The Journal of

THE BRITISH INSTITUTION OF RADIO ENGINEERS

FOUNDED 1925 INCORPORATED 1932

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

VOLUME 18 JULY 1958 NUMBER 7

A GUIDE TO RADIO ENGINEERING LITERATURE

REFERENCE has frequently been made in this *Journal* to the problems which beset the engineer who wishes to keep up-to-date with published work on his own and allied subjects. One way in which the Institution helps members is by maintaining a lending library.

It has been felt for some time, however, that the fullest use cannot be made of the library without a comprehensive and up-to-date catalogue of the material which is available. A new catalogue has therefore been compiled which will be sent to all members in the autumn.

The new publication will be entitled "Library Services and Technical Information for the Radio and Electronics Engineer." An up-to-date catalogue of all material in the Institution's library naturally forms the main part of the work.

Other reference sections include a collation of standards and specifications. This was the object of a most useful report by the Institution's Technical Committee in 1951 under the title "Good Engineering Practice" and has now been brought fully up-to-date—the number of British standards directly associated with radio and electronic engineering has, for instance, almost doubled in the seven years since the preparation of that report. This section also lists the relevant Codes of Practice and standards on terms and symbols, as well as a selection of standards relating to general engineering matters, and certain industry and government specifications.

Another important section is an up-to-date version of a report prepared by the Technical Committee in 1953 on radio and electronic engineering literature. This indicates the availability of professional and commercial journals, government publications, and library facilities, and includes useful information on patents and the universal decimal classification.

With the growing extent of bodies concerned with international co-operation on scientific matters, it is sometimes difficult for the engineer to decide which particular organizations deal with given subjects. Accordingly some notes on the main bodies associated with radio engineering should prove a useful guide.

The references which accompany papers surveying the latest advances in electronics, as well as the regular feature in the *Journal*, "Radio Engineering Overseas", show that an enormous amount of useful data is published in languages other than English. Details are therefore given of the translating services which exist in Great Britain and elsewhere.

Finally, particulars are given of facilities which exist in two fields indirectly connected with information and are of considerable and growing importance. The Institution has for the past two or three years published details in the *Journal* of technical films which are available, and some information is given of how these may be obtained. Similarly, a list is given of post-graduate awards which are available in Great Britain in the form of scholarships, grants or fellowships, and which may be held by graduates of universities in the United Kingdom or overseas.

No *one* source can possibly guide the engineer in his search for specific information, but it is hoped that this new Institution publication will materially assist him to solve some of his problems.

INSTITUTION NOTICES

Royal Garden Party

The President, Mr. G. A. Marriott, and Mrs. Marriott had the honour of an invitation to the Royal Garden Party at Buckingham Palace on the 17th July last.

President visits Reed's School

The President was guest of honour at Reed's School Speech Day on 14th June. In the course of his address Mr. Marriott stressed that the control and proper use of new developments was just as important as their discovery. The prizes were presented by Mrs. Marriott.

The School has made a number of improvements in its buildings recently, including new science laboratories, dormitories, and a gymnasium.

ATV and the Institution

Donations totalling £21,000 in support of the Arts and scientific bodies concerned with television were recently announced by Mr. Norman Collins, deputy chairman of Associated Television Ltd., one of the programme companies concerned with independent television broadcasting.

The principal donation among those to technical bodies is a sum of £400 per annum covenanted for seven years to the Institution.

Welcoming this innovation in patronage of the Arts and sciences, Sir Ivone Kirkpatrick, chairman of the Independent Television Authority, said that it was the intention of other programme companies to make similar gifts, which would then total about £100,000 a year. A co-ordinating committee was being set up to ensure that donations by individual companies did not overlap, but each company would decide its allocations.

The list of recipients of gifts from A.T.V. includes repertory theatres, orchestras, opera companies and art galleries, as well as schools and colleges concerned with music and drama, and there will be prizes for original writing for television.

Summer School on Non-Destructive Testing

Sponsored by the British National Committee for Non-Destructive Testing, on which the Institution is represented, a summer school on "The Principles and Practice of Non-destructive Testing" will be held in the Department of Mechanical Engineering at Manchester College of Science and Technology from 8th to 12th September. The course is intended for engineers already having some training in inspection, and they should hold appointments of at least Senior Inspector. The fee for the course, which includes accommodation and meals, is £17 10s. Application forms may be obtained from the Institution.

Course on Colour Television

A full evening course in the Principles and Practice of Colour Television has been authorized by the Ministry of Education to be held by the Northern Polytechnic during the coming session. The course will be conducted by a senior lecturer, Mr. R. S. Roberts (Member) and specialist lectures will be given by research engineers from the B.B.C. and industry. The fundamentals of television transmission and reception in colour will be covered, and provision has been made for practical work on colour receivers. Further information can be obtained from the Department of Telecommunications, Northern Polytechnic, Holloway Road, London, N.7.

Examinations for Technical Authors

The present shortage of competent technical writers has led the City and Guilds of London Institute to set up a scheme of courses and examinations in Technical Authorship. The scheme of instruction is intended for those with engineering, technical or scientific training and experience, who wish to become technical authors in industry or government service. The course of training recommended has been designed with the needs of the younger entrants in mind, but the examinations will also be open to practising technical authors. The Intermediate examination will be offered for the first time in 1960, and the Final in 1961.

Correction

In the paper "Dectra: a long range radio navigation-aid" by C. Powell, which appeared in the May *Journal*, an error occurred on page 287, second column, three lines from bottom of first paragraph. After the word "separation" the qualification "(in the direction of propagation)" should be added, since the actual distance between the reflection points is invariably equal to half the distance between the transmitters.

RECENT DEVELOPMENTS IN COMMUNICATIONS MEASURING INSTRUMENTS*

by

E. Garthwaite, M.B.E.† and A. G. Wray, M.A. (Associate Member)†

Read before a meeting of the Institution in London on 18th December 1957.
In the Chair: Mr. S. R. Wilkins (Member)

SUMMARY

Rapid expansion in radio communication systems has created a corresponding demand for both new and improved forms of instrumentation. The paper gives a brief summary of the present position as seen through the eyes of the instrument designer. It is shown how needs are being met by: (1) improving existing design by the process of continuous development; (2) developing and exploiting new measuring techniques; (3) producing test sets to fulfil certain specific functions. Examples are given by way of illustration and reference is made to some of the technical and economic factors affecting the instrument manufacturer.

1. Introduction

In recent years, a rapid increase in the number of applications in the art of radio engineering has taken place and because all these parallel developments have to be found a place in a finite frequency spectrum, systems are being adopted which conserve existing channel spacing at the already overcrowded lower frequencies, or are being developed to operate at higher frequencies where further unused channels are still available.

One of the most important aspects of modern communication is thus that of bandwidth. Extremely narrow bandwidths are being employed at h.f. for world-wide telegraphic and telephonic communications and again at v.h.f. for mobile communication. At the other extreme, in the centimetric region, very wide bandwidths are being used to accommodate many channels of comunication. It can thus be seen that this question of bandwidth has considerable bearing upon recent developments in telecommunication test equipment.

The introduction of new systems may demand new test equipment, but, more often, the urgency to obtain measuring apparatus as soon as the necessity for it is discovered, dictates that improvements be made in existing instruments. It can be said that this is possibly the biggest challenge to the designer of communication test gear.

Another field of endeavour for the instrument designer, which has resulted from general purpose test gear tending to become more complicated, is in the development of specialized apparatus for routine testing. An assembly of the necessary unit pieces of the general purpose equipment is impracticable for this purpose although it would have obviously been used in the development stage.

The improved performance required from modern test apparatus highlights certain aspects, such as stability, ease of resetting, signal-to-noise ratio, microphony, etc. In addition, especially with portable instruments, a high degree of flexibility has to be maintained for economic reasons. This latter fact is sometimes overlooked by the critics of general test equipment when they evaluate its performance against specialized apparatus which is designed solely for a specific purpose.

When speaking of electronic measuring apparatus, one usually thinks in terms of packaged instruments but, it is believed, modern trends will soon out-date the present system, and give way to many more applications of so called Systems Test Gear and Test Sets. An alternative approach is by way of modification

---

* Manuscript received 27th February 1958. (Paper No. 459.)

† Marconi Instruments Ltd., St. Albans, Herts.

U.D.C. No. 621.317.7:621.396.61/2

of existing equipment to allow a multiplicity of instruments to be used for a particular test (Fig. 1). Some of the recent improvements in instruments have been made for this very reason, and it is thought that a considerable reduction in weight and size should be a prime factor in the re-design of any piece of standard equipment.

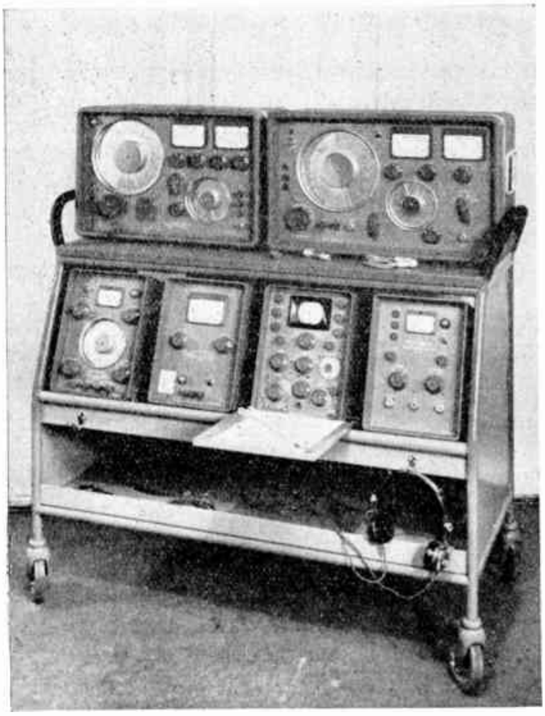


Fig. 1. Trolley designed to carry a number of "standard" instruments.

2. Improvements in Design by Continuous Development

2.1. *Signal Generators*

Signal generators can be considered to be the basic tools used for making measurements. The biggest single factor which has recently caused modifications to be made in this group of instruments is the narrowing of the channel spacing, coupled with the increased use of high frequencies. Nowadays, practically all fixed and mobile apparatus has, of necessity, to be crystal controlled which, in turn, has resulted in much more stringent stability requirements from associated test equipment. In particular, much effort is being put into improving the short-term stability of the oscillator.

In the case of amplitude-modulated signal generators, attention has also to be given to the problem of reducing spurious frequency modulation associated with the amplitude modulation process. Where practicable, this is carried out by modulating at a point suitably buffered from the oscillator. One well-known method is to insert an untuned buffer stage between oscillator and modulator so that any change of input capacitance of the modulator, resulting from the modulation process, is only reflected back into the anode circuit of the buffer. Accordingly the oscillator remains unaffected. Obviously, similar results could be obtained by introducing attenuation between the oscillator and the modulator but this would not be desirable, as already the problem of power dissipation of the oscillator affects considerably the short-term stability, and in the higher frequency signal generators the power loss in the oscillator coil is a matter of some concern.

Up to the moment only sinusoidal modulation has, in fact, been considered; there is another problem in amplitude modulation concerned with pulsing of signal generators. The latest equipment in this field requires suppression of the oscillator to the order of 80 db; this cannot be accomplished in one modulating stage, and resort has had to be made to modulating at least two stages simultaneously to obtain this suppression of the carrier.

In the case of frequency-modulated signal generators, the use of narrow channels has called for smaller maximum deviation, with the result that the residual frequency modulation, due to hum and noise voltages and also microphony, becomes extremely important. In the band now used for communication, 450–470 Mc/s, the residual f.m. is quoted as being at least 40 db below the test deviation of 10 kc/s, i.e. less than 100 c/s deviation. At these frequencies, deviations of this order can be obtained from small vibrations of capacitor vanes due to incident noise received from the particular locality where the generator is being used, and it has been necessary to produce a considerable amount of specialized test equipment to enable an acceptable performance to be achieved with current generators.

The question here arises of the desirability of also providing crystal control for the test gear, as has had to be done for the equipment under test. However, it will soon be realized, when operating equipment in this form, that the difficulty arising from the spread in the fundamental crystal frequencies (due to manufacturing tolerances, etc.) will soon cause difficulties in making measurements. Any slight misalignment will appear as a change in sensitivity or signal-to-noise ratio rather than just the fact that the receiver and transmitter are not properly aligned. Although these discrepancies have to be accepted in the communication system itself, it is undesirable when making measurements, say, of sensitivity, to find that these are being affected by the slight inaccuracies of the two crystals in use. A more flexible system will obviously have to be found to overcome this increasingly difficult problem as bandwidths are further decreased. A system of locking a high-frequency signal from a much lower frequency where the question of microphony can be treated in a somewhat more robust manner is one possible solution.

Another requirement of frequency-modulated mobile equipment is that the channel separation is such that precautions must be taken to ensure that equipment operating on adjacent channels will not interfere with communications on the channel in question. To this end, it is necessary to take into account another factor, and this is the noise spectrum of the carrier itself. It can be readily seen that the white noise energy modulating a c.w. carrier can be considerably greater than might be expected and, here again, additional precautions have had to be taken to guard against this. To meet existing Post Office specifications for testing v.h.f. receivers, it is necessary to see that the noise in the carrier is at least 80 db down on the carrier itself. The only known method at present of detecting this level is actually to make a measurement on a receiver using two signal generators and noting the worsening of signal-to-noise ratio of a wanted signal in the presence of an unwanted carrier on the edge of the band.

At the lower frequencies when testing receivers used with frequency-shift keying equipment, the bandwidth is extremely narrow and scintillations of the oscillator may become important. A special version of a signal generator made to meet this application utilizes a crystal locking system in which provision is made to lock the carrier at each megacycle interval throughout the band of the generator from a single 1 Mc/s crystal oscillator.

The increasing use of very high frequencies has necessitated detailed modifications in the output systems of signal generators operating in these bands. It is most important at these frequencies to ensure that the signal generator presents a resistive source to the equipment under test, and considerable difficulties are involved when trying to meet this particular point of specification in very wide band signal generators. One way of carrying this out in a typical instrument using a piston attenuator is illustrated in Fig. 2.

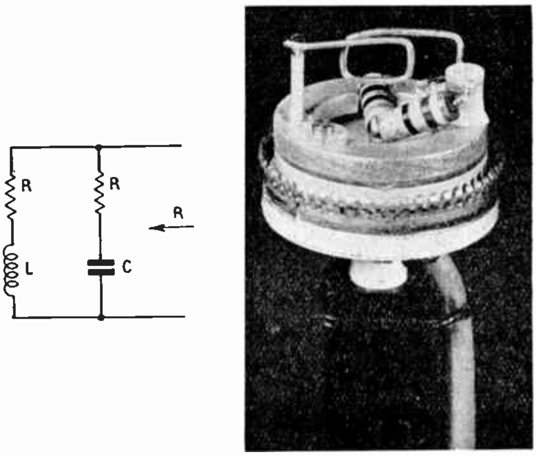


Fig. 2. Launching loop assembly and functional circuit diagram of piston attenuator launching loop.

Signal generators for operation above 500 Mc/s have their own additional problems. At these frequencies, it is not possible to use lumped circuits and, therefore, to produce signal generators covering any significant range a considerable amount of mechanical engineering is required. Up to 1500 or 2000 Mc/s disc seal triodes can be utilized in line oscillatory circuits. To provide the necessary stability, however, such circuits should not include moving contacts and, to this end, non-contacting plungers (Fig. 3) have been developed to enable frequency variations to be made and precisely recorded.[1] Some idea of the problems encountered in designing such an oscillator unit can be derived by examination of Fig. 4. Here is shown a functional diagram of an oscillator which forms part of a signal generator covering 450–1200 Mc/s. It can readily be seen that two sets of tuning plungers are needed. The outer line between anode and grid is tuned with a Z-shaped plunger (as in Fig. 3), the inner line between grid and cathode with a plain "bucket". Both plungers are ganged together and operated from a single control. In addition, two probes are introduced into the outer cavity, the one feeding the attenuator system, the other sampling the field for monitoring purposes. Arrangements are also made to gang the movements of these two probes together so that as the monitor attenuator probe is withdrawn (to set the voltage to a predetermined level) the output loop is withdrawn in sympathy. By this means it is therefore possible to determine the voltage injected into the output system.

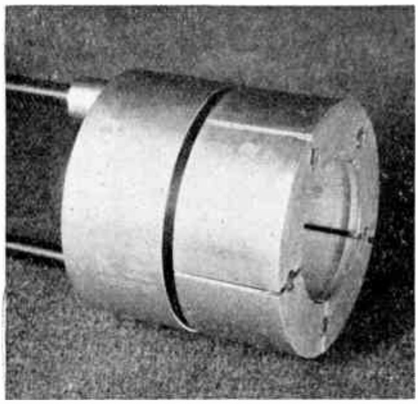


Fig. 3. Z shaped non-contacting tuner plunger.

Above 2,000 Mc/s it is generally necessary to resort to klystrons where further difficulties are encountered. In addition to having to maintain accurate tuning it is also necessary to adjust automatically the klystron reflector voltage in sympathy if single knob control is to be attained over any band at all. Signal generators using this principle have to date been developed for frequencies up to 8,000 Mc/s, having a tuning range of approximately 2:1.

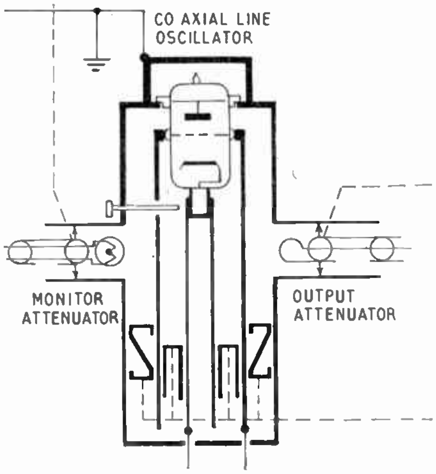


Fig. 4. Functional diagram of coaxial line oscillator.

2.2. *Oscillators, Voltmeters and Allied Equipment*

Parallel with the developments concerning signal generators, further improvements in traditional equipment, such as valve voltmeters, low frequency power meters, deviation meters, distortion meters, beat frequency and resistance-capacitance oscillators, have also proceeded. Improvements in these instruments are mostly confined to mechanical refinements and, where possible, improvements in the specification brought about by recent advances in the thermionic devices available to the instrument designer. As an example, Table 1 compares the performance of a typical valve voltmeter designed in 1947 with the corresponding instrument of 1957. It can be seen that the specification has been improved with regard to frequency characteristics from 100 Mc/s to 1,000 Mc/s. This, in part, is due to the introduction of special diodes with low transit time and very small capacitance—two factors which, in themselves, are contradictory. An exploded view of a diode probe making a 1,000 Mc/s voltmeter possible is shown in Fig. 5. It can be seen that a cylindrical form of construction has been employed in which the diode, disc type blocking capacitor and probe element are mounted coaxially.

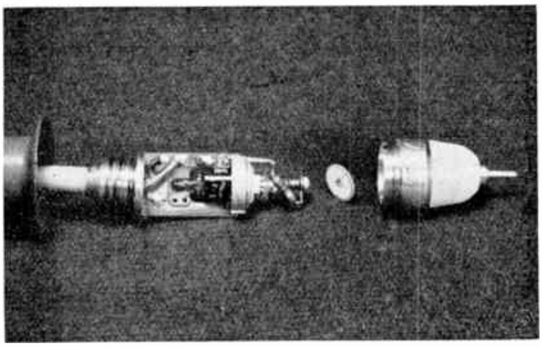


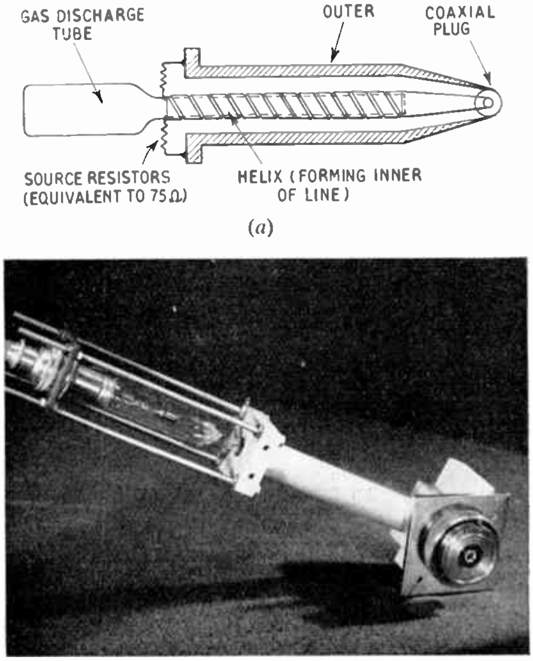
Fig. 5. Exploded view of a diode probe suitable for operation up to 1,000 Mc/s.

2.3. *Noise Sources*

Increasing use is now made of noise generators. In this particular field, considerable work has been undertaken to produce noise sources above 1,000 Mc/s. At these frequencies, the only source of white noise as yet available is the discharge tube. One interesting recent development in this field is the introduction of the discharge tube with a coaxial system using a helical line as coupling element.[2, 3] (Figs. 6 (*a*) and (*b*)).

2.4. *Power Meters*

Absorption-type power meters, for frequencies up to 5,000 Mc/s and above have also had considerable attention in recent years, and have resulted in the now familiar instrument in which a resistor designed as a correct termination to the feeder is used as a dummy load. A known fraction of the power is in turn passed to some suitable detector such as a crystal diode or thermocouple. Development in this field of measurement is taking place on quite conventional lines. On the other hand, efforts are being made to extend the frequency range over which a satisfactory terminating load may be obtained and, at the same time, loads capable of higher power ratings are being sought. These two factors have a marked bearing on each other, for resistances of large dimensions have, of necessity, large residual inductance and capacitance and prove more difficult to turn into wide-band terminations. Both coaxial and slab-line techniques are in current use and, of course, forced air or oil cooling of the load is employed where the necessity arises.[4, 5] An idea



(*b*)

Fig. 6.

(*a*) Sketch showing construction of helical line noise source.

(*b*) A 2,000 Mc/s noise generator.

Table 1

Valve Voltmeter Performance

	1947	1957
Voltage Range:	0·1–150 V	0·05–300 V
Accuracy:	±2% f.s.d.	±2% f.s.d.
Frequency Characteristic:	Flat within 0·2 db 100 c/s–100 Mc/s (Error of 2 db at 175 Mc/s)	Flat within 0·2 db 50 c/s–450 Mc/s (Error of 2 db at 1000 Mc/s)
Input Conditions:		
(*a*) Shunt Capacitance:	6·5 pF	1·5 pF
(*b*) Input Resistance:	1 MΩ at 1 Mc/s falling to 10 kΩ at 100 Mc/s	1 MΩ at 1 Mc/s falling to 150 kΩ at 100 Mc/s

of the problems involved in producing a satisfactory termination can be obtained by examination of Fig. 7, in which the slab-line principle is employed. The instrument of which this load forms a part is capable of measuring up to 25 watts from d.c. to 500 Mc/s to an accuracy of 5 per cent. The load itself has a v.s.w.r. better than 1·2 over the whole frequency band.

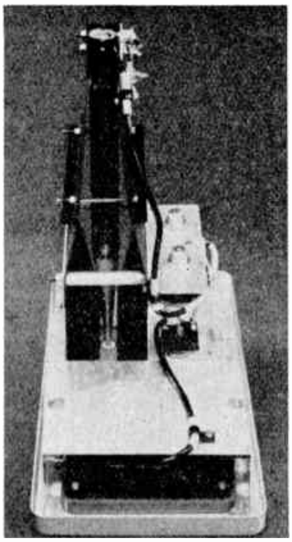


Fig. 7. Termination for r.f. power meter.

2.5. *Frequency Measurement*

In the measurement of frequency, it is quite certain that the counter-type frequency meter is here to stay.[6,7] An example of such an instrument can be seen in Fig. 8 and it is obvious also that the future holds possibility of having at least a certain part of this instrument operated entirely from transistors.

Fig. 8. Counter type frequency meter.

In addition, work has proceeded on transfer oscillators—allowing this type of measurement to be extended to the higher frequencies. One approach to this problem has been made by utilizing a variable capacitor as tuning element, whose law can be corrected accurately to enable direct frequency calibration to be obtained to an accuracy of 1 in 10^5 to possibly 1 in 10^6 by a cam operating upon an auxiliary capacitor. This allows a 2 to 1 frequency range to be covered and the harmonics of this frequency are used as the calibrating source.

3. Heat Dissipation

One of the biggest problems the instrument designer now has to face is that of removing excess heat generated inside his equipment. This has been aggravated by the introduction of miniature valves, small components and the corresponding desire to put the "quart into the pint pot". Naturally one looks to the increased use of transistors and other semi-conductor devices for ultimate relief but in the meantime several innovations have been introduced in which heat is conducted away from the valve envelope in the most efficient manner. One example is illustrated in Fig. 9. It can be seen that good thermal contact between the valve envelope and metal block (into which the valves are placed) is ensured by the use of a metallic spring (like a length of flexible curtain rail) held under compression. In addition, by placing a metallic sheet over the whole of the block a screened compartment is obtained—a desirable feature in the manufacture of signal generators, etc.—which, nevertheless, has extremely good heat dissipating properties.

4. Recent Advances in Measuring Techniques

With the added complexity of many modern pieces of electronic apparatus, static methods of test and adjustment are becoming increasingly tedious and out-dated. Accordingly there a growing tendency to use dynamic techniques wherever possible. It is not surprising therefore to find that many of the more interesting developments in measuring apparatus are centred around the use of a cathode-ray tube to display certain functions against time or frequency.

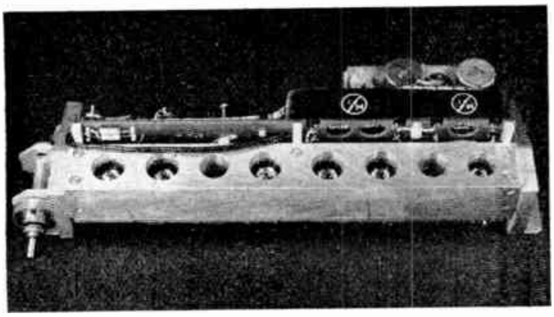


Fig. 9. Heat dissipation by improved thermal conduction.

Before passing on to one or two specific examples of advancement in measurement techniques one must not fail to mention the way in which the cathode-ray oscilloscope itself has been developed as an indispensable measuring instrument.

Increased bandwidth and writing speeds, higher sensitivity, better discrimination, brighter displays and numerous other features are all being claimed by the manufacturers. As in many other types of instrument these advancements have, in the main, been accomplished by the introduction of new and improved components, in particular by the availability of the modern precision high-sensitivity cathode-ray tube.

4.1. *Derivative Test Set*

In designing a microwave link system to carry a large number of independent telephone circuits simultaneously great care must be taken to avoid cross-talk between channels. This means specifying extreme linearity throughout the whole system and in particular involves a rigorous control of modulator and demodulator circuits where intermodulation is most likely to arise. As practically all link systems now use a frequency-modulated microwave carrier, the problem, in a nutshell, is to devise a method by which the linearity of their frequency amplitude characteristic can be determined to an accuracy of at least one order better than that obtainable with conventional distortion measuring apparatus.

The equipment illustrated in Fig. 10 has been developed to fulfil this need.[8] In essence, it consists of a dual sweep oscillator and associated display unit whereby the slope of the demodulator (or modulator) characteristic is plotted against the instantaneous carrier frequency. Accordingly, whilst the relationship between frequency and amplitude remains linear, no change in slope is apparent and a horizontal trace on the cathode-ray tube face is obtained; when any non-linearity is present, this results in an amplitude variation on the display. It is fairly obvious, therefore, that the smallest detectable non-linearity is but a function of the amplification introduced into the *Y* deflection system. Examination of the block functional diagram of a typical Derivative Test Set (a name coined from the calculus analogue) shows that measurements are carried out at the i.f. of the link system—in this case 70 Mc/s. The dual sweep is derived from the mixing of signals from two separate oscillators —the one oscillator (A) centred on 200 Mc/s being swept ±10 Mc/s at a recurrence frequency of 50 c/s by the use of a ferrite modulator; the other (B) centred on 470 Mc/s is swept ±100 kc/s at a recurrence frequency of 20 kc/s. Thus after heterodyning the fundamental of oscillator B with the second harmonic of A and passing through a suitable filter unit a signal is obtained centred on 70 Mc/s with a sweep of ±20 Mc/s at 50 c/s on which is superimposed the smaller sweep at 20 kc/s. This composite signal is amplified in a wide-band amplifier with a response curve flat within 0·1 db over the required bandwidth (40 Mc/s) and then fed into the test demodulator. The resulting demodulated signal should, of course, consist only of 20 kc/s and 50 c/s components. However, if any non-linearity is present the 20 kc/s will be amplitude modulated with 50 c/s. Thus the display unit consists of

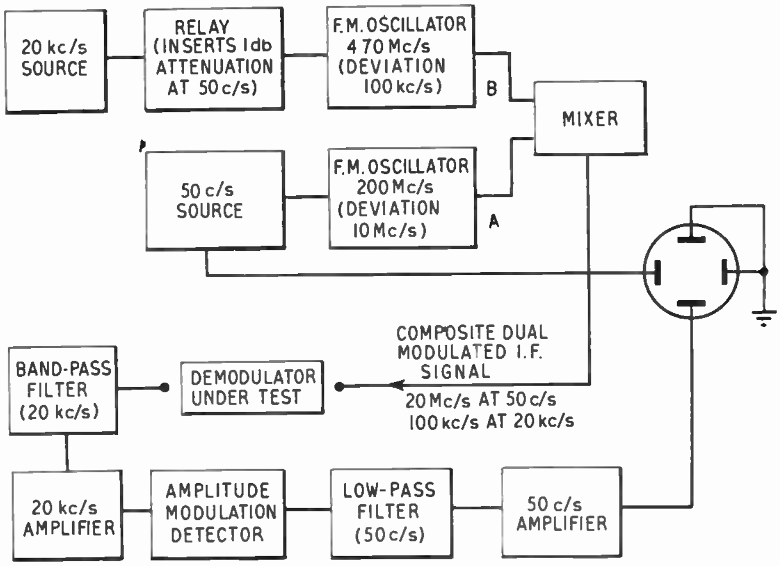


Fig. 10. Block diagram of the derivative test equipment.

a high-pass filter to reject 50 c/s followed by an amplifier centred on 20 kc/s. This, in turn, is fed into an amplitude modulation detector, and any resulting 50 c/s component is passed to the Y deflection system of the cathode ray tube. Obviously the amplitude of this 50 c/s component is a measure of the non-linearity present. A built-in calibrating facility is provided by introducing a 1 db attenuation in the 20 kc/s modulating signal on each alternate cycle of the 50 c/s sweep. As a 50 c/s signal is used as the X deflection voltage two traces are obtained on the tube face separated by 1 db. By adjusting the gain of the Y amplifier the separation can be set to any desired value. With this particular equipment measurement of linearity to an accuracy of 0·1 per cent. is possible, and, of course, using such a dynamic system the setting up of a demodulator (or modulator) is made a very simple task indeed.

4.2. *Group Delay Measurement*

A development on somewhat similar lines has taken place in the measurement of phase in which apparatus has been produced to display group delay against frequency.[9]. The task of adjusting the phase characteristic of a video amplifier to a predetermined law for instance is made considerably less laborious with such equipment.

In essence the method consists of utilizing a low video frequency as both reference and search signal (Fig. 11). In this case the signal derived from a sweeper unit designed to give a frequency excursion to cover the desired bandwidth (either at video or i.f.) is amplitude modulated from the video source. The composite signal is then passed through the network under test. Assuming that over the interval of frequency occupied by this signal group delay is uniform, any departure from constancy of phase change of the video modulating signal is a measure of the group delay variations occurring within the test network.

To obtain the desired information the signal derived from the network is demodulated and the component which consists of the video output phase modulated at the sweep recurrence frequency selected. This, in turn, is passed through suitable amplifiers and limiters to a phase comparator. The phase comparator derives its reference signal from the video source. By designing a comparator which in effect linearly converts variations in phase to corresponding changes in amplitude, an audio-frequency output is available which after further amplification can be used as the vertical deflection voltage of a cathode-ray tube display.

At the same time horizontal deflection is produced at the sweep recurrence frequency so that the over-all display represents the group delay/frequency characteristic of the network under test.

5. Systems Test Gear

Where conditions warrant, it is often desirable to design a specific instrument or instruments for testing one particular radio installation. All apparatus falling into this category can well be lumped together under the general heading "Systems Test Gear". In reality the title "Systems Test Gear" covers a very wide field ranging on the one hand from apparatus made in portable form for simple fault diagnosis in remote geographical locations to, on the other hand, whole racks of equipment for the complete testing of a component of a system in a base workshop or laboratory. A few selected examples will help to illustrate this point.

5.1. *Portable Equipment*

In Fig. 12 is illustrated portable test equipment designed for the complete testing of v.h.f. mobile transmitter/receivers in the field. Essentially it consists of two separate units. One unit consists of a high stability f.m./a.m. signal generator covering the frequency bands 68–174 Mc/s and 450–470 Mc/s with facilities for producing crystal controlled outputs at five preferred intermediate frequencies. The second unit contains suitable circuits for carrying out a range of tests including the measurement of voltage, current, a.f. power, r.f. power and carrier frequency deviation.

The viewpoint taken in designing such instruments is to try to provide facilities for testing as many different types of v.h.f. mobile radios as possible. Nevertheless when the equipment is offered for commercial sale it soon becomes apparent that many other potential customers could use the apparatus if but small changes could be made in the specification. For instance, a most common request is for a small modification to be made in the frequency bands covered.

It is quite obvious that in the first place every care must be exercised in laying down the original specification to endeavour to foresee these additional requirements. On the other hand, however, it is of paramount importance that, having once committed oneself, the temptation to give just that little bit more to exploit its sales potential must be fought most vigorously—for in all probability the added

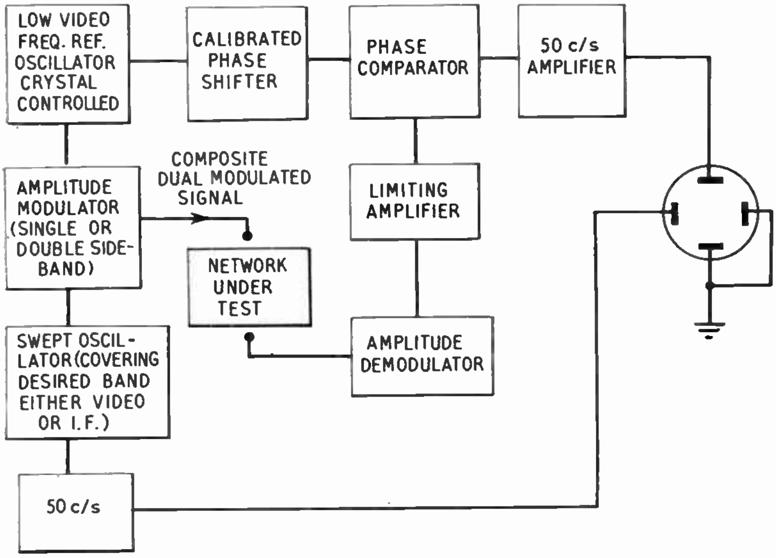


Fig. 11. Block diagram of group delay measurement equipment.

complexity that results invariably makes the equipment too expensive for its original purpose. In addition, of course, any added bulk would distract from the equipment's portability.

5.2. *Fixed Installations*

For testing many installations a complicated array of instruments is often needed to carry out each measurement. This problem may be approached in two alternative ways. One is to develop a number of standard units, each designed to perform certain essential functions, power packs, voltmeters, oscillators, being cases in point. These are then utilized as building bricks by way of which a comprehensive test set may be synthesized.

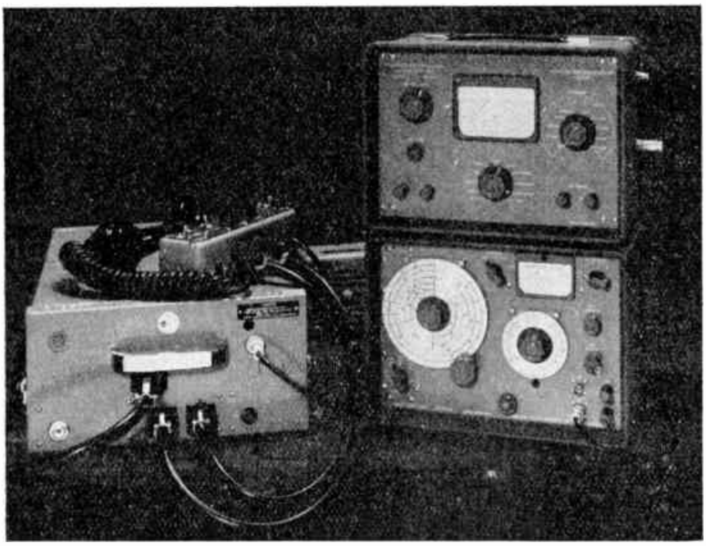


Fig. 12. Portable signal generator and meter unit used to test v.h.f. mobile equipment.

More often, however, the test set is tailored to suit the application in view, be it the testing of a component or a complete system. Rack mounting is generally preferred, the 19-in. panel being adopted as a standard. Sometimes, in the interests of versatility it is desirable to construct standard cases to house the panels. By making provision for bolting the cases together it is then possible to either replace the rack or, alternatively, where the situation arises, create portable units which may be used individually.

Many applications of rack mounted systems test gear can be given. Perhaps some of the more recent have been in the field of guided weapon instrumentation. It is common practice to break down the electronic sections of a missile into a number of units which can be separately "potted". Arrangements are made to test each individual unit before and after the encapsulation process. As units are then connected together further over-all performance checks are performed. Now to carry out such work it is fairly obvious that the test apparatus must fulfil a number of functions. It must be capable of supplying the necessary input signals to the unit under test; it must also be able to analyse the corresponding output signals and, in addition, provide all necessary h.t. and l.t. supplies. The test gear must, of course, also simulate the actual input and output conditions that will be met in practice.

Accordingly, to test each potted unit normally requires a complete rack of equipment. In practice the unit to be tested is located on an appropriate desk unit with all necessary supplies and connections brought to it by multi-way cables. The specialized items of test equipment, together with a number of common panels which may include voltmeters, oscilloscopes, and regulated power supplies, are then mounted into the rack to complete the installation of the necessary test apparatus.

5.3. *Factory Test Gear*

Nowadays much routine testing of complicated circuits is carried out in establishments and factories by relatively unskilled personnel. This is made possible by introducing the skill into the test gear and producing equipment which is extremely simple to operate, the principle of "Go/No-Go" testing being adopted. Naturally the simplicity of use can only be brought about by often utilizing complicated circuits and complex switching.

In most arrangements the operator performs a number of tests by simply turning a selector switch to an appropriate position and noting that the meter pointer is located within certain specified limits.

Naturally the provision of such apparatus involves a high initial cost but this is considered worthwhile if its introduction cheapens the mass production of the equipment it is designed to test.

6. Future Trends

A review of instrumentation over the past ten to fourteen years indicates, in some measure, the improvements that one can expect in the future. Very few absolutely new techniques have been evolved and it has mostly been a process of continuous development, leading to greater accuracy, higher tuning precision, improvements in the signal-to-noise factor, etc., which are, of course, the most essential improvements in all communication systems. From time to time, interest has been taken in miniature equipments of pocket size which can be used to make very simple measurements, yet in spite of this the trend seems to be that measuring equipment will be even more complicated than the equipment under test.

As previously mentioned, routine testing of complicated communication equipment is becoming so essential that the speed at which measurements can be made may be a controlling factor in future designs. This is bound to lay emphasis upon the analog type of measurement or some system of digital presentation of the answer by multiple sampling of several parts of the circuit at extremely high speed. The general use of transistors in any one of the forms will ultimately require that only dynamic testing can be accepted, as these devices are not, at least in their present state, capable of accepting any great overload, which could occur with the usual type of static test procedure.

7. References

1. W. H. Huggins, "Broad-band non-contacting short circuits for coaxial lines," *Proc. Inst. Radio Engrs*, **35**, p. 906, September 1947.
2. K. W. F. Steward, "Helix-coupled gas tube noise sources," *Marconi Review*, **21**, No. 129, p. 43, 1958.
3. M. Kollanyi, "Application of gas discharge tubes as noise sources in the 1700–2300 Mc/s band," *J.Brit.I.R.E.*, **18**, September 1958 (to be published).
4. C. T. Kohn, "The design of a radio-frequency coaxial resistor," *Proc. Instn Elect. Engrs*, **101**, Part IV, p. 146, 1954. (*I.E.E. Monograph No.* 83*R*).
5. W. B. Wholey and W. N. Eldred, "A new type of slotted line section," *Proc. Inst. Radio Engrs*, **38**, p. 244, March 1950.
6. L. R. M. Vos De Wael, "Direct-reading frequency measuring equipment for the range of 30 c.p.s. to 30 Mc," *Proc. Inst. Radio Engrs*, **40**, p. 807, July 1952.
7. A. F. Boff, "Frequency meter uses digital counters," *Electronics*, **27**, p. 189, June 1954.
8. G. C. Davey, "New equipment for testing modulators and demodulators in f.m. multi-channel equipment," *Electronic Engineering*, **30**, p. 487, August 1958.
9. J. S. Whyte, "An instrument for the measurement and display of v.h.f. network characteristics," *Post Office Elect. Engrs J.*, **48**, No. 2, p. 81, July 1955.

CONTROLLED THERMO-NUCLEAR RESEARCH*

by

Sir John Cockcroft, O.M., F.R.S.†

This Address to the Parliamentary and Scientific Committee is published in order to provide members with authoritative background information on important advances in fields such as nuclear engineering. It continues the introductory account published in the Journal *in May 1957*

We started to work on the C.T.R. project in Britain ten years ago—due to the enthusiasm and vision of a young Australian scientist, Dr. Thonemann, working in Oxford. This work, which was moved to Harwell in 1950, has culminated in the apparatus which we call ZETA—zero energy thermo-nuclear assembly. The name is given because it was built to try to produce temperatures of a few million degrees in deuterium gas—a temperature just sufficiently high for fusion reactions between deuterons to be detectable, but not sufficiently high for any appreciable amount of thermonuclear energy to be produced.

ZETA consists of a large aluminium torus, 1 metre in core diameter—shaped like a motor car tyre. Vacuum pumps enable a high vacuum to be produced so that all impurity gases can be removed before the torus is filled with deuterium gas.

The torus is encircled by an iron core with electrical windings which form the primary of a transformer. A powerful current is passed through these windings from a bank of capacitors. The current impulses last for a thousandth of a second and are repeated every 10 seconds. These pulses induce an electric field round the axis of the torus by transformer action.

Before the current pulses pass, the deuterium gas inside the torus is made electrically conducting by passing through it a high frequency electrical discharge—so it is now in a similar state to a neon glow lamp and ready to conduct electricity. The capacitors are then discharged through the primary of the transformer and this causes a current of up to 200,000 amperes to circulate in the torus. The current heats up the gas first of all by the same process as any electrical conductor is heated. The electrons are set in motion by the electric field round the torus and the electrons transfer energy to the nuclei of deuterons.

The hot gas would now begin to lose its heat by conduction to the walls of the torus but fortunately for the experimenter Nature comes to his rescue. A conductor carrying an electrical current is surrounded by magnetic lines of force which lie in circles about the current. Now Michael Faraday showed over 120 years ago that these magnetic lines of force can be considered to be exerting a pressure on the electric conductor. They behave like encircling rubber bands squeezing the gas conveying the current and compressing it. The cooling gas is thus compressed into a central channel well away from the walls of the tube and between the gas channels and the tube walls is a high vacuum. The conduction of heat to the walls is prevented and at the same time the compression of the gas heats it up still further.

As the gas is heated up the electrons surrounding the atomic nuclei are stripped away. Radiation from a hot gas is mainly produced when the electrons move from one state round the atomic nucleus to another, so that if they are stripped from their nuclei they cannot radiate in this way and instead can only radiate feebly as they pass a nucleus at a distance. The result is that radiation from the hot gas increases only at the square root of the temperature instead of as the fourth power of the temperature.

---

* Read before the Parliamentary and Scientific Committee on 22nd April, 1958, and published by permission of the Secretary. (Paper No. 460.)

† Member for Scientific Research, U.K. Atomic Energy Authority, London, S.W.1.

U.D.C. No. 621.039

So far Nature has been helping. But now another natural phenomenon intervenes to plague the experimenter. The channel of hot gas shows a natural tendency to wriggle. For if any kink develops the magnetic field surrounding the current tend to make it bigger—so in a natural state violent wriggling develops. This would result in the hot gas touching the walls and losing its heat. This was the experience in early work by Ware.

The experimenter overcomes this by threading magnetic lines of force through the torus before the current circulates. This is done by an auxiliary winding on the torus which produces an axial magnetic field.

When the current passes, these magnetic lines of force are compressed into a smaller volume—they are trapped in the highly conducting hot gas and move with the hot gas. This can be observed by measuring the axial magnetic field and it is found to increase as the lines of force move closer together.

The threading of these magnetic lines of force through the hot conducting gas now acts as a stiffener to the current channel and prevents any kinks of small dimensions developing. However, the current channel can still move bodily up and down or sideways without kinking. But here Nature helps again for as the current channel moves towards the torus walls electrical currents are induced which repel the approaching current channel and stop the motion. In these experiments the current channel has been stabilized sufficiently well to prevent conduction of heat to the walls for just as long as the powerful current flows.

At the end of the pulse however, as the magnetic field encircling the current grows weaker, the channel finally expands and touches the walls. However, provided more energy can be fed into the torus to keep the current circling, it ought to be able to go on for much longer times.

By these means then we produce and maintain a channel of very hot gas. The next question is how hot this gas is. We aimed in ZETA at a temperature of several million °C.

Now measurement of these very high temperatures is far from an easy matter. We are interested in the random speed of movement of the atomic nuclei because this is characteristic of the hot gas and this is the important parameter in producing controlled thermo-nuclear reactions. The first method we employ has been used for a long time by astrophysicists interested in the temperature of stellar atmospheres, namely, the Doppler effect. Approaching atoms emit light of a higher frequency and receding atoms a lower frequency.

In ZETA we cannot use the visible radiation from electrons surrounding deuterium nuclei, because all the electrons are stripped away. However, there is a small amount of oxygen and other impurity atoms mixed with the deuterium. About five of the electrons are stripped away from the oxygen but three are left. So we can look at the radiation from these partially stripped atoms and measure the spread of frequency. From this we calculate the temperature of the gas. The width of spectral lines interpreted as temperature gives values in the range 1 to 5 million °C, over the current range of 100,000 to 200,000 amperes.

We can check the temperature in several other ways. The first is by estimating the heat produced by the known current circling through the resistant gas. An additional method of heating is provided by the act of compressing the current channel and this effect can also be calculated. The results of these calculations agree within a factor of two with the temperatures measured spectroscopically.

A more important check is to investigate whether the temperature has risen sufficiently high for fusion reactions between deuterons to begin. If they are taking place, neutrons would be produced and they are looked for first of all by scintillation counters. We also see whether foils of indium placed in the neighbourhood become radioactive. We find that neutrons are emitted through a large part of the current pulse and with currents of 200,000 amperes about four million neutrons per pulse are emitted. This is rather greater than the number expected from a gas at these temperatures. There is, however, the possibility that not all the neutrons are produced by the random collisions of deuterons in the hot gas but by a more ordered motion of the deuterons. If strong electrical fields exist in the discharge in spite of the voltage round the torus being only 1·5 kilovolts, the deuterons might by some unknown mechanism be moving in an ordered way rather than a disordered way. Neutrons produced in this way have in fact been observed by other experimenters — particularly Kurchatov in Russia and Colgate in U.S. working with straight discharge tubes. The electric fields were due to instabilities in the discharge column.

We are now studying the motion of the deuterons and the mechanism of the observed fusion reactions. We know that the deuterons and the charged products of the fusion reactions (tritons) are confined by the magnetic field, to the region of the hot plasma. This is an important point. We are now studying the energy of the neutrons since this throws light on the motion of the deuterons. As we increase our temperatures the neutron yield from thermo-nuclear reactions should increase a great deal—perhaps a million-fold by the time we get to 25 million degrees. We would then expect the contribution of the random motion due to fusion to be greatly increased and the interpretation of the phenomenon should become much easier.

Another interesting series of observations studies the nature and intensity of the radiation from the different kinds of atom in the discharge. As the current increases and the temperature rises the light from the deuterium atoms disappears, showing their electrons have been stripped away. A little later light from helium atoms disappears as their two electrons are removed and then falls off from the heavier atoms as more and more electrons are removed. As the temperature rises we find that we have to measure radiation on shorter and shorter wavelength—we are already having to work with radiation from the far ultra-violet and will soon have to work with the still shorter radiation of soft X-rays.

We believe then that we have got to the fringe of temperatures where thermo-nuclear reactions should be beginning, though we have not yet got a proof that all the observed fusion reactions are due to true thermo-nuclear processes.

Our next step is to modify ZETA to feed ten times more energy into it from a bigger capacitor bank. We shall at the same time make some modifications to the torus and increase the stabilizing axial field. With these modifications, temperatures should rise well beyond the central temperature of the sun which is 15×10^6 degrees and the neutron yield should increase at least a million-fold. But even so the energy required to heat up the gas will be far greater than the energy released in the fusion reactions. However, as we push on further, the energy released by fusion reactions should increase exponentially with the temperature whilst the radiation loss will increase only as the square root of the temperature. So we should ultimately reach a break-even point when the energy output equals the energy input. This temperature is likely to be well over 100 million °C for deuterium gas or about 40 million °C for a mixture of deuterium and tritium.

The following stage which we are now about to embark on is to design and build a successor to ZETA, ZETA II, aimed at getting within striking distance of the break-even point and perhaps even surpassing it. We shall design this so we can experiment with methods of transforming part of the energy directly into electricity. It is already possible in principle to see how a good part of the energy might be directly converted, though escaping neutrons will carry away part.

Even if this stage of the project is successful, four or five years from now we shall still be a considerable distance from a commercial fusion power station. Stage three would be the building of a fusion power station prototype. If the power station is an enlarged kind of ZETA we can predict that the ring of hot gas would be carrying a current of the order of several million amperes.

After that there would be stage four—commercial application. So I think fusion power is still at least twenty years away and perhaps much longer for we may meet many difficulties.

Complementary work has been carried out by the A.E.I. Laboratory at Aldermaston. This work, which was started originally at Imperial College by Sir George Thomson, has culminated in the construction of a 12-in. bore torus, Sceptre III. Within this torus temperatures of 4 million °C have been produced and about 100,000 neutrons per pulse are observed.

RADIO STUDIES DURING THE INTERNATIONAL GEOPHYSICAL YEAR 1957-8*

by

W. J. G. Beynon, Ph.D., D.Sc.†

Read at a meeting of the Institution in London on 5th February 1958. In the Chair: The President.

SUMMARY

The knowledge gained in the previous International Polar Years is briefly reviewed and some of the plans for radio measurements in the present I.G.Y. are described. The ionospheric investigations to be carried out are discussed under headings of vertical soundings, ionospheric drift measurements, back-scatter soundings, radio noise and atmospheric studies, and rockets and satellites; methods used and particular problems it is hoped to solve are briefly described.

1. Introduction

The present International Geophysical Year 1957-58 is the third in the series of large scale international co-operative researches. The two previous projects were called "Polar Years" and although the present enterprise was originally termed the "Third Polar Year" the title was changed to its present form when it became clear that observations would certainly not be confined to polar latitudes. Modern geophysical research owes much to the development of radio in one form or another and it is of some interest to review the progress of radio science, with particular reference to ionospheric studies, in the light of these three Geophysical Years organized in 1882, 1932 and 1957-58 respectively.

2. The First and Second International Polar Years

In the First International Polar Year (1882-3) the principal studies were in the fields of meteorology, geomagnetism and aurorae. Radio, of course, played no part in these geophysical activities. However, if radio waves were then undiscovered, the year of the First International Polar Year is of particular interest in ionospheric history since it was in 1882 that the British magnetician Balfour Stewart published his hypothesis that currents in a conducting layer, high in the terrestrial atmosphere, might explain the well-known regular variations in the magnetic elements. It had long been known that such variations occur and that these showed both solar and lunar influences, and in 1882 a remarkable article on "Terrestrial Magnetism" appeared in the ninth edition of the Encyclopaedia Britannica. In this Stewart discussed many hypotheses concerning these variations in the magnetic field and concluded (to quote his actual words) "I am driven by the method of exhaustions to look to the upper regions of the atmosphere as the most probable seat of the solar influence in producing diurnal magnetic changes, and it can be said that the only conceivable magnetic cause, capable of operating in such regions, must be an electrical current." Stewart then proceeded to suggest that "convective currents established by the sun's heating influence in the upper regions of the atmosphere are to be regarded as conductors moving across lines of magnetic force, and are thus the vehicle of electric currents which act upon the magnet."

This article by Balfour Stewart ensures that the year 1882 will be a landmark, not only in the history of International Geophysical Years, but also in the history of ionospheric studies. The suggested existence of an ionosphere thus originated in the field of geomagnetism; and, over the subsequent years, notable contributions to our knowledge of its electrical properties came from geomagnetic studies. The original "dynamo" hypothesis of Stewart was put

---

* Manuscript received 9th April 1958. (Paper No. 461.)

† University College of Swansea. Dr. Beynon is C.S.A.G.I. Reporter for the Ionosphere.

U.D.C. No. 621.396.11

on a quantitative basis by Schuster, and later developed in great detail by several workers, notably by Professor Sydney Chapman (the President of the I.G.Y.). However, the problem is still far from completely solved and is one which is receiving close attention in both the geomagnetic and ionospheric field in the I.G.Y.

The first Polar Year concentrated attention on the North polar area. Some 20 laters later, in 1902, there was a smaller scale effort in the Antarctic and, oddly enough, this year 1902 happens also to be a milestone in ionospheric history. This was the year of course, that A. E. Kennelly, a Harvard professor, and Oliver Heaviside, the English engineer and mathematician, independently suggested the existence of an electrically-conducting layer in the high atmosphere. These engineers Kennelly and Heaviside advanced the hypothesis in order to explain the success of another engineer, Marconi, in sending wireless signals from Cornwall to Newfoundland around a large part of the circumference of the earth. Heaviside made his suggestion in a rather casual manner in an article on the "Theory of Electric Telegraphy" which appeared in the tenth edition of the Encyclopaedia Britannica. After discussing the possibility of diffraction around the earth's surface as an explanation of long-distance wireless communication, Heaviside wrote: "There is another consideration. There may possibly be a sufficiently conducting layer in the upper air. If so, the waves will, so to speak, catch on to it. Then the guidance will be by the sea on one side and the upper layer on the other."

It is a matter of interest to note that the 1882 paper by the magnetician Balfour Stewart, and the 1902 hypotheses of the engineers Kennelly and Heaviside, mark the beginning of *two* facets of ionospheric studies. The one, the link with the terrestrial magnetic field, marks the purely *scientific* side of this branch of geophysics, and the other (the ionosphere as the medium for long-distance radio propagation) certainly emphasizes the *practical* aspect of the ionosphere. Today there is greater interest than ever before in both these aspects of the subject, and studies during the I.G.Y. will, without doubt, contribute much to our understanding of problems in both fields.

In the period 1902-1920 there was little direct reference to the ionosphere as such in the published literature, but there was of course much experimental confirmation of the hypotheses already advanced for an electrically charged high atmosphere. Direct experimental investigation of the ionosphere did not take place until the early 1920's with the pioneer work of Sir Edward Appleton in Britain and Breit & Tuve and Taylor & Hulburt in the U.S.A.

In the years immediately preceding the Second International Polar Year (1932-33) progress was rapid, and the year prior to the project witnessed some very important developments. It was in 1931 that Professor Chapman published a paper in which he made, what he subsequently rather modestly called "one tentative step" towards a theory of the formation of the ionosphere by solar ultra-violet light. Investigations over the past 20 years or so have clearly shown that that step has more of a *permanent* than a *tentative* character. We now know how correct are so many of the predictions of the Chapman theory, especially in respect of the E and F1 layers of the ionosphere. In fact these layers are now commonly referred to in the literature as "Chapman layers". It was in 1931, too, that Appleton developed the so-called "critical frequency method" of studying the ionosphere, whereby a comparatively simple radio measurement enables us to deduce the maximum electron densities in the various ionized layers. In 1932 Appleton, Hartree and others extended an earlier treatment by Lorentz and developed the general theory of electromagnetic wave propagation in an ionized medium in the presence of a magnetic field. Looking back, we realize now how fortunate it was that such work had been carried out just before the start of the Second Polar Year, thus providing a sound background against which the ionospheric observations of that Year could be planned and carried out. In 1932 the existence of the ionosphere had not merely been established but it itself had become a subject for special geophysical research. However, it was still very much the infant in the geophysical family and out of the 48 countries which joined in the observations of that year, only seven made any kind of ionospheric observation.

This is indeed in marked contrast to the present project in which elaborate ionospheric studies are being carried out by every participating nation.

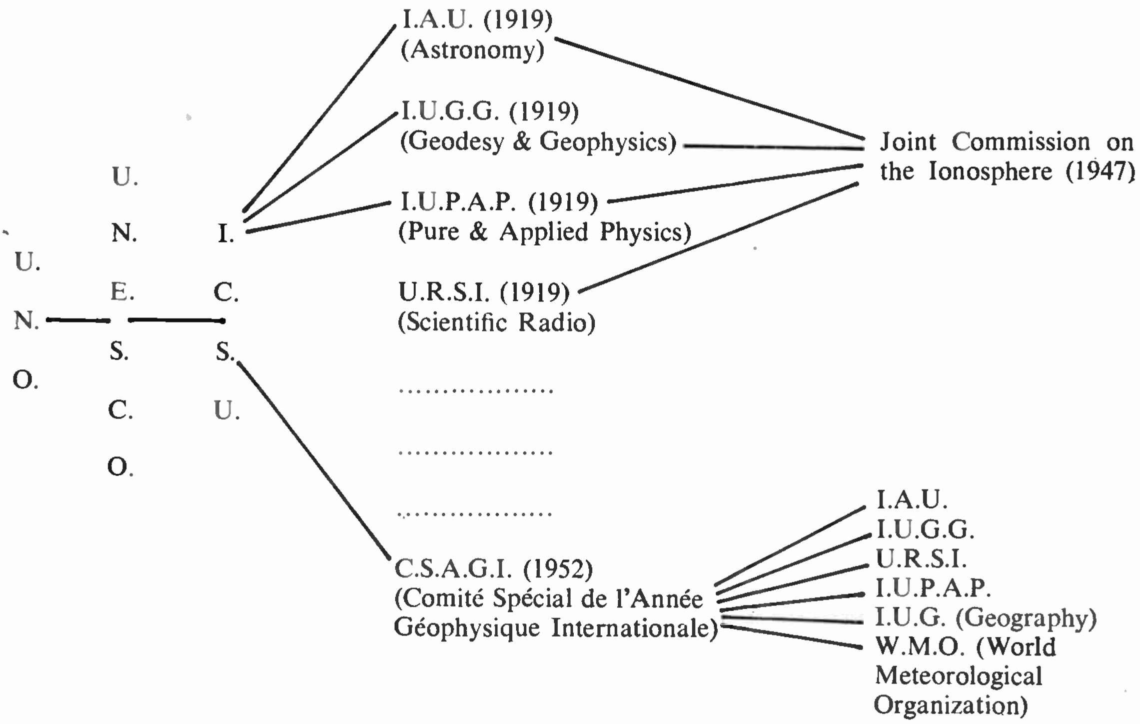
3. The Present I.G.Y.

There can be little doubt but that the present I.G.Y. is the most ambitious international scientific enterprise ever undertaken and for radio engineers and physicists it is a matter for some pride to recall that it was a small group of scientists, primarily interested in ionospheric physics, which first gave impetus to the proposal for an International Geophysical Year in 1957-58.

Today there is a growing and elaborate organization whereby co-operation in a venture such as the I.G.Y. may be effected. The set-up in international science is shown schematically in the Table. The premier international scientific body is the International Council of Scientific Unions (I.C.S.U.), a subsidiary of the United Nations Educational, Scientific and Cultural Organization (U.N.E.S.C.O.), which is itself a subsidiary of the United Nations Organization. At present there are eleven Scientific Unions affiliated to I.C.S.U. and a number of these were founded immediately after World War I. These International Unions are linked to the individual scientists of each nation by the "National Committees", these Committees being sponsored by the premier scientific body in the country concerned. It sometimes happens, as in the case of the ionosphere, that there is a field of interest common to scientists from several Scientific Unions. Thus four International Unions—Astronomy, Physics, Geomagnetism and Radio—are interested in the problems of the ionosphere, and in 1947 these Unions each nominated three or four representatives to form the "Joint Commission on the Ionosphere." This Commission, consisting of some 12 members, met first in Brussels in 1948 and has since held four

TABLE

The International Organizations concerned with I.G.Y.



meetings at which current ionospheric problems have been discussed. The special I.G.Y. interest attached to the Joint Commission on the Ionosphere is that it was this body, in September 1950, which first sponsored the project. The proposal for holding an I.G.Y. originated in April 1950 at a small informal meeting of a few scientists in the U.S.A. Two of those concerned in these informal discussions (Professor Sydney Chapman and Dr. Lloyd V. Berkner), were also members of the J.C.I. and they brought the proposal to a meeting of the Commission in Brussels in August 1950. This Commission endorsed the proposal, prepared a memorandum on it and later the project received the support of the various International Scientific Unions. In 1952 I.C.S.U. formed a special committee to organize the scientific programme to be undertaken during the I.G.Y. This Committee, usually known as "C.S.A.G.I." —from the initials of its title in French (Comité Spécial pour l'Année Géophysique Internationale)—first met in 1953 and in the period 1953-56 it prepared detailed plans for intensive observations in all the various geophysical disciplines. Within the C.S.A.G.I. organization the 14 major sections are (i) World Days, (ii) Meteorology, (iii) Geomagnetism, (iv) Aurora and Airglow, (v) Ionosphere, (vi) Solar activity, (vii) Cosmic rays, (viii) Latitudes and longitudes, (ix) Glaciology, (x) Oceanography, (xi) Rockets and Satellites, (xii) Seismology, (xiii) Gravity measurements, (xiv) Nuclear radiation. In at least nine of these disciplines radio plays a vital part, and in the case of ionospheric studies radio is, of course, the prime means whereby such investigations are made.

4. Ionospheric Studies during the I.G.Y.

4.1. *Vertical Soundings*

In planning the I.G.Y. ionospheric programme first priority has been given to measurements at "vertical incidence". Radio sounding of the ionosphere employs a pulse-modulated sender with a suitable receiver and auxiliary gear for recording the signals. In routine sounding apparatus the sender and receiver are located in the same equipment so that signals emitted by the sender and received again at the same site will have been incident vertically on the upper atmosphere. The most important parameter measured with such equipment is the vertical incidence critical penetration frequency (f_c). This is the highest frequency which can be reflected at vertical incidence by any particular layer and its scientific and practical importance lies in the fact that if f_c is measured then we can at once give the maximum electron density (N_{max}) in the layer concerned, for it can readily be shown that $N_{max} = (\pi m/e^2)f_c^2$ or $N_{max} = 1{\cdot}24 \times 10^{-8} f_c^2$ when the values of e and m appropriate to electrons are inserted.

One of the reasons for holding the Third International Geophysical Year some 25 instead of 50 years after the Second is the rapid advance in technique which has taken place since 1932-33, especially in the radio field, and this advance can be illustrated by reference to this one type of measurement, namely the measurement of critical frequency and hence of electron density.

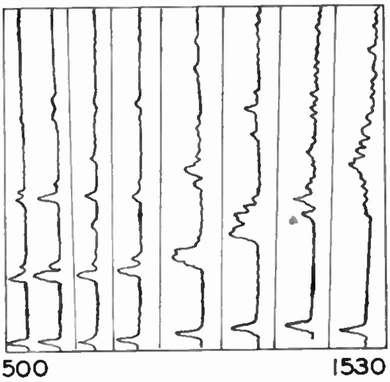
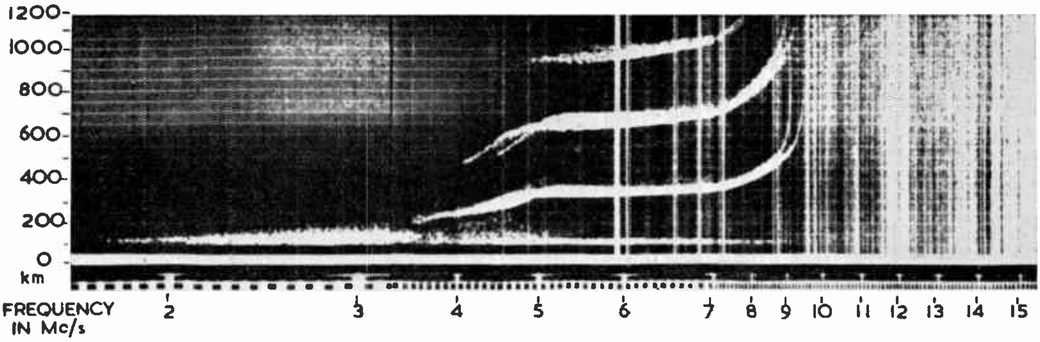
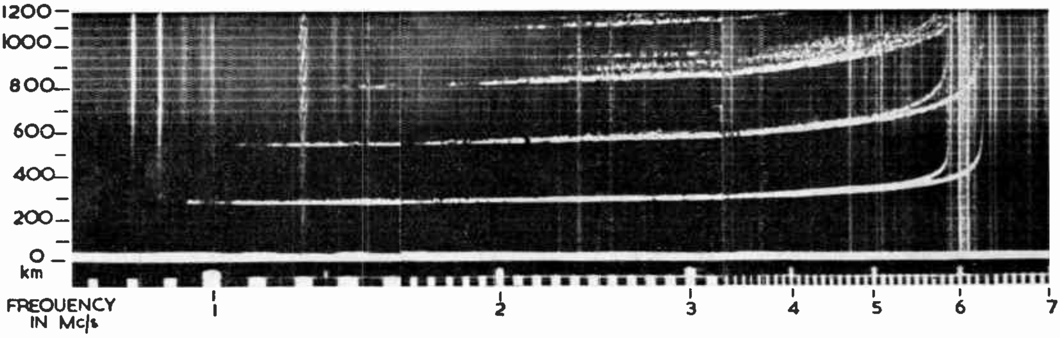


Fig. 1. Ionospheric record taken at Trömso by British expedition during Second International Polar Year 1932-3. (Reprinted by courtesy of the Royal Society.)

Twenty-five years ago, at the time of the last Polar Year, this critical frequency technique was in its earliest stages of development and critical frequencies were in fact then measured by taking a series of snap photographs of the face of the cathode-ray tube at different frequencies. Thus Fig. 1 shows a set of eight such snap pictures taken by the British team at Trömso, Norway, (70°N) on the occasion of the British Polar Year Expedition to that site in 1932-33. These snap pictures were taken at



(*a*) Daytime record.



(*b*) Night record.

Fig. 2. Typical ionograms from a modern ionosonde

intervals of about 0·25 Mc/s from 4·25 Mc/s to 6 Mc/s and it will be seen how the signals penetrate the layer with increasing frequency. This was the type of ionospheric record obtained during the last Polar Year and used to estimate the electron densities in the ionospheric regions. Such records are to be contrasted with modern records shown in Fig. 2. These show equivalent height of reflection for the complete range of frequencies and are typical of records taken regularly at many observatories throughout the world. Fig. 2 (*a*) shows a sweep from 1·5 Mc/s to 15 Mc/s during the daytime and Fig. 2 (*b*) a sweep from 0·5 Mc/s to 7 Mc/s made at night. Such sweeps take one or two minutes—the equipment working quite automatically being switched on by a clock. The clarity of the records, the ease and accuracy with which critical frequencies and heights of reflection can be measured, are obvious. Recorders are now available which cover the whole frequency band in a matter of seconds and permit the observation of transient phenomena which would have been quite impossible some years ago.

Records of this kind, so-called "*p*/*f* records" or "ionograms", are being taken during the I.G.Y. at least hourly, and often quarter-hourly or at 5 minute intervals, at 170 observatories and they form the most important raw material of ionospheric research. Indeed many of the outstanding problems of the ionosphere arise from the study and interpretation of such records. Some of the ionospheric problems which it is hoped the greatly improved I.G.Y. network of vertical incidence stations will help to solve may be summarized as follows:

(i) To what extent do the E and F1 layers depart from the predictions of the simple theory for the formation of these layers by solar ultra-violet light first propounded by Chapman in 1931?

There is evidence that the assumption of isothermal conditions will need revision and recent work suggests that some of the discrepancies between theory and observation results from the influence on the E layer of the electric current system first proposed in 1882 by Balfour Stewart.

(ii) Why is the electron density in the F2 layer less in local summer than in local winter? Expansion of the layer in summer with a consequent reduction in electron density was the suggestion originally made for this anomaly but various reasons now make such a simple explanation untenable.

(iii) Is the F2 layer formed by solar radiation in the manner accepted for regions E and F1 or are both the F1 and F2 layers formed by a single ionizing process with the latter appearing as a consequence of the fall in recombination coefficient with height? (A proposal originally made in 1938 by Bradbury.)

(iv) What is the precise mechanism whereby the F2 layer suffers the very marked geomagnetic distortion shown in observations at low latitude stations?

(v) What are the true heights of the ionospheric layers?
It may seem a little surprising that there should still be uncertainty about the actual heights of the various layers in the ionosphere. Conventional radio sounding methods can only give the equivalent heights of the layers and in certain conditions these heights (e.g. in the case of the F2 layer on a summer day) can be grossly different from the true height of the layer. Elaborate methods are now available for calculating these true heights of reflection but some important uncertainties still remain.

(vi) What are the causes of the various types of "sporadic E" ionization which appear on ionograms?
Studies of records from widely spaced observatories suggest that there may be many different types of sporadic E ionization and that there are likely to be a number of different causes for this ionization near the 100 km level.

The above form just a small sample of the long list of problems which await answers. Many of these will still be unsolved at the end of 1958 and no doubt new problems will have arisen, but it is hoped that I.G.Y. observations will throw light on at least some of these.

The years since 1932-3 have witnessed, not only remarkable progress in matters of tech-

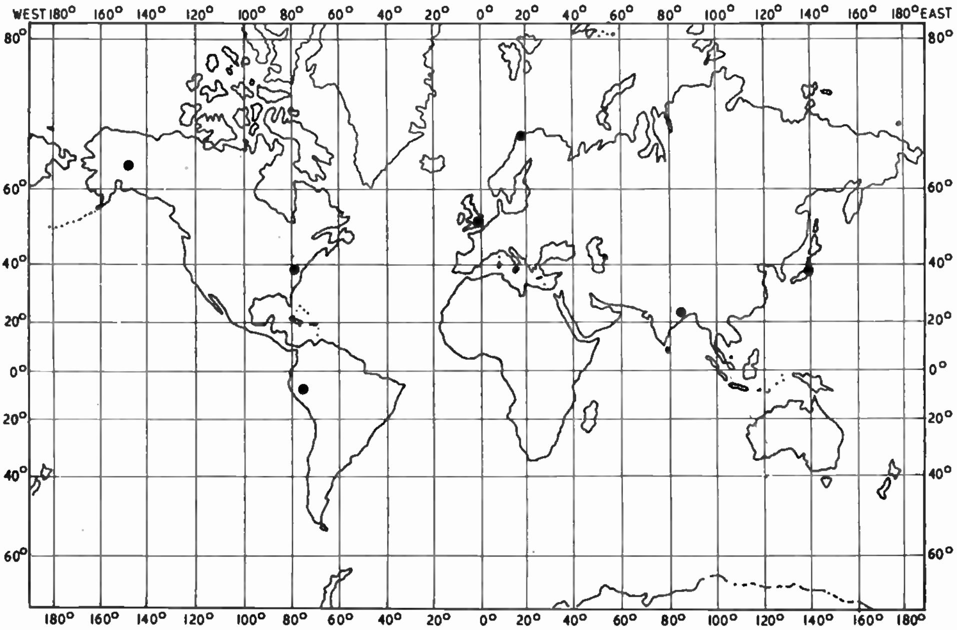


Fig. 3. Location of Ionospheric stations during Second International Polar Year 1932-3.

nique but also a considerable increase in the *types* of ionospheric measurement and, of course, in the *number* of locations at which regular ionospheric observations are made. In 1932 *some* ionospheric data were obtained from the seven locations shown in Fig. 3, but at only two or three stations were any kind of routine measurements made. Not only were there very few stations, but, owing to the limited technical resources, the programme of observations was also quite restricted. Thus the International Programme for that Year recommended *noon* measurements of critical frequency on a total of 31 days during the Polar Year (16 noon measurements of the E layer critical and 15 of the F layer critical frequency). The enormous expansion in the scale of ionospheric measurements since 1932 is indeed emphasized when this modest programme of 31 noon measurements is compared with the schedule for the I.G.Y. In the I.G.Y. each of the *170* observing stations is recommended to make ¼-hourly observations on a normal day and at still more frequent intervals during the Regular World Days and Special World Intervals.

In the twenty odd years since 1932 routine ionospheric observatories were established in many places and by 1954 there were some 70 stations at which ionospheric observations were being made at least hourly. With 70 stations the prospect of obtaining a world picture of ionospheric conditions, and of their variations with time and place, was much nearer realization but even so, these stations distributed rather unevenly over the world inevitably left serious gaps in the network. In planning the distribution of I.G.Y. ionospheric stations we have tried, as far as possible, to take care of these gaps. Fig. 4 shows the locations of stations making routine vertical incidence soundings during the I.G.Y. It will be seen that there is a fair concentration of stations in equatorial latitudes and it is hoped that this will permit a closer study to be made of geomagnetic distortion in the neighbourhood of the magnetic equator. An attempt has also been made to provide meridional chains of stations near the three longitude zones 75°W, 0–10°E and 150°E thus permitting a study of the marked longitude effects observed in region F2. A special effort is also being made to form an ionospheric picture of the vast Antarctic area and there are at least 16 stations making measurements in the

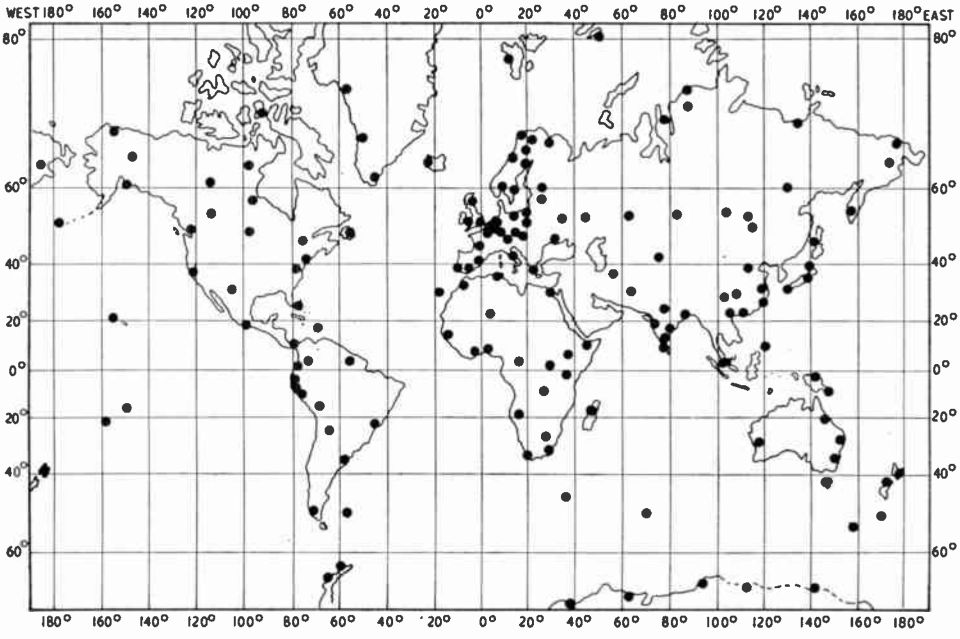


Fig. 4. I.G.Y. vertical sounding stations (between latitudes 70°S and 80°N).

Antarctic zone. The main British contribution is being made at Halley Bay (75·5°S, 26·6°W).

4.2. *Ionospheric Drift Measurements*

Another type of ionospheric measurement which figures prominently in the I.G.Y. programme, and which was completely absent on the occasion of the last Polar Year is the study, by radio methods, of movements or "drifts" in the ionosphere. It may appear strange that although in his original memoir of 1882 Balfour Stewart suggested *movement* of ionization as the cause for the magnetic variations, it is only within the last few years that we have again begun to think about the dynamics of the ionosphere. It is now established that there are quite pronounced movements in the ionosphere, some of which are regular in character with daily and seasonal variations whereas others appear to be of an irregular, turbulent nature. A number of radio methods are now available for observing these and they all depend on the identification and tracking of some irregularity in the ionosphere. It is to be emphasized that radio methods can of necessity only directly detect the movement of the *ionized* component in the high atmosphere and this may not necessarily mean that the unionized atmospheric constituents move with the measured velocities. In the case of region E there is evidence that the ionized and neutral constituents move together but in region F2 it is suggested that the apparent movement of irregularities may in fact be a manifestation of some form of travelling wave. In one method of measuring drifts ionospheric signals from a single pulse or c.w. sender are received at three fairly closely spaced receivers. These signals reflected from the ionosphere are, of course, continually fading in amplitude and if the fading patterns obtained with three closely spaced receivers are examined they are found to show a marked resemblance, but often corresponding irregularities show a clear time displacement. The fading itself is to be attributed to the influence of irregularities in the ionosphere and the time displacement of the fading pattern on the ground may be interpreted as due to the movement of these irregularities in the ionosphere. Hence, a measurement of time displacements at the three receiving stations can be used to calculate the speed and direction of movement of irregularities in the ionosphere. This so-called "radio fading method" has been used with marked success for studying horizontal movements in the E region of the ionosphere, and drift velocities of 50 metres/sec or so, with clear diurnal and seasonal variations, have been detected.

In a second method, which has been successfully employed to study the much larger scale irregularities often found in region F2, instead of three receivers we use *one* receiver and *three* pulse modulated transmitters. In this case the three pulse senders operate on a common frequency and may be located perhaps 50 km from the receiving site. The pulses from the three senders are usually recorded side by side on 35-mm film. As an irregularity moves across the reflection points of the three signals, some characteristic pattern appears in turn on the three traces. Measurement of the time delays gives the speed and direction of motion of the irregularity in the reflecting layer. Fig. 5 shows a typical example of an irregularity on three traces recorded recently at Swansea.

Another simple method which we have successfully used for tracking really large scale ionospheric irregularities consists in comparing vertical incidence records at three or more observatories. Sometimes there are quite

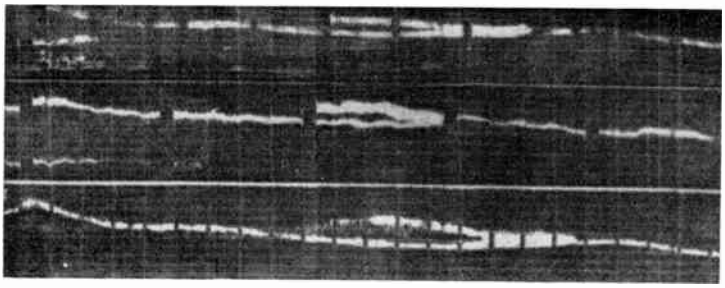


Fig. 5. Typical irregularities in equivalent height observed at Swansea on fixed frequency signal from three senders.

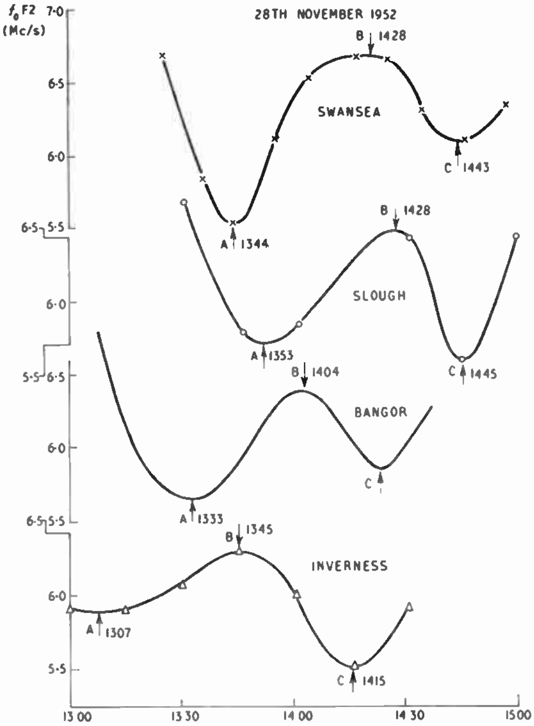


Fig. 6. The measurement of drift velocities by comparing vertical incidence ionograms. Typical example of a perturbation in f_0F2 observed at four stations in Great Britain separated by 180 to 700 km.

pronounced changes in electron density or in height of the layer, which can be observed at ionospheric sounding stations hundreds of km apart. Fig. 6 shows an example of an irregularity in the F2 layer which travelled at least 700 km in ¾ hr or so.

At *one* or *two* stations a fair amount of data have now been collected on ionospheric movements and in some cases a fairly definite pattern seems to emerge. Thus in the E layer there appear to be quite well defined semi-diurnal tidal variations and a clear seasonal variation in the direction of drift. The magnitude of the drift velocity also seems to show some degree of correlation with magnetic activity (Fig. 7). There are of course, many new problems arising in connection with movements in the ionosphere and during the I.G.Y. we cannot hope to solve more than a fraction of them, but there is at least one important problem on which we hope to get valuable information. This concerns the vertical structure of the ionospheric wind system. There is a growing body of evidence that in the ionosphere the drift velocities show a marked variability with height in both magnitude and direction. In the lower part of region E radar observations on meteor trails have revealed very large height gradients in the wind speed and there is evidence too for a general increase in velocity from region E to region F2 and beyond. The vertical structure of these movements will undoubtedly be related to the temperature gradients and to other physical parameters such as the kinematic viscosity of the medium and it is certain that the study of horizontal movements will lead to an improved knowedge of these basic properties. Although during the I.G.Y. there are some 40 stations making ionospheric drift measurements, it is clear that this number is quite inadequate to yield the complete world pattern of atmospheric movements above the 80 km level. Perhaps, when the next I.G.Y. is organized, there will be as many stations making routine drift measurements as are at present making vertical soundings.

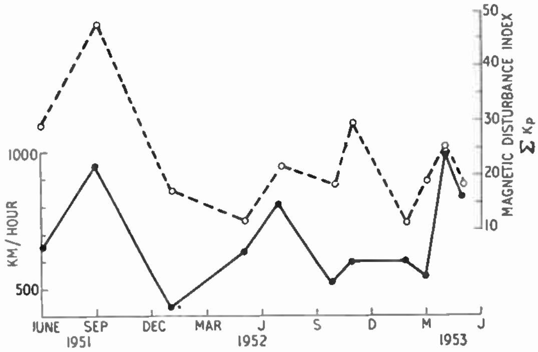


Fig. 7. Correlation between magnitude of drift velocity in region F2 and the degree of magnetic disturbance (ΣKp).

4.3. *Back Scatter Studies*

A new technique of radio sounding which has been developed rapidly in recent years is that known as "back scatter sounding" and studies using this technique are being made during the I.G.Y. at many sites. Many years ago it was observed by T. L. Eckersley and others, that when a fairly high power radio sender is employed, signals can be detected at receiving points near the sender, which have arrived back after scattering at the ground many thousands of kilometres away. It is now established that the type of transmission shown in Fig. 8 often occurs and that back scattering is especially pronounced around the edge of the "skip zone" centred on the sender and receiver.

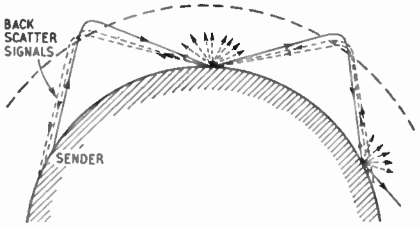


Fig. 8. Reception of signals near the sender after back-scattering at the ground.

Studies of these back scatter signals can thus be used to investigate ionospheric conditions at points which may be several thousands of kilometres from the sending and receiving stations. At present this technique cannot yield the precise information that is given by vertical soundings but by using highly directional and rotatable aerial systems it can provide valuable data concerning the ionosphere in remote and inaccessible areas. In the I.G.Y. there are about 20 stations making such measurements.

4.4. *Radio Noise and Atmospheric Studies*

Studies of atmospheric noise and its variations with frequency and with time will be made at some 40 stations during the I.G.Y. The term "atmospheric radio noise" is used to denote electromagnetic radiation arising from phenomena in the earth's atmosphere and it is generally accepted that most radio noise originates in the lightning flashes associated with thunderstorms. These lightning flashes radiate energy over a wide range of wavelengths and the noise received at any station will consist of the integrated effect of the radiation from a large number of storms. The intensity of the noise is greatest in the equatorial land masses where the storms are most prevalent, but may be important also in temperate regions where the noise is received, partly from local storms, and partly by way of radiation propagated via the ionosphere from distant storms. It is clear that a knowledge and understanding of atmospheric radio noise is of immense practical importance in radio communication problems but until recently the proper scientific study of terrestrial noise has been hampered by a lack of agreement on what characteristics should be measured. In planning the I.G.Y. work in this field, much thought has been given to this problem and one of the objectives of I.G.Y. radio noise studies is to obtain as large a body as possible of comparable data from many observing points.

In addition to collecting reliable data on radio noise, many groups will also be studying the waveform and frequency spectrum of low frequency atmospherics and investigating the influence of the ionosphere on the propagation of such audio frequency radio waves.

An interesting special kind of low frequency atmospheric is that to which the name *whistler* has been given. A "whistler" is an audio-frequency atmospheric having a characteristic note generally of descending frequency and was first observed by the German physicist Barkhausen during the first world war. It is now believed that whistlers originate in lightning flashes and that the very low frequency components of the associated atmospherics are propagated along the lines of the earth's magnetic field from one hemisphere to the other. Now although theory shows that radio waves of low frequency will, in general,

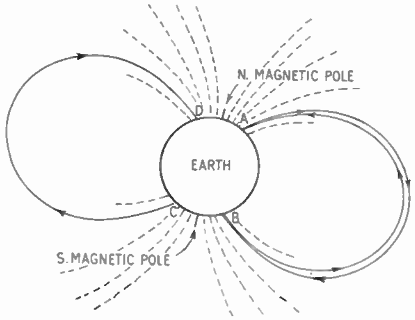


Fig. 9. The production of "whistler" type atmospherics. An atmospheric originating at point A may be reflected at the conjugate point B and give rise to a "long whistler" at or near A.
An atmcspheric originating at point C produces a "short whistler" at D.

be *reflected* by the ionosphere one finds that at extremely low frequencies one of the magneto-ionic components (the "extraordinary" ray) can in fact penetrate the ionosphere. These very low frequency radio signals can then be propagated along the lines of the earth's magnetic field, be reflected again from the point in the other hemisphere and thus return back along the magnetic field to the hemisphere of origin (Fig. 9). The changing pitch of the whistler arises from the dispersion of the different component frequencies which can occur in the long propagation paths possible in the outer atmosphere of the earth. The result of this dispersion is that the frequency of maximum energy changes with time and thus produces an audio note of changing frequency. The tops of the trajectories of these whistler atmospherics may be several thousand km above the earth, well above the ionosphere, and thus the study of whistlers can provide, and is providing, invaluable information on regions of the earth's atmosphere quite inaccessible to ordinary radio sounding from the ground.

4.5. *Rockets and Satellites*

One of the features which will really distinguish the I.G.Y. of 1957-58 from earlier Polar Years is of course the use of rockets and satellites for the study of the earth's upper atmosphere and for direct observation of the incoming solar radiations. Rocket upper air research began in the U.S.A. in 1945 when a number of V2 rockets captured from the Germans were fired. Now although it is 13 years since the rocket programme began and some hundreds of rockets have been fired into the high atmosphere the actual observing time has only totalled a matter of hours, since the complete flight up and back takes about 6 minutes, and of this only 2 or 3 minutes are spent in the ionosphere. Rockets are very expensive but research with them has been considered worthwhile because the rocket makes possible direct observations of the many quantities which cannot otherwise be observed at all (e.g. the ultra-violet end of the solar spectrum). Plans for many rocket firings during the I.G.Y. have been announced by the U.S.A. and the U.S.S.R. In this country successful tests have recently been made of the British high altitude rocket "Skylark" and five University groups working under the auspices of a Royal Society Committee have been invited to co-operate in experiments with this rocket. A group at University College London is proposing to measure air temperature and wind speed; wind structure is also being studied by a group at Imperial College; air-glow studies are being organized by the Belfast group; the mass and charge of particles in the ionosphere is being studied by the Birmingham group and the group in Swansea is undertaking certain radio propagation experiments using rocket-borne radio equipment.

Perhaps of even greater interest is the launching of artificial earth satellites recently achieved by the U.S.S.R. and by the U.S.A. The launching of a satellite for real scientific purposes and not merely as a stunt was considered by the U.S.A. I.G.Y. Committee some four or five years ago and it was concluded that there were several valuable geophysical and solar researches which could be carried out with such a vehicle. Studies with a satellite will complement those made with a conventional rocket but will not replace them. This is clear when one considers what the satellites actually do. Remaining for some considerable time in their orbits above the atmosphere, they should enable one to obtain a picture of conditions outside or on the fringe of the atmosphere over extended periods of time. The rocket is only at these levels for a matter of seconds but the satellites can be there for weeks, months or even years. With satellites, quantities such as the amount of solar energy entering the earth's atmosphere can be studied; careful observation of the orbits should enable accurate measurements of terrestrial distances to be made or deductions made about the shape of the earth and the world wide study of cloud cover is another possibility. Observations on radio signals from satellites will clearly be valuable for ionospheric studies.

5. I.G.Y. Data Centres and Publications

Any survey of the I.G.Y. programme would be incomplete without some reference, however brief, to the quite considerable effort which has been, and still is being, devoted to the problem of the collection, analysis and subsequent publication of the immense body of data obtained. It has been fully realized that the mere collection of observations in all the various fields of geophysics is only the beginning of the task and is in itself of little use, unless research workers everywhere are given the opportunity to study the data and publish the results of their findings. To this end we have, in each I.G.Y. discipline, established a number of World Data Centres, at which all I.G.Y. data in that particular field will be collected, catalogued and generally preserved in an orderly manner. Four Data Centres have been established for ionospheric and radio data—Washington, Moscow, Tokyo and in this country at the Radio Research Station, Slough. In each of these Centres it is planned that I.G.Y. data in the ionosphere and radio fields will be collected and made available to all bona-fide research workers. The question of publications is being handled by a strong international Committee which has already initiated a series of publications under the title *Annals of the I.G.Y.* The great majority of the scientific papers dealing with I.G.Y. studies will, of course, appear in the normal scientific journals, but the *Annals of the I.G.Y.* will contain all information relevant to present and past projects of this kind together with certain basic I.G.Y. observations. The *Annals* also contain various Instruction Manuals and programmes for the different disciplines and later they will contain a great deal of authoritative post-I.G.Y. surveys of results in the different fields.

6. Conclusion

In this paper, it has been quite impossible to do more than touch upon some of the activities of radio scientists during the I.G.Y. A familiar question relating to the I.G.Y. concerns results to be expected. In reply it can be said that certain short-term benefits from the I.G.Y. programme (by way of solutions of certain specific problems) are fairly obvious but, like all other purely scientific projects, the long-term benefits of this great enterprise are unpredictable.

DISCUSSION

H. V. Griffiths*: Dr. Beynon will understand that although Tatsfield is one of the I.G.Y. centres observing ionospheric phenomena, and has indeed made such observations for many years, a receiving and measurement station cannot well tolerate the use of pulse transmitters for making vertical incidence critical frequency measurements on site. The pulse signal would sweep through frequency bands and thus be likely to interfere with normal radio reception and relaying undertaken in the locality. There might be a similar objection to the other, very valuable method of exploring ionospheric conditions by the back-scatter technique which Dr. Beynon also described.

For this reason, we have taken advantage at Tatsfield of the very large number of regular, long period transmitters of all types which are distributed over the h.f. and v.h.f. bands and are located in North America. Experienced observers, given data on the signals including their frequencies, times of probable operation and approximate power, can quite quickly tune a receiver through the frequency bands and locate the "highest receivable frequency" (in our abbreviation, the h.r.f.) for the path to North America at hourly or two-hourly intervals throughout the day and night, and these h.r.f. values give a practical condition for the path. We limit the stations observed to the line northward of latitude 30° N in U.S.A., since the conditions for more southerly paths differ. A similar type of observation may be made for the eastward path but with rather greater difficulty because the spectral distribution of the fewer and less closely-spaced transmissions in that direction tends to widen the "steps" of the frequency scale of the h.r.f.

Although the h.r.f. may not exactly represent the m.u.f. for the path, it gives what I may suggest to be a rather realistic value, as distinguished from the m.u.f. derived from a single

---

* British Broadcasting Corporation, Technical Receiving Station, Tatsfield.

vertical-incidence measurement *at one end of the total path,* such as the critical frequency measured in U.K. The h.r.f. for the westward, U.S.A. path is also sensitive in indicating ionospheric disturbances of the long period type, and of the day-to-day fluctuations about the monthly mean m.u.f. It gives warning of the likelihood of long distance interference with U.K. television and, for the eastward path, of the more intense cases of sporadic-E layer refraction. For the short period disturbances or S.I.D.S, we record continuously the strength of a West European broadcast in the 6 Mc/s band which is responsive to increases in absorption.

D. W. Heightman (Member)*: In reviewing some of the problems upon which it is hoped the I.G.Y. would throw more light, Dr. Beynon first referred to reduction of the F2 layer critical frequencies which is found to occur from winter to summer. From observation work on maximum usable frequencies of the F2 layer over the period of a solar-cycle, I have noted that the *difference* between the winter and summer F2 layer m.u.f.s is considerably *less* during sun-spot minimum years than years of maximum solar activity.

Dr. Beynon also referred to the fact that F2 critical frequencies are normally found to be lower over the equator than in sub-tropical latitudes in northern and southern hemispheres. I have also observed, however, that under ionosphere storm conditions, trans-equatorial maximum usable frequencies are often abnormally high, whilst higher and polar latitudes have very low m.u.f.s.

It seems to me that these two effects point to the possibility that the F2 layer ionization could result from two forms of radiation or corpuscular "stream" originating on the sun. According to local geomagnetic conditions, and the relative intensities of the radiations, these radiations might be complementary to one another, or otherwise.

Commenting on recent observations of exceedingly high sun-spot activity, I confirm that maximum usable frequencies observed for trans-Atlantic routes during November and December 1957, have been higher and more consistent than those observed in the past two sun-spot maximum cycles. M.u.f.s exceeding 50 Mc/s were noted on the majority of days during November and December 1957. Similar m.u.f.s have continued in early 1958 but there has been a falling off in the North Atlantic frequencies.

T. W. Bennington†: Replying to Dr. Beynon's invitation to Mr. Heightman's points I think his first observation must be due to the effect which has been described by Sir Edward Appleton. He found that during ionospheric storms there is a positive phase (during which the critical frequencies and m.u.f.s are increased) as well as a negative phase (during which they are decreased). In high latitudes one observes the negative phase only and then in mid-latitudes there is a short positive phase followed by a long negative phase. As one follows the course of the disturbances from the auroral zone towards the Equator the positive phase gets longer and longer, until in equatorial regions one is left with the positive phase only. Hence this enhancement of usable frequencies during storms in equatorial regions may account for Mr. Heightman's observations. Certainly in this country we often observe a definite increase in m.u.f.s before the negative phase of a storm starts.

As to Mr. Heightman's second point I think the discrepancies between calculated and observed m.u.f.s are not yet completely solved. Now that we are able to observe the propagation of very high frequencies like that of the Crystal Palace sound channel in places as far distant as South Africa we can observe that the seasonal variation in daytime m.u.f. is certainly as predicted: a decrease in m.u.f. towards midsummer. I don't think, therefore, that the discrepancy between calculated and observed m.u.f. is now very great in the daytime. Observations on North Atlantic circuits, however, show that signals are received during the night on frequencies well above the calculated m.u.f. However, when we mention this to the telegraph people they say that they cannot "print" on these frequencies. Hence, though quite often apparently good signals are received

---

* Radio Rentals Ltd.

† British Broadcasting Corporation, Research Department.

on these frequencies, the signal structure would appear to lack coherence, the implication being that the signals are due to some form of scatter, and not to the normal refractive process.

I would like to point out that the ionosphere is at present capable of propagating signals on exceptionally high frequencies, and that, at least during the daytime, these high frequencies are not only observed but predicted. The predicted m.u.f. for the North Atlantic has of late been well over 42 Mc/s, and since this is a monthly median value, one would expect that on certain days frequencies of the order of 50 Mc/s would be propagated. That such frequencies are at present propagated is well borne out by observations, for my colleague, Mr. Griffiths, regularly observes reception on 50 Mc/s across the Atlantic at Tatsfield, and on one occasion I believe the frequency received was 59 Mc/s.

M. S. Trojanowski*: The launching of artificial satellites into orbits around the world and equipped with high frequency radio transmitters means that, for the first time in the history of ionospheric studies, we have a signal source actually in the ionosphere.

My colleagues and I have been actively engaged in the propagational aspect of satellite tracking, but it was also our good fortune to obtain a recording of the "round the world" echoes. This recording is quite impressive. Amplitude recordings were also made, and the presence of fadings due to various causes is easily detectable. One other method of ionospheric investigation is provided by noting the appearance of signals on 40 Mc/s and on 20 Mc/s on the same transit, the lower frequency being received later due possibly to reflection from the "upper surface" of the ionosphere.

From the amount of data collected by us and other workers, it is obvious that transmissions on lower frequencies are very desirable. It is a great pity to notice that some satellites are being launched without being equipped with high frequency transmitters. Could I ask Dr. Beynon as the Secretary of the International Joint Commission on the Ionosphere and the Member of the C.S.A.G.I. to use his influence in persuading the launching authorities to include high frequency pulsed transmitters in further satellites for ionospheric research.

E. D. R. Shearman†: Some results obtained by the back-scatter technique may be of interest in the discussion of long range propagation. As part of the I.G.Y. programme of observations at the D.S.I.R. Radio Research Station at Slough, we are operating a back-scatter sounder using the principles to which Dr. Beynon referred. (See, e.g., Wilkins & Shearman, *J.Brit.I.R.E.*, **17**, p. 601, 1957). Pulse transmissions at 17 Mc/s are radiated from a rotating directional aerial, and the back-scatter echoes from distant ground areas are displayed on a plan position indicator. This display shows the locus of the boundary of the skip-zone surrounding Slough, and records of this show the variation of skip distance at 17 Mc/s with direction, time of day, season and sunspot cycle. A typical winter-day skip distance two years ago was 2,000 km, whereas in this year of high sunspot activity skip distances of 500 km are usual, and on one occasion, zero skip distance of 17 Mc/s was observed. This implies a vertical-incidence critical frequency of 17 Mc/s, which corresponds to a limiting maximum usable frequency for long distance transmissions of 50 to 60 Mc/s depending on the layer height.

D. C. Mellon (Member)‡ stated that in his experience the highest receivable frequency over trans-Atlantic paths was 56 Mc/s. During propagation trials at Gander, Newfoundland, and in Greenland, he had received simultaneously transmissions at this frequency from Texas and from Paris. Calculations had shown that these were due to reflections taking place in the F2 layer.

Dr. J. M. Stagg§: It is good for radio engineers to be reminded that they do not have a monopoly of the ionosphere! As Dr. Beynon has reminded us, Balfour Stewart postulated the need for a conducting layer in the high atmosphere 75 years ago to explain the regular quiet day variations in the earth's magnetic field. What Dr. Beynon did not have time to tell us

---

* Propagation Research Group, Research Laboratories, Marconi's W.T. Co. Ltd.

† Radio Research Station, Slough.

‡ Communications Division, Marconi's W.T. Co. Ltd.

§ Meteorological Office.

is that the current systems produced in the ionospheric dynamo must carry up to about 90,000 amperes even on magnetically quiet days, and they probably carry still greater currents, up to half a million amperes at times, above the arctic and antarctic zones of maximum auroral frequency on days of great magnetic disturbances.

The geomagnetic records leave no doubt that these currents exist at some level in the ionosphere but the records alone cannot specify their precise height above the earth's surface.

Can Dr. Beynon tell us whether there is any direct evidence from the radio side about these high level current systems, and is any special effort to be made during the I.G.Y. in order to determine their shape, height and intensity by radio means? Some information about the high density electro-jet above the geomagnetic equator needed to account for the magnetic quiet day variations at places like Huancayo on that equator would be specially valuable.

K. Burrows (Associate Member)*: In the Geophysics Department of the Imperial College of Science and Technology we hope to investigate the density and height distribution of any ionospheric currents by measuring their associated magnetic fields by nuclear precession magnetometers. The magnetometers will be carried up to heights greater than that of the E region by means of "Skylark" rockets launched from the Woomera rocket range.

Dr. Beynon (*in reply*): Mr. Griffiths has very properly drawn attention to the valuable work being carried out at the B.B.C. Receiving Station at Tatsfield. The usual pulse method of sounding the ionosphere is certainly a source of interference to other users, especially since we must cover the whole frequency band, and it is good to be told about the unobtrusive ionospheric studies which go on at Tatsfield. There is little doubt that careful measurements of this kind can provide very reliable measures of the highest and optimum frequencies suitable for long distance h.f. transmissions.

I am glad to hear Mr. Bennington say that there is now good agreement between calculated and observed m.u.f.s, at least in the daytime. Years ago, soon after Sir Edward Appleton and I developed our parabolic layer method for calculating m.u.f.s, we were involved in the controversy concerning the discrepancy between calculated and observed values and in our search for the cause of the trouble we received much helpful data on observed m.u.f.s from the practical users including Mr. Bennington. I should say that from the theoretical side one would anticipate a greater likelihood of a discrepancy in the daytime and if this is now cleared up then I think that the cause for any discrepancy at night must be sought in some unusual transmission process such as pronounced lateral deviation or scatter.

The difference between winter and summer F2 layer m.u.f.s over the sunspot cycle noted by Mr. Heightman is consistent with long-period vertical incidence ionospheric soundings. The m.u.f. is really determined by two factors—one factor is dependent on layer height and thickness and the other is the vertical incidence critical frequency (f_0F2). The factor dependent on the height and thickness diminishes slightly with increasing solar activity but the m.u.f. itself greatly increases over the sunspot cycle because of the increase in f_0F2. From the 1944 sunspot minimum to the 1948 maximum the value of f_0F2 at this latitude changed from 5 Mc/s to about 8 Mc/s in summer but from 6 Mc/s to 12 Mc/s in winter, and this seasonal difference between the solar cycle variation is probably the explanation of Mr. Heightman's observation. It is interesting to hear from Mr. Shearman that the backscatter measurements confirm that recently the transmission of frequencies of 50 to 60 Mc/s over long distances is to be expected.

I think Mr. Trojanowski has voiced the opinion of all ionospheric workers in hoping that future satellites will be equipped with transmitters radiating suitable signals for studying the ionosphere.

Dr. Stagg's question about radio detection of the ionospheric current systems is very topical since it is in the last year or so that we believe we have successfully detected the effect of the *Sq* current system in the form of a small distortion of the height and electron density of the E-layer. Appleton, Lyon & Turnbull (*Nature*, **176**, p. 897, 1955) have shown that at

---

* Department of Geophysics, Imperial College of Science and Technology.

Slough at 1000-1100 hours there is a small depression in the height and critical frequency of the E-layer such as might be expected from a downwards vertical drift produced by the *Sq* current (which has a maximum E-W component at this time acting across the horizontal component of the earth's magnetic field). In another approach to the problem my colleague G. M. Brown and I have shown that the latitude variation in region E critical frequencies shows certain anomalies near latitudes ±35° which might well be attributed to the fact that the foci of the *Sq* current systems are located near these latitudes. (Beynon & Brown, *Nature*, **177**, p. 583, 1956.)

The direct way of detecting these currents of course is to use rocket borne instruments. In 1949 a rocket carrying a magnetometer was successfully launched from a ship near the magnetic equator (Singer, Maple & Bowen, *Nature*, **170**, p. 1093, 1952). It is stated that results of this experiment provided very clear evidence for a current sheet at about 93–105 km above ground. It is clear that much further rocket work of this kind is desirable and it is good to know that experiments are planned.

I.G.Y. ROCKET EXPERIMENTS

The following communication, received from the Royal Society recently, forms an interesting postscript to Dr. Beynon's paper and the above discussion.

The 15th to 24th June 1958 was a special world-wide period for firing rockets for research in connection with the International Geophysical Year. June 18th, being a Regular World Day in the I.G.Y. Calendar, was specially selected for a concentrated series of firings and all countries contributing to the rocket programme hoped to fire one or more research rockets on that date. The British firings were at the Weapons Research Establishment, Woomera, Australia, using the "Skylark" upper atmosphere research rocket. Following a series of test firings the first fully instrumented I.G.Y. "Skylark" was successfully fired on April 17th, 1958, and the second on May 20th, and further launchings have taken place at intervals of about four to six weeks. Plans were made to fire two "Skylarks" during the special rocketry interval, both equipped to carry out similar experiments.

A group from the Physics Department of University College London measured the temperature and horizontal and vertical wind speed up to heights of 60 miles or so using a sound ranging method. Grenades were ejected from the rocket at regular intervals to explode after about two seconds and the arrival of the sound pulse from each explosion was timed at an array of ground-based microphones, whilst at the same time the arrival of the flash from the explosion was observed on several wide-angle cameras. Analysis of the data, using electronic computation, makes it possible not only to calculate the variation with height of the speed of sound, but also to obtain information about the winds at different heights from their effect on the propagation of the sound waves. The speed of sound in air is proportional to the square root of the air temperature so that, from the observed variation with height of the speed of sound, the vertical temperature distribution may be derived.

The wind distribution was also the subject of an experiment by a group from the Meteorology Department at Imperial College, London, using a different method. Clouds of radar-reflecting aluminium strips were ejected at heights of about 30 to 50 miles. The movement and spread of the clouds under the influence of the winds was followed by radar as they fell.

Equipment to determine the constitution of the ionosphere was flown in the rockets by a group from the Electron Physics Department, Birmingham University. The ionosphere was sampled and the mass and charge of the particles measured by means of a mass spectrograph. The results were relayed continuously to the ground by radio telemetry as the rocket ascended.

MEASUREMENT OF PERMEABILITY AT V.H.F. USING TRANSMISSION LINE TECHNIQUE*

by

J. C. Anderson, M.Sc. (Associate Member)†

SUMMARY

The accurate measurement of the propagation constant of a transmission line, particularly in the v.h.f. region, is severely limited by the inaccuracy inherent in the calibration of the meter used for measurement. A comparative method, due to Wieberdink, is described here, and its theory discussed. The method can be applied to the measurement of the surface impedance of a conductor, and the theory is given for specimens in the form of cylindrical wire and flat strip. From the values obtained for surface impedance, in the case of a ferro-magnetic specimen, the permeability at v.h.f. can be deduced. Some results obtained by use of this method are given for certain commercial Permalloys in the form of strip, and for nickel in the form of wire.

1. Introduction

The experimental method used is to excite the transmission line by a generator of variable frequency at the sending end, and to place an adjustable short-circuit at the receiving end. In this way the reflection coefficient at the end of the line is made equal to unity and standing waves are set up. It will be shown that the current in the short circuit at the receiving end of a line of propagation constant P is proportional to $1/|\sinh(Pl)|$ where l is the length of the line, and $P = \alpha + j\beta$, β being the wavelength constant and α the attenuation constant of the line. This expression has maxima when $l \cong \frac{1}{2}n\lambda$, where λ is the wavelength on the line, and n is an integer.

By measurement of the distance between successive peaks to determine λ, the wavelength constant β, given by $2\pi/\lambda$ may be evaluated.

The attenuation constant α is shown in the next section to be related to the width of the peak at $l = \frac{1}{2}n\lambda$, measured at a height equivalent to the height of the peak at $\frac{1}{2}(n+1)\lambda$. Thus measurement of the width of the first peak, yields α without the necessity of measuring the absolute height of the peaks. This has the further advantage of rendering the measurements independent of the characteristics of the detector used to indicate the current in the short-circuit termination, and avoids also the use of standing-wave indicators. With the determination of α and β the propagation constant P is known.

2. Theory of the Method

It is convenient to lump together the primary constants of a transmission line as

$$Z = (R_0 + j\omega L_0) \qquad \text{.........(1)}$$

$$\text{and } Y = (G + j\omega C_0) \qquad \text{.........(2)}$$

where the symbols have the usual significance. The well-known solutions to the simultaneous differential equations governing transmission of voltage V and current, I, along the line are

$$V = A e^{-Px} + B e^{+Px} \qquad \text{.........(3)}$$

$$\text{and } I = \frac{1}{Z_0}(A e^{-Px} - B e^{+Px}) \qquad \text{.........(4)}$$

where P is the propagation constant given by $P = (ZY)^{\frac{1}{2}}$ and Z_0 is the characteristic impedance given by $(Z/Y)^{\frac{1}{2}}$.

Since the measurements to be made are of length it is preferable to introduce the wavelength, λ, by means of

$$\lambda = \frac{2\pi}{\beta} \qquad \text{.........(5)}$$

In the actual experiments the boundary conditions are $V = V_s$ at $x = 0$ and $V = 0$ at $x = l$, where x is distance along the line measured from the sending end, and l is the total length of line. Using these to evaluate the

---

* Manuscript first received 27th January 1958, and in final form on 3rd March 1958. (Paper No. 462.)

† Department of Physics, University of the Witwatersrand, Johannesburg.

U.D.C. No. 621.317.41.029.62:621.372.2

E

constants of integration A and B leads to

$$V = \frac{V_s \sinh P(l-x)}{\sinh Pl}$$

$$\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad \ldots\ldots\ldots(6)$$

$$\text{and}\quad I = \frac{V_s}{Z_0}\,\frac{\cosh P(l-x)}{\sinh Pl}$$

Hence at the receiving end where $x=l$ the current will be given by

$$I_R = \frac{V_s}{Z_0}\cdot\frac{1}{\sinh (Pl)} \qquad \ldots\ldots\ldots(7)$$

It is useful to consider how $|I_R|$ varies with the length of the line, l. From eqn. (7) it may readily be shown that

$$|I_R| = \frac{V_s}{Z_0}\left(\frac{2}{\cosh 2\alpha l - \cos 2\beta l}\right)^{\frac{1}{2}} \ldots\ldots\ldots(8)$$

Then

$$\frac{\partial |I_R|}{\partial l} = \frac{V_s}{Z_0}\left[\frac{-\sqrt{2}(2\alpha \sinh 2\alpha l + 2\beta \sin 2\beta l)}{(\cosh 2\alpha l - \cos 2\beta l)^{3/2}}\right]$$

Equating to zero for maximum or minimum yields the condition

$$\alpha \sinh 2\alpha l = -\beta \sin 2\beta l \qquad \ldots\ldots\ldots(9)$$

It is convenient to express l in terms of wavelength λ, by defining the quantity

$$u = \frac{l}{\lambda} \qquad \ldots\ldots\ldots(10)$$

A simplified expression for P may be obtained in terms of β and of the loss-angles defined by

$$\tan\delta_1 = \frac{R_0}{\omega L_0}$$

$$\tan\delta_2 = \frac{G}{\omega C_0}$$

$$\text{and } \delta = \tfrac{1}{2}(\delta_1+\delta_2)$$

$$\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad \ldots\ldots\ldots(11)$$

Taking the square root, the loss angle associated with P is given by

$$\left(\frac{\delta_1+\delta_2}{2}\right) = \tan^{-1}\left(\frac{\alpha}{\beta}\right)$$

$$\text{Thus}\quad P = \alpha + \mathrm{j}\beta = \left(\frac{\alpha}{\beta}+\mathrm{j}\right)\beta = \frac{2\pi}{\lambda}\left(\frac{\alpha}{\beta}+\mathrm{j}\right)$$

Now β is always a lagging phase angle and has a negative sign, whence we may write

$$P = \frac{2\pi}{\lambda}\,(\tan\delta + \mathrm{j}) = (\alpha + \mathrm{j}\beta) \qquad \ldots\ldots\ldots(12)$$

Then using eqn. (10) in eqn. (9) and substituting for α and β from eqn. (12)

$$\sin(4\pi u) = -\tan\delta\,.\,\sinh(4\pi\, u \tan\delta) \quad \ldots\ldots(13)$$

The solution of this equation gives values of u for which the current in the termination is a maximum. In general this does not occur at exactly half-wavelength intervals.

The accurate solution of (13) must be obtained by numerical methods, but an approximate solution may be obtained by Newton's method. This states that if $x=x_1$ is an approximate solution of the equation $f(x)=0$, then a more accurate solution is given by $x_2 = x_1 - \dfrac{f(x_1)}{f'(x_1)}$.

Putting $x=4\pi u$, and considering $\tan\delta \ll 1$,

$$f(x) = 0 = \sin x + x\tan^2\delta$$

$$\text{and}\quad f'(x) = \cos x + \tan^2\delta$$

To the order $\tan^2\delta$ the first three roots of the equation are $x=0$ (exactly), $x=\pi$, and $x=2\pi$ (approximately). But eqn. (11) was obtained by differentiation for a maximum or minimum, and thus we may take only alternate roots for maxima, where it is known that $x=0$ must

---

Now we have $P = (\alpha + \mathrm{j}\beta) = \sqrt{(R_0 + \mathrm{j}\omega L_0)\,(G + \mathrm{j}\omega C_0)}$

$$= \sqrt{\sqrt{(R_0G - \omega^2 L_0C_0)^2 + (\omega C_0R_0 + \omega L_0G)^2}\;\; \underline{\big|\tan^{-1}\left(\frac{\omega C_0R_0 + \omega L_0G}{(R_0G - \omega^2 L_0C_0}\right)}}$$

Considering the phase angle

$$\tan^{-1}\left(\frac{\omega C_0R_0 + \omega L_0G}{R_0G - \omega^2 L_0C_0}\right) = -\tan^{-1}\left(\frac{R_0/\omega L_0 + G/\omega C_0}{1 - R_0G/\omega^2 L_0C_0}\right)$$

$$= -\tan^{-1}\left(\frac{\tan\delta_1 + \tan\delta_2}{1 - \tan\delta_1\tan\delta_2}\right)$$

$$= -(\delta_1+\delta_2)$$

correspond to a maximum. Designating the value u_1 for the root $x=0$ and u_2 for the root near $x_1=2\pi$, then we get

$$(u_2-u_1)=\tfrac{1}{2}(1-\tan^2\delta+\ldots) \quad \ldots\ldots\ldots(14)$$

If we designate the distance between successive peaks by d then $(u_2-u_1)=\dfrac{d}{\lambda}$ and to a first approximation we may write

$$\lambda=2d(1+\tan^2\delta) \quad \ldots\ldots\ldots(15)$$

In general we may write

$$\lambda=2d(1+\mathrm{f}(\tan\delta)) \quad \ldots\ldots\ldots(16$$

By the process of measurement we may state the condition that u_3 and u_4 are positions where the current in the short circuit termination equals its value at u_2 as

$$\sinh(Pl_{3,4})=\sinh(Pl_2) \quad \ldots\ldots\ldots(17)$$

Substituting as before leads to

$$\cosh(4\pi\tan\delta u_{3,4})-\cos(4\pi u_{3,4})=$$
$$=\cosh 4\pi\,.\,\tan\delta u_2-\cos 4\pi u_2 \quad \ldots\ldots(17a)$$

This equation may be solved for u_3 and u_4 as follows:—

If we take the approximate value $u_1=\frac{1}{2}$ then

$$u_2=1-\tfrac{1}{2}\tan^2\delta$$

Since if the loss angle δ is zero the peaks will be infinitely sharp we may assume, for small δ, that the width of the peak will be a linear function of $\tan\delta$.

Let $u_4=u_1+\alpha_1\tan\delta=\frac{1}{2}+\alpha_1\tan\delta$

and $u_3=u_1-\alpha_1\tan\delta=\frac{1}{2}-\alpha_1\tan\delta \quad \ldots\ldots\ldots(18)$

Then the width of the peak will be given by

$$u_4-u_3=\frac{b}{\lambda}=2\alpha_1\tan\delta \quad \ldots\ldots\ldots(19)$$

Substitution for u_2, u_3 and u_4 in eqn. (17a), assuming $\tan\delta$ sufficiently small that cos and cosh functions involving it may be treated as unity, and sine and sinh functions as the angles themselves; and finally neglecting powers of $\tan\delta$ higher than the second, we get

$$u_4-u_3=\frac{b}{\lambda}\sqrt{3}\tan\delta+\ldots \quad \ldots\ldots\ldots(20)$$

Thus we have $\dfrac{u_4-u_3}{u_2-u_1}=\dfrac{b}{d}=\dfrac{\sqrt{3}\tan\delta+\ldots}{\frac{1}{2}(1-\tan^2\delta+\ldots)}$

$$\text{i.e. } \frac{b}{d}\tan^2\delta+2\sqrt{3}\tan\delta-b/d=0 \ldots\ldots\ldots(21)$$

Whence, using eqn. (16) $\mathrm{f}(\tan\delta)=\dfrac{1}{1-\tan^2\delta}-1$

$$\ldots\ldots\ldots(22)$$

Table 1 gives values of $\tan\delta$ and $\mathrm{f}(\tan\delta)$ for various values of b/d, calculated from the foregoing equations. Also included are values of $\tan\delta$ calculated numerically by Wieberdink, which show the errors involved in the approximations used in the development of the above equations. The numerically calculated values of $\mathrm{f}(\tan\delta)$ agree with those shown.

TABLE 1

$\frac{b}{d}$	$\tan\delta$ (Approx.)	$\tan\delta$ (Numerical)	$f(\tan\delta)$
0·01	0·0029	0·0029	—
·02	·0058	·0058	—
·03	·0087	·0087	0·0001
·04	·0115	·0115	·0001
·05	·0144	·0144	·0002
·06	·0173	·0172	·0003
·07	·0202	·0202	·0004
·08	·0231	·0229	·0005
·09	·0260	·0257	·0007
·10	·0288	·0285	·0008
·11	·0314	·0313	·0010
·12	·0346	·0341	·0012
·13	·0375	·0368	·0015
·14	·0414	·0396	·0016
·15	·0432	·0423	·0019
·16	·0461	·0449	·0021
·17	·0485	·0476	·0024
·18	·0518	·0502	·0027
·19	·0547	·0528	·0030
·20	·0575	·0554	·0034

Thus, using $\dfrac{u_4-u_3}{u_2-u_1}=\dfrac{b}{\mathrm{d}}$ we may determine $\tan\delta$ and $\mathrm{f}(\tan\delta)$. From eqn. (12) we have

$$P=\frac{2\pi}{\lambda}(\tan\delta+\mathrm{j})$$

$$\text{i.e. } \alpha+\mathrm{j}\beta=\frac{2\pi}{2d}\frac{(\tan\delta+\mathrm{j})}{(1+\mathrm{f}(\tan\delta)} \quad \ldots\ldots\ldots(23)$$

Thus the propagation constant is determined.

3. Evaluation of Primary Constants

The primary constants, R_0, L_0, C_0, and G_0 for the line may be evaluated from knowledge of P and the geometric configuration of the line. Normally one may calculate C_0 from the physical dimensions and knowledge of the dielectric used. The total inductance L_0 is made up two parts, the external inductance L_e, calculable from physical dimensions, and the internal or surface inductance L_i which may be calculated from the appropriate skin effect equation. The resistance R_0 may also be found by calculation from the same equation, providing permeability is known in each case. This leaves G_0 as a result of the measurements. In the experiments for which this theory has been developed it was required to find the permeability of the specimen.

In such a case the external inductance and capacitance are calculated, the leakance G_0 is assumed negligible—permissible in the case of an air dielectric line at v.h.f.—and the measured value of P is used to yield a value for permeability via the skin-effect equation.

4. Measurement of Permeability

It is known that in the v.h.f. range the induction B in a specimen lags behind the magnetizing field H. Thus in the equation

$$B=\mu_r\mu_0 H$$

the relative permeability must clearly be a complex quantity given by

$$\mu_1 - j\mu_2 \qquad \text{.........(24)}$$

It is also probable that the phase and magnitude of B with respect to H will vary from point to point throughout the specimen, so that a value for the macroscopic permeability has little physical significance. Accordingly, following the suggestion of Kittel[2], we define permeability as that parameter which, when inserted in the appropriate Maxwell equations for a good conductor, makes the calculated impedance equal to the measured impedance. It is permeability defined in this way which is the result of the measurements indicated above.

Since the apparatus employed comprised a concentric Lecher line system with air dielectric and an outer conductor of relatively large diameter, the leakance G_0 is taken to be negligible. Then $\tan\delta_2=0$ and, using eqn. (11) we have

$$\tan 2\delta = R_0/\omega L_0 \qquad \text{.........(25)}$$

Also from eqn. (12)

$$P=\alpha+j\beta=(j\omega C_0(R_0+j\omega L_0))^{\frac{1}{2}}$$

whence $\alpha^2-\beta^2=\omega^2 L_0 C_0$ and $2\alpha\beta=\omega C_0 R_0$. Now $\alpha^2=\beta^2\tan^2\delta$ therefore $\beta^2(1-\tan^2\delta)=\omega^2 L_0 C_0$ and, using (5)

$$\lambda=\frac{2\pi}{\omega(L_0C_0)^{\frac{1}{2}}}(1-\tan^2\delta)^{\frac{1}{2}} \qquad \text{.........(26)}$$

In the experimental apparatus the specimen under examination comprises the inner conductor of the concentric line system, the outer being of silvered copper. We therefore assume that all the losses in the line are those associated with the specimen. Thus the resistance R_0 per unit length is taken to be the surface resistance of the specimen which also has an internal inductance L_i per unit length. The total inductance per unit length is given by $L_0=L_e+L_i$. Let the specimen be characterized by a resistivity, ρ, and a relative permeability $\mu_r=\mu_1-j\mu_2$.

The internal impedance for unit width and unit length of a semi-infinite plane solid[3] is given by $Z=(j\omega\mu_r\mu_0\rho)^{\frac{1}{2}}$ ohms per square. Thus provided the current penetration is small, for a cylindrical wire of radius r_0 the impedance is

$$R_0+j\omega L_i=\frac{(\pi f(\mu_1-j\mu_2)\rho)^{\frac{1}{2}}}{2\pi r_0}(1+j) \qquad \text{.........(27)}$$

Where the specimen is in the form of a strip of width a, large compared with its thickness, we have

$$R_0+j\omega L_i=\frac{(\pi f(\mu_1-j\mu_2)\rho)^{\frac{1}{2}}}{2a}(1+j) \qquad \text{.........(28)}$$

The external inductance for a wire is given by the well-known equation

$$L_e=\frac{\mu_0}{2\pi}\log_e\left(\frac{r_1}{r_0}\right)\text{ henrys/metre} \qquad \text{.........(29)}$$

and for a strip, by the method of conformal transformation[4], we get the result

$$L_e=\frac{\mu_0}{2\pi}\cosh^{-1}\left(\frac{2r_1}{a}\right) \qquad \text{.........(30)}$$

where r_1 is the radius of the outer conductor. For a loss-free line the loss-angle δ will become zero, and we have

$$\lambda_0=\frac{2\pi}{\omega(L_eC_0)^{\frac{1}{2}}} \qquad \text{.........(31)}$$

where λ_0 denotes the free-space wavelength.

Using (31) to eliminate C_0 in (26)

$$\omega L=\omega L_e\left(\frac{\lambda_0}{\lambda}\right)^2(1-\tan^2\delta) \qquad \text{.........(32}$$

Combining (32) with (25) yields

$$R_0 = \omega L_e \left(\frac{\lambda_0}{\lambda}\right)^2 2\tan\delta \qquad \text{.........(33)}$$

Dealing first with the strip inner, squaring and equating real and imaginary parts leads to

$$\mu_2 = 4a^2 \,.\, \frac{R_0^2 - \omega^2 L_i^2}{\omega\rho\mu_0} \qquad \text{.........(34)}$$

$$\text{and} \quad \mu_1 = 8a^2 \,.\, \frac{R_0 L_i}{\rho\mu_0} \qquad \text{.........(35)}$$

Now using (32) and (34) and $L_0 = L_i + L_e$ we have

$$\mu_2 = \frac{4a^2}{\omega\rho\mu_0}\left[\omega^2 L_e^2 \left(\frac{\lambda_0}{\lambda}\right)^4 4\tan^2\delta - \omega^2 L_e^2 \left(\left(\frac{\lambda_0}{\lambda}\right)(1 - \tan^2\delta) - 1\right)^2\right]$$

We may write

$$g = \left(\frac{\lambda_0}{\lambda}\right)^2 2\tan\delta$$

$$\text{and} \quad h = \left(\frac{\lambda_0}{\lambda}\right)^2 (1 - \tan^2\delta) - 1 \qquad \text{.........(36)}$$

and since $\dfrac{4a^2\omega^2 L_e^2}{\omega\rho\mu_0} = \dfrac{8\pi a^2 L_e^2 C}{\rho\mu_0\lambda_0}$

we define a constant $K_s = \dfrac{8\pi C a^2 L_e^2}{\rho\mu_0}$ ....(37)

whence we have $\mu_2 = K_s(g^2 - h^2) \,.\, 1/\lambda_0$ ......(38)

and similarly from eqn. (35) we have

$$\mu_1 = K_s \,.\, \frac{2gh}{\lambda_0} \qquad \text{.........(39)}$$

By the same treatment, for the wire specimen, the expressions (38) and (39) are correct if we define a constant K_w in place of K_s, where

$$K_w = \frac{8\pi^3 c r_0^2 L_e^2}{\rho\mu_0}$$

The constants K_s and K_w are evaluated for any particular specimen. Thereafter, by measurement of the quantity b/d for a succession of different frequencies the values of $\tan\delta$ and f($\tan\delta$) are found. Substitution of these provides the new parameters g and h, finally enabling the calculation of μ_1 and μ_2 providing that the frequency of operation, or rather the free-space wavelength corresponding to it, is accurately known. It remains to consider the accurate measurement of this.

5. The Low-Loss Line

A second Lecher system comprising silvered copper conductors is used to determine λ_0, by measurements similar to those described above. If we used primed symbols to represent quantities already defined for the specimen line, we have from eqn. (15)

$$\lambda' = 2d'(1 + \tan^2\delta' + \ldots) \qquad \text{.........(40)}$$

Since both conductors are non-ferromagnetic the permeability is real and $\mu_2 = 0$. Thus from (34)

$$\left(\frac{\lambda'}{\lambda_0}\right)^2 = 1 - 2\tan\delta' - \tan^2\delta' \qquad \text{.........(41)}$$

Combining (40) and (41), neglecting powers of $\tan\delta'$ higher than the first,

$$\lambda_0 = 2d'(1 + \tan\delta' + \ldots)$$

From (14) and (20), again ignoring squared terms,

$$\frac{b'}{d'} = 2\sqrt{3}\tan\delta' \qquad \text{.........(42)}$$

$$\text{Whence} \quad \lambda_0 = 2d' + \frac{b'}{\sqrt{3}} + \ldots \qquad \text{.........(43)}$$

This gives an accurate measure of the free-space wavelength.

6. Apparatus

Although the above theory is perfectly general and may be applied to any transmission line system, the apparatus described below was found particularly suitable for the measurement of permeability of specimens in the form of strips or wires. The general layout is shown in Fig. 1. The output from the oscillator is taken via carefully screened, high-quality coaxial feeder which can be plugged in to either the wavemeter line W or the test line, T. It was found advantageous to provide stub-matching on this line. Coupling into each line

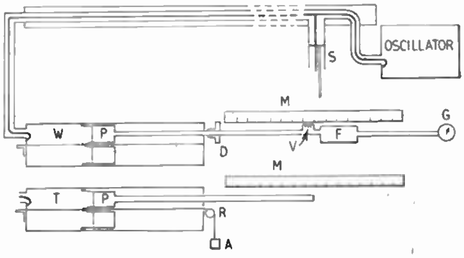


Fig. 1. Layout of apparatus.

was by means of a small coupling loop, whilst the output from the line was taken from a small loop on the shorting piston leading directly to a crystal, X, as shown in the detailed diagram of the piston in Fig. 2. From the crystal the output was taken through the tube which served as an operating arm for the piston, to an r.f. filter, F. Decoupling was also provided by the capacitor, C, of the ceramic lead-through type. On the filter was mounted a vernier plate, V, which was read against the metre rule, M, and could be transferred from one line to the other. Observation of the current was made on a standard galvanometer. A slow-motion drive, D, was found necessary for the wavemeter line, because of the sharpness of the peaks.

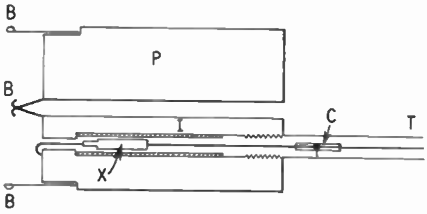


Fig. 2. Detail of piston.

Referring to Fig. 2, the crystal was insulated from the body of the piston by a polythene sleeve, I; the contacts, B, were of beryllium-copper and were silvered.

7. Results

In all, thirteen specimens of nickel-iron alloys of different compositions were examined, the results given here being representative. Figs. 3, 4, 5 and 6 show Permalloys B, and C, Mumetal, and pure Nickel respectively. The history and physical properties of the specimens are given in Table 2.

The negative values for μ_2 in the pure nickel curves of Fig. 6 deserve comment as they may seem to imply a negative surface resistance. This is not the case, as the following considerations show.

We have, from eqn. (27), that the surface impedance of the wire is given by

$$R_0+j\omega L_i=\frac{(1+j)}{2\pi r_0}[\pi f(\mu_1-j\mu_2)\rho]^{\frac{1}{2}}$$

$$=\frac{1}{2\pi r_0}[\pi f\rho(\mu_2+j\mu_1)]^{\frac{1}{2}}$$

The well-known relation for the square root of a complex number gives

$$(\mu_2+j\mu_1)^{\frac{1}{2}}=\left(\frac{(\mu_1^2+\mu_2^2)^{\frac{1}{2}}+\mu_2}{2}\right)^{\frac{1}{2}}+j\left(\frac{(\mu_1^2+\mu_2^2)-\mu_2}{2}\right)^{\frac{1}{2}}$$

and so we have

$$R_0+j\omega L_i=\frac{(\pi f\rho)^{\frac{1}{2}}}{2\pi r_0}\left[\left(\frac{|\mu_r|+\mu_2}{2}\right)^{\frac{1}{2}}+j\left(\frac{|\mu_r|+\mu_2}{2}\right)^{\frac{1}{2}}\right]$$

where $|\mu_r|=(\mu_1^2+\mu_2^2)^{\frac{1}{2}}$

from which it can be seen that, whatever the signs of either μ_1 or μ_2 both R_0 and L_i must be

TABLE 2

Name and Source	Composition	Dimensions (Inches)	Heat Treatment	Resistivity (Ohm-metres)
Permalloy B (S.T.C.)	45% Ni 55% Fe	Strip $\frac{1}{4}\times 0{\cdot}002$	Annealed at 1000° C. for 1 hr. in dry H_2, furnace cooled for 10 hrs.	6×10^{-7}
Permalloy C (S.T.C.)	78% Ni, 4% Mo, 5% Cu, 13% Fe	Strip $\frac{1}{4}\times 0{\cdot}002$	As above	6×10^{-7}
Pure Ni (Mond)	100% Ni	Wire 0·1104 diam	As above	9×10^{-8}
Mumetal (Telcon)	Not known	Strip $\frac{1}{2}\times 0{\cdot}01$	Not known	8×10^{-7}

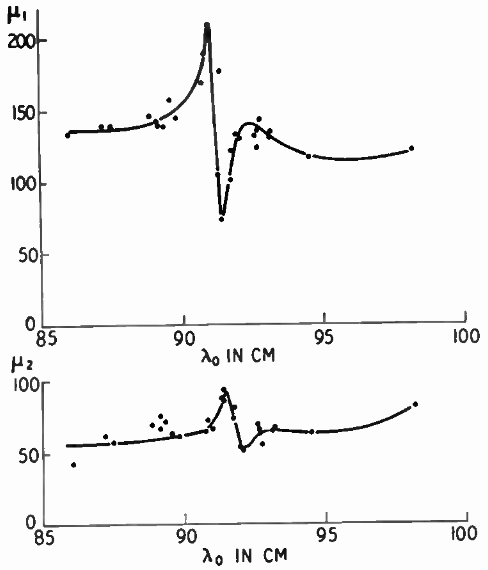


Fig. 3. Permalloy B.

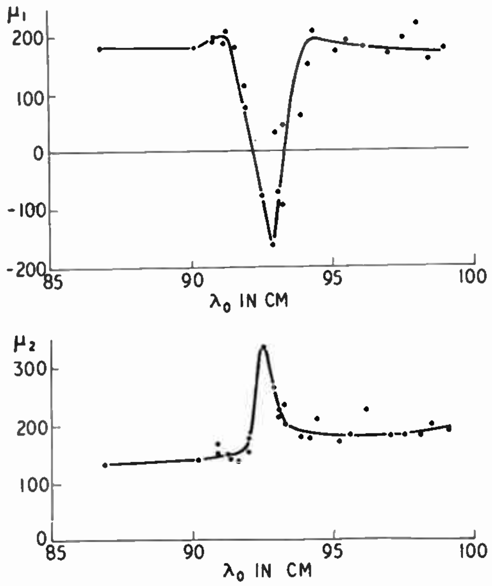


Fig. 4. Permalloy C.

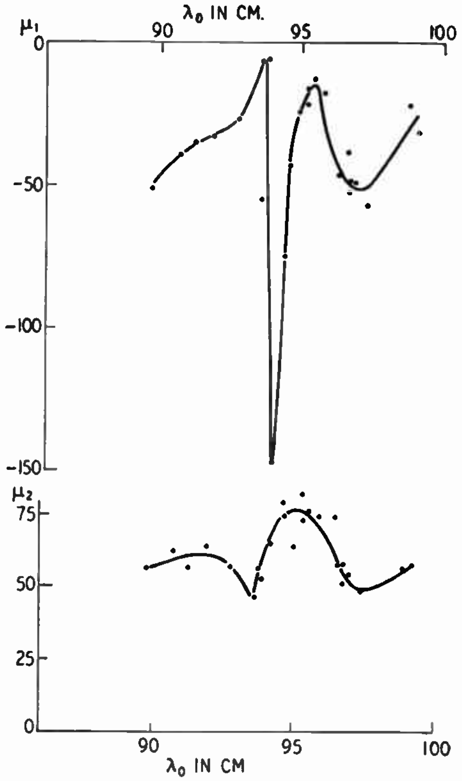


Fig. 5. Mumetal.

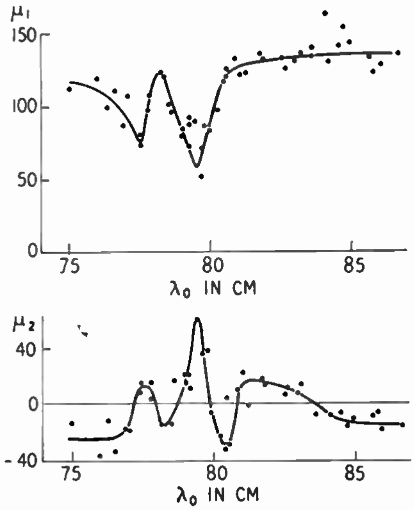


Fig. 6. Pure nickel wire.

positive quantities, provided we always take the positive roots in this expression.

These results are discussed from the physical point of view, and a mechanism accounting for the deviations has been proposed, by Anderson and Donovan[5].

8. Conclusions

It has been shown that, by suitable arrangement of transmission line theory, accurate measurements may be made without the aid of calibrated instruments or standing wave detectors. These measurements are sufficiently fine to show detailed structure in the permeability against frequency curves.

9. Acknowledgments

The author wishes to express his thanks to the Mond Nickel Co. Ltd., Standard Telephones & Cables Ltd., and the Telegraph Construction Co. Ltd., for their help in the provision, preparation and treatment of specimens. He also wishes to express his gratitude to the Principal of the Northern Polytechnic, and to the Head of Telecommunications Department, where this work was carried out.

10. References

1. A. Wieberdink, "On the determination of the complex permeability of ferromagnetic conductors at high frequencies," *Applied Scientific Research* (*The Hague*), **B1**, pp. 439-452, 1950.

2. C. Kittel, "Theory of the dispersion of magnetic permeability in ferromagnetic materials at microwave frequencies," *Physical Review*, **70**, pp. 281-290, September 1 and 15, 1046.

3. S. Ramo and J. R. Whinnery, "Fields and Waves in Modern Radio," p. 239. (John Wiley, New York, 1953.)

4. J. C. Anderson, "The calculation of characteristic impedance by conformal transformation," *J.Brit.I.R.E.*, **18**, pp. 49-54, January 1958.

5. J. C. Anderson and B. Donovan, "On the complex permeability of iron-nickel alloys at high frequency," *Proceedings of the Physical Society*, **70**, pp. 186-191, February 1957.

FACTORS IN THE DESIGN OF AIRBORNE DOPPLER NAVIGATION EQUIPMENT*

by

E. G. Walker†

Read before a meeting of the Institution in London on 15th April 1958.
In the Chair: Mr. H. F. Schwarz, B.Sc. (Member).

SUMMARY

The paper describes the use of a Doppler-sensor of aircraft component-velocities as an input for self-contained dead-reckoning navigation. Choice of radio frequencies, beam configuration, radiated power and other system parameters is discussed and some basic quantitative expressions derived. Design features of the individual units of the sensor are given and requirements of computer and heading-reference outlined. System accuracy is discussed and the heading information is shown to be the factor presently limiting system performance.

LIST OF SYMBOLS

φ	aerial beam depression angle
$\varphi_{\alpha DR}$	effective beam depression angle in the presence of pitch, drift and roll
β	beam lateral angle
I	beam incidence angle
γ	beam skew angle
h	height
α	aircraft pitch angle
D	aircraft drift angle
R	aircraft roll angle
N	ratio of across-heading to along-heading beamwidth
λ	wavelength (cm)

Other symbols are defined where they occur.

1. Introduction

There are several methods of aircraft navigation all of which may be grouped under the general headings of ground-based, ground co-operative, or self-contained. In military applications the advantages of an accurate self-contained system lie primarily in the ability of an air fleet so equipped to navigate independently to all regions of the world without prior reference and without being subject to widespread failure due to a single cause. In the case of civil aircraft other features of the self-contained system take precedence: there is no question of intervening atmospheric disturbance interrupting the receipt of information, the aircraft has the facility of using all airspace to make best use of prevailing conditions rather than being confined to specified routes, and there is no practical limit to the number of aircraft engaged.

The components of a self-contained navigational aid are shown in Fig. 1. If initial position co-ordinates are known, then integration of subsequent velocity resolved in relation to a heading reference will give present position, and comparison with destination co-ordinates in the same frame of reference will give course and distance to go.

This is the dead reckoning system which has previously been limited in accuracy by using true airspeed as a sensor of vehicle velocity and forecast or estimated wind information. Alternative inputs may be derived by inertial means or from a Doppler sensor.

Inertial navigation consists of detecting and measuring the components of an aircraft's linear accelerations and axial rotation in a given frame of reference with subsequent integration giving displacement from origin. Inertial methods are not yet sufficiently developed to find application in high accuracy long range navigation.

The Doppler sensor has been used in military aircraft for several years and is now being

---

* Manuscript received 22nd March 1958 (Paper No. 463.)

† Marconi's Wireless Telegraph Company Ltd., Chelmsford, Essex.

U.D.C. No. 621.396.933.1

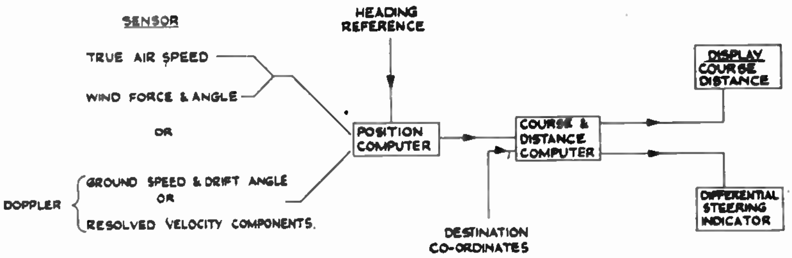


Fig. 1. Components of a self-contained navigational aid.

applied to civil aviation. Such a sensor is capable of high accuracy and can provide velocity information to a present-position computer either in the form of ground speed and drift angle or as the resolved velocity components of the aircraft.

It should be noted that a sensor alone does not constitute a navigational aid, it requires the addition of a heading reference and computer. The degree to which the high inherent accuracy of a Doppler sensor may be realized is limited by the inaccuracies of the other components, notably the heading information.

The navigational velocity and direction relationships are shown in Fig. 2. The terminology is that presented by Aeronautical Radio Incorporated for adoption in air navigation.

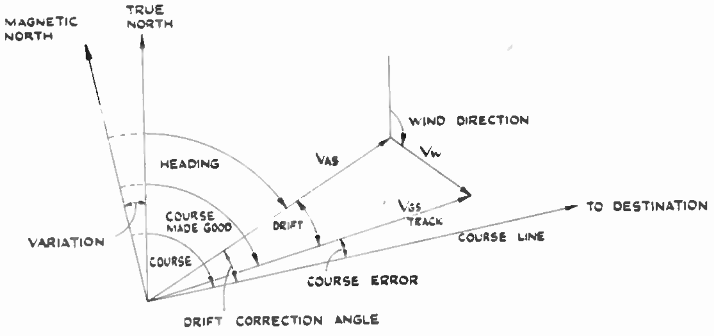


Fig. 2. Velocity and direction relationships.

2. The Doppler Effect

The sensor to be described depends for its action upon an effect noted by C. J. Doppler about a century ago, namely, that when there is relative motion between a wave source and an observer, there is a difference between the received and transmitted frequencies.

Consider an aircraft moving with a horizontal velocity V_H radiating a beam at an angle α with the velocity vector, as in Fig. 3(a) If a wave $A \sin 2\pi Ft$ is transmitted it will travel to the ground in a time $t=r/c$ where r is the slant range and c the velocity of propagation, be scattered at the surface, and a fraction returned to the aircraft with a power loss dependent upon the nature of the terrain, after a further time interval r/c.

The relative phase of transmitter and received signal is then $2\pi f \,.\, 2r/c$ radians. However, the aircraft has a component of velocity resolved along its beam of $V_H \cos \varphi$; hence the instantaneous range is a time-dependent quantity $r_0 + V_H \cos \varphi . t$.

Omitting the constant term r_0 and any constant phase shift occurring at the ground or in the system, the relative phase is then

$$\frac{2\pi f \,.\, 2V_H \cos \varphi . t.}{c} \text{ radians}$$

Thus there is a time-dependent phase relation between the transmitted and received signal producing a difference frequency of $1/2\pi$ times the rate of change of phase, that is,

$$\text{Doppler shift } f_D = \frac{2f}{c} V_H \cos \varphi \text{ cycles/second} \qquad \text{.........(1)}$$

or, since $c = f.\lambda$

$$f_D = \frac{2}{\lambda} V_H \cos \varphi \text{ c/s} \qquad \text{.........(2)}$$

Hence, if λ the transmission wavelength and φ the depression angle are known and constant, the detected Doppler shift is a direct measure of the aircraft's horizontal velocity.

Since, in practice, the beam has finite width in the fore and aft plane, (Fig. 3(*a*)) the returned signal is a band of frequencies centred on f_D. If the beamwidth at half-power points is $\delta\varphi$, then spectrum quarter-power bandwidth

$$\Delta f_D = \frac{2v}{\lambda}\left[\cos\varphi_1 - \cos\varphi_2\right]$$

$$= \frac{2v}{\lambda}\left[\cos\left(\varphi - \frac{\delta\varphi}{2}\right) - \cos\left(\varphi + \frac{\delta\varphi}{2}\right)\right]$$

$$= \frac{2v}{\lambda}\left[2\sin\varphi \,.\, \sin\frac{\delta\varphi}{2}\right]$$

and if $\delta\varphi$ is small

$$\Delta f_D = \frac{2v}{\lambda} \,.\, \sin\varphi \,.\, \delta\varphi \qquad \text{.........(3)}$$

and the fractional bandwidth

$$\frac{\Delta f_D}{f_D} = \tan\varphi \,.\, \delta\varphi \qquad \text{.........(4)}$$

An aircraft's velocity vector can be resolved into three mutually perpendicular components, V_H horizontally, V_L laterally and V_V vertically, and an independent measure of at least V_H and V_L is required for navigational purposes.

3. Choice of Radio Frequency

In order to obtain a narrow beamwidth with a practical aerial the radio frequency has to be in the microwave region. Reference to eqn. (2) shows that if, typically, $\lambda = 3$ cm, and $\varphi = 60°$, then the Doppler shift is 17 c/s per knot ground speed which, for normal aircraft speeds, gives a readily measurable range of audio frequencies.

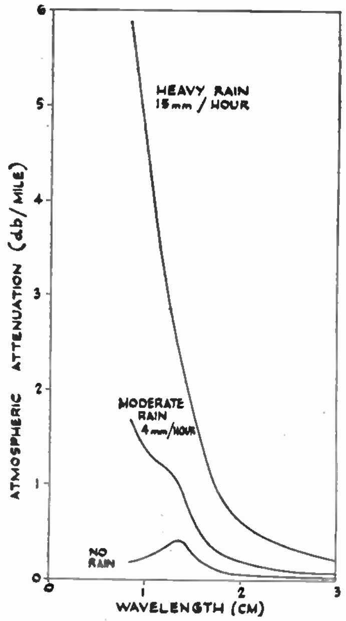
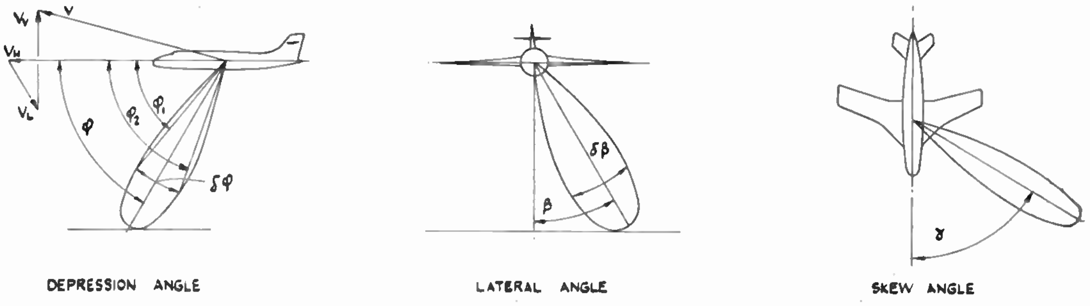


Fig. 4. Atmospheric attenuation v wavelength.

A top limit to frequency is set by atmospheric attenuation.[1] Oxygen has a magnetic molecular moment and water vapour an electric moment, resulting in gaseous absorption of energy from passing wavefronts since the molecules behave like dipoles and tend to oscillate. There are oxygen resonance peaks at 0·25 cm and 0·5 cm and a water vapour resonance at 1·35 cm. Also, in an atmosphere containing precipitation, scattering and absorption occurs more severely at high frequencies.

Figure 4 shows the resultant attenuation against wavelength for different precipitation rates. It will be seen that about 1·8 cm is the shortest wavelength usable, clear of water-



(*a*) (*b*) (*c*)

Fig. 3. Beam angle relationships.

vapour resonance. The next lower practical value is 0·9 cm but here attenuation due to rain becomes excessive. A further effect observed at very short wavelengths is spectrum-broadening due to back scatter from clouds. This effect is not important at X-band.

Due to availability of microwave components the first Doppler sensors used a 3 cm wavelength and although some equipments have operated at 13·5 Gc/s (Ke band) it is probable that the wavelength for sensors for civil use will be standardized in the Xl band (3·33–3·53 cm).

4. Back Scatter from the Ground Plane

The transmitted energy incident upon the ground plane is back-scattered from individual centres with a loss which is dependent upon the nature of the terrain. Measurements have been made of back-scattering from various surfaces[2, 3] and Fig. 5 shows the scattering coefficients plotted against angle of incidence for land and three sea states. The sea conditions are defined by the Beaufort number on the International scale. Whereas nearly perfect scattering occurs over land, specular reflection from calm sea surfaces results in a large loss factor as the incidence angle moves away from the normal.

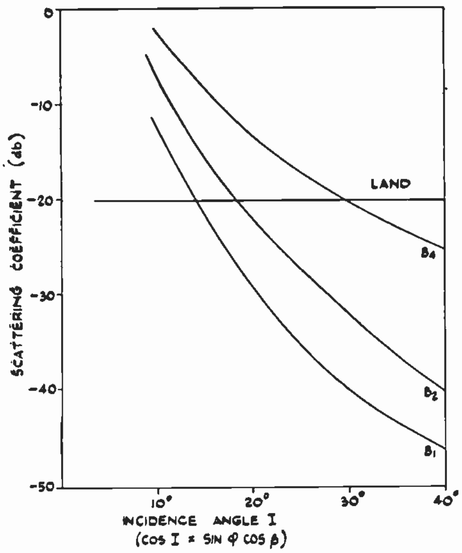


Fig. 5. Signal back-scatter.

The effective radar cross-sectional area per unit area illuminated tends to increase at shorter wavelengths but over sea any gain is dependent upon the particular sea-state. There is no significant difference in strength of signal returned between differing polarizations.

5. The Aerial

5.1. *Beam Configuration*

If the beam, after depression through the vertical angle φ, is also rotated to port through β in the lateral plane (Fig. 3(*b*)), then in plan view the beam will be directed at a skew angle γ relative to the aircraft's axis (Fig. 3(*c*)), where

$$\tan\gamma = \tan\varphi . \sin\beta \qquad \ldots\ldots\ldots(5)$$

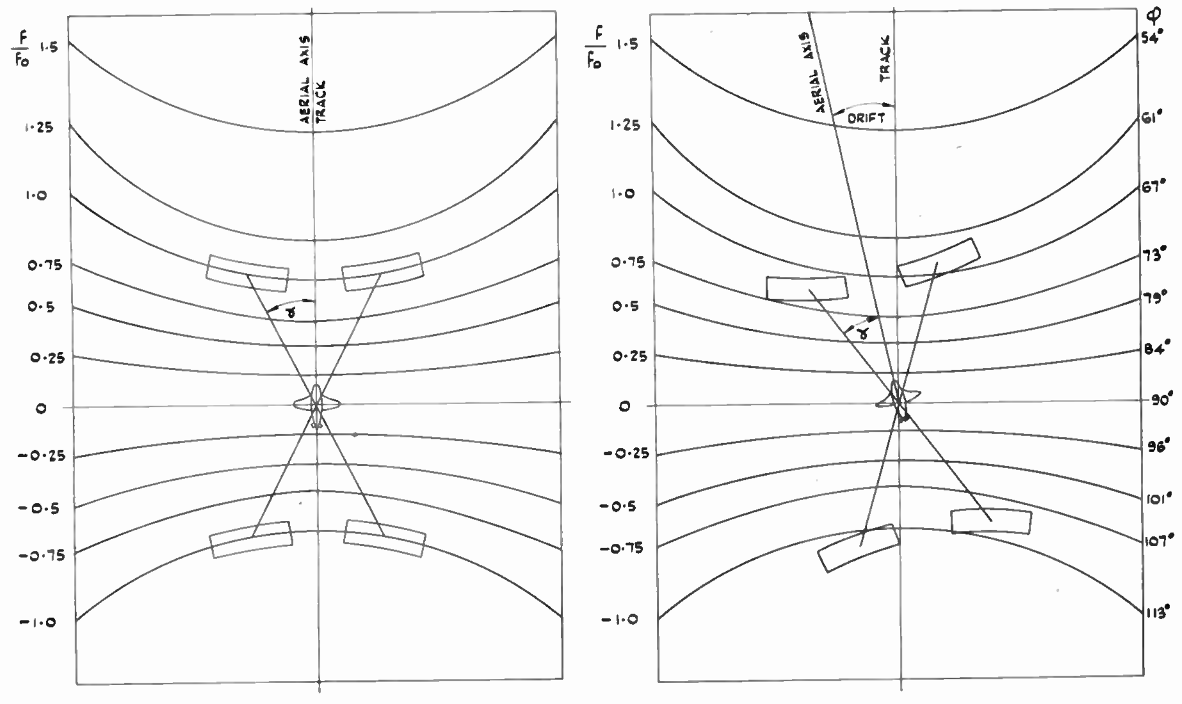
The aircraft's velocity down the beam is reduced by $\cos\gamma$, hence the Doppler shift from this beam will be given by

$$f_D = \frac{2\,V_H}{\lambda}\cos\varphi\cos\gamma \text{ c/s} \qquad \ldots\ldots\ldots(6)$$

If a similar beam is directed to starboard then it will produce the same Doppler shift, providing the aircraft's velocity vector bisects the skew angles.

Doppler shift is proportional to $\cos\varphi$ and all points on the ground-plane subtending a given angle at the aerial will contribute equal shifts; the locus of these points is a hyperbola. Thus Fig. 6 (*a*) may be drawn showing a family of hyperbolae relating to different amounts of Doppler shift, the ordinate in this particular case being normalized to the shift resulting from a depression angle of 67 deg. The aircraft may be visualized to be flying above such a pattern on the ground; the pattern moves with the aircraft and there is no relative movement.

If a wind vector causes the aircraft to drift to starboard as in Fig. 6(*b*) then the effective skew angles are no longer equal, that of the port beam becoming $(\gamma + D)$ and of the starboard beam $(\gamma - D)$. Hence the port shift is lower than the starboard shift and from the sign and magnitude of this difference the aircraft's lateral velocity may be computed. Alternatively, if the difference-frequency is used as an error signal to drive a servo system which rotates the beams until the difference is zero, then the aerial system must have turned through the drift angle D and this angle may be measured.



(*a*) (*b*)

Fig. 6. Hyperbolae of constant Doppler shift.

A two-beam system may thus be used to measure ground speed and drift but the assumption so far has been that the aircraft possesses only horizontal velocity and maintains a normal attitude. If the aircraft climbs then a knowledge of vertical velocity is required to eliminate this component from the Doppler information. Similarly, if the aircraft pitches or rolls then a knowledge of the local vertical is required to compensate for changes in the effective depression angles of the beams.

These data may be obtained from other sources if convenient but an extension of the beam system is able to resolve vertical velocity and, as will be shown, can contribute materially in attitude compensation.

In Fig. 7 beams are shown directed both port and starboard, fore and aft of the aircraft. The configuration shown in Fig. 7(*c*) is basically sufficient to extract all three velocity components but the symmetrical arrangement of Fig. 7(*d*) is often used in certain applications which will be discussed. Where multiple beam systems are referred to, except where returns are required to be present at the same time for r.f. mixing purposes, it may be taken that either independent beams are used or one beam switched in sequence and information stored between successive signals from any one direction. By combining the Doppler shift information from the three-beam system, as shown in Appendix 1, the three velocity components may be separated.

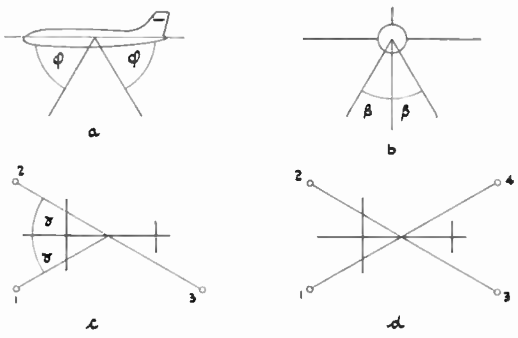


Fig. 7. Beam configuration.

The skew angle used is governed by the desired sensitivity in drift detection. Drift is observed as the frequency difference between port and starboard spectra, that is,

$$F = f_{Dp} - f_{Ds}$$

$$= K(\cos\gamma_1 - \cos\gamma_2) \text{ where } K = \frac{2v}{\lambda}\cos\varphi$$

and $\delta F = K\,2\sin\gamma\,.\,\delta\gamma$

or the fractional drift sensitivity

$$\frac{1}{f_D}\,\frac{\delta F}{\delta\gamma} = 2\tan\gamma \qquad \ldots\ldots\ldots(7)$$

In an aerial system fixed in azimuth the skew angle chosen depends upon the drift magnitude likely to be encountered. For example, if the system is required to provide equal navigational accuracies along and across heading and there can be said to be a probable drift angle *D*, then the ratio of tolerable along-heading to across-heading percentage error is tan *D*.

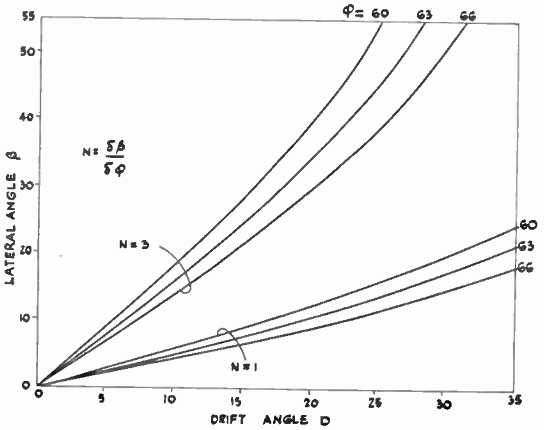


Fig. 8. Beam relations for equal along and across heading accuracies.

The percentage error in measuring spectra centre is proportional to percentage bandwidth.

$$\%\text{ error}\frac{\text{along}}{\text{across}} = \%\text{ bandwidth}\frac{\text{along}}{\text{across}}$$

$$= \text{bandwidth (c/s)}\frac{\text{along}}{\text{across}} \times$$

$$\times \text{ centre frequency (c/s) } \frac{\text{across}}{\text{along}}$$

The ratio, centre frequency (c/s) $\frac{\text{across}}{\text{along}} = \tan\gamma$ and the ratio,

$$\text{bandwidth (c/s) } \frac{\text{across}}{\text{along}} = \frac{\delta\beta}{\delta\varphi} = N$$

$$\text{then } \tan D = \frac{\tan\gamma}{N}$$

$$\text{or } N\,.\,\tan D = \sin\beta\tan\varphi \qquad \ldots\ldots\ldots(8)$$

This relation is shown in Fig. 8 for a range of values φ and *N*. The depression angle is usually set by the need to obtain sufficient signal back-scattered from the ground, and *N* depends upon the aerial aperture available and the need for an extended duration of return in some transmitter-receiver systems. Substitution of values in eqn. (8) will give the optimum lateral angle for a given application, values in the range 10 – 25 deg. having been used.

5.2. *Aerial Stabilization*

For navigational purposes the horizontal components of the aircraft velocity are required: essentially a Doppler system measures velocity along the aerial axis which may or may not be fixed relative to the aircraft's reference planes. If the aerial attitude moves from the horizontal, errors occur due to changes of the effective beam depression angles. Consider a single forward beam depressed through φ. If a pitch angle α occurs it is directly additive to φ and the error is at the rate of 4% per degree for the usual values of φ (60 – 70°).

Aerials using forward and backward looking beams, the returns from which are combined, are referred to as Janus arrays after the Roman god of doorways who is depicted with a face on each side of his head. The prime purpose of the Janus array is in connection with the transmitter system, but it has other features which will be mentioned first.

By comparing Doppler shift from fore and aft beams in Janus systems the pitch error may be reduced, since one increases at nearly the same rate as the other decreases. This is shown in Appendix 2 to be according to (cos α – 1), about – 1·5% per 10 degrees pitch, a considerable improvement.

Alternatively, pitch and roll information derived from a central gyro reference within the aircraft may be fed into the computer, thus providing data stabilization to the system.

If such information is not available physical stabilization may be used in either or both vertical planes. Such an aerial system may be controlled by servos driven pendulously or using as an error input the actual frequency divergence of Doppler shifts from respective aerials. In the latter case the Doppler sensor can be a prime source of attitude information.

Whether data or physical stabilization against pitch and roll is used depends largely upon whether the sensor resolves lateral velocity by computation or presents drift angle directly by rotating the aerial assembly in azimuth until the port and starboard Doppler shifts are equal. In the former case the aerial assembly is fixed and data stabilization would be used. In the azimuth driven aerial it would be a natural extension to provide gimbals in one or both of the vertical planes. In the absence of pitch and drift, the effect of roll is merely to move the beams along lines of constant Doppler shift on the ground plane, hence roll stabilization is not normally employed, unless extreme attitudes are likely to be encountered resulting in loss of signal. Appendix 3 deduces a general equation for the effective depression angle in the presence of drift, pitch and roll.

Whether a fixed or moving aerial is used depends upon several factors. In the presence of drift the spectrum from a fixed aerial broadens by an amount depending upon the precise beam pattern on the ground. In a particular system, for example, the fractional bandwidth increases from 8 per cent. to 25 per cent. when a drift of 30 deg. occurs, with a corresponding reduction in the accuracy with which the spectrum centre may be measured. Also the terrain distortion (a factor dependent on the back-scatter characteristic and discussed in Sect. 8) on any one beam increases. Further, although data stabilization may correct frequency error over a considerable range of pitch and roll, eventually signal returns fall off over relatively smooth surfaces, due to the increasing angle of incidence of the beam on the ground-plane. Also, with a fixed aerial, extreme attitudes may result in ambiguity if the beam crosses the line of zero Doppler shift.

On the other hand, the fixed aerial has the advantage of simplicity, can be made an integral part of the aircraft's skin, and uses the effective aperture more efficiently than a moving system. It can also be made a rigid assembly thus presenting less variation, due to vibration, in impedance seen by the transmitter than a moving aerial, a factor important in continuous wave systems.

5.3. *Type of Aerial*

It is required to produce beams each of known depression angle φ, narrow fore and aft width $\delta\varphi$, and a ratio $\delta\beta/\delta\varphi$ varying between ten and unity, depending upon application.

In general two types of beam may be used, pencil or fan-shaped. A fan-shaped beam, one having a large $\delta\beta/\delta\varphi$ relation, provides the long duration of returned signal needed in some pulse systems discussed later. The fan lies along contours of constant Doppler shift as shown in Fig. 6(*a*) and the fractional beamwidth is small. In a fixed aerial system the use of a fan-beam results in spectral-broadening with drift and a pencil beam is sometimes used.

Linear and planar arrays are generally to be preferred to combinations of horns with parabolas or lens aerials. They normally occupy less volume, are lighter, are particularly suitable for fixed aerial applications, and readily provide large $\delta\beta/\delta\varphi$ ratios. They also lend themselves to frequency and temperature compensation techniques.

If the Doppler shift is to be an accurate measure of aircraft velocity either the depression angle and wavelength must be held constant or their mutual variation arranged to cancel.

In a slotted waveguide array in which adjacent slots are in-phase, the beam emergent angle is given by $\cos\varphi' = \sin a$ and in an array in which adjacent slots are antiphase $\cos\varphi'' = \sin a - \lambda/2s$ where

φ' and φ'' are the depression angles

s is the slot spacing

$\sin a$ is a function of wavelength and waveguide resonant dimensions.

If in a Janus system an in-phase array looks forward and an antiphase array backward, then the resultant Doppler shift

$$f_D = \frac{2v}{\lambda}(\cos\varphi' - \cos\varphi'')$$

$$= \frac{2v}{\lambda}\cdot\frac{\lambda}{2s} = \frac{v}{s}\ \text{c/s} \quad \ldots\ldots..(9)$$

that is, independent of wavelength. Similarly, the use of phased and antiphased arrays in pairs holds the Doppler shift sensibly constant against alteration in guide dimensions due to changes in ambient temperature.[4] In systems using separate transmit and receive aerials compensation may be achieved by looking at any one quadrant with a receive array of opposite nature to that by which the quadrant is illuminated. Linear arrays can be manufactured with sufficient mechanical accuracy to hold the beam-emergent angle to within design limits, hence system calibration flights are unnecessary.

To obtain the three or four beam systems of Fig. 7 a series of phased and anti-phased linear arrays fed in turn by an r.f. switch may be used or, with a fixed feed, deflection hoods rotated to direct the beams to alternate quadrants. The most efficient use of the aerial cut-out is made by a multiple-port planar array with a mechanical or ferrite switch to couple the transmitter in turn to the appropriate inlet.

6. Transmit-Receive Systems

6.1. *C.W. Systems*

The continuous-wave transmitter-receiver would appear to be a first choice for a Doppler sensor. The techniques are straight-forward and economical and the component reliability better than in a highly-stressed pulse system. The bandwidth can be narrow and the system is capable of working at zero feet. A very considerable difficulty does however arise from the presence of unwanted cross-coupling between the transmitter and receiver. The presence of a sample of transmitter signal is in itself no problem, in fact in the basically sufficient direct-detection circuit it is necessary, but modulation usually occurs in the leakage paths giving rise to noise products of considerable bandwidth which limit the altitude range over which Doppler shift of sufficient signal-to-noise ratio can be detected. Increasing transmitter power is no solution.

By careful design of microwave circuits, the use of separate transmit and receive apertures positioned for minimum coupling and of fixed antennas to avoid modulation due to vibration, c.w. techniques have been extended for the system to be practicable but not popular.

The early Doppler sensors resorted to pulse systems not only due to the formidable cross-coupling problem, but at that time the only suitable microwave valve was the low duty-ratio magnetron.

6.2. *Pulse Systems*

In a pulsed-system the receiver is gated-off when the transmitter is on; thus there can be no cross-coupling and one aerial can be used for transmission and reception.

To measure the small Doppler shift in frequency and to obtain the best signal-to-noise ratio in detection it is necessary for the transmitter frequency to be stable. A coherent c.w. oscillator may be used as a reference to drive the transmitter and the returned signals mixed with the reference. As in any radar either an intermediate frequency amplifier may be employed to obtain a low noise factor or a direct crystal to audio frequency amplifier system used if sufficient signal is in hand. In the latter case the background noise spectrum slope, which is inversely proportional to frequency, needs to be considered in the frequency-measuring circuits.

To avoid the complexity of a reference oscillator the transmitter may be connected to a forward and backward-looking aerial simultaneously and the returns from these aerials will be self-coherent providing they are present in the mixer crystals at the same time. Hence the extended return duration of the fan beam is needed in this, the Janus system, to allow time overlap in the presence of pitch and roll.

The Janus system, therefore, allows normal radar techniques to be used with no special requirement on frequency stability. A typical schematic is shown in Fig. 9. The transmitter feeds via a hybrid coupler into the aerial and a sample is taken to the automatic frequency control circuit. The receiver is protected during transmission by the T.R. cells. The returned-signal splits in the hybrid and recombines in a balanced mixer fed by the local oscillator. I.f. amplification is followed by detection wherein $2f_D$ is produced. The only requirement of the

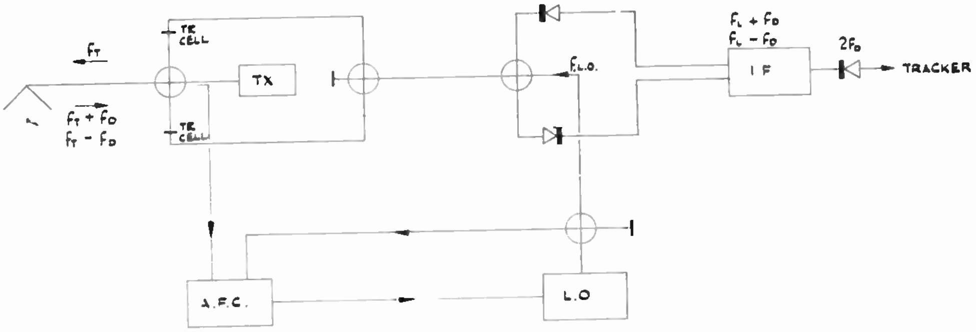


Fig. 9. Typical Janus transmitter-receiver.

automatic frequency control circuit is to keep the heterodyned signal within the i.f. band.

To avoid ambiguities the pulse recurrence frequency must be at least twice the highest Doppler shift to be measured. In a Janus system this has led to a p.r.f. of 50 kc/s which is unusual in radar technique.

To keep within the magnetron rating in this sensor, the pulse length was kept short at 0·45 μ sec with consequent need for a wide i.f. bandwidth of 3 Mc/s. In this application the duty ratio was effectively decreased by operating the transmitter in bursts. More recent microwave valves capable of high duty-ratio working permit long-pulse techniques to be used.

The advantages of Janus working which have been mentioned, namely, self-coherence, pitch compensation, and frequency and temperature stability, are offset by several factors. Negative velocity measurement, such as would be required in a sensor for helicopter use, can be achieved only quantitatively, the sign being lost in Janus detection which is a scalar process concerned only with the difference between fore and aft Doppler shifts. Also, as shown in Appendix 1, the same process eliminates the vertical velocity component as this is common to all quadrants. Further, the absence of a strong reference signal leads to a relatively large pre- to post-detector Doppler signal-to-noise ratio derating due to the mixing of two Doppler spectra in the presence of noise. The magnitude of this loss is a function of pre-detector signal-to-noise, transmitter duty-ratio and the pre- and post-detector bandwidths. A helpful feature of Janus detection is that if the two spectra are each of bandwidth Δf_D on $\pm f_D$ then the resulting spectrum, although broadening to $\sqrt{2} . \Delta f_D$, has a smaller fractional bandwidth since the new centre is at $2 f_D$.

The gating of the receiver during transmission leads to two related subsidiary effects, a minimum working height in the order of 200 ft., and a series of critical altitudes at which the return occurs during a subsequent transmission. Only the first critical altitude, which for a p.r.f. of 50 kc/s and a depression angle of 65 deg. occurs at 9,000 ft., is significant since thereafter the return duration is sufficiently spread out not to be lost in the gating pulse and the signal in hand at 9,000 ft. in a system designed for, say, 60,000 ft., means that no material loss of information occurs. To avoid the effect altogether the p.r.f. may be altered randomly or with altitude.

Pulse sensors have given good service for some years but a practical solution to the c.w. cross coupling problem has continued to be sought.

6.3. *Frequency Modulated Systems.*

In the pulse system cross-coupling is overcome by gating the receiver during transmission; much the same effect can be achieved by a frequency-modulation technique which makes the receiver insensitive to near-echoes.

If a transmitter is modulated with an index m and the return-signal mixed with a local oscillator similarly modulated, or with a transmitter sample, then the product will have a modulation index, dependent upon the phase delay of the returned signal, varying between 0 and $2m$. The power distribution in the product is dependent upon the modulation index, that is, the power in any particular sideband is dependent upon the signal path-length.

Hence the receiver may be protected from breakover by the use of a suitable modulation frequency dependent upon the guard-time required, and the selection of a sideband dependent upon the required sharpness of transition from protection to reception. For any given sideband there is an optimum modulation index. The shape and width of the oscillator mode has to be considered in the selection of parameters.

The protection is obtained at the expense of power loss due to the limiting use of one or a pair of product sidebands. There is an inherent low altitude limit but it is only in the order of a few feet; alternatively, straight c.w. working can be used at low levels.

In any non-Janus system isolation has to be provided between the transmitter and the aerial to avoid spurious modulation due to mismatch-pulling by vibration in the waveguide and aerial assembly.

6.4. *Power Requirements*

The general radar equation gives the power relations in the small target case but where the target is the earth's surface and all power radiated is incident thereon, the vertical-incidence image condition is approached where

$$P_R = \frac{P_T\,\sigma_0\,A}{4\pi\,R^2}\ \text{watts} \qquad \ldots\ldots\ldots(10)$$

where P_R = received power

P_T = average radiated power

σ_0 = effective cross-section per unit-area illuminated

R = slant range

$A = \frac{G\,.\,\lambda^2}{4\pi}$ = aerial aperture

G = aerial gain relative to an isotropic radiator

λ = wavelength

The average received power is the integral of the contribution from each discrete scattering centre within the beam. The factor σ_0 is a function of the terrain, angle of incidence, wavelength and polarization; it is independent of height since as the average power per unit area decreases, the number of scattering centres increase. It is shown by Moore and Williams[5] that in a pulse system the variation of signal with range is dependent also upon the relation between pulse length and illuminated area. At a given altitude, if the pulse is long such that the area is simply a function of aerial pattern, the inverse square law holds but above the critical height where the area illuminated is limited by the pulse length the signal-to-noise ratio falls off with the cube of height.

The range limitation is set by signal-to-noise ratio and this is unity when

$$P_R = K.T.B.F\ \text{watts} \qquad \ldots\ldots\ldots(11)$$

where K = Boltzman's constant ($1{\cdot}38 \times 10^{-23}$)

T = absolute temperature

B = tracked-spectrum bandwidth

F = receiver noise factor

In practice, a working signal-to-noise ratio, N, greater than unity is required at maximum range. From eqns. (10) and (11) and introducing other factors, Doppler signal-to-noise for a given transmitted power is given by

$$N = \frac{P_T.\sigma_0.A.\eta.L.S}{K.T.B.F.\,4\pi(h.\text{cosec}\,\varphi)^2} \qquad \ldots\ldots\ldots(12)$$

where h = height

η = aerial efficiency factor

L = atmospheric attenuation

S = system loss relative to c.w.

S represents sideband power loss in coherent pulsed and f.m. systems, also fold-over detection noise in the former and spurious modulation loss in the latter. In Janus systems S includes losses due to small-signal mixing in the presence of noise and non-coherence of successive pulses above the altitude where return-pulse overlap occurs.

The radiated powers of systems in current use (to obtain adequate signal at 60,000 ft. over a sea-state of Beaufort 1) vary between one to twenty watts for c.w. sensors and up to 8 kW pulse-power for short-pulse Janus.

The relation between P_T and φ shown in eqn. (12) is purely the range function but the depression angle is implicit in σ_0. Fig. 5 shows that the returned-signal increases with greater depression of the beam. An increase in received power obtained in this fashion is at the expense of a larger bandwidth, greater terrain distortion and faster variation of Doppler shift with change of aircraft attitudes.

7. The Tracker

The prime function of a tracking-unit is to provide a single-valued output, discrete frequency or voltage or shaft-position analogue, representative of the mean-frequency of the Doppler spectrum.

The Doppler spectrum occurs within a bandwidth set by the vehicle velocity-range and the background noise within this bandwidth requires that a window-filter of width comparable to the spectrum be used. This narrow-band filter is put-on to the signal and a servo system tracks any subsequent change in signal position.

The tracking-unit has the following general functions complementary to frequency-tracking:—

(*a*) *Search:* That is, original acquisition of the signal and subsequent location of it if, for any reason, the accurate narrow-band servo-system becomes unlocked. The search circuit drives the window-filter until the latter is within servo pull-in range of the signal. Search may be entirely manual for simplicity but for civil application where it is desired that no crew-member be allocated specifically to monitor navigation data, automatic search is necessary. This task is essentially a measure of relative signal-to-noise across the Doppler band and may be performed in any of several ways. A series of fixed filters may be interrogated in turn, or a band-pass or band-stop filter moved across the speed range. A choice can be made between sweeping the band continuously or examining it only when signal is lost by the window-filter. The search circuit can be considered as a less-accurate but broader ranged tracking circuit; it has only to locate the spectrum centre to within the servo pulling-in range, say, 15 or 20 per cent., and a knowledge of true air-speed may be used as a starting point.

(*b*) *Signal-to-noise measurement:* This may be done automatically in conjunction with search. At extreme altitude, as signal-to-noise tends to the design limit, indication of approaching unreliability is given and the sensor is put into a memory mode, either manually or automatically.

(*c*) *Memory facilities:* If shown necessary by signal-to-noise measurement the window-filter servo loop is fixed and the tracker continues to give the last known velocity data. Navigation may continue making use of this or alternative inputs as discussed later. Visual warning is given that the equipment is in the memory-mode. The memory-output requirement dictates that the search function shall be performed by an auxiliary circuit.

(*d*) *Control and presentation:* Either a subsidiary unit or the tracker itself may provide these functions, or they may be performed in the computer if this unit is integral with the Doppler sensor.

The tracker may be based upon digital or analogue methods. Track computation is simplified if ground speed and drift angle are available as shaft positions, but a fixed aerial system giving velocity components may use digital outputs. In a digital system one problem is the provision of memory in the absence of signal.

The nature of the input to the tracker is shown in Fig. 10(*a*). The band $f_1 - f_2$ is set by the range of Doppler frequencies required to be tracked and in the case of a Janus system operating from 100 – 1,000 knots would typically be 3 kc/s to 30 kc/s. The bandwidth of the Doppler spectrum is set by the aerial beamwidth and is usually of the order of ±5 per cent. of its mean frequency. The spectrum shape can be assumed of normal distribution. The problem resolves to that of measurement of narrow-band spectra in the presence of broadband noise and is of a statistical nature.[6]

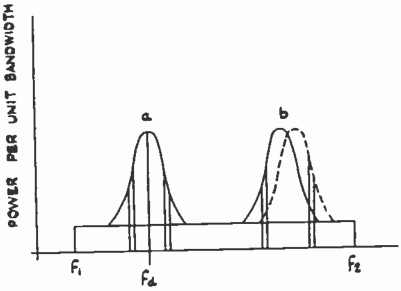


Fig. 10. Nature of tracker spectra.

One frequency measuring circuit, the axis-crossing counter, gives a mean frequency equal to the radius of gyration of the total power spectrum but requires a high signal-to-noise ratio to overcome noise-bias.

The schematic of another system, the discriminator-tracker, is shown in Fig. 11. A two-tone oscillator generates frequencies $\pm P\%$ on f_0 and each tone switches a ring-modulator in one channel of a discriminator to which the Doppler spectrum total band is fed. The percentage-separated frequencies may be generated by a tone-wheel or electronic means. The channels terminate in similar low-pass-filters and detectors but the polarity of detection differs. The filters constitute a pair of windows of fixed percentage separation, Fig. 10(*a*). Assuming the tracker is initially locked onto the Doppler spectrum i.e. $f_0 = f_D$, the detector outputs will be equal and opposite as the window-pair sit astride the Doppler spectrum. If they are not symmetrically disposed one detector output will be greater than the other and the difference may be used via an integrator circuit to control the oscillator frequency such that balance is maintained, i.e. any change in f_D is tracked. The oscillator frequency f_0 is then equal to the mean Doppler frequency and may be used directly as a digital output of velocity. Also, the position of the oscillator control element (say, a potentiometer) is an analogue of velocity. The integral of velocity will give the further output of distance flown.

If the noise spectral density is not uniform a measurement error occurs which is dependent upon signal-to-noise ratio; this effect is most evident in direct crystal-audio systems, since crystal noise per unit bandwidth is inversely proportional to frequency.

If, in a multiple-beam system, port and starboard spectra are examined alternately, the occurrence of drift will show as a cyclic variation in f_D (Fig. 10(*b*)) and thus in detector unbalance which may be phase-sensitive-rectified by switching at the aerial-change-rate and the direct voltage produced used to control a servo system which rotates the aerial assembly in azimuth until the variation is nulled, i.e. the aerial aligns along the aircraft track so that the port and starboard spectra are identical. The aerial shaft position is then an analogue of drift.

The window width and oscillator tone spacing control discriminator sensitivity and require to be related to the Doppler spectrum width. The integrator time-constants are a compromise between smoothing signal fluctuation and allowing the servo system to follow signal-centre shift as the aircraft accelerates or its attitude, and hence effective depression angle, changes. The last requirement is relaxed by the pitch compensation afforded in the Janus aerial.

In the case of a sensor for helicopter use, where drift angles of all magnitudes may occur and negative velocities need to be identified, the above system can be extended directly or

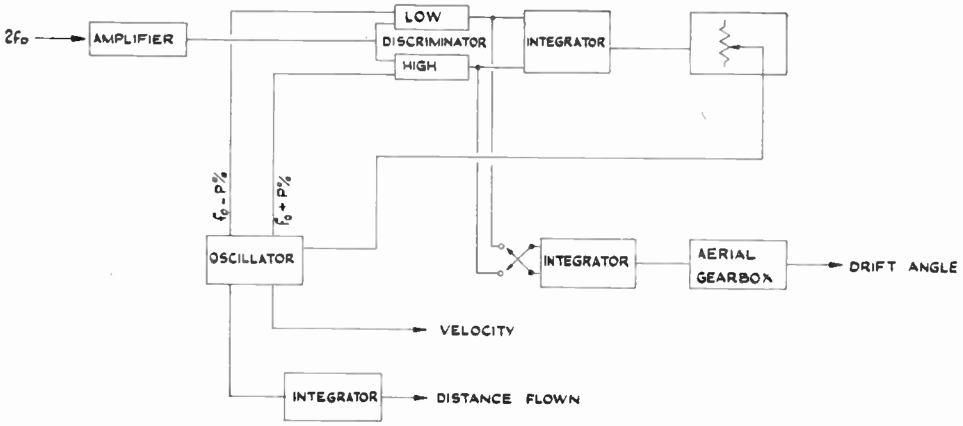


Fig. 11. Typical discriminator-tracker.

by using a heterodyne oscillator to shift the frequency origin. In this case a Janus aerial cannot be used since it does not provide directional sense.

There are several variants of the system described, all capable of measuring ground speed and drift angle, or the equivalent velocity components to ±0·1 per cent of mean value. This is the tracker accuracy alone and other factors introduce comparable or larger errors.

8. Factors Affecting Accuracy

The basic accuracy of the Doppler sensor is subject to derating from a number of causes:—

(*a*) When first installed, the aerial system requires careful alignment with the aircraft heading datum. This can usually be achieved to within 0·1 deg.

(*b*) Whether Janus stabilized or servo-controlled in all planes, residual pitch and roll errors may occur which alter the effective beam angles. Similarly, if a fixed aerial is used any inaccuracies in vertical reference derate the sensor performance.

(*c*) Each illuminated scattering element on the ground plane contributes to the received spectrum an amount dependent upon the angle of the particular incident ray. Fig. 5 showed the relationship between depression angle and signal backscatter for different surfaces. The slope of the graph and, to a lesser degree, the change in range across the aerial beamwidth leads to a shift from the expected centre-frequency of the received signal due to emphasis on the return from the more-nearly normal incident rays. This effect has been termed Terrain Distortion; it is small over land but becomes significant over sea where the amount is dependent upon sea-state, being greatest over calm surfaces.

Referring to Fig. 12 it can be shown that a spectrum centred at f_1 results from applying a slope of N db across the bandwidth of a spectrum centred at f_2 where $(f_1 - f_2) = K(N.B)$. Thus the error is proportional to the slope of the curves in Fig. 5 and to the spectrum bandwidth. For a given slope the signal differential N is itself proportional to spectrum width, hence the terrain distortion is proportional to the square of the bandwidth. Terrain distortion can be limited by using a small depression angle, thus operating on the flat portion of the backscatter curves and keeping the aerial beamwidth as narrow as practicable. The overall navigation error due to terrain distortion depends upon the manner in which separate aerial returns are combined. As an illustration of the effect, the error with a depression angle of 67 deg. and a 3-deg. beamwidth is −1 per cent. and −1·5 per cent over B4 and B1 sea-states, respectively. This error may be limited in one of two ways. A mean error can be computed for all terrain conditions with appropriate probability weighting and this factor designed into the system constants, or a manually-operated switch provided so that the tracker constant (c/s per knot) can be varied to compensate for particular surface conditions. By this means the residual error can be kept to about 0·2 per cent. An automatic compensation requiring no action on the part of the crew is desirable.

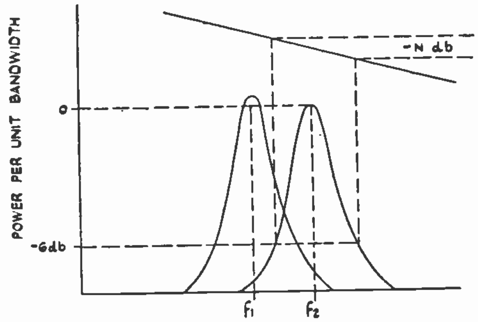


Fig. 12. Terrain distortion spectrum shift.

(*d*) Water surface movement due either to ocean currents, or wind-blown droplets, can cause errors in Doppler measurement. The errors are vectorially random with flight-time and in any case small compared with modern aircraft ground speeds. Over a reasonable stage length at normal speeds the effect is not significant but a helicopter hovering by noting zero-Doppler-effect would in fact be referenced to the mean surface movement.

(*e*) For navigational purposes a heading reference is required. With accurate swinging in a sterile area, careful alignment and good maintenance, the modern gyro-magnetic compass can give a heading accuracy of about 0·5 deg. but in-flight conditions will not normally yield better than 1 deg. This is large compared with the basic Doppler measurement and represents the present limit to practical navigational accuracy. Magnetic variation requires to be set-in and this is not well known for all regions.

(*f*) Computational errors in the order of 0·5 per cent will arise due to instrumental error and assumptions concerning the shape of the earth.

(*g*) Doppler systems usually integrate velocity to give a distance-gone output and due to the change in length of one minute of arc with altitude, a height factor occurs which amounts to 48 parts per million per one thousand feet altitude. The effect may be reduced by computing for a mean height or if precision is required the tracker constant (c/s per knot) must be modified with altitude.

It will be noted that items (*a*), (*b*), (*c*) and (*d*) affect the basic Doppler outputs whilst the remainder concern the navigational data developed. Some errors are random and others systematic, the latter can be allowed for in design, the residual errors add in root-mean-square fashion.

Present equipments are capable of distance flown accuracies better than 0·5 per cent. and, depending upon heading reference used, 0·5 deg. to 1 deg. in course or equivalent lateral velocity, resulting in a positional error of 1 to 2 per cent. of distance flown.

9. The Computer and Heading Reference

For navigational purposes the outputs of the sensor along with a heading reference and, if the system is data-stabilized, aircraft attitude information, are fed into the computer which, as shown in Fig. 1, usually evaluates present position and course and distance to destination.

The computer may or may not be designed as an integral part of the whole system. For a given application the integration of sensor and computer has obvious advantages since the functions of detection, analysis and presentation are closely related, any mechanical division being simply a matter of acceptable installation. An alternative approach is the design of separate units requiring standard inputs, capable of working in any combination which may be preferred.

Both stages of computation could be performed by either analogue or digital methods but, as the inputs are generally in analogue form, this is usually continued throughout. Present position may be computed in its simplest terms as range and bearing from an origin but this is suitable only for short-term flights intending to return to base. Alternatively, for normal navigation but in a restricted coverage, using an arbitrary grid reference, the velocity components can be integrated and presented as distance travelled along and across a selected track or resolved as "northings" and "eastings". For presentation in the generally applicable terms of latitude and longitude, whereas the N—S component of distance travelled gives change of latitude directly, the resolved E—W departure requires to be operated on by the secant of latitude to give the longitudinal increment.

Information on course-and-distance, derived from comparison of present position with destination co-ordinates, may be presented in either rhumb-line or great-circle terms. Rhumb-line flying, that is a leg or series of legs each of constant heading, is necessarily longer than the great-circle distance, but the approximation over short ranges in moderate latitudes is good enough and the computation is somewhat simplified. Great-circle flying is to be preferred for unrestricted global navigation.

Heading information is generaly obtained from a gyro-magnetic compass up to about 70 deg. latitude, beyond which it becomes unreliable due to increasing magnetic dip and the magnitude and large rate of change of magnetic variation. In moderate latitudes the accuracy available may be no better than ±1 deg. in heading. Variation requires to be set-in to provide the true heading required for navigation. This may be done manually, or automatically by means of a profile cam controlled by position co-ordinates, but provision for manual override must be made to allow locally used data to be set-in since variation is not well tabulated over all regions. The cam would need to be replaced periodically to cope with change of variation. For polar flying the gyro-magnetic compass may continue in free-gyro mode with an accuracy decreasing with flight-time according to gyro residual drift-rate, which may be in the order of 1 deg. per hour. Since 1 deg. in heading represents 1·7 per cent. in across error, it is seen that the compass is at present the limiting factor in navigational accuracy.

An alternative to the gyro-magnetic compass is being developed in the Earth Rate Directional Reference which is an inertial system detecting the earth's rotational rate and can be servoed onto a rate-null and thus indicate true north. It is independent of magnetic or variation data but requires compensating inputs of vehicle velocity and latitude both of which can be supplied by the Doppler sensor. Since the system is continually servoing onto the earth-rate-null it is not time dependent. The average expected accuracy over the latitude range 0 – 75 deg. is 0·5 deg. (95 per cent. probability). The earth-rate-signal falls off with increasing latitude and the system is usable only up to 75 deg.; after this use is made of free-gyro mode, the accuracy of which is expected to be a whole order better than gyros in present use. In case of sensor failure resulting in the absence of compensating speed and latitude inputs, the E.R.D.R. can revert to a gyro-magnetic mode. It may be noted that the weight and complexity of the modern heading-reference is comparable with that of either the Doppler sensor or computer.

As mentioned earlier, if Doppler information is temporarily lost the equipment can continue to function on memory using as sensor input the remembered ground speed and drift-angle. Navigation on this basis is valid, providing no change is made in heading and the wind is constant. If true-air-speed is fed into the computer the velocity triangle can be solved to present wind data and an alternative memory-mode would be to revert to basic dead-reckoning using the remembered wind as sensor-input. In this case changes of heading may be permitted whilst on memory but the navigational accuracy holds only over the wind-credibility period. As it is at least equally likely that wind will veer as that heading is required to change within a given period it is not obvious which system is to be preferred. The added complexity of wind-evaluation may be justified by the meteorological value of full wind-reporting with use of this information for subsequent flight-plans.

It is a requirement of the computer that alternative reliable position information derived from either visual fixes or accurate ground-station references, when available, may be fed in. Therefore a store mechanism is usually provided into which the Doppler system can continue to feed information during the time taken to adjust the computer to show correct positional data. The store then discharges into the computer thereby maintaining continuity of navigation. It must at present be left to the human operator to weigh the reliability of alternative sources of positional data.

10. Some General Features

The first Doppler navigational equipment produced in Great Britain[7] was a pulsed-system weighing about 250 lb. including computer but excluding power-supply and heading reference and occupying a volume of 14 cubic feet. It consumed 750 W from a supply with special compound regulation to cope with the pulse nature of the load; the aerial cutout was 42 in. × 25 in.

Comparable figures for the most recent navigator are 130 lb., 3 cubic feet, 400 W (from 200V±5% 400 c/s±5% 3-phase standard supply) and aerial cutout of 26 in. × 20 in.

The reduction in weight and volume is achieved primarily through the use of an f.m. c.w. system which eliminates heavy pulse components and, by use of lower potentials, is able to operate at high altitude in non-pressurized regions of the aircraft without recourse to pressure-sealed construction.

The separate units constituting the sensor are suitable for installation anywhere in the aircraft, only the control unit or, if integral, computer needs to be in the radio rack. The aerial system is rarely in a position which permits internal access, usually it is necessary to remove the radome to reach it. Hence it is preferred that the design shall not incorporate any component on the aerial assembly which can be located elsewhere. This serviceability requirement limits the compact design which may otherwise be achieved, for example, if the transmitter is remote from the aerial the necessity for waveguide or co-axial interconnection derates the advantages of micro-strip techniques.

The reliability of the pulsed system referred to has been comparatively good, due in the main to the use of wired-in valves and the elimination of plugs and sockets except for main-unit interconnection. Civil applications will require a very high degree of reliability and this may be achieved by the use of a dual installation with the possible exception of the basic aerial assembly. The individual units would be selected at the control position.

Analogue equipments are fail-safe in the sense that in the event of signal-to-noise deterioration the sensor continues to feed last-known data into the computer. In this case, or if a fault-condition arises, visual indication is given that the sensor is operating in the memory-mode. Facilities can be designed into the system for extensive in-flight testing but in civil use the requirement will probably be limited to the provision of means such as a calibrate-signal or deliberate servo offsetting whereby the operator can decide whether to continue to place confidence in the information presented or to change-over to the standby-equipment.

11. Conclusions

The Doppler sensors now in production or under active development can be expected to make a major contribution to aircraft navigation for several years to come. Whilst it may be assumed that the Doppler form of self-contained navigational aid will eventually yield to pure inertial methods there are likely to be one or more generations of Doppler-sensor design in the interim period, probably leading to a composite Doppler-inertial system.

The design trends will be towards even higher accuracy, completely automatic navigators capable of integration with flight control systems on the one hand and, on the other, towards a simpler solution offering limited accuracy and facilities good enough for normal purposes in applications where economical aspects are the prime consideration.

In both cases increased reliability and reduction of weight, volume and power requirements will be design targets. For some purposes techniques will be extended to permit operation in extreme environments.

It is probable that future designs will incorporate facilities for transmission, automatically or when interrogated, of position and steering data and possibly wind information.

The high accuracy offered by Doppler navigators should contribute to increased flight safety and ease the problem of air traffic control.

12. Acknowledgments

Acknowledgment is made to the Engineer-in-Chief of Marconi's Wireless Telegraph Company Limited for permission to publish this paper.

13. References

1. K. L. S. Gunn and T. W. R. East, "The microwave properties of precipitation particles," *Journal of the Royal Meteorological Society*, **80**, pp. 522-545, October 1954.
2. J. C. Wiltse, S. P. Schlesinger and C. M. Johnson, "Back-scattering characteristics of the sea in the region from 10 to 50 kMc/s," *Proceedings of the Institute of Radio Engineers*, **45**, pp. 220-228, February 1957.
3. C. R. Grant and B. S. Yaplee, "Back-scattering from water and land at centimeter and millimeter wavelengths," *Proceedings of the Institute of Radio Engineers*, **45**, pp. 976-982, July 1957.
4. J. E. Clegg and T. G. Thorne, "Doppler navigation," *Proceedings of the Institution of Electrical Engineers*, Paper No. 2568R (March 1958, 13 pp.)
5. R. K. Moore and C. S. Williams, Jr., "Radar terrain return at near-vertical incidence," *Proceedings of the Institute of Radio Engineers*, **45**, pp. 228-238, February 1957.
6. W. W. H. Clarke and R. F. Nikkel, "Mean frequency determination of narrow-band noise spectra," *Proceedings of the Institution of Electrical Engineers*, **102**, Part B, pp. 364-370, May 1955.
7. G. E. Beck and T. G. Thorne, "An airborne Doppler navigation equipment," *Proceedings of the Institution of Electrical Engineers*, Paper No. 2572R (March 1958, 10 pp.)

14. Appendix 1 : Velocity Components

Referring to Fig. 7(*c*):—

Aircraft velocity down any one beam is the sum of the resolved components

i.e. $V_1 = V_H \cos\gamma + V_L \sin\gamma - V_v \sin\varphi$

$V_2 = V_H \cos\gamma - V_L \sin\gamma - V_v \sin\varphi$

$V_3 = V_L \sin\gamma - V_H \cos\gamma - V_v \sin\varphi$

and $f_{D1} = \frac{2}{\lambda}\cos\varphi . V_1$

$$f_{D2} = \frac{2}{\lambda}\cos\varphi . V_2$$

$$f_{D3} = \frac{2}{\lambda}\cos\varphi . V_3$$

Now $f_{D1} - f_{D3} = \frac{4}{\lambda}\cos\varphi . V_H \cos\gamma$

hence $V_H = \frac{\lambda(f_{D1} - f_{D3})}{4\cos\varphi . \cos\gamma}$

and $f_{D1} - f_{D2} = \frac{4}{\lambda}\cos\varphi . V_L \sin\gamma$

hence $V_L = \frac{\lambda(f_{D1} - f_{D2})}{4\cos\varphi \sin\gamma}$

and $f_{D2} + f_{D3} = -\frac{4}{\lambda}\cos\varphi . V_v \sin\varphi$

hence $V_v = -\frac{\lambda(f_{D2} + f_{D3})}{2\sin 2\varphi.}$

Referring to Fig. 7(*d*):—

Proceeding in a similar fashion, in the Janus system

$$f_{D1} - f_{D4} = \frac{2}{\lambda}\cos\varphi(V_H \cos\gamma + V_L \sin\gamma) = F_1$$

$$f_{D2} - f_{D3} = \frac{2}{\lambda}\cos\varphi(V_H \cos\gamma - V_L \sin\gamma) = F_2$$

whence $V_H = \frac{\lambda}{4\cos\varphi . \cos\gamma} . (F_1 + F_2)$

and $V_L = \frac{\lambda}{4\cos\varphi . \sin\gamma} . (F_1 - F_2)$

15. Appendix 2 : Pitch and Climb Errors

Referring to Fig. 13,

velocity down forward beam

$$V_F = V_H \cos(\varphi - \alpha) - V_H \tan C \sin(\varphi - \alpha)$$

velocity down rear beam

$$V_R = -V_H \cos(\varphi + \alpha) - V_H \tan C \sin(\varphi + \alpha)$$

In a Janus system indicated velocity $= V_F - V_R$

$$= V_H \{\cos(\varphi - \alpha) + \cos(\varphi + \alpha) + \tan C [\sin(\varphi + \alpha) - \sin(\varphi - \alpha)]\}$$

$$= 2V_H \cos\varphi(\cos\alpha + \tan C . \sin\alpha)$$

instead of $2V_H \cos\varphi$

Hence the fractional error is

$$(\cos\alpha + \tan C \sin\alpha) - 1$$

In the particular case where $C = 0$

the fractional pitch error $= (\cos\alpha - 1)$

Also it may be noted that error is zero when $\alpha = 0$ or $2C$.

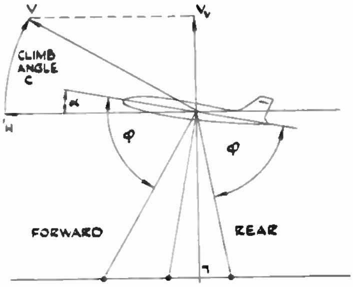


Fig. 13. Pitch and climb errors.

16. Appendix 3 : General Equation for $\varphi_{\alpha DR}$

Referring to Fig. 14, a beam having a constant depression angle φ and with varying lateral angle β generates the surface of a cone of semi-vertical angle φ

The equation of the cone

$$r^2 = y^2 + h^2 = x^2 \tan^2\varphi$$

whence $\cos^2\varphi = \frac{x^2}{x^2 + y^2 + h^2}$

where x, y and h are the co-ordinates of a point P on the ground plane.

If the reference axes are rotated through a drift angle D then

$$x = x' \cos D - y' \sin D$$

$$y = y' \cos D + x' \sin D$$

$$h = h'$$

If the axes are then pitched through an angle α

$$x' = x'' \cos\alpha + h'' \sin\alpha$$

$$h' = h'' \cos\alpha - x'' \sin\alpha$$

P now lies on a hyperbola generated by the intersection of the ground plane with a cone of effective semi-vertical angle of $\varphi_{\alpha D}$ and by substitution of the co-ordinates, noting that

$$y = h \tan \beta$$

$$x = h \cot \varphi \sec \beta$$

and taking a roll angle R additive to β then

$$\varphi_{\alpha DR} = \varphi[\cos \alpha \cos D + \tan \varphi \sin \alpha \cos(\beta + R) \cos D - \tan \varphi \sin(\beta + R) \sin D]$$

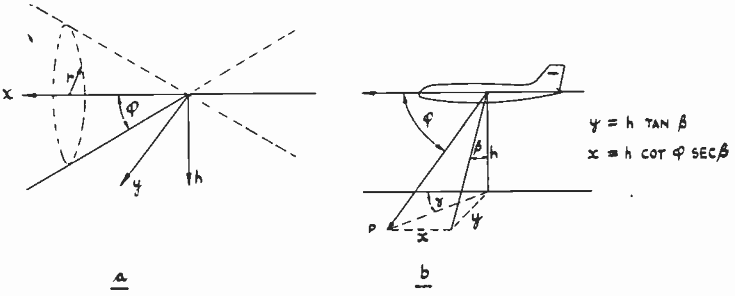


Fig. 14. Beam co-ordinates.

DISCUSSION

T. Gray*: I have found Mr. Walker's paper most interesting and instructive. I have, however, one or two comments. I note a distinct bias in favour of frequency modulated systems, the implication being that such systems can offer substantial advantages over pulse systems for a given performance. However, I think it is certain that Mr. Walker was referring only to short pulse systems, and this is by no means the most efficient type of operation. If, however, the pulse length is considerably increased so that the duty ratio lies in the region between 20 per cent. and unity, a completely different form of system emerges.

Let us examine the disadvantages associated with the short pulse system, and note the effects of increasing the pulse length. The short pulse system requires high peak power and as a corollary to this high operating voltages which leads to considerable stressing of certain components. Operationally this system suffers from the fact that at comparatively low altitudes the law of signal return changes from an inverse square dependence on height to an inverse cube dependence on height.

In the case of the long pulse system, however, by using a c.w. type magnetron, a system can be developed using a peak power in the region of 20 watts, and a mean power of about 5 watts, which will offer a signal inversely proportional to the square of height up to an altitude of between 50,000 and 60,000 ft. It is also possible to use much narrower broadside aerial beam-widths than with the short pulse system because the period of illumination per pulse is much longer. This has an added advantage that the return signal never becomes a great deal longer than the pulse length. It is frequently stated that the latter condition is a desirable one in order to achieve time coincidence of return, but it brings with it disadvantages in respect of law of signal return with height.

In the long pulse system mentioned no voltages are present higher than about 800 or 900 volts, and there is no necessity for rigidly controlled supplies for the oscillator since coherence is assured without close control of transmitter frequency. A system of the type described exists, the total weight of which is 65 lb. for a system capable of measuring ground speed and drift only. It should be made clear that the transmitter receiver part of this system, which weighs 20 lb, does not use transistors.

It would seem on a basis of Mr. Walker's figures that an appropriately designed pulse system does not necessarily show any disadvantages as compared with the f.m. system. In the latter case a very low efficiency transmitting valve is required which means comparatively high power consumption for a given performance and in the case of a system such as that described recently by the Defence Research Board of Canada, in which signals are mixed before tracking, it is probable that the Doppler power per transmitted watt is very similar to that obtained with the long pulse system. This is due to the normal harmonic loss with the f.m. system, coupled with the fact that by Janus

---

* Decca Radar Ltd.

mixing before tracking part of the advantage of coherent detection is lost. An f.m. signal with tracking before mixing would seem to offer a better signal-to-noise performance but would appear to call for intolerably close control of transmitter frequency for high altitude working. It has been suggested by some sources that about 20,000 ft. would be the limit at which a spectrum capable of being adequately tracked could be expected.

It may be that the author has a great deal more information than I have on this point, but a brief examination of the stability requirements suggests that a very closely regulated ripple-free supply would be required for the klystron. A klystron completely free of microphony and spurious f.m. would be required and very close control of the modulation waveform would be necessary. It would seem that this must be a real problem when beating a signal return of some 100 microseconds echo time with the transmitter.

K. W. B. Fouweather (Associate Member)*: I should like to enquire about two aspects of the Doppler navigator. Does the equipment "fail safe" when a major fault occurs and is any indication given that the equipment has failed? Should a minor defect occur can the equipment continue to operate and give erroneous information?

Secondly, what degree of reliability can one expect from this highly complex equipment, bearing in mind the weight involved?

D. M. O'Hanlon (Associate Member)†: Mr. Walker has mentioned that the serviceability of the equipment has been shown to be satisfactory. I have had access to some of the figures, and these would not be acceptable in civil airline use.

Is Mr. Walker permitted to give the actual figures, say in failures per 1,000 hours of flying, and could he say if there has been a considerable improvement recently?

M. Catton‡: In his paper Mr. Walker refers to the use of a pitch-stabilized aerial, the error signal for stabilization to be obtained from the difference in the beat frequencies obtained from the forward and aft-looking beams. Unlike pulse systems, where the necessity for pulse overlap frequently requires the use of pitch stabilization, no performance advantage is offered by this in a c.w. system. Could he explain why this is done?

As a second point, I had the impression from the paper that post-tracker mixing of the spectra was used instead of r.f. mixing. This means that the broadening of the spectra due to unwanted frequency modulation is not cancelled out. Does this not result in a large decrease in signal-to-noise ratio?

G. E. Beck§: On the subject of fixed versus moving aerial systems there now seems general agreement that the moving aerial system discussed by Mr. Walker is desirable when drift angles up to 30 degrees are encountered. But there is still a divergence of views on the merits of alternative transmitting systems as the discussion this evening has shown.

It is interesting to note that the ARINC organisation in the United States has been able to draft an Equipment Characteristic defining both operational performance and the form factor of the units, for a civil airline Doppler radar, and that manufacturers advocating pulse, c.w., or f.m.c.w. have all accepted this characteristic. Within these limits therefore it appears that a number of systems can be made to function, and it may be that the differences will only prove significant when future designs or aircraft call for better capabilities from the doppler equipment.

Although there is considerable operational experience of short pulse systems in jet aircraft, and a recent issue of *Aviation Age* (January 1958, p. 88) quotes some measurements of c.w. Doppler spectra obtained at an altitude of 40,000 feet, knowledge based on actual experience above, say, 50,000 feet is still lacking. In these regions of high altitude, and at high speeds, the relative merits of various Doppler systems have still to be proved. From the rate of technical progress made so far, however, I think that we can be confident that suitable Doppler equipments will be developed in time for each succeeding generation of aircraft.

---

* Air Registration Board.

† British European Airways.

‡ Decca Radar Ltd.

§ Marconi's W.T. Co. Ltd.

AUTHOR'S REPLY

In the paper I set out to deal with design features of Doppler navigational aids in general without favour to any particular method or reference to specific requirements. As it seems Mr. Gray detects a natural enthusiasm showing through and since there seems to be considerable interest in the f.m.c.w. principle as used in a system with which I am acquainted, perhaps the steps which led to the adoption of this system in an equipment considered suitable for general use may be described.

Whilst all systems can be made to work and optimum design may vary with application, the adoption and development of a method suitable for general use in a range of applications has considerable technical and commercial merit. The self-coherent pulse system (Janus) allowed practical Doppler equipment to be designed at a time when alternative systems were handicapped by limitations in circuit technique and component design but in a transmission system suitable for broad application, the loss of negative and vertical velocity information, and the inefficient detection process were considered no longer acceptable.

The alternatives are either a coherent pulse system or c.w. operation. The complexity of the former led to an attempt to overcome the cross-coupling problem associated with straight c.w. working and resulted in the f.m.c.w. design.

The individual spectra are tracked separately, thus achieving the advantage of coherent detection mentioned by Mr. Gray. The degree of control of oscillator stability called for is by no means intolerable. Ripple reduction is achieved by standard circuit design and a d.c. heater supply is generated for the transmitting valve, which is isolated from mismatch pulling by a ferrite Uniline. The transmitter microphony requirements are readily met by commercially available klystrons. The modulation waveform is not critical and no attempt made to control harmonic content.

I agree with Mr. Catton that single-ended working gives no cancellation of spurious modulation but this is no function of the f.m. system, being precisely the same as in straight c.w. The amount of deviation is held within acceptable limits.

I can reassure Mr. Gray that suggestions of 20,000 ft. as an altitude barrier are as pessimistic as were the early opinions on Doppler applications, since an f.m.c.w. equipment radiating 1 W has successfully completed trials at 45,000 ft.

A natural extension of drift resolution method led to aerial attitude stabilization by pitch data extracted from fore and aft Doppler signals, in preference to reliance upon external reference gyros or acceleration conscious pendulum techniques. I would emphasize to Mr. Catton the "single-ended" nature of the system —rotating the aerial in azimuth and pitch allows the use of one time-shared tracker rather than a discrete tracker per beam. An extra output from this system is that of aircraft angle of attack.

In reply to Mr. Fouweather and Mr. O'Hanlon, I would stress that figures so far published have referred to early pulse sensors and there has in fact been a marked improvement in recent designs. In the concluding section of reference 7 a table is given of component-hours per failure versus type of component for A.R.I.5851 and a separately assessed flight-reliability of 95 per cent. is quoted. In service use this Doppler has a reliability comparable with the standard v.h.f. set. I agree that this performance is not as high as the civil user must expect. It is just those pulse-components most prone to failure (magnetrons, T-R cells, e.h.t. rectifiers) which are eliminated in a c.w. design. I note that Mr. Fouweather is bearing in mind the weight involved, a significant feature, since "reliability through redundancy" techniques can proceed up to any line that the user is prepared to draw.

In the event of failure, visual indication would be given that the equipment has reverted to memory-mode. Here it will continue to feed out last known data. In general, only a combination of faults could produce an erroneous answer without warning being given. This is a remote possibility but is covered by the provision of in-flight testing facilities which can check the equipment either continuously or when desired.

APPLICANTS FOR ELECTION AND TRANSFER

As a result of its June meeting the Membership Committee recommended to the Council the following elections and transfers.

In accordance with a resolution of Council, and in the absence of any objections, the election and transfer of the candidates to the class indicated will be confirmed fourteen days after the date of circulation of this list. Any objections or communications concerning these elections should be addressed to the General Secretary for submission to the Council.

Direct Election to Full Member

HARRIS, Kennyth Ernest, B.Sc. *New Barnet.*

Transfer from Associate Member to Full Member

PATTINSON, Thomas Henry. *Stevenage.*

Direct Election to Associate Member

GREEN, Peter William. *Evesham.*
LEDGER, Arthur Stanley Powell, B.Sc. *Leicester.*
THOMAS, Major Dennis Reginald William, M.B.E., R.E.M.E. *Orpington.*
WALTERS, John, B.Sc. *Wigan.*
WILLIAMS, William Thomas. *St. Albans.*

Transfer from Associate to Associate Member

DALTON, John. *Bolton.*
HALL, William Cuthbert. *Walton-on-Thames.*

Transfer from Graduate to Associate Member

ELLAMS, Sqdn. Ldr. George, R.A.F. *Shawbury.*
GRAY, Flt. Lt. Donald Ernest, R.A.F. *Hillingdon.*
HOULDCROFT, David Richmond. *Southport.*
NICHOLSON, Charles Henry. *West Molesey.*
ORMISTON, Peter Thomas. *Crawley.*
PASIK, Mieczyslaw. *Isleworth.*
SCOTT, Brian George. *Weybridge.*
TAIT, David Adams Gilmour. *Hounslow.*
WARD, Eric Henry. *Addlestone.*

Transfer from Student to Associate Member

REIDY, Kevin John. *London, N.16.*
TOMLINSON, Edward Rex. *Kidsgrove.*

Direct Election to Associate

BRODIE, Robert George. *Horley.*
COLBOURNE, Robert Pickering. *Sutton.*
HARDY, Duncan Anthony. *Weymouth.*
LEARNEY, Lewis Philip. *Crawley.*
MASTRONARDI, Flg. Off. Edward John, M.C., B.A., R.C.A.F. *Winnipeg.*
RAJENDRA, Yashawant Laxman. *Nasik.*
SMITH, Eric George. *Rotherham.*
WAITE, Major John Albert, R.Sigs. *Brighton.*
WALTERS, Keith Paul. *Ibadan.*

Direct Election to Graduate

CLARK, Ernest Edgar. *Aldershot.*
DORMER, Flt. Lt. Donald Edward, R.A.F. *Bassingbourn.*
GLEAVE, Flg. Off. Gordon, R.A.F. *Cheltenham.*
HIGGINS, John Christopher, M.A.(Cantab.), *London, N.7.*
JOHNS, Anthony Gwyn, B.Sc. *Teddington.*
McKEOWN, Edward. *Greenock.*
NORRIS, Ian Stuart, B.Sc. *Morden.*
SYMONS, William Charles. *London, E.17.*
WILLIS, Douglas Rowland. *Chorley Wood.*

Transfer from Associate to Graduate

CHAN, York Chye. *Singapore.*
SARMA, Lieut. D. Parameswara Prasad, M.Sc., Indian E.M.E., *Poona.*

Transfer from Student to Graduate

GEORGE, Julian. *Muar, Malaya.*
HATTANGADI, Vasant Annaji, B.Sc. *Gadag.*
HEWITT, Patrick John. *London, W.4.*
ISLAM, Capt. Sayed Sultan-ul, Pakistan Sigs. *Rawalpindi.*
LAM, Yat Wah. *London, N.W.7.*
SHORT, Allan. *Oakington.*
SNASHALL, Gerald Herbert, B.Sc. *Godstone.*

STUDENTSHIP REGISTRATIONS

AGARWAL, Gita Ram. *Saharanpur.*

BARRY, 2nd Lt. Jugal Kishore, M.Sc., Indian Sigs. *Faizabad.**
BHASIN, Karam Chand. *Juna Garh.*
BISWAS, Paresnath, B.Sc. *Sukchar.*
BLAND, Cecil Allan. *Wilmslow.*
BORSTNIK, Bozo. *Morecambe.*
BROCKLEY, Alan James. *Smethwick.*

CANNON, Michael Roy. *Woomera, Western Australia.*
CROSS, Richard Gordon. *Toronto.*

DALE, Collis Seymour. *Tangmere.*
DAS, Mukunda Madhale, B.Sc. *Calcutta.*
DEY, Swadesh Kumar. *Bombay.*
DUARTE CATULO, Fernando Jose Euginio. *Goa.*

ELLIS, Victor Eric Henry. *Newcastle-on-Tyne.*

FRASER, John Stanley. *Harwell.*

GUPTA, Dharam Singh, M.Sc. *Delhi.*
GUPTA, Makhan Lal. *Allahabad.*

HALL, George. *Malvern.*
HANSEN, Anno Martin Cathreus. *Causeway, S. Rhodesia.*
HAR KRISHAN JIT SINGH, B.Sc. *Jullundur.*
HUSAIN, Syed, B.Sc. *Khairahabad.*

KANWAL, Jagjit Singh, B.Sc. *Ambala City.*
KAPUR, Tilak Raj., B.Sc. *Meerut City.*
KUMAR, Sailen Krishna, B.Sc. *Calcutta.*

LOBO, Leo Cyril, B.Sc. *Kampala, Uganda.*

MADNAIK, Bapu Dada, B.Sc. *Udgaon.*
MARTIN, Donald Joseph. *Hamilton, Ontario.*
MATHUR, Surendra Kumar. *Jamnagar.*
MAZUMDAR, Satya Brata. *Coimbatore.*
MEHTA, Ravindra Pal, B.A. *Patiala.*

ONI, David Adelegan Omofadesola. *London, W.2.*

PANDIT, Tarunkrishna, B.Sc. *Panihati.*
PRABHALAPAN NAIR, Eswara Pillay, B.Sc.(Eng.).

RAFIQUE, Mohammad, B.Sc. *Rawalpindi.*
RAMAN, P. S., B.A., M.Sc. *Madras.*
RAMAKRISHNAN, Audikesavalu. *Gudiyattam.*
RENGARAJALA, S., B.A. *Orattanad.*
ROLLS, William Frederick. *St. Eustache-sur-le-Lac, Canada.*
ROY, Debabrata. *Calcutta.*

SHAH, Shanker Ambalal, B.Sc. *Bombay.*
SHUKLA, Avanish Chandra, B.Sc. *Basti.*
SRIVASTAVA, Rajendra Prasad, B.Sc. *Ghazia Pur.*
STEYN, Hendrik Jacobus, B.Sc. *Kloofsig, South Africa.*

TSAI, Wai Man. *Hongkong.*
TROWMAN, Alfred William. *Birmingham.*

UNGAR, Jehuda. *Givet Rambam, Israel.**

VELUPILLAI, Murugesu. *Colombo.*

WHITE, Raymond William. *Warlingham.*
WHITTINGHAM, Clifford Frederick. *Cardiff.*

---

* Reinstatement.

# of current interest . . .

B.B.C. Colour Television Tests

The B.B.C. has now issued a report* on the first series of colour television transmission tests carried out in co-operation with the radio industry. So far as reception of the colour picture is concerned, the B.B.C.'s verdict is that the colour pictures produced by the N.T.S.C. system as adapted to 405 lines, with the picture sources and display tubes that are at present available, are satisfactory. The problem of registration with the three-tube colour camera requires attention and certain features of the display tube could with advantage be improved, but the technical performance of the system is adequate for a satisfactory colour television service in the frequency bands at present in use.

The tests radiated from Crystal Palace from November 1956 to April 1957 included live studio performances, film and slides. Eighty-nine per cent. of the observers regarded the reception of the live scenes as satisfactory. The 35-mm film was regarded as satisfactory by 100 per cent. of the observers, the 16-mm film by 93 per cent., and the slides by 98 per cent.

The quality of ordinary black and white television, when received on a colour television set, was found to be generally satisfactory. The quality of the colour transmissions, when received in black and white on ordinary television sets, was also carefully examined; 94 per cent. of technical observers found the pictures completely acceptable.

The B.B.C. intends to carry out further experimental transmissions from time to time in addition to the second series of tests which has recently been concluded and is now under analysis. It is pointed out that there are many other problems to be solved: for example, the production of a reasonably priced colour receiving set and agreement on the future standards to be applied to the development of television in the United Kingdom. The decision whether or not there is to be a public service of colour television, and if so the system to be used, rests with the Postmaster-General.

Insignia Awards

Two Associate Members of the Institution have recently received Insignia Awards from the City and Guilds of London Institute. Reference has previously been made in the *Journal* concerning the C.G.I.A. and it will be recalled that the conditions of the Award are that the applicant holds a Full Technological Certificate, has been professionally employed in a position of responsibility, and submits an acceptable thesis.

The members who have been granted the Award are Mr. K. G. Beauchamp, of Newbury, Berkshire, whose thesis subject was "Efficiency Diode Scanning Circuits"; and Mr. P. W. Seymour, of Sydney, New South Wales, whose thesis was entitled "A Critical Review of Methods used in the Field of Linear Network Analysis."

Mr. Seymour has recently been awarded an Australian National University Scholarship, tenable for three years, in order to read for a Ph.D. degree in theoretical physics at the Research School of Physical Sciences, Canberra.

Steady Spread of the "Sandwich" Course

A list of approved "sandwich" courses in technical colleges has been recently published by the Ministry of Education and gives details of 263 courses of this type to be held during the 1958-59 session—65 more than were approved for last year.

There are now 144 courses—21 more than last year—available at Colleges of Advanced Technology and Regional Colleges. About a third of these lead to degrees or diplomas in technology, and the remainder to other high qualifications which in many cases give exemption from the examination requirements of professional bodies.

Sandwich courses offered at other technical colleges have also increased from 75 to 118. Many new subjects are offered in the various branches of engineering and technology, and telecommunications is well catered for. About half the courses in this group are intended to lead to the Higher National Diploma.

---

* W. N. Sproson, S. N. Watson and M. Campbell, "The B.B.C. Colour Television Tests: An Appraisal of Results." B.B.C. Engineering Division Monograph No. 18, May 1958.

. . . Radio Engineering Overseas

A selection of abstracts from European and Commonwealth journals received in the Library of the Institution. Members who wish to borrow any of these journals should apply to the Librarian stating 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. The Institution regrets that translations cannot be supplied.

621.316.99

An electronic ground detector. D. W. R. McKinley. *Transactions of the Engineering Institute of Canada,* **2**, January 1958.

This electronic earth detector provides warning of hazardous faults appearing in the unearthed 115 V. a.c. supply for hospital operating rooms. It is equally sensitive to balanced or unbalanced earths, either resistive or capacitive. It is normally set to trip on an earth fault of 56,000 ohms, but it has sufficient sensitivity for satisfactory operation on 120,000 ohm faults, if desired. A 15 c/s square wave oscillator samples, in turn, either side of the line through a high-impedance diode bridge. This bridge output is rectified, suitably filtered, and applied to a voltage discriminator circuit which turns on a red light and a loudspeaker tone when the ground impedance becomes 56,000 ohms or less. At the detection threshold the average detector current is less than 0·3 mA. Solid-state diodes and transistors are used throughout. The instrument may also be operated as a high-voltage a.c. ohmmeter.

621.317.794

Experimental wide-band thermistor mounts. J. Swift. *Proceedings of the Institution of Radio Engineers, Australia,* **19**, pp. 261-264, June 1958.

Several simple thermistor mounts are described which consist basically of a coaxial line terminated by two thermistors placed across an untuned cavity. When capsuled thermistors are used a v.s.w.r. of less than 1·1 is obtained over frequency bands centred at 900 Mc/s, 2,000 Mc/s, and 4,000 Mc/s. With uncapsuled thermistors, a mount has been constructed which covers the band 450-5,000 Mc/s with a maximum v.s.w.r. of 1·3.

621.317.799:621.391.029.63

A 2,100 Mc/s microwave propagation test set. F. Ivanek, *Elektrotehniski Vestnik (Ljubljana),* **26**, pp. 17-38, 1958.

The c.w. oscillator, using a "lighthouse" triode, transmits an output power of $\sim$4 W. The superheterodyne receiver has a substantially logarithmic response, a bandwidth of 2·5 - 3 Mc/s and a noise figure of 12 db; its measuring range extends downward to at least -94 dbm. Parabolic antennae are used, 1 m. in diameter having a gain of 24 db. The complete test set can measure attenuations of over 174 db. over line-of-sight paths up to 150 km. in length, having fading values of more than 30 db below the free-space level. The accuracy of fading measurements is within the limits of $+4$ db and -2 db. The test set is designed for unattended operations over periods of several days and its mechanical ruggedness meets stringent requirements regarding transportation. Theoretical considerations of the design and a review of comparable sets are given.

621.372.8

Characteristics and properties of long-slot directional couplers. E. Schuon. *Archiv der Elektrischen Übertragung,* **12**, pp. 237-243, May 1958.

Considering the long-slot directional coupler as a single waveguide in which two field distributions exist, the boundary conditions at the input of the directional coupler can be satisfied by the superimposition of the two types of field. Their different cut-off wavelengths cause finite field strengths to appear at the output of the two partial waveguides. Coupling factor and directivity factor can be reduced to the differences of the cut-off wavelengths and eigen values, respectively. The two quantities are determined for conventional cross-sections by analogue measurements. Measurements confirm these considerations.

621.376.3:621.384.5

Frequency modulation by gas-discharge tubes. P. Stiubei. *Telecomunicatii, (Bucharest),* **1**, pp. 166-168, No. 6, 1957.

A method for obtaining frequency modulation using gas-discharge tubes, is described. The study was carried on a metre wave oscillator, the coil of which enclosed a gas-filled tube with direct current discharge.

621.385

A further group of papers read at the International Congress of Hyperfrequency Valves, held in Paris in June 1956, has been published in *L'Onde Electrique* (**38**, February 1958). The papers include:—

On electromagnetic space-charge modes. G. H. Joshi and N. Marcuvitz. (pp. 83-89). (In English).

Study of travelling wave tubes using an analogue computer. M. Ettenberg, C. Lwang and V. R. Learned. (pp. 90-94). (In English).

Periodic structures with two and three dimensions—possible applications to travelling wave tubes. G. Mourier. (pp. 95-100).

Low noise travelling-wave tubes: verification of fundamental theory and explanation of higher order effect. W. R. Beam and R. C. Knechtli. (pp. 101-115). (In English).

On the theory of the carcinotron M. M. de Bennetot. (pp. 116-118).

On a model of a high power travelling wave tube amplifier operating under pulse conditions. A. Dubois. (pp. 119-124).

Type M backward-wave tube oscillators for pulse working. M. Favre. (pp. 125-131).

The cerenkov effect and the generation of centimetric waves. G. Mourier. (pp. 132-135).

621.385.1

Noise in space charge diodes. K.-H. Locherer. *Archiv der Elektrischen Übertragung,* **12**, pp. 225-236 and 265-270, May and June 1958.

The fundamental equations for shot noise of a planar space charge diode are deduced in the transit time region, with consideration of the velocity distribution of the electrons, and a numerical solution of an example is given. From the numerical results the quadripole noise parameters of the ideal triode are calculated using the equivalent-diode representation. For low frequencies the fundamental equations can be solved by power series with respect to w; for $w = 0$ the result of Schottky and Spenke is obtained.

621.396.65:621.376.4

Radio frequency powers and noise levels in multi-channel radiotelephone systems using angular modulation. T. D. Thomson. *Proceedings of the Institution of Radio Engineers, Australia,* **19**, pp. 211-220, May 1958.

The paper shows how to calculate the radio power required at the input to a receiver to ensure a specified noise standard in a band of frequencies, e.g. in one channel of a multi-channel telephone system. The effect of increasing the number of receivers, as in a multi-path system, is discussed together with the effects of fading, or equipment deterioration, on one or more paths simultaneously. Simple formulae are developed and curves are drawn from them. The method is applied to the design of a five-channel phase-modulated radiotelephone system employing 16 repeater sections. Finally, a simple process of frequency inversion of the telephone channels is suggested which can either halve the transmitter power output required or double the length of a given system for the same noise performance.

621.396.674

On 3- and 4-element antennas. E. Nicolau and A. Dobrescu. *Telecomunicatii, (Bucharest),* **1**, pp. 168-173, No. 6, 1957.

The conditions for attaining maximum gain in the design of antenna systems with three and four radiating elements are studied. The influence of antenna thickness on input impedance in four element optimum gain systems is discussed.

621.396.822

A simple noise generator. V. Herles. *Automatisace, (Prague),* **3**, pp. 86-88, March 1958.

The article deals with the construction of the simple noise generator (after A. M. Petrovskij) in which the variations of contact resistance among the steel balls in the rotating drum are utilized. The generator can be used in control systems as a source of white noise in the very low frequencies and gives an output of up to 1 W.

621.396.933

The flight testing of radio facilities. M. Cassidy. *Proceedings of the Institution of Radio Engineers, Australia,* **19**, pp. 253-260, June 1958.

This paper describes the extent of the radio facilities which make up the Airways System operated by the Australian Department of Civil Aviation to provide navigational aids for domestic airlines operating throughout the Commonwealth. These facilities are regularly flight-tested as an overall check that their performance is in accordance with I.C.A.O. Standards. The test vehicles used are DC-3 aircraft and the installation of test equipment therein and the techniques and ancillary equipment are described. Recent developments in civil aviation arising from the introduction of high performance aircraft require parallel developments in flight testing radio facilities, and the Department's plans to meet this situation are outlined. The application of standard testing techniques to the solution of problems of more general interest is also considered.

621.396.96:656.7.05

S.A.T.C.O.—a new system for air traffic control. *Tijdschrift van het Nederlands Radiogenootschap,* **23**, pp. 135-145, May 1958.

The first part deals with the general background details of the S.A.T.C.O. system. The second part describes the laboratory model of the data processing equipment. Finally the specific radar items required for the system are discussed.

621.397.9

An N.T.S.C. colour modulator for C.C.I.R. standards. F. Jaeschke. *Archiv der Elektrischen Übertragung,* **12**, pp. 271-288, June 1958.

Circuit examples and design rules are given for the development of a colour modulator for the transmission of colour television pictures by the N.T.S.C. method. Particular attention is here paid to the problem of the conversion of the three monochrome signals supplied by the picture sender into the luminance and chominance components used for coding by the N.T.S.C.'s system (matrixing). The accommodation of the colour information, in addition to the monochrome video signal information, requires a number of circuit measures (band limiting and application of a carrier to the chrominance components), which are explained in detail by reference to circuit examples. A separate section deals with the measuring facilities required for levelling and operation of the modulator; circuits are again proposed for their practical realization.

Abstracts in English are available for the following papers from *The Journal of the Institute of Electrical Communication Engineers of Japan:*

Vol. **41**, No. 1, January 1958:

Microwave mixer uninfluenced by undesired sideband components. T. Kawahashi. (pp. 9-15).

An electronic a.f.c. system of the non-hunting type using zero-beat detection. H. Michishita, K. Kawai, Y. Tadenuma and T. Fukushima. (pp. 23-29).

Transmission of the circular TE_{01} wave in curved circular wave guides. Y. Shimizu. (pp. 29-35).

The effects of the circular TE_{1m} waves on the propagation of the circular TE_{01} wave in curved waveguides. Bun-ichi Oguchi and M. Kato. (pp. 35-42).

Fading characteristics in line-of-sight propagation of microwaves. H. Enomoto. (pp. 42-50).

Vol. **41**, No. 2, February 1958:

On the bearing of ionospheric radio waves. K. Miya, M. Ishikawa and S. Kanaya. (pp. 137-144).

Multi-apertured parametron. Ken-ichi Fukui, K. Onose, K. Habara and M, Kato. (pp. 147-151).

Power output density spectrum of non-linear circuits. M. Nakagami and K. Tanaka. (pp. 151-156).

Topological considerations of linear networks. H. Hirayama and S. Nomura. (pp. 156-162).