTAR, Faheem. *Chelmsford, Essex.*

STUDENTS REGISTERED

ABDULLAH, Julian. *Nottingham.*
AL-BORND, Mohammed Malik. *Nottingham.*
ALDRED, David Charles. *Beeston, Nottinghamshire.*
AL-SAUDI, Jamal Moh'd Zuhein. *Nottingham.*
AL-SHARABRTI, Adel Moh'd Ahmed. *Nottingham.*
BARON, Paul Jackson. *Nottingham.*
BENYON, Paul Robert. *Nottingham.*
BOURNE, David Ronald. *Nottingham.*
BERRY, Michael Charles. *Nottingham.*
CARDY, David Royston. *Nottingham.*
COOPER, Alan James. *Nottingham.*
DE LACERDA, Pedro Manuel Lacerda. *Nottingham.*
ELLISON, Martin Ernest. *Nottingham.*
GANT, Ian Michael. *Nottingham.*
GARRETT, John Edward. *Dublin.*
HUTCHINSON, Joan Neil. *Long Eaton, Nottingham.*
HOUSDEN, Jeremy Richard. *Nottingham.*
HUNTER, Philip James. *Felixstowe,* Suffolk.
JOWERS, Brian Charles. *Ipswich, Suffolk.*
KHRAIM, Iyad Hussni. *Nottingham.*
KONG, Chee Khiong. *Nottingham.*
KTORIS, Christakis Z. *London.*
LAWDAY, Richard Mark. *Nottingham.*
LESLIE, James Barrett Maclaren. *Nottingham.*
LINDSAY, Peter Stewart. *Nottingham.*
LONGSON, Stephen Clive. *Nottingham.*
MAHMOOD, Arshad. *Nottingham.*
MARSHALL, Christopher John. *Crayford, Kent.*
MARSHALL, Stephen. *Nottingham.*
McGEOUGH, Geoffrey Joseph. *Nottingham.*
MORGAN LLOYD, Mark Robert Francis. *Nottingham.*
MURPHY, Martin. *Nottingham.*
NADESAN, Thilaganathan. *London.*
PARKER, Michael Andrew. *Nottingham.*
POOLE, Simon Blanchette. *Nottingham.*
RAMPTON, Rodney Howard Oliver. *Reading, Berkshire.*
RICHARDS, David Alan. *Nottingham.*
ROBSON, Harry Frederick. *Nottingham.*
SAIEPOUR, Mansour. *Nottingham.*
SANDLER, Reuel Zeev Dov. *London.*
SEET, Ai Choo. *Nottingham.*
SHORT, Christopher Alan. *Bristol.*
SHIM, Siong Lit. *Nottingham.*
SINGH, Kulwant. *Leicester.*
SINGLETON, Mark Andrew Ralph. *Nottingham.*
SMITH, Nigel Christopher Victor. *Ipswich, Suffolk.*
STINSON, Mark William. *Nottingham.*
STONE, Kenneth Rodney. *Nottingham.*
SWITHINBANK, David Michael. *Nottingham.*
TANG, Stephen Shun Lam. *Nottingham.*
TATTERSHALL, Paul Richard. *Ipswich, Suffolk.*
TAYLOR, Richard Carey. *Nottingham.*
THOMPSON, Keith Martin. *Nottingham.*
TURNER, Steve George. *Nottingham.*
TYDEMAN, John Robert. *Nottingham.*
WAN YAACOB, Wan Rakiah. *Nottingham.*
WIMPENEY, Jonathan Francis. *Nottingham.*
WOOD, James Robert Duncan. *Nottingham.*
YEAP, Soon Guan. *Nottingham.*
YEUNG, David Yui Kwong. *London.*
YOUNG, Stephen John. *Nottingham.*
ZIAHMEHR, Mehrdad. *Nottingham.*

OVERSEAS

CORPORATE MEMBERS

Transfer from Associate Member to Member

SAUNDERS, Roger Thomas. *Hong Kong.*

Transfer from Student to Member

LEE, Siu Kee. *Sunnyvale, California.*

Direct Election to Member

CHANG, Yi Ping. *Kuching, Sarawak, Malaysia*
CHIEW, Ah Peng. *Kuala Lumpur, Malaysia.*

NON-CORPORATE MEMBERS

Transfer from Student to Graduate

CHAN, Wai Chung. *Hong Kong.*
LAU, Wai Man Paul. *Hong Kong.*
NG, Tat-Keung. *Hong Kong.*
TALHA, Lamin. *Tripoli, Libya.*
TANG, Chi Wai. *Hong Kong.*
WONG, Hon-Shu. *Hong Kong*

Direct Election to Graduate

JAYADEVA, Kanthasamy. *Point Pedro, Sri Lanka.*
SIMPSON, Michael. *B.F.P.O.* 30, *Germany*
ZAHID, Ali Amin. *Chicago, Illinois.*

Transfer from Student to Associate Member

CLIFTON, Archibald McKenzie. *Guyana.*
LINNELL, Graham John. *Nicosia, Cyprus.*
LOW, Kum Choy. *Singapore.*
NG, Sin Hai. *Singapore.*
YUEN, Chuk-Leung. *Hong Kong.*

Direct Election to Associate Member

AKINWALE, Stephen Abidun, *Ibadan, Nigeria.*
ALAVI, Mohammad Bagher. *Abadan, Iran.*
BODENSHON, Karlheinz. *Mbabane, Swaziland.*
BURAIMOH, Fatai Olawale. *Lagos, Nigeria.*
CHIN, Toh Watt. *Singapore.*
FOO, Chee Hong. *Selangor, Malaysia.*
HARRIS, Harold Henry. *Ottawa, Ontario.*
NSA, Okon Eyo. *Ughell, Nigeria.*
SOYINKA, James Oluranti. *Lagos, Nigeria.*
STEEL, John William. *Manama, Bahrain.*
YERIMA, Yusufu. *Zaria, Nigeria.*

Direct Election to Associate

BABRA, Ravinder Singh. *Campinas, Brazil.*
JOSHI, Umiyashanker. *Nairobi, Kenya.*
THOMAS, Gordon Reginald. *Limassol, Cyprus.*

STUDENTS REGISTERED

BOK, Kwee Eng. *Singapore.*
CHEE, Chong Por. *Singapore.*
LEE, Fook Meng. *Singapore.*
LIM, Jui Khaing. *Singapore.*
LIM, Kim Eng. *Singapore.*
OBITAYO, Rasaki Abimbola. *Ile-Ife, Nigeria.*
ONG, Boon Ngo. *Singapore.*
ROSLAN, bin Julis. *Selangor, Malaysia.*
SOH, Kok Ghee. *Singapore.*
YEO, Lily. *Singapore.*

STANDARD FREQUENCY TRANSMISSIONS

(Communication from the National Physical Laboratory)

November 1976	Deviation from nominal frequency in parts in 10^{10} (24-hour mean centred on 0300 UT)	Relative phase readings in microseconds NPL—Station (Readings at 1500 UT)	
	Droitwich 200 kHz	*GBR 16 kHz	†MSF 60 kHz
1	0·0	OFF AIR	OFF AIR
2	0·0	OFF AIR	OFF AIR
3	−0·1	OFF AIR	OFF AIR
4	0·0	OFF AIR	OFF AIR
5	0·0	OFF AIR	610·0
6	0·0	OFF AIR	610·0
7	0·0	700·0	610.0
8	0·0	700·0	610·0
9	−0·1	701·6	610·1
10	0·0	702·8	610·0
11	0·0	702·3	609·8
12	0·0	701·7	610·0
13	−0·1	—	610·1
14	−0·1	—	610·0
15	0·0	699·3	609·8
16	0·0	701·8	609·8
17	0·0	700·0	610·0
18	0·0	701·0	609·7
19	0·0	701·5	609·7
20	0·0	—	609·8
21	0·0	701·5	609·7
22	0·0	701·0	609·7
23	0·0	—	609·4
24	0·0	700·5	609·6
25	0·0	—	609·4
26	0·0	701·7	609·5
27	—	701·3	609·5
28	0·0	—	609·4
29	0·0	701·3	609·5
30	0·0	—	609·3

December 1976	Deviation from nominal frequency in parts in 10^{10} (24-hour mean centred on 0300 UT)	Relative phase readings in microseconds NPL—Station (Readings at 1500 UT)	
	Droitwich 200 kHz	*GBR 16 kHz	†MSF 60 kHz
1	0·0	701·6	609·4
2	0·0	701·1	609·2
3	0·0	701·9	608·7
4	0·0	701·0	608·7
5	0·0	699·6	608·7
6	0·0	699·5	608·7
7	0·0	699·3	608·4
8	0·0	699·5	608·5
9	0·0	699·9	608·3
10	0·0	701·7	608·1
11	0·0	700·6	608·0
12	0·0	700·3	608·0
13	0·0	700·9	608·0
14	0·0	700·6	608·0
15	0·0	701·1	607·8
16	0·0	699·7	608·0
17	0·0	699·9	607·6
18	0·0	700·3	607·7
19	0·0	700·1	607·5
20	0·0	699·1	607·3
21	0·0	699·6	607·4
22	0·0	698·9	607·4
23	0·0	698·3	607·4
24	0·0	697·3	607·2
25	0·0	699·8	607·4
26	0·0	699·2	607·4
27	0·0	699·5	607·2
28	0·0	699·3	607·2
29	0·0	699·5	606·8
30	0·0	699·5	606·8
31	0·0	699·6	606·6

All measurements in terms of H-P Caesium Standard No. 344 agrees with the NPL Caesium Standard to 1 part in 10^{11}.

* Relative to UTC Scale; (UTC_{NPL}–Station) $= +500$ at 1500 UT 31 December 1968.

† Relative to AT Scale; (AT_{NPL}–Station) $= +468{\cdot}6$ at 1500 UT 31 December 1968.

Forthcoming Institution Meetings

Wednesday, 2nd March

EDUCATION AND TRAINING GROUP

Colloquium on THE FUTURE OF HIGHER DIPLOMAS

Southampton College of Technology, 10.30 a.m.

Tuesday, 8th March

JOINT IEE/IERE/BES MEDICAL AND BIOLOGICAL ELECTRONICS GROUP

Physiology for engineers—5

Botany Lecture Theatre, University College London, 6 p.m.

Wednesday, 16th Marth

COMMUNICATIONS GROUP

Colloquium on A COMPARISON OF SAWS, CCDS AND DIGITAL SYSTEMS

Royal Institution, Albemarle Street, London W1, 2 p.m.

Advance registration necessary. For further details and registration forms, apply to Meetings Officer, IERE.

Tuesday and Wednesday, 22nd and 23rd March

AUTOMATION AND CONTROL SYSTEMS GROUP

First IERE Easter Vacation School on THE PRACTICAL USE OF CONTROL THEORY

Reading University

For further details see December Journal page 631. Advance registration is necessary. Apply to Meetings Officer, IERE.

Thursday, 24th March

COMMUNICATIONS GROUP

Colloquium on RECENT DEVELOPMENTS IN AMATEUR RADIO

Royal Institution, Albemarle Street, London W1, 2 p.m.

Advance registration necessary. For further details and registration forms, apply to Meetings Officer, IERE.

Thursday, 21st April

JOINT IEE/IERE COMPUTER GROUP AND IERE AUTOMATION AND CONTROL SYSTEMS GROUP

Design philosophy of pocket calculators

By Clive Sinclair (*Sinclair Radionics*)

Manson Theatre, London School of Hygiene and Tropical Medicine, 6 p.m.

Tuesday, 26th April

ELECTRONICS PRODUCTION TECHNOLOGY GROUP

Colloquium on NEW TECHNIQUES AS AIDS TO PRODUCTION

Royal Institution, Albemarle Street, London W1, 10.30 a.m.

Advance registration is necessary. For further details and registration forms, apply to Meetings Officer, IERE.

Thames Valley Section

Wednesday, 23rd February

Signal processing in conjunction with the H-P 3000 computer

By D. Cox (*School of Signals, Blandford Forum*)

School of Electronic Engineering, Arborfield, Berks., 2.30 p.m.

Tuesday, 22nd March

Development of interactive computer-aided design of closed-loop control systems

By A. H. Allen and P. Atkinson (*Reading University*)

(see Eastern Vacation School, London Meetings)

Reading University, 7.30 p.m.

Thursday, 28th April

Annual General Meeting followed by

L.S.I. logic systems design

By Professor D. Lewin (*Brunel University*)
Caversham Bridge Hotel, Reading, 7 p.m.

South Western Section

Wednesday, 2nd March

Acoustical imaging and holography

By Professor J. W. R. Griffiths (*Loughborough University of Technology*)

Room 2E3.1, Bath University, 7 p.m. (Tea 6.30 p.m.)

Wednesday, 23rd March

Train control developments in British Rail

By J. R. W. Birkby (*British Rail Research Department*)

Westinghouse Brake and Signal Company, Chippingham, 6 p.m. (Tea 5.30 p.m.)

Tuesday, 5th April

JOINT MEETING WITH IEE

Automatic handwriting and speech recognition systems

R. Watson and B. Payne (*National Physical Laboratory*)

The College, Regent Circus, Swindon, 6.15 p.m. (Tea 5.45 p.m.)

Wednesday, 27th April

Electrical and avionic systems in helicopters

By R. N. Lake and J. C. Firmin (*Westland Helicopters*)

Queens Building, University of Bristol, 7 p.m. (Tea 6.30 p.m.)

Southern Section

Tuesday, 1st March

Communications for disabled persons

By Dr. A. F. Newell (*Southampton University*)

Synopsis: The lecture will explain some of the problems of disabled people who cannot use speech to communicate, and discuss electronic techniques which can provide alternative means of communication. A description will be given of the 'Talking Brooch' developed at Southampton University, and of current research projects including a simultaneous translation facility for the deaf. Dr. Newell will also describe some developments in this field at establishments in North America which he has recently visited as a Winston Churchill Travelling Fellow.

Bournemouth College of Technology, 7 p.m.

Wednesday, 2nd March

Electronics on Saturday

By Dr. K. J. Dean (*South East London College*)

Synopsis: The techniques used in electronic engineering can be broadly classified as analogue and digital. Increasingly the engineer finds that digital methods are the answer to current technological problems. Sometimes, however, we fail to realise the inroads that digital methods have made into everyday life away from work; in short, on a Saturday. For example, motoring, banking and shopping are three areas of this kind. Digital goods are on sale, digital toys are not far behind. At home, on the road, in the town, as well as at work, we all of us are faced with an increasingly digital world, not just Monday to Friday, but electronics on Saturday, too.

Brighton Technical College, 7 p.m.

Wednesday, 9th March

Surface acoustic wave devices

By J. Heighway (*Plessey, Caswell*)

Lecture Theatre F, University of Surrey, Guildford, 7 p.m.

Wednesday, 16th March

JOINT MEETING WITH IEE

M.R.C.A. Avionics

J. E. Daboo (*EASAMS*)

Farnborough College of Technology, 7 p.m.

Thursday, 24th March

Annual General Meeting followed by

Figaro—a communication system

By D. C. Smith and G. G. Papworth (*Plessey*)

Synopsis: Figaro is a radio system that provides two-way communication between firemen operating in highly electro-magnetically screened locations. Successful operation of the system depends critically on the selection of the link radio frequency. The paper will describe the considerations that determined the design of the equipments and the results achieved.

Southampton University, Lanchester Theatre, 7 p.m.

Tuesday, 31st March

CEI LECTURE

A motorway and you

By A. W. Jacomb (*Hampshire County Council*)

The Guildhall, Southampton, 7 p.m. (Doors open at 6.30 p.m.)

Synopsis: You the Engineer, the people affected. The motorway—a road with special characteristics, the implications for the Engineer and for the Public. The concept development of a south coast road, strategy for a national motorway. Preparing for construction—design considerations for M27, design time, resources applied, site investigations, administrative procedures, Public Inquiries, the Residents and other Groups, the Public's opportunity at Inquiries, the Lilley Alternative in particular.

Construction of a Motorway, alternatives available, concrete versus black top, the Portsmouth Harbour problems, conveyor belt, slipform pavers, public relations during construction and particular problems arising such as Hamble Bridge, and Funtley Tunnel. The lecture will be illustrated by films and slides of the conveyor system in Portsmouth Harbour, site plant such as a slipform pavers at work.

Free tickets available at the door or from: IERE Southern Section Honorary Secretary J. F. Pengelly, 2 Downlands Close, Holmesland Gardens, Botley, Southampton, Hants, SO3 2SG.

Beds & Herts Section

Tuesday, 15th March

Electronics in medicine

By Dr. B. W. Watson (*St. Bartholomew's Hospital*)

Synopsis: Electronics has made a great impact on medical diagnosis and to a lesser extent on therapy. Past achievements will be reviewed and the potential for the future discussed with emphasis on the clinical and physiological aspects rather than the technological problems, which can often be overcome if they are correctly formulated for the engineer to solve.

Hatfield Polytechnic, College Lane, Hatfield, 7.45 p.m. (Tea 7.15 p.m.)

Thursday, 28th April

Annual General Meeting followed by

Instruments of the new music

By K. Winter (*University of Cardiff*)

Music Centre, Hatfield Polytechnic, College Lane, Hatfield, 7 p.m. (Tea 6.30 p.m.)

Kent Section

Thursday, 10th March

Fibre-optic data transmission

By T. Morgon and other guest speakers (*Marconi-Elliott*)

Synopsis: This presentation will deal generally with the many applications of fibre optics to data transmission and cover the roles that single fibre and multi-fibre bundles play in solving data transmission problems from the long haul high bandwidth telecommunication links to the short low data rate links required, for example, for aircraft. Components, installation and maintenance techniques including light emitting diodes, connectors, cables and fibre terminations necessary to implement such links will also be presented.

St. Georges' Hotel, New Road, Chatham, 7 p.m. (Tea 6.30 p.m.)

Thursday, 14th April

Annual General Meeting followed by

The ins (pick-ups) and outs (loudspeakers) of hi-fi systems

R. E. Cooke (*KEF Electro-Acoustics*) and a representative from Shure Electronics Boxley Country Club, Boxley, Nr. Maidstone, 7 p.m. (Tea 6.30 p.m.)

East Midlands Section

Tuesday, 15th March

Visit to Ratcliffe-on-Soar Power Station 7.30 p.m.

Tuesday, 19th April

Annual General Meeting

Hawthorn Building, Room 08, Leicester Polytechnic, 7.15 p.m.

South Midlands Section

Thursday, 24th March

Using a microprocessor—a design engineer's view

By C. Bliss (*Rapid Recall*)

Majestic Hotel, Park Place, Cheltenham, 7.30 p.m.

Wednesday, 20th April

Electromagnetic compatibility in perspective

L. J. Fountain (*School of Signals*)

Followed by Annual General Meeting Foley Arms Hotel, Malvern, 7 p.m.

West Midlands Section

Tuesday, 17th March

JOINT MEETING WITH IEE

Concorde electronics

By N. Brenchley (*B.A.C. Filton*)

Synopsis: The paper will describe, briefly, the overall electronics fit on *Concorde*. It will then discuss, in detail, the systems that are novel to *Concorde* due to the unusual characteristics of the aeroplane. In particular, the autopilot, air intake control system, engine control system and fuel system will be covered.

Lanchester Polytechnic, 6.30 p.m. (Tea 6 p.m.)

Wednesday, 6th April

Annual General Meeting followed by

Newspapers into the 80's

By D. Humphreys (*Express and Star*)

The days of Caxton and movable type are becoming part of the past with modern newspapers. Computer typesetting, computer controlled photosetters capable of producing 340 lines a minute at least and 3,000 lines a minute at most, facsimile transmission, remote control presses, computer controlled publishing and packing areas. All this and plastic plates replacing type signify the major changes the newspaper industry is undergoing.

Wolverhampton Polytechnic/Express and Star Offices, 7 p.m. (Tea 6.30 p.m.)

Merseyside Section

Wednesday, 9th March

The Royal Seaforth container terminal

By D. Smith

Department of Electrical Engineering and Electronics, University of Liverpool, 7 p.m. (Tea 6.30 p.m.)

North Eastern Section

Tuesday, 8th March

Mobile radio

By Professor W. Gosling (*University of Bath*)

Y.M.C.A., Ellison Place, Newcastle, 6 p.m. (Tea 5.30 p.m.)

Tuesday, 12th April

Multimicroprocessor system

By Dr. E. L. Dagless (*University College of Swansea*)

Y.M.C.A., Ellison Place, Newcastle, 6 p.m. (Tea 5.30 p.m.)

North Western Section

Wednesday, 30th March

JOINT MEETING WITH IEE

Who runs industry? Engineers or accountants

A discussion with professional accountants.

Manchester Business School, 6.15 p.m. (Refreshments available before meeting)

Thursday, 21st April

Flight simulation

By J. Morrison (*B.A.C. Warton*)

Renold Building, U.M.I.S.T., Manchester 6.15 p.m.

South Wales Section

Wednesday, 16th March

JOINT MEETING WITH IEE

Digital applications in television

By H. Jones (*BBC Research Department*)

Room 112, Department of Physics, Electronics and Electrical Engineering, UWIST, Cardiff, 6.30 p.m. (Tea 5.30 p.m.)

Scottish Section

Wednesday, 23rd February

Symposium on TELETEXT

Napier College of Commerce and Technology, Colinton Road, Edinburgh, 1.45 p.m.

Advance registration necessary. For further details and registration forms, apply to D. Houliston, IERE, c/o The Institute of Geological Sciences, Global Seismology, Unit, Murchison House, West Mains Road, Edinburgh EH9.