FOUNDED 1925
INCORPORATED BY
ROYAL CHARTER 1961

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

THE RADIO
AND ELECTRONIC
ENGINEER

The Journal of the Institution of Electronic and Radio Engineers

VOLUME 33 No. 1 JANUARY 1967

The Presidential Address of

Professor Emrys Williams, Ph.D., B.Eng., F.I.E.E., M.I.E.R.E.

Delivered after the Annual General Meeting of the Institution on 15th December 1966

A reader of the history of the Institution is immediately struck with the obvious advantage which the Institution has enjoyed in the ability and intellectual stature of its Presidents. Because I have no claim to outstanding achievement, I am all the more conscious of the honour that members have paid in electing me as President for the ensuing year.

In asking myself why this mantle has fallen upon me, I have looked back into our history and into the association which Past Presidents have had with particular aspects of our work. Because of my lifelong association with the education and training of engineers, apart from a short time spent in the manufacturing industry, it seems I may best serve the Institution at this particular time when so much change is taking place in education and training. It is inevitable that the Institution will play a significant part not only in contributing to planning for the future, but also in safeguarding and developing educational needs for our own profession of radio and electronic engineering.

I have admired the statesmanship of Colonel Raby and have learnt much from him. I am delighted to have the assurance that he will continue to be active in our Institution and I would like to thank him for the kindly way in which he has presented me to you tonight.

I have not been able to confine my Address to one theme, as did my predecessor. I propose to deal with certain aspects of the Institution's work which, in my submission, affect not only the well-being of our profession but indeed, the material prosperity of mankind.

Technology and Pure Science

As a professional engineering Institution, we are concerned with technology. One of the essential things about a technology is that it is related to getting things made.

The classification of technologies into categories—and, in parallel with this, the evolution of professional institutions—has always been based on the material end-product. Some of the categories are easily identified and differentiated; bridges and buildings, mechanical machinery, mines, ships, aeroplanes, chemicals and chemical plants—the list is already beginning to sound like a list of the constituent institutions of the C.E.I.!

In each category there is built up a systematic body of knowledge which is not merely 'applied' or 'technical' knowledge but includes pure science and pure mathematics. To say this is not merely to repeat the obvious fact that technology is essentially based on pure science and mathematics, but to make the point that most of the major technologies have their own specialized fields of pure science and mathematics, the development of which has been far more accelerated by the demands of the technologist than by pure scientists. To see the truth of this, one has only to ask what it was that propelled such engineers as Heaviside, Gauss and Coulomb to their well-deserved eponymous immortality.

This identification of a technology with a particular field of pure science and mathematics is particularly striking in the case of electronic and radio engineering. For example there are certain fields of physics in which the experts are more likely to be found in the

Electronic Engineering departments of our universities than in the Physics departments. There are branches of mathematics in which electronic engineers are on the whole more adept than the professional mathematician. It would be strange if it were otherwise, since electronic engineering, by its very nature, has driven its devotees to concentrate their attention on these aspects of pure science and mathematics.

To some extent this same situation applies to most branches of technology, but it is so marked in Electronic Engineering (and perhaps also in Electrical Engineering) that it raises special problems, particularly in connection with education and in the matter of our relationships with other branches of engineering.

Electronic Engineering Education

Consider first the effects of this situation in the field of engineering education. Throughout the twentieth century the history of university undergraduate studies in engineering has been one of increasing specialization. Departments of Engineering have proceeded to split into Departments of Civil, Mechanical and Electrical Engineering. It is only since the last war that Departments of Electronics or of Electronic Engineering have been set up in a few British Universities. Indeed, the magic word 'electronics' had so much recruiting potential that there was then a scramble in other universities to add the words 'and Electronic' to the title of their departments of Electrical Engineering—and also to create second chairs within the department and to appoint specialists in Electronics to these chairs.

The mathematics and physics departments of all Universities have found themselves called upon to provide more and more extensive and advanced supporting courses. Professors of Mathematics crossing a 'redbrick' courtyard have been known to vanish mysteriously among the parked vehicles because they have seen the Professor of Electronic Engineering approaching with that air of eager friendliness which always accompanies a request for a further extension of the mathematics syllabus.

Along with this increased emphasis on pure science and mathematics, for students of electronic and electrical engineering, there has inevitably had to be a decrease of emphasis on some other aspects. Surveying disappeared from the curriculum at a very early stage. Engineering Drawing has almost disappeared. There is greatly diminished emphasis on the mechanical aspects of design. In varying degree, fluid-mechanics, stress-analysis and applied thermodynamics are ceasing to be thought essential parts of electrical engineering—and especially of electronic engineering. Moreover, electronic engineering educators see less and less reason why their students should concern themselves with the design of heavy electrical machinery.

All these developments have arisen from the acute awareness of the explosive growth of the science and practice of electronics, with the resulting need to specialize if the graduate is to be able to practise in the twentieth century electronics. Not surprisingly, this feeling has also resulted in a hardening of the resistance to suggestions that *undergraduate* courses should include any substantial content of management studies or economics—though Statistics, rightly in my opinion, is increasingly included.

Despite much heart-searching on the question of including management studies, the examinations of our own Institution—and, I think I may say, of the Institution of Electrical Engineers also—are based upon very much the same view as is taken by the universities on the question of specialization. Surely the Institutions could not have done otherwise, since their obligation is to administer examinations on the basis of which they will certify persons as having had an education appropriate for Chartered Electronic and Radio Engineers and for Chartered Electrical Engineers respectively. The contents of the journals published by the two Institutions give a fair indication of the scope of modern Electronic and Radio Engineering and Electrical Engineering—and a fair indication, at the same time, of the relevance or otherwise of such subjects as fluid mechanics, stress analysis, applied thermodynamics and management.

Specialization

Yet there is a school of thought which is profoundly disturbed at the degree of specialization which has taken place in engineering education and which seizes upon this as the explanation for a whole assortment of ills.

The protagonists of this view have long sought an explanation for the national shortage of technologists, for they see clearly the connection between this and Britain's failure to expand her export markets. They have long been puzzled that the profession of engineering seems to have so little appeal to the British sixth-form boy.† They have looked at the output of the technological departments of our universities and have commented on a lack of preparedness for managerial posts.

Against this background of ills, they see in the universities and technical colleges an increasing preoccupation with the more scientific and mathematical aspects of individual technologies. They see Ph.D.'s being awarded to electronic engineers who do not

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† 'Technology and the Sixth Form Boy'. A study of recruitment to higher scientific and technological education in England and Wales. (Oxford University Department of Education, 1963.)

understand gas-turbines, and to mechanical engineers who could not describe a laser.

Without looking further afield they hasten to put two and two together—and 'Specialization' becomes a dirty word.

Almost inevitably, the first thing to crystallize out from this background of ills was the view that something must be done to improve the public image of the professional engineer, together with the thought that the first step was to establish in the public mind a clear distinction between the qualified professional engineer and the man who comes to repair the vacuum cleaner. Clearly the newly formed C.E.I. could play an important part in establishing such a distinction by unifying the existing variety of professional qualifications under the single title, 'Chartered Engineer', and at the same time making more uniform the standard of the requirements for qualification in the various branches of engineering.

Before one can spell out the requirements for qualification as a professional engineer however, it is necessary to decide (or at least to be sure in one's mind) what it is that distinguishes the professional engineer from technicians and other grades of engineer. Inasmuch as any decision has been made by C.E.I. on this basic question, it has been made indirectly and at too late a stage. It has merely emerged in the course of discussions on the structure and syllabus of the C.E.I. examination. It has emerged as a majority opinion, profoundly unacceptable to the minority.

The 'Complete Engineer'

So far as I have been able to piece it together, the majority opinion within C.E.I. is that the essential distinguishing feature of a professional engineer is that he is a man with such education, training and experience as will enable him to see a major engineering project through to completion. He is the whole engineer, the complete engineer, the man who can see the whole picture. It follows that those who hold this opinion believe that there can indeed be such a person and that there is a definable body of engineering science and knowledge which is a requirement common to *all* branches of the engineering profession.

Those who think this way are the very people who are disturbed at the degree of specialization which has taken place in British undergraduate courses in engineering, especially in Electronic Engineering. Yet I have seen no evidence whatever of reforming zeal or of any wish to influence the British universities in the direction of more general courses in Engineering. Indeed, I am sure that the C.E.I. would disclaim any such intention. Though I find it difficult to believe, I am forced to the conclusion that proper consideration of this matter has gone by default because those who hold this view of 'the complete engineer' are simply unable to imagine that there could be any legitimate contrary view.

The Common Factor

I have stated that an essential thing about a technology is that it is concerned with getting things made, with providing material amenities for the community. Whilst it would be reckless to propose this as a definition of technology, it does seem to embody the essence of what the thirteen founder institutions of C.E.I. have in common and the essence of what distinguishes them from physicists, chemists, mathematicians and other pure scientists. I think, too, that it is this common feature which is at the root of very many of the common problems which impelled the Engineering Institutions jointly to create C.E.I.

I am sure that there is no one in this room tonight who feels the slightest doubt that electronic engineering is essentially concerned with providing material amenities for the community. Let us test the truth of this by asking *just what is the particular material amenity, or end-product, which electronic engineering specializes in providing?* Radio communication equipment, broadcast and industrial television equipment, navigation and blind landing equipment, telemetry systems, guidance and tracking systems, radio telescopes, electronic computers, electronic simulators, electronic trainers and language laboratories, recording and reproducing systems, instrumentation alarm and control equipment in nuclear generating stations, in factories, in aircraft and in banks—and now prisons! Add to this, research tools in physics, chemistry, botany, zoology, physiology, medicine, etc., etc., etc.

It begins to appear that, with a variegated list like this, there may be some difficulty in categorizing our particular technology in terms of one end-product!

The truth is that the specialized interest of the electronic engineer, and the 'know-how' of which he is the special custodian, stop short of the final mechanical construction of the material end-product. To an extent, this is also true of the electrical engineer. *It is not true* of the mechanical engineer or the civil engineer. To them, indeed, it may seem heresy to suggest that it could be true of any 'engineer'.

Yet these are the facts of life in the manufacturing industries. It pays to use specialist manpower for specialist purposes. 'Complete engineers' are spread more thinly than a widow's butter.

Versatility within a Specialism

I have long ceased to be surprised at seeing a paper on, say, 'A model of the human kidney', published in a medical journal, and written by an electronic engineer. Electronics is the greatest intellectual 'nosey-parker' of all time; it has a finger in everybody else's business and is the handmaid of all sciences. This is why, when asked to name the particular material amenity which Electronic Engineering provides for the community, we cannot say 'Ships', or 'Aeroplanes' or 'Mines', and leave it at that—but are forced to name a long list of products which have only this in common: that they are electronic apparatus. None of them would be possible were it not for the pervasive magic of Electronics.

And if that pervasive magic can one day design an electronic system which can translate Russian into English, and the next day another electronic system which can guide missiles to the moon, who is going to complain that the engineer-scientists who produce this magic were trained in a school which taught them more of physics and mathematics and less of civil and mechanical engineering—and which specialized heavily in the magic itself?

Dangerous Doctrine

The era of the complete engineer able to turn his hand to any aspect of engineering saw its close thirty years ago. The last strains of the lament for the general practitioner were drowned in the tumult of the 1939–45 war. Now it is difficult to be a general practitioner even in the limited field of Electronic Engineering, so wide has that field become.

If we truly comprehend the significance of the constant accumulation of knowledge it becomes all the more difficult to understand why C.E.I. should want to put the clock back by imposing on modern studies the heavy weight of irrelevant classical technical subjects, well knowing that in the end no man will ever become the complete engineer.

To build into the C.E.I. examination the nostalgic doctrine of the complete engineer would have consequences so serious that the following implications must now be examined in detail:

I. The effect on recruitment to the profession.

II. The effect on electronic engineering education and the position of this Institution.

III. The effect on C.E.I. itself.

I. Recruitment

It is at the higher levels of management that a general knowledge begins to be more important than a specialized knowledge. Management, like whisky, is an acquired taste; neither of them has much drawing-power for most schoolboys. In a suitable environment, however, both tastes are fairly readily acquired, later in life. In both cases, detailed study is best deferred until that maturity has been reached which ensures a proper appreciation and a painless indoctrination free from garbled oversimplification.

It is important to take full advantage of the very considerable momentum of the science-based motivation of the schoolboy. We must not push the opposite way on the door which he is trying to get through. That is what we are doing if, with an eye to preparing him for the higher levels of management, we prevent him from concentrating adequately on the branch of technology which has fired his enthusiasm.

The motivation of the schoolboy is inspirational and specialized. In my experience, civil engineering students are motivated by the impressive and daring magnitude of civil engineering structures and projects. The most common and most potent motive for becoming an electronic engineer is a fascination with the ingenuity and versatility of electronic devices. In electrical, aeronautical, mechanical, marine engineering, the motivation arises again predominantly from the spectacular nature of modern developments in those particular fields.

The resulting image of the engineering profession may be immature, but it is alive, potent and durable —and an excellent demonstration of what makes engineers kinsmen. It would be not only iconoclasm but folly to daub this lively image with worldly wisdom, as is done by some industrialists who visit schools and give the impression that marketing, management and costing are the most important ingredients of engineering practice. If we are to add to these casual indiscretions a permanent recruiting poster showing the 'complete engineer', clad in pre-war clothing and vainly trying to be all things to all men—instead of fixing his eye upon the particular 'marvels' which have inspired him—then we must not be surprised if even more of the best sixth-form schoolboys opt for higher studies in pure science and the arts rather than technology.

II. Education and the Professional Institutions

Our Institution came into being to meet an unsatisfied demand for specialized education and certified qualification in what is now called Electronic and Radio Engineering. Looking back at those early days, one sees that one of the impediments to the provision and recognition of such specialized education was a dogged adherence to an earlier version of this doctrine of the 'complete engineer' coupled with a failure to appreciate the integrity and the growth-potential of a new applied science.

How wrong-headed was this obstruction was seen not only during the war, but in the phenomenal growth of electronic engineering and the application of electronics at the present time. Electronics is now recognized as being one of the most potent forces in our national economy.

We all recognize that the impediments faced by our own Institution in its early days were but a repetition of the difficulties experienced by our sister Institutions, including the Electricals and the Mechanicals. Alas, there still seems to be resistance to new development.

Specialization is the *raison d'être* and the life blood of every professional Engineering Institution. It was the evolution of an adequately well-defined new specialism, sufficiently viable to promote its own sector of industry, which brought every professional Institution into being. This is a simple example of the law of supply and demand, and if any professional Institution fails to meet the real demand for its services, over the whole or part of its specialized territory or over any newly-discovered adjacent territory, then that unsatisfied demand will inevitably be met by others.

Impelled partly by this, the Institution's Education and Examinations Committees regularly survey our territory to see what further ground should be covered in the final stages of the Institution's examination, and what consequential changes are required in the earlier parts of the examination. It is now proposed, however, that this task, and the corresponding activity in each of the other thirteen constituent Institutions, shall be undertaken by the C.E.I. How has this come about?

C.E.I. as an Examining Body. One of the purposes for which the thirteen founder Institutions came together in the Council of Engineering Institutions was to enable them to rehabilitate the public image of the professional engineer by unifying existing qualifications under the single appellation 'Chartered Engineer'. For this purpose it would clearly be necessary to ensure uniformity of the *standard* of educational qualifications demanded in the various branches of engineering.

But this does not explain why C.E.I. has found it necessary to conduct its own examinations. It would have been perfectly possible for C.E.I. to have been not an examining body but a certifying body, looking at the examinations conducted by the constituent Institutions and pronouncing judgement on whether they were of adequate standard for the award of the 'C.Eng.' qualification. The task would not have been an invidious one since there was already agreement among the constituent Institutions, and with representatives of government, that the standard should be that of a pass-degree in a British university. Several of the constituent Institutions were already conducting examinations of their own which are approximately of this standard, and accepted by government and other major employing authorities as giving a reliable assurance of qualification as a professional engineer.

The original ideas which prompted the Institutions to form a common Council were to encourage cross-fertilization of knowledge and to enable the engineering profession as a whole to speak in unison on matters of common interest. In the process of forming the Council the question of common standards had to be considered and was first resolved by confining membership of the Council to those engineering Institutions which, by the possession of their Royal Charters of Incorporation, had already proved their competence to certify the qualifications of specialist professional engineers.

Notwithstanding correspondence in *The Times* and elsewhere, as recently as 1965, the function of the C.E.I. *as an examining body* was not popularly understood and was neither specified nor precluded in its Royal Charter. In retrospect, it may seem surprising that this extension of powers from certification to examining was not clearly defined before the granting of the Royal Charter.

The probable reason why no constituent Institution raised the matter is that it was not understood at that time that the intention was for the C.E.I. examination completely to supersede the examinations of the constituent Institutions, without the possibility of these being considered as exempting qualifications. Nor was it anticipated that the doctrine of the 'complete engineer' would find majority acceptance, or that the examination would be based on the assumption that no specialization would be permitted for the first eighteen months of the proposed three-year course of full-time study after G.C.E. A-level examinations.

There has not perhaps been full realization of the significance of majority decisions until after they had been taken. The present position is that our Institution (in common with all the others) is now expected by C.E.I. to discontinue its own Graduateship examination in favour of a C.E.I. examination syllabus which bears a strong resemblance to the syllabuses of thirty years ago—those same examination syllabuses whose inadequacy for the purposes of the radio and electronic engineer led to the formation of our Institution.

Therefore, this is not a matter of awkward detail, but is fundamental. I would not have said so much about it in this Address had I not believed that this may be a turning point not only in the affairs of our own Institution, but in the future well-being of the C.E.I. itself.

III. The Effect on C.E.I.

The earnestness of my criticism of the doctrine of the 'complete engineer' and of the proposed examination structure must not be allowed to obscure the enthusiasm of our Institution for the Council of Engineering Institutions and the purposes expressed in its Charter. In the light of the ideals embodied in its Charter my criticism will, I trust, be seen to be constructive since the decision to create a Ministry of Technology, together with successive ministerial statements, have made it clear that the British government recognizes the vital role of technology in maintaining the economic virility of this country. One of the first necessities for maximizing the contribution of technology to national prosperity is an efficient two-way channel of communication between government and technologists. C.E.I. will, we hope, be the telephone exchange at the 'technology end' of this hot line.

The process has already begun of establishing permanent lines of communication between the technologists of Britain and the technologists of the continent of Europe, with C.E.I. playing the key role. He would indeed be far-sighted who could foresee all the benefits of establishing this channel of communication. It is clear, however, that one of the early tasks will be for British technologists to establish their credentials in Europe and vice versa. Without the Council of Engineering Institutions this would be a much more difficult undertaking, and other undertakings which depend upon mutual recognition could be delayed or even neglected.

Despite the community of interest which has brought together the constituent Institutions of C.E.I., it is inevitable that the different fields in which they operate lead to differences of emphasis and differences in interest. There are aspects of the work of any one Institution which may be unknown to others or, if known, may not be similarly valued. Although there has been a degree of association in the past, the regular and formal voluntary association within C.E.I. will undoubtedly increase mutual understanding and reveal new areas of profitable collaboration.

Frank discussion of attitudes which may hitherto have been regarded as irreconcilable, may lead to acceptable compromises or, better, to an imaginative reconciliation which does not involve compromise. The two attitudes to the doctrine of the 'complete engineer' perhaps come into this category. Novel degree courses such as the Newcastle degree in 'Arts and Engineering' and the Swansea degree in 'Industrial Engineering' which are intended to co-exist with (and not replace) existing specialized courses in the individual branches of Engineering, may suggest an approach to such a reconciliation.

Guide Lines

If these high hopes for C.E.I. are to be realized, there are certain quite clear guide-lines which must be followed. Since C.E.I. will collect and collate expert knowledge and advice from its constituent institutions, who are the specialists in their own fields, it follows that C.E.I. must never aspire to exert any control in the interests of administrative uniformity, which would restrict the availability of this expert knowledge or reduce the ability of the constituent institutions to develop and expand the activities which generate this expert knowledge.

It is thus essential for the achievement of the objects of C.E.I. that it shall be thought of as a *Council* and not as an incipient mammoth institution. Opinions have differed violently on the question whether Britain could, with advantage, replace her present multi-institution structure by a single institution for all engineers, notwithstanding warning examples from overseas. Any attempt, by those who favour such a course, to use C.E.I. as the first stage in the process, would make C.E.I. impotent to discharge its main functions.

The goodwill that now exists among the participating institutions is, in my view, already robust enough for the lifting of any taboo on discussion of this very basic issue. The resulting clarification would bring a bonus of even greater goodwill, besides helping to establish a much needed criterion for deciding whether this or that proposed activity is proper to the C.E.I. or should continue to be undertaken by the individual institutions.

Decisions on such questions are already being taken without recourse to any guiding principle. Examples are the function (if any) of provincial centres of C.E.I.; the relation (if any) of C.E.I. with technician bodies; the function (if any) of C.E.I. in extending the work of individual institutions in commonwealth countries. As indicated earlier, I firmly believe that the examining function is one which should have remained with the individual institutions.

Definition of Engineering

There is a second guide-line, which follows logically from our hopes of what C.E.I. can achieve in the way of maximizing the contribution of technology to prosperity. The word 'Engineering' in the title 'Council of Engineering Institutions'—and in the reference to 'Principles of Engineering' in the bye-laws—must not be given a restrictive interpretation. It is here that I most fear the implications of the doctrine of the 'complete engineer'.

Let me explain. I have heard it said that if the I.E.R.E. cannot accept a common examination which is so eminently acceptable to Civil, Mechanical and Chemical Engineers, and others, then Electronic Engineers cannot really be Engineers at all, but are Applied Scientists.

Such a viewpoint (it is far more common than we realized) bespeaks a willingness to define Engineering as something less than the whole field of technology. A restricted definition of this kind would inevitably result in a damaging restriction in the effectiveness of C.E.I. Had there been any such *understood* restriction on the interpretation of 'Engineering', it would not have been proper for this Institution, and, I suggest, others, to have been one of the founder members of C.E.I.

Perhaps the most serious danger arising from such a restricted definition of Engineering lies in the barrier which it could erect to the recognition by C.E.I. of new branches of technology. There can be no doubt that, within the lifetime of many of today's Chartered Engineers, new professional bodies will be called into being by the growth of new specialist technologies which cannot easily be fitted into the territory of existing professional institutions. It would be ironical (to say the least) if a corporate organization for the promotion of technology were to feel itself in any way *embarrassed* by the emergence of new technologies.

A mere twenty-five years ago, there was no nuclear engineering, no semiconductor industry, no computer industry, no radio astronomy, no space programme, no jet aircraft and even no television service anywhere in the world except the one that was in deep freeze at Alexandra Palace, awaiting the return of peace. No one can doubt that the remaining thirty-four years of this century are likely to produce an even more impressive list of spectacular technological innovations.

Research and Development

Presidential addresses have a licence to speculate about the future. Some of the predictions made by my predecessors have been uncannily accurate. With the greatest respect I suggest that they would have been even more accurate if they had depended not on the intuition of one man, but upon a systematic piece of team-work, aimed at monitoring all available information about current research and development in this and other countries. It would be invaluable (commercially, scientifically and socially) to have even half a glimpse of what will be the main achievements of the next ten or twenty years. A by-product of such a project would be the greater insight with which British research could be directed into the most profitable channels.

To what extent should research be so directed? It would be idle to deny that some of the profoundest discoveries have been made by dedicated men and women free to think about pure science and mathematics for its own sake. It would be folly not to insist that opportunities shall continue to exist for this to go on happening. But it would be foolish, and at least equally dangerous, to encourage the fashionable belief that pure research, research without any discernible application, is the only research that matters—or to condone the superstition that only such purer-than-pure investigations deserve the name of research and that the rest should be dubbed 'development'.

It was *not* a scientific discovery, born of pure research, which eventually made it possible for men to see what is happening a thousand miles away. It was the invention and development of the cathode-ray tube and its associated electronic circuitry. (It is true that earlier discoveries in the field of pure physics are involved, but no one is going to call either Clerk Maxwell or J. J. Thomson the inventor of television.)

The organization of *pure* research in a community is inherently difficult; one can do little more than to organize the provision of opportunities and support. The organization and co-ordination of *applied* research, on the other hand, even where the application is relatively remote or ill-defined, is not only possible but would pay enormous dividends. I feel sure that posterity will look back at the twentieth century with astonishment—astonishment at the lack of a systematic and sophisticated organization for the development of our potential of inventiveness. It is possible that one of the impediments to the development of such organization is an uncertainty about who will reap the enormous dividends. It is possible that another impediment is the fear that 'pure research' with its licence for free-thinking, would be 'organized' out of existence. Frank discussion and straight thinking could remove both these impediments.

But the greatest impediment of all is that at present no one, even among those who sense the possibilities, can foresee at all clearly the kind of systematic and sophisticated organization which will be necessary. The first step to take is however fairly obvious, at least in general terms. It is to make the maximum use of modern computer techniques for the collection and dissemination of scientific and technological information.

Selective Dissemination of Information

I am proud that it was our own Institution, led by our Charter President, Lord Mountbatten, which was the first to see this clearly and which had sufficient faith and tenacity to press for the formation of the National Electronics Research Council and to give vital support to the project which has come to be known by the letters S.D.I. (the Selective Dissemination of Information).

The academic problems associated with this project are at least as challenging as those associated with the use of computers for translating the written word from the language of one country to that of another. The technological problems involved will probably be such as to limit the scope of the project, but there can be no doubt that there will be pressures from other quarters (industrial, sociological and military) to solve such technological problems. With their solution, the scope of the S.D.I. project may be extended almost beyond recognition, perhaps providing an automated extension to man's memory and his power of association of ideas which will have repercussions in many walks of life.

In this connection the events of the past month have aptly demonstrated the plea that I have made for Institutions to work together for a common purpose without losing their identity. I refer to the future administration of the S.D.I. project.

It is over twenty years ago that members of this Institution were enthralled by the idea of applying electronics in the form of computers for tackling the information explosion, but it was only when the National Electronics Research Council was created that we were able to see the means whereby this vision of the future could be turned into practical reality.

Our sister Institution—the Institution of Electrical Engineers—has for nearly seventy years also been addressing itself to the problem of retrieving information useful to the engineer, and in this time they have garnered great experience in tackling first by hand, then by mechanical processing, and now by computer, the production of their *Science Abstracts*.

As you all know, the experimental work done by the National Electronics Research Council—incidentally in our Institution's own building—to determine the feasibility of the S.D.I. project, finally resulted in *The Institution of Electronic and Radio Engineers* being offered management of the project with the aid of a 100% government financial grant. We recognized, however, the national need to 'slot in' as far as possible all information retrieval systems, whilst at the same time keeping before us the immediate purpose of the S.D.I. project, which is to ensure current awareness. It was therefore in the national interest that we suggested it would be advantageous for the I.E.E. to administer the S.D.I. project, bringing to that project their experience and knowledge, and perhaps 'slotting in' their *Science Abstracts*.

It is typical of the cordial relations which we have established with our sister Institution that they have invited us to join the Board responsible for the production of their Abstracts and also to continue our association with the S.D.I. project.

This invitation is completely in character, as I can vouch from my own personal experience as our Institution's representative on the joint I.E.E.-I.E.R.E. committee formed under the aegis of the Department of Education and Science to administer the Higher National Certificate and Diploma scheme in electrical engineering and electronics. It is but one manifestation of our collaboration in various fields in the interests of the engineering profession as a whole.

One further word on the future activities of the National Electronics Research Council. The view I have expressed on the great advantages accruing from being able to 'glimpse ahead' aligns exactly with the function that I see N.E.R.C. performing in the future —as indeed has already been demonstrated by proving the feasibility of the S.D.I. project.

Conclusion

I regret having omitted from this Address greater reference to the role which our Institution can play not only in Europe but in those Commonwealth countries in which we have a valued membership. I have, however, indicated ways in which we can through C.E.I. assist in promoting stronger links with our members outside Great Britain. It is very satisfying to record that our association with N.E.R.C. has also provided a means whereby we can share with our Commonwealth membership future ideas for technological development in electronics.

At this time of year we are all involved in traditional customs. We regret the things that have not been done or, more commonly, not been done properly, and look forward to a new year with great hopes.

Our hopes and wishes can be achieved only if we work together in order to obtain what is good for all. The role of the engineer in ensuring the future happiness of the world is now recognized.

With you all, I hope that our Institution may make a great contribution to securing the happiness we all want for the future. My task as President is to assist our membership in the achievement of that aim.

(*Address No. 37*)

U.D.C.621.372.57

Synthesis of R-C Zero Sections

By

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Summary: A passive R-C synthesis is presented for transfer functions containing complex or imaginary zeros in the left half of the p-plane. The poles of the function are required to be negative real.

The synthesis procedure is extremely simple and requires very little computation. The networks described and realized are basically twin-T structures which can contain a load, series source impedance or a bridging network depending on the nature of the transfer function to be synthesized. Examples of frequency response curves are given.

Primarily this synthesis procedure is intended to provide for the realization of zero sections in active filter synthesis.

1. Introduction

It is frequently advantageous or necessary to avoid the use of inductors. This is especially apparent when low-frequency applications are considered. Following the trends towards integrated circuitry and micro-miniaturization, R-C networks are found to be most convenient.

Due to this, investigation into the design of R-C circuits, even at the cost of increased circuit complexity and a reduction in maximum gain, have been carried out. In R-C synthesis of passive networks the poles of the network function appear on the negative real axis in the $p = \sigma + j\omega$ plane. Poles having other locations can only be realized by active R-C-synthesis methods.[1] With the present synthesis procedure the zeros may lie anywhere in the left half of the p-plane or on the $j\omega$-axis. Due to this fact, the poles of the voltage transfer function are restricted to the negative real axis, the quality of approximation to an ideal filter characteristic is hereby seriously limited. For high-order realization of functions however one normally resorts to a cascade connection of low-order sections.

The realization of high-order networks as a complete entity is not very attractive.[2,3] The main reason for this lies in the fact that it is not possible to ensure maximum gain for the networks thus realized. Furthermore it becomes extremely difficult, if not impossible to control the component value spread and the sensitivity with regard to component variations.

2. Basis of the Synthesis

The transfer functions of networks employing lumped elements are rational functions of frequency.[4] The biquadratic voltage transfer function for this synthesis procedure is of the general form

$$D(p) = H \cdot \frac{p^2 + 2\delta p + \omega_o^2}{p^2 + 2\sigma p + \omega_n^2} \qquad \ldots\ldots(1)$$

Here H is the gain constant always associated with voltage transfer functions. Equation (1) represents the transfer function of a basic second-order network unit. It was stated above that the zeros can be anywhere in the left half of the p-plane, but it is also possible to have an all-pole function and thus eqn. (1) represents a second-order function for which any passive R-C network can be derived. The voltage transfer function of eqn. (1) can also be expressed in terms of the network admittance parameters as

$$D(p) = \frac{-Y_{21}}{Y_{22}} \qquad \ldots\ldots(2)$$

Considering the biquadratic function eqn. (1) the realized R-C network is expected to be of the parallel ladder type.[5,6] Because of this the numerator and denominator of eqn. (2) is conveniently split into two parts representing the individual ladder structures. For all-pole functions however only a single ladder is realized and thus eqn. (2) need not be modified.

Thus the numerator Y_{21} is split into two parts Y_{21a} and Y_{21b}. Similarly for the denominator one obtains the admittances Y_{22a} and Y_{22b}. One of these admittances when realized represents a high-pass and the other a low-pass ladder.

Next the gain constant H of the voltage transfer function has to be taken into account. If $H = \omega_n^2/\omega_o^2$, then maximum realizable gain at all frequencies is ensured for the synthesized network. For this present synthesis method, H is associated with the denominator polynomial so that eqns. (1) and (2) can be rewritten as

$$D(p) = \frac{p^2 + 2\delta p + \omega_o^2}{(\omega_o^2/\omega_n^2)p^2 + (\omega_o^2/\omega_n^2)2\sigma p + \omega_o^2}$$

$$= -\frac{Y_{21az} + Y_{21b}}{Y_{22az} + Y_{22b}} \qquad \ldots\ldots(3)$$

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For the realization it is now necessary to choose a divisor polynomial $F(p)$; this polynomial can be one order less than the transfer function polynomial. A realizability condition is that the constant term of the divisor polynomial be larger than 2δ. Thus it is convenient to write

$$F(p) = p+(\omega_m+2\delta) \qquad \text{......(4)}$$

Realization requires that $\omega_0^2 \geq \omega_n^2$; if $2\delta = 0$ the realized network would be a loaded or unloaded twin-T while for $2\delta \neq 0$ the whole T structure would be bridged by an element Y_z. The identification of the admittance parameters eqn. (3) is given as

$$Y_{21az} = \frac{2\delta p+p^2}{(\omega_m+2\delta)+p} \qquad \text{......(5a)}$$

$$Y_{22az} = \frac{\xi p+p^2}{(\omega_m+2\delta)+p} \qquad \text{......(5b)}$$

$$Y_{21b} = \frac{\omega_o^2}{p+(\omega_m+2\delta)} \qquad \text{......(6a)}$$

$$Y_{22b} = \frac{\left(\dfrac{\omega_o^2}{\omega_n^2}-1\right)p^2+\eta p+\omega_o^2}{p+(\omega_m+2\delta)} \qquad \text{......(6b)}$$

As can be seen two ladders of the h.p. and the l.p. type are established. The suffix 'z' in the admittance parameters of the '*a*' ladder indicates its association with the bridging element Y_z. It is necessary to remove Y_z from these parameters before carrying out the Cauer synthesis. One can easily see that the coefficient of p in the numerator of the biquadratic function eqn. (3) is solely determined by the admittance of the bridging element Y_z multiplied by the constant term of the divisor polynomial. Thus the bridging admittance becomes

$$Y_z = \frac{2\delta p}{\omega_m+2\delta} \qquad \text{......(7)}$$

Removing Y_z from eqns. (5a) and (5b) produces the new admittance parameters of the 'a' ladder

$$Y_{21a} = \frac{p^2\omega_m/(\omega_m+2\delta)}{(\omega_m+2\delta)+p} \qquad \text{......(8a)}$$

$$Y_{22a} = \frac{p^2\omega_m/(\omega_m+2\delta)+p(\xi-2\delta)}{(\omega_m+2\delta)+p} \qquad \text{......(8b)}$$

Now all the zeros of the Y_{21}s are at the origin or infinity, thus facilitating the application of the Cauer synthesis from which the following realizability conditions are found:

$$\left.\begin{aligned} &\xi > \omega_m+2\delta \\ &\eta > \frac{\omega_o^2}{\omega_m+2\delta}+(2\delta+\omega_m)\left(\frac{\omega_o^2}{\omega_n^2}-1\right) \end{aligned}\right\} \qquad \text{......(9)}$$

Introducing two factors μ and γ which have to be larger than unity the inequalities (9) can be made to hold. So (9) can be written as

$$\left.\begin{aligned} &\xi = \mu\omega_m+2\delta \\ &\eta = \gamma\frac{\omega_o^2}{\omega_m+2\delta}+(\omega_m+2\delta)\left(\frac{\omega_o^2}{\omega_n^2}-1\right) \end{aligned}\right\} \qquad \text{......(10)}$$

By inspection of eqn. (3) it can easily be shown that

$$\xi+\eta = 2\sigma\frac{\omega_o^2}{\omega_n^2} \qquad \text{......(11)}$$

and further using an asymmetry condition from the twin-T realization

$$\eta-\xi = \left(\frac{\omega_o^2}{\omega_n^2}-1\right)(\omega_m+2\delta) \qquad \text{......(12)}$$

it is possible to determine the coefficients ξ and η so that condition (9) will hold. Equation (12) is found by making the p-term coefficients of both Y_{22a} and Y_{22b} equal after the load element Y_4 has been removed. With this the asymmetry of the branches a and b is controlled to a certain extent. There are however cases where it is necessary to depart from the asymmetry determined by eqn. (12) because certain transfer functions may otherwise not be realizable.

The following transfer function may here serve as an example for such a case:

$$D(p) = H\frac{p^2+10}{p^2+2{\cdot}4p+1} \qquad \text{......(13)}$$

Using eqns. (11) and (12) to determine ξ and η produces $\xi = 7{\cdot}5$ and $\eta = 16{\cdot}5$. Clearly the inequality for η in condition (9) does not hold so that realization with these coefficients is not possible. For $\omega_m = 1$ it is found that $\mu = 7{\cdot}5$ yet for realization it is only required to be > 1. Thus if $\mu = 2$ then $\eta = 22$ and condition (9) holds. In fact it can be shown using condition (9) that $1 < \mu < 5$ will produce a realizable network. This shows that eqn. (12) in a number of cases can be improved upon by simply choosing $\mu > 1$. For cases where the pole pairs of a transfer function are very near the point of coincidence, μ and γ will be seen to be less than 2 and the component spread of the realized network may be extremely large. This coincidence of the pole pairs of the transfer function represents the limit of passive R-C realization and it can be approached as closely as required provided the component spread realized can be tolerated.

With twin-T structures as they are realized here, best sensitivity with regard to variations in the passive components is obtained when the network is asymmetrical, i.e. when the component spread is large. Sensitivity studies using a digital computer have verified this.

Investigations carried out indicate that if a network having equal asymmetry can be obtained for a given transfer function, then this will provide for best sensitivity.

It is interesting to note that the asymmetry of the two network branches can be varied individually by the choice of μ and γ respectively. Thus if one sets $C_1 = C_2$ then $\mu = 2$ or for $R_1 = R_2$ for which $\gamma = 2$.

If

$$\frac{\sigma^2}{\left(1+\dfrac{\omega_n^2}{\omega_o^2}\right)^2} > \frac{2}{\dfrac{1}{\omega_n^2}+\dfrac{1}{\omega_o^2}} \qquad \ldots\ldots(14)$$

then $\gamma = 2$ and $\mu = 2$ with

$$\omega_m = \frac{\sigma}{1+\dfrac{\omega_n^2}{\omega_o^2}} + \sqrt{\frac{\sigma^2}{\left(1+\dfrac{\omega_n^2}{\omega_o^2}\right)^2} - \frac{2}{\left(\dfrac{1}{\omega_n^2}+\dfrac{1}{\omega_o^2}\right)}}$$

For a given transfer function ξ and η can be obtained using eqns. (11) and (12). The constant term ω_m of the divisor polynomial is either chosen arbitrarily or calculated using eqn. (10) or perhaps eqns. (11) and (12) depending on which conditions have been imposed. For most applications it is convenient to choose $\omega_m = 1$.

If the synthesis as outlined above is carried out, then the realized network will be of the form as in Fig. 1 with the component specifications as follows:

$$C_1 = \frac{\dfrac{\omega_m}{\omega_m+2\delta}}{1-\dfrac{\omega_m}{\xi-2\delta}}$$

$$C_2 = \frac{\xi-2\delta}{\omega_m+2\delta}$$

$$C_3 = \frac{\eta-(\omega_m+2\delta)\left(\dfrac{\omega_o^2}{\omega_n^2}-1\right)}{(\omega_m+2\delta)-\dfrac{\omega_o^2}{\eta-(\omega_m+2\delta)\left(\dfrac{\omega_o^2}{\omega_n^2}-1\right)}}$$

$$C_4 = \left(\frac{\omega_o^2}{\omega_n^2}-1\right)$$

$$R_1 = \frac{(\omega_m+2\delta)-\dfrac{\omega_o^2}{\eta-(\omega_m+2\delta)\left(\dfrac{\omega_o^2}{\omega_n^2}-1\right)}}{\omega_o^2}$$

$$R_2 = \frac{1}{\eta-(\omega_m+2\delta)\left(\dfrac{\omega_o^2}{\omega_n^2}-1\right)}$$

$$R_3 = \frac{1-\dfrac{\omega_m}{\xi-2\delta}}{\xi-2\delta}$$

$$C_z = \frac{2\delta}{\omega_m+2\delta}$$

Now, for a twin-T,

$2\delta = 0$ and $\omega_0^2 = \omega_n^2$, i.e. $C_z = 0$, $C_4 = 0$

for a bridged twin-T,

$\omega_0^2 = \omega_n^2$, i.e. $C_4 = 0$

for a loaded twin-T,

$2\delta = 0$, i.e. $C_z = 0$

whereas for a loaded and bridged twin-T the elements are as derived above.

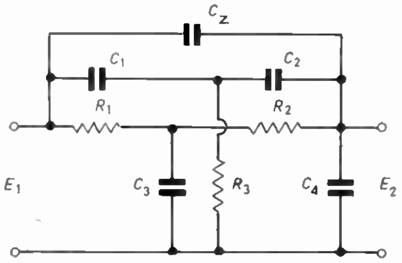


Fig. 1. Basic R-C zero section network.

For the realization of high-pass transfer functions the usual transformations apply. If a h.p. is to be obtained from a l.p., then the inverse values of the l.p. resistors provide the h.p. capacitors and the inverse of the l.p. capacitors values give the h.p. resistors. Thus the bridging element in the h.p. becomes a resistor R_z and the load is then R_4.

Attention is drawn to the fact that it is possible to realize the bridging element of the l.p., h.p. or notch filter either as a resistor or a capacitor. If it is required for the bridging element in a l.p. to be a resistor, then the y-parameters (eqns. (5) and (6)) as well as the divisor polynomial must be modified. However to avoid complications at this stage, this latter realization procedure will not be discussed further.

3. Transformation from Load to Series Source Admittance

In practical applications it may be necessary to change the impedance at the source or load end of the twin-T. Also for reasons of accuracy it may be desired to take into account the impedance of the source. In such cases it would be advantageous to have a series source admittance rather than a load connected to the twin-T. It will be shown how a transformation of this kind can be carried out.

For the basic argument it is necessary to compare the circuits of Figs. 2 and 3. The requirement now is that the voltage transfer functions be equal. The chain matrix $[A]$ for a twin-T can be written down

$$[A] = \begin{bmatrix} \dfrac{\dfrac{Y_aY_b+Y_bY_c}{Y_a+Y_b+Y_c}+\dfrac{Y_1Y_2+Y_2Y_3}{Y_1+Y_2+Y_3}}{\dfrac{Y_aY_b}{Y_a+Y_b+Y_c}+\dfrac{Y_1Y_2}{Y_1+Y_2+Y_3}} & \dfrac{1}{\dfrac{Y_aY_b}{Y_a+Y_b+Y_c}+\dfrac{Y_1Y_2}{Y_1+Y_2+Y_3}} \\[2ex] \dfrac{\|Y\|}{\dfrac{Y_aY_b}{Y_a+Y_b+Y_c}+\dfrac{Y_1Y_2}{Y_1+Y_2+Y_3}} & \dfrac{\dfrac{Y_aY_b+Y_aY_c}{Y_a+Y_b+Y_c}+\dfrac{Y_1Y_2+Y_1Y_3}{Y_1+Y_2+Y_3}}{\dfrac{Y_aY_b}{Y_a+Y_b+Y_c}+\dfrac{Y_1Y_2}{Y_1+Y_2+Y_3}} \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \qquad \ldots\ldots(15)$$

with

$$\|Y\| = \frac{Y_aY_bY_c}{Y_a+Y_b+Y_c}+\frac{Y_1Y_2Y_3}{Y_1+Y_2+Y_3}+\frac{Y_aY_bY_2Y_3+Y_aY_cY_2Y_3+Y_aY_cY_1Y_2+Y_1Y_2Y_bY_c+Y_1Y_3Y_bY_c+Y_1Y_3Y_aY_b}{(Y_a+Y_b+Y_c)(Y_1+Y_2+Y_3)} \qquad \ldots\ldots(16)$$

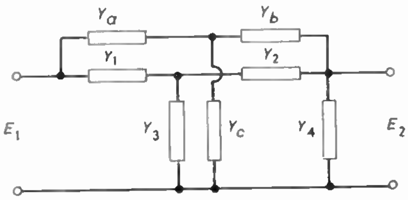


Fig. 2. Basic twin-T section in admittance form with load.

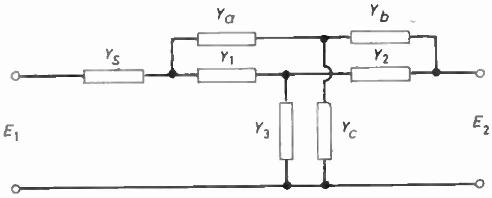


Fig. 3. Basic twin-T section with series source admittance.

The $[A]$ matrix for Fig. 2 is given as eqn. (17) with the A-parameters being those of the standard twin-T eqn. (15):

$$[A] = \begin{bmatrix} A_{11}+A_{12}Y_4 & A_{12} \\ A_{21}+A_{22}Y_4 & A_{22} \end{bmatrix} \qquad \ldots\ldots(17)$$

and the matrix for Fig. 3 with the series source admittance Y_s is given as

$$[A] = \begin{bmatrix} A_{11}+\dfrac{A_{22}}{Y_s} & A_{12}+\dfrac{A_{22}}{Y_s} \\ A_{21} & A_{22} \end{bmatrix} \qquad \ldots\ldots(18)$$

For the transfer functions of Figs. 2 and 3 to be equal the following has to hold

$$Y_4Y_S = \|Y\| \qquad \ldots\ldots(19)$$

where $\|Y\|$ is given by eqn. (16). Equation (19) applies for all cases. If $\omega_0^2 = 1$ and $\omega_n^2 \leq 1$, the transformation will yield a series resistance for the low-pass transfer function, whereas a series capacitance is realized for a high-pass function. For $\omega_0^2 > 1$ however the series admittance becomes a rather complicated network containing about five elements for a second-order transfer function. Unfortunately inductors are realized in these networks.

This now means that given transfer functions where $\omega_0^2 > 1$ will have to be transformed so that $\omega_0^2 = 1$ for which it is known that

$$(Y_a+Y_b+Y_c) = (Y_1+Y_2+Y_3).$$

Because of this relationship eqn. (19) can be modified to

$$Y_S = \frac{2}{Y_4}\left(\frac{Y_aY_bY_c+Y_1Y_2Y_3}{Y_1+Y_2+Y_3}\right) \qquad \ldots\ldots(20)$$

It now remains to be shown how any given transfer function is converted so that $\omega_0^2 = 1$.

If the given transfer function is of the form

$$D(p) = H\frac{p'^2+\omega_o'^2}{p'^2+2\sigma' p'+\omega_n'^2} \qquad \ldots\ldots(21)$$

then by setting $p' = \omega_0' p$ the following conversion is obtained:

$$D(p) = H\frac{p^2+1}{p^2+\dfrac{2\sigma'}{\omega_o'}p+\dfrac{\omega_n'^2}{\omega_o'^2}} \qquad \ldots\ldots(22)$$

where

$$\frac{2\sigma'}{\omega_o'} = 2\sigma \quad \text{and} \quad \frac{\omega_n'^2}{\omega_o'^2} = \omega_n^2$$

The new function therefore becomes

$$D(p) = H\frac{p^2+1}{p^2+2\sigma p+\omega_n^2} \qquad \ldots\ldots(23)$$

What exactly has happened here is that a frequency scaling has been applied to the transfer function. In order to obtain the exact frequency behaviour initially laid down by the original transfer function eqn. (21) it is necessary to reapply this frequency scaling factor once the network has been realized from eqn. (23). In fact all that has to be done is to multiply the denormalizing frequency by ω_0' of eqn. (21) so that the modified frequency denormalization is

$$\Omega_n = f_n 2\pi\omega_0' \qquad \ldots\ldots(24)$$

4. Practical Results

Table 1 lists the component values computed for six different voltage transfer functions. The coefficients ξ and η were obtained using eqns. (11) and (12) and the divisor polynomial was chosen to be $F(p) = p+1$. Incidentally, one may choose this polynomial for any synthesis by this method, unless a different choice is stipulated by imposed conditions. For all functions where $\omega_0^2 = \omega_n^2 = 1$, twin-T circuits of the standard type shown in Fig. 1 are obtained with $C_z = 0$ and $C_4 = 0$. The value of σ in the transfer function determines the bandwidth between the frequencies for which the attenuation is 3 dB. Thus if σ is large the bandwidth will be large. The smaller σ becomes the less is the bandwidth and the more rapidly the attenuation in the stop-band increases. For cases however where the poles of the function are complex, active synthesis procedures have to be applied. All component values of Table 1 are normalized except for those in brackets which have been denormalized to $R_n = 2000\ \Omega$ and $\Omega = 6283$ rad/s ($f_n = 1000$ Hz).

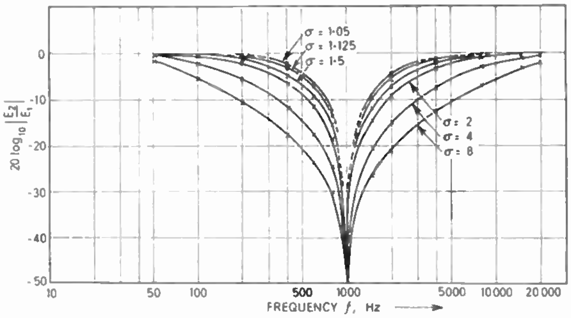


Fig. 4. Frequency responses of twin-T networks of varying selectivity.

The frequency responses of the experimental twin-T's listed are displayed in Fig. 4. As can be seen, the selectivity of a passive R-C twin-T can be varied over a considerable range.

In Table 2 three examples of low- and high-pass filters are given. The first two transfer functions represent low-pass filters, whereas the third is a

Table 1

Computed twin-T elements

σ	$R_1(\Omega)$	$R_2(\Omega)$	$R_3(\Omega)$	C_1(F)	C_2(F)	C_3(F)
8	0·875 (1750)	0·125 (250)	0·1093 (219)	1·1428 (0·091 μ)	8 (0·63 μ)	9·1428 (0·728 μ)
4	0·75 (1500)	0·25 (500)	0·1875 (375)	1·3333 (0·106 μ)	4 (0·318 μ)	5·3333 (0·424 μ)
2	0·5 (1000)	0·5 (1000)	0·25 (5000)	2 (0·159 μ)	2 (0·159 μ)	4 (0·318 μ)
1·5	0·3333 (666)	0·6666 (1333)	0·2222 (444)	3 (0·238 μ)	1·5 (0·119 μ)	4·5 (0·358 μ)
1·125	0·1111 (222)	0·8888 (197)	0·0987 (197)	9 (0·716 μ)	1·125 (0·089 μ)	10·125 (0·806 μ)
1·05	0·0477 (95)	0·9523 (1905)	0·0453 (91)	21 (1·6719 μ)	1·050 (0·0835 μ)	22·05 (1·7555 μ)

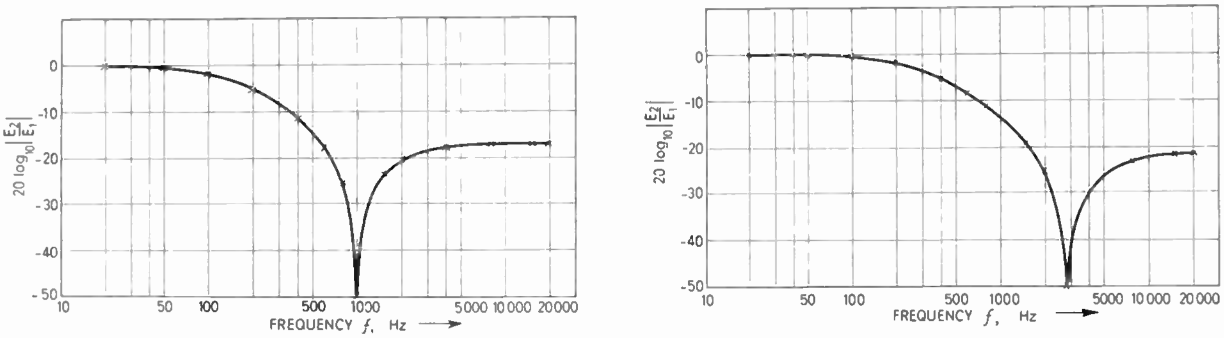
The numbers in brackets give the actual element values denormalized for $R_n = 2000\ \Omega$ and $\Omega_n = 6283$ rad/s ($f_n = 1000$ Hz). From the frequency responses in Fig. 4 it can be seen that the selectivity of a passive R-C twin-T can be varied over a considerable range. For these examples $\omega_0^2 = \omega_n^2 = 1$.

Table 2

Computed loaded twin-T elements

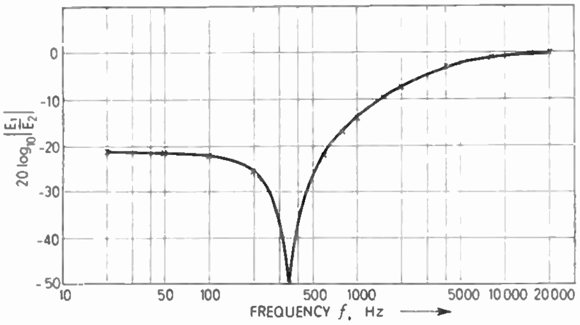
Example	2σ	ω_0^2	ω_n^2	$R_1(\Omega)$	$R_2(\Omega)$	$R_3(\Omega)$	$R_4(\Omega)$	C_1(F)	C_2(F)	C_3(F)	C_4(F)
1	1·17	1	0·15	0·0625 (125)	0·9375 (1875)	0·0585 (117)	— —	16 (1·273 μ)	1·0666 (0·085 μ)	17·066 (1·358 μ)	5·666 (0·451 μ)
2	3	8	0·7	0·0413 (82)	0·08365 (167)	0·0768 (154)	— —	1·0912 (0·087 μ)	11·928 (0·949 μ)	36·2 (2·882 μ)	10·428 (0·83 μ)
3	3	8	0·7	0·9163 (1834)	0·08365 (167)	0·0276 (55)	0·0958 (192)	24·212 (1·927 μ)	11·928 (0·949 μ)	13·016 (1·036 μ)	— —

The element values in brackets have been denormalized to $R_n = 2000\ \Omega$ and $\Omega_n = 6283$ rad/s ($f_n = 1000$ Hz). The circuit shown in Fig. 1 is applicable to all these three examples. However, in the case of example 3, C_4 is replaced by R_4 as this is a high-pass case. The frequency responses of these examples (1, 2 and 3) are shown in Figs. 5(a), (b) and (c) respectively.



(a) Low-pass frequency response of capacitance loaded twin-T (Example 1, Table 2).

(b) Low-pass frequency response of capacitance loaded twin-T (Example 2, Table 2).



(c) High-pass frequency response of resistance loaded twin-T (Example 3, Table 2).

Fig. 5.

high-pass, obtained from example 2 using the transformation $p = 1/p$. All component values listed are normalized with those in the brackets representing the actual element values denormalized to $R_n = 2000\,\Omega$ and $\Omega_n = 6283$ rad/s ($f_n = 1000$ Hz). The network configurations are as in Fig. 1 with $C_z = 0$ and the h.p. having a resistive load R_4. The typical frequency responses are depicted in Fig. 5.

Table 3 shows the transformation from the loaded twin-T to the series source admittance twin-T. A particular transfer function is used to demonstrate the steps of the procedure. First the transfer function is synthesized as it stands. In the second stage, the function is first frequency scaled as described in Section 3, eqns. (21) to (24), and then synthesized, and finally the load C_4 of this latter network is transformed into the series source resistance R_s. When the transformation of the admittances is carried out the com-

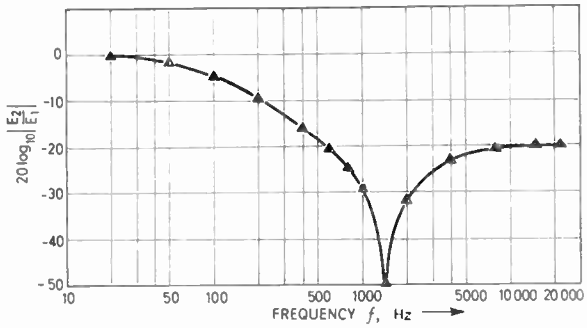


Fig. 6. Low-pass frequency response for the comparison of loaded and series source admittance twin-T (Δ = experimental points).

Table 3

Computed elements for loaded and series source admittance twin-T

Transfer function	$R_1(\Omega)$	$R_2(\Omega)$	$R_3(\Omega)$	$R_s(\Omega)$	C_1(F)	C_2(F)	C_3(F)	C_4(F)	Ω_n (rads/s
$D(p) = H\dfrac{p^2+2}{p^2+3p+0{\cdot}2}$	0·4047	0·0852	0·0861	—	1·106	10·5	12·98	9	6283
	(809)	(190)	(172)	—	(0·088 μ)	(0·835 μ)	(1·033 μ)	(0·716 μ)	—
$D(p) = H\dfrac{p^2+1}{p^2+2{\cdot}122p+0{\cdot}1}$	0·834	0·164	0·137	—	1·194	6·1	7·292	9	8884
	(1673)	(328)	(274)	—	(0·067 μ)	(0·343 μ)	(0·41 μ)	(0·506 μ)	—
$D(p) = H\dfrac{p^2+1}{p^2+2{\cdot}122p+0{\cdot}1}$	0·834	0·164	0·137	0·618	1·194	6·1	7·292	—	8884
	(1673)	(328)	(274)	(1236)	(0·067 μ)	(0·343 μ)	(0·41 μ)	—	—

The element values in brackets have been denormalized to $R_n = 2000\,\Omega$ and $\Omega_n = 6283$ rad/s (or 8884 rad/s) as the case may be. Frequency response curves are shown in Fig. 6. R_s is the series source resistance when $C_4 = 0$.

ponents of the twin-T are not changed. The experimental investigation into the three networks of Table 3 showed their frequency responses as depicted in Fig. 6. The component values were normalized, but those in brackets are the actual component values denormalized to $R_n = 2000\,\Omega$ and $\Omega_n = 6283$ or 8884 rad/s ($f_n = 1000$ Hz) as the case may be.

5. References

1. A. G. J. Holt and K. M. Reineck, 'An active transfer function synthesis using a passive zero section and its sensitivity', *Nachrichtentechnische Zeitschrift*, 19, No. 5, pp. 267–72, May 1966.
2. E. A. Guillemin, 'Synthesis of RC-networks', *J. Math. Phys.*, 28, pp. 22–42, April 1949.
3. B. J. Dasher, 'Synthesis of RC transfer functions as unbalanced two terminal-pair networks', *Trans. Inst. Radio Engrs on Circuit Theory*, CT-1, pp. 20–34, December 1952.
4. N. Balabanian, 'Network Synthesis' (Prentice-Hall, Englewood Cliffs, N.J., 1958).
5. L. G. Cowles, 'The parallel-T resistance-capacitance network', *Proc. I.R.E.*, 40, pp. 1712–17, December 1952.
6. A. E. Hastings, 'Analysis of a resistance capacitance parallel-T network and application', *Proc. I.R.E.*, 34, p. 126, March 1946.

Manuscript received by the Institution on 2nd May 1966. (*Paper No. 1089*).

Joint I.E.E.—I.E.R.E.—I.E.E.E. Conferences in 1967

Integrated Circuits

A three-day conference on Integrated Circuits will be held at the Congress Theatre, Eastbourne, from 2nd to 4th May 1967.

The conference will discuss all current aspects of microelectronics whether semiconductor, thin film, thick film or hybrid. The scope may be outlined as follows:

Basic technological processes and design (*including materials*)*:* design aspects of components, circuits and internal connections; packaging.

Performance characteristics and properties: characterization of linear and digital circuits; ratings; reliability; simulation and analysis of circuits.

Applications: systems design; equipment engineering; case histories.

Advanced techniques and devices: large scale integration; microwave applications; opto-electronics.

Registration forms and further information will be available in due course from the I.E.R.E., 8–9 Bedford Square, London, W.C.1.

Frequency Generation and Control for Radio Systems

A conference on Frequency Generation and Control for Radio Systems will be held at the Institution of Electrical Engineers from 22nd to 24th May, 1967.

The scope of the conference will include:

Sources: atomic sources (fixed and portable); crystals; measurement and correction.

Control and derivation of frequency: system requirements; synthesizers and analysers; phase and frequency locking and tracking systems.

Applications: communication systems; navigation and position finding systems; surveying; test equipment.

Registration forms and further details will be available from the I.E.R.E., 8–9 Bedford Square, London, W.C.1.

Solid State Devices

The Institute of Physics and The Physical Society, with the collaboration of the Engineering Institutions, are arranging a conference from 5th–8th September, 1967 to be held at the University of Manchester Institute of Science and Technology. It is intended that this conference will be complementary to the annual conference on 'Solid State Physics' organized by the I.P.P.S. each January.

The object of the conference is to provide a forum for the presentation of applied research work in the physics and characterization of solid-state devices together with associated technologies. Areas to be covered include: microwave devices; electro-acoustic devices; display devices; electro-optic and opto-electronic devices (including radiation detectors); power and control devices; MOS structures (including surfaces); integrated circuits (monolithic, thin film and hybrid); device fabrication technologies; devices using new principles and structures, etc.

Invitations for survey and keynote papers have been issued to experts in solid-state device work in various countries. In addition contributions of about 15 minutes presentation time are welcomed and prospective contributors should submit two copies of an outline of approximately 200 words in length to the Programme Chairman, Dr. I. M. Mackintosh, M.I.E.R.E., c/o Elliott-Automation Microelectronics Ltd., Queensway Industrial Estate, Glenrothes, Fife, Scotland, *before 9th June 1967*. 'Late-news' papers of not more than 10 minutes presentation time may be considered if outlines of not longer than 100 words are received by the Chairman by *1st August 1967*.

Residential accommodation will be available in University Halls of Residence. Further details and application forms will be available from the I.P.P.S., 47 Belgrave Square, London, S.W.1, in May.

INSTITUTION NOTICES

New Year Honours

The Council of the Institution congratulates the following members on their appointments to the Most Excellent Order of the British Empire which were announced in the New Year Honours List 1967.

Military Division

To be an Ordinary Commander (C.B.E.):

Air Commodore John Goodman, R.A.F. (Member)

To be an Ordinary Officer (O.B.E.):

Wing Commander William Wilkinson, R.A.F. (Associate Member)

To be an Ordinary Member (M.B.E.):

Captain Lawrence Wilkinson Moran, Royal Corps of Signals (Associate)

Civil Division

To be Ordinary Officers (O.B.E.):

Arthur Frederick Bulgin, M.B.E. (Member) (Mr. Bulgin served for a number of years on the Membership Committee)

Alfred Maxwell Keeling, T.D. (Associate Member)

To be an Ordinary Member (M.B.E.):

Ian Claud Imlach Lamb (Associate Member) (Mr. Lamb is the chairman of the Yorkshire Section)

A Change of Appearance

The beginning of a New Year is an auspicious time at which to introduce any innovation. With this issue of *The Radio and Electronic Engineer*, the first in Volume 33, several changes have been made to appearance and typographical layout.

The cover design which was adopted with the new format in 1961, and slightly amended in 1964 when the name of the Institution was changed, is now altered in concept though not in colour—the combination of dark blue ink on a pale blue paper has been the Institution's 'house style' since 1950.

Within the covers, the contents are listed on pages (iii) and (iv) and a typographical change has been made to the displayed headings of papers and articles. A modern continental typeface, known as Univers, has been employed in place of the Perpetua lettering used for several years. Order forms, the conference calendar, and advertisements relating to appointments will in future be printed on tinted paper at the end of the *Journal* for ease of identification.

Conference on Design and Production

A joint conference is being arranged by the I.E.R.E. and the Institution of Production Engineers on the theme 'The Integration of Design and Production in the Electronics Industry'. It will be held at the University of Nottingham from 10th–13th July 1967.

The subjects to be covered in the three main sessions of the conference are as follows:

Design for production: marketing considerations; industrial design; design for production (including cost control); value engineering in the electronics industry; reliability; quality failure loss analysis; maintainability.

Economical production: control of production; batch and flow production and their inter-relation; modern materials and techniques.

Future developments: impact of integrated electronic circuits on the company; computer-aided design; automatic assembly and testing.

Further information on the Conference will be published in the Institution's *Journal* and *Proceedings* as it becomes available, together with application forms for registration details.

Conference on R.F. Measurements and Standards

The Organizing Committee for the Joint I.E.R.E.-I.E.E. Conference on 'R.F. Measurements and Standards', which will be held near London in November 1967, invites offers of papers dealing with measurements and standards of the following:

Power, Impedance, Attenuation, Noise, Voltage and Current, including Field Strength.

(The frequency range to be covered is 100 kHz to 3 GHz but frequency measurements and standards as such will *not* be dealt with.)

Offers of papers, accompanied by synopses, should be sent to the Secretary, I.E.R.E., 8–9 Bedford Square, London, W.C.1, as soon as possible.

Correction

The first sentence of the brief description of the paper 'The Effect of the Upper Sideband on the Performance of a Parametric Amplifier', by K. L. Hughes and J. D. Pearson, printed on the Contents page (i) of the December 1966 issue of *The Radio and Electronic Engineer*, should be amended to read as follows:

Parametric amplifiers employing wide-band idler circuits tend to have an objectionably high noise-figure *under certain operating conditions.*

U.D.C. 621.396.969.3.004.6

An Investigation into Marine Radar Reliability

By

Captain F. J. WYLIE,
O.B.E., R.N.(Rtd.), C.Eng.,
M.I.E.R.E.†

Presented at the Radar and Navigational Aids Group Symposium on 'The Reliability of Marine Radar Equipment', held in London on 15th December 1965.

Summary: An interim report is given of a survey undertaken during 1963–64 on the failures encountered during a six-month period in 1000 sea-going marine radars of sixty-five different types.

1. Introduction

In 1960, the Radio Advisory Service made a study of current shipping and manufacturing opinion on the subject of the 'Highlights and shortcomings of radar performance'.‡ This showed that an improvement in radar reliability was regarded as a prime necessity.

About a year later several shipowners in the U.K. were becoming concerned at the rate of radar breakdowns in their ships and a pilot investigation was made in 1962 based on reports of past troubles experienced by about 100 ships. Two main conclusions were drawn from it, firstly that the frequency of breakdown was serious enough to warrant a much larger scale research and second, that no reliable basis could be formed from mere recollections of past troubles: it would be necessary to have the vital data recorded for several consecutive months. The radio organizations of the Chamber of Shipping and the International Chamber of Shipping agreed that a major effort should be made.

2. Design of the Survey

A great deal of thought was given to devising an appropriate questionnaire and this was distributed firstly to a large number of British ships, mainly those using and returning the R.A.S. radar log of targets. Later it was sent to a large number of ships of other countries whose owners are members of the International Chamber of Shipping. A total of about 4000 questionnaires were sent out and they required a record to be kept for six months. About 1800 were completed, but as a considerable number did not cover the full six months it was decided to base the analysis on 1000 complete replies, which covered a variety of ships and of radar sets.

The questionnaire was designed to disclose for each radar installation: its type and age; the kind of occasions when used; the number of days in the six months spent at sea; the number spent in radar operation and the number of times switched into the operational condition; the number of times it failed on switching on and the number of failures when running; the length of time for repair and by whom it was effected; the nature of the failure; the professional status of the maintainer and his qualifications, and the presence or absence of a regular periodic system of maintenance.

On the whole the reports were very faithfully made and therefore a vast store of items of information was available. Even this number, however, gave little enough depth when the data were related to a particular type of set. In the 1000 sets, 65 different types were included and the number of sets of a given type varied from 1 to 141. We held the view that not less than 15 sets were needed to justify drawing conclusions on the behaviour of any one type.

The main problem in planning the analysis was to decide what kind of presentation of the facts would be of the greatest value to users and manufacturers. The intention was ultimately to give each contributing shipowner and interested manufacturer all the details of the behaviour of the radars with which each was concerned. But clearly no comparisons, odious or otherwise, might be made between types of set in any general context.

For the shipowner's benefit it was necessary to decide on practical and meaningful generalizations, which would indicate how his own radar sets compared in behaviour with what he might be justified in expecting. It was decided that it would be wrong to give him comparable figures for all sets examined, and this for two reasons. Firstly, it would be somewhat unethical and second, it could be wildly misleading

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‡ 'Fifteen years of marine radar', presented at a meeting of the Deutsche Gesellschaft für Ortung und Navigation, in September 1960, and published in *J. Inst. Navigation*, **13**, No. 4, p. 419, October 1960.

due to the shallowness of the sample in some cases. Comparison between the average of each type and the average of the 1000 should be as informative as any statistical analysis can be and this was the method chosen.

The two criteria selected were the 'mean radar operating time between failures' (m.o.t.b.f.) and 'availability'. Each of these needs some explanation. The m.o.t.b.f. for a set is obtained merely by dividing its total hours in operation in the six months' period by its total number of operating intervals between breakdowns. The latter number, of course, is one more than the number of breakdowns; no breakdown occurred at the precise moment of commencing or ending the record.

Availability, by our definition, is the ratio of hours in operation to hours which the radar would have been in operation if it had not broken down. The latter figure is assessed from the operating hours of the sets which did not break down.

Each of these criteria gives a slightly different aspect of reliability and the truest way to obtain an overall order of merit was to mean the results of the two. Many of the 65 types were so close together in the marking as to make any practical distinction impossible.

Many of the less general figures were of very great interest. Most of them are necessarily averages. Throughout the analysis we have tried to discover patterns of behaviour. These would be difficult enough to discern even were all the questions answered in the way they were intended to be. Differences in interpretation undoubtedly tend to obscure patterns.

The analysis was divided into three main sections: availability of the radar for operations, occurrence and nature of defects and methods of use and maintenance. Before describing the results, some basic general data must be given.

As already stated, 1000 sets were involved; 23 of the ships had two sets, thus we were actually concerned with 977 ships; to avoid complications where factors of personnel, hours at sea, etc., were concerned, and because the study concerned sets rather than ships, each separate set was treated as a ship. Of these 1000 'ships', 958 carried radio officers and 42 did not. One hundred and fifty-three sets had true motion facilities (15·3%).

Although each of the 1000 reports covered the whole period of 184 days, the days at sea per ship varied enormously from 175 to 15; the average was 103 days. Similarly, the time during which the radar was used operationally differed widely—from 98 days to 1 day, with an average of 25½ days (616 hours).

Failures had to be reported separately according to whether they occurred on switching to the operational state (A) or while fully operational (B).

3. Operational Considerations

Ships were asked to report in what circumstances they used radar. There were 994 replies of which 960 were almost identical, stating that they used it for general navigational purposes and in poor visibility. It is of some interest that 32 of those ships stated that they always used radar at night. Eleven stated that it was used all the time and 8 *only* in poor visibility.

The 1000 sets operated for a total of 25,667 days and experienced failures on 2950 occasions (3950 operating periods). The 801 sets which contributed the 2950 failures, operated for a total of 21,288 days (3751 operating periods).

The mean operating time between failures derived from the total operating time for the sample divided by the total operating periods, gave, for the 1000 sets an m.o.t.b.f. of 6·49 days (155·5 hours) and, for the 801 sets only an m.o.t.b.f. of 5·67 days (136·08 hours).

The total failures also represent, for the 1000 sets 2·95 per set and for the 801 sets 3·68 per set. The worst set had 26 failures in six months. These averages may be further subdivided, for the 1000 sets, into 3·02 (958 ships) over 1600 gross registered tonnage and 1·33 (42 ships) under 1600 g.r.t. For the 801 sets the figures were 3·74 (774 ships) over 1600 g.r.t. and 2·07 (27 ships) under 1600 g.r.t.

The presumption is that the lower figures for ships under 1600 g.r.t. are due to the more frequent opportunity for shore maintenance which these smaller vessels have.

For all the 801 sets the average 'availability' was 94·6%, the best and worst among the different types being 99·9% and 78·4% respectively. The overall British and U.S. contributions were within 0·5% of one another.

4. Technical Aspects

Technically, the most interesting evidence becoming available from the first analysis concerns the relationships between failures and such factors as age of equipment and the method and quality of maintenance. It will be appreciated that an analysis such as this involves an enormous amount of meticulously accurate work. Even after twelve months' study we seem to have given but a superficial glance at what are probably the most important permutations. Some of these are:

(*a*) The incidence of breakdowns as it affects operational availability. This could, of course, be treated in much more detail than the somewhat revealing averages already given.

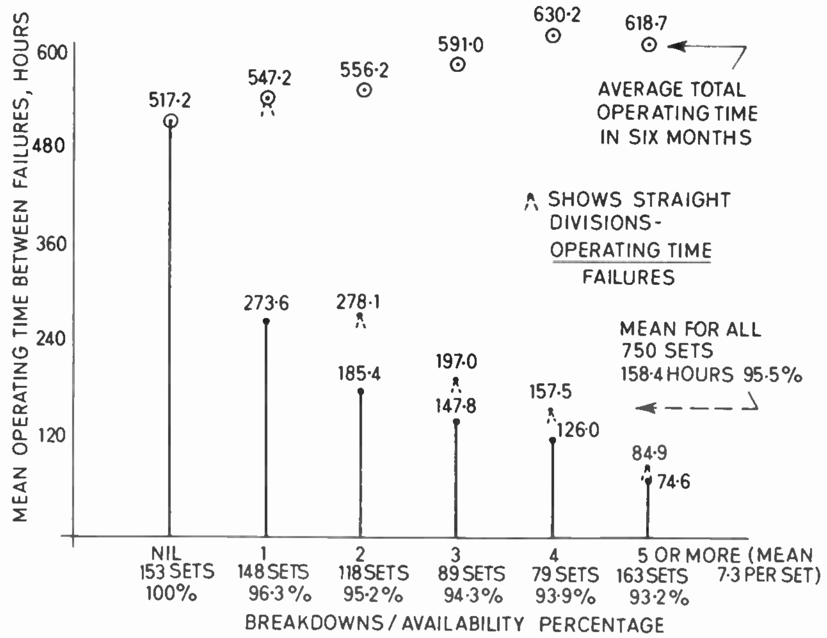

Fig. 1. Incidence of breakdowns as they affected operational availability. Twenty types of radar with more than 15 sets in the sample—total 750 sets.

(*b*) The relation between 'A' breakdowns and frequency of switching.

(*c*) The proportion of 'A' failures to 'B' failures.

(*d*) The relation between 'A' failures + 'B' failures and total time operational.

(*e*) The connection, if any, between fault incidence and the type and quality of maintenance.

(*f*) The connection, if any, between fault repair time and the type and quality of maintenance.

(*g*) The connection between fault incidence and age of equipment.

(*h*) The proportion of failures which could not be due to fair wear and tear, i.e. component life.

A closer and more detailed study of a selection of the important permutations can be most rewarding, bearing in mind that the statistics are based on extracts from answers to questions by the users of marine radar under sea-going conditions.

4.1. *Incidence of Failures and Operational Availability*

In the case of the incidence of breakdowns as they affected operational availability, it was first necessary to establish a criterion.

Of the 199 (19·9%) of the sets which did not break down, it was found that the average total operating time was 21% of the total voyage time in the six-month period. It was, therefore, considered not unreasonable to assume that of the unserviceable sea time in those ships whose radar sets failed, 21% was lost operating time.

Operational availability was therefore expressed as a percentage of the total operating time divided by the total operating time plus 21% of the total sea time unserviceable.

Based on the type of radar, for 750 sets, comprising 20 different types of radar with more than 15 sets each, the best and the worst availability percentages were 99·08% and 89·92% respectively, and the average was 94·37%.

A more realistic set of figures was found by relating availability to the number of failures, for the same group of sets (Fig. 1).

A graphical presentation of the information showing the mean operating time between failures against breakdowns, emphasizes more vividly the effect which failures have on availability as well as on the trouble-free total operating periods.

Although 153 sets (20·4%) had no breakdowns during the six-month survey, it was statistically probable that some of them did break down during their next operating period. Moreover, it was seen that the average operating time for the 153 NIL failure sets was 16% less than the average for the 597 sets which had breakdowns. The actual averages were

517·2 and 600 hours respectively. This difference of 83 hours average operating time might well be significant. NIL failure sets were therefore considered to have an m.o.t.b.f. equal to their total operating time and, from the evidence presented, this was considered to be far more practical than if the operating time had simply been divided by the number of failures. By this latter method the NIL failure sets would have had an m.o.t.b.f. of infinity—a term which was impractical as a yard-stick against which to assess the performance of 80% of the total number of sets involved.

For these reasons, the method chosen for computing the m.o.t.b.f.'s does not seem unreasonable or unpractical.

As a matter of some importance in estimating the validity of the data presented in graphical form, it was established that the mean total operating hours for sets in each category of breakdowns varied by 22%. The NIL failures being taken as 100%, the four failures were 121·8% while the remainder came somewhere between these two extremes. The mean operating time was 580 hours or 112% for the whole 750 sets relative to the NIL failure sets (Fig. 2).

The factor (mean total operating hours) may or may not be significant, but needs to be examined further.

Table 1 shows availability as a function of unserviceable time at sea for all the 1000 sets, the numbers out of action at sea for varying periods from less than 24 hours to 1000 hours and over. All the ten manufacturers covered by the overall analysis had some sets in the 1000 hour and over category.

The proportion of sets unserviceable at sea for five days or more (120 hours and over) was 28·2% (282 sets), and these were fitted in vessels belonging to 80 different shipping companies. The 1000 hour unserviceable and over category were fitted in vessels belonging to 15 different shipping companies. Even in the 1000 hour and over category, all the ten radar manufacturers represented in the overall analysis had some sets.

4.2. *Effect of Switching on Failure Incidence*

Failures, as already stated, were divided into two classes: those which happened when the sets were switched on into the operational state denoted 'A', and those which occurred while the sets were fully operational, denoted 'B'. There were 967 'A' failures against 1983 'B' failures, roughly two 'B' to one 'A'.

Much had been heard about the faults which were supposed to occur through excessive switching of the radar. The result was quite unexpected.

Another set of statistics and a graph were prepared to show switching totals in relation to the number of 'A' failures reported (Fig. 2). These showed that 57·7%, or 433 sets out of the 750 sample selected, were switched at the maximum average of 165 times and had NIL breakdowns in the 'A' category. This was 10% above the 150 average times switched for all 750 sets. One hundred and forty-seven sets with one 'A' failure and 29 sets with five or more 'A' failures were each switched on average 144 times.

Ironically the lower average of switchings, 121 times, occurred in the sets contributing three 'A' failures in each of 39 sets.

Three sets reported switching in excess of 1000 times and one in excess of 2000 times during the six-month period.

One only had one 'A' failure to report.

The relation between 'A' and 'B' failures and the total time operational had so far produced no pattern or significant trend. Operational hours were quite considerable in a large number of the ships. One hundred and twenty-one reported more than 1000

Table 1

Sea-time unserviceable (1000 set breakdown)

Hours	Number of types	Number of radar sets	Number of breakdowns 1	2	3	4	5 or more
NIL	46	199	—	—	—	—	—
½ to 23½	61	288	113	73	47	9	46
24 and over	61	513	85	93	82	94	159
48 and over	58	420	58	75	67	76	144
72 and over	54	373	48	65	58	70	132
96 and over	52	330	43	55	49	66	117
120 and over	51	282	40	50	44	40	108
240 and over	46	188	24	35	30	31	68
480 and over	30	66	6	11	11	12	26
1000 and over	16	23	4	4	2	3	10

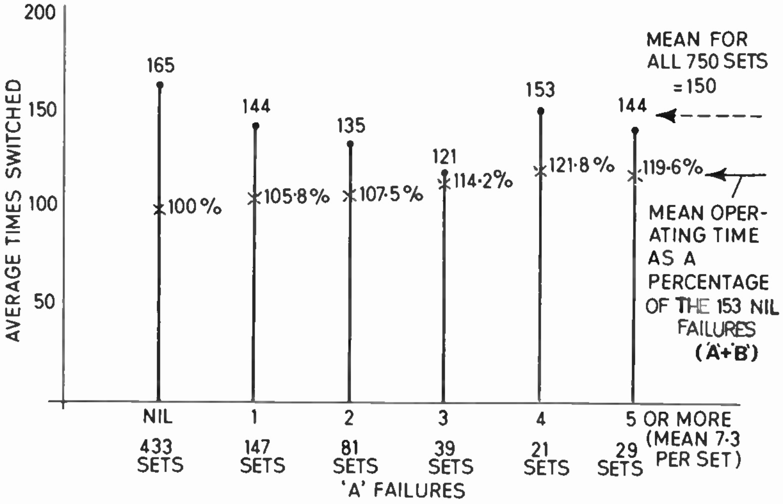

Fig. 2. 'A' breakdowns as a function of 'times switched' into the operational state. Twenty types of radar with more than 15 sets in the sample—total 750 sets. The percentages shown indicate the mean operating time of each category of ship with 'A' + 'B' failures as a percentage of the mean operating time of the 153 ships with no failures of either type.

hours and seven, more than 2000 hours. This was not continuous operation but the total for all the operating periods per ship in six months.

The average 'A' and 'B' failures for the 20 types of radar (750 sets) was 2·92 and their average operational time was 583 hours.

4.3. *Fault Incidence and Maintenance*

The connection, if any, between fault incidence, as well as fault repair time, and the type and quality of the maintenance were subjects on which it was hoped the investigation would throw some light. Maintenance of radar forms the basis on which the whole readiness for operation depends. Self-sufficiency at sea should be the aim, as regards failure prevention, fault diagnosis and when necessary repair.

For obvious reasons it was difficult to compare the different classes of maintainer—Radio Officer, Deck Officer, Electrical Officer, Shore Engineer and sometimes an Agent ashore. However, one class afforded a direct comparison, and these were the Radio Officers. Statistics were extracted showing Radio Officers holding the (now) Board of Trade Radar Maintenance Certificate and those *not* so certified.

For the ships in which all these officers were the primary maintainers, Table 2 shows the number of Radio Officers in either category against the total hours of radar unserviceability at sea.

Out of the total 1000 sets in the overall analysis, 126 were primarily maintained by Radio Officers holding an approved radar maintenance certificate and 341 by uncertificated Radio Officers. This was a ratio of roughly 1 to 3 and for ease of comparison the greater numbers were reduced by two-thirds and extracted as a separate figure.

Table 2

Unserviceable time at sea as a function of the type and quality of maintenance

Radar unserviceable at sea (hours)	Board of Trade certificated radar maintainers (126 Radio Officers)	Non-certificated radar maintainers (341 Radio Officers)
NIL	14 (18·3)	55
less than 12	40 (33·3)	100
12 to 24	9 (7·6)	23
24 to 48	14 (9·0)	27
48 to 72	8 (5·0)	15
72 to 96	4 (5·6)	17
96 to 120	5 (2·6)	8
120 to 240	14 (9·0)	27
240 to 480	16 (14·6)	44
480 to 600	2 (2·3)	7
over 600	NIL (6·0)	18

The figures in brackets are one-third the actual totals for the non-certificated Radio Officer maintainers. This permits direct comparison between the two categories of radar maintainers.

The two categories follow a not dissimilar trend. Each have peaks in the 24–48 hour, 120–240 hour and 240–480 hour unserviceable periods.

The uncertificated radar maintainers are alone in the 600 hour and over period, with 5·2% of the sets maintained by them; overall, there is little to choose between the two categories.

Another interesting observation was that of the 199 sets with no breakdowns, 130 were maintained by other than Radio Officers.

4.4. *Relation between Age of Radar and Fault Incidence*

On the question of fault incidence related to the age of the radar, this was expected to show a definite trend but here again, as with switching, the facts told quite a different story.

In the overall analysis, the ages of the radar sets varied from one to sixteen years (Table 3). Apart from the three oldest groups which had few sets in the sample, the thirteen-year-old sets had the best average failure rate (2·7). Eight age groups between one and thirteen years had a better average failure than that for the overall average of the 801 sets which failed, which was 3·68.

Table 3

Fault incidence as a function of the age of the equipments. (1000 set breakdown)

Age in years	No. of sets with NIL failures	No. of sets with failures	Average failures	NIL failures as a percentage of total in age group
1	23	107	3·47	17·7
2	16	80	3·08	16·6
3	20	69	3·39	22·4
4	20	83	4·52	19·4
5	21	75	3·21	21·8
6	17	63	3·57	21·2
7	15	65	3·38	18·7
8	13	49	4·26	20·9
9	20	52	4·15	27·7
10	12	50	3·60	19·3
11	8	41	4·16	16·3
12	4	26	4·04	13·3
13	6	20	2·70	23·1
14	2	7	4·14	22·2
15	1	12	4·66	7·7
16	1	2	2·50	33·3
Totals	199	801	3·68	19·9

4.5. *Types of Failure*

Turning to the types of defect in the 801 'ships' which reported failures, the primary classification was into the various units which make up the radar system.

As it was not possible to discover which defects were the result of fair wear and tear and which were not, it was assumed that the total in the latter category of defect in the valves would equal the number of 'fair-wear-and-tear' defects in the other components. Subtracting all the valve failures, from the total defects, therefore, gave a figure for the non-fair-wear-and-tear defects in the other components.

Out of a total 4134 defects, valves accounted for 1081 or 26·1%, the remaining 73·9% or 3053 defects were therefore classed as not due to fair wear and tear (Table 4).

Table 4

Defects reported in the more important units of the 801 sets which failed

Scanner defects	356	(includes 126 aerial drive-motor faults)
Transmitter defects	146	
Receiver defects	545	(includes 163 mixer crystals)
Display defects	643	(includes 168 time-base faults)
Display ancillaries	83	(includes 24 gyro-repeater faults)
Power supply defects	618	(includes 54 transformer faults)
Unspecified	171	
Fuse failures	491	
Thermionic valves	1081	(26·1% of the total defects)
Total	4134	

Less valves the total is 3053 or 73·9%.

4.6. *Scale of Preventive Maintenance*

Regular preventive maintenance at sea is a subject on which some shipping companies are well on the way to achieving, though the facts reported from sea and covered by this analysis are perhaps the most disturbing of all the statistics available.

The figures show, for all the 1000 sets, that regular preventive maintenance at sea was undertaken, daily by 35 ships, weekly by 102 and monthly by 97 ships. Of the remainder, 290 said that they carried out preventive maintenance as circumstances permitted, which probably meant *no* regular maintenance at all. Two hundred and twenty-six left it until the end of the voyage, which again probably meant that it was left to the shore staffs.

In all, therefore, only 234, or 23·4%, undertook any form of regular preventive maintenance at sea (13·7% only, daily or weekly).

Another aspect of maintenance which caused loss of availability of the radar at sea was a surprising inadequacy of ship spares for the more important valves—magnetron, klystron, modulator, p.p.i., etc., and in some cases mixer-crystals for the receiver.

Difficulty was also reported in obtaining spares in remote areas of the Eastern archipelago, Pacific Ocean and, in a few cases, in U.S.A. ports.

5. General Statistics

The 1000 sets analysed represented 65 different types manufactured by ten companies (five British, three U.S.A., one Federal German Republic and one Norwegian).

At the date of the survey (1963–64) there were 22 types of radar in current production and fitted in ships for which no statistics were gathered. These were made by seven companies (four British and three U.S.A.). Three of the sets were of the new transistorized types. A separate survey is pending to collect information on this new class of radar which is now being fitted in increasing numbers.

Of the total number of ships in the analysis, 550 were British and 450 were Foreign Flag vessels.

Forty-two vessels were of less than 1600 g.r.t. and these were maintained by Deck Officers and shore assistance with success.

Approximately 800 sets were fitted in ships engaged in regular trading, a large proportion being on routes to the Middle and Far East and Australasia. The remainder were irregular traders except for the 42 sets fitted in ships carrying radiotelephony equipment only which were on coastal voyages in N.W. Europe.

Of the 20 types of radar with more than 15 sets each (total 750 sets), the top ten, according to the availability formula mentioned earlier, included seven British and three U.S.A. types and the bottom ten also included seven British and three U.S.A. types.

The ratio of British to U.S.A. sets was 731 to 259, or 2·8 to 1·0.

The average unserviceable time per set at sea over the six-month period was 7·22 days for the 801 sets which failed, whereas the average total unserviceable time per set, at sea *and* in port was 11·56 days (1·6 : 1·0) [c.f. 11·56/3·68 or 3·14 days per failure.]

A probable contributory factor in the radar breakdowns was believed to be vibration, particularly in the larger types of motor ships. This might suggest mechanical weaknesses in the radar, but insufficient evidence is available to be certain on this point.

Lloyds' Register statistical tables show that at December 1964 the world fleets comprised 40,859 vessels over 100 g.r.t. and 17,914 vessels over 1500 g.r.t. All except 42 of the 1000 ships in the survey were of 1600 g.r.t. and over, so that the sample analysed represents about 5·5% of world fleets over this tonnage. World radar fittings are estimated at 25,000.

6. Conclusions and Acknowledgment

It is still too early to be dogmatic as regards any firm conclusions, but from what has been brought to light so far, it is clear that a closer and more detailed examination needs to be made of the various forms of shipboard maintenance represented in this analysis.

The author is very much indebted to Mr. D. Deacon of the R.A.S. to whom most of the detailed analytical work has fallen.

Manuscript received by the Institution on 6th January 1966. (Paper No. 1090/RNA60.)

U.D.C. 621.396.969.3.004.6

The Application of A.G.R.E.E. Principles to Commercial Marine Radar

By

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Presented at the Radar and Navigational Aids Group Symposium on 'The Reliability of Marine Radar Equipment', held in London on 15th December 1965.

Summary: Reliability is probably the most important single factor in marine radar today. Improved components and the introduction of solid-state devices have radically improved the prospects of achieving high reliability, but more comprehensive control of quality, particularly under extremes of environmental conditions, is necessary during design and throughout production. This paper describes how the principles established by the Advisory Group on the Reliability of Electronic Equipment in the U.S.A. were utilized in the design and production of commercial electronic equipment.

1. Introduction

The obvious need for reliability in a commercial radar equipment at sea is accentuated by the lack of skilled electronic maintenance personnel amongst most ships' crews, coupled with the relatively long duration of many voyages. The greatly increased use of radar at sea which occurred during the 1950's was not accompanied by a similar increase in inherent reliability. Indeed, with conventional valve equipment, it is theoretically impossible on the basis of component population to produce an equipment which will have a reasonable confidence level of meeting the user requirement to operate over a period of months without failure. Manufacturers have always recognized the need for reliability as a prime consideration and over the years paid close attention to procedures aimed at improving the reliability of the product. These procedures have included the detailed specification of components, the use of preferred items, environmental testing and close inspection at all stages in production. The author's organization has always given, in addition, particular attention to the compilation of reliability statistics relating to equipment in service. Details of every installation and subsequent service performed by depots throughout the world are reported to the service headquarters and fed into a punched card system. The resultant analyses provide an invaluable index of performance covering some 16 000 marine radar equipments currently in service. From this information, the need for remedial or retrospective action quickly becomes apparent. A continual improvement to existing and past designs is thus possible and a number of improved components have been developed by close liaison with component suppliers, followed by controlled trials at sea, usually in trawlers.

In spite of the very close control exercised at all stages of design and production, together with the feedback of service information, it was obvious in the early 1960's that a radical improvement in reliability was required. One obvious improvement was in the use of the transistor and the decision to produce a complete range of marine radar equipment of high reliability employing transistors coincided with the publication of the important work undertaken in the United States by the Advisory Group on Reliability of Electronic Equipment (A.G.R.E.E.). The A.G.R.E.E. report, together with the work done in this country by the Ministry of Aviation, was studied most carefully with a view to adapting the recommended procedures for commercial equipment.

The objectives of adapting the A.G.R.E.E. principles reduced to their most simple form were:

(*a*) to produce equipment in which inherent faults were removed before production rather than appearing after a year or two at sea;

(*b*) to ensure that the transition from the development phase to production did not cause potential faults;

(*c*) to maintain reliability standards throughout the production life and particularly to guard against latent defects due to changes in manufacturing techniques or standards, both at the production works and with component suppliers.

The A.G.R.E.E. report is a massive document which sets out a comprehensive programme of pro-

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† Decca Radar Limited, Croydon, Surrey.

cedures to be adopted from initial design to quantity production aimed at improving both the intrinsic reliability of equipment design and the control of production quality. The report is, in effect, a comprehensive engineering philosophy but the most radical departure from existing practice lies in the recommendation to subject relatively large samples of equipment to controlled environmental testing. Such testing is applied to batches of equipment at three stages:

(*a*) development prototypes;

(*b*) pre-production models;

(*c*) continued batch testing during production.

2. Design

At the initial design stage, a realistic specification for environmental testing is drawn up based on experience of the worst conditions likely to be met in service. This also covers, and in many instances is considerably more rigorous than, the type approval requirements of the Board of Trade in this country and similar requirements of foreign governments.

Components selected during design must be drawn from a Company Preferred Items List for which a Decca specification exists. If no suitable component is available on this list, a specification for the new component is established and following specification testing, the item is included in the Preferred range.

Throughout the design process, the development engineers in the laboratory have working alongside them reliability engineers from the Engineering Group of the Company's Service Division. It is the function of these engineers, who work completely independently of the design, production and inspection teams, to examine and comment on the reliability aspects of new designs as they are prepared, basing their comments on their own service experience and the extensive accumulated performance data of earlier equipments in the Service Division records. Apart from the obvious advantages of introducing any changes thought desirable at the earliest possible stage in development and of providing the essential feedback loop from field to laboratory, this arrangement also tends to reduce the economic risks attendant on any pre-ordering of long delivery items for production before the release of production drawings to the factory.

Extensive environmental testing facilities are available at the laboratories for the examination of materials, components and experimental and prototype sub-assemblies and equipments. Much of this equipment is of the standard kind now commercially available from several manufacturers, but it has been found necessary to supplement the range with a number of non-standard items. Among the larger pieces of equipment are a low frequency mechanical vibration and bump table, a large 4000 lb medium-frequency hydraulic vibrator and a 550 lb and 50 lb high-frequency electrical vibrator. Of six test cabinets, the largest has a capacity of 67 ft^3 and a temperature range of $-25°$ to $+100°C$ and the smallest a 3 ft^3 refrigerator working down to $-70°C$. A large chamber, 21 ft × 16 ft × 10 ft high with a temperature range of $-30°$ to $+75°C$ is fully equipped for testing complete equipments *in situ* and will accommodate a minimum of ten working radars.

Driving rain and splash test equipment is available and there is a range of other test rigs for exploring special equipment characteristics—the sealing of radar aerials, for example, is tested by immersing them in a tank of water, the temperature of which is cycled to stress the seals. Finally, there are laboratory instruments for such physical tests as hardness and tensile strength.

3. Development

Several development prototypes are made for exhaustive test and evaluation. One of these is sent to sea for a long operational trial, another is supplied to the Service Division for a thorough reliability analysis. Although Service Division engineers have been concerned in the development of the equipment, the analysis is carried out *ab initio*. First, a count is made of the numbers and types of components used in the equipment and from this count a theoretical estimate of reliability, called the design capability is calculated. This figure is then used as a yard-stick in the detailed examination of the circuit arrangement. Component running conditions are measured (not calculated) to ensure that no component is run at more than 80% of its rating at any time including switching surges. At the same time, note is taken of the accessibility of components, especially those that are most likely to need to be changed for maintenance purposes.

As a result of the report issued after this analysis, further prototypes are made, which are subjected to a full environmental test procedure lasting some months. The specification for this testing is based on Defence Specification DEF 133 and it is believed to be the most stringent that has been applied to a commercial marine radar.

4. Production

The next stage is to produce a number of pre-production prototypes for A.G.R.E.E. testing. This is a most important stage in the procedure as it ensures that equipments made from production drawings and tools still satisfy the same requirements as development prototypes. After A.G.R.E.E. testing the pre-production equipments are used at agents' conferences and introductions and for training purposes.

The A.G.R.E.E. procedure next calls for a severe environmental test to be applied throughout the production life to sample equipments taken regularly from the production run. This procedure has been adopted for commercial production and it has for some time been applied to production models in the 'Transar' marine radar series. The routine monthly sample is not less than ten equipments and these are subjected to 500 hours temperature cycling between −15° and +55°C in the large chamber mentioned above. The cycle rate is once per day and the equipment under tests starts the day at −15°C when it is switched on with the input voltage set at the lower specification limit, which is (nominal −20%) and given a performance test. The equipment is then left running as the chamber heats up and is examined hourly to ensure that it is still operating. The chamber reaches +55°C after about 7 hours and the equipment continues running, now with the input voltage increased to the upper specification limit (nominal +10%) for a further 3 hours. Then during the next 2½ hours all the equipments in the chamber are given a further performance check and switched off. The chamber is then vented to atmosphere for an hour and re-sealed and cooled ready for the next day's cycle of operations.

Aerials and gearboxes, which are of course fitted in the open on board ship, are subjected to temperature cycling between −25° and +70°C and in addition are subjected to driving rain and bump tests.

Short repairs or adjustments to faulty equipments are made by an engineer working in the test chamber but for larger jobs the equipment is withdrawn into an adjacent cubicle at ambient temperature. This, of course, is to keep the time spent by engineers in the chamber at these extreme temperatures to a minimum. Even so, strict safety precautions have to be taken and engineers working in the chamber are examined medically at regular intervals.

5. Supervision of A.G.R.E.E. Testing

The whole A.G.R.E.E. procedure is centred on the Service Division. A.G.R.E.E. testing is controlled by a Test Committee consisting of the Development Director, the Service Director and the Company's Chief Inspector. This committee lays down the specification for testing and reviews the results at regular intervals. A report on each batch is submitted to the Committee, detailing the faults encountered during test, sub-divided into those which would have caused a service call and other subsidiary faults, together with an opinion by the engineer in charge of testing as to whether the fault was due to design, production, inspection, material defect, etc. The reports on each batch are considered regularly by the Test Committee who decide whether action is necessary as a result of any trends shown up during testing.

6. Conclusions

The introduction of A.G.R.E.E. testing has meant a large capital investment and a continuing heavy operating cost. Obviously, in a commercial environment, one looks for a financial return on costs of this nature and it has already been found that the return comes from two sources, namely an increase in sales of a highly reliable range of equipment and, secondly, a reduction in maintenance costs. A.G.R.E.E. testing was introduced in mid-1963, and it is believed that the author's company is the only manufacturer in the world to apply the A.G.R.E.E. principles to commercial electronic equipment.

It is, of course, very difficult to isolate advantages accruing from A.G.R.E.E. testing from the normal advantages that would appear due to the natural evolution of more reliable equipment through improved components and better design. Naturally some faults occur in service which are not detected in the chamber, but these are more than compensated for by the forewarning given of likely future trouble that the arduous cycling in the chamber reveals in the present. One fault that showed up quite early in the chamber, for example, was, at the same time, reported in trials equipment that had completed 2000 hours operation; another example concerns a class of component that has shown several failures in the chamber but has not yet failed in service: the component has therefore been replaced by a more reliable one.

There is no doubt that the major requirement of users of marine radar at sea is high reliability. The A.G.R.E.E. procedures that have been adopted and are now standard practice have undoubtedly been a major contribution to meeting this requirement.

Manuscript received by the Institution on 15th December 1965. (Contribution No. 93/RNA61.)

U.D.C. 621.396.969.3.004.6

Radar Reliability on Trawlers

By

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Presented at the Radar and Navigational Aids Group Symposium on 'The Reliability of Marine Radar Equipment', held in London on 15th December 1965.

Summary: Records of reliability and maintenance of radar equipment on a specified group of ships (deep-sea trawlers) operating from a specified port under controlled conditions are presented. The reasons for the very long 'mean-time-between-failures' under these conditions are considered to be: (a) the equipment is not switched on and off but allowed to run for a long time; (b) the operators have been given training on the maintenance of this particular set; (c) the spares provisioning is at a high level, and (d) a rigid system of preventive maintenance is applied. All these factors are considered to be significant in achieving high reliability.

1. Introduction

The collection of information on radar reliability at sea from many ships, on different duties, using different maintenance procedures, and operating all over the world, is a very difficult undertaking. Associated with the author's organization, there is, however, a special group of radar-fitted ships, deep-sea trawlers, where the conditions of use and the maintenance procedure are very thoroughly known, and the fault data are completely trustworthy. This group, therefore, forms a valuable sample from which to judge the reliability of a particular equipment under operational conditions. This paper summarizes the basic data collected in the year 1964, and draws certain conclusions from them. While these can only be considered to apply with certainty to this group of ships operated under these conditions, it is felt that the conclusions have some significance for all ships.

2. Population Sample

The ships concerned are 64 deep-sea trawlers operating from Hull and Grimsby, and fitted with either type 14/9 or 14/12 radars. These sets are identical except for the display unit, one being 9 inch and the other 12 inch. The skippers insist on the radar being fully operational before they leave port, and it may remain switched on until they return about three weeks later. This cycle is repeated roughly each month, so that the radars operate on the average nearly 3000 hours per annum, in some instances over 5000 h/a, i.e. about half the time at sea. The arduous conditions on a trawler are well known—bad weather, different vibration when steaming, trawling or hauling the net, large variations of weather conditions, and so on—so that these ships are a good field for reliability assessment, in which data are accumulated faster than in any other service.

There are certain peculiarities about the operation of radar in these ships, which make them exceedingly valuable as a source of data, and which are, perhaps, not found in other circumstances. They are:

(*a*) The ships are on contract maintenance, i.e. for the payment of a fixed sum per annum by the shipowner, the manufacturer's service department contracts to bear all the cost of keeping the radar in operation. This is carried out by a system of preventive maintenance by which, each time the ship is in its home port, each set is restored to the condition in which it passes the schedule of factory tests it met originally. Because of the conditions of use, almost no maintenance takes place other than in the home port, or on board during a fishing trip. Hence, the maintenance is strictly controlled, and fully known.

(*b*) The ships carry at least one officer (the skipper or the radio operator) who has had a training course in maintenance of the radar at the local service depot. This man can diagnose faults at sea and, because of the ready availability of spares, can usually correct them with minimum loss of operating time.

(*c*) Each ship carries a stock of spares, not merely valves and components, but in many cases complete units. On contract maintenance, the cost of replacing these when used is borne by the service department.

(*d*) Another peculiarity of trawler operation ensures that the data on maintenance can be trusted. On his return from each fishing trip, the skipper reports to his owners. If he is not personally responsible for radar maintenance, he is accompanied by the officer who is, and part of his report deals with radar operation, faults, etc. The manufacturer's service engineer

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† Radar Development Department, Kelvin Hughes, a division of Smiths Industries Limited, Dagenham, Essex.

is also present at this meeting, to take any action indicated. The skipper's report is therefore restrained by two opposing influences:

- (i) He will not understate his case, since he, and his owner, demand that the radar be fully operational for the next trip, probably within a week.
- (ii) He will not overstate his case, since the engineer will examine the radar, or may have already done so.

This report may, therefore, be relied upon as a true statement of the state of the equipment and its maintenance history.

3. Faults Recorded

Faults are classified into two types:

(*a*) Failures—where the fault renders the equipment completely unserviceable, e.g. scanner motor bearing collapsed.

(*b*) Defects—where the equipment is still serviceable despite the fault. These can be of three types:

- (i) The loss of some facility, e.g. dial lights, where the control knob indication can be seen by the use of a torch.
- (ii) A known small reduction in performance, e.g. 12 dB deterioration in receiver noise figure, measured on the performance monitor. This sounds serious, but would in fact reduce the range performance on large targets by no more than 50%, possibly less, and on small targets by only 25%; the equipment would still exceed the Board of Trade specification minimum requirements by a comfortable margin.
- (iii) Component failure which can be repaired at sea, so that the availability of the equipment for operational use is interrupted for only a relatively short time.

It will be noted that because of this classification, repair of a fault at sea as in (iii) above can reduce a failure to a defect.

Table 1

Radar log: *Stella Orion* (Type 14/12 radar)

Trip date	State	Fault	Corrective action
13. 1.64	working		
5. 2.64	working		
28. 2.64	working	magnetron u/s	changed at sea
18. 3.64	working		
7. 4.64	working		
27. 4.64	working		
21. 5.64	working		
11. 6.64	working		wafer H.Sl. changed
24. 7.64	part working	loss of near signals	t/r cell replaced
17. 8.64	working		
14. 9.64	working		
6.10.64	working	modulator u/s	changed at sea
3.11.64	part working	instability at all ranges	
26.11.64	working		

Hours run—5620　Hours service—49½
Failures—nil　Faults—4

Table 2

Radar log: *Starella* (Type 14/9 radar)

Trip date	State	Fault	Corrective action
15. 1.64	part working	intermittent loss of picture when changing range	
4. 2.64	working		
24. 2.64	working	time-base u/s	R13 replaced at sea
14. 3.64	working		
6. 4.64	unserviceable	p.p.i. motor u/s	replace motor
23. 4.64	working		
11. 5.64	working		
1. 6.64	working	breaks in calibration rings	clean slip rings p.p.i.
22. 6.64	working		
15. 7.64	working		
4. 8.64	working	poor signals	t/r cell replaced
26. 8.64	working		
16. 9.64	unserviceable	short circuit on D.180V	
7.10.64	working		
29.11.64	part working	intermittent trace and poor signals	
17.11.64	working		

Hours run—5730　Hours service—50½
Failures—2　Faults—7

From the user's reports, a radar log is maintained in the service depot for each ship. Two examples have been abbreviated to the form shown in Tables 1 and 2. The column headed 'State' gives the equipment condition at the end of the trip. The date is that of the return from each trip.

The record of the radar log given in Table 1 shows that fourteen trips were completed in the year considered, making a total of about 7000 hours at sea, and the radar was never completely unserviceable on return. Two major repairs were executed at sea by replacement from spares on board. The availability of the set for operational use is hardly affected by these faults, hence, the nil return for complete failures. The four faults at sea divide the time into five periods, indicating over 1000 hours m.t.b. faults. It is likely that in the average of 3½ hr per trip spent by the depot engineer on preventive maintenance, other minor components (e.g. crystal) may have been replaced, and other repairs made (see entry for 11.6.64 in Table 1), but these could not be many because of the cost aspect. The point is that this maintenance procedure undoubtedly reduced the fault incidence at sea, and the training of the crew and provision of spares mitigated the effect of the faults that did occur.

In the case under Table 2, the radar was completely out of action on return from two trips out of sixteen. This would have been three if one repair had not been executed at sea. Seven listed faults indicate over 700 hours m.t.b. faults, while the three working periods, between failures indicate 1910 hours m.t.b. failures. The service time averages about 3 hours per trip.

These two examples illustrate the typical basic information.

4. Fault Analysis

We next analyse the complete failures throughout all the ships as shown in Table 3.

This shows that 64 ships operated a total of 188 000 hours—an average of nearly 3000 hours/annum/ship, for a total of 72 failures. Adding the number of ships, this gives 136 operating periods between failures in the test interval, and a m.t.b. failures of 1385 hours. It will be noted that the type 14/12 appears consistently better than type 14/9. This is surprising since the only difference is the display unit, but the display appears to be responsible for no more than a reasonable proportion of the failures. A possible reason is that the 14/12 display is bigger, and so tends to be fitted on bigger ships, with better sea-keeping qualities, more accessible unit sites, better power-supply regulation, etc., but this is only a speculation.

A more interesting point appears from the separate analysis of the two ports. The Hull trawlers appear to operate about twice as many hours per annum as the Grimsby trawlers, and have about twice the m.t.b. faults. The 14/12's in both ports appear to operate longer hours than the 14/9's, which could have a bearing on the difference between the two nominally similar sets, while the consistent ratio of about 2 : 1 between operating hours/ship/annum, and m.t.b. faults gives qualitative evidence in support of the desirability of leaving a set running as long as possible, and not switching off and on. The figures suggest that these ships have one failure every six calendar months, regardless of operating time, and therefore the mariner may as well have his radar switched on and immediately available, all the time at sea.

Table 3

Failures

HULL AND GRIMSBY	14/9	14/12	Total
Number of ships	46	18	64
Total operating hours	112 500	75 000	187 500
Failures	56	16	72
m.t.b. failures	1120	2220	1385
GRIMSBY			
Number of ships	41	10	51
Total operating hours	86 500	31 000	117 500
Failures	50	11	61
m.t.b. failures	950	1476	1050
Hours/ship/annum	2110	3100	2300
HULL			
Number of ships	5	8	13
Total operating hours	25 970	44 480	70 450
Failures	6	5	11
m.t.b. failures	2360	3420	2930
Hours/ship/annum	5196	5560	5420

Table 4

Faults, i.e. failures plus defects for Hull trawlers.

	14/9	14/12	Total
Number of ships	5	8	13
Total operating hours	25 970	44 480	70 450
Total faults	31	60	91
m.t.b. faults	722	655	678
Total maintenance hours	225	405	630
Maintenance hours/ship/annum	45	51	48½
Operating hours/ship/annum	5196	5560	5420

Distribution of faults

Unit		No. of faults	Faults clearable at sea
Scanner		11	
Transmitter/receiver		32	19
Display 5 Type 14/9	8		
8 Type 14/12	31		
	39	39	3 (c.r.t.)
Rotary converter		6	
Compass resolver		3 (same ship)	
		91	22

A more detailed analysis has been made of all faults in Hull only and is shown in Table 4. The last column enumerates faults due to major replaceable components—magnetron, klystron, etc.—which could be cleared at sea by replacement from a spare on board. This was done in 11 cases only.

The analysis brings out two points. First, there is no undue weakness of any one unit, since the faults in each unit correspond roughly to its complexity. Second, the time spent on preventive maintenance is less than 1% of the operating time, not an unreasonable investment.

5. Conclusions

It is believed that these figures indicate that this particular group of ships enjoys higher reliability than others in respect of the availability of the radar installation for operational use. Owing to the difference in methods of fault evaluation and collection of information, it is not possible to make direct comparisons with figures from other sources, but the m.t.b.f. appears to be about four times higher than the 156 hours quoted by Captain Wylie,† while the m.t.b. failures is considerably higher.

It is considered that this higher reliability is a consequence of the following items.

(*a*) Virtually all maintenance is carried out by one group of technicians—each ship is the specific responsibility of one service man. In the whole period, only one Hull ship called at another port for service. Not only does this lead to familiarity with individual equipment and users but, in the words of the famous American quotation, 'The buck stops here'!

(*b*) The service contract arrangement has exerted economic pressure on the adoption of a highly developed system of preventive maintenance. The service man is on board for 3 or 4 hours each month, the equipment is re-checked to the factory inspection standard, and incipient faults are corrected before they occur, leading to the avoidance of breakdowns at sea.

(*c*) At least one officer on each ship has been trained in fault diagnosis and repair of this specific radar set—some admittedly to a higher standard than others, but all to some extent.

(*d*) Spares provision on board covers not only components such as the magnetron, c.r.t., etc., but in some cases complete units such as the modulator and time-base. This is considered necessary in a trawler, where the radar is regarded as essential to the operation of the vessel, which must be self-sufficient for the duration of the trip, about three weeks.

(*e*) One final difference; these radar sets are regularly switched on for long periods and switched off sometimes only on return to port. The number of switching cycles per year probably does not exceed 100, including maintenance.

Each of the above points is considered to have some bearing on the achievement of high reliability, and no single point can be said to be of major importance.

Manuscript received by the Institution on 7th February 1966. (Contribution No. 94/RNH 62.)

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† F. J. Wylie, 'An investigation into marine radar reliability', *The Radio and Electronic Engineer*, 33, pp. 17–23, January 1967.

U.D.C. 621.396.969.3.004.6

The Attainment of High Reliability of Marine Radar

By

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Presented at the Radar and Navigational Aids Group Symposium on 'The Reliability of Marine Radar Equipment', held in London on 15th December 1965.

Summary: The paper comments on the general requirements which should be met by designers of marine radar equipments. It suggests that in planning a new design the minimum standard of reliability that should be set is 500 hours mean time between failures. Some basic design precautions are then described covering various aspects of the problem from initial design and selection of components to installation, environmental and operational conditions. Short notes on maintenance and training aspects are also included. The paper concludes with an example of the extremely high reliability achievable by the use of a twin inter-switchable radar system wherein the probability of trouble-free operation over a specified period can be raised from 95·3% to 99·8%.

1. Operational Requirements

Since radar is an indispensable part of the modern ship's safety equipment, the user naturally requires the maximum degree of reliability which is available at a reasonable cost. Reliability has usually been expressed in terms of the mean time between failures (m.t.b.f.), failure rate or probability of survival, since these methods of assessment are most readily amenable to mathematical calculation and engineering control. In the Radio Advisory Service (R.A.S.) analysis‡ one of the figures measured is the average availability percentage. To the shipowner this is probably a more useful index than any m.t.b.f. figure. 'Availability' introduces a factor of 'time taken to correct each fault' which is not easily predictable as a design parameter since it is largely a function of the adequacy of training and maintenance arrangements.

The R.A.S. review showed somewhat disappointing overall figures, but our own Company's analysis of one of the types which was represented in substantial numbers on the R.A.S. review showed an average availability percentage of 97·85. The average time out of service per fault was 0·75 day, compared with the rather high 'national average' of two days per fault. This particular type of radar was one which was fitted some three to four years ago. With the latest designs of equipment it is becoming evident that much higher figures should be obtained and radar designers should not aim at anything less than an m.t.b.f. of 500 hours. (No doubt it is generally appreciated that this does not guarantee a period of 500 hours of trouble-free performance. The probability of failure-free operation during that period would in fact be 36·8%.)

2. Methods of Increasing Reliability

2.1. *Basic Design Factors*

The first and most obvious action which a designer can take is in the selection of the most suitable components and the reduction to a minimum of the number of individual components necessary to fulfil a particular function. (This will be qualified later.) Components can be grouped in two categories, the first class being those which may be described as 'permanent', as distinct from the second variety which are 'consumable' items, i.e. those with a finite life. In selecting components of the first category adequate margins of safety should be embodied, particularly in respect of voltage ratings and temperature limits. In general reduction in the ratio of operating to rated value reduces failure rate. Excessive caution, however, may produce inferior results; for example, certain types of resistors operated at stress levels below 10% may show increased failure rates. (In equipment operating under humid conditions the electrical stress on a resistor during operation may be too small to evaporate the moisture on its surface and this will lead to a resistance value substantially

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† The Marconi International Marine Company Limited, Chelmsford, Essex.

‡ F. J. Wylie, 'An investigation into marine radar reliability,' *The Radio and Electronic Engineer*, **33**, No. 1, pp. 17–23, January 1967.

less than the value under normal dry conditions.) In selecting types and quality of component, the designer must be influenced by the quantity of each used in an equipment. For example, for apparently simple items such as fixed resistors, of which there may be many hundreds in a typical installation, individual component reliability must be of an extremely high order if the overall failure rate of the equipment is to be held to the desired level. Conversely, components of which only one or two appear per set give the designer a greater flexibility of choice.

In the category of consumable items, the most obvious are valves and the reduction in the number of these used per equipment is a logical step for designers to take. Thus in many new designs the number of valves is reduced to the basic minimum of magnetron, klystron, cathode-ray tube and, possibly, the transmitter modulator. A further enhancement of the reliability of these remaining radar valves would seem to be the next essential step since it will be evident from the R.A.S. survey that failures due to these items represent about half the total number of valve failures and thus still account for one-tenth of the total equipment failures. Nevertheless, the use of semiconductor devices wherever appropriate should contribute much more to the overall improvement of reliability than the resulting elimination of a number of valves would seem to indicate. In particular, their use helps to reduce the temperature rise in other parts of the equipment and may also eliminate the secondary problems which often arise from the use of forced ventilation systems. For added reliability, other examples include replacement of relays by diode switches and the use of brushless motors.

Reverting to the subject of 'permanent' components, some existing radar equipments show evidence of inadequate thought having been given to the selection and rating of individual components. The point to be emphasized is that the rating should take into account, not merely the normal conditions (including the full range of temperature and humidity), but also the abnormal conditions that may arise as the result of a fault in an associated circuit. Far too many major failures in the past have been the consequential result of a relatively minor circuit breakdown elsewhere in the unit. The adoption of semiconductors has made most designers more alive to the possibility of such secondary failures but sometimes the precautions taken appear to be afterthoughts (for example, the addition of protective diodes) rather than evidence of thoroughness in the initial approach. A little more careful study of the initial problem can often produce an alternative circuit configuration which can give a much greater degree of self-protection under such fault conditions.

In a similar category is the problem of surge protection. In shipboard installations alarmingly high transient peak voltages frequently occur. This is particularly the case in small ships such as fishing trawlers where the power supply is barely adequate for the total load and where the latter can include some high consumption devices such as winches. On these vessels the primary power supply is often a d.c. system and therefore some conversion machinery or static power unit is necessary. The older type of rotary machine used for this purpose had the advantage of providing considerable isolation against supply voltage surges. With the more modern static converters the problem is much more acute due to the absence of the inertia effect provided by a large rotary machine.

Related to this problem is that of fuse or safety cut-out systems. Many otherwise excellent equipments give endless trouble to their users due to the unnecessary failure of fuses. Many engineers tend to dismiss a fuse failure as a very minor type of equipment fault, but it must be realized that, to the user, a failure from such a cause may prove just as serious as one which has arisen due to a fault in a more vital component. Reference to the R.A.S. review shows that fuse failures account for as much as 12% of the total. This is much too high a figure to be dismissed lightly. On the subject of fuses, it is essential that care must be taken to ensure that the type of fuse fitted is one whose rating is clearly evident from inspection, and its speed of operation chosen to give sufficient allowance for short switching surges while still affording complete protection to the equipment.

In this category we must not forget the provision of mechanical 'fuses' to safeguard mechanisms. An important example is the design of an aerial driving unit, which should include protection for the gearbox and driving motor in the event of the scanner being fouled by a halyard.

So far the failures mentioned have been those which have caused complete breakdown of equipment. There is also the other type of failure where the equipment ceases to display the required information due to progressive degeneration or 'drift' of certain components away from their specified value. One of the most potent devices available to the engineer to counter the incidence of this type of failure is the use of generous margins of performance. In many cases, economic factors based only on first cost make it difficult to provide adequate margins, but a more balanced view of the overall cost of maintaining an adequate performance, at all times, during the life of the equipment, may show that it is prudent to use relatively generous ratings of the basic factors, such as magnetron power, overall gain and noise factor of the receiver.

2.2. *Environmental Conditions*

Whereas the Board of Trade type approval tests ensure reasonable ability of an equipment to operate efficiently in a wide range of climatic conditions, it does not necessarily follow that an equipment so tested can tolerate all the conditions likely to be encountered on merchant ships. The installing engineers therefore should ensure that the sites chosen on board ship are satisfactory in at least two respects: (1) ventilation must be adequate to inhibit undue temperature rise; (2) the vibration encountered must not be excessive.

Recent measurements have shown that the vibration levels encountered on modern ships can exceed both in amplitude and frequency the conditions simulated during type approval. Where the designer has allowed only for the latter conditions, then additional precautions may be necessary during installation to minimize the disruptive effects of vibration. The most severe cases usually arise on motor ships where the navigating bridge is placed well aft. It is relevant to mention that amendments to the Board of Trade type approval specification in this respect are now under consideration. Operational evidence suggests that designers should cater for vibration frequencies up to at least 50 Hz at accelerations of 1 g, although much greater than 0·08 g on the radar display unit makes detailed picture inspection and plotting impossible.

A third hazard likely to be experienced on practical installation is that of voltage variations in excess of the conventional design limits of $\pm 10\%$. While it may be uneconomic to design for full performance to be available over a range of more than $\pm 15\%$ of a nominated voltage, it should not be a difficult matter for the designer to ensure that the equipment will continue to function without self-damage over a much wider range, including short term surges of 40% above nominal. On smaller vessels there is also the further additional risk of accidental reversal of polarity of the ship's d.c. supply.

2.3. *Operational Use*

An apparently obvious but sometimes overlooked point is that the equipment should be made proof against clumsy handling. For example, while it may be reasonable practice to use a thermal device to delay the application of certain voltages during a short warm-up period, the designer may overlook the possibility of damage arising when the equipment is switched off and then switched on again before the thermal delay has had time to reset.

2.4. *Maintenance*

It would seem that, even with the use of the best available design techniques, we are still left with a 'hard core' of a number of consumable items, including the specialized radar valves. With present standards of reliability it would seem from the R.A.S. survey these may account for as much as 10% of the total failures. It will thus be necessary for some time to come to provide for adequate first-line maintenance on board ship, both by supplying an appropriate quantity of spares for these items and by training shipboard personnel to carry out their replacement as expeditiously as possible. Where a radio officer is given the responsibility for first-line maintenance, this represents a simple task. The designer should bear in mind, however, that replacement of these parts may have to be made by less skilled personnel; thus the disposition of consumable units and the access to them should be made as straightforward as possible. Even in the case of fuse replacement care should be taken to give a simple and clear instruction on the location and the rating of these items and their spares. This simple precaution may save hours of consequential maintenance work. Where fuse ratings are accurately defined there must be strict discipline to thwart any misguided attempts to replace them by fuses of a higher rating.

Still within the category of consumable parts, are mechanisms such as aerial driving units, gyro repeaters and synchro motors. Where properly designed and fitted these items should not introduce many unexpected failures. Preventive maintenance and regular inspection by shore-based staff should be so organized that replacement of gears, brushes or bearings can be made long before complete failure occurs.

2.5. *Training*

It follows from the above that for first-line maintenance a primary essential is to give adequate training to radio officers or other ship's personnel responsible, including clear instruction on replacement of consumables, and to ensure that they will not indulge in any unnecessary adjustment of various preset controls.

For shore maintenance staff or officers on a ship engaged on unusually long voyages away from service bases a more detailed training is essential. In this training, the initial emphasis should be on imparting a sound appreciation of the principles and techniques embodied before attempting to instill a mass of detail regarding a particular item of equipment. The author's Company has found it helpful to take advantage of the many training courses now being organized by the technical colleges in order to cover this type of general background and to give a sound basic training in the principles of logical diagnosis. Where this is done the specialized training in a particular design can then be given in relatively few weeks and the men so trained can usually be depended upon to get down to the root cause of a failure instead of merely correcting the apparent result.

3. Economic Factors

The attainment of extremely high standards of reliability becomes essentially a matter of economics. In terms of availability (as used in Captain Wylie's analysis), to go up from figures of 98% to 99·5% may represent a substantial additional cost on the equipment and even the latter relatively good figure may not satisfy the user, for it still leaves him with the prospect that over a six-month period his radar may be out of action for a period of over half-a-day at a time when its use may be vital. (99·5% availability, based on R.A.S. averages, would represent 0·6 day out of service during the 25 days when it would probably be in operational demand.) This is one of the reasons why many shipowners are now specifying a twin radar installation with complete interswitching to give full duplication of all major units. This practice, coupled with improved reliability of units, should provide an adequate standard of reliability, in terms of availability.

It may be useful as a final comment to note the actual quantitative performance which would thus appear to be possible. If we consider a single radar installation with an m.t.b.f. of 500 hours, then the probability of reliable service over any period of twenty-four hours is 95·3%. If the installation is duplicated, then the probability of achieving complete reliability over any period of twenty-four hours rises to 99·8%. To achieve such a high level with one equipment would require an m.t.b.f. figure of 3000 hours.

Manuscript received by the Institution on 3rd December 1965. (Contribution No. 95/RNA63.)

Discussion on "The Reliability of Marine Radar Equipment"

Under the chairmanship of Mr. R. N. Lord

Mr. L. F. North: Did the A.G.R.E.E. system increase the purchase price, and if so by what percentage?

Mr. M. G. Miller (*in reply*): All our equipment carries a comprehensive guarantee covering both labour and material costs. Experience to date shows that the cost of A.G.R.E.E. testing is fully compensated by a reduction in guarantee costs.

Mr. W. Heilner: Having heard so much about the m.t.b.f. of marine radar equipment it would be interesting to learn something about the number of components per equipment or alternatively about the failure rates of components under service conditions.

Referring to A.G.R.E.E. techniques described by Mr. Miller, although one cannot but admire the tremendous efforts made by his company, in the employment of temperature cycling in order to achieve higher reliability, one cannot help noticing that the American A.G.R.E.E. report calls for vibration testing in addition to temperature cycling.

At sea additional environmental hazards are encountered, such as high humidity, salt spray, condensation, vibration due to the ships engine, roll, pitch, shock and acceleration which are not being simulated by temperature cycling.

It would be fortuitous if by temperature cycling we could detect all types of failures which would normally be caused by a variety and combination of adverse environments normally encountered at sea.

Does the author of this paper really believe that the m.t.b.f. observed during temperature cycling is a reliable prediction for the m.t.b.f. to be expected during service conditions?

Mr. Miller (*in reply*): The question regarding component failure rates and population is too wide to answer here. We do, however, maintain very detailed analyses of component failure rates as a percentage of population.

In our opinion the procedures laid down in the A.G.R.E.E. document for shipborne equipment are inadequate and we have set much more severe temperature cycling conditions than are advocated by A.G.R.E.E. We are currently investigating the value of vibration testing, but results of vibration during A.G.R.E.E. testing so far have shown it to be of doubtful value.

The type of environmental conditions specified in the question are fundamental to the design of marine equipment. Very severe testing under these conditions is carried out in the design proving stage, including a 42-day tropical humidity test. Provided that the design is then shown to be satisfactory it is unlikely that subsequent equipment would fail to meet the specification. In addition, of course, it is quite impossible to subject relatively large numbers of production equipment, destined for the customer, to this type of test. It is part of our overall policy to take one or two sets per year and subject them to the full environmental specification, accepting that such equipment is written off at the end of testing.

There is no known method of fully simulating service conditions and thereby uncovering every fault that is likely to occur; we consider, however, that the A.G.R.E.E. procedures as currently being applied are the best available method of ensuring reliability in service. We do not profess to predict m.t.b.f. in service as a result of A.G.R.E.E. testing, but we do consider that this procedure eliminates many potential faults due to possible weaknesses in design, component manufacture and production and inspection.

Mr. J. W. Mordin: Radar reliability as experienced by the shipowner is an effect resulting from two inter-related causes:

(1) The inherent reliability of the circuit design and construction of the radar.

(2) The efficiency of the manufacturers' worldwide service organization.

Whereas the manufacturers accept full responsibility for the design and construction of their equipments, their ability to provide expert and experienced service personnel at every port where service may be needed is constrained by many factors, some of them not within their own control. Even in the most efficient service organization trouble can be caused by inexperienced personnel operating at ports many thousands of miles away from the factory in the United Kingdom.

I suggest that the Institution's Radar Group might like to examine a system whereby service engineers are awarded, after examination, a certificate of competence. Such a system is already operating in the United States under the auspices of the F.C.C. A suitable syllabus for such an examination would at least assure a basic level of training and would thus act as a safeguard to manufacturers and shipowners alike.

Mr. L. F. North: When radars are run continuously over long periods, does it affect reliability in any way if the set is put to 'Stand-by' instead of being kept fully on?

Mr. G. J. McDonald (*in reply*)*:* Since many component parts of a marine radar involve mechanisms, including aerial driving unit, servo motor systems, etc., it is normally desirable to minimize the wear on these parts by switching the set to standby on occasions when the radar is not being viewed for appreciable periods. In the case of the electronic components, the cathode ray tube and, possibly the magnetron, may benefit by having the e.h.t. removed while not actually required for operational use.

Mr. Miller (*in reply*)*:* Undoubtedly switching to 'stand-by' rather than operating with the set fully 'on' improves reliability because the components which are life-conscious, such as magnetrons and modulators, are not operating during 'stand-by'.

Mr. A. H. George: There may be some confusion brought about by the actual presentation of reliability information. M.t.b.f. is often quoted as a measure of reliability and this is usually in units of *operating* time.

Where the duty cycle is very high then the m.t.b.f. units approximate to calendar time. For a valved equipment a high duty cycle or continuous operating is likely to yield the highest m.t.b.f. figures but also the largest number of defects.

For a low duty cycle, where the equipment is frequently switched 'on' and 'off', the m.t.b.f. quoted in operational hours will usually be lower but the total defects for a specified period of calendar time fewer.

Thus the duty cycle adopted in the case of radar equipments might well depend on maintenance cost and the effort available.

I would predict that for a transistorized equipment the low power circuits will probably benefit from being left 'on', for almost all the components should have a life greater than the equipment life. Short-life components such as transmitter valves would, however, continue to have their h.t. supplies switched as required for minimum failure contribution.

Mr. J. H. Beattie: In my experience some of the faults which occur on switching on are primarily due to space heater failures or to failure of the ship's staff to leave the ship's main supply switched to the radar in harbour where possible so that space heaters are energized. There seems to be some lack of understanding by ship's staff in larger ships on the necessity for and operation of space heaters. I visited one British ferry which had repeated switching-on faults due to isolation of the radar supply in harbour. We have now included a special note in our operational manuals on space heaters. For small ships like fishing vessels in which there is no electrical supply in harbour, the equipment must be designed to work without space heaters and we have done this with the Decca Navigator and D202 radar.

Mr. T. W. Welch: There appears to be emerging from the discussion a suggestion that the Masters of ships would be wise, to improve the reliability of their radar, to leave it switched 'on' and running for long periods even though not immediately required. Unless this is qualified by an indication that the radar should be switched to 'stand-by', there is danger that we might find ourselves at variance with the National and International Regulations relating to unnecessary transmissions, a step which I feel that we, in this Institution, should not endorse.

Mr. G. C. Arnold: Since it is extremely expensive to try to approach 100% reliability in marine radar equipment, intelligent usage would seem to play a significant part in increasing the effective reliability, i.e. the reliability at times when the equipment is actually required for navigational use.

If the user's approach is that the radar is only to be switched 'on' when it is actually urgently required, then obviously faults can only become apparent when the set is most needed. If it is given a regular daily test, together with appropriate preventive maintenance and/or switched 'on' some hours before it is required for a known hazard, then there is a chance that a proportion of faults will show up at a time when availability of radar is not so vital.

Captain Wylie (*in reply*): It would be interesting to know whether the average m.o.t.b.f. of the 137 ships which did daily or weekly preventive maintenance differed significantly from that of the remainder. This may perhaps be learned as the analysis progresses.

Major A. Cribb: There would seem to be two basic approaches to the problem of the introduction of reliability by intent at the design stage. The first involves the use of specialists in reliability to instruct the design teams, who are then left alone to get on with their work; the second approach allows the reliability engineer to monitor the design as it evolves and recommend changes. He is thus 'breathing down the neck' of the designer. Could any of the speakers give their views on the relative merits of these two approaches?

Mr. Harrison (*in reply*): Both approaches are necessary: you cannot add reliability at a later stage.

The Chairman: In my day, this used to be called 'good engineering practice'!

Major Cribb: I ask this question as one does come more and more upon a school of thought which considers that 'Reliability Cells' can be established, as a service to the designer, with the express purpose of monitoring the design. My own view is that this is the wrong approach and that, whilst it is a good thing to have design engineers taken away occasionally, instructed in the art of reliability, and then brought back to spread the news throughout their department, the actual work of designing should be carried out without hindrance under the supervision of one engineer who carries the responsibility for all aspects of his design.

Mr. Miller (*in reply*): Our experience is that design should be carried out by a team led by a project engineer, who has full responsibility for the design; however, it is of paramount importance that the project team should be given an agreed and realistic enviromental specification. Proving of the design on prototype equipment should then be the joint responsibility of the project leader and the reliability engineer.

Mr. J. L. Smith: Will Captain Wylie please tell us how the selection of the ships in the sample was made and, in particular, if there was a tendency to issue the questionnaires to those ships which had reported sustained unreliability or whether the sample included ships about whose reliability records there was no prior knowledge?

Captain Wylie (*in reply*): We had no prior knowledge of the performance of particular ships. The criteria used were the completeness and intelligence of the reply to the questionnaire and the aim of covering as many types of radar as practicable.

Mr. T. W. Welch (*communicated*): It seems a pity that no one is really able to define in a quite non-commercial spirit how best to build-in high reliability. It might be feared, however, that even if such definition were possible the cost of its implementation in any single equipment might double or treble its market price. For my own part I am sure that the simplest and probably the cheapest solution is to fit two similar but quite independent outfits; the resulting rise in total reliability could probably never be obtained in any less expensive way.

I do, however, much regret the type of specification now appearing from certain shipping companies which involves very elaborate switching arrangements to bring any part of either set into function in exchange for a similar part of the other. To my mind there is in this kind of specification a great risk of superposing unreliability in the switching circuits which will lead to a system reliability worse than that possessed by either set alone.

Captain Wylie (*in reply*): Regarding the inter-switching of duplicated radars I do not really agree with your assessment. I feel that the switchgear, from the same design stable, of course, should have a reliability of quite a different order to that of the radar units. This, I think, is borne out by experience in ships to date. However, time will tell.

Mr. Harrison (*in reply*): The paper 'An integrated marine radar system'† was the first public announcement of this principle in civil marine radar. This paper is a statistical analysis of the improvement in reliability to be obtained by inter-switching and its cost to the user. In broad terms the paper shows that, regarding the reliability and cost of a single radar installation as unit, two independent radars have a relative cost of 2 and a relative reliability of 3, whereas two correctly inter-switched radars have a relative cost of 2·2 and a relative reliability of 6. The 'cost effectiveness' of inter-switching is therefore almost double that of two independent sets from a reliability standpoint. There are also operational advantages.

Actual fault experience over the last few years confirms these conclusions. For instance, as stated in the paper, in 3000 operating hours on board S.S. *Canberra*, despite the occurrence of faults, there were always at least two radar displays fully operational.

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† A. Harrison and D. Chamberlain, *The Radio and Electronic Engineer*, **26**, No. 2, pp. 157–72, August 1963.

U.D.C. 621.396.933.23

I.L.S. Far-field and Radio Environment Monitoring

By

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Presented at the Radar and Navigational Aids Group Symposium on 'Monitoring of I.L.S. Ground Equipment for Automatic Landing', held in London on 4th April 1966.

Summary: Experimental investigations into the techniques of far-field localizer and glide-path monitoring for Category III I.L.S. installations are described. The results of monitoring at an operational airport over an extended period are presented. Two novel techniques are briefly described: (a) a system of spaced aerials for monitoring beam-bend noise, and (b) an independent side-band receiver for the detection of radio interference.

1. Introduction

It has been shown that to achieve the required safety when using the current Instrument Landing System for landing in reduced weather minima, extensive monitoring of specified parameters is needed.[1-3]

Adequate integrity of the ground transmitter and aircraft receiver components of the I.L.S. can be achieved by the use of redundancy, i.e. a combination of monitoring and multiplexing.

The remaining simplex component of the I.L.S. system is the ground-to-air transmission path. This may be affected by interference which might give rise to anomalous guidance information being received in the aircraft. Such interference may be:

(a) re-radiated—such as reflections from static or moving surfaces,

(b) external—such as man-made noise interference and rogue transmissions.

Far-field and radio environment monitors, respectively, are the names given to the equipments required to detect this interference.

Although serious interference will be rare in a well-designed, installed and maintained system, the orders of probability with which one is concerned in automatic landing reliability are such that some degree of multiplexing or monitoring (or a combination of both) of the propagation path is essential.

The practicability of multiplexing the transmission path can be quickly discarded in the context of present-day systems, since it would involve heavy penalties in time and cost. However, the feasibility of using separate carrier frequencies, or separate aerial arrays (such as an additional down-wind localizer) should certainly not be dismissed from consideration of second-generation I.L.S. facilities.

It may well be that for certain situations an unmonitored, un-duplicated transmission path will achieve the desired integrity, but this will certainly not be proved until several years of operation of Category III systems have been experienced. For present-day systems, therefore, there is no alternative but to monitor the propagation path.

It has been proposed that a comprehensive monitor in the aircraft could possibly detect spurious changes in guidance information which cause abnormal aircraft correction signals to be generated. However, apart from not detecting a gross setting-up error (which would normally be detected by the near field monitor), it might not detect guidance pattern deterioration, particularly at low frequencies, which the aircraft could follow. Again, if a ground monitor can be used, the expense of installation in existing aircraft is avoided.

The performance required of a monitoring system cannot be directly specified with certainty since no comprehensive data at operational airfields were available. The work described here fulfilled the dual purpose of proving the feasibility of far-field and radio environment monitoring and collecting much needed statistical data on I.L.S. interference.

2. Far-field Monitoring

2.1. *Localizer Monitor*

Most emphasis has been put on deriving data for the localizer. A recording localizer monitor was designed and built which could measure and record variations in course-line with a measuring accuracy of about 0·01% difference in depth of modulation (d.d.m.) (i.e. about 0·1 μA standard I.L.S. receiver

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† Formerly with Elliott-Automation Radar Systems Limited, Borehamwood, Hertfordshire; now with the International Electrotechnical Commission, Geneva, Switzerland.

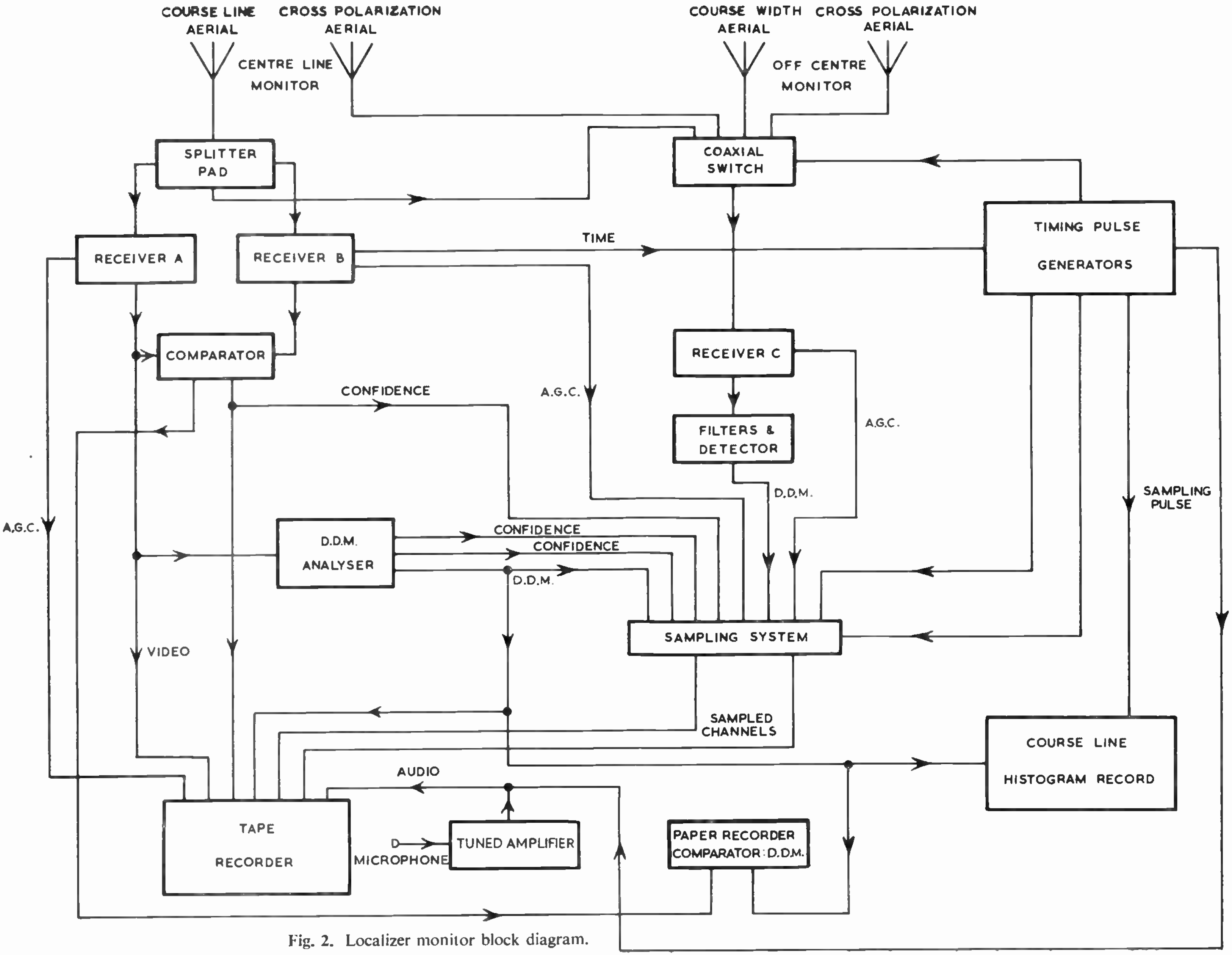

Fig. 2. Localizer monitor block diagram.

deflection). It also recorded variations in course sensitivity, signal level, the cross-polarized field components, and external interference due to events such as over-flying aircraft.

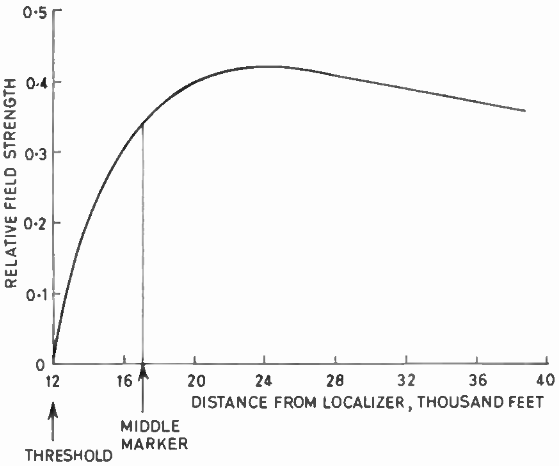

Fig. 1. Signal contour for 1 :50 clearance plane from threshold (Runway 28L, London Airport).

At London Airport (Heathrow) a convenient location was available at the 28L runway middle marker site, where ground was available for the erection of two aerial masts 64 ft high (i.e. an elevation of about 0·2° from the transmitter), and a building could be used to house the receiving and recording equipment. It may be seen from Fig. 1 that this site is not far from the optimum when received signal level is measured in the airfield clearance plane of gradient of 1 :50.

One aerial tower was erected on the extended runway centre-line with the other offset laterally by a distance of about 30 ft which corresponded to 1 % d.d.m. of the I.L.S. signal. Additional aerials, used to measure the cross-polarized radiation component, were also mounted on these masts. The experimental monitor is shown diagrammatically in Fig. 2. The most important parameter to be monitored was course line stability, and to check that deviations were not due to receiver drifts, dual receivers (A and B) were used with a comparator to determine when the outputs differed by a pre-determined amount.

In order to achieve accuracies of the order of 0·01 % d.d.m. a phase-detector d.d.m. analyser was used as the primary measurement device.[4] Smoothed and unsmoothed course-line information was made available continuously at the output of the d.d.m. analyser. In addition, a third receiver (C) was used on a time-shared basis to derive information on course-width and cross-polarization. Conventional filters and detectors were used at the third receiver output since accuracies of the order of 0·05 % d.d.m. only were required for these parameters.

A central timing unit, which could be locked to an external source, controlled the switching process, and sampled each parameter for 15 seconds every two minutes. Suitable amplifier time responses were used to ensure stable readings during the sampling period.

Displayed outputs of course-line deviation both in histogram and in pen-recording form were made available at the monitor as an aid to alignment and maintenance. All other outputs were recorded on a multi-channel magnetic tape recorder and replayed and analysed in controlled laboratory conditions.

2.2. *Glide Path Monitor*

The site of the glide path monitor was chosen at a point 1000 ft from the transmitter on 28L runway at London Airport (Heathrow) at an angle of approximately 40° to the runway centre line (Fig. 3). This was the most convenient site that could be found on the airport and an initial survey of the I.L.S. glide path signals indicated a linear width characteristic and high signal strength. The elevation angle of the monitor aerial to give zero d.d.m. was measured as precisely 3°, i.e. the glide path angle. A 55 ft high mast with three guy positions was erected at this site and the aerial boom was adjusted to a height of 51 ft. While suitable signals for monitoring were available initially with the null-reference transmitter aerials, the subsequent change to a three-element M-array glide path aerial did not permit useful monitoring at this site.

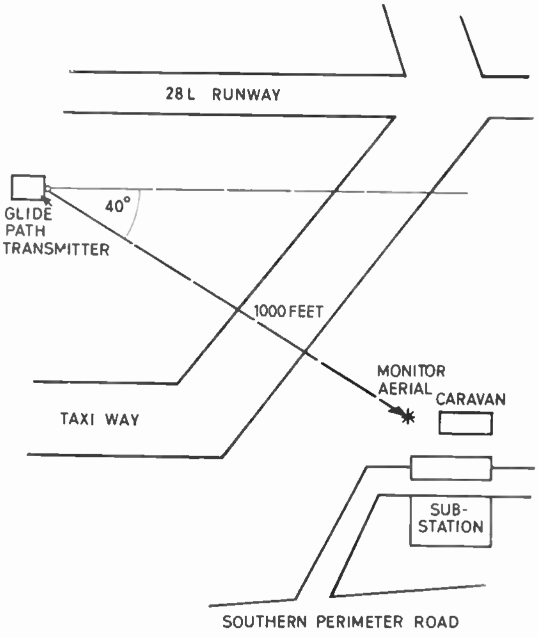

Fig. 3. Plan of glide path site at London Airport.

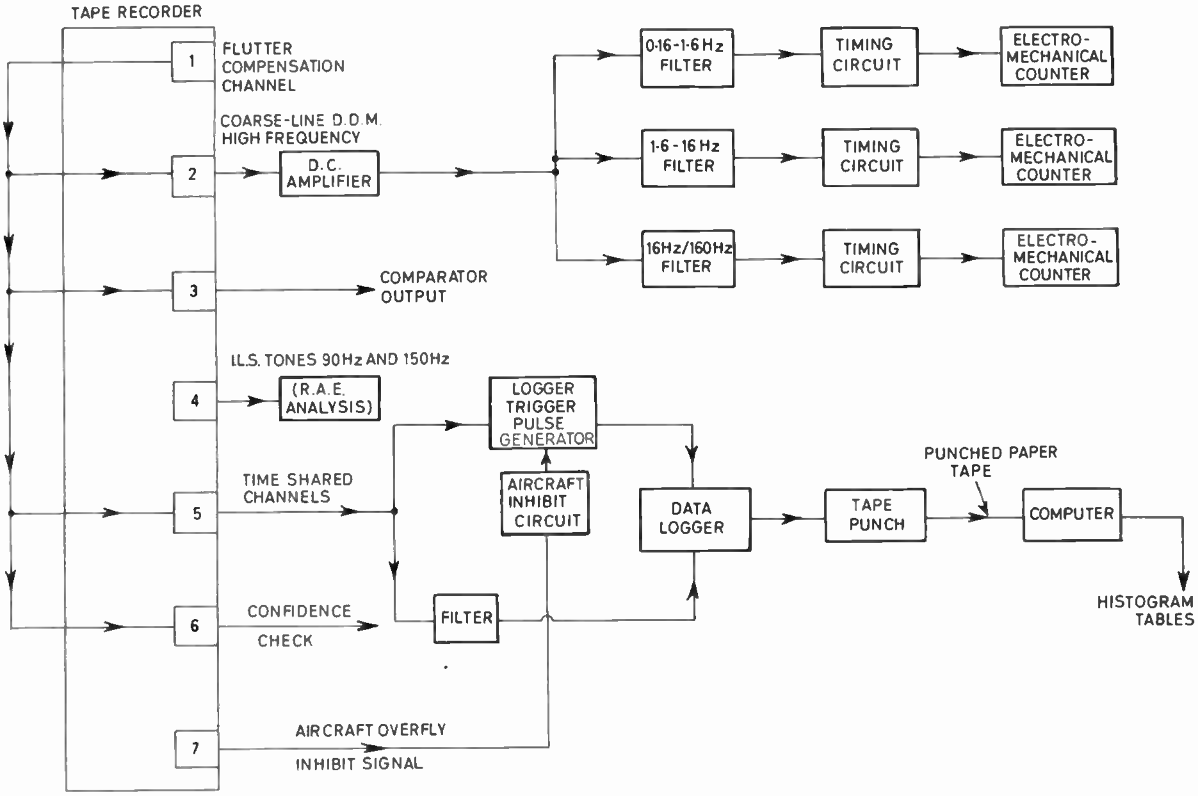

Fig. 4. Overall data reduction block diagram.

An examination of the radiation pattern of this latter array on the side away from the runway did not reveal a convenient point where a zero d.d.m. could be obtained. Further investigation will be needed to determine if monitoring on this side of the aerial gives results which relate directly to the actual behaviour of the beam in the approach region.

The monitor for the glide path had exactly the same design and mechanical layout as the localizer monitor. The only difference was the fact that a tone filter and diode d.d.m. detector were included in the receiver. This dispensed with the need for external filters and detectors in the glide path monitor.

2.3. *Data Collection, Analysis and Results*

The monitors had three methods of storing the information derived from the receivers and d.d.m. analysers:

(a) magnetic tape recorder,

(b) numerical histogram (course-line only),

(c) paper recorder (course-line and comparator only).

The tape recorder was the main data storage device and was used to store all the course information and also to reproduce signals which gave checking facility on the correct functioning of the monitor. These latter signals were a.g.c. voltages of the receivers and signal levels in the d.d.m. analyser.

A microphone, mounted on the roof of the monitoring hut, detected overflying aircraft. A band-pass filter section in the accompanying audio amplifier restricted false alarms due to low-frequency vehicle noise. The amplifier output was recorded on a channel of the tape recorder and used to inhibit the accumulation of data on playback when noise exceeded a preset level.

The playback system is shown in Fig. 4. The complete tape was played back at 16 times the recording speed, i.e. 15 inches per second, and the 24 hours of information recorded on the tape could be analysed in one and a half hours. The main channels of interest were the continuous recording of course-line d.d.m. and the sequentially sampled data. The sequential information was transcribed on to punched tape to be fed into a computer for detailed analysis. The continuous course-line d.d.m. recording was frequency-analysed in the bands 0·01–0·1, 0·1–1·0 and 1·0–10 Hz.

The numerical histogram comprised an automatic data storage and display system which gave a histogram in numerical tabular form of the course-line d.d.m. distribution in quanta of 0·1% d.d.m.

The paper record was intended as a continuous check of the immediate history of course-line d.d.m. which could readily be examined on site.

The results from an initial monitoring period at R.A.E., Bedford, are shown in Fig. 5. The monitor was used as a near-field monitor with the aerials situated 200 feet in front of the transmitter aerial.

Analysis of the long term histogram of the course line shows an overall mean value of + 0·05% d.d.m. with a standard deviation of 0·04% d.d.m. for the period 15th June to 1st October 1965. These figures may be compared with the results of transmitter monitoring carried out by S.T.C.[5] over the period 2nd November 1964 to 22nd June 1965, which gave a mean course line value of + 0·01% and a standard deviation of 0·036%. The difference in mean value is 0·05% d.d.m. and the standard deviation is almost the same. This was an excellent indication of the accuracy and stability of the monitor. (A deviation of 0·1% d.d.m. is equivalent to approximately 2 ft displacement at the runway threshold.)

There was no detectable variation in the band 0·1 to 10 Hz at the output from the phase-sensitive d.d.m. detector on any of the records from Bedford.

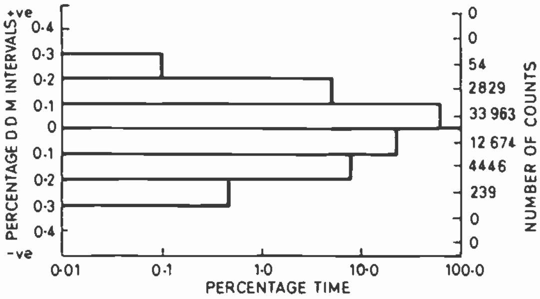

Fig. 5. Course-line d.d.m. (R.A.E. Bedford). Long-term histogram for the period 15th June 1965 to 1st October 1965.

The results of localizer monitoring at London Airport during the first three months of 1966 are given in Table 1.

Table 1

Results of localizer monitoring at London Airport during January, February and March 1966

		Mean value	Standard deviation or variation
Course-line		− 0·12% d.d.m. (2·5 ft right)	0·06% d.d.m. (1·3 ft)
Course-sensitivity (referred to runway threshold)		0·75 μA/ft	0·04 μA/ft
Signal level	at receiver input	75 μV	± 15 μV
Vertical polarized component		5 μV	± 1 μV

The discrepancy between the measured course sensitivity and the nominal I.C.A.O. value of 0·43 μA/ft was briefly investigated. It was discovered that some beam distortion existed which could be measured near the surface in the undershoot region of the runway.

In addition, random excursions of the course-line signal, with amplitudes up to the limit of the recording equipment (± 1% d.d.m.), were recorded. Over the period of recording, the frequency of occurrence (at all amplitudes) was approximately 0·1% of the time. It is considered that most of these are due to unrecorded aircraft movement at the other end of the runway, since their duration was generally of the order of a minute or two.

The frequency analysis showed that most noise occurs in the band 0·01 to 1 Hz. It varies considerably from day to day, but on average exceeds the equivalent of 2 μA deflection for about 3% of the time.

3. Course Bend Monitoring

Another important aspect of ground monitoring requiring investigation is the possibility of detecting changes in course-bend structure. An experimental programme was undertaken in order to try to establish the feasibility of localizer course-line monitoring using a system of longitudinally spaced aerials.

Bends in the localizer guidance beam are produced by phase interference between signals received directly from the localizer and signals received after reflection from some obstacle. If such bends are of sufficient amplitude, they are potentially dangerous to an aircraft in the final stages of its approach and landing, particularly if the aircraft is using the I.L.S. information in an automatic guidance system.

Calculation of the spatial pattern of the bends introduced by a single reflector is quite straightforward. However, when the effects of several reflectors, discrete and distributed, are taken into account, it becomes extremely difficult to determine the precise nature of the bend pattern mathematically. Since very little is known about the changes in bend structure of a typical localizer installation, an investigation was undertaken with the aim of collecting information which would be helpful when a Category III localizer far-field monitor system came to be specified.

The method suggested for investigation of course line bends involved the use of a system of aerials spaced along the nominal course line. The aerials would be sampled in turn and a d.d.m. value extracted

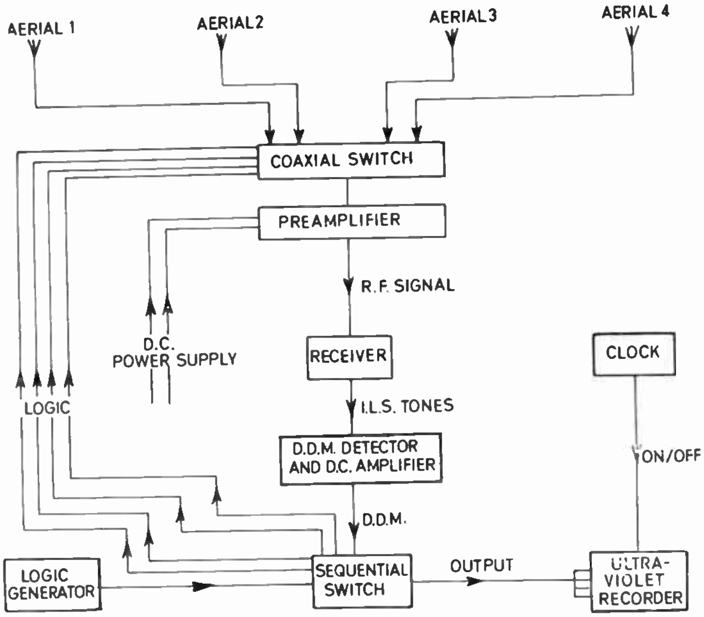

Fig. 6. Block diagram of sampled spaced aerials monitor.

from the signal at each. Any difference between the d.d.m.'s would indicate the presence of bends in the course line, and observation over a period of time would determine the stability of the bend pattern.

The Royal Aircraft Establishment airfield at Farnborough was chosen as a suitable location for the initial installation. A site was available beyond the south-west end of the main runway where four aerials could be mounted on conveniently placed Calvert lighting poles. Although the poles were at only 100 feet intervals, so that any bends detected would be of too short a wave length to interfere with landing aircraft, it was considered that valuable information and experience could be gained by operating such a system. A block diagram of the system used is shown in Fig. 6.

Early records from the system at a sampling rate of 1 sequence every 12 seconds clearly showed the existence of course-line bends. During the limited time that the monitor was used in this configuration, no significant change in the d.d.m's from the four aerials was observed. The information from four aerials was obviously inadequate for detailed examination of the bend structure, but indications are that a similar system using a greater number of aerials would be capable of showing the severity and wavelength of course-line bends.

When higher sampling rates were used, it became clear that the experimental system was able to provide usable information on course-line stability. A comparison between the mean d.d.m. output of the sampled aerials system and the d.d.m. output from a receiver using a single aerial revealed that the sampled output had the lower noise content. This seemed to indicate that a considerable proportion of the noise on the localizer beam was caused by variations in signal reflection paths whose effects may be averaged out by a spaced aerial monitor. The sampled spaced aerials technique thus suggests itself as the basis for a course-line monitor which would be more insensitive to transient reflection effects, such as that produced by overflying aircraft, than a single aerial and capable of giving a better indication of course-line stability than a single aerial monitor.

In order to reproduce the longest wavelength beam-bend amplitude of interest for an aircraft control system it would be necessary to extend the linear aerial array over several thousands of feet. It appears probable, however, that the existence of shorter wavelength spatial beam bends indicates the presence of longer wavelength bends, and changes in the shorter wavelength bend structure imply alterations in the longer wavelength bends.

4. Radio Environment Monitoring

A further monitoring technique requiring investigation was that of detecting the presence of external interfering signals in the receiver pass-band and, if possible, predicting the probability of their interfering with the I.L.S. guidance signals. To this end considerable effort was expended in designing an independent side-band receiver.

The function of the independent side-band (i.s.b.) receiver is to receive an I.L.S. transmission and to obtain separate guidance signals from the upper and lower pairs of sidebands. This has the advantage of presenting two sets of guidance information. If interference is present in the information band that affects the guidance signal from one pair of sidebands only this will be readily observable. This is in contrast to a conventional I.L.S. receiver where interference could lead to the presentation of incorrect guidance information without any indication that it was incorrect. With the addition of suitable output circuits an i.s.b. receiver can be used for ground monitoring the I.L.S. transmission band for interference signals.

The design requirements were that the receiver should separate the tone sidebands from the signal and distinguish co-channel interference. The receiver should also be capable of distinguishing on which side of the carrier the interference occurs.

The original simple experimental system is shown as a block diagram in Fig. 7. In this system, the final i.f. at 460 kHz is taken from a conventional I.L.S. aircraft receiver and fed to an amplitude limiter to remove the amplitude modulation components. This is then mixed with a crystal controlled source of 100 kHz to give a frequency of 560 kHz, which is re-mixed with the 460 kHz i.f. signal to yield an output consisting of the sidebands about a stable 100 kHz carrier frequency. The tone sidebands are then filtered out, detected, and used to produce the two sets of guidance information. This receiver worked well for this purpose but could not differentiate between an interference signal in the receiver passband of frequency higher than the I.L.S. carrier frequency and its image below the carrier frequency. This was determined to be due, primarily, to phase modulation effects in the mixers and limiter. To overcome this difficulty a second receiver design was formulated that used an auxiliary voltage controlled 560 kHz oscillator to drive mixer 2 (Fig. 7). This was stabilized by comparison with the original 560 kHz output of mixer 1 by means of a phase discriminator, and phase locked to it by means of feedback. This system gave only a 10 dB difference in level between the true interference signal and its image. An attempt to improve this by incorporating a narrow band-pass filter in the loop was not successful, but replacement of the loop by a frequency-lock device using a crystal discriminator was more successful (Fig. 8).

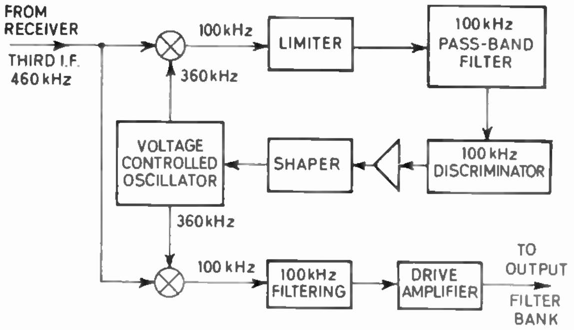

Fig. 8. Frequency-locked loop receiver.

Preliminary tests on the frequency-locked loop receiver indicate that an image rejection of the order of 20 dB can be attained even when the interference is within 30 Hz of the carrier. When the interference is 10 dB below the carrier, lock is maintained when the interference is swept through the carrier frequency. The range of lock is better than ± 12 kHz and the tracking rate in excess of 500 Hz/s.

This type of receiver, with a bank of narrow-band filters at the final i.f. output, can therefore be used as a radio environment monitor. The detected filter

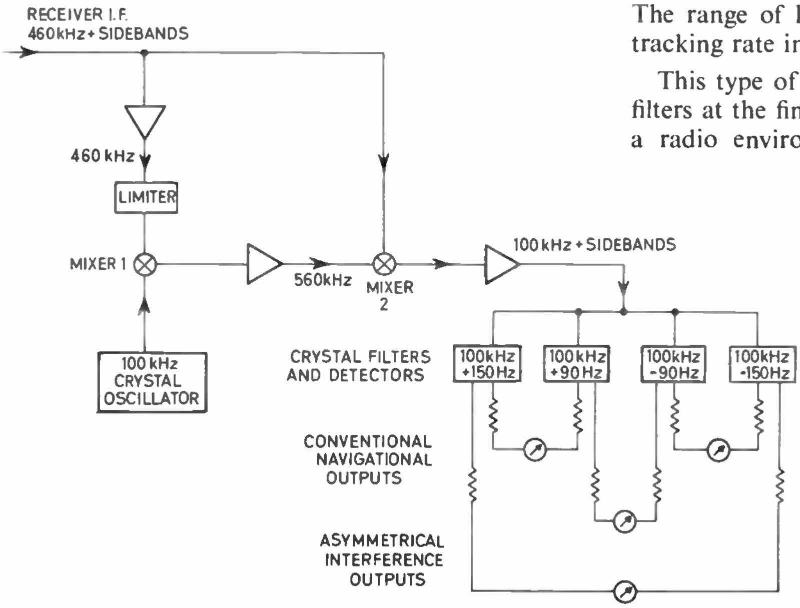

Fig. 7. First independent sideband receiver block diagram.

output signals ascertain the level and frequency of the interference, and signals moving slowly across the band may be tracked, and a prediction made of when they are likely to interfere with the tone sidebands.

5. Conclusions

The following conclusions have been reached as a result of the studies described in this paper.

5.1. *Localizer*

(a) Far-field monitoring of I.L.S. localizer signals, in the approach region, is feasible and desirable from the point of view of improving the integrity of landing systems used in low visibilities.

(b) A far-field monitor of this type will need a long reaction time to avoid a high false-alarm rate due to transient disturbances. It is also proposed that course-bend measurements be incorporated wherever feasible, since single point measurements will tend to be pessimistic with respect to mean course-line position.

(c) Important additional benefits accrue from low visibility landing systems as a result of far-field monitoring, i.e. less flight calibration, compilation of statistical data on the guidance signals, and its use as a maintenance and alignment aid.

5.2. *Glide Path*

Insufficient investigation of glide-path monitoring has been conducted to enable firm recommendations to be proposed. Null-reference transmitter aerial arrays may be monitored successfully in the far-field, but M-array aerial monitoring requires further investigation.

5.3. *Radio Environment*

It has been shown that receiver techniques are available which enable interfering signals to be isolated, and their effect on the guidance signals (both localizer and glide-path) to be assessed.

6. Acknowledgments

This work was undertaken as part of the Ministry of Aviation's I.L.S. feasibility study. Thanks are due to the Radio Department of the Royal Aircraft Establishment, Farnborough, for their help and guidance. The assistance and patience of the Telecommunications staff at London Airport is gratefully acknowledged.

Acknowledgment is also made to Elliott-Automation Radar Systems Limited for permission to publish this paper.

7. References

1. R.A.E. Tech. Memo No. RAD655, March 1964.
2. S. S. D. Jones, 'I.L.S. monitoring—a statement of the problem', *The Radio and Electronic Engineer*, **32**, pp. 287–92, November 1966.
3. R.A.E. Tech. Report No. 65022, February 1965.
4. G. K. Lunn, 'New precision techniques for I.L.S. parameter measurement', *The Radio and Electronic Engineer*, **32**, pp. 351–6, December 1966.
5. F. G. Fernau, 'I.L.S. transmitter monitors for automatic blind landing', *The Radio and Electronic Engineer*, **33**, pp. 45–50, January 1967.

Manuscript first received by the Institution on 27th April 1966 and in final form on 29th November 1966. (Paper No. 1091/RNH64.)

U.D.C. 621.396.933.2

I.L.S. Transmitter Monitors for Automatic Blind Landing

By

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Presented at the Radar and Navigational Aids Group Symposium on 'Monitoring of I.L.S. Ground Equipment for Automatic Landing', held in London on 4th April 1966.

Summary: The safety requirements of an automatic blind landing system imply that the ground I.L.S. transmitters must have a high 'integrity', a high degree of accuracy and reliability. This, in turn, implies that there must be monitors at the transmitters which can measure the main parameters of the radiated signal and react fast to any fault condition.

Two types of monitor are available, near-field monitors taking their signals from field probes and internal monitors using signals from the aerial feed cables. A study of internal monitors applied to existing localizers was made as part of the R.A.E. I.L.S. feasibility study and showed that these monitors could provide accurate performance measurements and also that the localizers did achieve the required standard of stability.

The integrity of the I.L.S. beacons depends largely on the way in which monitors are used; one possible monitor configuration for blind landing involves four monitors arranged to give good continuity of service and a very high probability that faults will be detected. One monitor measures the performance of the stand-by transmitter and the other three measure the radiated signals; if there is disagreement between these three the action is determined by 'majority vote'.

1. Introduction

When I.L.S. localizer and glide path signals are used to guide aircraft during automatic approach and landing in zero visibility there must be a high degree of confidence that these signals are accurately aligned and will stay accurately aligned throughout the landing. There must be a very high degree of confidence in the stability and reliability of the ground I.L.S. equipment. The Air Registration Board has said that it will only licence British aircraft to use a blind landing system if it can be shown that the system will not increase the risk of an accident; as the present rate of accidents to aircraft is about 1 per 10^6 flights it follows that the risk introduced by a blind landing system must not exceed 1 in 10^7. An automatic landing system is a complex one involving a variety of equipment, ground I.L.S. beacons, airborne I.L.S. receivers, the autopilot, radio altimeters, the flare computer etc., and the total risk must be divided among the component parts. This division is largely arbitrary but the general conclusion is that the localizer and glide path ground transmitters can each have only one-fiftieth of the total risk; each may not cause an accident more often that once in every 5×10^8 landings. It will be largely the responsibility of monitors associated with the transmitting equipment to ensure that this very severe requirement is met.

There are two general mechanisms by which an accident can be caused: errors in the component parts of the system, adding up to an excessive total, and failure of a channel of guidance information such as the I.L.S. localizer beacon. It is usual to divide the risk equally between these two mechanisms which means that, for example, the localizer must have a standard deviation of its centre-line error of less than three feet at the runway threshold, and it means that the risk of an accident caused by a localizer failure must be less than 1 in 10^9. Monitors are only involved in the question of stability of the I.L.S. beacons to the extent that an accurate monitor helps the operating staff but an inaccurate monitor could mislead the operating staff into making wrong and unnecessary adjustments to the transmitter controls and thus increasing the errors. The principal function of the transmitter monitors is thus the detection of faults in the radiated signals; only monitors closely associated with the transmitters can achieve the short response time that is required and they must be designed to ensure that the risk of an accident caused by a transmitter failure is less than 1 in 10^9. In this context 'fault' means radiation of signals which are outside their limits for more than one second, and 'faults' can

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be divided into two cases with an equal partition of the risk. The first case is total failure of the radiated signals; if duplicated transmitters with a fast automatic change-over system are used then this safety requirement can be satisfied with transmitters whose mean time between failures (m.t.b.f.) is only of the order of 100 hours, but other arguments concerned with safety during overshoot procedure suggest that with duplicated transmitters each should have an m.t.b.f. of more than 4000 hours. The second case is transmission of erroneous signals, a far more dangerous situation than the first case because there will probably be no indication in the cockpit that anything is wrong and in poor visibility an aircraft will be guided into a situation of very high risk; the transmitter monitors must ensure that this will not occur more often than once in 2×10^9 landings.

The transmitter monitor consists generally of two or perhaps three receivers with alarm circuits added, and the characteristics of an ideal transmitter monitor can now be summarized as follows: It makes a continuous and accurate assessment of all the important parameters of the radiated signal and its stability is such that drift of the monitor does not appreciably alter the levels of error at which the alarm circuits operate and does not mislead operating staff into making a wrong adjustment of the transmitter controls.

It reacts fast (in about one half of a second) to transmitter faults but ignores the transient effects of aircraft taking off over the localizer aerial even though these effects consist of large errors lasting several seconds.

The ideal monitor must warn the operating staff if any of the transmitter parameters has drifted near its alarm limit because there is then an abnormally high probability of change-over occurring during the landing and the aircraft is, therefore, exposed to an unnecessary risk.

Finally, the ideal monitor must be presumed to fail occasionally; its failures must give a warning in the control tower, but must not switch off a perfectly satisfactory transmitter. The mean time between failures which permit radiation of erroneous signals to continue without change-over taking place must be at least 200 000 hours and the mean time between failures which result in erroneous signals with no indication in the control tower that anything is wrong must be at least 2 million hours.

Even with the best modern techniques a single monitor of the normal type cannot hope to meet these requirements and a redundant configuration of monitors is essential. This increase in the quantity of equipment brings a further requirement; monitors must be extremely simple and reliable.

This ideal transmitter monitor must be built up out of a combination of two general types of near-field monitors and internal monitors.

2. Near-field Monitors

Near-field monitors are units which receive their radio frequency signals from dipoles mounted within a few hundred feet of the transmitter aerial system. Normally there is one dipole on the centre-line providing a measurement of the course line accuracy and one offset to one side providing a measurement of course sensitivity, the relationship between the difference in depth of modulation of the tones giving navigational guidance and angular deviation from the course line. In systems using a separate 'clearance' radiation to provide the required azimuth coverage a third near field unit is generally employed, measuring the 'clearance' pattern. This group of two or three receivers forms one monitor.

A near-field monitor can assess the performance of the whole transmitter system including the aerial array but it is subject to some forms of interference such as aircraft taking off over the localizer, causing severe transients in the received signals which the monitor must ignore.

2.1. *Internal Monitors*

Internal monitors are units fed with radio frequency signals taken from the aerial feeder cables; they are, therefore, immune to external interference and measure only the performance of the transmitter. The monitor units can be identical to the ones used for near-field monitors provided that the aerial feeder cable signals are suitably mixed to give composite signals corresponding to those received by near-field dipoles.

As part of their study on the feasibility of using I.L.S. for automatic blind landing the Royal Aircraft Establishment made a study of internal monitors applied to existing localizer installations with two aims: to investigate the problems associated with these monitors, and to measure the performance of the localizer transmitters.

The experimental internal monitor equipment consisted of two units, one fed with signals corresponding to the course line and the other course sensitivity (width). Between them they made the following measurements:

(i) movement of the course line,

(ii) changes in course sensitivity,

(iii) changes in the sum of the 90 and 150 Hz modulation depths from the nominal value of 40%,

(iv) changes in the radiated field strength,

(v) changes in the difference frequency between the course and clearance radiations (this is a measure of the radio frequency stability),

(vi) changes in the frequency of the 90 and 150 Hz tones, and

(vii) dynamic errors, cyclic movements of the course line which lie in the frequency range 1 cycle in 100 seconds to 10 Hz per second.

A special recording instrument was designed to select each measurement in turn once a minute and record it by registering a count in the appropriate place in a row of counters corresponding to a histogram bar chart.

Two sets of this experimental equipment were connected to the Standard Telephones and Cables Ltd., STAN 7 localizers, one at the Blind Landing Experimental Unit, Bedford, and the other at London Airport (runway 28 L). Over a period of about one year 4×10^6 readings were taken and analysed giving the following values of standard deviation for the more important parameters:

Course line	0·004 degree
Course sensitivity	1·5%
Sum of modulation depths	0·1%
Tone frequency	0·07%

These have been included in this paper because they illustrate the smallness of errors with which I.L.S. monitors are concerned; the course line standard deviation of 0·004 degree corresponds to less than one foot at the runway threshold which is about two miles from the localizer.

The work from which these figures were obtained was confined to measurement of the stability of the transmitter at the transmitter and other factors must be taken into account in assessing the stability of the localizer signals in space. However, these values of standard deviation show that modern I.L.S. localizers are capable of giving the stability necessary for a civil automatic landing system, and also that internal monitors can measure transmitter performance with an adequate standard of accuracy and stability.

3. A Configuration of Transmitter Monitors for Automatic Landing

So far this paper has indicated the parameters that should be monitored and the order of accuracy and stability that should be achieved, but the integrity of the system as a whole depends very largely on the number of monitors and the way in which they are used. The configuration of monitors must ensure primarily that the stringent safety requirements are met, but also that there is a good probability that the I.L.S. signals will be available when required. If, under conditions of bad visibility the automatic landing system of an approaching aircraft fails, then that aircraft must divert, but if the ground equipment fails then all aircraft must be diverted; a reasonable compromise must be found between safety and availability.

Figure 1 shows a configuration of transmitters and monitors commonly used for Category I I.L.S., in

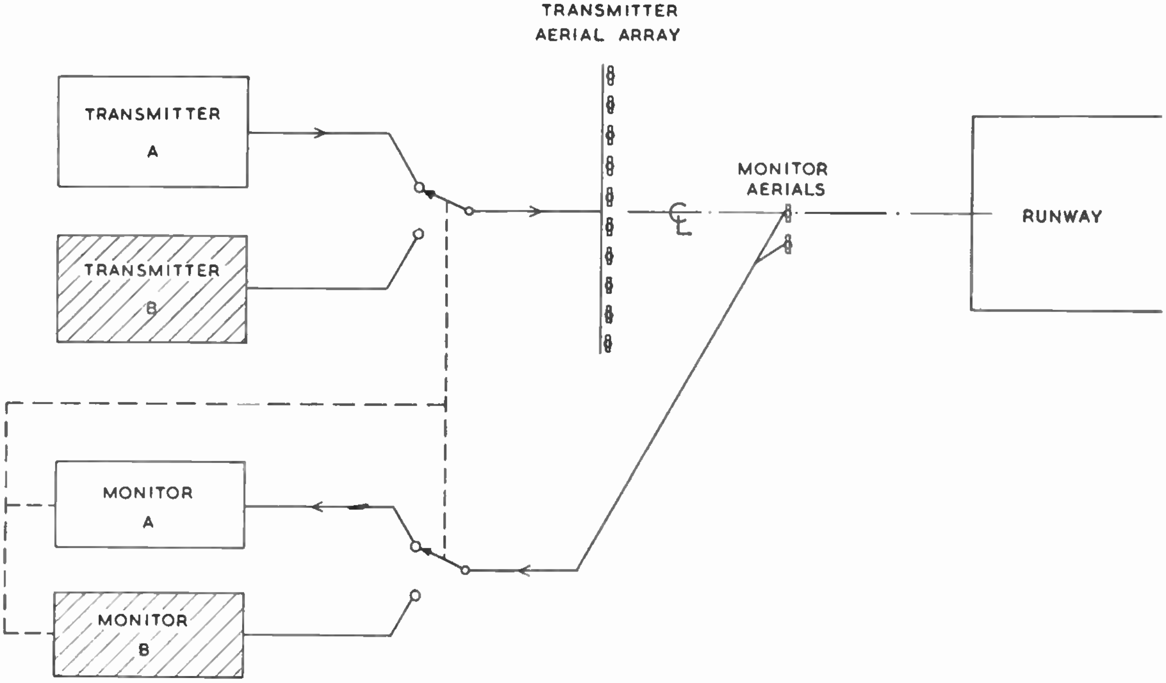

Fig. 1. Category I localizer.

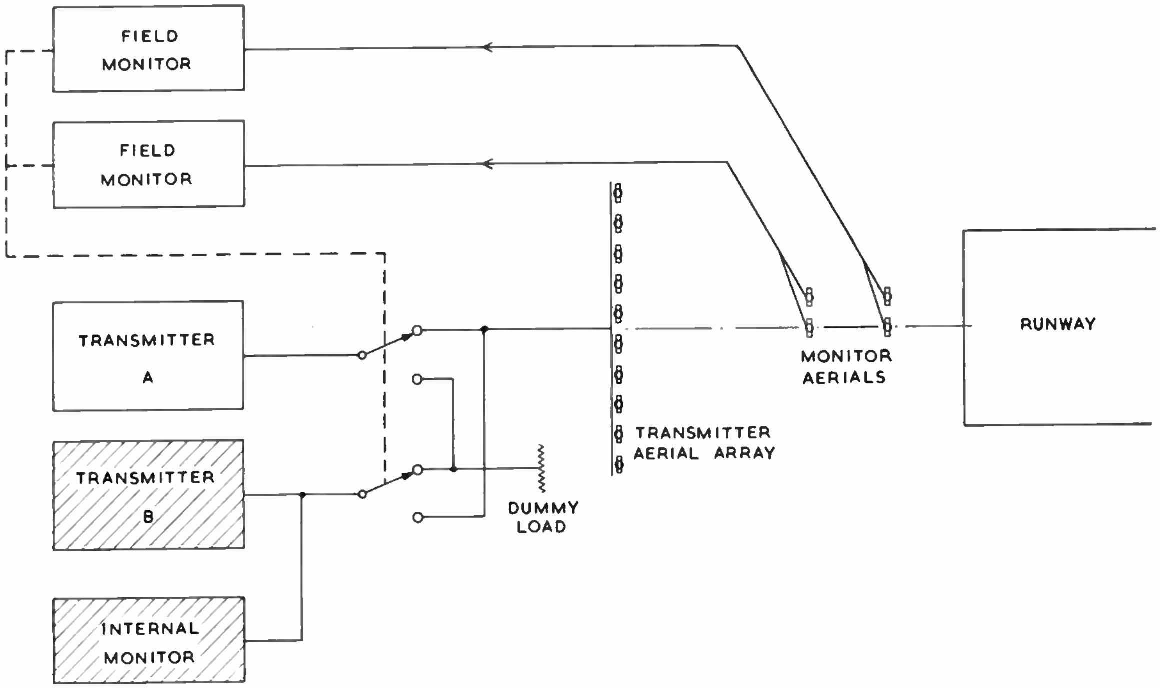

Fig. 2. A modified localizer configuration.

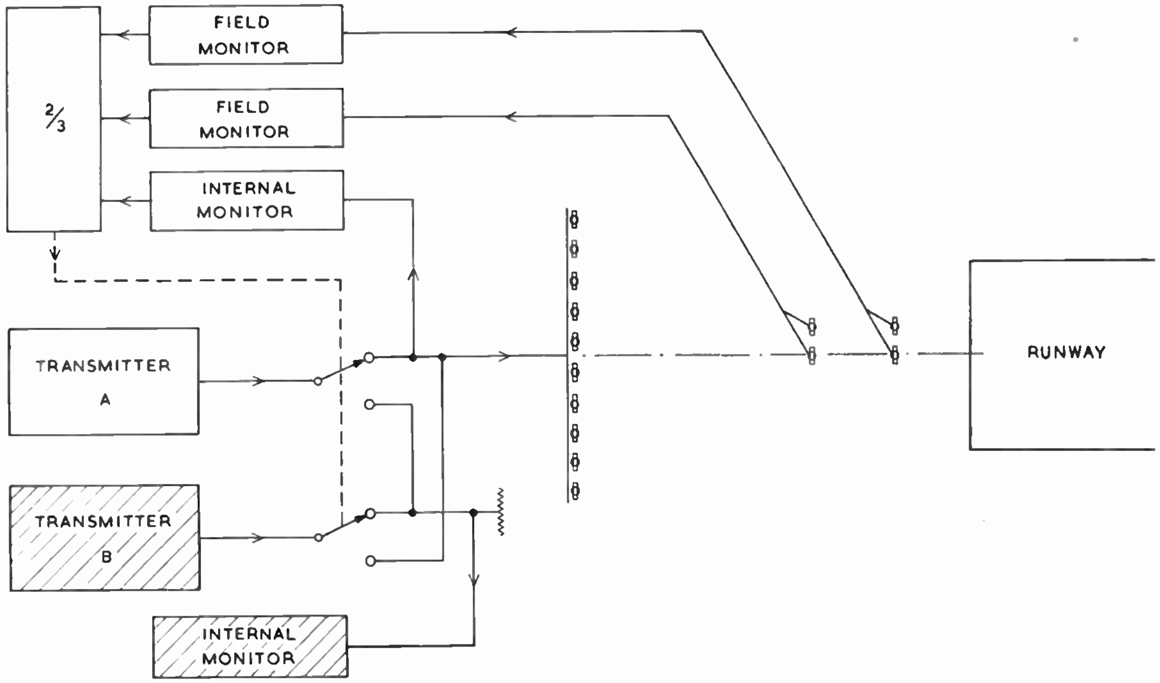

Fig. 3. A possible localizer configuration for blind landing.

this case a localizer. There are two transmitters; one is feeding the aerial system and the other, shown shaded in the diagram, is the stand-by which is normally switched off. Between the aerial and the 'stop' end of the runway are monitor field probes positioned so that they can detect changes in the course line and course sensitivity. These feed signals to monitor A which is probably a complex of units measuring seven or eight parameters. If monitor A detects a fault it actuates the change-over mechanism indicated by the dotted line, switching on transmitter B and monitor B and operating the change-over coaxial relays.

It is worth considering this arrangement to see how it compares with the ideal monitor discussed earlier and to see what changes are necessary for automatic landings. Basically the system is good; when a fault is indicated by monitor A the system cannot deduce whether the fault lies in the transmitter or in the monitor, and it switches both off, replacing them with the stand-by units. However, it is by no means perfect, and there are several ways in which it fails to satisfy the requirements.

It is possible that monitor A could have a fault resulting in a slow steady drift in one direction of some indication and that, perhaps, different members of the maintenance staff could in the course of a period of time make a series of small adjustments to the transmitter resulting in an appreciable error. It may be quite impossible to calculate the probability of such a situation but it is clear that a second independent monitor could give a considerable improvement in the system integrity.

It is possible that the transmitter could drift so that one parameter is near the point at which the alarm system is actuated causing automatic change-over to the stand-by. Under these circumstances, there is a high risk of change-over and an abnormally high risk that the whole beacon will be shut down; clearly either maintenance staff must make frequent checks of all parameters that can cause change-over or they must be given an automatic warning system.

It is possible that a fault has developed in transmitter B or monitor B since they were last tested or used; as both are normally switched off this fault is not detected and there is a considerable risk that the stand-by will not be available if called upon. The only cure is to have the stand-by transmitter continuously running and continuously monitored.

Finally, it is possible that the monitor will fail to perform its one vital function, to actuate the alarm and change-over system when there is a fault. It is possible to design circuits where virtually every conceivable fault results in an alarm indication, but there will always be a finite probability that the circuit will fail in a manner that gives a permanent 'all's well' indication regardless of the received signal. It may be that the theoretical mean time between failures of this nature is 10^7 hours or even 10^8 hours, but these theoretical calculations are based on average figures derived from a variety of equipments and it is not possible to say with confidence that this performance will be achieved in practice by a particular circuit using a particular layout and particular components; it is only possible to quote with confidence a much lower figure, such as 10^6 hours. At first sight 10^6 hours which corresponds to about one hundred years, seems adequate for a blind landing system, but ground I.L.S. equipment suffers from one severe disadvantage compared with airborne equipment. With airborne equipment there are highly-skilled, highly-trained men sitting a few feet away and they can check vital parts of the automatic landing system, such as alarm circuits, ten minutes before the landing at a time when the equipment is not in use; but ground equipment is in almost continuous, unattended service and can only be checked at wide intervals such as a month or a week or perhaps a day. Taking a week as the maintenance interval the risk of erroneous signals being radiated without detection is the risk of an unsafe monitor failure followed by a transmitter failure sometime during the rest of the week. With a figure of 10^6 hours for the monitor failure and assuming a highly reliable transmitter with an m.t.b.f. of 10 000 hours, the risk of erroneous signals is approximately 1 in 10^6. This does not meet the requirement of 1 in 2×10^9 and a different configuration of monitors is required.

Figure 2 shows an attempt at an improvement. The stand-by transmitter is now continuously running, monitored by an internal monitor, and there are two field monitors. If either field monitor indicates a fault then change-over takes place. This gives a very considerable reduction in the risk that the beacon will radiate erroneous signals, but at the same time the basic system redundancy has been lost; a fault in either field monitor will cause a complete shutdown of the beacon. This configuration of monitors clearly cannot be used for automatic blind landing.

One way in which the system can be modified to bring back its failure survival properties is to add another monitor, as shown in Fig. 3. The stand-by transmitter is still measured by its internal monitor but there are three monitors measuring the radiated signals, two near field and one internal. These monitors no longer control the change-over mechanism directly; they feed their information to a logic unit, shown in the diagram as 2/3, which compares their outputs and accepts the majority vote. If one monitor indicates a fault no action is taken except for alarm signals in the control tower equipment room, but if two out of three agree that a fault exists then the stand-by transmitter is put into service. An aircraft is not allowed to start a blind automatic landing if any monitor indicates a fault. In addition to the alarm circuits there are 'warning' circuits with somewhat narrower brackets.

Taking the transmitter and monitor m.t.b.f.'s as 10 000 hours for each unit with 10^6 hours for monitor unsafe failures, it is now possible to predict how this system will perform. The first question is the probability of complete signal failure during a 30-seconds landing period; this will occur if either both transmitters fail or if two of the three 'radiated signal' monitors fail and its probability is better than 1 in 10^{11}. Secondly, overshoot: the pilot will have to overshoot if during the approach which lasts about ten minutes any of the units fail; the probability is 1 in 10 000. Thirdly, diversion: a pilot may have to divert to an alternative airfield if the I.L.S. is not in service; assuming that on average it takes one hour to repair a fault or replace a unit the probability is 1 in 1600. Finally—erroneous guidance: an aircraft can only receive erroneous guidance signals if two of the three 'radiated signal' monitors fail in an unsafe way sometime during the maintenance period and the transmitter then fails during the 30-seconds landing period, or if all three monitors fail in an unsafe way and the transmitter then fails sometime during the rest of the maintenance period. Even with monthly maintenance the probability of this is less than 1 in 10^{10}. In all cases this performance meets the reliability requirements.

If the glide path equipment has the same configuration it will give the same performance.

There are many other monitor configurations which could be used for Category III I.L.S., some perhaps simpler, this being chosen only as an example. The internal monitor tests at London Airport and Bedford demonstrate that the stability requirements can be met; this example of a transmitter and monitor configuration demonstrates that the reliability requirements can also be met; between them that I.L.S. localizer and glide path transmitters can achieve the high level of 'integrity' demanded by an automatic blind landing system for civil aircraft.

Manuscript received by the Institution on 15th November 1966. (Paper No. 1092/RNA65.)

STANDARD FREQUENCY TRANSMISSIONS

(Communication from the National Physical Laboratory)

Deviations, in parts in 10^{10}, from nominal frequency for **December 1966**

December 1966	24 hour mean centred on 0300 UT		December 1966	24 hour mean centred on 0300 UT	
	MSF 60 kHz and GBR 16 kHz	Droitwich 200 kHz		MSF 60 kHz and GBR 16 kHz	Droitwich 200 kHz
1	− 299·6	− 0·1	**17**	− 300·9	− 1·4
2	− 300·1	− 0·2	**18**	− 301·2	− 1·7
3	− 300·6	+ 0·1	**19**	− 301·1	− 2·0
4	− 300·5	+ 0·1	**20**	− 300·3	− 1·4
5	− 300·8	− 0·2	**21**	− 300·3	− 1·0
6	− 300·5	0	**22**	− 300·5	− 0·6
7	− 299·8	− 0·4	**23**	− 299·5	− 0·1
8	− 299·8	− 0·2	**24**	− 299·8	+ 0·2
9	− 300·1	− 0·5	**25**	− 299·3	+ 0·2
10	− 300·2	− 0·6	**26**	− 298·3	+ 0·7
11	− 300·2	− 0·9	**27**	− 298·1	+ 0·7
12	− 300·1	− 0·9	**28**	− 298·7	+ 0·2
13	− 300·9	− 0·9	**29**	− 301·0	− 0·2
14	− 299·5	− 1·2	**30**	− 300·9	− 0·1
15	− 299·7	− 0·6	**31**	− 300·5	− 0·2
16	− 300·3	− 1·1			

Nominal frequency corresponds to a value of 9 192 631 770·0 Hz for the caesium F,m (4,0)–F,m (3,0) transition at zero field.

The frequency offset for 1967 will be -300×10^{-10}.

From 1st December the measurements of v.l.f. standard frequency transmissions reverted to GBR Rugby (16 kHz), following extensive modernization and the reconstruction of the transmitter.

Since 5th January 1966 measurements had been made on GBZ Criggion (19·6 kHz).

(A note on the new transmitter will be published in a future issue of the *Journal*.)

Discussion on
'Monitoring of I.L.S. Ground Equipment for Automatic Landing'

Under the Chairmanship of Mr J. S. Shayler

Mr. G. Harrison: I would like to suggest to Mr. Jolliffe and his co-authors,† regarding interference from overflying aircraft, that the overflying aircraft paths giving maximum interference would have less curvature when considering a 'real' landing aircraft rather than when considering a stationary measuring receiver? If this is agreed, how significant is interference likely to be in the case of parallel runway operation where the aircraft speeds are similar?

Mr. S. A. W. Jolliffe (*in reply*): I believe the point made in the first part of the question to be valid. It is true that a dangerous Doppler condition might persist for several seconds with aircraft landing at similar speeds on adjacent runways. Calculations suggest however that the amplitude of the reflected signal would not be large enough to cause significant interference because of the localizer radiation diagram factor, i.e. the slope of the azimuth pattern with angle. (It should be noted that the calculations suggest that about 10 dB protection is required from the radiation diagram.)

Mr. P. F. Cook: If it were practicable to obtain some frequency (or channel) multiplex redundancy in the I.L.S. propagation path by having transmitters and receivers simultaneously operating on two or three channels, can Mr. Jolliffe say how materially would this assist in the various interference problems that had been studied?

Mr. Jolliffe (*in reply*): We do not suggest that frequency diversity alone will provide sufficient redundancy to increase reliability. In fact it would only be of some benefit from the viewpoint of co-channel interference, and rogue transmissions, but even for this type of interference the probability of anomalous propagation occurring over the whole of the 4 MHz band is not significantly smaller than the probability for a single 100 kHz channel.

Channel diversity as envisaged by us would combine both frequency and space diversity, e.g. an upwind plus a downwind localizer system.

Mr. D. R. Reiffer: Could the authors say how the results quoted in Section 2.1 of their paper have been affected by the re-introduction of the permanent (in-line) localizer facility. Examination of the different lobe structures of the two types of equipment would seem to suggest that some reduction in the amplitude of the disturbance noticed would result from the re-introduction of the permanent localizer installation. Would the authors care to estimate, what, if any, reduction in their quoted figure of $\pm$ 16 μA might be expected?

Mr. Jolliffe (*in reply*): The use of a narrower beam localizer on runway 5, at London Airport (Heathrow) should reduce the disturbing effect produced by the Control Tower, because, being located about 18° off the runway centre-line, it would be less strongly illuminated than during the tests reported. A narrower, beamed localizer might halve the illumination.

A narrower beam localizer would not however significantly reduce the effects of the B.E.A. Engineering Base which is located only 7½° off the centre-line. This is unfortunately located on the blunt nose of the lobe where the slope of the azimuth pattern with angle would still be small.

Mr. J. Benjamin: Mr. Jolliffe has suggested that the use of multiple upwind localizers would be a method of avoiding interference from overflying aircraft. It is clear, however, that redundancy of transmissions from the upwind position will only be effective in identifying interference *external* to the I.L.S. system. The avoidance of interference from aircraft taking off over the upwind localizer calls for re-siting of the installation, and an experimental aerial is being tested by Ministry of Aviation which is installed in the undershoot and is overflown by the *landing* aircraft.

In reply to a question he said that to avoid co-channel interference he would prefer to frequency modulate the I.L.S. transmissions rather than achieve it by frequency stability and staggering. It seems doubtful if f.m. would help. In order not to distort the guidance signals it must be of small deviation and at a slow rate. This will increase the chance of two transmissions overlapping and the fact that positive and negative rates of change of frequency are generated will ensure coherence with the interfering signal over some of the sweep. On the other hand the frequency stability required is easily obtained (1 in 10^6) and in conjunction with co-channel staggering this affords a positive assurance that interference will not occur.

Mr. Jolliffe's paper concludes that the ideal monitor would use an air to ground transmission. This should not pass without comment. One of the difficulties in civil aviation is that the type of aircraft instrumentation to be used is not subject to the same control as is exercised by I.C.A.O. in terms of ground equipment. It would, therefore, be difficult to make a beacon in each aeroplane mandatory. Furthermore, if a beacon were to be installed it could be used more effectively to extend p.a.r. monitoring accuracies by means of interferometry. In addition for the

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† S. A. W. Jolliffe *et al.*, 'The character of the received I.L.S. signal and its relation to monitoring', *The Radio and Electronic Engineer*, **32**, No. 5, pp. 293–312, November 1966.

beacon monitor to work in a warning role requires a very reliable communication or data link back to the aircraft; this again requires a service which does not adequately exist.

The logical place to monitor is in the aeroplane, and it is possible that some flight control systems will be able to do this. Even so it is a difficult task and it is unreasonable to suppose that ground monitoring could do the job either better or as well. Mr Jolliffe's paper highlights the difficulties and inadequacies of ground monitoring, but it is doubtful if the beacon solution could be 'sold' either to I.C.A.O. or the airlines.

Mr. Jolliffe (*in reply*): Mr. Benjamin appears to have misunderstood what I actually said.

In discussing the work that had been undertaken to secure the high integrity of service demanded I mentioned that in the present envisaged systems integrity was aided by redundancy of equipment both at the ground and in the aircraft, but all existing systems relied on a single information channel radiated from virtually a single point—the site of the conventional upwind localizer aerial. I then suggested that better system integrity might be attained if the guidance information could be conveyed on two discrete frequency channels radiated from two widely spaced points, (e.g. either end of a runway) which would provide *space* as well as *frequency* diversity. Spaec diversity would ensure that there would be a time lag between the reception of unwanted signals reflected from overflying aircraft or ground-based obstacles.

I am sorry Mr. Benjamin inferred from my remarks that we preferred to solve co-channel interference by frequency-modulating the I.L.S. transmissions rather than by frequency stability and staggering. Obviously the latter is preferable but we were doubtful, and still are, if it could be effectively enforced internationally. In the absence of highly stable, staggered transmitters, our point was that it is preferable to have the frequencies of co-channel transmitters sweeping in a known manner over a large fraction of the channel (and then they have a well-defined probability of overlapping), rather than leaving them to drift in an unknown manner over a smaller fraction of the channel.

Mr. Benjamin does not support our conclusion regarding the location of the preferred executive monitor. We are not suggesting the use of a new separate beacon in the aircraft—simply the allocation of a channel in the existing v.h.f. multi-channel equipment. We do not however underestimate the administrative difficulties of obtaining A.T.C., airlines and I.C.A.O. support for this proposal.

We believe that the 'decision point' of the preferred 'executive' monitor should be ground based—and the decisions should be made on analysis at the ground of the actual signal received by the landing aircraft's receiver. If the loss of pay load necessary to accommodate complex equipment for processing the received data is of no concern to airline operators then an 'executive' monitor can be located in the aircraft as preferred by Mr. Benjamin. But which airline operators will allow further 'poaching' of their revenue-earning capacity?

The presence of low-frequency course-bends, resulting from reflections from fixed and moving obstacles, makes it doubtful whether the processing of the aircraft receiver's output will alone provide an indication of pollution, or the onset of it, in the guidance signal, to the reliability required for blind-landing.

One can think of two approaches to the solution of this problem; (a) to identify course-bends by a separate facility, e.g. a line of monitoring aerials, and (b) the establishment of a reference guidance signal computed from the landing aircraft's actual position, e.g. a ground-based interferometer utilizing radar techniques. If the 'reference' information of either (a) or (b) is to be used with an airborne monitor a communication channel will be required to convey it to the aircraft.

If we conclude that (b) is preferable to (a) we have virtually another guidance facility and we may well ask what is the optimum use of such information? Should it be used as a 'reference' for a ground based or airborne monitor or should it be used as an independent landing aid?

One can visualize a major terminal-area like London, providing a ground-based I.L.S. 'executive' monitor service to all aircraft using the airports in the area. By suitably processing the guidance output of a landing aircraft's receiver it should be possible, by utilizing a suitable high-speed computing service, to predict the onset of dangerous conditions and automatically issue a warning to interested parties (e.g. the crew of the landing aircraft and A.T.C. authorities). It is visualized that data from other monitors, near- and far-field, would be automatically utilized in making the continuous assessment.

Mr. F. Jones: Did Mr. Fernau† find at any time during his field trials any evidence of concurrent changes in course line position and course deviation sensitivity?

Secondly, were all course sensitivity variations symmetrical about the course line?

Mr. F. G. Fernau (*in reply*): All the measurements we made were in a statistical form which did not show whether changes in one parameter had occurred simultaneously with changes in another, but the two mechanisms by which the course line and course sensitivity are generated are separate and one would expect them to be independent.

Changes in course sensitivity at the transmitter will inevitably be symmetrical about the course line, but in the far field it is quite possible for a reflecting obstacle to cause a local disturbance which would give unsymmetrical changes in sensitivity.

Mr. Jones: Can one use an asymmetric monitoring aerial system with only one half-sector being monitored for deviation sensitivity, and have confidence, within the I.L.S. reliability requirements, that this aerial will not

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† F. G. Fernau, 'I.L.S. transmitter monitors for automatic blind landing', *The Radio and Electronic Engineer*, 33, No. 1, pp. 45–50, January 1967.

show 'in tolerance' when in fact the unmonitored half-sector is out of tolerance due to aerial phasing or other causes? Would a bi-static array symmetrical about the course line be better?

Mr. Fernau (*in reply*): In the near field of a localizer aerial it is very difficult to get any effect which is not linear in the region of the course-line because the region of interest is very narrow, but it is quite likely that a sensitivity monitor using two aerials would have advantages in this respect, though it would have the disadvantage of increasing the complexity of the system.

Mr. J. Kinnear: With regard to the 'executive' monitor version in which the actual signal received by the landing aircraft's receiver is used to modulate an airborne transmitter suitably and is transmitted to the ground for processing, what information in addition to the actual signal received by the landing aircraft's receiver must be sent over the transmission to the ground in order to achieve adequate monitoring? I would imagine that it is not sufficient to relay to the ground the I.L.S. guidance signal received in the aircraft unless the instantaneous position or the path of the aircraft is also known.

Secondly, what are the implications of this form of monitoring on the communications system of the aircraft?

Mr. Jolliffe (*in reply*): To establish a ground-based 'executive' monitor necessitates the allocation of a channel of the existing v.h.f. multi-channel equipment. This channel would be assigned to each landing aircraft during the final period of approach and landing—say for a period of three minutes, or six miles flight, prior to landing.

In my reply to Mr. Benjamin's question I have indicated what information, in addition to that present at the output of the landing aircraft's receiver, would probably be required to make an 'executive' decision.

Mr. D. H. Colston: I have been particularly interested to learn from Mr. Jolliffe's paper of the intention to carry out scale-model experiments to determine the combined effect of a number of scatterers. There is a great need for information of this sort, particularly in respect of mobile obstructions such as vehicles and aircraft. With respect to permanent obstructions however, while it is important to have information regarding the magnitude of the effect, it is a fact that any requirement to impose stringent limitations on building development would certainly have severe financial repercussions due to the very high development value of land on, and adjacent to, major airports. It is therefore, I would suggest, extremely important that all possible steps should be taken to reduce to a minimum the illumination of such obstructions by limiting as much as possible the angle of radiation of the elements of the system.

Mr. Jolliffe (*in reply*): Mr. Colston's comments highlight the fact, that as in most problems, the acceptable solution is invariably a compromise.

Interference, at some airfields, resulting from site topography, might well be reduced by employing localizer aerials with sharper beams. The 'downwind' aerial, besides possessing other advantageous characteristics, generates a much sharper pattern than currently available localizer aerials.

However if the beam is too narrow a pilot can experience difficulty in positioning the aircraft on the approach line and it may prove necessary to assist him in this task of 'beam-joining' either by radar director control or the provision of an additional aid such as a T.V.O.R. beacon at the appropriate location.

Mr. G. Harrison: How good does Mr. Flounders† consider the correlation between aircraft-received interference and echo-monitored interference can be made in terms of the few microamperes of erroneous signal which it is desired to detect?

Mr. J. G. Flounders (*in reply*): Initial results have shown that the general correlation is good, but many more measurements are required before we will be able to define the degree of correlation in detail. It should be borne in mind however, that the main function of the equipment will be to supplement a general omni-directional r.f. environment monitor, by indicating which interfering frequencies are also being received by the aircraft, and which of these are likely to produce false guidance signals. It can thus be considered as a filter which will significantly reduce the number of false alarms which would otherwise be generated by ground monitors and could not otherwise be ignored.

Mr. D. R. Reiffer: Would Mr. Flounders describe any problems which are associated with frequency drift, in the transmissions of the I.L.S. localizer, which are within the working tolerance of the installation?

Mr. Flounders (*in reply*): We have observed a cyclic frequency change in the transmission from the runway 28L localizer at London Airport which was apparently caused by the temperature control system operating on the crystal controlling the transmitter frequency. The effect showed itself as a continuously cycling frequency change of ± 200 Hz with a period of approximately 1 minute. This is of course well within the permitted frequency limits for the localizer, but nevertheless necessitated some circuit modification to the a.f.c. system used in the echo monitor. The need for these had not been anticipated since the experimental localizer installation at Farnborough did not exhibit the same drifts.

Once the echo monitor circuits had been modified to ensure that the zero Doppler notch filters could be tracked to follow the frequency excursions of the transmitter no further trouble was experienced.

It is understood that transmitters offered for Category III certification will, for other reasons, have a very tightly controlled frequency, so this problem should not occur in the final system.

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† J. G. Flounders, 'Experimental I.L.S. echo-monitoring system', *The Radio and Electronic Engineer*, **32**, No. 6, pp. 357–62, December 1966.

Mr. S. A. W. Jolliffe: I have listened to Mr. Flounders's excellent paper with great interest. The illustrations showing the echo-monitor recordings compared with recordings taken in the landing aircraft indicates that this project has progressed considerably and I sincerely respect his confidence in the system. However, in order to remove any misunderstanding I would like to restate my views and fears.

If we are really concerned about an overall system unreliability of only 1 in 10^7 a 'warning' or 'executive' monitor must receive an exact replica of the signal actuating the landing aircraft's guidance system. I believe, in practice this implies that the signal, on which executive action is taken, must be extracted from the actual landing aircraft's guidance receiver. It then seems an obvious step to suggest that this signal is transmitted to the ground for processing.

I fully appreciate the significance of the criticism that the system requires an air–ground communication link which is unlikely to be agreed internationally. If this is in fact the case, then, of all the ground-based monitors as yet proposed, the echo monitor is the best suggestion to date for an executive monitor.

What I fear in the echo monitor is the destruction of the wanted information by the direct signal which, under certain circumstances, can enter the echo-monitor aerial by either reflection from overflying aircraft or by reflection from moving ground-based vehicles, e.g. taxying aircraft and service vehicles.

Furthermore, due to differences in the radiation diagrams of the aircraft localizer aerial and the aircraft body, it is possible that the aircraft's instrumentation can be receiving disturbance without the echo monitor being aware of it.

Mr. Flounders has shown that the echo monitor can record a replica of the signal the aircraft is receiving, but I understand that to date he cannot say how often the echo monitor will either 'miss' the occurrence of a dangerous disturbance or give a false alarm. I appreciate that the answer I seek involves a statistical problem and time alone will confirm if my doubts are warranted.

Mr. Flounders (*in reply*): The fear that the direct signal from the ground transmitter can enter the echo monitor aerial via paths other than via reflection from the landing aircraft is certainly a justifiable one, and a considerable amount of the time spent on the development of the monitor to date has been occupied with this problem. The preferred solution is to treat the problem on classical c.w. radar lines where unwanted signals having zero or small Doppler shifts are considered as a form of transmitter spectral noise and the system is designed to reject them. Transmitter noise frequency components can be filtered out adequately, provided the range of Doppler frequencies of interest is separated by a sufficient margin from the noise frequencies. For landing aircraft this is generally the case, taxying aircraft, road vehicles etc., have much lower relative velocities than the directly approaching aircraft, and hence can be recognized and rejected on this basis. Overflying aircraft, particularly those passing close to the transmitter, can produce large-amplitude low-frequency modulation of the transmitter signal entering the monitor aerial, and special limiter techniques have had to be employed to reduce these effects to acceptable limits. Overflying aircraft which are at ranges and elevations where they could produce Doppler shifted signals of the same order as those produced by the landing aircraft, are not normally within the coverage of the directional receiving array used for the echo monitor.

Whilst agreeing with the view that many more measurements are necessary before we can determine the percentage of missed or false alarms, on the evidence of the very limited results to date, no experiment has so far missed interference which was detected in the aircraft, and on at least one occasion interference has been detected both in the aircraft and on the echo monitor, when it was not detected on conventional ground monitors.

Mr. E. R. G. Warner: Will Mr. Lunn† further explain his contention that the Wayne-Kerr device will measure offset d.d.m. to better than 1%. (I am not questioning differences in tone amplitude—in this factor the instrument obviously sets new standards.)

My question arises from the first observed field trial of an instrument containing the modified receiver described by Mr. Lunn. On this occasion an anomaly was observed between the 'actual' and measured modulation depth. This difference resulted in a d.d.m. error of approximately twice the proportion of the modulation depth error and was certainly outside the accuracy claimed. It should be stated that when the instrument was normalized to the standard modulation depth of 20% excellent correlation between both sets of measuring equipment was obtained, therefore it is only the ability of the instrument to determine modulation depth initially to the required accuracy which is in question.

Mr. G. K. Lunn (*in reply*): This was an experience that proved slightly embarrassing when the cause of the error was realized after the trial. The instrument and the receiver were both operating from dry batteries, which were purchased in good faith from a local radio shop and should have given 3 or 4 hours of life. Apparently the voltage dropped rather rapidly and was soon below the stabilization minimum in the receiver, so that the receiver working point was not correct and the modulation depth accuracy became erratic. I think that in future demonstrations Mr. Warner will see that the 1% accuracy on modulation depth and offset d.d.m. is justified.

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† G. K. Lunn, 'New precision techniques for I.L.S. parameter measurements', *The Radio and Electronic Engineer*, **32**, No. 6, pp. 351–56, December 1966.

U.D.C. 621.375.421

A Design Basis for Synchronously Tuned Multi-stage Linear Amplifiers taking into account Spread in Device Parameters

By

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Summary: A generalized design procedure is presented for the stage by stage build-up of synchronously tuned multi-stage linear amplifiers. The individual stages herein may be near identical and either unilateralized by external passive feedback or mismatched resistively at their ports. The design can be usefully based on the average parameters of the device type selected and its circuit components.

This is illustrated by the design of a high-gain amplifier with a large fractional bandwidth utilizing non-unilateral electron devices without unilateralizing feedback. A non-unilateral amplifier was constructed based upon this stage by stage design with 'average' parameters, but using transistors of non-average parameters and circuit components with a few per cent tolerance. The measurements carried out on this amplifier, whose total stages were varied from two to seven confirm the good accuracy of the theory and design.

List of Symbols

Lower-case letters refer to stage network while upper-case letters refer to chain or cascaded network.

B		half power angular bandwidth of chain network.
g_{l}		loop gain of stage network, $\dfrac{p_{12}p_{21}}{p_1 p_2}$ (with source and load terminations).
g_{li}		inherent loop gain of stage network, $\dfrac{p_{12}p_{21}}{p_{11}p_{22}}$ (with zero source and load terminations).
$g_{\mathrm{lir\,max}}$	=	$\dfrac{p_{12}p_{21}}{(p_{11}+\sigma_{\mathrm{S}})(p_{22}+\sigma_{\mathrm{L}})}$, when constrained to be real and maximized (for zero $\rho_{\mathrm{S}}, \rho_{\mathrm{L}}$; $\sigma_{\mathrm{S}}, \sigma_{\mathrm{L}}$ variable).
$g_{\mathrm{max\,c}}$		maximum available power gain (m.a.g.) of stage network with conjugate matched terminations, if $s \geqslant 1$.
$g_{\mathrm{max\,s}}$		maximum power gain of stage network for a given stability factor $s \geqslant 1$.
k_{l}		'Stern's inherent stability factor' of stage network (equals inverse of $g_{\mathrm{lir\,max}}$).
$\begin{bmatrix} p_{11} & p_{12} \\ p_{21} & p_{22} \end{bmatrix}$		two-port matrix of stage network, where $p = h, z, y$ or g.
$\left\lvert\dfrac{p_{21}}{p_{12}}\right\rvert$		'measure of non-reciprocity' of stage network
p_{S}		source immittance of stage network.
p_{Sc}	=	p_{S} for conjugate matching, if $s \geqslant 1$.
p_{L}		load immittance of stage network.
p_{Lc}	=	p_{L} for conjugate matching, if $s \geqslant 1$.
p_1		total self-immittance at input port or port 1 ($= p_{11}+p_{\mathrm{S}}$).
p_2		total self-immittance at output port or port 2 ($= p_{22}+p_{\mathrm{L}}$).
p_{p1}		total immittance at input port or port 1 $\left(= p_1 - \dfrac{p_{12}p_{21}}{p_2}\right)$.
p_{p2}		total immittance at output port or port 2 $\left(= p_2 - \dfrac{p_{12}p_{21}}{p_1}\right)$.
Q_{p1}		Q-factor of p_{p1}.
Q_{p2}		Q-factor of p_{p2}.
R	=	$\dfrac{\lambda}{2\rho_1\rho_2}(\eta^2-1)^{\frac{1}{2}}$.
s		author's invariant 'stability factor' of two-port stage network ($= \eta+\sqrt{\eta^2-1}$ or inverse of loop gain modulus with conjugate matched terminations, if $s \geqslant 1$).
s_{i}		author's invariant 'inherent stability factor' of two-port stage network ($= \eta_{\mathrm{i}}+\sqrt{\eta_{\mathrm{i}}^2-1}$ or inverse of loop gain modulus with conjugate matched terminations, if $s_{\mathrm{i}} \geqslant 1$).

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T electrical turns ratio of transformer.

Γ an inductance or capacitance.

$\lambda = |p_{12}p_{21}|$.

$\mu = \mathrm{Re}\,(p_{12}p_{21})$.

$\nu = \mathrm{Im}\,(p_{12}p_{21})$.

$\rho = \mathrm{Re}\,(p)$.

$\sigma = \mathrm{Im}\,(p)$.

η 'invariant factor' of stage network $\left(= \dfrac{2\rho_1\rho_2-\mu}{\lambda}\right)$.

η_i 'invariant inherent factor' of stage network $\left(= \dfrac{2\rho_{11}\rho_{22}-\mu}{\lambda}\right)$.

A symbol with superscript 'd' refers to device network without a transformer at output port; that without 'd' as superscript refers to device network with output transformer or stage network, while that with a numerical superscript refers to a particular stage network.

1. Introduction

1.1. *Synchronously Tuned Single Stages*

A vacuum triode or transistor is a three-terminal electron device which can amplify power in any of its three 'configurations'. These configurations correspond to having one each of its terminals—i.e. 'source' (cathode–emitter), 'control' (grid–base) or 'drain' (anode–collector)—common between input and output terminal pairs.

An electron device in a chosen configuration can be terminated at its ports by 'elements'—namely resistance and reactance—in series or in shunt combinations giving rise to four 'matrix environments'. Figure 1 illustrates these environments. It is then convenient to characterize the device by that set of matrix parameters p (equals h, z, y or g) which corresponds with the environment of the device. For example, if elements are in shunt at input and output ports as in Fig. 1(c), it is convenient to express the device by its y- or admittance parameters. The environment of a device has greater significance in external feedback circuits as summarized in Fig. 2. For example, y-environment external feedback of Fig. 2(c) corresponds to current feedback to input proportional to output voltage.

An active two-port 'stage network' is said to be 'absolutely stable' if it is stable for all passive terminations at its ports. Otherwise it is said to be 'potentially unstable'. Characterize the device by its p-matrix, where

$$[p] = \begin{bmatrix} p_{11} & p_{12} \\ p_{21} & p_{22} \end{bmatrix} \qquad \ldots\ldots(1)$$

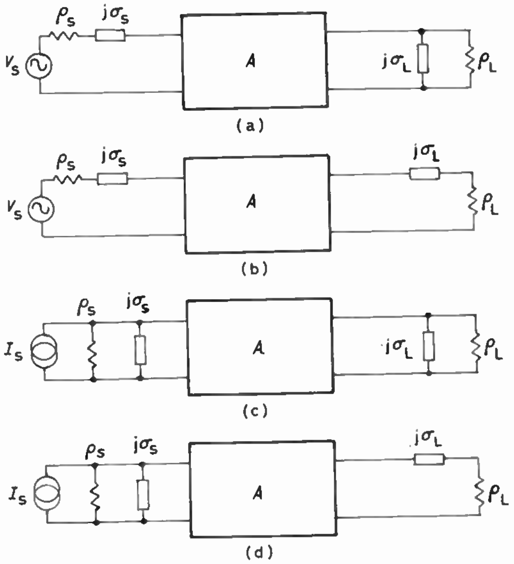

Fig. 1. Possible matrix environments for a two-port active network.

(a) h-environment with series input and shunt output terminations. (Source impedance, $\rho_S + j\sigma_S$; load admittance, $\rho_L + j\sigma_L$.)

(b) z-environment with series input and output terminations. (Source impedance, $\rho_S + j\sigma_S$; load impedance $\rho_L + j\sigma_L$.)

(c) y-environment with shunt input and output terminations. (Source admittance, $\rho_S + j\sigma_S$; load admittance $\rho_L + j\sigma_L$.)

(d) g-environment with shunt input and series output terminations. (Source admittance, $\rho_S + j\sigma_S$; load impedance, $\rho_L + j\sigma_L$.)

and

$$p = h,\ z,\ y \text{ or } g \qquad \ldots\ldots(2)$$

Assume that p_{11}, p_{12}, p_{21} and p_{22} have no poles or zeros on the imaginary axis or on the finite right-half complex plane whether p equals h, z, y or g. This ensures that the network is stable whether each of its ports be open or short circuited, a stipulation satisfied by a wide range of networks including valve and transistor amplifier stages. Networks violating one or more of the above conditions can be made to satisfy them by the addition of resistances at the ports or external passive feedback or both.

A two-port stage network is 'potentially unstable' if its 'inherent loop gain', g_{li} (loop gain

$$\frac{p_{12}p_{21}}{(p_{11}+\sigma_S)(p_{22}+\sigma_L)}$$

for zero real parts of source and load immittances ρ_S, ρ_L) has a value greater than unity, when it is constrained to be real by varying σ_S, σ_L and is maximized. It is achieved for the condition[2, 3]

$$\frac{\sigma_{11}+\sigma_S}{\rho_{11}} = \frac{\sigma_{22}+\sigma_L}{\rho_{22}} = \frac{\lambda-\mu}{\nu} \qquad \ldots\ldots(3)$$

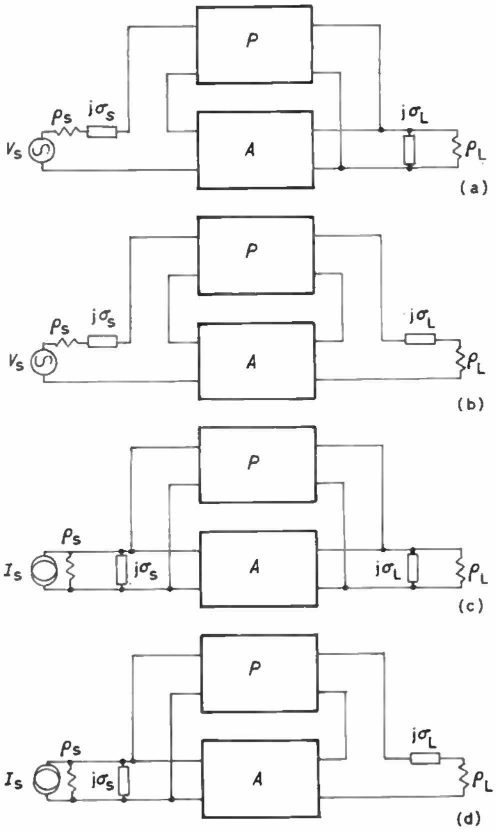

Fig. 2. Possible matrix feedback arrangements for a two-port active network.

(a) *h*-environment feedback; voltage feedback proportional to output voltage.

(b) *z*-environment feedback; voltage feedback proportional to output current.

(c) *y*-environment feedback; current feedback proportional to output voltage.

(d) *g*-environment feedback; current feedback proportional to output current.

where

$$p = \rho + j\sigma \qquad \text{......(4)}$$

$$p_{12}p_{21} = \mu + j\nu \qquad \text{......(5)}$$

and

$$|p_{12}p_{21}| = \lambda \qquad \text{......(6)}$$

The inverse of this maximum value of real inherent loop gain is Stern's 'inherent stability factor',[4] k_i. Thus

$$k_i = \frac{1}{g_{\text{lirmax}}} = \frac{2\rho_{11}\rho_{22}}{\lambda + \mu} \qquad \text{......(7)}$$

The network is 'absolutely stable' if k_i of eqn. (7) is greater than unity or g_{lirmax} is less than unity.

1.1.1. Absolute stability through indirect mismatch

A potential unstable network can be made 'absolutely stable' by 'indirect mismatch'[5-7] as follows. The 'device network' which is potentially unstable (or otherwise) can be modified by the addition of a passive 'device source immittance', ${}^dp_S$ equals ${}^d\rho_S$, and a passive 'device load immittance' ${}^dp_L$ equals ${}^d\rho_L$, to produce a 'modified network' as shown in Fig. 3, which is 'absolutely stable'. It can be now conjugate matched to yield a maximum available power gain[8-10] for the modified network. This power gain can be equal to or less than the 'measure of non-reciprocity' or maximum stable gain,[11] $|p_{21}/p_{12}|$ of the network.

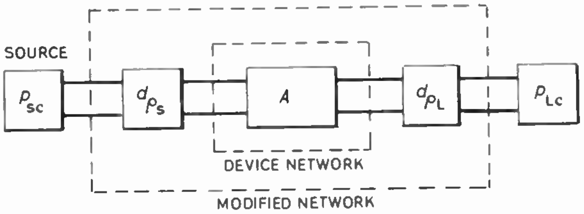

Fig. 3. Device and modified two-port network. Ideal source is a voltage type for *h* or *z* environment and is a current type for *y* or *g* environment. $p_{Sc} = \rho_{Sc} + j\sigma_{Sc}$ and $p_{Lc} = \rho_{Lc} + j\sigma_{Lc}$ are conjugate matching source and load immittance for the modified network but resistively mismatched terminations (reactively tuned terminations) for the original device network.

The 'device network' is 'potentially unstable' if its 'invariant inherent stability factor',[3,5,12,13] s_i, is minus unity or complex; s_i then lies on the circumference of a unit circle of 'potential instability' as depicted by Fig. 4. Here

$$s_i = \eta_i + \sqrt{\eta_i^2 - 1} \qquad \text{......(8)}$$

and

$$\eta_i = \frac{2\,{}^d\rho_{11}\,{}^d\rho_{22} - {}^d\mu}{{}^d\lambda} \qquad \text{......(9)}$$

η_i is referred to as the 'invariant inherent factor'.[3,12,13] The superscript 'd' refers to the device network.

By modifying the network, the 'invariant stability factor', s ($> s_i$) is made equal to or greater than unity. Here

$$s = \eta + \sqrt{\eta^2 - 1} \qquad \text{......(10)}$$

and

$$\eta = \frac{2({}^d\rho_{11} + {}^d\rho_S)({}^d\rho_{22} + {}^d\rho_L) - {}^d\mu}{{}^d\lambda} = \frac{2\,{}^d\rho_1\,{}^d\rho_2 - {}^d\mu}{{}^d\lambda}$$

$$= (2\rho_{11}\rho_{22} - \mu)/\lambda \qquad \text{......(11)}$$

The 'modified device network' is now 'absolutely stable' and the locus of s lies on a straight line[3] as depicted by Fig. 4. The matrix parameters of the modified network are denoted by the absence of the superscript 'd' as in eqn. (11).

The maximum available power gain of the 'modified network' is now given by[3,5,12]

$$\underset{s\geqslant 1}{g_{\max c}\cdot s} = \left|\frac{p_{21}}{p_{12}}\right| \qquad \ldots\ldots(12)$$

while the 'maximum power gain' of the 'device network' for a given s value is given by

$$\underset{s\geqslant 1}{g_{\max s}\cdot s} = \left|\frac{p_{21}}{p_{12}}\right| \qquad \ldots\ldots(13)$$

Note that conjugate match for 'modified network' may correspond to resistive mismatch for 'device network'.

When $s \geqslant 1$, it may be identified physically[3,7] as the modulus of 'internal loop loss', i.e. the modulus of the inverse of internal loop gain, for the associated terminations. These terminations correspond to conjugate match for the 'modified network' but 'resistive mismatch' (reactive tuned) for the 'device network'.

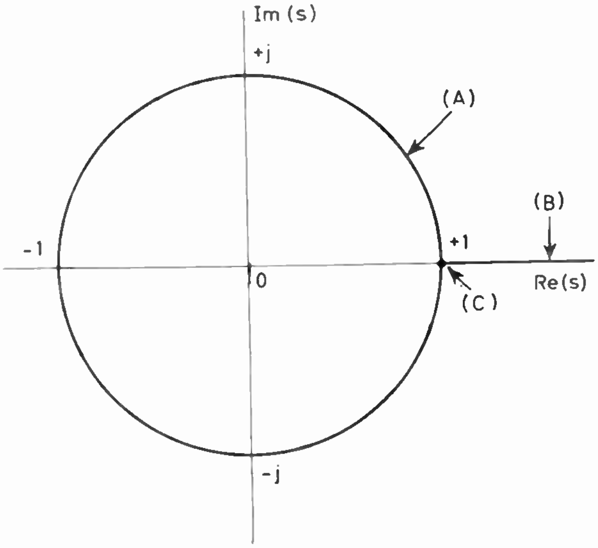

Fig. 4. Locus of the values of the invariant stability factor, s, on the complex plane for real values of the invariant factor, η, from -1 to $+\infty$.

(A) Unit circle of potential instability for $-1 \leqslant \eta < 1$ or complex s values or $s = -1$.

(B) Straight line of absolute stability for η or $s > 1$.

(C) Point of marginal stability for $\eta = s = 1$.

The qualifying word invariant in 'invariant stability factor' signifies that the value of s is invariant in matrix environments or for 'immittance substitution'. It is also invariant when input and output ports are interchanged, i.e. it is reciprocal. Since 'potential instability' signifies varying port reactances, s is also invariant for pure reactive terminations. In the following sections, s_i and s will be referred to as 'inherent stability factor' and 'stability factor' respectively. So far, the essential theory of single stage amplifiers has been reviewed. It is now logical to summarize the theory of cascaded amplifiers built up from several such absolutely stable stages.

1.2. *Synchronously Tuned Multi-stages*

1.2.1. Stability and power gain

In a two-port network of m cascaded stages, the magnitude of the ratio of its forward to reverse transfer parameters or 'measure of non-reciprocity' equals[6] the continued product of the measures of non-reciprocity of its m constituent networks, namely,

$$\left|\frac{P_{21}}{P_{12}}\right| = \prod_{q=1}^{q=m} \left|\frac{{}^{q}p_{21}}{{}^{q}p_{12}}\right| \qquad \ldots\ldots(14)$$

In eqn. (14), superscript q refers to the qth stage of the cascaded network.

Consider a general arrangement of m stages, where the input stage is coupled to the source immittance, P_S, the output stage is coupled to the load immittance, P_L, and adjacent stages coupled to each other through lossless reactance two-port networks; let these couplings be such as to provide conjugate match at the input and output ports of each stage. This is illustrated schematically in Fig. 5. Details of such matching networks are given elsewhere.[8,14] For the above situation, the maximum available power gain of the chain network, $G_{\max c}$, is the continued product of the maximum available power gains of the individual networks[6]; herein, the individual networks may be unilateralized or mismatched, or both, and have stability factor values equal to or greater than unity. Thus

$$G_{\max c} = \prod_{q=1}^{q=m} {}^{q}g_{\max c} \qquad \ldots\ldots(15)$$

As before, the superscript q refers to the qth stage of chain network.

From eqns. (12), (14) and (15), it follows that the stability factor of the chain network,

$$S = \prod_{q=1}^{q=m} {}^{q}s \qquad \ldots\ldots(16)$$

Note that upper-case letters are used in eqns. (14) to (16) to denote the chain network. This will be the practice throughout.

1.2.2. Bandwidth

Where the stability factor of each individual stage is equal to or greater than ten,[6] its 'internal loop gain' modulus with conjugate matched terminations is equal to or less than a tenth; as such the interaction between the tuning circuits of input and output ports is small. Hence the amplifier has a good 'alignability' and negligible 'skew'† in its power gain/frequency

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† Skew is defined as $(\sqrt{f_1 f_2} - f_0)/f_0$, where f_1 and f_2 are lower and upper half-power frequencies respectively.

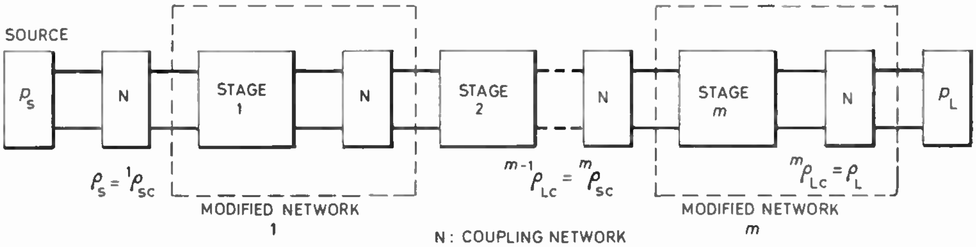

Fig. 5. A cascade of two-port active and lossless passive (coupling) networks; here the modified networks are conjugate matched throughout. Consequently the power gain of the chain network is the product of the power gains of the individual networks.

response due to internal feedback[6]; any residual skew is mainly due to the characteristics of the self and forward transfer parameters of the device network.

Let us make the following assumptions:

the m individual stages are near identical,

their forward transfer parameters do not govern bandwidth (otherwise this can be compensated by a proper choice of load termination),

their stability factor values be each equal to or greater than ten,

and their total port immittance Q-factors, with conjugate matching, be Q_{p1}, Q_{p2} throughout.

Then the half-power angular bandwidth, B, of this chain network is given by[6]

$$B \simeq \frac{\omega_0}{Q_{p1}+Q_{p2}}\{2^{1/m}-1\}^{\frac{1}{2}} \qquad \ldots\ldots(17)$$

for

$$p = z \text{ or } y \qquad \ldots\ldots(18)$$

and

$$B \simeq \frac{\omega_0}{|Q_{p1}-Q_{p2}|}\{2^{1/m}-1\}^{\frac{1}{2}} \qquad \ldots\ldots(19)$$

for

$$p = h \text{ or } g$$

with

$$Q_{p1}/Q_{p2} \gg 1 \text{ or } \ll 1 \qquad \ldots\ldots(20)$$

In eqn. (17), ω_0 refers to the angular frequency of maximum power gain. Equation (19) is applicable only when $Q_{p1}/Q_{p2} \gg 1$ or $\ll 1$, whereas eqn. (17) is applicable for all values of Q_{p1}/Q_{p2}. However, use of eqn. (17) gives a maximum error for the case Q_{p1} equals Q_{p2}; this error[6] is less than 13% for two stages, less than 7% for four stages, and less than 4% for seven stages.

2. General Design Basis

Let it be required to design a multi-stage synchronously tuned linear amplifier with a source immittance, P_S, a load immittance, P_L, operating power gain, G (equals m.a.g.) and half-power angular bandwidth B. Assume the amplifier to have passive coupling networks at its input, interstages and output such that these networks provide conjugate matching. A table of several useful networks is provided by Cheng.[8, 14]

2.1. *Individual Stage Specifications*

If there are m near-identical stages in the amplifier, the gain, g, of each stage must approximately equal $G^{1/m}$. Provided the stability factor, s, of each stage is equal to or greater than 10, eqn. (17) or eqn. (19) yields an 'equivalent angular bandwidth', b_{eq}, for each such stage which is approximately $B/(2^{1/m}-1)^{\frac{1}{2}}$. It will nearly be the actual angular bandwidth of the stage in isolation, with conjugate matching terminations, if $Q_{p1}/Q_{p2} \gg 1$ or $\ll 1$. The actual gain and 'equivalent angular bandwidth' of each of the m near-identical stages selected must satisfy the conditions

$$g \geqslant G^{1/m} \qquad \ldots\ldots(21)$$

$$b_{eq} \geqslant B/(2^{1/m}-1)^{\frac{1}{2}} \qquad \ldots\ldots(22)$$

2.2. *Optimization of Equivalent Bandwidth of Individual Stages*

To make the amplifier 'alignable' and reduce the 'skew' in its gain/frequency response curve due to internal feedback, the stability factor, s, of each stage must be equal to or greater than 10. This imposes an upper limit of $0{\cdot}1|p_{21}/p_{12}|$ on the m.a.g. of the individual stages, where $p = h$, z, y or g. This limit does not depend on the bandwidth of the amplifier. For a given gain equal to or lower than this upper limit, the equivalent bandwidth of the stage can be optimized. This is different from maximizing power gain for a given bandwidth.[10] As is shown in the Appendix, if $p = z$ or y, maximized equivalent bandwidth is

$$b_{\text{eq max}} \simeq \frac{1}{2}\left\{\frac{\lambda s}{\Gamma_{p1}\Gamma_{p2}}\right\}^{\frac{1}{2}} \qquad \ldots\ldots(23)$$

and occurs when

$$Q_{p1} \simeq Q_{p2} \quad \text{or} \quad \Gamma_{p1}/\rho_{p1} \simeq \Gamma_{p2}/\rho_{p2} \quad \text{......(24)}$$

Here, Γ_{p1} and Γ_{p2} refer to 'total port' inductance or capacitance, ρ_{p1} and ρ_{p2} refer to 'total port' resistance or conductance at ports 1 and 2 respectively. They are defined from

$$p_{p1} = \rho_{p1} + \mathrm{j}\omega_0\Gamma_{p1}(\omega/\omega_0 - \omega_0/\omega) \quad \text{......(25)}$$

$$p_{p2} = \rho_{p2} + \mathrm{j}\omega_0\Gamma_{p2}(\omega/\omega_0 - \omega_0/\omega) \quad \text{......(26)}$$

If $p = h$ or g, limiting equivalent bandwidth,

$$b_{\mathrm{eq\,lt}} \simeq \frac{\lambda s}{\rho_{p1\,\mathrm{min}}\Gamma_{p2}} \quad \text{for } Q_{p1}/Q_{p2} \ll 1 \quad \text{......(27)}$$

and

$$b_{\mathrm{eq\,lt}} \simeq \frac{\lambda s}{\rho_{p2\,\mathrm{min}}\Gamma_{p1}} \quad \text{for } Q_{p1}/Q_{p2} \gg 1 \quad \text{......(28)}$$

$\rho_{p1\,\mathrm{min}}$ is the minimum value of ρ_{p1}. Since the stage has a low loop gain, its $\rho_{p1\,\mathrm{min}}$ is approximately equal to $2\rho_{11}$. Similarly, $\rho_{p2\,\mathrm{min}}$ is the minimum value of ρ_{p2} and approximately equals $2\rho_{22}$.

To achieve an optimum equivalent bandwidth for $s \geqslant 10$ (also greater than $4\rho_{11}\rho_{22}/\lambda$), an extra resistance must be added suitably, i.e. in series or in parallel depending upon the matrix environment, external to the device at the port of much greater Q to make

$$4\rho_{11}(\rho_{22}+\rho_{\mathrm{L}})/\lambda \simeq s \quad \text{for } s \geqslant 10 \text{ and } Q_{p1}/Q_{p2} \ll 1 \quad \text{......(29)}$$

$$4(\rho_{11}+\rho_{\mathrm{S}})\rho_{22}/\lambda \simeq s \quad \text{for } s \geqslant 10 \text{ and } Q_{p1}/Q_{p2} \gg 1 \quad \text{......(30)}$$

2.3. *Minimum Number of Stages*

For a chosen device (vacuum tube, etc.), configuration (common source, etc.) and matrix environment (series-parallel, etc.), the upper limiting power gain consistent with the requirements of alignability and negligible skew in power gain frequency response is $0{\cdot}1|p_{21}/p_{12}|$; the optimum equivalent angular bandwidth for s equals 10 can be obtained through eqns. (23), (27) or (28) as appropriate. Substituting these values for gain and angular bandwidth in eqns. (21) and (22), the minimum number of stages that simultaneously satisfies these conditions and hence the design specifications may be obtained. This value rounded to the nearest higher integer decides the optimum number of stages for the amplifier.

2.4. *Selection of Average Parameters*

If spread in device parameters is expected, ρ_{11} and ρ_{22} of the stages have to be artificially increased, such that these are fairly constant for all the stages and $s \geqslant 10$ for each of them. The gain of the chain network will be given by

$$G \simeq \frac{|P_{21}|^2}{4\,\mathrm{Re}(P_{11})\,\mathrm{Re}(P_{22})} \simeq \frac{|P_{21}|^2}{4\,{}^1\rho_{11}\,{}^m\rho_{22}}$$

$$\simeq \frac{|{}^1p_{21}\,{}^2p_{21}\ldots{}^{m-1}p_{21}\,{}^mp_{21}|^2}{(4\,{}^1\rho_{11}\,{}^1\rho_{22})(4\,{}^2\rho_{11}\,{}^2\rho_{22})\ldots(4\,{}^m\rho_{11}\,{}^m\rho_{22})} \quad \text{......(31)}$$

Equations (14) to (16) and (31) suggest the use of geometric means in the selection of 'average' parameters to increase the accuracy in design. For example, average power gain of stage

$$g_{\mathrm{av}} = G^{1/m} = ({}^1g\,{}^2g\ldots{}^{m-1}g\,{}^mg)^{1/m} \quad \text{......(32)}$$

2.5. *Stabilization or Adjustment of Power Gain and Bandwidth of Stages*

Bandwidth may be stabilized by 'reactive loadings'[10] without affecting power gain. Reactive loading is the name given to terminating port by an inductance and capacitance which is equivalent to terminating that port by an inductance or capacitance alone at the frequency of maximum power gain. It results in a larger port Q-factor and hence a lower bandwidth. This reduction in bandwidth stabilizes the bandwidth of the stage; thus extra reactances stabilize bandwidth while extra resistances stabilize power gain. For an s value greater than 10, if the stage has a greater b_{eq} than required, this 'bandwidth' can be trimmed by this method.

Non-unilateral multi-stage amplifiers can be rendered alignable[15] by mismatch. This somewhat stabilizes power gain simultaneously for changes of device[1] of the same nominal type or of operating conditions for the same device. For large values of s, maximum power gain is given by

$$g \simeq \frac{|p_{21}|^2}{4\rho_{11}\rho_{22}} \quad \text{......(33)}$$

If s value has been increased by stabilizing ρ_{11}, ρ_{22} through mismatch, the spread in power gain with changes in device of the same nominal type approaches a lower limit due to the spread in $|p_{21}|^2$. Hence, this gain spread depends upon the device, configuration and matrix environment selected.

For transistors, at $f \ll f_\alpha$, spread in $|p_{21}|^2$ is a minimum when they are used in their common-base configuration and h-matrix environment, i.e. where stabilization of self parameters is achieved by a resistance in series at the input port and by a resistance in shunt at the output port. Interstage matching (for modified networks) may be simply accomplished by a tapping of the tuning coil in parallel with a variable capacitor. Through a combination of mismatch at the ports and reactive loadings, it is possible to adjust power gain and equivalent bandwidth as required.

3. An Illustrative Design

The following example illustrates the detailed design procedure.

'Design a transistor amplifier from average characteristics that will give constant gain and bandwidth in spite of parameter spreads in a group of devices of the same nominal type and whose specifications are as follows:

Gain, $G = 90$ dB
Bandwidth, $B/2\pi = 180$ kHz
Central frequency, $f_0 = 465$ kHz
Source termination, $P_S = 75\ \Omega$
Load termination, $P_L = 75\ \Omega$

3.1. *Selection of Device Type, Configuration and Matrix Environment*

The spread in power gains is least in common-base configuration and *h*-matrix environment, provided $f_\alpha \gg f_0$. For a high gain amplifier with a wide bandwidth, signal/noise ratio can be high only if it can handle a large signal level; the theory developed is linear and hence it is necessary to select an arrangement that is linear for large signal levels. h_{21} in common-base of germanium transistors satisfies this important requirement. But for some silicon transistors this is not true.[16] Therefore a germanium transistor in its common-base configuration, *h*-environment and with $f_\alpha \gg 465$ kHz must be selected. A suitable type is OC 44 whose average f_α at $I_e = 1$ mA, $V_c = -6$ V and $K = 298°$, is approximately 12 MHz. Here, I_e refers to emitter current (d.c.), V_c to collector voltage (d.c.) and K to temperature on Kelvin scale.

3.2. *Matching Considerations*

In order to realize maximum gain, interstage matching is necessary. Let it be simply achieved by a suitable tap on the collector side tuning coil; even if this coil is embedded in a ferrite pot core, it is difficult to retain a constant transformation of resistance over a wide fractional bandwidth owing to the distribution of self and stray capacitance across the 'primary' and 'secondary'. This imposes an upper limit on the electrical turns ratio, T, of the transformer which is usually ten. This limitation is imposed by matching considerations on amplifiers whose fractional bandwidths are large; it may require the stability factor, s, to be even greater than ten. T and s are interrelated; a greater s value ($s \geqslant 10$) gives a smaller value for T (refer to Section 3.4).

3.3. *Average Parameters Used*

The following are the values of the hybrid parameters for a typical OC 44 transistor in its common-base configuration about 465 kHz. They are based on the 'average'[†] parameters as specified by the manufacturer at $I_e = 1$ mA, $V_c = -6$ V, $K = 298°$ with collector capacitance, $C_c = 10{\cdot}5$ pF, extrinsic base resistance, $r_{b'} = 110\ \Omega$, $f_\alpha = 12{\cdot}3$ MHz and $\alpha_0 = 0{\cdot}99$.

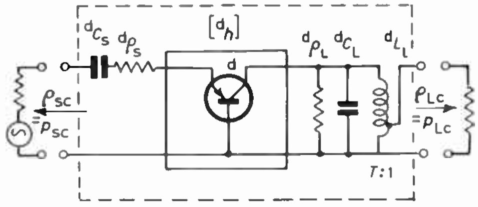

Fig. 6. One of seven stages for the cascaded amplifier of required specifications. d transistor OC 44 at $I_e = 1$ mA, $V_c = -6$ V and $K = 298°$ with average characteristics. ${}^{d}\rho_S = 45{\cdot}4\ (\Omega)$; ${}^{d}C_S = 0{\cdot}0269\ (\mu\text{F})$; ${}^{d}\rho_L = 168\ (\mu℧)$; ${}^{d}L_L = 1{\cdot}06$ (mH); ${}^{d}C_L = 92{\cdot}0$ (pF); $p_{Sc} = \rho_{Sc} = 75\ (\Omega)$; $p_{Lc} = \rho_{Lc} = 1/75\ (℧)$; $T = 8{\cdot}73$. Biasing arrangements are not shown.

$$ {}^{d}h_{11} = {}^{d}\rho_{11} + j\,{}^{d}\sigma_{11} = 26{\cdot}8 + j2{\cdot}94\gamma \qquad \ldots\ldots(34)$$

$$ {}^{d}h_{12} = {}^{d}\rho_{12} + j\,{}^{d}\sigma_{12} = (1{\cdot}11 + j3{\cdot}38\gamma)10^{-3} \qquad \ldots\ldots(35)$$

$$ {}^{d}h_{21} = {}^{d}\rho_{21} + j\,{}^{d}\sigma_{21} = -0{\cdot}99 + j0{\cdot}0341\gamma \qquad \ldots\ldots(36)$$

$$ {}^{d}h_{22} = {}^{d}\rho_{22} + j\,{}^{d}\sigma_{22} = \{(0{\cdot}8 + 0{\cdot}104\gamma^2) + j30{\cdot}7\gamma\}10^{-6} \qquad \ldots\ldots(37$$

where

$$\gamma = f/f_0 \qquad \ldots\ldots(38)$$

At the central frequency of 465 kHz,

$$\begin{aligned} {}^{d}h_{12}{}^{d}h_{21} &= {}^{d}\mu + j\,{}^{d}\nu \\ &= -(1{\cdot}213 + j3{\cdot}308)10^{-3} \\ &\simeq -(1{\cdot}21 + j3{\cdot}31)10^{-3} \qquad \ldots\ldots(39) \\ |{}^{d}h_{12}{}^{d}h_{21}| &= {}^{d}\lambda = 3{\cdot}523 \times 10^{-3} \\ &\simeq 3{\cdot}52 \times 10^{-3} \qquad \ldots\ldots(40) \end{aligned}$$

3.4. *Minimum Number of Stages*

For the device with a *h*-matrix given by eqns. (34) to (38) and terminated in a series resistance ${}^{d}\rho_S$ at the input port and in a shunt conductance ${}^{d}\rho_L$ at the output port as shown in Fig. 6, the stability factor, s, is given by

$$s = \eta + (\eta^2 - 1)^{\frac{1}{2}} \qquad \ldots\ldots(41)$$

where

$$\eta = \frac{2({}^{d}\rho_{11} + {}^{d}\rho_S)({}^{d}\rho_{22} + {}^{d}\rho_L) - {}^{d}\mu}{{}^{d}\lambda}$$

$$= \frac{2\,{}^{d}\rho_1{}^{d}\rho_2 - {}^{d}\mu}{{}^{d}\lambda} = \frac{2\rho_{11}\rho_{22} - \mu}{\lambda} \qquad \ldots\ldots(42)$$

and ${}^{d}\rho_1$, ${}^{d}\rho_2$ refer to the series total self-resistance at the input port for a short circuit at the output port and the shunt total self-conductance at the output port for an open circuit at the input port of the

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[†] Only $|h_{21}|$ parameter spread is important in this design; in common-base configuration, the geometric and arithmetic means of $|h_{21}|$ are nearly the same because $|h_{21}|$ is close to unity. Hence manufacturer's average parameters are permissible for this design.

network with ${}^{\mathrm{d}}\rho_{\mathrm{S}}$, ${}^{\mathrm{d}}\rho_{\mathrm{L}}$ but without the output transformer.† They are to be evaluated at 465 kHz. ρ_{11}, ρ_{22}, μ and λ refer to the parameters of the network with ${}^{\mathrm{d}}\rho_{\mathrm{S}}$, ${}^{\mathrm{d}}\rho_{\mathrm{L}}$ and the output transformer, i.e. the modified network.

Further series reactive termination at the input port and shunt reactive termination at the output port with the tapped coil (lossless) at the output port acting as a transformer of 'electrical turns ratio' $T:1$ as shown in Fig. 6 makes the conjugate matching terminations of the modified network real and equal. For details of this arrangement in relation to matrix environments refer to an earlier paper,[6]

$$T^2 = \frac{1}{\rho_{\mathrm{Sc}}\rho_{\mathrm{Lc}}} = \frac{1}{{}^{\mathrm{d}}\rho_1\,{}^{\mathrm{d}}\rho_2\,{}^{\mathrm{d}}R^2} \qquad \ldots\ldots(43)$$

where

$${}^{\mathrm{d}}R^2 = \frac{{}^{\mathrm{d}}\lambda^2}{4\,{}^{\mathrm{d}}\rho_1^2\,{}^{\mathrm{d}}\rho_2^2}(\eta^2-1) \qquad \ldots\ldots(44)$$

In eqn. (44), η is the invariant factor† of the modified network. From eqns. (42) to (44)

$$\eta = \frac{1}{{}^{\mathrm{d}}\lambda T^2}\{1 \pm (1+2\,{}^{\mathrm{d}}\mu T^2 + {}^{\mathrm{d}}\lambda^2 T^4)^{\frac{1}{2}}\} \ldots\ldots(45)$$

For $T = 10$, in the present example

$$\eta = 5\cdot504 \simeq 5\cdot50 \qquad \ldots\ldots(46)$$

The second value of 0·173 for η denotes a 'potentially unstable' network according to Fig. 4; it violates the initial assumptions of Section 1.1.1 and is therefore rejected.

Equations (41) and (46) make

$$s = 10\cdot92 \simeq 10\cdot9 \qquad \ldots\ldots(47)$$

Hence the power gain of a single stage

$$g = \frac{1}{s}\left|\frac{p_{21}}{p_{12}}\right| = 25\cdot49 \simeq 25\cdot5 \simeq 14\cdot1\ \mathrm{dB} \ldots\ldots(48)$$

The minimum number of stages required for a gain of 90 dB is the nearest higher integer to 90/14·1 or 7.

3.5. *Circuit Components for Stages*

If seven stages in the common base configuration are to be employed, the power gain of each stage must be nearly 90/7 dB, i.e. 12·86 dB or 19·31 times. This makes the stability factor,

$$s = \frac{|h_{21}/h_{12}|}{g} = 14\cdot42 \simeq 14\cdot4 \qquad \ldots\ldots(49)$$

From eqns. (41) and (49)

$$\eta = \frac{s^2+1}{2s} = 7\cdot244 \simeq 7\cdot24 \qquad \ldots\ldots(50)$$

Further from eqns. (39, (40), (42), (44) and (50)

$${}^{\mathrm{d}}R = \frac{{}^{\mathrm{d}}\lambda}{2\,{}^{\mathrm{d}}\rho_1\,{}^{\mathrm{d}}\rho_2}(\eta^2-1)^{\frac{1}{2}} = 1\cdot039 \simeq 1\cdot04 \ldots\ldots(51)$$

Equations (39), (40), (42), (43), (50) and (51) now yield

$$T = \left\{\frac{1}{{}^{\mathrm{d}}R^2\,{}^{\mathrm{d}}\rho_1\,{}^{\mathrm{d}}\rho_2}\right\}^{\frac{1}{2}} = 8\cdot725 \simeq 8\cdot73 \quad \ldots\ldots(52)$$

Now the conjugate matching source resistance[8-10]

$$\rho_{\mathrm{Sc}} = {}^{\mathrm{d}}\rho_1\,{}^{\mathrm{d}}R \qquad \ldots\ldots(53)$$

The stipulation $\rho_{\mathrm{Sc}} = 75$ in design, eqns. (51) and (53) make

$${}^{\mathrm{d}}\rho_1 = 72\cdot19 \simeq 72\cdot2 \qquad \ldots\ldots(54)$$

whence

$${}^{\mathrm{d}}\rho_{\mathrm{S}} = {}^{\mathrm{d}}\rho_1 - {}^{\mathrm{d}}\rho_{11} = 45\cdot4 \qquad \ldots\ldots(55)$$

From eqns. (43), (51) to (53)

$${}^{\mathrm{d}}\rho_2 = \frac{1}{\rho_{\mathrm{Sc}}\,{}^{\mathrm{d}}RT^2} = 168\cdot6\times10^{-6} \simeq 169\times10^{-6} \qquad \ldots\ldots(56)$$

Therefore

$${}^{\mathrm{d}}\rho_{\mathrm{L}} = {}^{\mathrm{d}}\rho_2 - {}^{\mathrm{d}}\rho_{22} = 167\cdot7\times10^{-6} \simeq \frac{1}{5\cdot96\times10^3} \qquad \ldots\ldots(57)$$

Again[8-10]

$${}^{\mathrm{d}}\sigma_{\mathrm{S}} = -{}^{\mathrm{d}}\sigma_{11} + \frac{{}^{\mathrm{d}}\nu}{2\,{}^{\mathrm{d}}\rho_2} = -12\cdot749 \simeq -12\cdot7 \ldots\ldots(58)$$

and therefore

$${}^{\mathrm{d}}C_{\mathrm{S}} = \frac{1}{\omega_0\times12\cdot75} = 0\cdot02685\times10^{-6} \simeq 0\cdot0269\times10^{-6} \qquad \ldots\ldots(59)$$

From Section 2.1 the 'equivalent angular bandwidth' of stage

$$b_{\mathrm{eq}} = \frac{B}{\{2^{1/m}-1\}^{\frac{1}{2}}} = 3504\times10^3 \simeq 350\times10^4 \ldots\ldots(60)$$

For this *h*-environment, $Q_{p1} \ll Q_{p2}$; hence from eqns. (19) and (60)

$$Q_{p2} - Q_{p1} = \frac{\omega_0}{b_{\mathrm{eq}}} = 0\cdot8337 \simeq 0\cdot834 \quad \ldots\ldots(61)$$

But

$$Q_{p1} = \frac{|{}^{\mathrm{d}}\sigma_{\mathrm{S}}|}{2\rho_{\mathrm{Sc}}} = 0\cdot08500 \simeq 0\cdot0850 \quad \ldots\ldots(62$$

as a result of eqn. (58) and $\rho_{\mathrm{Sc}} = 75$, a design requirement. Equations (61) and (62) now yield

$$Q_{p2} = 0\cdot9187 \simeq 0\cdot919 \qquad \ldots\ldots(63)$$

Now

$$Q_{p2} = \frac{1}{2\,{}^{\mathrm{d}}\rho_{\mathrm{Lc}}\omega_0\,{}^{\mathrm{d}}L_{\mathrm{L}}} = \frac{1}{2\,{}^{\mathrm{d}}\rho_2\,{}^{\mathrm{d}}R\omega_0\,{}^{\mathrm{d}}L_{\mathrm{L}}} \ldots\ldots(64)$$

From eqns. (51), (56), (63) and (64)

$${}^{\mathrm{d}}L_{\mathrm{L}} = 1\cdot064\times10^{-3} \simeq 1\cdot06\times10^{-3} \quad \ldots\ldots(65)$$

---

† Ideal transformers at the ports of a network do not affect its invariant and stability factors, forward and reverse power gains, port *Q*-factors or its bandwidth.

Now[8-10]

$$^{\mathrm{d}}\sigma_{\mathrm{L}} = -{}^{\mathrm{d}}\sigma_2 + \frac{^{\mathrm{d}}\nu}{2\,{}^{\mathrm{d}}\rho_1}$$

whence

$$^{\mathrm{d}}\sigma_2 = 299{\cdot}46 \times 10^{-6} \simeq 299 \times 10^{-6} \quad \ldots\ldots(66)$$

or

$$^{\mathrm{d}}C_2 = 102{\cdot}5 \times 10^{-12} \simeq 103 \times 10^{-12} \quad \ldots\ldots(67)$$

making

$$^{\mathrm{d}}C_{\mathrm{L}} = {}^{\mathrm{d}}C_2 - {}^{\mathrm{d}}C_{22} = {}^{\mathrm{d}}C_2 - C_{\mathrm{c}} \simeq 92{\cdot}0 \times 10^{-12} \quad \ldots\ldots(68)$$

Equations (55) and (59) give the values of the resistance (Ω) and capacitance (F) to be placed in series at the input port; eqns. (57), (65) and (68) give the values of the resistance (Ω), inductance (H) and capacitance (F) to be placed in shunt across the output port of the device. Equation (52) gives the 'transformation ratio', T, to be satisfied by the tapped coil, $^{\mathrm{d}}L_{\mathrm{L}}$, acting as a transformer. The modified device network is shown in Fig. 6. It can now be conjugate matched at 465 kHz by a resistance of 75 Ω at each of its two ports.

Seven such basic units—as in Fig. 6—in cascade, with suitable biasing and decoupling arrangements form the synchronously tuned multistage amplifier.

4. Tuning and Experimental Results

4.1. *Tuning of Stages*

On the collector side, tuning is accomplished by a trimmer of 1 to 32 pF capacitance in parallel with a fixed capacitance of 70 to 85 pF depending on the stage owing to variations in collector capacitance, tuning coil self-capacitance and stray capacitance. Since $Q_{p1} \ll Q_{p2}$, a fixed capacitor of approximately 0·0269 μF in value is connected in series at the input port; this value represents the conjugate matching capacitance for the 'average' device. With cascaded amplifier, tuning the output port of any stage tunes the input port of the next stage and hence tunes the interstage. Thus having a fixed capacitor in series at the input port slightly lowers the power gain of the individual stages but the gains of multi-stage amplifiers are practically unaffected.

4.2. *Experimental Alignability and Skew in Response*

One 'to and fro' tuning trip makes the amplifier gain practically the maximum obtainable. As expected theoretically,[6] each tuning circuit is affected slightly by the tuning of its 'immediate neighbours' but is practically unaffected by more 'distant neighbours'. The geometric skew in gain/frequency response for amplifiers with total stages from 2 to 7 is less than 2% and is negative. This is due to a small positive feedback at lower frequencies owing to an inductive susceptance and a small negative feedback at higher frequencies owing to a capacitive susceptance.

4.3. *Experimental Power Gains and Bandwidths*

The measured power gains (m.a.g.) of the individual stages and their sums are tabulated in Table 1; the measured power gains and bandwidths of multi-stage amplifiers with total stages from 2 to 7 are also given therein. The sum of the gains of the individual stages is slightly less than the m.a.g. of the cascaded amplifier with these individual stages because of interstage tuning with the cascaded arrangement.

Table 1

Experimental power gain of individual stages as also power gain and bandwidth of amplifiers with total stages from 2 to 7

Stage number	Power gains (dB)	Sum of power gains (dB)	M.a.g. of cascaded amplifier (dB)	Bandwidth of cascaded amplifier (kHz)	Stages in cascaded amplifier
1	12·7	12·7	—	—	—
2	12·7	25·4	25·5	345	1–2
3	12·8	38·2	38·3	274	1–3
4	13·0	51·2	51·4	238	1–4
5	12·6	63·8	64·1	212	1–5
6	12·5	76·3	76·9	193	1–6
7	13·0	89·3	90·1	176	1–7

The ratio of bandwidths of amplifier with stages from 1 to m to an amplifier with stages from 1 to 2 as obtained experimentally is

$$1 : 0{\cdot}79 : 0{\cdot}69 : 0{\cdot}61 : 0{\cdot}56 : 0{\cdot}51$$

whereas the theoretical formula,

$$[2^{1/m} - 1]^{\frac{1}{2}} / [2^{\frac{1}{2}} - 1]^{\frac{1}{2}}$$

gives

$$1 : 0{\cdot}79 : 0{\cdot}68 : 0{\cdot}60 : 0{\cdot}54 : 0{\cdot}50$$

The experimental m.a.g. and bandwidth for the non-unilateral seven-stage amplifier are 90·1 dB and 176 kHz, with a geometric asymetry in gain/frequency response or skew of −1·9%. These may be compared with the design requirements of $G = 90$ dB and $B/2\pi = 180$ kHz. The agreement is very close for an amplifier design based on average parameters.

5. Conclusions

Based on the author's stability factor, a generalized design procedure for the construction of multi-stage amplifiers with near identical stages, on a stage by stage basis, has been established and experimentally verified. This procedure is simple and closely accurate; it is equally applicable for stages incorporating vacuum tubes or transistors in any configuration and matrix environment with mismatch at the ports or unilateralizing feedback. This type of design synthesis has not been accomplished previously.[15, 17-20]

Where the best design is sought, this simple procedure can be repeated for each available device in all its configurations and matrix environments with and without unilateralizing feedback. From considerations of skew in response, spread in power gain and bandwidth with a change of device of a nominal type or of operating point, minimum number of stages, noise, linearity of response, useful life, size, weight, cost, etc., the design appearing most promising may be selected.

A mismatched amplifier with values for invariant stability factor greater than ten for its individual stages is not significantly different in performance as regards addition of power gain in decibels and compression in bandwidth with increasing number of stages, alignability and negligible skew in gain/frequency response compared with an amplifier with unilateral or near unilateral stages. The slight complexity in calculations of mismatched amplifier performance is more than compensated by the practical ease of mismatching and the guarantee of stability with spread in device parameters compared with optimum unilateralizing for the 'average' device.

6. Acknowledgments

The author is grateful to Professor R. King, visiting Professor at the Indian Institute of Technology, Delhi, for many helpful discussions and criticisms. He is also indebted to Dr. P. K. Kelkar, Director, Indian Institute of Technology, Kanpur, for providing facilities. The paper is partly based on a Doctoral Thesis of the University of London.[1]

7. References

1. S. Venkateswaran, 'Stability, Power Gain and Bandwidth of Linear Active Four-pole Networks, with particular reference to Transistor Amplifiers at Higher Frequencies', University of London Ph.D. Thesis, June 1961.
2. J. B. Rodgers, 'The Stability and Power Gain of a Tuned Grounded Emitter Transistor Amplifier Stage', Mullard Research Laboratories Report 333, January 1960.
3. S. Venkateswaran, 'An invariant stability factor and its physical significance', *Proc. Instn Elect. Engrs*, **109C**, pp. 98–102, 1962 (I.E.E. Monograph No. 468E; Sept. 1961).
4. A. P. Stern, 'Considerations on the stability of active elements and applications to transistors', *Conv. Rec. I.R.E.*, Part 2, pp. 46–52, 1956.
5. S. Venkateswaran, 'Frequency of merit for three terminal electron devices', *Int. Conv. Rec. I.R.E.*, Part 3, p. 17, 1962.
6. S. Venkateswaran, 'Stability, power gain and bandwidth of synchronously tuned cascaded linear active two-port networks', *Int. Conv. Rec. I.R.E.*, Part 2, pp. 49–60, 1962.
7. S. Venkateswaran, 'Stability and power gain of linear two-port active networks', *The Radio and Electronic Engineer*, **23**, p. 276, March 1963.
8. A. W. Lo and R. O. Endres, 'Transistor Electronics' (Prentice Hall, Englewood Cliffs, N.J., 1955).
9. W. W. Gartner, 'Transistors—Theory, Design and Applications'. (Van Nostrand, London, 1961.)
10. S. Venkateswaran and A. R. Boothroyd, 'Power gain and bandwidth of tuned transistor amplifier stages', *Proc. I.E.E.*, **106B**, Suppl. 15, pp. 518–529, January 1960.
11. M. A. Karp, 'Power gain and stability', *Trans. I.R.E. on Circuit Theory*, CT-4, pp. 339–340, December 1957 (Letters).
12. A. R. Boothroyd, 'The transistor as an active two-port network', *Scientia Electrica*, 7, No. 1, pp. 3–15, March 1961.
13. A. Singhakowinta, R. King and J. M. Rollett, 'Invariant stability parameters', *Proc. I.E.E.E.*, **51**, pp. 398–399, February 1963 (Letters).
14. C. C. Cheng, 'Simplified design procedures for tuned transistor amplifiers', *R.C.A. Review*, **16**, p. 339, Sept. 1955.
15. J. G. Linvill and J. F. Gibbons, 'Transistors and Active Circuits'. (McGraw Hill, New York, 1961.)
16. L. P. Hunter *et al.*, 'Handbook of Semiconductor Electronics', Section 12-26. (McGraw-Hill, New York, 1956.)
17. L. G. Cripps, 'Cascaded Amplifiers with Uniform Stability Factors', Mullard Research Laboratories Report 313, 1959.
18. M. Lim, 'Power gain and stability of multi-stage narrow band amplifiers employing non-unilateral electron devices', *Trans. I.R.E. on Circuit Theory*, CT-7, p. 158, June 1960.
19. B. P. Lathi, 'Optimal Design on Multistage Tuned Transistor Amplifiers considering Gain, Stability and Sensitivity', System Technical Laboratories, Stanford University, Technical Report 755-3, July 1960.
20. M. S. Ghausi, 'Principles and Design of Linear Active Circuits'. (McGraw-Hill, New York, 1965.)

8. Appendix

For $s \geqslant 10$,

$$s \simeq 2\eta \simeq \frac{4\,{}^{d}\rho_1\,{}^{d}\rho_2}{{}^{d}\lambda} \qquad \ldots\ldots(69)$$

Consider the z- or y-environment. According to eqns. (17) and (22)

$$b_{\mathrm{eq}} = \frac{\omega_0}{Q_{p1}+Q_{p2}} \qquad \ldots\ldots(70)$$

Now

$$Q_{p1} = \frac{\omega_0\,{}^{d}\Gamma_{p1}}{{}^{d}\rho_{p1}} \simeq \frac{\omega_0\,{}^{d}\Gamma_{p1}}{2\,{}^{d}\rho_1} \quad \text{for } s \geqslant 10 \ldots\ldots(71)$$

Similarly for Q_{p2}. Hence

$$b_{\mathrm{eq}} \simeq \frac{2\,{}^{d}\rho_1\,{}^{d}\rho_2}{{}^{d}\Gamma_{p1}\,{}^{d}\rho_2 + {}^{d}\Gamma_{p2}\,{}^{d}\rho_1} \qquad \ldots\ldots(72)$$

According to eqn. (69), ${}^{d}\rho_1{}^{d}\rho_2$ is a constant for a given s value. Therefore eqn. (72) can be differentiated with respect to ${}^{d}\rho_1$ (or ${}^{d}\rho_2$) for maximum. This gives the maximum equivalent bandwidth of eqn. (23).

For h- or g-environment, according to eqns. (19) and (22),

$$b_{\mathrm{eq}} = \frac{\omega_0}{|Q_{p1}-Q_{p2}|} \qquad \ldots\ldots(73)$$

provided

$$Q_{p1}/Q_{p2} \gg 1 \text{ or } \ll 1 \qquad \ldots\ldots(74)$$

Here

$$b_{\mathrm{eq}} \simeq \frac{2\,{}^{d}\rho_1\,{}^{d}\rho_2}{|{}^{d}\Gamma_{p1}\,{}^{d}\rho_2 - {}^{d}\Gamma_{p2}\,{}^{d}\rho_1|} \qquad \ldots\ldots(75)$$

There is no mathematical maximum for b_{eq} here, but it has an upper limiting value reported in eqn. (27) or (28) according to whether $Q_{p1}/Q_{p2} \ll 1$ or $\gg 1$ respectively.

Manuscript first received by the Institution on 17th December 1965 and in final form on 14th October 1966. (Paper No. 1093.)

U.D.C. 621.396.962.38

SECAR—A Modern Secondary Surveillance Radar Ground Interrogator and Decoding Equipment

By

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Presented at a meeting of the Radar and Navigational Aids Group in London on 6th October 1965.

Summary: It is shown that there was a need to develop an equipment with special characteristics to meet the requirements of the current admixture of sidelobe suppression standards. Various configurations of interrogator are discussed and that adopted in the SECAR design is described in detail. The concept of 'system beamwidth' is introduced and discussed in relation to aerial design. Some of the design problems of the decoder are discussed and the application of the chosen technique is described.

1. Introduction

This paper deals in detail with the design of the ground element of a Secondary Surveillance Radar (S.S.R.) system. Secondary radar has its origins in the I.F.F. system developed during World War II.[1,2] It has finally emerged as an advanced and generally well-specified system.

Secondary radar differs fundamentally from primary radar in that it requires the co-operation (albeit automatic) of equipment carried by the target. The target is usually an aircraft, and in the following this will be assumed. The total system is made up of:

(*a*) Ground station transmitter/receiver (interrogator/responser).

(*b*) Ground station aerial system producing a narrow azimuth beam, rotating in azimuth.

(*c*) Target-carried transmitter/receiver (transponder).

(*d*) Omni-directional aerial mounted on the target.

(*e*) Means of extracting and displaying information at the ground station.

Briefly the system operates as follows: The interrogator transmits groups of position-coded pulses via the narrow beam aerial. The spacing between pulses of a group defines the 'mode of interrogation'. As the beam sweeps across and 'interrogates' a target, the pulses are detected by the transponder receiver and certain threshold and timing criteria are applied. When these criteria are met, the transponder 'replies' by transmitting a train of position-coded pulses via the omni-directional aerial. These are received by the ground station (responser). Again, threshold and timing criteria are applied and the signals meeting these are passed to de-coding circuits which extract the information contained in the position-coding of the replies. An all-important feature of the system is that the ground to air path operates at a different radio frequency from that of the air to ground path. Most of the implications of the system design have been described and discussed elsewhere.[3,4]

To keep the S.S.R. system in perspective, from an operational point of view, it is instructive to consider S.S.R. as an automatic ground-air communication system which uses the radar principle to obtain target positional information.[4] Considered in this way it is easy to see why S.S.R. is fast gaining acceptance as a powerful tool in air traffic control: indeed some major A.T.C. agencies have declared that S.S.R. is to be the prime source of radar derived information in the very near future. The carriage of transponders in aircraft is already mandatory in certain regions of British air-space and plans are being made for these regions to be extended.

2. System Specification

Secondary radar has had, and is still suffering from a very strange evolutionary history. Largely because it needs co-operative airborne elements, the specification of its performance has taken a very long time and has been subject to political considerations at many international meetings. However, it is now possible to write the modern requirements of the civil system fairly briefly as follows:[5]

(*a*) Ground to air transmission frequency: 1030 MHz

(*b*) Air to ground transmission frequency: 1090 MHz

(*c*) Maximum permitted p.r.f.: 450 interrogations per second.

(*d*) Ground transmission: interrogations consisting of pairs of pulses, the spacing descriptive of the mode of interrogation as follows:

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† The Marconi Company Ltd., Air Traffic Control Group, Radar Division, Great Baddow, Chelmsford, Essex.

Mode	*Spacing*	*Function*
A	8 μs	identity (civil/military)
B	17 μs	identity (civil)
C	21 μs	altitude
D	25 μs	unassigned

(*Note:* Mode A has the same spacing as military mode 3 and is called the 'common mode'. It gives the possibility of civil and military co-operation.)

(*e*) *Transponder replies:* The aircraft reply consists of a pair of pulses spaced 20·3 μs apart (called framing or bracket pulses). Twelve pulse positions, each with a designated order of significance, are spaced between the framing pulses and space is left for a 13th pulse. Any or all of these 12 may be present in replies, giving 4096 different combinations or codes for each of the four different modes of interrogation. A special pulse placed 4·35 μs after the second framing pulse can be added to the reply by aircrew action.

(*f*) *Interrogator and reply pulse length:* 0·8 μs and 0·45 μs respectively.

(*g*) *Maximum permitted e.r.p.:* 52·5 dBW (aim is 200 nautical miles range).

(*h*) *Aerial beamwidth:* Horizontal (to −3 dB points) not more than 2·5°.† Vertical (to −3 dB points) not more than 45°.

(*j*) *Interrogation side-lobe suppression* (*i.s.l.s.*): When i.s.l.s. is used mode A must be a three-pulse system. All other modes may be either a two- or three-pulse system. The requirements of the signals in space are illustrated in Fig. 1.

The foregoing points are those which are either specified or recommended by I.C.A.O. To these we may add the following requirements in the broader context of the role of S.S.R. in air traffic control.

(*k*) Synchronization in time and azimuth with an existing associated primary radar.

(*l*) The ability to combine different modes in sequence.

(*m*) The ability to allow the information gathered to be used by radar operators in an easy manner.

Using these stated requirements, the designer is faced first with the choice of a philosophy of design before he can think of the equipment. The first choice to be made is—does one make a two-pulse s.l.s. system, a three-pulse s.l.s. system, or one capable of both?—this is a controversy that will not be resolved for some time yet.

To design a 'two-pulse-only' system is technically easier but precludes the use of mode A. To design a 'three-pulse-only' system is more attractive but difficulty is experienced when certain special military modes are required. Also the three-pulse system is fundamentally subject to serious operational disadvantages not appearing in the two-pulse system. One is almost forced, then, into the task of designing an equipment with either two- or three-pulse capability, with some reservations regarding the performance in military modes other than mode A. The user then has a choice of either two-pulse or three-pulse operation. There is, however, still the limitation that, if mode A is to be used, the other modes must also be three-pulse, unless one final solution is adopted.

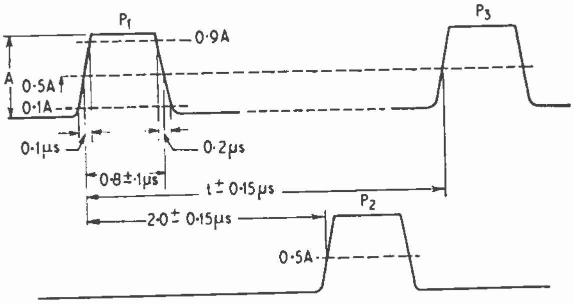

Fig. 1. I.C.A.O. Specification for S.S.R. output pulse position and spacing.

This ultimate solution is to design the system such that when mode A is required the interrogation is three-pulse, but for any other mode a choice can be made between two- or three-pulse systems. It is this latter solution which has been adopted in the SECAR equipment. As it represents the most elaborate performance, meeting all requirements of two- and three-pulse systems, it is obvious for commercial reasons that the fundamental design should permit the choice of either system by reducing the scale of the full equipment. This philosophy has been embraced in the SECAR design. It has led to a number of features not found in equipments operating solely on the two- or three-pulse system. An obvious penalty paid by the adoption of any universal system is the high cost of development and this has certainly been true of the equipment to be described here.

3. The Equipment

The complete ground system which has been produced consists of the following major elements:

1. Interrogator/responser.
2. Integrated control and interrogate aerial.
3. Turning gear, servo system, and mountings allowing the S.S.R. aerial to be co-mounted on primary radar aerials, or separately mounted and slaved in azimuth to the primary radar aerial.

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† The current I.C.A.O. specification no longer includes this parameter. It is replaced by a recommendation that the reply width on the display shall be not more than 3°.

(4) Special remote-control elements.
(5) A digital defruiter.
(6) A multi-channel code extractor.
(7) Active and passive decoding elements.
(8) Special test equipment for both interrogator and decoding complex.

4. Design Considerations

The design difficulties can be appreciated by reference to Fig. 1 which shows the stringent specification of output pulse position and spacing.

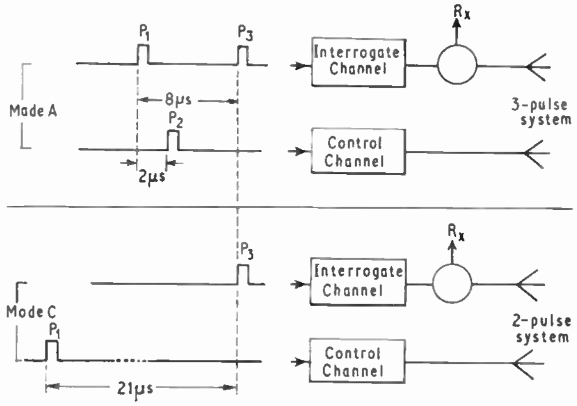

Fig. 2. Basic pulse routing.

The frequencies of P_1, P_2 and P_3 are 1030 MHz ± 0·2 MHz and their frequency differences not greater than 0·2 MHz. Figure 2 represents basically the output pulse routes for the two systems (two- and three-pulse) for any S.S.R. with i.s.l.s. Mode A and mode C have been taken as examples for three- and two-pulse systems respectively.

It should be noted that P_3 is always at a fixed time relative to the radar system for all modes.

The real object of the interrogator is to provide sufficient effective radiated power (e.r.p.), up to the I.C.A.O. maximum, with the correct relationships specified by the s.l.s. system requirements. This e.r.p. is a product of effective aerial gain and the power at the aerial terminals. We thus see that the power output requirements from the interrogator are direct functions of the aerial gain and until the aerial design is fixed the interrogator transmitter chain cannot be specified. This is more true of the 'control' channel than the 'interrogate' because other factors determine, to the first order, the interrogate aerial gain, e.g. an azimuth beamwidth of 2·25° implies a horizontal aperture of some 25 to 30 ft and hence gains of the order 21 to 25 dB.

Consider the simplest interpretation of the s.l.s. requirements, in terms of signal strength at the transponders. Limits (*a*) and (*b*) are imposed by threshold tolerances in the transponder, thus:

	(*a*) *Transponder must suppress*	(*b*) *Transponder must reply*
Two-pulse case	$P_1 \geqslant P_3 + 10$ dB	$P_3 \geqslant P_1 - 1$ dB
Three-pulse case	$P_2 \geqslant$ (P_1 and P_3)	(P_1 and P_3) $\geqslant P_2 + 9$ dB

These conditions could be met if, in either case, the e.r.p. of the control channel was omni-directional *and at a certain minimum level.* It can immediately be said that for this condition both two- and three-pulse systems suffer serious limitations.

(i) In the two-pulse case the absolute range of the interrogator will be limited by the weaker e.r.p. of P_1 (the control channel). P_1 and P_3 must *both* be present at the transponder to elicit a reply.

(ii) In the three-pulse case the resultant azimuth beamwidth is much greater than it need be.

The last point introduces an all-important concept in the ultimate system design. The i.s.l.s. technique, because of the use of a control pulse acting as a transponder reference, can be regarded as a means of governing the real system beamwidth, i.e. the higher the control pulse signal strength then the less will be the time that given interrogation pulses exceed the required level and the fewer will be the replies from a given transponder.

Consider now a near-ideal solution to the problem of providing correct relative e.r.p.'s for interrogate and control channels in both the two- and three-pulse system. These are illustrated in Fig. 3.

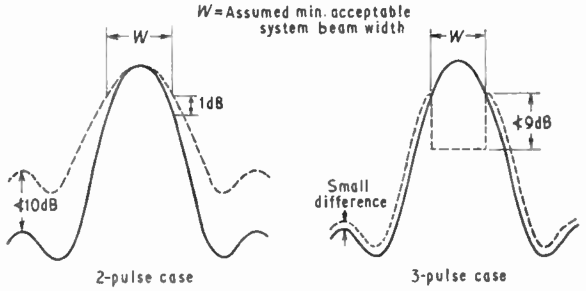

Fig. 3. Near-ideal i.s.l.s. beam shapes. Full line—interrogate, dotted line—control.

The two control patterns are vastly different in shape around the main interrogate beam and require different levels of power in other areas. Neither pattern can be regarded as omni-directional. The

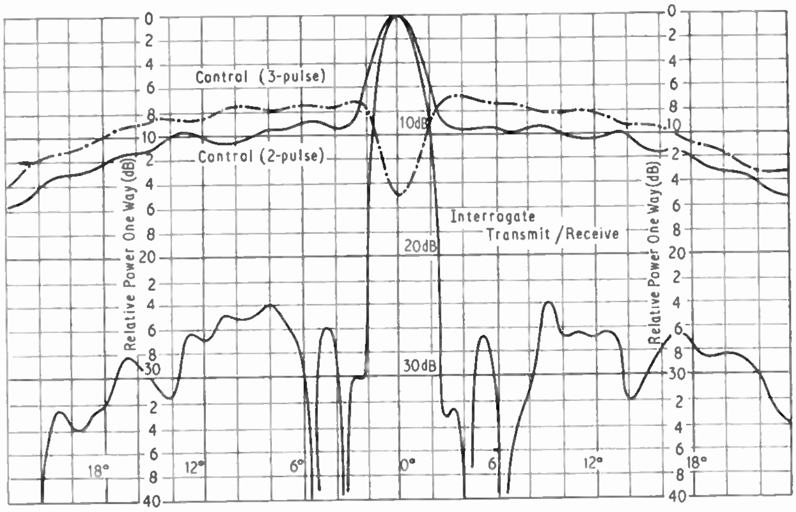

Fig. 4. SECAR horizontal radiation patterns.

general design compromise is to make the control pattern directional to the extent that it is wide enough to encompass the major interrogate sidelobes and their second order neighbours. It can be looked upon then as 'omni-directional' over the important region. This will be called 'broad-beam' in subsequent discussion and curve A of Fig. 9 illustrates the shape. It is seen that this solution implies a great deal of control power in the two-pulse case, where a difference of 10 dB must be maintained in favour of the control channel outside the maximum angle of interrogation. It also appears that, with a single shape of control pattern for both two- and three-pulse systems, no opportunity exists for optimizing the system beamwidth. The only degree of freedom exists in the choice of power level to be used.

It is clear then that a simple approach to the design of control radiation leaves much to be desired, especially in a universal two-/three-pulse system.

The SECAR aerial design has overcome this inelegance by arranging for the gain of a broad-beam control aerial to be modified over the main interrogate beamwidth by some 7 dB. In the two-pulse case, the 7 dB is added gain and in the three-pulse case it is reduced gain. The means by which this is achieved is described in a later section on the aerial design. Reference to Fig. 4 shows how the SECAR aerial has achieved two important things.

(*a*) The virtual increase of control aerial gain on axis has reduced the power output required from the control transmitter to make P_1 and P_3 equal on axis whilst exceeding the two-pulse s.l.s. requirement.

(*b*) The s.l.s. performance on three-pulse is extremely good and a near-ideal shape is achieved.

It is now pertinent to consider the power output required of the interrogator. The interrogate aerial gain is some 23 dB, leaving a balance of 29½ dBW to find from the transmitter, i.e. of the order of 900 watts. This, of course, is a requirement at the aerial terminals and implies a real transmitter output of 900 watts plus any losses *en route* to the aerial.

In the case of a broad-beam control aerial the gain is typically 12 dB and the beamwidth is some 12°. This means that to achieve parity of e.r.p. between P_1 and P_3 in the two-pulse case, an output level of 11 dB above the interrogate transmitter at the control aerial terminals is required. The same system losses are likely to be experienced by both control and interrogate output routes and 3 dB may be allowed for this. The requirements for transmitter outputs are therefore

$$\left.\begin{array}{l}1\cdot8\ \text{kW—for interrogate}\\ 22\tfrac{1}{2}\ \text{kW—for control}\end{array}\right\}\begin{array}{l}\text{for } 52\tfrac{1}{2}\ \text{dBW}+3\ \text{dB}\\ \text{system losses}\end{array}$$

The values for SECAR are less, because of the aerial gain performance. The interrogate aerial gain is 24 dB and the control aerial gain is 19 dB on axis and 12 dB over other regions of highest side-lobes. The resultant power requirements from the transmitters allowing 3 dB system loss are

$$\left.\begin{array}{l}1\cdot5\ \text{kW for interrogate}\\ 5\ \text{kW for control}\end{array}\right\}\begin{array}{l}\text{for } 52\tfrac{1}{2}\ \text{dBW and 3 dB}\\ \text{system loss.}\end{array}$$

Having established the power output requirements, the design of the interrogator transmitter can be considered.

5. The Interrogator/Responser

5.1. *Two- and Three-pulse Transmitter Configurations*

There are a number of different ways in which the transmitters can be designed and some of these basic configurations are illustrated in Fig. 5(a), (b) and (c).

The arrangement of Fig. 5(a) has the advantage of simplicity but the duplication of parts of the power amplifier chain is uneconomic. We have seen that there are cases where the control power output must be as high as 20–25 kW. This can be provided by currently-available tetrode valves but great care is needed in the design of modulators. It may be necessary to employ anode modulation, which is more difficult to achieve than control and screen grid modulation. Fortunately there is no requirement here for duplicating pulses within a short time at this high output level as is required for the lower level interrogate outputs in the three-pulse case.

Travelling-wave tubes can provide suitable output power for the control channel, but there are a number of design problems here among which are the limited modulation speed due to the high input resistance and shunt capacitance of t.w.t.'s. Gain stability is more difficult to achieve and full h.t. modulation is required. It is doubtful whether the rise and fall times required by the I.C.A.O. specification can be maintained in long service.

The scheme of Fig. 5(b) has much to recommend it in that a common transmitter chain up to fairly high level can be used. The high-speed switch is shown at the output end of the chain but obviously it can be put at various points further back. If this were done, some advantage may be lost in that duplication of power amplifiers is necessary after the switch, to maintain power levels. Currently available solid-state high-speed switches are capable of handling powers of up to 5 kW and so, for the 20 kW control power requirement for some interrogators, a single post-switch control amplifier of 6 dB gain would suffice if the switch were put in the indicated position. Here there is the possibility of inefficiency in that a potential interrogate power of 5 kW is available and must be attenuated before reaching the aerial or the final control amplifier must produce more gain, allowing the switch input level to be lowered. For three-pulse operation only, the final control amplifier may be omitted altogether. This arrangement is thus much more flexible in that there is a wider choice from which to select an optimum.

The last example given in Fig. 5(c) is basically that adopted in the SECAR design but it has been combined with the idea of a common transmitter chain shown in Fig. 5(b). One sees here a challenging requirement for high-speed power switching and synchronous switching of aerial radiation patterns, both at relatively high power levels. The advantages gained, albeit at the cost of formidable design problems, are that the system is extremely economical of transmitter power, it is able to provide either two-pulse only, three-pulse only, or two- and three-pulse interrogations, so that not only can modes of interrogation be interlaced at p.r.f. rate, but also the type of s.l.s. system can be interlaced.

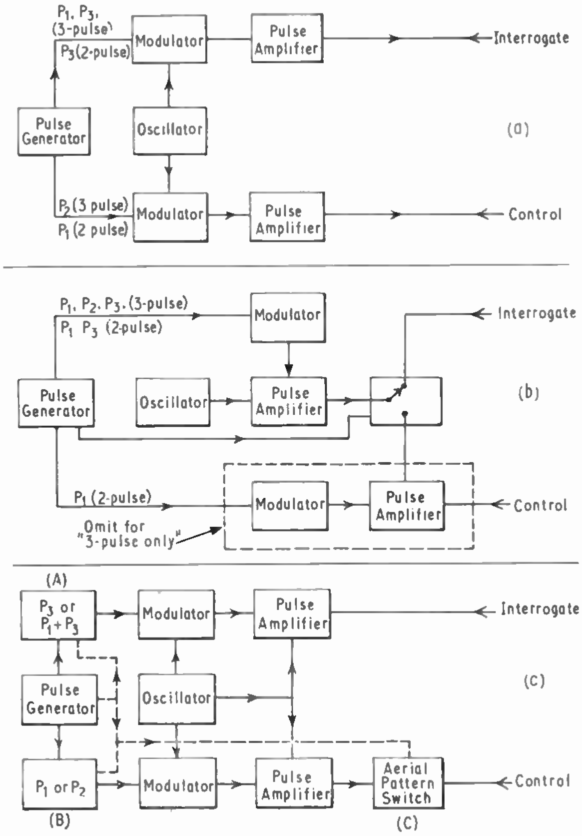

Fig. 5. Interrogator configurations. Note that (*a*) becomes 'two pulse-only', by substituting P_1 for P_2.

(*a*) Two- or three-pulse only.

(*b*) Two- or three-pulse only.

(*c*) Universal two- and three-pulse system. Switches A, B and C are synchronous.

The output power requirements are 2 kW and 5 kW respectively for interrogate and control channels. The chain of amplification and modulation is shown in Fig. 6.

The output frequency of 1030 MHz is generated by solid-state multipliers from a crystal-controlled oscillator operating at 42·91 MHz. A c.w. amplifier provides output at 1030 MHz at a level of 2 W to the first of a chain of pulsed amplifiers. The first two of the chain use disk-seal triodes of the same type as is used for the c.w. amplifier. Each stage has separate low-level modulators for control and interrogate pulses feeding the control grids of the triodes. The resultant output is 800 W peak and is applied as drive to a tetrode valve which uses a separate hard-valve modulator giving both control and screen grid modulation to the amplifier. This final modulator

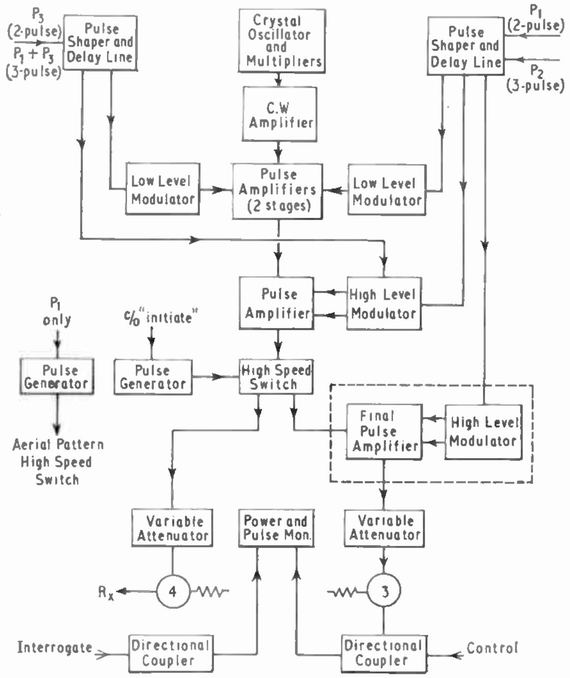

Fig. 6. Block diagram of SECAR interrogator transmitter.

really governs the pulse length of all transmissions (P_1, P_2 and P_3). The r.f. output, at a level of 5 kW maximum, is applied to the high-speed solid-state switch. This is pulsed in synchronism with the interrogate and control pulses in such a way as to divert power into the correct output routes. These are identical except that there is a final pulsed amplifier in the control arm which is identical to that of the stage before the switch. The output capability of this stage is 10 kW maximum. It is regarded as an optional amplifier which can be removed if either a 'three-pulse-only' system is required or the 52½ dBW e.r.p. is not required.

5.2. *Modulation*

The technical and economic problems associated with the requirement to produce two sharp pulses (P_1 and P_2) within 2 μs of each other have been solved by using separate modulators for (P_1 and P_3) and P_2. Not much space or power penalty is paid because these are low-level modulators using transistors throughout. In the final stages a hard-valve modulator is used with sub-modulators using transistors. The design of the high-power modulators requires e.h.t.'s of 6 kV and provides outputs of 1 and 4 kV pulses for control and screen grid modulation. The results of this technique can be seen from Fig. 7 which shows pulse spacings far shorter than are used for civil modes. This is a photograph of the outputs after the high-speed switch.

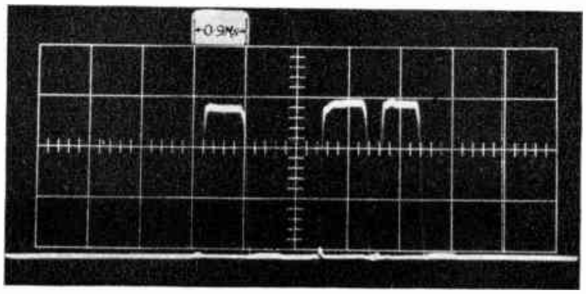

Fig. 7. Illustrating the pulse edge speeds and high speed switching performance.

5.3. *High-speed Switch*

This is virtually a T-section of line which has short circuits applied, at points close to the T-junction, by diodes in each of the branch arms. The switching speed achieved is fast enough not to modify the pulse durations or shapes. The unit is quite small, being only 6×4×2 in (15×10×5 cm) complete with diode drive circuits. A separate pulse generator is used to provide trigger pulses to the diode drive circuits at a suitable time relative to the P_1, P_2 and P_3 pulses. The change-over time is 100 ns and units have proved to be reliable in service.

5.4. *Output Arms*

Each channel is virtually identical, containing a power divider, used as an attenuator, for adjusting the two outputs to the correct relative values. The interrogate arm reaches the aerial via a four-port ferrite circulator and a directional coupler. The control channel uses a three-port ferrite circulator, since it has no receiver arm. The directional couplers allow the outputs to reach monitoring circuits after 20 dB attenuation to enable pulse shapes to be examined and peak power to be measured on a meter. The complete assembly is illustrated in Fig. 8. The right-hand section of three vertical sliding racks houses the control and interrogate transmitter. The centre section is given over to power supplies and distribution. The left-hand section houses the mode encoding circuits and part of the receiver. The top drawer accommodates the r.f. output power distribution and monitoring circuits together with the r.f. head of the receiver.

5.5. *Mode Generation*

The pulses for modulating the interrogator are generated within the interrogator cabinet. The principle of using a tapped delay line for governing the spacing of P_1 and P_3 is used here as in most designs. However, to achieve better stability and closer tolerances of pulse spacing and duration, a digital delay line technique is used rather than lumped constant delay lines which are subject to larger production manufacture tolerance variations and are liable to give pulse shape changes.

The input to the digital line is derived from a synchronizing pulse whose origin usually must be at the same p.r.f. as an associated primary radar. The I.C.A.O. specification limits the number of interrogations to 450 per second. Thus sync. pulses from a primary radar of, say, 500 p/s, must not be allowed to generate interrogations at every input. The common technique for reducing the primary radar sync. pulse effective p.r.f. to below 450 p/s is to use a straight pulse divider, thus 500 p/s becomes 250 p/s. This reduces the potential interrogation rate by 200 p/s less than permitted, i.e. nearly half the information rate is lost.

The SECAR system has a p.r.f. limiter circuit which overcomes this limitation and permits the maximum interrogation rate to be used. The circuit is so arranged that the output consists of selected primary radar sync. pulses, still with their own time separation. Some of the sync. pulses are inhibited but only when necessary. Taking the example above of a 500 p/s primary sync. input, only 50 p/s will be lost by use of this technique. Because there is no synchronism between the aerial rotation and p.r.f. the 'lost' interrogations never occur at the same azimuth but will continually precess.

The selected sync. pulses are then used as drive to the digital delay line and each input to the line generates a train of pulses which will define all the necessary mode spacing between P_1 and P_3. P_1 is routed to a 2 µs delay circuit which automatically produces P_2 for any mode when required.

5.6. *Mode Interlacing*

The requirements for eventual use of a number of modes in sequence, changing regularly at each p.r.f., makes it essential to provide means of changing a mode interlace program very easily. It is even more important to provide this in the present situation where the use of modes and codes is largely an unknown factor. The usual technique is to set up a

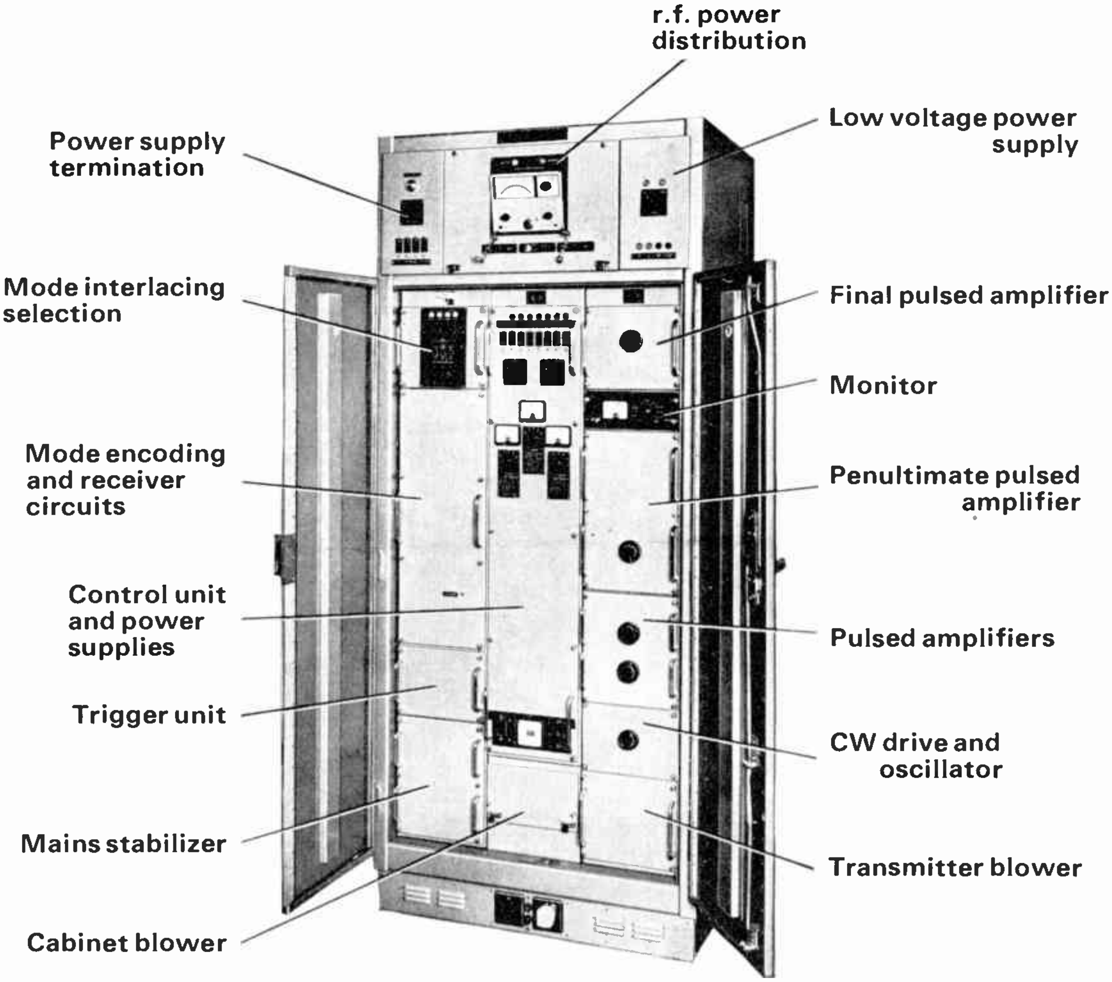

Fig. 8. The SECAR interrogator/responser.

mode interlace program by pre-selecting a series of gates which are opened in sequence and if a change to the program is required then the selection must be altered. This is not much of a limitation when the program is to be kept for long periods of time but a difficulty is encountered when it is realized that not only can interlace be carried out from pulse to pulse but more extensive use of the available modes can be obtained by alternating between two mode patterns at successive aerial revolutions. For instance, a mode pattern A B C A B C precludes use of mode D, since more than three modes in one pattern is usually prohibited for reasons described later.

If we now arrange for the A B C pattern to change after one aerial revolution we can obtain, say, A D C A D C A D C . . . By reverting after another aerial revolution to A B C, we have use of all the civil modes, albeit at half the available data rate for two of the modes. It should also be realized that there are other modes which can, with advantage, be used in an operational environment dealing with both civil and military aircraft, thus the facility for changing or selecting any mode interlace pattern is operationally worthwhile.

The desired flexibility has been provided in SECAR by an arrangement of up to six gates and two shift registers used as gate drives. One shift register changes state at p.r.f. rate and the other at aerial rotation rate. The shift registers can be selected to give either two-phase or three-phase outputs and, by pre-selecting any of the six gates and driving them with the registers, it has been possible to make any combination of modes for any interlace pattern inclusive of change of pattern with aerial rotation. The advantage of this is that the pattern can be changed by remote control and this is often a highly desirable feature.

The pulses forming the interlaced mode pattern are fed at low impedance to the transmitter modulators and are also used in the decoding equipment to act as a 'label' for replies received from each interrogation. This permits replies to be routed into the correct mode channel in the decoder and thus even if something goes wrong with the mode program, the replies will still have their correct mode label.

5.7. *Responser*

The first decision to be made by the designer is whether an r.f. amplifier is to be used or not. The S.S.R. system is fundamentally able to provide good signal strength at the ground station from aircraft even at long range. The decision whether or not to use an r.f. amplifier is governed by

(*a*) the loss from aerial to receiver,

(*b*) the noise figure of a suitable mixer,

(*c*) the noise figure of the i.f. amplifier.

A common specification for receiver sensitivity is -90 dB(mW) for a 2 to 1 signal + noise to noise ratio. An r.f. amplifier has been avoided in SECAR by the use of low-loss r.f. cable to the aerial and a balanced mixer of good noise performance. The pass-band of the receiver, from input to video output, has been formed by a four-cavity filter of very high quality and extreme temperature stability. It has been followed by a head amplifier closely associated with the balanced mixer which embodies a 3 dB coupler. The i.f. amplifier is essentially very broad band, wide enough in fact not to influence the effect of the tuned cavities, except at the skirts of the pass-band. It is of a rather special design providing not only a 'linear-log' type of input/output characteristic but it also prevents pulse stretching which can occur in amplifiers using successive diode detection techniques. A novel form of instantaneous a.g.c. has been incorporated to effect this which acts in a time comparable with a reply pulse rise-time. Negative feedback has been applied to the transistor detector and video amplifier. The receiver has thus preserved the pulse shapes and restricted their dynamic range of amplitudes, providing good quality input to the decoding complex.

6. System Beamwidth

The concept of system beamwidth will now be examined in greater detail. If we accept that

(*a*) an a.t.c. service can best use S.S.R. by interlacing three modes on an equal basis,

(*b*) the greater the number of repetitions of a given reply, the greater is the certainty of the decoding accuracy,[6]

we see that the parameter sacrificed is azimuth resolution. This must be preserved at a reasonable level. Let us take this to be such as will allow separation of two targets at 200 nautical miles range on one 10 n. mile wide airway. It is desirable that the system beamwidth be not greater than 2·0°.

We have seen earlier that the airborne transponders have indeterminate triggering levels. The tolerance area is called the 'grey region', and it is 9 dB wide. We have also seen that the system beamwidth limits resulting from this are, to a degree, adjustable by varying the relation between the control and interrogation e.r.p.'s. For a given aerial design this resolves into a variation of control and interrogate power outputs. Let us examine the system beamwidth variations implied by the grey region for different aerial patterns and power levels. Consider the situation shown in Fig. 9.

An interrogate aerial of 23 dB gain and a control pattern 12° wide at -3 dB has been assumed. The

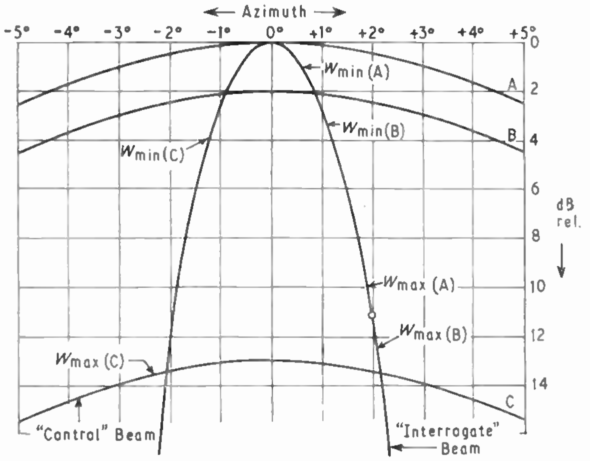

Fig. 9. Showing system beamwidth limits for broad beam control pattern.

e.r.p.'s have been equalized at 0° azimuth assuming 1 kW and 20 kW interrogate and control power. These are realistic figures for a two-pulse s.l.s. system. We see that the grey region implies two azimuth values, $W_{\min}$ and $W_{\max}$. In the practical case for two-pulse radar these are 1·2° and 3·8° (control curve A). Reduction of the control power by 2 dB (and hence range by 20%) changes these values to 2·2° and 4·2° (control curve B).

If the same control pattern is used for three-pulse s.l.s. the logical step is to use the same output level for both control and interrogate transmissions. This effectively lowers the control curve by 13 dB (control curve C) relative to the peak of the interrogate pattern. The three-pulse s.l.s. criteria now produce beamwidth limits for the grey region of 2·4° to 4·2°.

We see that the beamwidth limits are in the ratio ($W_{\max}/W_{\min}$) of about 3 to 1 and 2 to 1 for both of the two-pulse conditions and less in the three-pulse case. It should be borne in mind that, for the three-pulse case, the transponder must be at a range such that P_2 can be received at sufficient strength for it to have an effect upon the 'guaranteed' minimum system beamwidth. It is not unusual to find that the vertical radiation pattern produces P_1 and P_3 e.r.p.'s sufficient to cause replies to be made at ranges in excess of 400 n. miles. At the elevation angles of these lobes, P_2 will be usable in the transponder at ranges up to 100 n. miles and so the idea of system beamwidth in this case is valid. The idea is entirely valid in the two-pulse case since P_1 and P_3 must both be present to form an interrogation. Consider now the SECAR type of pattern arrangements. Reference to Fig. 4 shows that

the two-pulse beamwidth limits are 2·1° to 4·5°;
the three-pulse limits are 2·1° to 3·5°.

This is when the two systems are operated in the universal system. If the three-pulse system only is required, the 'notch' of the control pattern can be deepened to give beamwidth limits which are closer together. The effect is brought about by the faster rate of divergence between control and interrogate e.r.p.'s.

We can see from this a number of significant points.

(*a*) In the two-pulse case the broad-beam control pattern produces a narrower maximum beamwidth than does the 'directional' control pattern. The advantage lies with the broad beam pattern here, but at the expense of much higher transmitter power.

(*b*) The broad-beam control pattern produces a a minimum two-pulse beamwidth limit which yields 9 interrogations per beamwidth at 10 rev/min and the maximum permitted interrogation rate of 450 per second. If the interrogation rate is reduced the number of replies per mode per beamwidth for a triple mode interlace is less than the necessary bare minimum of 3 (one for defruiting which is lost and two for code correlation). The advantage lies with the 'directional' pattern here, especially if the 450 interrogations/second can be maintained as in SECAR.

(*c*) For two-pulse working, the broad beam control pattern produces very wide beamwidth limits when the maximum range is required. The minimum beamwidth is likely to be too small for triple mode interlace. The maximum beamwidth is wide enough to permit three-mode interlace, thus the system operational efficiency is lowered because of the necessity to cater for the minimum case.

(*d*) In the 'directional' control pattern case, the three-pulse system is a better match to the operational requirement for three-mode interlace, especially when linked with the use of maximum interrogation rate.

(*e*) The universal system (SECAR) has to accept wider system beamwidth limits than can be achieved in an optimized three-pulse system on account of the need to cater for two-pulse working.

7. The Aerial System

We have seen earlier that the aerial performance has profound impact on the design of the interrogator. This is true of other unrelated system problems, for instance:

(*a*) The system beamwidth, i.e. the number of replies on a given mode from a given transponder, is determined by the relation between the control and interrogate e.r.p.'s.

(*b*) The side-lobe performance at the receive frequency of 1090 MHz largely determines the degree to which the system suffers from receipt of asynchronous replies (fruit) for a given interrogator and traffic density.

(*c*) The structure and position of the vertical radiation pattern for both control and interrogate aerials determine the variation in s.l.s. performance to be achieved over the whole elevation range.[7]

(*d*) The back radiation has to be considered when the degree of swept gain used in the receiver is determined.

(*e*) The almost unavoidable lobe and gap structure of the vertical radiation pattern is determined by the ground directed radiation. This has considerable effect on the range of reliable gap-free radar cover.[8]

There are drawbacks in using either a true omni-directional control aerial or a pattern that can be considered as omni-directional over the important azimuths (the broad-beam pattern). Of the two, the second is to be preferred because a true omni-directional pattern produces either a different mean aerial height of interrogate and control radiators, or a different immediate local position; for the true omni-directional aerial need not rotate, and a simple design approach is to mount the omni-directional aerial alongside the interrogate aerial. Thus, reflections, obstructions, etc., are not the same for control and interrogate. The net result is that the true radiation patterns in both horizontal and vertical planes are subject to different variations and the proper relation between e.r.p.'s is disturbed, thus creating uneven s.l.s. performance.[9]

The use of a broad-beam control aerial permits the radiators for both interrogate and control aerials to assume almost an identical mean height and matching e.r.p.'s over the whole elevation range is automatically assured. We are still left, however, with the problem of optimizing the system azimuth beamwidth.

We have seen that the SECAR design has overcome both of the fundamental drawbacks since the interrogate and control radiators are in one assembly and it has also allowed a closer approach to the optimum system beamwidth.

How has this been achieved? Its mechanism is capable of fairly simple explanation.

The radiating assembly consists of a row of 38 boxes, each with its own unipole exciter fed in correct phase and amplitude to produce the narrow beam for the interrogate pattern. The centre two boxes are given over to forming the basic broad-beam control azimuth pattern. This is general practice for integrated S.S.R. aerials, except that sometimes the control radiators are separate and mounted just above the interrogate array. The special feature of the SECAR design lies in the following: arrangements are made, through a high-speed switched phase shifter network, to couple (during the control transmission) a small amount of power into the interrogate array. This produces a narrow beam 'modulation' on top of the broad control-beam and the enhancement of gain is related to the degree of coupling to the interrogate radiators. This gives the near-ideal pattern for the two-pulse case and we can see from Fig. 4 that the degree of saving of control power is directly related to the gain lift on the beam axis.

The switched phase-shifter can be considered as a four-position switch of which only three positions are used. Position 1 couples all the radiating boxes in phase to produce the narrow beam required for interrogation in both two- and three-pulse systems. Position 2 produces the coupling and phase required for the two-pulse control pattern. Position 3 puts a 180° phase shift into the cross-coupling for generation of the three-pulse control pattern.

By reversing the sense of the coupling of control power into the interrogate radiators the increase in gain of the control aerial is turned into a decrease. The high-speed switching required is achieved by using the same type of solid-state diode switches as for power switching in the interrogator. It will be appreciated that for any three-pulse s.l.s. transmission the pattern switching must be executed in fractions of a microsecond. It is by use of this technique that any mode in any interlace pattern can be to either two- or three-pulse standards, for instance

A B C A B C . . . can be

A_3 B_2 C_2, A_3 B_2 C_2—where the subscripts represent the type of s.l.s. used.

The type of s.l.s. for any mode is pre-selected by plug and socket connection within the circuits generating the mode interlace pattern.

8. The Aerial Mechanical Drive and Servo System

The basic design problem is not a difficult one, for most S.S.R. aerials are relatively light weight and the azimuth alignment error permitted between primary and secondary radar aerials is of the order of $\frac{1}{4}$°. The windage effects on typical primary radar aerials produce some 7% to 10% peak velocity modulations on a mean still air speed. Wind on the S.S.R. aerial mounted near the primary radar aerial may produce effects which are out of phase with those on the primary radar aerial. The designer of the S.S.R. turning gear must assume therefore that these effects can be in anti-phase.

The design choice is limited, first by the justified reluctance to embrace hydraulic techniques, to an

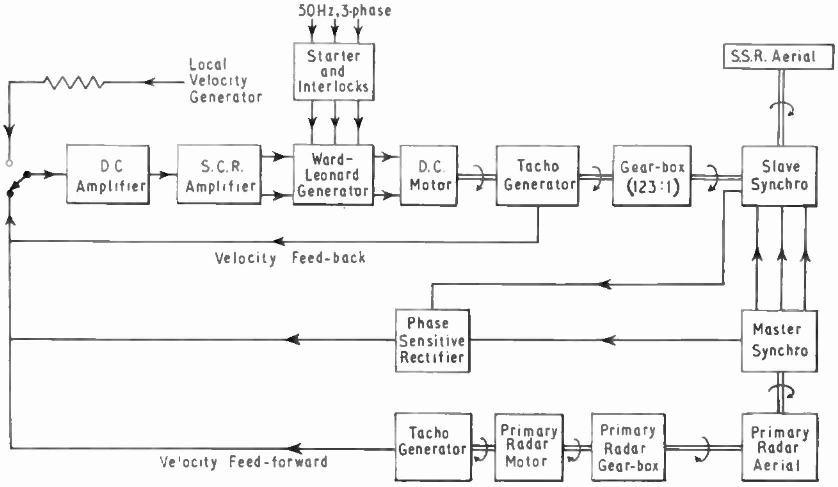

Fig. 10. SECAR aerial drive and servo system.

electrical system. The next choice is whether to use a silicon controlled-rectifier technique or to go to rotating magnetic amplifiers. The former leads to a compact design but is more expensive, at the power levels required, than the latter choice.

The final design must produce alignment errors of the order of ±¼° for a range of turning speeds from 5 to 15 rev/min since this is the usual turning speed range for terminal area and long range primary radars. Wind speeds of up to 90 knots must be catered for under operational conditions.

A natural choice is to go to a Ward-Leonard type of control system wherein a d.c. motor, driving the aerial shaft via a gearbox, derives its field current from a generating set. This was adopted in the first SECAR design. Figure 10 is a block diagram of the basic drive and servo system. The following points are of interest.

The gear box ratio is 123 : 1 requiring a motor speed of up to 2200 rev/min producing a peak torque of some 30 lb ft to permit servo action at 15 rev/min. The motor is able to deliver 5 h.p. to the gearbox. The generator delivers a peak of 200 V d.c. to the motor. Feedback from the generator to its input amplifier permits the effective gain of the rotating amplifier to be stabilized at a level allowing a 10 mV servo input signal to produce a static positional error of 1 minute of arc. This is not the true dynamic error, of course, since the synchro elements themselves produce errors of about ±5 minutes of arc. The quality of these synchros largely determines the positional error.

Velocity feedback is used to reduce modulation of turning speed of the S.S.R. aerial. The original design used fixed d.c. values to compensate for different fixed rotational speeds but the performance has been greatly improved by the addition of velocity feed-forward derived from a tachometer generator mechanically geared to the primary radar aerial shaft. This allows short-term speed modulation of the master aerial to be accounted for. An acceleration limiter circuit is included and full torque is produced for a 10 mV servo input signal. The acceleration performance is 0·9 rad/s and the system sensitivity is 0·5 V per degree. Thus the follow accuracy over the wide turning speed range is extremely good, full torque being developed when the error exceeds 12 minutes of arc. A recent s.c.r. servo and drive system for SECAR has produced performance to the same standard.

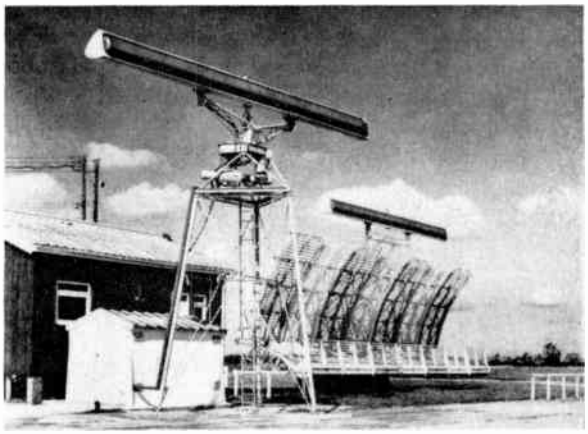

Fig. 11. The SECAR aerial assembly. In the background the SECAR radiator can be seen mounted on top of a primary radar aerial.

The aerial assembly showing the drive motor and gear box is illustrated in Fig. 11.

9. The Decoding System

It can be argued that S.S.R. embodies the radar principle solely to obtain accurate positional information on aircraft. S.S.R. itself can be regarded as a communication system with limited message capacity in one direction. If it were not for the need to gain positional information, the radar technique could be abandoned. The all-important feature of the system is the means of extracting and presenting the information gained from interrogations. The high discretion of replies implies their careful handling to ensure accuracy of the information and demands advanced information handling techniques.

The problems can be placed in the following groups:

(*a*) Defruiting. All S.S.R. stations use 1030 MHz and 1090 MHz for interrogate and reply functions respectively. A given aircraft may be within reply range of a number of different interrogators at one time. It is thus possible for each interrogator to receive replies from one aircraft in answer to other interrogators. This would lead to ambiguous range indication. To avoid this each interrogator must have its own unique p.r.f. This still leaves the possibility of one interrogator receiving replies to other 'foreign' interrogations. These asynchronous replies are known as 'fruit' and 'defruiting', naturally, the process of removing them. Defruiters can be considered as narrow band filters centred upon the 'home' station p.r.f.

(*b*) Sorting out expected replies on some modes from all other replies (passive decoding).

(*c*) Learning the code of any individual reply on any mode (active decoding).

(*d*) Separating replies to one's own interrogator which occur at times differing by approximately a reply time or less (de-garbling).

(*e*) Presenting all the information to a radar controller in an easily assimilable form.

The solution to this last problem is in a specialized field and will only be touched upon lightly in this paper.

Each of these problem areas can be treated as separate entities and various techniques can be used with varying degrees of success. For example:

Defruiting:

(*a*) Magneto-striction delay line techniques with coincident gating.

(*b*) Continuous amplitude-proportional delay elements such as quartz, mercury, or water delay lines.

(*c*) Storage tube techniques.

(*d*) Digital delay line techniques with discrete storage for small range increments.

Passive Decoding:

(*a*) Real time comparison between received replies and expected replies using a tapped lumped-constant delay line principle.

(*b*) As (*a*) but using digital delay lines.

Active Decoding:

(*a*) Real time detection of the presence of pulses in a reply by matching against a tapped lumped-constant delay line.

(*b*) As for (*a*) but using a digital delay line.

The magneto-striction line technique is simple and clean but the requirements to define fast rising pulses almost preclude the use of these elements unless defruiting is done to a basis of excluding blocks of signals equal in time to a reply, i.e. 24·65 μs (if the s.p.i. is included). This is obviously inefficient.

The mercury or quartz delay line technique is feasible provided the problem of their limited bandwidth is overcome (either by achieving the required bandwidth or designing circuitry which reduces the bandwidth required to a tolerable level of some 3 MHz). The engineering problems (being mechanical, optical and chemical in nature) are severe, and multi-mode operation demands a separate delay channel per mode. For quartz delay lines the solution becomes very expensive. Both mercury and quartz delay elements are virtually fixed in length (or capable of very limited variation), thus they are suitable for only one pulse repetition frequency.

The storage tube technique does not suffer from most of the disadvantages of the techniques above. It has its own limitations, however, such as the problem of read-write registration which degrades performance.

The digital technique has none of those disadvantages and provided the range is broken into small enough increments the effective bandwidth can be such as to reproduce faithfully the pulse trains of the replies.

Comparison of the above list shows that all the problem areas are capable of employing digital techniques in their solutions. This has been the corner stone of the design of the SECAR decoding system developed by the Compagnie Française Thomson Houston.

9.1. *The Defruiter*

The technique here has been one wherein the radar range is broken into equal, discrete, contiguous small increments. A ferrite core memory plane is used to store in real time information pulses returned in answer to a given mode of interrogation, i.e. for triple mode interlace there are three memory planes. When replies are received each is compared in real time with the contents of store locations directly analogous to the time of arrival of the reply from the previous interrogation in the same mode. When coincidence is found between store contents and current video, the signals are allowed to pass into the code extractor. This coincidence can only occur for replies due to the 'home' station's interrogations. Any replies, at necessarily different p.r.f.'s, received in answer to 'foreign 'interrogators are rejected. The discretion of the system is a direct function of the range increments used and these may be chosen from between 3·6 µs and 0·8 µs. Obviously the smaller the increment the more is the storage capacity required. A simple coincidence gating circuit is used which can be by-passed for presentation of raw video when required. If double defruiting is desired the process of storage and coincidence is repeated.

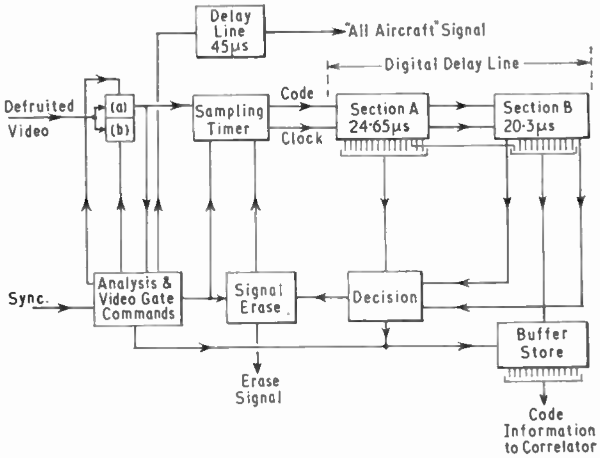

Fig. 12. Single channel code extractor.

9.2. *Code Extraction*

This is virtually a two-stage operation. The first stage rejects all signals of less than 0·3 µs duration and below a certain minimum amplitude. The emergent signals are then introduced into a digital delay line in the form of a shift register by means of a clock pulse generator and a series gate circuit. The system is illustrated in Fig. 12. The input gate circuit is really two complementary gates.

At the start of each new p.r.f. the gate (*a*) is opened. Thus the first pulse to appear is allowed through. The analysis and command gate circuits cause gate (*a*) to be open only for the duration of an information pulse, i.e. not greater than 0·7 µs, which allows for system tolerances and jitter. This process of sampling incoming video for 0·7 µs at 1·45 µs intervals is carried on by the analysis and command gating and establishes replies in section A of the digital delay line. While any information exists in section A of the delay line, there is no output from Section B. As soon as all information is transferred from A to B, and framing pulses have been sensed, an output is sent from Section B to the code correlator circuits. The decision circuit also gets the gate (*a*) ready to receive the next reply.

This mechanism is effective for straightforward reception but the situations where garbling and interleaving of replies have to be handled, present difficulties. The single channel extractor illustrated in Fig. 12 can deal with certain forms of reply ambiguity, e.g. where two replies are separated by an integral number of pulse spaces ($n \times 1{\cdot}45$ µs). In this case the 'erase' circuit will inhibit the information of the first of two 'confused' replies but produce positional information for both replies and the full information for the second reply. There are some conditions of overlapped replies which permit not only full positional information to be gained, but also proper decoding of the information pulses within the main body of the replies. This is accomplished by use of two code extractors. Both share a common video input and virtually a 'two-phase' analysis and command circuit. Arrangements are made such that when gate (*a*) is open for one extractor, the other is closed. Since these are AND gates, the changeover from open to closed will occur either when the gate drive stops or the video signal collapses. By this simple means it is possible to organize two overlapping replies, each in their own digital delay line. In both cases a 45 µs delay line is used, before any code extraction is performed, to furnish outputs for all aircraft responses whether they conform to the I.C.A.O. 20·3 µs standard reply length or not. All replies which do conform produce an output from the digital delay lines when the two bracket or framing pulses spaced 20·3 µs have been detected. This output is called the 'all common system' signal and indicates to the operator that the reply may contain information which can be read out by active decoding processes.

9.3. *Code Correlation*

After extraction of codes it is necessary to check that the information contained in them is worthy of acceptance by the control organization. For passive decoding, correlation can be assumed if the reply emerges from the code filter set up by the operator. In active decoding this assumption is no longer valid and an independent check has to be made. This is the function of the correlator. All signals are fed in parallel form into a ferrite core store. In this case there is one storage plane for each of the possible 15 bits in a reply (2 framing pulses, 13 information bits, only 12 of which are currently used, and special position identity pulse). Each mode is served by its own group of 15 planes. The same system of range quantization is used as in the defruiter so that the principle of 'real time' operation is maintained. Again, as in the defruiter, comparison is made between current video and that in the store. The information read from store is held in a buffer register whilst the comparison is carried out. If correlation is obtained the code is released from the buffer and the new video installed in the store. If there is no correlation, an inhibition signal is sent to the unit feeding information to the operator's positions and modifies the 'validity' indication.

9.4. *Validity*

We can regard the process of passive decoding as having its own inbuilt validity checking, i.e. if the codes do not identically match with the preset filters there will be no output. One can look upon the quality of the p.p.i. response, or a count of replies in a beamwidth, as an expression of reply/decoder accuracy in the passive decoding role. For active decoding this is no longer true, since active decoding presupposed ignorance of the code in use. Thus there is a need here to sense and indicate the accuracy with which the active decoding has been accomplished. This has been done by taking a large number of signals within the decoded system which are expressive of circuit states and combining them in such a way as to indicate to the operator the quality of the decoding for a given actively decoded reply. A scale of 5 is used and is indicated by decimal digits, 5 representing a 'best score'. The number 5 represents:

(*a*) no garbling by interleaving or ambiguous timing,

(*b*) correlation exists.

The number 4 represents:

(*a*) garbling by ambiguous timing,

(*b*) correlation exists.

This scale is continued into conditions of decreasing value but usually an operator would not accept any validity less than 4 and would repeat the decoding process until this level was reached.

9.5. *Display of Information to Operators*

The signals, before going to the operator, go through many processes to determine the real information and its accuracy. For normal p.p.i. working the S.S.R. signals can be conveniently of the same form as those of primary radar. After replies have passed all the necessary criteria, they cause pulses to be generated in the decoder for p.p.i. presentation. When a reply has been successfully decoded the operator can choose to display the target as a single, primary radar-like, response (a 'single bar') or as a 'double bar' or as a 'bloomed' response, which is a filled-in 'double bar'. The operator thus has a variety of display symbols for each aircraft in his battery of passive decoder slots. For active decoding the operator is given an alpha-numeric display of the mode and code of any target which he isolates with a controllable p.p.i. marker. The altitude of the craft is also shown when a reply to mode C interrogations is made. The photograph in Fig. 13 shows this display in operation. The right-hand digits are the 'validity' figures for the two actively decoded replies. The altitude reply has low validity (2) and the operator would repeat decoding of this target to get a more accurate answer.

Fig. 13. Prototype model of operator's S.S.R. decoder control unit. The operator has actively decoded a reply on mode B. The code is 0071 (high accuracy is indicated by validity = 5). The altitude is 5500 ft. (Poor accuracy is indicated by validity = 2. The operator would repeat this decoding until validity = 4 at least.)

It is, of course, possible to arrange for all targets to be automatically decoded by use of computer techniques and for high traffic densities this is most attractive. In this case the p.p.i. would indicate by alpha-numeric characters, in the correct position, the aircraft information (e.g. identity and altitude) and the operator would not need to operate a large number of controls but simply read the written information.

10. The Remote Control System

The S.S.R. system will almost always be closely associated with a primary radar of one kind or another and share either common displays or a display system. Like primary radar, the aerial and interrogator will very often be at a distance from the display equipment and it is necessary to provide means of controlling the transmitter equipment from the remote display and decoder environment. It is usually the case that where S.S.R. is required, a primary radar already exists with remote control facilities of its own and the connection between sites is either by cable or radio link. The system designer is now faced with the problem of providing remote control facilities for the S.S.R. The means at his disposal are the same, i.e. radio link or cable. There is, however, one particular case where a difficulty arises. This is where a primary radar cable link exists but over a route or of such a length that makes it impossible or uneconomic to instal a separate set of cables for the S.S.R.

This remote control problem has been solved in the SECAR design in a manner that permits all three of these circumstances to be met. The nature of the signals to be passed really fall into two groups:

(*a*) Command and indicator signals governing and showing the transmitter equipment state.

(*b*) Radar synchronizing pulses and responser output signals.

When it is economic and possible to instal separate S.S.R. cables, two are used, one coaxial and the other multi-core. The coaxial cable is used to pass radar sync. pulses from the display site to the interrogator and also the responser output signals in the other direction, together with pulses which describe the mode in use for a given interrogation period. All of these pulses have stringent rise-time requirements and the system must introduce very small jitter, since in some arrangements the primary radar trigger must be derived from the S.S.R. trigger system and m.t.i. performance must not be affected. This requirement has been met by use of a 22·5 MHz carrier modulated by the S.S.R. trigger pulse with a compensating amplifier and detector at the far end of the cable. The same technique is applied for transmission of the replies from aerial site to the decoder equipment. Here the carrier is 60 MHz and the two frequencies are separated at either end by suitable filters. The mode recognition pulses are mixed with replies but are given a different amplitude. An amplitude discriminator at the receiving end allows separation of the mode recognition pulses from the transponder replies. All the commands and indications are linked by multi-core cable from site to site.

When an existing coaxial cable must be used, the signals and sync. pulses are introduced to it using the technique described above. The other command and indicator signals are passed as audio tones modulating sub-carriers within the range 7 to 11 MHz. A total of 40 functions has been provided in this way and the system is capable of extension. This technique of passing all the signals over one coaxial cable is suitable for adaptation to radio links and so all conditions of remote control can be met.

11. Conclusion

The solution to the problem of designing a secondary surveillance radar interrogator/responser has been shown to be heavily dependent upon operational requirements. An equipment has been described which is capable of meeting all known civil A.T.C. requirements of an S.S.R. and of meeting other requirements demanding closer mode spacing than 8 μs. It has also been shown that an interrogator design, meeting the requirements of the two-pulse s.l.s. system, need not have the high transmitter power usually assumed necessary for control purposes.

12. Acknowledgments

The author wishes to thank the Marconi Co. Ltd. for kind permission to publish this paper. He also wishes to acknowledge the help given by the Company's design engineers.

13. References and Bibliography

1. D. H. R. Archer, 'I.F.F. and civil S.S.R.', *World Aviation Electronics*, 4, pp. 210–20, 246, May 1964.
2. D. G. Terrington, 'Development of secondary surveillance radar for air-traffic control', *Proc. Instn Elect. Engrs*, **112**, No. 5, pp. 861–71, May 1965.
3. D. H. R. Archer, 'Secondary surveillance radar, Pt. 1 and 2', *Electronic Engineering*, **33**, Nos. 401 and 402, pp. 414–20, 490–94, July and August 1961.
4. H. W. Cole, 'S.S.R.—some operational implications in technical aspects', *World Aerospace Systems*, **1**, No. 10, pp. 468–70, October 1965.
5. Issue No. 7 of Annex to I.C.A.O. Standards and Recommended Practices for Aeronautical Telecommunications.
6. D. H. R. Archer, 'Reply probabilities in S.S.R. systems', *World Aviation Electronics*, **1**, No. 4, December 1961.
7. K. E. Harris, 'Some problems of secondary surveillance radar systems', *J. Brit. Instn Radio Engrs*, **16**, pp. 355–83, July 1956.
8. N. D. Vincent and P. A. Lynn, 'The assessment of site effects of radar polar diagrams', *Marconi Review*, **28**, No. 157, pp. 109–34, 1965.
9. G. F. Springler, 'Air Traffic Control Radar Beacon System. 3 pulse S.L.S. Experimentation'. Final F.A.A. Report No. RD64-36 on Project No. 108-3X. March 1964.

Manuscript first received by the Institution on 4th October 1965 and in final form on 22nd September 1966.

(*Paper No. 1094/RNA66.*)

Radio Engineering Overseas . . .

The following abstracts are taken from Commonwealth, European and Asian journals received by the Institution's Library. Abstracts of papers published in American journals are not included because they are available in many other publications. Members who wish to consult any of the papers quoted should apply to the Librarian giving full bibliographical details, i.e. title, author, journal and date, of the paper required. All papers are in the language of the country of origin of the journal unless otherwise stated. Translations cannot be supplied.

LOGARITHMIC VIDEO AMPLIFIERS WITH NON-LINEAR FEEDBACK

Amplifiers with logarithmic input-output characteristics have many applications in measuring equipments and other electronic systems, including radar. A Soviet paper studies the problem of obtaining a logarithmic amplitude characteristic in a transistor amplifier. The input voltage dynamic range is considerably extended by using amplifiers with parallel or series non-linear negative feedback. The required variation of the resistance of the non-linear element in the feedback path is determined. Results of an experimental investigation of the circuit developed are also presented.

'Transistor logarithmic video amplifier with series-parallel nonlinear feedback', V. M. Volkov and V. V. Sidorenko, *Telecommunications and Radio Engineering* (English edition of *Elektrosvyaz* and *Radioteknika*), **21**, No. 4, pp. 82–86, April 1966.

MODE SELECTION IN GAS LASERS

Mode selection in the semiconcentric cavity of a gaseous optical maser oscillator (laser) is considered. The output power and the structure of the laser emission spectrum are investigated as a function of cavity length. It is shown that with a cavity of certain length it is possible to emit a single transverse fundamental mode. The diffraction losses in a semiconcentric cavity are calculated.

'Mode selection in the semiconcentric cavity of a gaseous laser oscillator', A. V. Korovitsyn, L. V. Naumova and Z. T. Lebedinskaya, *Radio Engineering and Electronic Physics* (English edition of *Radiotekhnika i Elektronika*), **11**, No. 4, pp. 572–76, April 1966.

HIGH-GAIN SUBMILLIMETRE AMPLIFIER

A Swedish paper describes how high gains at submillimetre wavelengths can be obtained. The gain of a travelling-wave amplifier for submillimetre waves is studied, and a periodic structure of the linear magnetron type is used as a delay line. The electron beam is homogeneous and has constant mean velocity.

The losses in the metallic walls play an important role at submillimetre frequencies so that high current densities of the electron beam are necessary for gain. The losses and the deformation of the r.f. field due to the current density are taken into account in solving the field equations. A numerical calculation is presented of an amplifier operating in the third spatial harmonic for waves with a vacuum wavelength of $\lambda_0 = 2\pi \times 10^{-4}$m.

'Submillimetre wave amplification in a periodic structure', J. M. Mayr, *Ericsson Technics*, **22**, No. 2, pp. 111–23, 1966. (In English.)

X-RAY PICTURES IN COLOUR

By means of a closed-circuit television system it is a simple matter to subtract two x-ray images from one another. One of the images is recorded in a magnetic store and the video signal obtained from the store is electrically subtracted from the video signal of the other image. This system has been employed for inspecting radiographs of the brain in various phases of the circulation of a contrast medium injected into the blood stream. By subtraction of the radiograph taken *without* the contrast medium the unwanted bone structure is eliminated from the picture.

A Dutch paper describes the extension of this subtraction method by the use of colour television. The x-ray images of various phases in the circulation of the contrast medium (or x-ray images of the same object which differ for other reasons) are retained in the store and the individual signals, after appropriate subtraction and mixing, are applied to the colour channels of a colour monitor. In this way the arterio-vascular system of the brain can be shown red, for example, and the venous system blue in the same radiograph. This is demonstrated by photographs.

'X-ray pictures in colour', W. J. Oosterkamp, A. P. M. van't Hof and W. J. L. Scheren, *Philips Technical Review*, **27**, No. 8, pp. 228–30. (In English).

MULTI-PATH TRANSMISSION IN STEREO F.M. BROADCASTING

A Japanese paper compares various v.h.f.-f.m. stereophonic broadcasting systems, and discusses the effects of multi-path propagation on system characteristics, especially for the two systems of f.m.-f.m. and a.m.-f.m.

It is shown that: (1) the stereophonic characteristics are mainly dominated by the effect of multi-path propagation on the sub-carrier; (2) distortion in the stereophonic f.m.-f.m. system is almost equal to that of the monophonic system; (3) distortion in the stereophonic a.m.-f.m. system is almost independent of the modulating frequencies and exceeds that of the monophonic system (beats between the modulating signal and the pilot signal are quite large); (4) in both systems, the amount of cross-talk is almost equal to that of distortion.

In conclusion, the author states that the f.m.-f.m. system is superior to the a.m.-f.m. system with regard to reception in the presence of multi-path propagation.

'Distortion and crosstalk caused by multipath transmission in stereo f.m. broadcasting', Yasuji Kurakake, *Electronics and Communications in Japan* (English Edition of *Denki Tsushin Gakkai Zasshi*), **48**, No. 12, pp. 11–18, December 1965.