The Journal of the

BRITISH INSTITUTION OF RADIO ENGINEERS

FOUNDED 1925 INCORPORATED BY ROYAL CHARTER 1961

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

VOLUME 22 AUGUST 1961 NUMBER 2

INCORPORATED BY ROYAL CHARTER

THE INSTITUTION has been informed by the Privy Council Office that the Queen was pleased, at the Council held by Her Majesty on 2nd August 1961, to approve the grant of a Charter to the British Institution of Radio Engineers.

This information will be received with deep satisfaction by all members, since it affords full recognition of the value of the Institution's work during the past thirty-six years.

The grant of a Royal Charter confers a great honour on the Institution as a corporate body, but it also imposes the obligation to fulfil the objects and purposes for which the Institution is now constituted, among which is the advancement of the science and practice of radio engineering, including the theory, science, practice and engineering of electronics and all kindred subjects and their applications.

Every corporate member of the Institution, who may now be designated as a Chartered Radio Engineer, is by his very membership required to ensure the maintenance of professional standards and the advancement of the status of the Institution by all means in his power.

The Royal Charter is the culmination of the work of all those who have helped to build and develop the Institution since its foundation in May, 1925. The problems that have been overcome and the achievements that have resulted are permanently recorded in "A 20th Century Professional Institution"—the history of our Institution, which in itself formed the basis of the Petition submitted to Her Majesty's Privy Council on 2nd July 1960.

There is now a new and momentous chapter to be added to that history so that all may understand that the realization of our professional ambition has been due to the skill and foresight of all those members who have played an active part in Institution affairs during the past thirty-six years.

In this connection it is not invidious to pay tribute to the consistent and active interest given throughout thirty years of membership by the member who is nominated in the Charter as the first President of the Chartered body, Admiral of the Fleet the Right Hon. the Earl Mountbatten of Burma, K.G. Under his guidance and wise counsel over the years, the officers of the Institution have been encouraged to develop the Institution in the ways in which it could best achieve its purpose, and thereby justify a petition for the grant of a Royal Charter.

The Petitioners for the Royal Charter, appointed by the members of the Institution at the now historic Extraordinary General Meeting held on 28th April 1960, give a formal report on page 82. This report has one omission, which should now be rectified. In 1937 a member of the Institution was appointed Honorary Secretary. His efforts on behalf of the Institution for nearly a quarter of a century have played a major part in the achievement of the Royal Charter, and it gives considerable satisfaction to all those who have been associated with him in the work of the Institution to record that in the Charter the first Secretary of the Chartered body is named Graham Douglas Clifford.

W.E.M.

NOTICE OF INCORPORATION BY CHARTER

The following is a record of the letter addressed to all corporate members of the Institution on 4th August 1961.

To all corporate members.

In accordance with the Special Resolution passed at the Extraordinary General Meeting of the Institution held in London on 28th April, 1960, we have acted on behalf of corporate members in petitioning Her Majesty The Queen in Council for the honour of a grant of a Charter of Incorporation.

We are now pleased to advise members that we have today received advice from Her Majesty's Privy Council that Her Majesty The Queen has been pleased to approve the grant of a Charter to the Institution.

Thus a most important chapter has been added to the history of the Institution. For the present, our affairs will be conducted under the present constitution. We are required, however, to submit to the Privy Council at an early date draft Bye-Laws covering the government of the Chartered body.

It is therefore our intention to call an early meeting of corporate members for the purpose of approving draft Bye-Laws and for the dissolution of the present Institution.

The honour granted to us will, we are sure, encourage every member to continue to use his best effort to implement the main object for which the Institution is Chartered—to advance the science and practice of radio and electronic engineering.

THE PETITIONERS FOR THE GRANT OF A CHARTER:

Signed: The 3rd day of August, 1961.

Mountbatten of Burma A.F

L. H. Bedford

E. E. Zepler

W. E. Miller

J. L. Thompson

Paul Adorian

[illegible]

C. Philip Clarke

G. P. Brown

George Marriott

Emrys Williams

U.D.C. 681.142

A Transistor Digital Differential Analyser

By

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AND T. R. H. SIZER†

Summary: The digital differential analyser described employs transistors throughout and has a magnetic core store. It has operated for about 2000 hours under laboratory conditions. The principles of the d.d.a. are discussed briefly, then its logical design is described in some detail. Complete circuit details are not given but three of the more interesting elements are described in an appendix.

1. Introduction

The computer described in this paper was designed and constructed as the result of a research project covering advanced computing techniques associated with aircraft navigation problems. Its name, CORSAIR, is derived from COR referring to the core store used, S for the surface barrier transistors used extensively in the fast logical circuits and AIR from the aircraft association.

The equipment, which employs transistors throughout, was designed and constructed at the Royal Aircraft Establishment after initial proposals were made in 1958. It took just under two years to complete and at the time of writing has operated for about two thousand hours. Although the computer assumes the form of production equipment it is emphasized that it is, in fact, equivalent to a bread-board prototype. The authors consider that with complex equipment of this nature the only way to achieve a high enough standard of reliability for a system assessment is to apply such a standard of engineering from the outset. Subsequent operation has justified this view as well as demonstrating the high order of reliability which can be obtained by the use of semi-conductor devices even in bread-board equipment where reliability problems are usually overlooked.

Reference to Table 1 which is the computer specification shows that the capacity is fifty integrators with a maximum accuracy of 0·01% and a power consumption of only 50 watts. Coupling these factors with the unique programming system‡ used in CORSAIR it is apparent that the d.d.a., apart from its navigational role, will eventually become a serious rival to the analogue computer in the field of simulation. It will be noticed that in this particular case an analogue computer operator could use CORSAIR with the very minimum of re-orientation; integrator flow diagrams may be drawn and the program plugged up on an address panel as on analogue machines. There is the added flexibility that non-linear differential equations do not require special techniques because the integrating element is not restricted to time as the independent variable.

Because of limitations on length it is not possible to give comprehensive circuit information. However, a detailed logical description is given and examples of three of the more interesting circuit techniques are given in an appendix. A general view of the machine is given in Fig. 15.

2. The Principle of the Digital Differential Analyser

The principle of the d.d.a. has recently been described[1], but in order to make this paper reasonably self-contained, a short review of the design consideration is made here.

Differential analysers were originally built in mechanical form using the wheel and disc integrator as the basic brick. Such machines owe their versatility to the fact that integration may be performed with respect to any variable and is not confined to time as in the electronic analogue machine.

Table 1

Technical Specification of CORSAIR

Type of machine	Sequential operation with serial arithmetic
Integration rate	500 steps per second
Number of integrators	50
Maximum accuracy	1 part in 2^{15}
Digit rate	500 kc/s
Integrator interconnection system	Plug board
Inputs and outputs	Whole number or incremental
Storage system	Ferrite cores
Power consumption	50 watts

† Royal Aircraft Establishment, Farnborough, Hants.

‡ British Patent Application. No. 18,178/60.

Examples of computations which may be performed are:

(i) Multiplication of two variables:

$$X.Y = \int X.\mathrm{d}Y + \int Y.\mathrm{d}X$$

(ii) Computation of sin θ and cos θ as the solution of the differential equations

$$\frac{\mathrm{d}X}{\mathrm{d}\theta} = Y, \quad \frac{\mathrm{d}Y}{\mathrm{d}\theta} = -X.$$

(iii) Computation of the exponential function as the solution of

$$\frac{\mathrm{d}Y}{\mathrm{d}X} + kY = 0.$$

The mechanical differential analyser, however, suffers from limitations in both accuracy and capacity and it is fair to say that the limit of its development for all practical purposes was reached some years ago. Recently, interest in the principle has been revived by the application of digital techniques resulting in a new type of computer known as the Digital Differential Analyser (abbreviated to d.d.a.) which, to a large extent, overcomes the limitations of the mechanical machine.

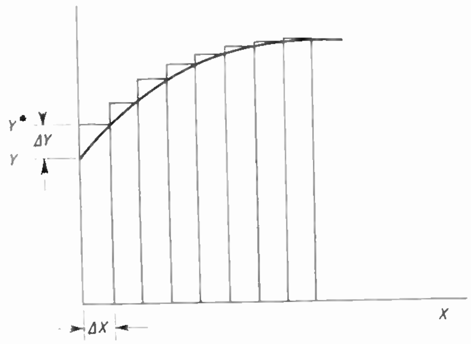


Fig. 1. Summation of rectangles.

2.1. *Digital Integration*

The basic operation of the d.d.a. is digital integration which is achieved by the summation of rectangles in a step-by-step process (Fig. 1). Electronic speeds of operation make it possible to utilize a small step size and thus an accurate answer is obtained. The errors in the process may be analysed to a certain extent[2] and they are found to depend on the size of the integration step and the discrete nature of the number representation in the machine. These are essentially digital phenomena and are known as "truncation" and "round off" respectively. The problem of error analysis for a single integrator is fairly straight-forward; where several integrators are involved it is more difficult.[2]

Reference to Fig. 1 shows that each step of the integration process consists of the following operations:

Addition of the increment ΔY to bring the integrand up to date, as described by the equation:

$$Y^* = Y + \Delta Y, \qquad \ldots\ldots(1)$$

Addition of the area of the rectangle to bring the integral up to date:

$$Z^* = Z + Y^*.\Delta X. \qquad \ldots\ldots(2)$$

where ΔX is the increment of the independent variable.

Both increments ΔX and ΔY may be positive, negative or zero and may come either from external sources or other integrators. For a general value of the independent variable increment ΔX the second equation implies that a multiplication is necessary. Usually, however, the machine is arranged so that the maximum change of X in one integrator step is one quantum and the equation is replaced by:

$$Z^* = Z + Y,^* \quad Z^* = Z - Y^*, \quad \text{or } Z^* = Z.$$

according as ΔX is $+1$, -1, or 0 respectively. The only operations then required are addition or subtraction and the design of the integrator is thereby simplified.

2.2 *The Digital Integrator*

In order that integrators may be interconnected it is essential that the inputs and the output be of the same form. Thus the requirement of any practical realization of the integration process is that it should take increments of the integrand and independent variable and put out increments of the integral.

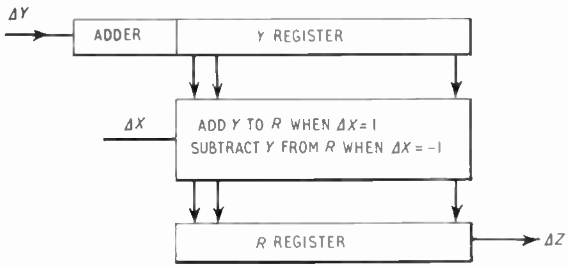


Fig. 2. The digital integrator.

Figure 2 shows the digital integrator which is normally used in the d.d.a. It consists of two stores or registers, one of which, the Y register, contains the integrand. Associated with the Y register is an adder and the Y number is kept up to date by the arrival of increments ΔY. There is also an R register which has associated with it an adder-subtractor controlled by the current value of the independent variable increment ΔX. The method of operation of the R register and its associated arithmetic unit is in the form of two simple instructions as follows:

1. If $\Delta X = +1$ or -1, add or subtract respectively the Y number to or from the number in the R register.
2. If $\Delta X = 0$, do nothing.

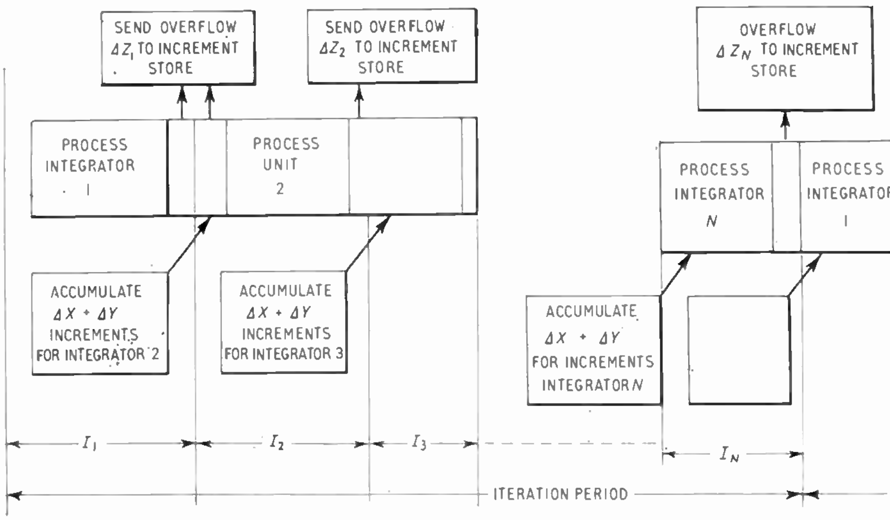


Fig. 3. The basic timing of a sequential digital differential analyser.

As the integration process proceeds, the R register, which has the same capacity as the Y register, overflows periodically and this overflow represents the increment of the integral. Space does not permit of a full discussion of the behaviour of this device here but more details may be found in the references.

2.3. *Organization of the D.D.A.*

A set of digital integrators with facilities for interconnection and input-output forms a d.d.a. but within this general framework there are many ways in which a machine may be organized in detail. Each integrator may have its own arithmetic unit and be self contained or, alternatively, the Y/R numbers may be read out in turn from a central store into a single time-sharing arithmetic unit. These two main types are known as "simultaneous" and "sequential" machines respectively. Each type has its own inherent advantages when compared to the other; for example other factors being equal the simultaneous machine does more integration steps per second than the sequential machine but the sequential machine is more economical in design than the simultaneous type. CORSAIR is of the sequential type of d.d.a.

It was mentioned previously that each integrator or Y/R number pair is read out of the main store in turn to undergo the integration process. The time taken to process all the integrators is known as the "iteration period" of the machine and one iteration is divided into integrator periods labelled $I_1, I_2, \ldots, I_N$, where N is the number of integrators. Figure 3 illustrates the basic timing.

The address or interconnection system of the machine is complicated by the fact that although integrator outputs appear at the end of the appropriate integrator periods they must be available during the whole of the succeeding iteration period to give complete flexibility of interconnection. For instance, if it is desired to connect the output of integrator 1 to the input of 10, the output of 1, which appears at the end of I_1, must be stored and made available at the beginning of I_{10}. Thus a sequential d.d.a. must have an integrator output or ΔZ store in addition to its main Y/R store.

Frequently when solving problems on the d.d.a. it is found that the integrand or ΔY input is connected to the output of several integrators. In this case the total ΔY increment is the sum of several outputs and is obtained by means of a forward-backward counter. As the extraction of the appropriate outputs from the ΔZ store and the accumulation of the ΔY increment take time, it is so arranged that these operations are performed in the preceding integrator period as shown in Fig. 3.

In order to make the machine fully operational input and output facilities are necessary. Inputs may be of three types, i.e. initial integrand values, constants, or continuous varying quantities which may come from other equipment. Similarly outputs may also be of two types, i.e. fixed quantities which result at the end of a machine run, or variables which may be transmitted to a plotting table or other external equipment.

The general organization of the sequential d.d.a. is shown in Fig. 4. The Y/R numbers emerge from the main store in sequence and undergo the integration process in the arithmetic unit. The arithmetic process results in a new Y/R pair which is written back into the main store and an overflow which is transmitted to the appropriate location of the ΔZ store. During each integrator period the address or program unit

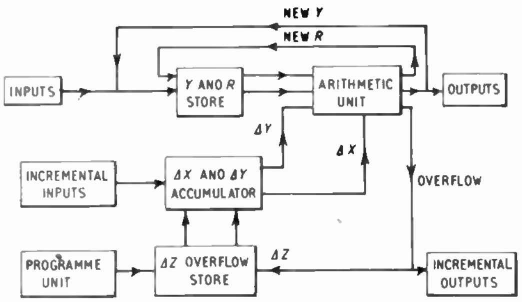


Fig. 4. General organization of sequential digital differential analyser.

extracts the appropriate ΔX and ΔY's from the ΔZ store and transmits them to the ΔX and ΔY accumulators which hold them in readiness for the next integrator period. Input and output devices are most conveniently connected to the main store. Sometimes incremental inputs and outputs are used and suitable places for connection are shown in Fig. 4.

3. The Basic Design

One of the main design aims has been to obtain maximum iteration rate while still retaining the economy of the sequential method of operation. The high digit rate (500 kc/s) is made possible by the use of the surface-barrier transistor and circuit development time has been minimized by the use of the direct-coupled technique.[3]

Previous machines[4] have been designed round the magnetic drum as the central store and, in consequence, have been limited to speeds of 60–100 steps per second. In CORSAIR the high digit rate and capacity make possible a speed of 500 steps per second and hence a faster store is necessary. For reasons of compactness and possible increase in capacity a ferrite core store is used. Whilst a completely serial organization of the store would lead to the most elegant design of machine, the high digit rate of the arithmetic made this impossible with the cores that were currently available. A compromise is therefore achieved between the digit rate and the read-write cycle time of the store by reading out the numbers in parallel and serializing them in two shift registers for transmission to the arithmetic unit. This results in a read-write cycle time which is equal to the word time of the machine.

Figure 5 shows the way in which the information flows and the corresponding timing of the operations is shown in Fig. 6. It may be noted that the use of buffer stores in the parallel loops allows the previous Y and R numbers to be written into the store at the same time as the current Y and R are undergoing the integration process, thus reducing the overall integration period of the machine.

In addition to the increased speed a new address or integrator interconnection system has been introduced. In the older magnetic drum type of d.d.a. the ΔZ outputs are written into a short circulatory store called the "precession line". In order to obtain complete flexibility of interconnection it is essential that the precession line circulates once per integrator period thus limiting the number of ΔZ's and hence the number of integrators to be less than or equal to the

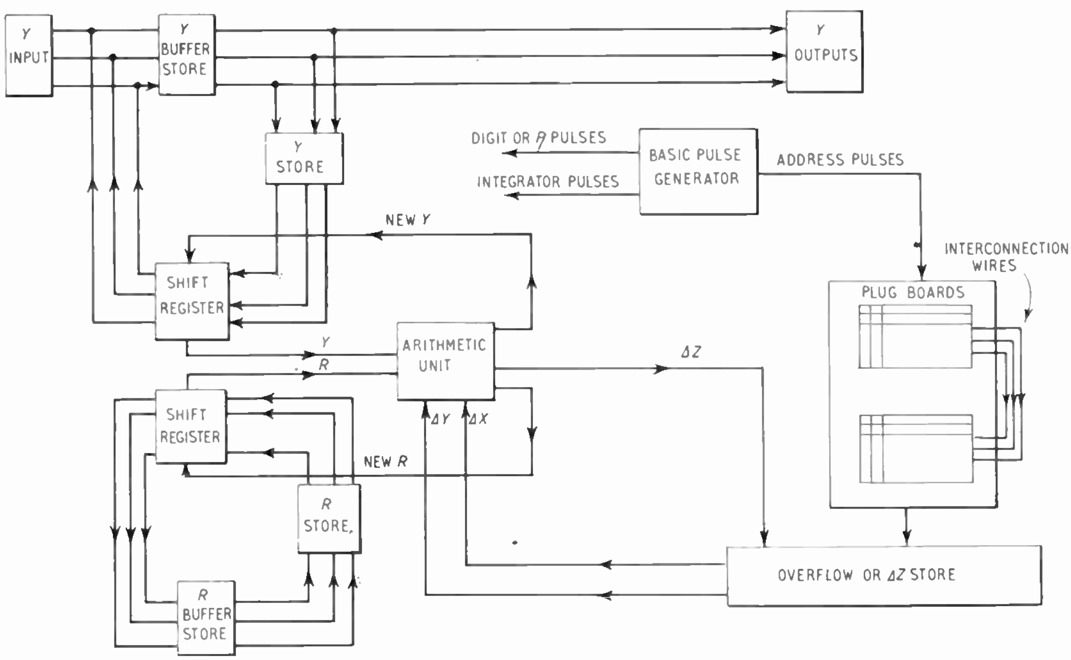


Fig. 5. Information flow.

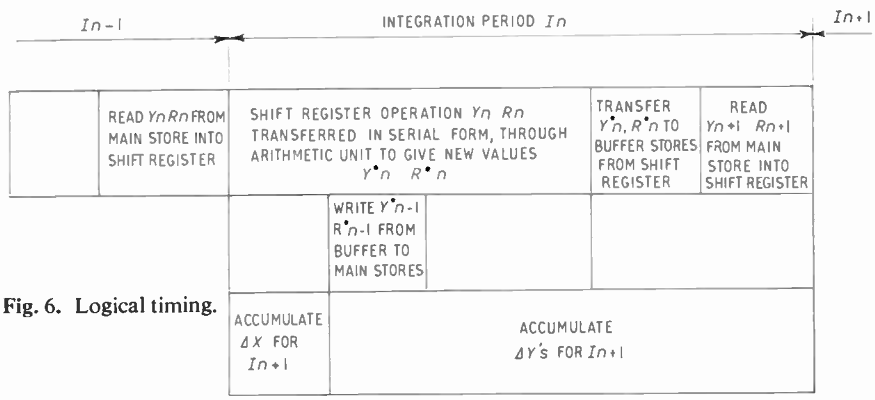


Fig. 6. Logical timing.

number of digits in a word. This limitation has been overcome by means of a new system in which the ΔZ's are stored on a set of static memory devices. Integrator interconnection is achieved by sampling the appropriate ΔZ stores during the appropriate integrator period of the machine cycle. The sampling signals are routed by means of plug-board connections so that, in addition to overcoming the limitations of the precession line type of address system, programs are plugged up directly from the integrator schematics as in analogue computers.

4. The Detailed Design

The principal units shown in the block diagram, Fig. 5, are as follows:

(1) The pulse generators which produce the basic timing and control waveforms.

(2) The arithmetic unit which accumulates the ΔX and ΔY increments and performs the integration process.

(3) The main store.

(4) The address unit which comprises the ΔZ store and the plug board.

(5) The serializing shift register and associated buffer stores.

(6) The input-output system.

4.1 *The Pulse Generators*

In the serially-operated sequential d.d.a. numbers and digits are identified, and operations are controlled by, related basic waveforms. The pulses required are shown in Fig. 7 and are of three main types, i.e. the p-pulses, P-pulses and the A-pulses.

The definition of the fifty integrators requires a waveform generator with fifty output lines, a pulse appearing at a particular output during the time when the associated number occurs. These pulses are designated A_1, A_2, . . ., A_{50} and are formed by combining pairs of outputs from a ten-state counter and a five-state counter in AND gates. (The outputs of these counters are called E- and F-pulses respectively.)

One integrator period consists of twenty digit periods of which sixteen are used for the arithmetic operations and the remaining four are required for certain transfer operations associated with the shift register.

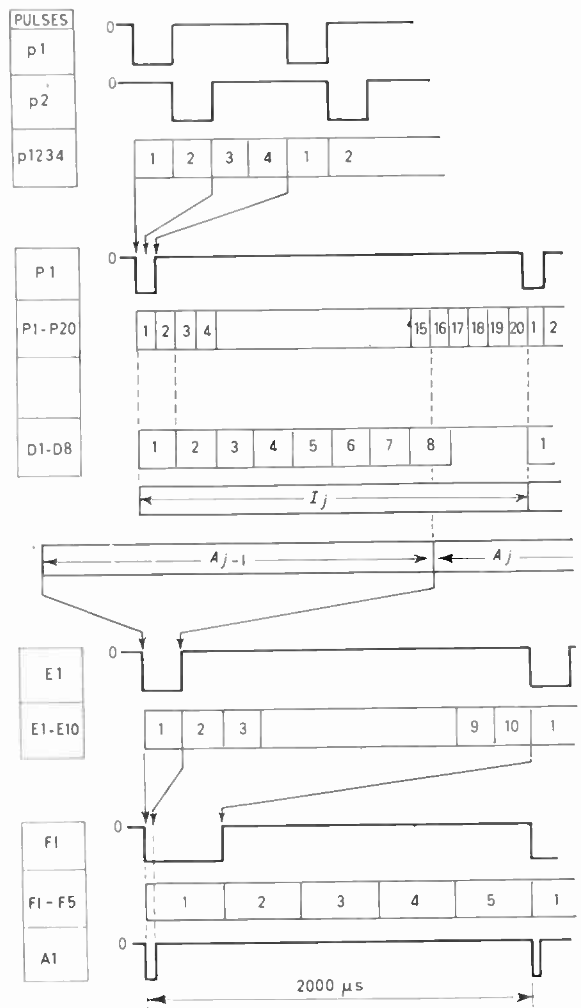
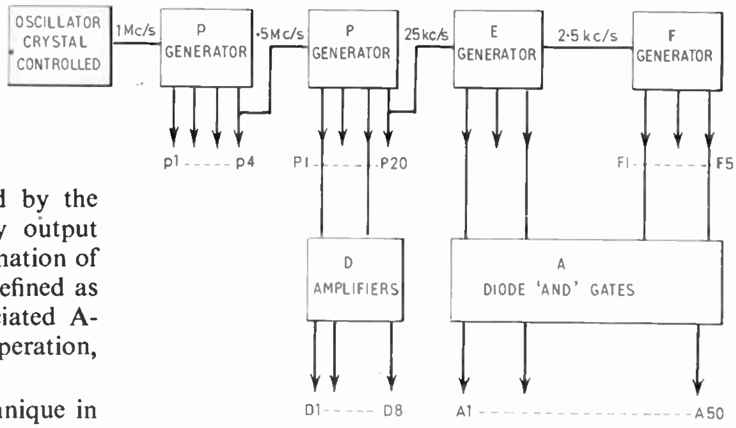


Fig. 7. Control pulse waveforms.

Fig. 8.
Block diagram of the control pulse unit.



(See Fig. 6.) The digit periods are defined by the P-pulses which are produced by a twenty output P-pulse generator. It may be noted on examination of Fig. 7 that whereas the integrator period is defined as the time between successive P_1's, the associated A-pulse, for reasons of convenience of machine operation, occurs between successive P_{16}'s.

Finally, the use of the direct coupled technique in the arithmetic unit requires that each digit be divided into four equal phases, and this is achieved by means of the p-pulse generator whose outputs are p_1, p_2, p_3, and p_4. The p-pulses are used for controlling the logical operations and restandardization where necessary.

The initiation of the pulses is controlled by means of a 1 Mc/s crystal oscillator and the block diagram of the complete generator is shown in Fig. 8.

Surface-barrier transistors are used in the p- and P-pulse generators in direct coupled circuitry; some point-contact diodes are also used. In the remaining pulse generators alloy-junction transistors and point contact diodes are used in conventional circuitry.

4.2. *The Arithmetic Unit*

As the machine is serially organized there is one arithmetic unit, used on a time sharing basis by all the integrators in a fixed sequence. The unit, in effect, mechanizes the process implied by the integrator schematic of Fig. 9. A block diagram is shown in Fig. 10.

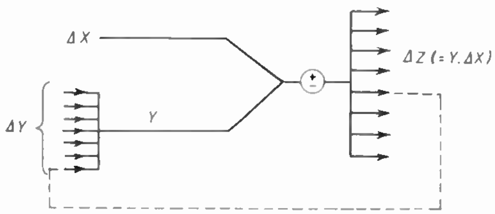


Fig. 9. An integrator schematic.

With reference to this last diagram, the ΔY increments are in a two-wire form, $+\Delta Y$ and $-\Delta Y$, and arrive at the input to a forward-backward counter. A total of seven increments is possible which means, in effect, that the outputs of up to seven integrators may be summed at this point. The count is in binary during the previous integration period; P20 of this period transfers the number in parallel to a shift register unique to the arithmetic unit. Here the output of the counter is serialized to form the four least significant digits of the $\Sigma\Delta Y$ number and is added to Y at a significance determined by the start digit.

The result Y^*, is transferred to the R adder via the ΔX gate which has the property of adding Y^* to R if $\Delta X = +1$ or the complement of Y^* if $\Delta X = -1$; $\Delta X = 0$ inhibits the transfer.

The arithmetic operation terminates in the ΔZ discriminator whose function is to produce the + or $-\Delta Z$ increment according to the specification given in Appendix 11.1.

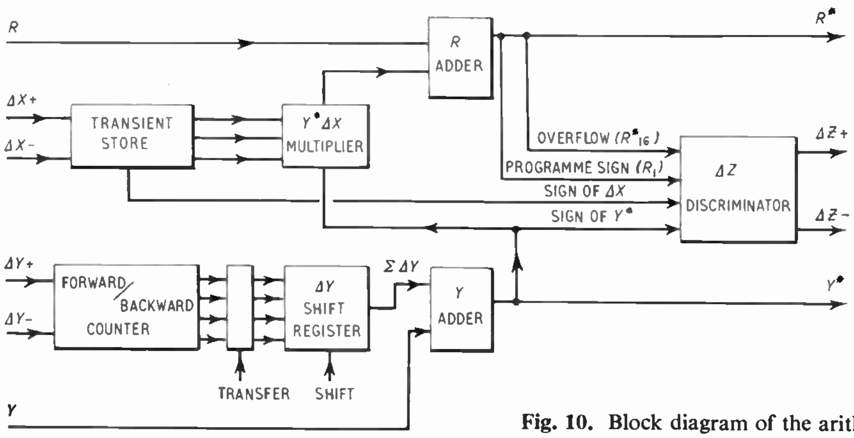


Fig. 10. Block diagram of the arithmetic unit.

A total number of 420 surface-barrier transistors Type SB 240 is used to mechanize the operations in the arithmetic unit. The form of circuitry is direct coupled throughout. Where signals emerge from or enter into the unit, compatibility circuit elements adjust current, voltage and impedance levels to those of the direct coupled logic. An example of the design techniques used in the arithmetic section is given in Appendix 11.2.

4.3. *The Main Store*

The fifty pairs of Y and R numbers are stored between arithmetic operations on a 50×32 ferrite core matrix. Since the numbers are required to be read and processed in a fixed sequence there is no necessity for random access to the storage locations and the address selection is relatively simple.

It is further simplified by the fact that the Y and R numbers are read in parallel as a single 32-bit word by passing down the column of 32 cores a controlled current pulse sufficient to switch completely every core. (Fig. 11.) The output signal on the wire threading each row of cores is detected by one of 32 read amplifiers and the original state of the core represented by 1 or 0 is set up on the appropriate element of the main shift register. The numbers are then shifted serially at high speed through the arithmetic unit and at the end of the integration period the shift registers contain the new values Y^* and R^*. These are returned to the main store via the buffer store, a set of bi-stables each controlling a current switch in series with a second wire threading the row of cores.

To write the new word into the column of cores, a half current "write" pulse is sent up the column and at the same time half-current pulses are sent along the row wires wherever a 1 is to be stored. The term "half-current" implies a pulse which is insufficient by itself to switch a core, due to the square hysteresis loop of the core, but can do so in conjunction with a similar pulse.

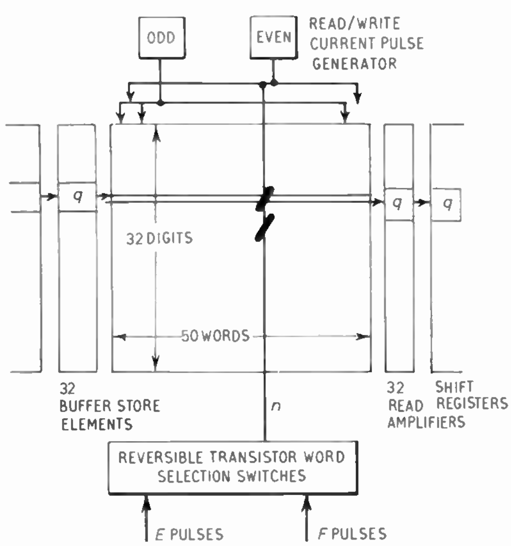


Fig. 11. Block diagram of the core store.

The word selection circuits comprise a single reversible transistor in each word wire which is controlled by a suitable signal applied to its base. Each transistor will in the "on" state conduct either "read" or "write" current pulses (which flow in opposite directions). The control signals are derived from the outputs of the main pulse generators which furnish the two sets of ten E-pulses and five F-pulses. Their relationship is indicated in Fig. 7.

It will be evident from Fig. 6 that the period during which a particular word, i.e. a column of 32 cores, is involved in transfer operations, spans a time equivalent to two adjacent integrator periods. Thus Y_n/R_n are read from the store at the end of period I_{n-1}; Y_n^*/R_n^* become available towards the end of I_n, when they are transferred to the buffer store. They are finally written back into the main store during the early part of I_{n+1}. This operation overlaps part of the corresponding operation on the number pair Y_{n+1}/R_{n+1} so to achieve the optimum simplicity in the drive circuits the store is divided into two effectively separate parts, denoted "odd" and "even" and comprising the contents of the odd- and even-numbered integrators. In each half there is now no overlapping, the sequence being as follows:

$$\text{Read } Y_n/R_n; \text{ Write } Y_n^*/R_n^*;$$
$$\text{Read } Y_{n+2}/R_{n+2}; \text{ Write } Y_{n+2}^*/R_{n+2}^*$$

The control signals are therefore arranged to close switch n over the later part of I_{n-1}, throughout I_n and during the first part of I_{n+1}. The read pulse applied during I_{n-1} finds only switch n closed and therefore reads the nth column. Likewise the write pulse during I_{n+1} can flow only in column n. An example of the read-write circuit techniques is given in the Appendix and a general view of the store and associated circuit boards is given in Fig. 12.

4.4. *The Address System*

The function of the address system is to connect the overflow, or ΔZ outputs of selected integrators to the inputs ΔX and ΔY of other integrators in accordance with the particular programme which has been set up. In a simultaneous machine this can be performed by direct-wired connections, each integrator having its own input and ouput channels.

A similar method is used in CORSAIR; however, as this is a sequential machine the mechanism of the address system is related to that of the time-shared arithmetic unit where the ΔX, ΔY and ΔZ channels are common to all integrators. Within this unit, the period I_j is alloted to the processing of the words Y_j

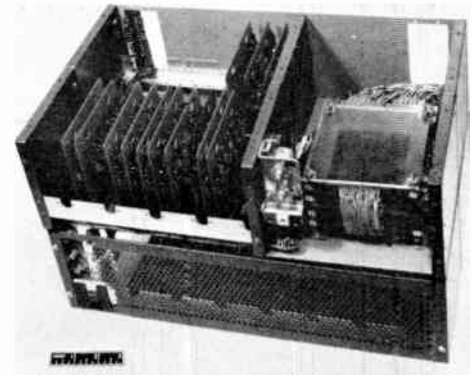


Fig. 12. Construction of the store and associated circuits.

and R_j and in a like manner the preceding period I_{j-1} is devoted to the accumulation of increments ΔX_j and ΔY_j. Therefore if a series of signals is applied to the ΔX and ΔY inputs of the arithmetic unit those occuring during the period I_{j-1} will be the increments appropriate to integrator j.

Say, for instance, that integrator j was to take its ΔX and ΔY inputs from the outputs of integrators l and m respectively (Fig. 13(a). Then during I_{j-1} the signal ΔZ_l must appear at the ΔX input of the arithmetic unit and ΔZ_m at the ΔY input of the arithmetic unit. Since each ΔZ must be available as an input to any integrator it is necessary to provide a store in which the ΔZ output of each integrator is held continuously. The ΔZ output of integrator m appears

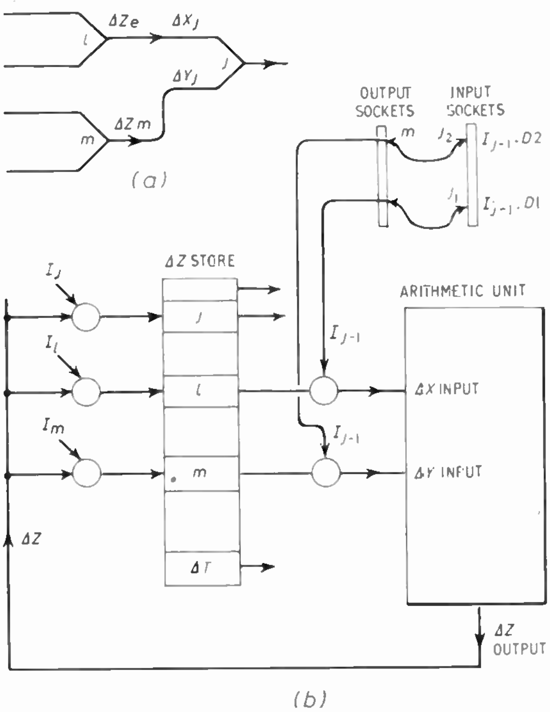


Fig. 13. Logical design of the address system.

during I_m so it must be gated into location m by the pulse I_m bringing the stored ΔZ_m up to date once per iteration cycle. Information from this store is then gated into the inputs by the signal I_{j-1} as indicated in Fig. 13(b).

The same figure shows how further time sharing is used to achieve the facility of connecting more than one output to a ΔY input. The I_{j-1} pulse is divided into eight sub-periods by gating it with a set of eight D-pulses which are in fact amplified alternate P-pulses. The input channel is time-shared between the ΔX signal, which is that occurring during D_1, and the seven possible ΔY signals, occupying D_2, D_3, . . ., D_8. Figure 13(b) also indicates the function in the system of the patch panel.

Each socket of the INPUT panel carries a pulse, repeated once per iteration cycle, which may be said to represent one of the eight inputs to a particular integrator. These sockets are naturally labelled to accord with the integrator number. The sockets of the output panel are connected to the gates between the ΔZ store and the $\Delta X/\Delta Y$ input channel and are likewise numbered to correspond with the ΔZ storage elements. In addition, there is a set of ΔT or MACHINE RATE sockets connected directly to the $\Delta X/\Delta Y$ input; these allow the injection of a permanent 1 input signal, i.e. the maximum increment rate, to any integrator. As far as the program is concerned the OUTPUT sockets may be treated as sources of ΔZ signals which are externally connected to the integrator INPUT sockets in accordance with the program or flow diagram.

Since a ternary transfer system is used in CORSAIR the ΔZ store must hold three values, $+1$, 0 or -1 for each location and the ΔX and ΔY input channels are duplicated, together with the interrogation gates. The ΔZ storage elements are in fact active tristable devices and a significant feature of the program panels is that some of the gating necessary to produce the pulses I_{j-1}. D_q from the basic D-, E- and F-pulses is performed by diodes and resistors moulded into the polythene plugs. An example of the tristable store is shown in Appendix 11.3.

5. The Serializing Shift Register

There are two separate shift registers, one for the Y numbers and one for the R numbers. As the two are identical in operation they can be considered as one unit for the purposes of description. Thus where the term number is used, this applies equally to both Y and R.

The number is read out of the store in parallel into the shift register, the timing of the process is shown in Fig. 6. Referring to the block diagram of Fig. 14 digit 16 is read via read amplifier 16 into shift stage 16; digit 15 via read amplifier 15 into shift stage 15 and so

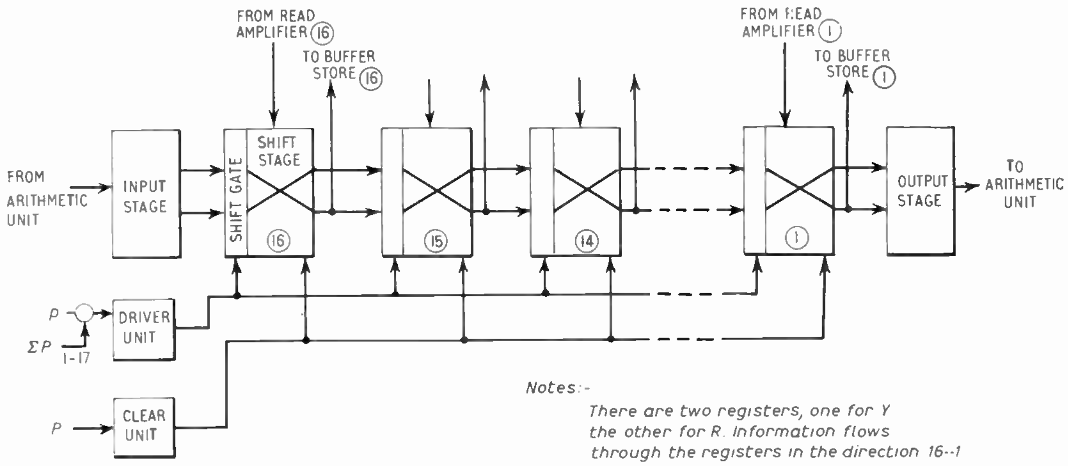


Fig. 14. Block diagram of serializing shift register.

on. This operation on digits 1 to 16 takes place in period P_{20} of I_{n-1}.

During period I_n the number is transferred out of the shift register in serial form and into the arithmetic unit. This operation is controlled by the driver unit where signal $\Sigma\, P_1 - P_{17}$ opens a control gate allowing a sequence of 500 kc/s p-pulses to shift the number out and the new number in after processing in the arithmetic unit.

Thus it can be seen that the action in the shift register is continuous, the new digit 1* of the number following the old digit 16 of the same number. There is a blank digit period between 1* and 16. The timing is arranged so that when the new digit 16* reaches the old digit 16 position, shifting action ceases and the new word is transferred in parallel on P_{19} of I_n to a row of buffer stores.

During the period of P_{20} of I_n the number for I_{n+1} is read into the shift register and at P_1 of I_{n+1} the whole process is repeated. Also during I_{n+1} the new number of I_n which had been held in the buffer store is returned to the main store.

6. The Mechanical Form

As can be seen from Fig. 15, the machine has been designed and engineered to assume the appearance internally and externally of production standard equipment. The decision to make the computer in this form was taken in the very earliest stages because it was realized that the construction of a digital computer, by its nature, involves the reproduction in large numbers of a few basic circuit elements. A fascinating compromise thus existed where quantity production techniques had to be considered on what was basically a research project.

It was a short step to take having accepted this philosophy to the conception of the machine as a fully engineered product. The necessity of having a clear, concise control and programme panels lead to the application of ergonomic design to the whole layout with the result that an extremely neat and compact design has been achieved as shown in Fig. 15(a).

The core-store and associated circuits, serializing shift register, pulse generators, arithmetic unit and address unit and are all contained in the large cabinet 36 in. high by 19 in. wide by 12 in. deep. Power supplies of which there are six voltage levels are contained in the second cabinet 26 in. × 19 in. × 12 in.

Circuit elements are formed on printed wiring boards $4\frac{1}{4}$ in. × $4\frac{1}{4}$ in. with rhodium flashed edge connections. The boards are mounted into 22-way sockets and grouped into units. These six units, in the form of self-contained trays, slide into the cabinet from the rear plugging into 32-way sockets secured to vertical channels immediately behind the front panels.

The computer is brought into operation firstly by switching on the individual power supplies in a fixed sequence; all current and voltages can be monitored on two meters and one selector switch. These controls are mounted on the power unit console.

On the computer console are three panels; the top one being the main control panel, the middle one the monitor and information access panel and the lower one the programme panel. The main control switch rests in an OFF position; a clockwise rotation brings the pulse generators into operation in a fixed sequence, the store is energized then an IDLE position is reached, during which the programme is set up and finally a RUN position when computation takes place.

The remaining controls are a Y and R selector switch, two switches for selecting the integrators, a row of sixteen push-buttons for manual filling of numbers, a fill button, a single shot button for stepped operation, and a further button for clearing the ΔZ store. These details can be seen in the view of the front panel.

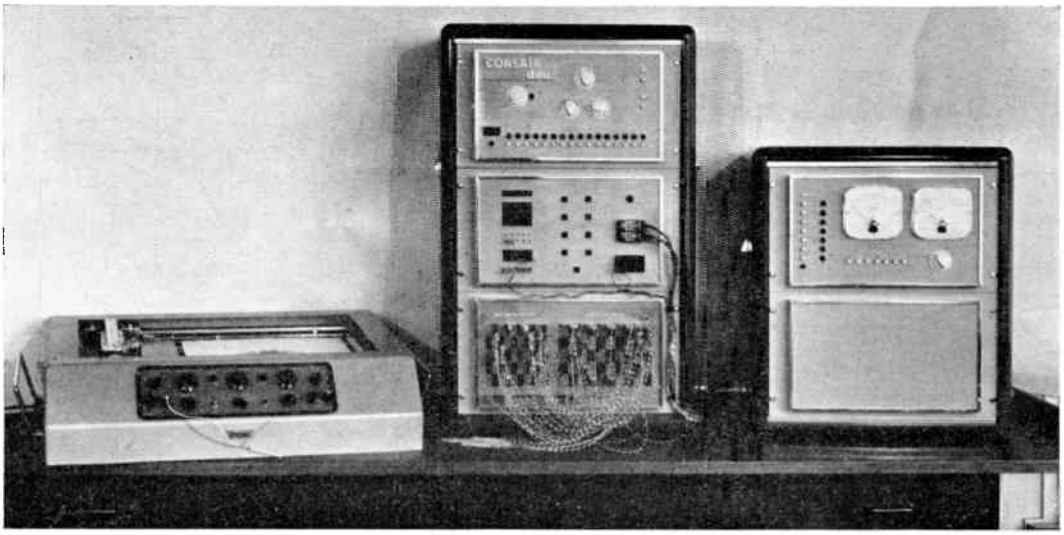


Fig. 15. (*left*) The control unit of CORSAIR. (*above*) General view of the d.d.a. operating in conjunction with a plotting table.

On the monitor side of the middle panel all the important waveforms are brought out to sockets together with computer earth.

7. Input-Output Systems

The computer accepts the input of initial conditions in binary form by means of push-buttons on the control panel or from a punched card reader. Selection of an integrator register for manual input is achieved by three rotary switches labelled Y/R; 1, 2, . . ., 10; and 1–10, 11–20, . . ., 41–50. Pressing the button labelled FILL transfers the information set up on the row of 16 buttons into the buffer store so that it is written into the appropriate store location. The card reader operates in a similar manner except that both integrator selection and the Y number are punched on the card (there is no card input for R numbers).

The contents, in binary, of any integrator register are available for display on a set of 16 lights corresponding to the setting-up buttons and using the same selector switches. On the access side of the middle panel all the Y numbers are brought out in parallel form as electrical signals. From these the contents of appropriate integrators are selected and converted to analogue voltages (output $\pm$ 100 V, accuracy 10 bits) which drive the two axes of a plotting table giving a continuous record of the function computed.

In addition an incremental output is available from selected locations in the ΔZ store.

8. Conclusion

The equipment described has been operating as a computing system for about two thousand hours; component parts have operated for a much longer period. Whilst there were initially the normal types of faults occurring, such as dry-joints, the flat part of the operational curve was reached after about 100 hours operation as a system. Since that time reliability has been remarkably high, faults amounting to one broken joint, two defective components and a modification to one circuit element. The period of operation has included six journeys between Farnborough and London by lorry and one week's operation at the 1960 I.E.A. Exhibition in Olympia.

The decision to build the machine in the form of an engineered equipment has been fully justified as has the use of printed wiring boards and edge connections. The decision to apply the principles of ergonomics to the design of the control and programme panels has also been justified by the ease with which programmes can be set up and by the very small number of errors made by programmers.

9. Acknowledgments

The authors are grateful to the Editor of *Electronic Engineering* for permission to reproduce in this paper some material from reference 1.

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11. Appendices

Space does not permit a full description of the circuit techniques used in the machine. However, three of the more interesting elements are described here in detail. The first deals with a part of the arithmetic unit known as the ΔZ discriminator. It is a typical example of the fast logic parts of CORSAIR and illustrates the use of direct-coupled transistor logic. In the second case a description is given of the symmetrical transistor switch which is used in the core store address selection circuits. Thirdly, a description is given of the tristable store used in the address units.

11.1 *The ΔZ Discriminator*

A block diagram of the discriminator is shown in Fig. 16; Y^* sign, ΔZ sign, Overflow and Sign Change represent input signals and $\Delta Z +$ and $\Delta Z -$ the outputs required. An operational specification is first drawn up thus:

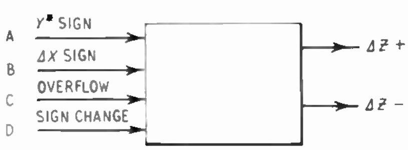

Fig. 16. Block diagram of the discriminator.

(1) If there is no overflow signal i.e. line C is at zero volts, then both $\Delta Z +$, $\Delta Z -$ are to be zero volts regardless of the states of inputs A, B and D.

(2) If Y^* sign and ΔX are both either at zero volts (condition 0) or at a negative potential (condition 1) then a negative voltage must appear at $\Delta Z +$, $\Delta Z -$ remaining at zero volts.

(3) If Y^* sign and ΔX differ than a negative potential must appear at $\Delta Z-$, $\Delta Z+$ remaining at zero volts.

(4) If the sign change line D is at a negative potential then the potentials of $\Delta Z +$ and $\Delta Z -$ are to be reversed for conditions (2) and (3) above.

Lines A, B and C are outputs of the arithmetic unit whilst line D is available to the program.

A truth table can now be drawn up in accordance with the specification. The notation used is that zero volts is represented by 0 and a negative voltage by a 1.

Table 2

INPUT LINES				OUTPUT LINES	
A	B	C	D	$\Delta Z +$	$\Delta Z -$
0	0	0	0	0	0
1	0	0	0	0	0
0	1	0	0	0	0
1	1	0	0	0	0
0	0	1	0	1	0
1	0	1	0	0	1
0	1	1	0	0	1
1	1	1	0	1	0
0	0	0	1	0	0
1	0	0	1	0	0
0	1	0	1	0	0
1	1	0	1	0	0
0	0	1	1	0	1
1	0	1	1	1	0
0	1	1	1	1	0
1	1	1	1	0	1

This truth table is now interpreted in two Boolean equations. The variables used, A, B, C and D, are derived in flip-flops and hence the inverses A′, B′, C′ and D′ are also available.

$$\text{Thus } \Delta Z+ = A'B'CD' + ABCD' + AB'CD + A'BCD$$
$$= [A'B' + AB)D' + (AB' + A'B)D]\,C$$
$$\text{and } \Delta Z- = AB'CD' + A'BCD + A'B'CD + ABCD$$
$$= [(AB' + A'B)D' + (A'B' + AB)D]\,C$$

It can be shown that two or more variables written MNO can be represented by transistors in series, collector to emitter configuration and two or more variables written $M+N+O$ can be represented by transistors in parallel with collectors to a common load resistor. Thus the circuit can then be written down directly from eqns. (1) and (2) and is shown in Fig. 17.

11.2 *The Symmetrical Transistor Switch*

A symmetrical transistor is a device which has similar characteristics when the conventional collector and emitter connections are reversed. Its virtue as a switch for driving cores is that it can be made, by signals applied to the base, to conduct or inhibit currents between emitter and collector in either direction. If the base is taken to a negative potential through

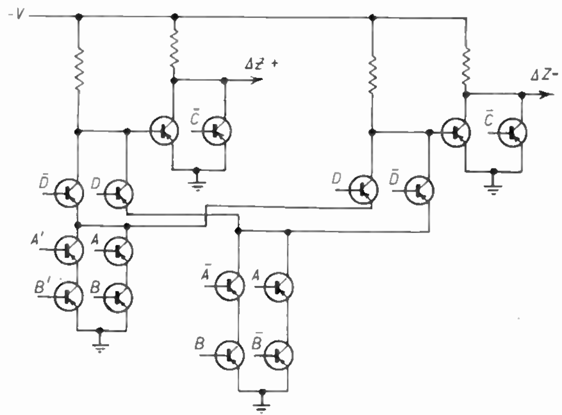

Fig. 17. Circuit of the discriminator.

a resistor, then a more or less defined base current will flow and the path between emitter and collector becomes a short circuit, one or both of the base emitter/base collector diodes being forward biased. Contrarily, if the base is taken to a relatively positive potential, so that both the emitter and collector diodes are reverse biased, then the transistor ceases to conduct. Clearly by applying a negative signal to one base, and positive signals to all others of a collection of such transistors in parallel, a current pulse applied to all will be conducted by the one selected transistor. In this way a current pulse on the bus bars of the store is caused to flow through one selected column of cores.

The terms "relatively positive" and "relatively negative" used above imply that the collector and emitter excursions must be limited to lie between the positive and negative potentials applied to the base. This is assured by limiting the open circuit output potential swing of the word current switches to these levels.

The basic store word circuit is illustrated in Fig. 18. The loads L1 and L2 represent columns of cores in the store, while the transistors drawn with two emitter symbols are the symmetrical switches. The

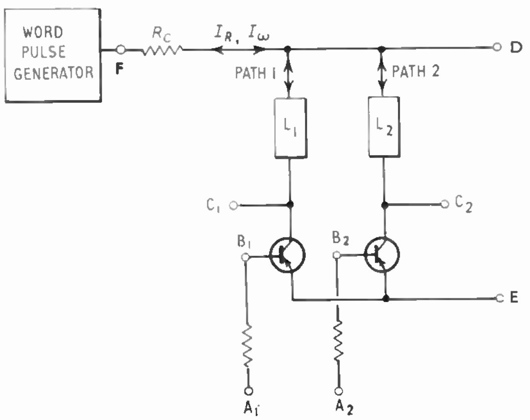

Fig. 18. Two columns of core store.

waveforms at the marked points A, B, C, etc. of the circuit are given in Fig. 19 for a cycle in which read and write pulses are applied first to load L1, then L2, and finally to an inactive store (all paths open circuit). The potential V_F at F, Fig. 19(b) varies unsymmetrically about that of the common line E, V_E, so that the read and write currents, which are approximately $(V_F - V_E)/R_C$ where R_C is the controlling resistor (Fig. 18) have the required values $I_R = 175$ mA, $I_W = -85$ mA. Clearly, the actual current is $(V_F - V_D)/R_C$, where V_D differs from V_E by the drop in the transistor,

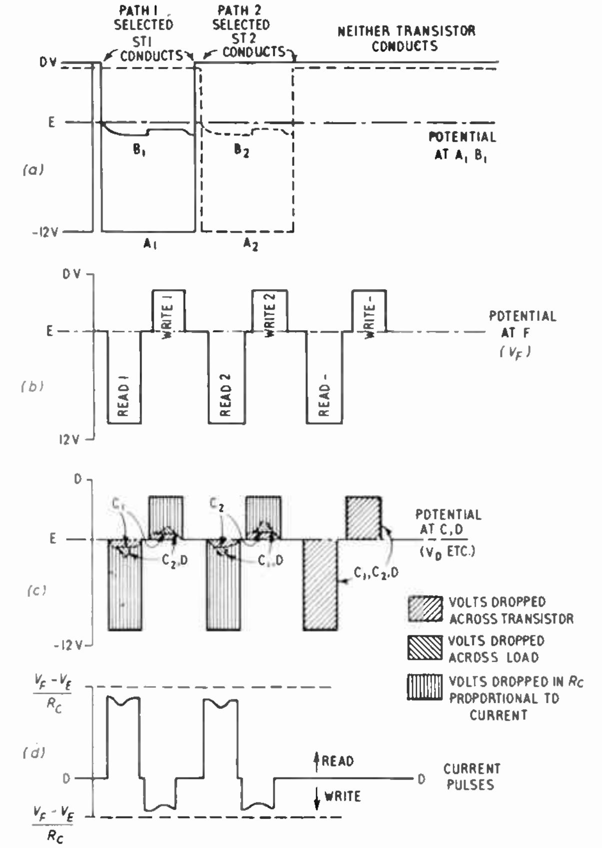

Fig. 19. Waveforms in core store word selection circuits.

more or less constant and restricted to be < 0·2 volt by selection of components, together with the drop in the load. The latter varies with the number of cores being switched, having a maximum value of about 32 × 25 mV = 0·8 volt on the read, and 32 × 18 mV = 0·56 volt on the write pulse. These figures correspond to a tolerable variation of ~ ± 5% in the amplitudes of the read/write current pulses, depending on the number of 1's recorded in the word.

It will be seen in Fig. 19(a) that the base of a selected transistor reaches a potential slightly negative with respect to V_E, while an unselected base is held at earth. As long as one path is selected, the potentials at D and at the unselected points C do not move far from that of E (Fig. 19(c), which is fixed by connection

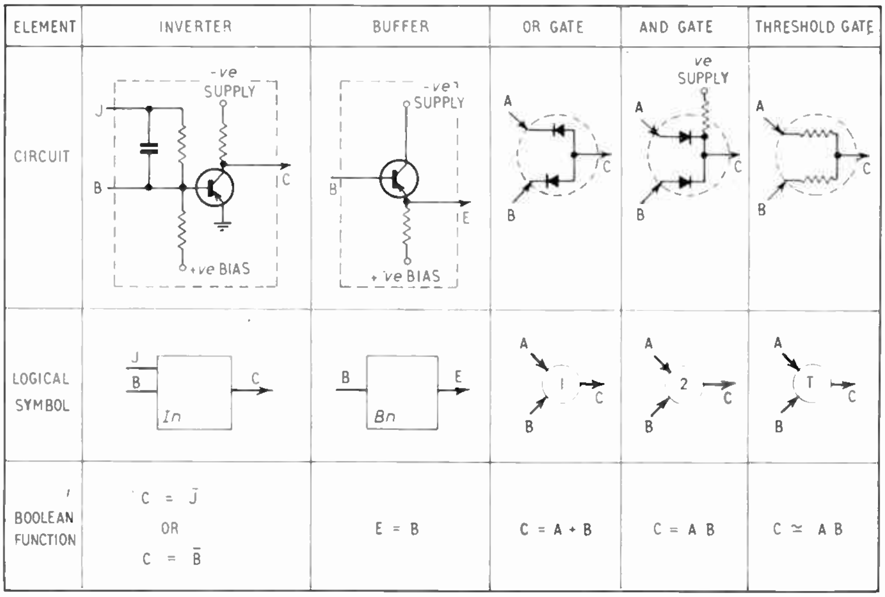

Fig. 20. Logical elements.

to a stabilized supply. If no path is selected, all these points (C1, C2 and D) follow the changes of V_F. Naturally, if two or more transistors were selected simultaneously, the current pulse would be divided between them.

In the normal running of the store, one transistor is selected for each read/write pulse, in which case Fig. 19(b) shows that the potential difference across any transistor never exceeds the combined drop in a transistor and its load, about 1 volt in the worst case.

It should be noted that the rise time of the current pulse (Fig. 19(a) is determined by the wave form at F, provided the transistor has been "turned on" by a base current before V_F begins to rise. The dips in the tops of the current pulses are typical of the switching back-e.m.f.s of a set of cores.

The switching time of the cores used in the store is about 4–5 μs at twice the coercive field, and adequate switching is obtained by using 6 μs current pulses.

11.3 *The ΔZ Store*

The objects of the address system and ΔZ store are as follows:

(1) To accept the information from the ΔZ output

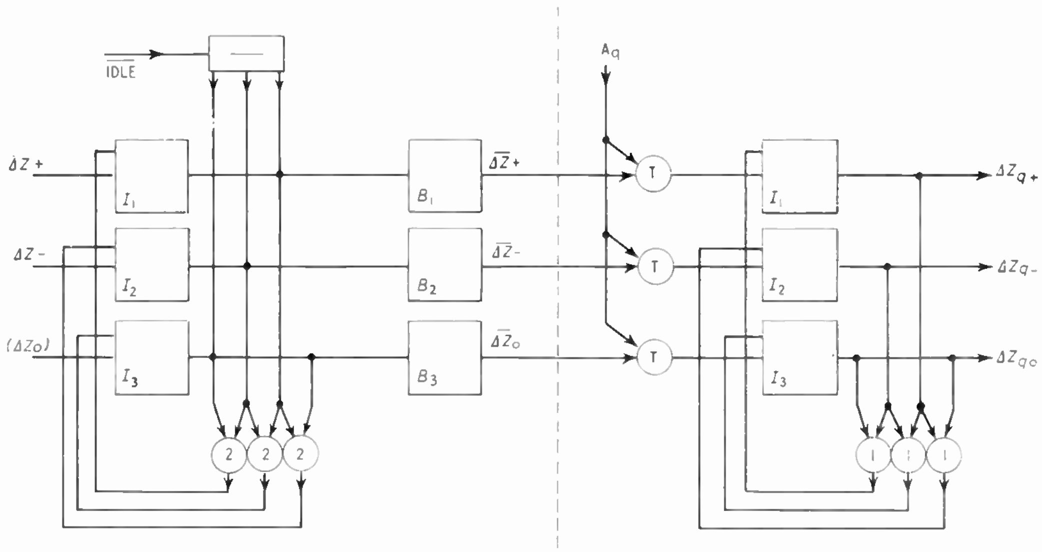

Fig. 21. (*a*) ΔZ converter, (*b*) ΔZ storage element no. "q".

of the arithmetic unit, which is the sequence of overflows from the R registers of integrators 1, 2, . . ., 50 denoted by $\Delta Z_1, \Delta Z_2, \ldots, \Delta Z_{50}$, and to write these signals into the correspondingly numbered locations of the ΔZ store. The sequence of ΔZ signals is repeated in every machine cycle, and the previous stored values of ΔZ are replaced by new values immediately these become available.

(2) To enable the ΔZ stored in any location (q, say) to be transferred to the ΔX or ΔY input of the arithmetic unit during the increment accumulation time of any integrator (j, say), where q and j are the numbers of OUTPUT and INPUT sockets respectively, connected by external plug leads. The ΔZ storage element and input converter are built of the logical elements of Fig. 20 and depicted complete in Fig. 21.

Each location of the ΔZ store has to be capable of holding ternary information and being interrogated non-destructively whilst fresh information is to be written once per machine cycle. Pairs of bistable elements would suffice for this purpose, but considerable economy is achieved by using naturally tristable elements. These consist of three inverters coupled by diode OR gates.

Each inverter (Fig. 20) has two inputs J and B which are logically equivalent, and an output C. Input J is compatible with the output C in signal level, while B works at lower voltage levels.

The diode gates are connected between the three inverters 1, 2 and 3 of the tristable (Fig. 21(b)) so that logically

$$J_1 = C_2 + C_3$$
$$J_2 = C_3 + C_1$$
$$J_3 = C_1 + C_2$$

or $J_n = C_{n+1} + C_{n-1}$ numbering cyclically

Remembering that for the inverter

$$C_n' = J_n$$

when there are no direct connections to the C outputs, these equations reduce to:

$$C_n' = C_{n+1} + C_{n-1}$$

Adding (OR) C_n to each side of the equation gives

$$C_n' + C_n = 1 = C_n + C_{n+1} + C_{n-1}$$

Therefore at least one of the C must be 1.
Multiplying (AND) each side by C_n gives

$$C_n'.C_n = 0 = C_n.C_{n+1} + C_n.C_{n-1}$$

Thus, no two adjacent C may both be 1.

And the stable states of the system have one output 1 and both others 0.

C_1, C_2, C_3, can therefore justifiably be used to represent $\Delta Z+$, $\Delta Z-$ and $\Delta Z0$, according to Table 3.

Table 3

ΔZ	C_1	C_2	C_3
+1	1	0	0
−1	0	1	0
0	0	0	1

The value of ΔZ is set into the store by applying the inverted binary signals $\Delta Z+'$, $\Delta Z-'$, $\Delta Z0'$ to the bases B_1, B_2, B_3 of the inverters.

Thus in storage location q

$$B_1 = \Delta Z+q' = Aq.\Delta Z+'$$
$$B_2 = \Delta Z-q' = Aq.\Delta Z-'$$
$$B_3 = \Delta Z0q' = Aq.\Delta Z0'$$

i.e. the ΔZ outputs from the arithmetic unit are inverted and gated into the tristables by the appropriate A-pulses. As the ΔZ output is only available for one digit period in each word, and the threshold input gates (Fig. 20) used are slow in operation the ΔZ signals are inverted and extended by the ΔZ converter (Fig. 21(a)).

This is similar to the ΔZ store but uses diode AND gates to obtain the logic

$$J_n = C_{n+1}.C_{n-1}$$

As usual $C_n = J_n'$

and manipulation of the equations shows that the stable states are as given in Table 3, and may be used to represent the inverses of the three ΔZ signals:

Table 4

ΔZ	C_1	C_2	C_3
+1	0	1	1
−1	1	0	1
0	1	1	0

These outputs, which are conveyed by bus bars to the threshold input gates of all the tristables, are buffered by emitter followers. The input signals $\Delta Z+$ and $\Delta Z-$ from the arithmetic unit are applied to the B_1 and B_2 inputs of the converter. As no signal corresponding to $\Delta Z0$ is generated, the converter is cleared to the 0 state by a P-pulse applied to B_3 just before the true ΔZ outputs.

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Radio Tracking of Artificial Earth Satellites

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Summary: The accuracy of position determination required for the various purposes for which earth satellites may be used is discussed briefly. The capabilities of optical tracking methods are indicated.

The three principal radio methods are those using radar, Doppler frequency shift and interferometer techniques. Although radar has already been used to some extent in satellite tracking, its main use is likely to be in connection with manned satellites and the arrangement for the U.S. project *Mercury* is described. The use of the Doppler frequency shift of the signals received from a moving satellite may be utilized in the determination of its orbit and, provided full use is made of the observed data and allowances made for ionospheric refraction, very precise orbital information can be obtained, as illustrated by the development of the *Transit* navigation system.

The tracking system in most general use at the present time is the interferometer in which directional information is obtained from measurements of the phase difference between the satellite signals received on a spaced aerial system. The U.S. Minitrack system is of this type and the construction, operation and performance of the station installed at the Radio Research Station Winkfield Field Station are described in detail.

The paper concludes with a brief review of future trends in satellite tracking by radio.

1. Introduction

One of the important parts played by radio in space research is the tracking of the vehicles which carry the research instruments into space. This applies to deep space probes as well as to earth satellites but it is only with the latter that we are concerned in this paper. Although tracking by radio on the frequencies at present in use is not so precise as it is by optical methods, it does provide more continuous observations since it is not limited by cloud cover or lack of solar illumination. Moreover radio frequency emissions enable observations to be made on satellites which, because of their size or distance, are too faint for tracking by the optical methods at present available.

In general there are three main systems of radio tracking. The first utilizes v.h.f. signals transmitted from the satellite and provides directional indication based on the interferometer principle; the world-wide network of Minitrack stations are of this type. The second uses radar technique with narrow beam steerable aerials to obtain direction and range. The employment of large steerable receiving aerials solely for directional measurements is not considered, since, up to the present time, it has been confined to space probes, though in future it may well be applied to earth satellite tracking as the use of much higher transmitting frequencies develop. The third system is that utilizing the Doppler frequency shift of the satellite signal for the measurement of range and velocity.

Radio direction finding systems other than those mentioned above have been used for satellite tracking. For example, azimuth measurements were made on the first two Russian satellites on frequencies of 20 and 40 Mc/s using a conventional cathode-ray Adcock direction-finder[1] and special types of equipment designed to measure the angles of arrival of radio waves in connection with propagation studies.[1,2] It is, however, the purpose of this paper to review the present state of radio tracking and to indicate, as far as is possible, the future trends in this rapidly developing art.

2. Tracking Requirements

The purposes for which information on the position of a satellite is required may be summarized as:

(*a*) to follow the progress of its flight and to predict its future position,

(*b*) to obtain its position at a given time for use in conjunction with radio propagation studies or measurements by instruments in the satellite,

† Official communication from D.S.I.R. Radio Research Station, Slough.

(*c*) to study irregularities in the motions of the satellite,

(*d*) to make geodetic measurements.

The accuracy with which the position of the satellite should be known for these purposes varies approximately in the reverse order in which they are listed above. For example, for general purpose prediction a directional accuracy of 1 degree of arc is normally adequate, though for setting special instruments such as astronomical telescopes or very narrow beam aerials a higher accuracy is required. For correlation with propagation or atmospheric measurements a positional accuracy of certainly less than 10 km is desired. For certain types of study of orbital perturbations positional accuracies of 1 km are required, while for geodetic measurements, including intercontinental surveys, the highest precision is called for. The above figures are, of course, only intended as a rough indication of the requirements.

It should also be borne in mind that the accuracy of the timing of a positional observation should be commensurate with the accuracy of the observation itself. For a satellite at an altitude of 500 km a directional precision of 1 degree of arc corresponds to a timing accuracy of about 1 second.

3. Optical Tracking

Although this paper is primarily concerned with radio tracking it is of interest to note how the requirements can be met by optical methods.

The simplest method is that of observing the satellite through binoculars or a small telescope, or with the naked eye if its brightness is sufficient, and noting the time at which the satellite is in a definable position relative to known stars. The direction of the satellite can then be determined with the aid of a star atlas and tables. The accuracy of such a method is about 1 degree of arc and is adequate for general prediction purposes.

For more precise observations photographic methods are employed. The kinetheodolite provides a means of determining direction to an accuracy of about 20 seconds of arc with a timing precision of 5 milliseconds. In operation the theodolite is made to follow the satellite and photographs of the latter are taken at precisely known times. The direction of the satellite is then obtained from the recorded readings of the theodolite scales with corrections applied to allow for any displacement of the satellite image from the telescope cross-wires. Corrections are also applied for misalignment of the instrument and scales as determined from measurements on known stars.

The most precise optical observations are obtained with transit cameras which photograph the satellite track against a star background. The track is broken at precise times by an electronically operated shutter and the positions of these "breaks" relative to the star images are measured on the negative. There are various types of such cameras and the most accurate now in use is the Baker-Nunn camera[3] which is capable of providing an accuracy of a few seconds of arc on satellites with a brightness greater than 11th magnitude. This accuracy, however, is realized only when the records are measured on high precision machines and many corrections applied to the raw data, a process which may take several days. The range of satellite altitudes over which the Baker-Nunn camera is most satisfactory is 500 to 8000 km and at these heights the positional accuracies attainable are about 5 m and 80 m respectively.

4. Radar Tracking

Although the interferometer has been, up to the present time, the primary instrument for satellite tracking, radar techniques also have been employed and have proved of value in the tracking of non-transmitting rocket carriers and nose cones. Successful observations were made in this country on the Russian satellites *Sputnik I* and *II* and their carrier rockets by both the Jodrell Bank Experimental Station[4,5] and the Royal Radar Establishment.[6] The former used the 250 ft radio telescope on frequencies of 36, 100 and 120 Mc/s and the latter a 45 ft telescope on a frequency of 3000 Mc/s.

In both the above cases the role of the satellite was that of a passive reflector but in general the radar tracking systems developed since that time utilize a transponder in the satellite in order to provide greater range as well as more precise range measurement.

One of the main functions of radar tracking at present seems to be that of position measurement on the final stage of the launching vehicle so that the injection parameters for preliminary orbital calculations can be accurately determined. An example of such use is that of the Millstone Hill radar system in U.S.A. for the tracking of the *Tiros I* vehicle during the launching phase and also on two subsequent orbits.[7] This system operated on a frequency of 440 Mc/s using a paraboloidal aerial with a conical scan and a half-power beamwidth of 2·1 deg. The final stage of the vehicle carried a transponder beacon and enabled measurements of spin rates and ignition and burn out times to be obtained in addition to the positional data.

Radar systems are likely to become the primary means of tracking manned satellites. The main reason for this is that such satellites will, in the first instance at least, have orbital lifetimes of only a few revolutions and radar methods are capable of giving the necessary information on the orbit achieved with the shortest possible delay. This is to be contrasted with the tracking requirements of an unmanned satellite for which, apart from prediction requirements, the orbital information is usually used as a *post-facto* parameter for research purposes.

For the first U.S.A. manned space flight, project *Mercury*,[7,8] eleven radar tracking stations have been installed so as to give round-the-world coverage between the 40 deg parallels of latitude. The network of stations involved also includes a main Control Centre and a Central Computing and Communications Centre as well as telemetry receiving stations. The vehicle is to be launched from the East Coast of Florida into a 33 deg inclination orbit and will stay aloft for three complete orbits.

Two types of radar equipment will be used: one type, designated Verlort, operates at approximately 3 Gc/s and the other, designated FPS–16, operates at approximately 5·5 Gc/s. A beacon transponder is carried on the vehicle for use with each type of radar. The Verlort system utilizes a rotating conical scan feed and provides azimuth, elevation and range tracking data outputs in digital and analogue form. The accuracy obtained with this system is of the order of 1·7 milliradians in angle and 11 metres in range.

The FPS–16 is a more accurate radar. Azimuth, elevation and range data outputs are provided in both digital and analogue form and the tracking accuracies obtained are of the order of 0·1 milliradian in angle and 5 metres in range. The characteristics of both these radars are summarized in Table 1.

In the use of precision tracking radars which have very narrow beams, target acquisition is a serious operational problem. In order to ensure the least time delay in the acquisition of the *Mercury* vehicle by the radars a separate automatic tracking aerial has been installed at all stations. It has a 20 deg beamwidth and pointing data from it is automatically transmitted to the radars.

The communication and computing facilities associated with the tracking network are such that the readings of azimuth, elevation and range can be transmitted from the radars to the computing centre where the orbit characteristics can be computed, essentially in real time, and information in form of predicted "look angles" transmitted to succeeding stations before the satellite comes within their range.

Table 1

Verlort and FPS–16 Radar Characteristics

	Verlort	FPS–16
Frequency	2700–2900 Mc/s	5400–5900 Mc/s
Peak Power	250 kW	250, 1000 kW
Pulse Width	0·8 μs	0·25, 0·5, 1·0 μs
Repetition Rate	410–1707 p/s	160–1707 p/s
Antenna Diameter	10 ft	12 ft
„ Gain	37 dB	44·5 dB
Beamwidth	2·5 deg	1·1 deg
Receiver Noise Figure	7–8 dB	9–11 dB
Bandwidth	3 Mc/s	1·6 and 8·0 Mc/s
Tracking Rate-Range	9144 m/s	7300 m/s
„ „ -Angle	0·9 rad/s	0·7 rad/s azimuth 0·54 rad/s elevation
Feed	conical nutating	4-horn monopulse
Mount	Az.-El.	Az.-El.

5. Doppler Tracking

The position and speed of a satellite may be determined from observations of the change in frequency of the signal received at a ground station from the moving satellite. This frequency shift, due to the well-known Doppler effect, is of the order of 600 c/s for low flying satellites transmitting on 20 Mc/s and increases proportionally with the transmission frequency and speed of the satellite. At a frequency of 100 Mc/s it is of the order of 3 kc/s.

The simplest method of measuring the frequency shift is to heterodyne the received signal against a locally generated reference frequency of high stability so as to obtain a low frequency signal which can be recorded on magnetic tape. The recording is subsequently analysed electronically to obtain values of frequency shift against time. A typical plot of such an observation is shown in Fig. 1. From this curve the time of nearest approach of the satellite to the receiving station is indicated by the point of maximum slope. The slant range at this time may be calculated from this rate of change of frequency and the orbital parameters deduced.[9,10,11] However, unless due allowance is made for the curvature of the track, for the relative movement of the earth and for drifts in transmitter frequency, grave errors can arise in this simple method of analysis.

It is considered that more profitable use can be made of the data if the full Doppler curve is used in the analysis. Guier and Weiffenbach[12] have used a single Doppler curve to determine all the elements of an orbit with reasonable accuracy. Their method was to compute the frequency shift using estimated orbital elements and making allowance for ionospheric effects. The theoretical curve was then compared with the measured one and the estimated parameters varied until a best fit was obtained between the two curves.

5.1. DOPLOC *System*

One practical system using the curve fitting technique is DOPLOC,[13] derived from Doppler phase-lock. This system is intended for operation on

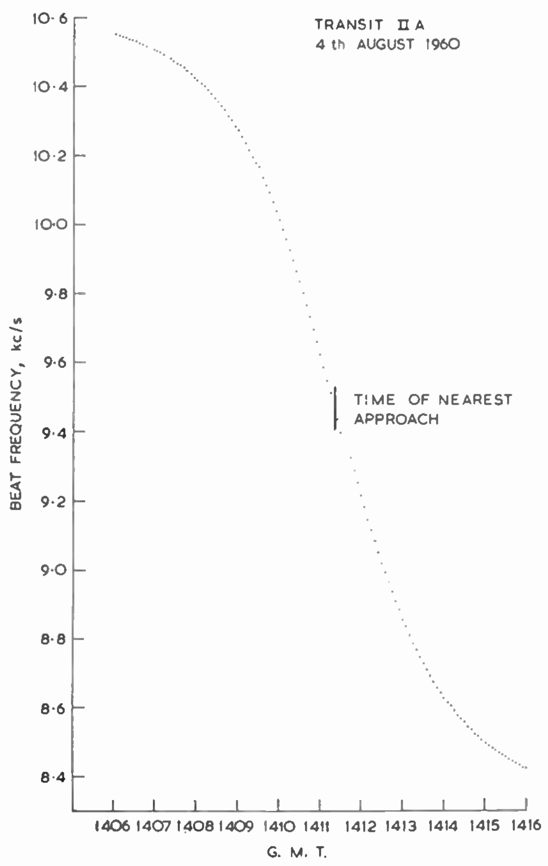

Fig. 1. Doppler curve from *Transit IIA* on 54 Mc/s.

frequencies greater than 100 Mc/s, and in the computation of the theoretical Doppler shift ionospheric and atmospheric refraction are neglected. An essential feature of this system, shown in Fig. 2, is the use of a phase-locked tracking filter which reduces the effective bandwidth of the receiver to a few cycles per second and enables useful frequency shift data to be obtained on very low signal/noise ratios. The beat signal obtained by heterodyning the received satellite signal with a locally generated reference signal is fed to a phase detector which compares the phase of the beat signal with that of a voltage-controlled oscillator (v.c.o.) and the error voltage developed is used to keep the v.c.o. in step with the beat frequency. The frequency of the relatively noise-free v.c.o. output is then recorded and also measured simultaneously on a frequency counter which provides a digital record of both frequency shift and time. Such a system has been shown to be capable of providing satisfactory orbital data from measurements made on a single satellite transit at a single receiving station, though the use of two or more stations provide greater accuracy.

It should be noted that the use of a tracking filter is not confined to the DOPLOC system. The technique is used in the Microlock system[14] for obtaining a high receiver sensitivity for the reception of telemetry signals from satellites. It has also been used in the analysis of recorded Doppler frequency shift on satellite signals of various frequencies.[15]

5.2. *Transit System*

In order to obtain the highest accuracy of which the Doppler type of measurement is capable it is essential to minimize the effect of ionospheric refraction. One method of doing this is to take advantage of the dispersive properties of the ionosphere and to use two satellite transmitter frequencies. It can be shown[12] that the Doppler shift in the presence of the ionosphere is

$$\Delta f(f,t) = -\frac{f}{c}\dot{\rho}(t) + \frac{\alpha(t)}{f} + \frac{\beta(t)}{f^2} + \ldots$$

where f is the transmitter frequency
and ρ the slant range

If two harmonically related frequencies are transmitted and the Doppler shift on one, multiplied by the frequency ratio, is subtracted from the Doppler shift on the other the second term in the above expression, which corresponds to the first order refraction, can be eliminated. If at a frequency of 200 Mc/s the magnitude of the first term of the expression, the vacuum shift, is of the order of 5·0 kc/s the first order refraction term will be 2·5 c/s and the second order one 0·01 c/s. Thus if the two frequencies are of this order the residual error due to

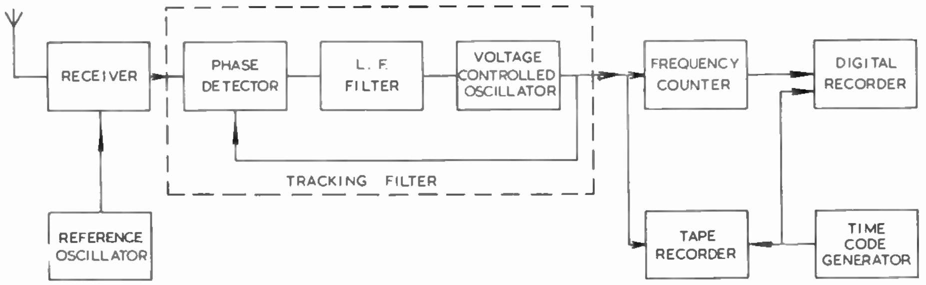

Fig. 2. Basic DOPLOC receiving system.

refraction (difference between the second order terms) will be negligible.

Doppler tracking using multiple frequency transmissions is being used in connection with the U.S.A. satellite navigation system, *Transit*.[12,16] In this system a two-frequency Doppler technique is being used both for precise determination of the satellite orbit and for position fixing relative to the satellite by mobile ground or airborne stations. The satellite transmits on two pairs of phase-locked frequencies, 162 and 216 Mc/s and 54 and 324 Mc/s. The frequency stability is better than 1 part in 10^9 over a 15-minute period. At the tracking station the two frequencies of a pair are received on receivers incorporating tracking filters and the Doppler frequency shifts are extracted using reference frequencies derived from a common source. They are recorded in digital form together with time at two second intervals. The first order refraction effects are then eliminated by computation in the manner indicated above. Additional instrumentation is now being developed, however, for combining the frequency shifts on the two signals so as to produce directly a recording of the corrected Doppler shift.

Operational data obtained to date indicate that satellite positions can be determined to an accuracy of the order of 0·2 nautical mile or better using the measurements from a number of these tracking stations.[17]

6. Interferometers

6.1. *General*

The radio interferometer is the type of instrument in most general use at the present time for satellite tracking. Its principle of operation may be explained by reference to Fig. 3 in which the layout of the aerial system is shown. The aerial system consists of two pairs of spaced aerials with the baselines of the pairs set at right angles to each other. Horizontal aerials are commonly used and the spacing between the aerials of each pair is ten to fifty wavelengths. By means of suitable receiving equipment the phase difference between the signals received at the two aerials of a pair is obtained and from it the difference in the wave-path lengths is computed. Similar simultaneous observations on the other pair of aerials allows the azimuth (α) and elevation (β) of the satellite at a given time to be calculated. There is, however, ambiguity in this determination because the phase measuring equipment cannot indicate directly the integral number of cycles in the phase difference. If, however, observations are made simultaneously on a second system with shorter baselines of one or two wavelengths, in which the alternative directions are more widely spaced, the ambiguity may be resolved.

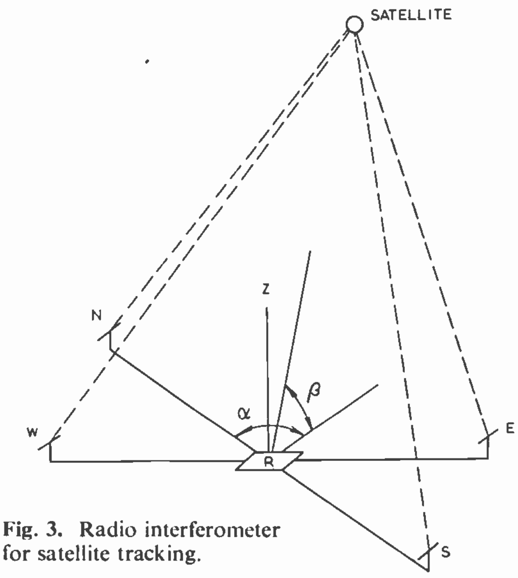

Fig. 3. Radio interferometer for satellite tracking.

6.2. *Aerials*

One of the primary considerations in the installation of the aerials is that they should be accurately set out with respect to each other and to the geographical co-ordinate system. If, for example, the phase difference measuring equipment is capable of measuring to one thousandth part of a cycle (0·36 deg), as is the case with the Minitrack system, then the aerial system should be set out to an accuracy of one thousandth of a wavelength, i.e. 2 mm for an operational frequency of 136 Mc/s. The corresponding accuracy of orientation of the baselines should be 5 seconds of arc.

Comparable precision should also be obtained in the adjustment of the aerial cables and special precautions taken to ensure that their electrical lengths remain constant.

The individual aerials may vary from a simple horizontal dipole over a ground screen to an array of dipoles producing a fan beam. An aerial system having a certain amount of directivity along the zenith is advantageous in the reduction of interference from ground sources and in giving increased sensitivity overhead where, because of reduced ionospheric refraction, directional measurements are most accurate.

6.3. *Measurement of Phase Difference*

Several methods of determining the phase difference between the aerial signals are used. In the systems for 20 and 40 Mc/s developed by the Radio Research Station[18] only the times at which the signals are in phase or in anti-phase are indicated. This is done by sampling the amplitude of the standing wave produced on the transmission line between the two aerials at

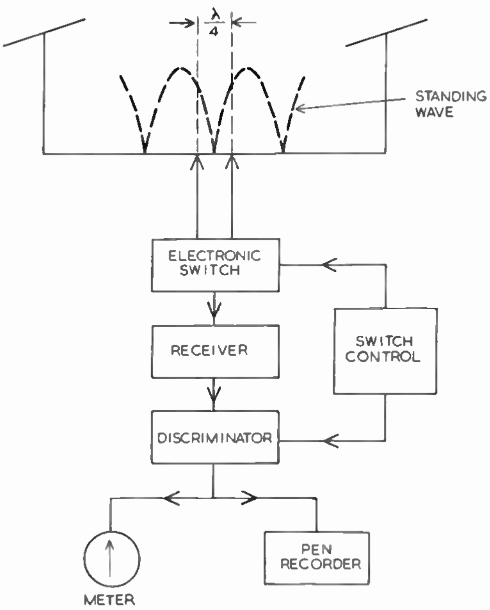

Fig. 4. Phase comparison interferometer for 20 Mc/s.

two points on the line a quarter-wavelength apart, as shown in Fig. 4. The receiver input is switched electronically at 100–200 c/s between these two points and the rectified output, switched in synchronism, is applied to a centre-zero d.c. meter and pen recorder. The record thus obtained during a satellite transit shows a succession of crossings of the zero line at each in-phase and anti-phase condition (Fig. 5). With the 150 m baseline used in the 20 Mc/s system there are forty such crossings, which, for high angles of elevation, correspond to directions spaced approximately 4 deg apart. Figure 5 also shows the records obtained on the shorter baseline system, 25 m spacing, for which there are only six crossings corresponding to angular spacings of approximately 24 deg. A comparison of the two sets of records enables the crossing of the central plane of the baseline to be identified as shown. The direction of arrival of the signals at any other time may be obtained by interpolation to an accuracy of about 0·5 deg. A plot of the phase differences and corresponding azimuths and elevations against time for a typical satellite transit is shown in Fig. 6.

Other methods of phase comparison enable the phase difference to be continuously indicated. By sampling the amplitude of the standing wave on the aerial transmission line at four points one-eighth of a wavelength apart and combining receiver outputs proportional to the squares of the sample amplitudes it has been possible to obtain continuous records of the sine and cosine functions of the phase difference angle. An interferometer operating on this principle has been designed by the Royal Aircraft Establishment[19] for a frequency of 108 Mc/s. The American-designed Minitrack system also provides continuous phase difference indications and details of its design and performance are given in the next section.

6.4. *Minitrack System*

The Minitrack system[8,20] was designed for the tracking of U.S. satellites and there is at present a network of fourteen stations distributed over the world as shown in Fig. 7. One of these was installed last year at Winkfield field station of the D.S.I.R. Radio Research Station. The equipment is supplied on loan by the U.S. National Aeronautics and Space Administration (N.A.S.A.) and the installation is operated by the staff of the Radio Research Station with full reciprocal arrangements for the use of the data derived. The stations were originally designed for operation on 108 Mc/s, and some still operate on this frequency, but the newer stations, including Winkfield, operate on 136–137 Mc/s, one of the bands recently agreed internationally for transmissions from

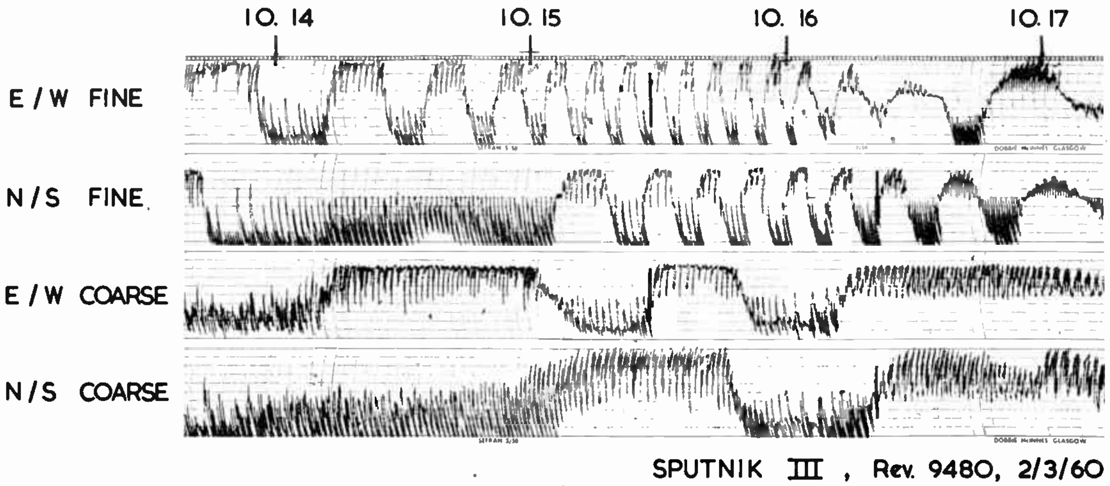

Fig. 5. Typical interferometer record.

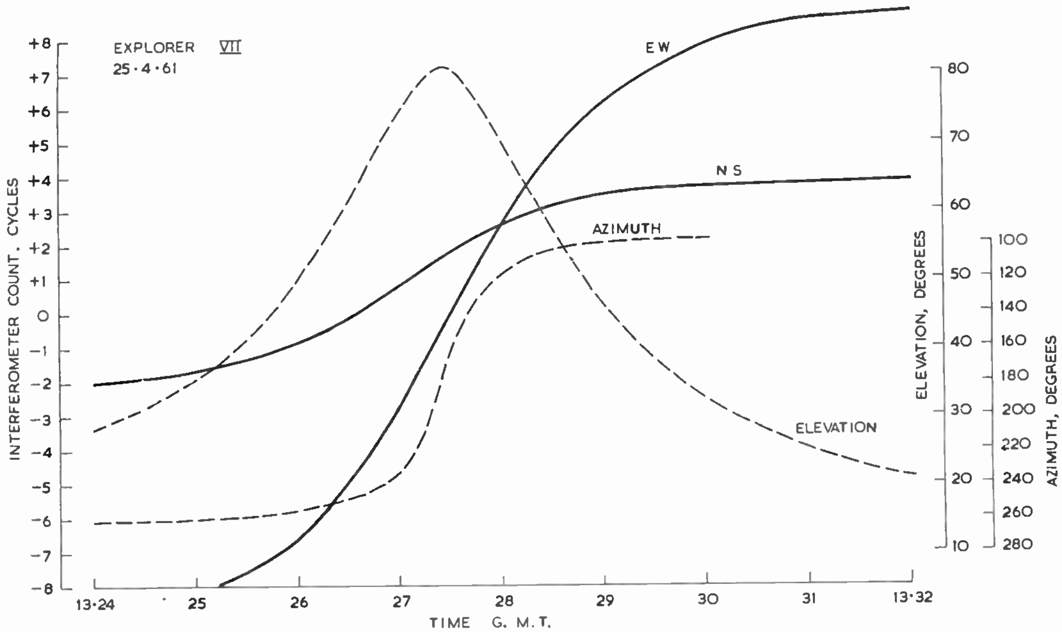

Fig. 6. Plot of interferometer readings and derived directions.

space vehicles, and many of the older stations are being converted in preparation for the general use of these frequencies for tracking purposes.

The general layout of the aerial system at the Winkfield station is shown in Fig. 8. There are in effect two separate interferometers; one (the equatorial system) is primarily intended for tracking satellites flying substantially in a W–E direction and the other (the polar system) for those flying in a N–S or S–N direction. Switching arrangements are incorporated so that either aerial system can be selected for connection to the receivers. The spacing between these "fine" aerials is about 50 wavelengths.

These aerials are identical in construction each comprising eight horizontal co-linear elements connected in phase with a tapered amplitude distribution. The arrays are mounted above horizontal ground screens measuring 50 ft by 25 ft and all arrays are in

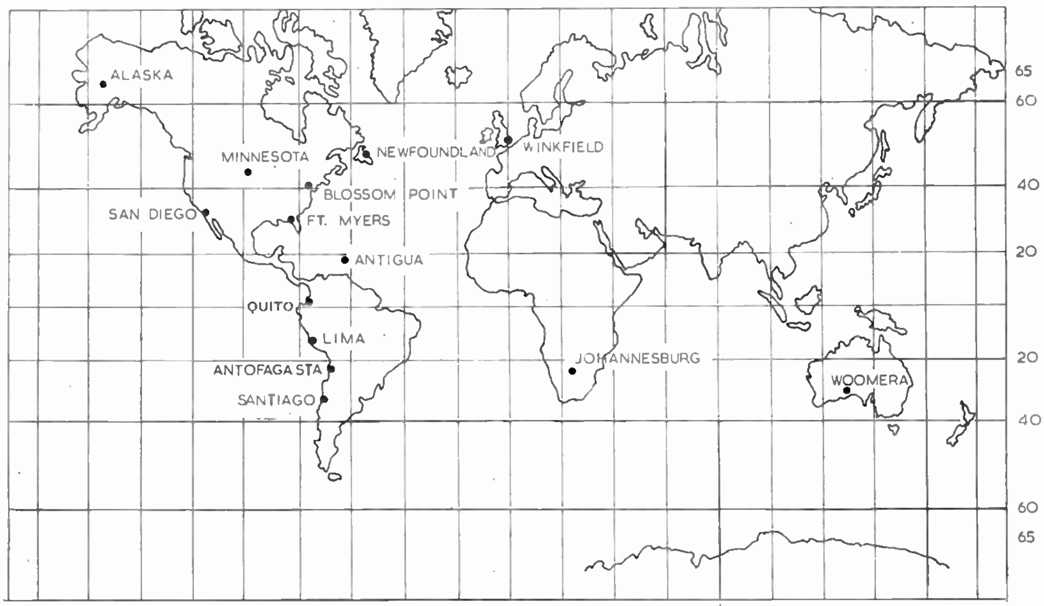

Fig. 7. Minitrack network.

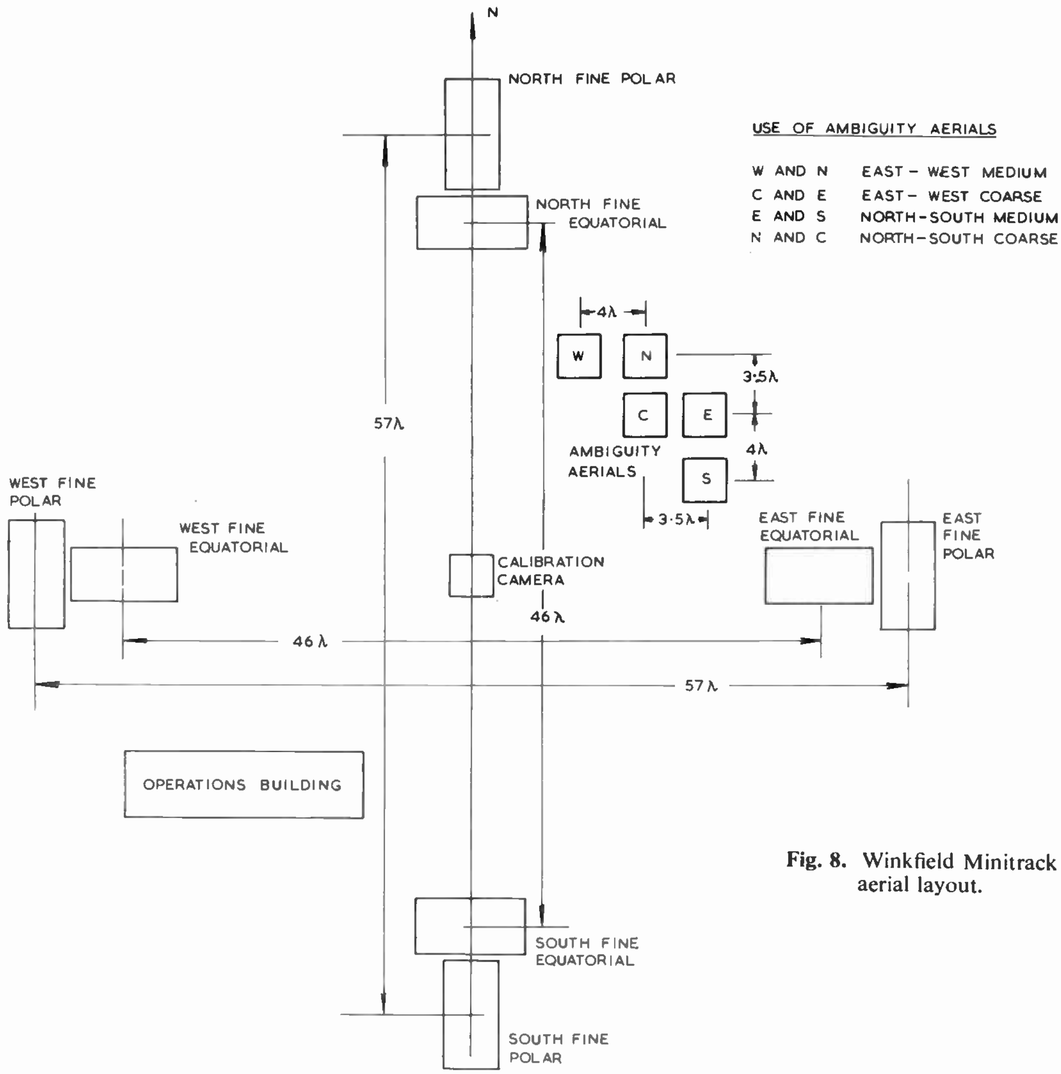

Fig. 8. Winkfield Minitrack aerial layout.

the same horizontal plane. The aerial arrays of the equatorial system are arranged with the line of the component elements in the E–W direction and those for the polar system lie in the N–S direction. Each array has a vertically directed fan beam with a width between 3 dB points of 11 deg in the H-plane and 76 deg in the E-plane. Thus effective tracking is carried out only when the satellite is within a few degrees of the vertical plane in the N–S direction when the equatorial aerials are used and within a few degrees of the E–W vertical plane when the polar aerials are used.

Directional ambiguities are resolved by the use of a group of five closely spaced aerials. Each of the "ambiguity" aerials consists of a single element mounted over an 18ft square ground plane and when operating in pairs they constitute a N–S and E–W "medium" system of 4·0 λ spacing and a N–S and E–W "coarse" system of 3·5 λ spacing.

All aerials are connected to the receiver by buried low-loss aluminium sheathed coaxial cables which are pressurized with dry nitrogen with the object of achieving stable transmission characteristics. At the cable terminations in the operations building, remotely operated coaxial switches select either the polar or equatorial fine system for connection to the receiver. The receiver has six identical channels to which are connected the following aerial pairs: N–S fine, E–W fine, N–S medium, E–W medium, N–S coarse, E–W coarse. The signals from each aerial of a pair, e.g. from N–S fine aerials, pass through separate pre-amplifiers (Fig. 9) and are then converted to intermediate frequencies differing from each other by exactly 100 c/s. The local oscillators of the frequency changers are crystal-controlled, the frequency difference between them being obtained by the addition of a 100 c/s signal phase-locked to a reference 100 c/s voltage derived from a precision 1 Mc/s oscillator.

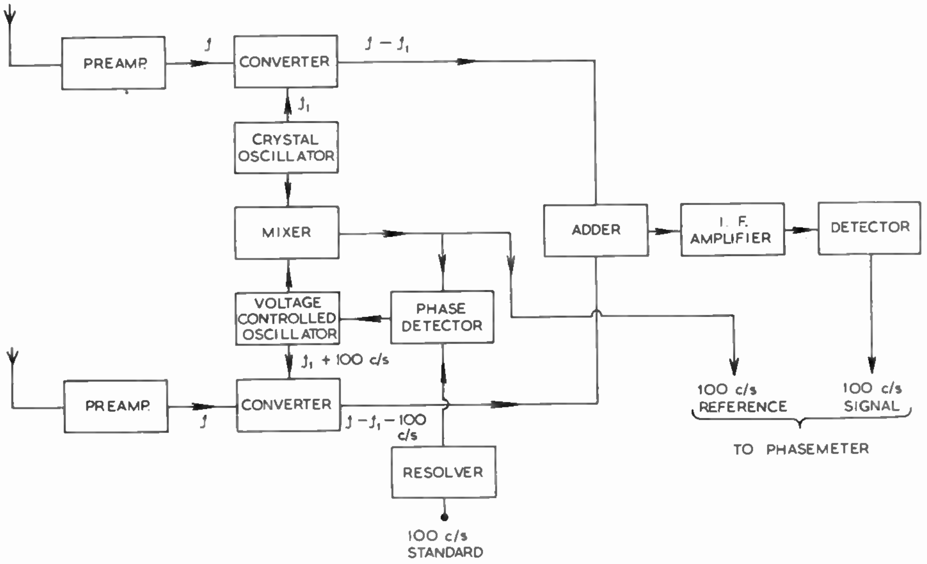

Fig. 9. Minitrack receiver: simplified block schematic of a single channel.

Both i.f. signals pass through the same amplifier and the phase of the 100 c/s beat note obtained at the output of the receiver relative to the phase of the 100 c/s reference frequency corresponds to the phase difference between the N and S aerial signals.

The measurement of phase difference is performed by the generation of a pair of pulses, at a repetition rate of 100 p/s, whose time separation is proportional to the phase difference. These pulses trigger a bistable switch whose integrated output over the cycle is recorded and provides a continuous analogue presentation of the phase. By using the pair of pulses to operate a gate system which counts the number of cycles of a 100 kc/s voltage a digital display of phase with a discrimination of 0·36 deg is also obtained. The analogue and digital outputs are applied to separate pen type recorders. The analogue chart, a section of which is reproduced in Fig. 10(a), shows the fine, medium and coarse phase differences while the digital chart (Fig. 10(b)) shows only the fine phase differences in the form of a decimal code, read out five times per second. The signal strength and time, in decimal code, are also recorded on both charts. The analogue record is used mainly to resolve ambiguities and the precise phase reading is obtained from the digital record. At the present time the phase differences required for the computation of directions are obtained by reading the charts at 0·2 second intervals over the period 3 seconds before to 3 seconds after the passage of the satellite across the N–S and E–W planes. Automatic tape punching equipment is now being installed, however, and in future all phase differences will be recorded on punched paper tape in a form suitable both for automatic processing and for transmission over a teleprinter circuit to the N.A.S.A. Goddard Space Flight Center.

Accuracy of the time marks on the charts is of equal importance to that of the phase measurements. Near the zenith the Minitrack interferometer is capable of recording an angular movement of 5 seconds of arc and for a satellite flying at a height of 500 km this occurs in about 1·5 milliseconds.

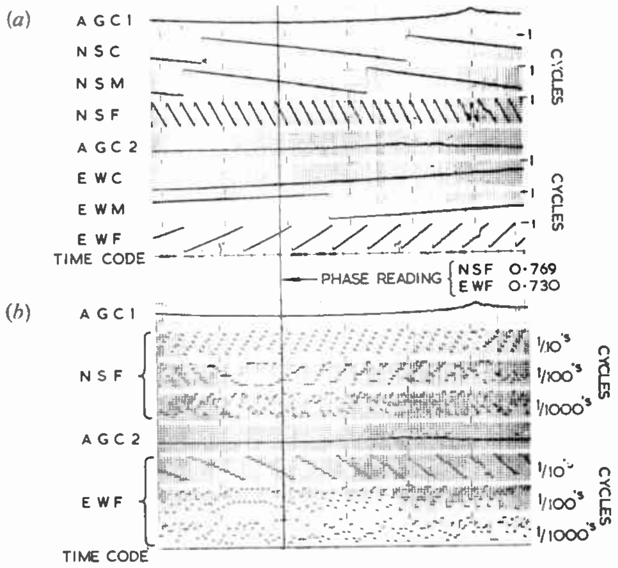

Fig. 10. Minitrack phase record.
(*a*) Analogue chart.
(*b*) Digital chart.

Time measurement to a precision of 1 millisecond is achieved by the use of a crystal controlled clock operating from the 1 Mc/s oscillator mentioned above. Its output is checked daily with the standard time signals from the WWV station.

6.5. *Accuracy of Measurement*

The accuracy of the interferometer for satellite tracking is dependent upon three factors: the accuracy of the phase measuring equipment, the electrical symmetry of the aerial system and the propagation of the radio waves. The internal accuracy of the equipment can be checked by the application of co-phasal test signals to the receiver inputs and means of rapidly making such a check and performing any necessary adjustments is usually built into the equipment.

In order to take account of aerial asymmetry and local site effects an overall calibration is necessary and this is usually done with the aid of a transmitter on a high-flying aircraft. The calibration is carried out at night so that the track of a light carried by the aircraft can be photographed against a star background. The aircraft lamp is switched by ground control in synchronism with the time marks recorded on the interferometer phase record and in this way corresponding radio and optical position of the airborne transmitter are obtained. Minitrack stations are calibrated at 3–6 monthly intervals. An analysis of the calibration results obtained on the older stations has been made to determine the phase stability of the system. This shows that the average error for all stations due to phase drift between calibrations is less than 20 seconds of arc.[8]

When all instrumental errors have been minimized, inaccuracies due to the deviation of the radio waves from the straight line path by ionospheric refraction may still be present. The magnitude of the deviation varies with the angle of elevation, being greatest near the horizon and least at the zenith; this is illustrated by the plots of Fig. 11 which were obtained from observations on satellite *Explorer VII* using the 20 Mc/s interferometer at the Radio Research Station. The deviation is also dependent upon frequency, decreasing as the frequency increases. For example, at an elevation of 45 deg it is of the order of 2 deg–3 deg on a frequency of 20 Mc/s and 0·05 deg–0·2 deg on 100 Mc/s under average ionospheric conditions. These deviations are considerably greater than the instrumental accuracy of the Minitrack system and, since the tracking data obtained over the entire solid angle covered at each of the stations are used in obtaining the initial orbital elements of a new satellite, corrections based on predictions of the index of refraction are applied As the orbit characteristics become better defined only that portion of the tracking data obtained within a few degrees either side of the zenith need be used. In this zone refraction corrections are small and errors due to refraction variations may be minimized to less than 20 seconds of arc.

7. Other Tracking Systems and Future Trends in Development

Although in the introductory remarks tracking systems have been divided into three categories, interferometer, radar and Doppler, the distinction is rather artificial as systems combining the techniques have been, or are being, developed.

One such example is the U.S. Navy Space Surveillance System[21] which makes complete provision for satellite detection and tracking without cooperation

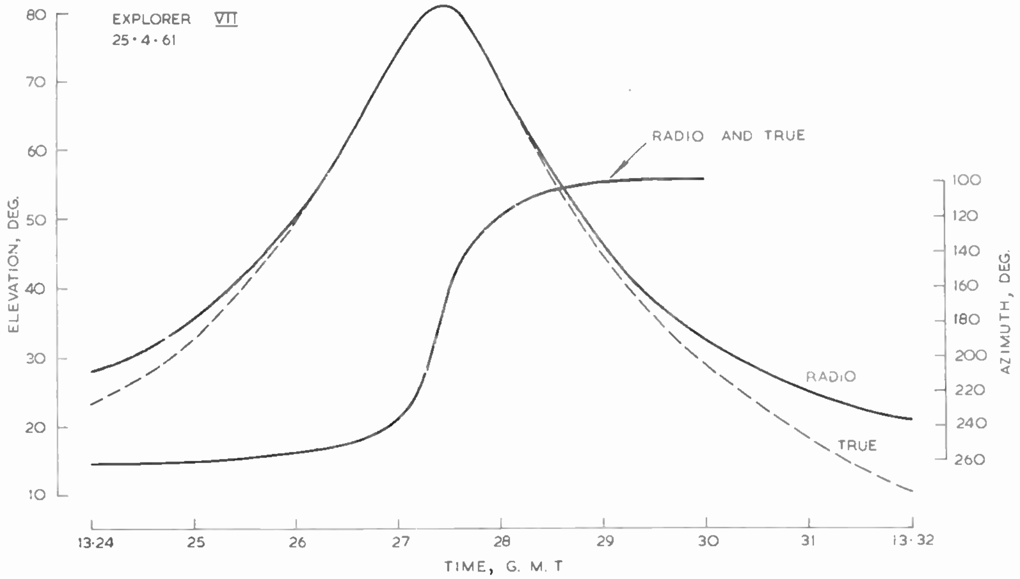

Fig. 11. Comparison between true and measured directions of observations on a satellite.

from the satellite. In this system the satellite is illuminated by a c.w. v.h.f. transmitter having a vertically-directed fan-shaped beam. Two receiving stations, placed on either side of the transmitter and separated from it by a hundred miles or more, employ interferometer equipments, similar to the Minitrack system, to measure the angle of reception of the reflected signals as the satellite passes through the transmitter beam. There are at present two groups of three stations located on an E–W line across the southern part of the United States and the directional data from the four tracking stations are transmitted to a central control centre where they are processed and used in orbital computations.

A development to be expected in order to improve the accuracy of interferometer systems is the use of longer baselines to increase instrumental precision, and of higher frequencies to reduce errors due to ionospheric refraction. Systems with baselines several hundred wavelengths long and operating at frequencies of a few thousand megacycles per second are being considered though it is realized that there are difficulties in the construction of such systems. The use of higher frequencies will result in considerably lower power radiation from the satellite and hence the need for a higher gain receiving aerial which in turn will demand high precision in construction, alignment and following if the potential accuracy of such a system, of the order of 1 second of arc, is to be realized.

In the field of precision radar tracking there is a trend from angle and range measurements at a single site to the determination of range only at a number of sites. One system under development, known as Mistram,[8] will utilize station baselines of the order of 100,000 ft and frequencies in the 10 Gc/s range. The estimated precision is such as to allow the determination of position and velocity of an overhead satellite at a range of 500 miles to less than 10 ft in any direction and less than 0·1 ft/s in each axis with less than 0·5 second smoothing. The realization of such precision will, however, necessitate compensating for tropospheric effects, which themselves can give rise to errors of hundreds of feet.

8. Acknowledgments

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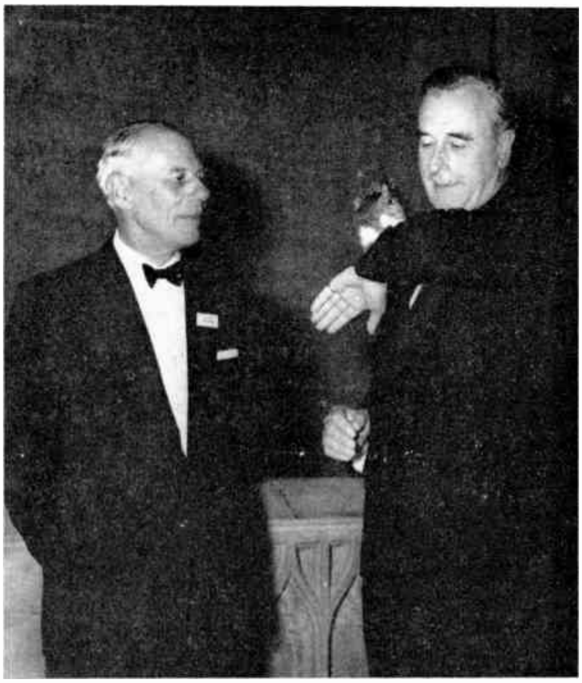
CONVENTION COMMENT

It is well worth recording in the *Journal*, for permanent reference, that the 1961 meeting in Oxford more than maintained the standard expected of Brit.I.R.E. Conventions.

Writing in the foreword to the Convention Handbook, the President welcomed delegates from many countries and said that the ". . . . Convention provides not only a forum for discussing 'Radio Techniques and Space Research'. It also brings together those scientists and engineers who have already started upon resolving some of the problems and a greater number of engineers who are qualified and willing to play their part in the development of space communication."†



The uninvited guest . . .

Throughout the reception and Banquet in Christ Church, a squirrel steadfastly attached itself to Admiral of the Fleet the Earl Mountbatten of Burma. In this picture the President shows his new pet to Mr. W. E. Miller.

Traditionally the social highlight of the Convention was the Banquet, held in the Hall of Christ Church on Friday, 7th July. The maximum accommodation of the Hall was utilized. Earlier in the day delegates had welcomed the President, who attended the afternoon session and took part in a lively discussion.

† The 1961 Convention Handbook had many interesting features. Its record of papers submitted and of delegates attending was supplemented by the daily issue to delegates of "Convention News", extracts from which it is hoped to publish in the next issue of the *Journal*.

Admiral of the Fleet the Earl Mountbatten of Burma, K.G., received guests at the Banquet Reception who included:—

Professor Sir Harrie Massey, F.R.S. (*Chairman of the British National Committee on Space Research*); Sir Cyril Hinshelwood, O.M. (*Immediate Past President of the Royal Society*); Sir Wilfred Le Gros Clark, F.R.S. (*President of the British Association*); Sir Lynn Ungoed-Thomas, Q.C., M.P.; with representatives of the Services, Government departments and space research organizations at home and abroad.

The ensuing Banquet was in every sense traditional of Christ Church and Brit.I.R.E. Conventions. It was followed by two brief speeches. The President proposed the toast of the Dean, Canons and Students of Christ Church in the following terms:

"Fifteen years ago I had the pleasure of sitting at High Table in 'The House' after the Senate of the University had honoured me with the degree of a Doctor of Civil Law, Honoris Causa.

I must confess to the members of this University that since June 1946 I have had little opportunity for post graduate work in the Faculty to which I was admitted! I have, however, tried to play my part in maintaining law and order in a civil as well as a military manner!

It is always pleasing and refreshing to return to the House and to enjoy its atmosphere and quietude.

On behalf of the British Institution of Radio Engineers and all the delegates who have attended the Convention I thank the Dean, Canons and Students of Christ Church for their hospitality.

I invited Lord and Lady Hailsham to dinner, but alas they had a previous engagement. I should, however, like to read out his letter:

'My wife and I are very sorry that we are not able to attend the British Institution of Radio Engineers' Convention Dinner.

But I should like all present to know that we are most grateful for your invitation, and wish you all a most enjoyable and happy evening.

As Minister for Science I am of course deeply concerned for the future of British radio and electronic engineering.'

I should like to express our thanks to the administrators of the Clarendon Laboratories for the facilities given us there, which I had an opportunity of enjoying this afternoon.

I was particularly glad to notice the plans which are being made for a new laboratory for nuclear physics. I am sure that the advanced work which is being pursued in the laboratories would astonish the first Earl of Clarendon who proposed that his endowment 'should be the nucleus of a fund for an academy for riding or other exercises at Oxford'.

I have, in the past, been responsible for the production of a technical text book on riding and polo, and I was therefore, personally, sorry not to have seen any stables or riding school at the Clarendon Laboratories, but there is no doubt that the Clarendon Laboratory is achieving a great deal more for the world today than the riding academy would have done.

But at the time the Clarendon Laboratory was established it would have taken a very unusual man to have anticipated that it would become one of our foremost centres of research in nuclear physics.

When we had our first Convention in Oxford in 1954, we were very rightly then concerned with the application of electronics to a very wide variety of industrial uses. Even in 1954, however, I doubt whether we could seriously have contemplated such a Convention as we have been holding this week.

In the Presidential Address that I gave to the Institution just one month ago, my main theme was the development of improved world-wide communications services. I mentioned in particular the possibility of integrating long-distance communications networks of the three services, and discussed the radio aspect of the problems involved. What I did not mention was the practical difficulties of the different procedures, and indeed even of the different languages at present used by the three services.

I will not dwell any more on the subject of the future development of communications tonight, except to say that what has been happening here this week is a most tangible contribution towards the development of using the great space outside this earth for communication purposes.

Our meetings have, and will again tomorrow, show the importance of radio techniques in space research, and especially the possibility of space communications.

Under new conditions, special attention is being given to the performance and reliability of engineering equipment. It is in this particularly that we can derive immediate benefit from our space research and development effort. Reliability is a subject which I hold to be of the greatest importance, unless we can multiply the reliability factor of British electronic equipment by at least ten we shall end up by having so many electrical maintenance men in our warships that there will be no room left for seamen. I am, therefore, particularly pleased to see the time that has been devoted to the reliability aspect of our work.

I wish to thank all those responsible for making such valuable contributions to our Convention. I fully realize the amount of intense hard work that this must have entailed. I should like to give a special word of thanks to those authors who have travelled from abroad, and who have not only joined in our discussions, but made such excellent contributions based, in so many instances, upon the practical work which is going on in their own countries.

It has become traditional in our Institution that a Convention banquet is the only social function in a week of serious work and activity. I would therefore like to thank our hosts and our guests for making this such a delightful occasion."

Replying to the President's Toast, the Dean, the Very Rev. C. A. Simpson, D.D., stressed now valuable were such meetings in providing cross-fertilization between various branches of learning and said he was particularly pleased to welcome the Institution back ot Oxford.

The Very Reverend Simpson punctuated his speech with many humorous anecdotes and particularly amused delegates by his recollection of a radio station in Canada, operated by a friend, which was the first to broadcast a religious service.

Dean Simpson concluded by pointing out that the whole development of radio had taken place within his adult life and that of many present. The latest advances into the use of space for communications struck him as very adventurous and in his thanks to the President he expressed his admiration for the work of the radio engineer.

The President and the Dean, the Very Rev. C. A. Simpson, in discussion after dinner. On the President's right Mr. Ieuan Maddock, Chairman of the Convention Committee, appears still to be thinking of space research problems!

U.D.C. 331.8: 621.396

The Demand for Trained Technicians

By

GRAHAM D. CLIFFORD,
(*Member*)†

Based on an Address to the Eighth Conference of the Radio and Television Retailers' Association held in Brighton on 26th April, 1961.

This year's Conference of the Radio and Television Retailers' Association was preoccupied with consideration for colour television. Doubt was expressed as to whether there were sufficient technicians competent to install and maintain such equipment—a theme developed by the General Secretary of the Institution, Mr. G. D. Clifford, when he addressed the Conference. Under the title of "Staying in Business", Mr. Clifford's paper aroused considerable interest both at the Conference and after and has been widely quoted. Requests during recent weeks for fuller details have suggested that an abridged version of the paper should be published for the interest of members.

In view of the gloomy forecasts which are always being given about the future of the British radio industry, I felt that to entitle my Address "Staying in Business" would not only be more apt, but might rivet attention on the importance of my subject, which is technical training.

Your Director has already said at this Conference that the retailers' part in the radio industry may for the next two or three years "... be largely concerned with maintenance and replacements until something new like colour was introduced". In fact "something new" is frequently being introduced by our virile and enterprising radio industry. Development of colour television is only one aspect—admittedly important—of the industry.

Moreover, may I suggest that before relishing the glorious technicolour of the future, it is necessary to be certain that you will be able to give the service that the public—who after all have to pay for these delights—will most certainly demand?

Shortage of Engineers and Craftsmen

We work in a highly technical industry which since the war has suffered from a shortage of both trained radio engineers and radio technicians. By constantly improving production methods, the industry nevertheless produces annually over two million radio sets and a further two million television sets, apart from transmitting, studio, industrial electronics and other equipment. *In addition* the radio industry has also produced for defence and export, radio and electronic equipment valued at some £400 million per annum.

All this has been achieved with an industrial pay roll of about 300 000 people. Add to that number all those employed in Government radio research, in broadcasting, and in the radio sections of the Post Office and Defence Services, in teaching, etc. and it will be appreciated that well *over* half a million people in these Islands are employed in one way or another in radio and electronics. And this does *not* include the technicians and mechanics in the retail trade and in relay and rental companies. It is unfortunate that the Ministry of Labour does not compile accurate figures relating to employment in the radio industry.

In the last few years there has been a great increase in the number of technical colleges offering suitable courses in radio and electronic engineering and in radio and television servicing, but the results have in no way kept pace with the demands of the industry.

Mr. Clifford next referred to the foundation of the Radio Trades Examination Board in 1942 and continued:

The Board had, of course, first to promote schemes of training in technical colleges before setting examinations. Entries have increased year by year, but there can only be modest satisfaction with the fact that in the last 17 years only 10 087 candidates have submitted themselves for examination and that of those less than a half, precisely 4182, have succeeded. The picture is even gloomier when one realizes that over 20% of the successful candidates only achieved their pass mark at a second attempt. Out of the successful candidates 2000 went on to take a final examination in television work. Only 1074 passed and there again 200 had to have two attempts before succeeding.

The value of the R.T.E.B. scheme may be questioned in three ways. Is it necessary? Is there sufficient incentive? Is the standard too high?

† The General Secretary of the Institution.

Testing, maintenance and servicing of complex technical equipment must not be left to untrained minds and hands. It is true that after the war some thousands of radio technicians and mechanics left the Services and were able to secure employment in both trade and industry without having to secure further technical training. That source of labour is not only diminishing, but is now not great enough to meet the demand.

Is the standard too high? The honest answer must be, no—and my reasons must be judged in relation to three factors: first, the basic standard of education and inherent ability of the youth who can be attracted to this kind of employment.

In this era of full employment, industry and commerce compete for the best of your youth. In general, it is the youth from the secondary modern and not the grammar schools that we have to cater for in planning craft training.

It is in the first year of craft training that so many students become discouraged and give up the course. Results vary throughout the country, but there is ample evidence that there is too wide a gap between the standard achieved when leaving school at 15 years plus, and the first year of a technical college course. Admittedly vocational assessment is very difficult at that age, and so often an employer has no alternative but to make the best use of the available applicants for employment. If, however, we are not to waste our manpower and the efforts of technical colleges, it is essential that more attention should be paid to vocational selection.

Critics who often argue that the R.T.E.B. scheme should be of a higher standard—and I am one—have therefore to remember that any scheme must be within the compass of the students who can be attracted to such a scheme. Higher standards of proficiency are slowly—perhaps too slowly—being achieved. The pace must however, be quickened if adequate and efficient *service* is to be given on such new techniques as, for instance, colour television.

The Efficiency of Technical Colleges

The second condition which affects the standard of efficiency is the type of college course. Colleges have their problems, both in recruiting lecturers, and in deciding what courses they can best offer and which will, at the same time, command maximum enrolment.

All colleges are concerned with the problem of the entrance level and the first year results to which I have already referred. In large manufacturing organizations it has been found advantageous to establish understanding with the technical colleges on the selection of apprentices and other technicians since this determines the level of the course.

The responsible employer in the radio trade could, I feel, do much more to collaborate with his local technical college, perhaps on a group or branch basis. Individually, trade employers are only concerned with one or, at best, a few trainees or apprentices. Co-operation within the areas covered by the branches of your Association, could do much to help the technical colleges to have economic classes.

All this is very important if we are to avoid wasting the effort and cost incurred by the employer, trainee and college. Remember that the student is committing himself to a course requiring a minimum of 150 attendance hours per year for perhaps as long as 5 years, in order to cover the R.T.E.B. scheme of examination. The course is similar in length to the more advanced courses taken by the trainee engineer although, for obvious reasons, the technicians' courses are more practical in their approach.

Most progressive employers recognize the fact that the increasing flow of technical knowledge and the higher standards that are demanded today, cannot be encompassed by a few hours a week at evening classes when the mind is not most receptive to new knowledge.

Thus, the vast majority of efficient technical college courses are based on a part-time day release basis. That is to say, the employee is released to attend the technical college on one day, or two half days, per week, and in addition attends for one or two three-hour periods in the early evening. This seems to be the pattern generally adopted throughout industry and has the advantage of requiring earnest endeavour by the student if he is to continue to enjoy his employer's co-operation.

Some of the larger employers in the radio industry prefer their apprentices to do full-time technical college training for short periods of, say, 7 or 8 weeks a year, rather than one day a week throughout the year. It is in the best interests of all concerned that apprenticeship and other trainee agreements should lay on the employer an obligation to provide some part-time day release. It is fairest to the employee and to the technical college.

By co-operation with local Technical Colleges and often with local manufacturing industry, group schemes enable apprentices to secure the right standard of technical training in the college and to have variety of experience by making the best use of workshop facilities which could be provided by a small group of retailers and/or manufacturers.

Our country is committed to a full development of its technological resources. For this reason alone, technical colleges are glad to have all the help that can be obtained from employers of technical manpower. Local employers can do a great deal by interesting themselves in the work of the local Education Authority, Committees and Colleges. Not only will it help to stimulate the flow of technicians, but your knowledge of local technical colleges may provide an outlet for your enterprise. I refer, of course, to the fact that technical colleges have to buy and maintain technical equipment. I see no reason why an enterprising and efficient retailer should not be able to stimulate and provide those needs!

Profit from Service

The third factor which influences my argument for securing higher standards of technical training is a simple one. It is to ensure our country's survival in a world increasingly dependent upon technology.

Do not dismiss that statement as a platitude. We still have some of the finest know-how in the world, particularly in the field of radio and electronics. Often, however, the sale and export of equipment is dogged by our shortage of technicians for installation, maintenance and servicing. We should also not forget that good technicians make the best salesmen.

Sir Robert Fraser† has emphasized that the success of launching colour television would, to a large extent, rely on adequate servicing and maintenance. There are not six colleges in the whole of the country that could immediately start training technicians for this new enterprise. The standards which may have sufficed for the maintenance of monochrome will not be good enough. It is another example of why we need more highly trained technicians.

There is a feeling throughout industry that we do not properly use our qualified engineers for too often the shortage of efficient technicians results in a qualified engineer having to do the work. This obviously increases manufacturing costs at a time when we all wish to try and reduce costs.

As part of the radio industry, the retailer also has new fields for service in the introduction of the many electronic devices which are now sold to industry and commerce. The introduction of automation is often limited because unless the buyer is big enough to justify employing his own radio and electronic technician, there is not anyone locally to whom he may turn for service and maintenance. The suppliers of such equipment often have to send an engineer to perform a task well within the compass of a qualified technician. This vista of new work for your service departments is not, I realize, easy for the small man. It can certainly, however, be tackled on a group basis and by the larger organizations within your Association.

I do not believe that members of your Association should be regarded only as retailers of radio and television sets. Their services are very similar to those operated by an efficient motor garage. Custom for new equipment invariably follows the provision of good technical services. As in other industries and trades, the provision of adequate technical services can provide a very worth-while financial reason for staying in business!

The Future

You may think that on the whole I have painted a gloomy picture. Not enough technicians, and all being competed for by the trade, manufacturing industry, users of equipment, etc. In point of fact, there are excellent grounds for optimism. The position today is that over 120 colleges throughout the country are providing courses designed to meet the requirements of the R.T.E.B. examinations. This year, 1961, no less than 3426 candidates have entered for the examinations which are to take place within the next two months. Although the standard of the examinations is increasing, it does not discourage the 10 000 young men who, throughout Great Britain, have embarked upon courses to equip them with the necessary knowledge to become competent radio technicians.

There is a corresponding increase in facilities for the training of radio and electronic engineers which has been very much stimulated by the British Institution of Radio Engineers. With the complementary work of the Radio Trades Examination Board there is now in Great Britain reasonable educational opportunity for young men wishing to qualify for employment in this expanding industry.

The whole business of technical training requires more thought by everybody, more co-operation and indeed, more money. But the investment is well worth-while. It is an investment in human beings who can be encouraged to take a pride and interest in being efficient craftsmen. And who will, with your guidance and help, enable you and the country to "Stay in Business".

Address No. 30.

† Director-General of the Independent Television Authority who addressed the Conference on 24th April.

U.D.C. 621.396.69

Some Aspects of Component Usage

By

Commander J. S. BROOKS,
R.N. (*Associate Member*) †

The Chairman's Address to the Southern Section at Southampton on 26th October, 1960.

Summary: An investigation undertaken by the Admiralty into the rationalization of components and spares for Naval electronic equipment is described. The problem is reviewed from the aspect of the variety of components specified. The methods used to reduce the number of different types carried by H.M. ships are detailed and reliability factors discussed.

1. Introduction

This paper is an account of an Admiralty exercise on the rationalization of components and spares. Whilst the work to be described arose out of a Naval requirement, the detailed work which was done, and the problems which were presented, are by no means peculiar to the Naval Service. Indeed similar problems have been seen to exist in varying degree elsewhere and it may well be that the solutions used will be of more than passing interest.

Before proceeding with this account, two points require some qualification.

Firstly illustrations are given of some samples of components of different manufactures. They are not very exciting components of the latest type but many of them are nevertheless still in very widespread use. In some cases they are Joint-Service Standards made by a number of manufacturers. These samples have been taken at random merely to illustrate the exercise and no preferences are implied amongst the standards, providing of course that they meet the necessary specifications.

The second point is that nothing of the work of the Admiralty Group on components was aimed in any way to contradict the excellent work of established Standardization Committees. It merely took some of this work a stage further in order to meet the particular Naval requirement. Indeed had it not been for the ready existence of shortened lists of standards its work would have been made incredibly more difficult. The Royal Navy had a maintenance and supply problem for which there is perhaps no exact parallel in any other large organization—it needs to carry spares and materials afloat sufficient for extended operations, yet be in a position to bring the right thing to hand at very short notice. Problems of packaging, stowage, identification and handling assume untoward proportions in the ship environment and need special consideration.

† Admiralty Surface Weapons Establishment, Portsdown, Cosham, Hants.

2. The Nature of the Problem

A few years after the end of the 1939–45 War an article appeared in a newspaper under the title of "A Screw by Any Other Name".† In it the writer referred to the useful work of standardization activities then current, suggesting however that so far only the fringe of the matter had been touched. He cited the example of the manufacturing firm whose inventory showed some thirty-two different names for a certain type of metal disc (none of which included the word "disc") and went on to quote the case of the factory which had amongst its stores four different bins in separate warehouses, variously labelled:

Kraft Paper Brown
Brown Paper Kraft
Paper Brown Kraft
Kraft Brown Paper

A rose by any other name did not smell as sweet however when it involved flying hundred of miles to procure items which were lying in abundance near at hand, as was often discovered by Military units in the field. Similarly, in the field of shipboard maintenance, a problem had grown up during the war and in the immediate post-war period—the problem of the complicated range of technical stores needed to be carried, all apparently essential, and all ostensibly different, such that one item could not be used in lieu of any other.

In particular, the problem of *identification* had become most time-consuming and difficult. In the field of electronic maintenance, because of the difficulty of identifying and obtaining the *correct* spare, many *ad hoc* and therefore undesirable substitutions were threatened in the interests of expediency. In the technical supplies field itself there was difficulty in getting internal stock records to present a reliable picture of usage, quantities of immobile dead stock had built up in wide ranges and a form of inflation was taking place because the difficulty of identifying technical equiva-

† R. Parmenter, *The Observer*, 19th October 1952.

lents led to "shopping list" methods being used on each occasion of replenishment.

The logistic bill in such circumstances becomes out of proportion with the contribution it makes to maintenance efficiency and it was on this score that efforts were started to seek out and reduce the main factors making up this problem.

A preliminary investigation into the actual nature of the stores holdings had suggested that whilst there was room for rationalization in almost every field, it seemed to be most marked in the electronics ranges, due allowance being made for the greater complexity of their characteristics. For example, out of the actual *variety* of items being carried for maintenance purposes in a small ship of frigate size, the following quite unrelated samples were typical:

Nuts, bolts and washers	376 varieties
Nails	62 ,,
Ball bearings	64 ,,
Spanners	126 ,,
Electric lamp bulbs	164 ,,
Radio capacitors and resistors . .	2558 ,,

When the quantity aspect was also taken into account it was seen that electronic spares, many of which were essentially insurance spares, represented more than half the overall stores accounting. It was therefore reasonable that the supply organization should approach the technical users for a detailed review of these ranges to see if anything could be done to simplify the holdings.

The need for doing this had been clear to technical user officers at the working level for some years and it was clearly in their interest to tackle this problem if only for its value in simplifying the maintenance task itself.

3. Reviewing the Material

A detailed review, from the technical angle, of the spares held for maintenance, together with a statistical survey of the spares actually being used was approved to be undertaken on a departmental basis, that is to say on a basis embracing the components and spares used for all electronic equipments, not only wireless and radar equipments, and regardless of from whence they had been procured, i.e. Admiralty designs, War Office, Air Ministry, Lease-Lend, Mutual Defence Aid Programme, and proprietary purchases. It was essential to work on this basis as preliminary study of the component usage in a cross section of equipment had shown that it would be ineffective to rationalize only those spares specified for the more orthodox radio equipments—the main difficulty in fact was with the proprietary and specialized equipments fitted in comparatively small numbers yet nevertheless requiring full logistic support. Expressed in terms of circuits, it was not the designer who had used the "100 K" resistor who posed the supply problem but the designer who found it necessary to use "95 K" instead.

This spares review amounted to a detailed re-examination of the characteristics of the components required to be replaced in the course of repairs and maintenance, examination of what information was then available on the rates (per operational year) at which components were likely to need replacement, and a re-appraisement of the capacity of maintenance staff for extemporary repair on board ship.

Very little data on the true rates of component failures were found to exist. Examination of the records of actual stores transactions showed them to be unsuitable for the estimation of maximum failure rates since they included components usage for a variety of purposes other than actual repairs, such as alterations and additions to equipment, minor modifications, tests and trials, and the topping up of ready-use stocks held by maintenance activities. What was needed to be known was the rate at which maintenance staff were consuming spares to make good actual failures at sea, in order to arrive at realistic maximum allowances. Arrangements were therefore made for maintenance staff to render a monthly return listing all components, including valves and cathode-ray tubes, used to replace failed items. This scheme would run parallel to the technical investigation into the variety of types of spares, it being hoped that sufficient usage data would be analysed towards the end of the exercise to enable reduced numbers of selected spares to be apportioned on a realistic scale. Machine analysis was used to sift the bulk data, so as to highlight those aspects worth closer examination from the technical angle.

Regarding valves and cathode-ray tubes, it was clearly impossible to effect an early reduction in the variety of types, mainly owing to the work involved in retrospective changes and this has only been gradually achieved as part of a continuing post-design programme. Duplications of the "Brown Paper Kraft—Kraft Paper Brown" type were however eliminated and the quantitative aspect was closely examined in the light of the usage data, valuable storage space being freed as a result.

A limited stock review was also undertaken at this time, the unearthing of such items as a batch of "0·5 jar condensers" being amusing if entirely live examples of the tendency for redundant stock to stay put owing to the metaphorical (and physical) difficulty of "getting to the back of the shelf".

4. Component Reliability

Much useful information on reliability trends was contained in the spares usage data. This has not so far been analysed exhaustively and it will be possible here to touch only on those aspects which were needed for the purpose of the present exercise. It can be stated however that the financial savings which can be achieved by realistic provisioning against known maximum rates of usage can be considerable and the method is most appropriate where a sufficiently accurate return can be obtained without going to special efforts to procure it. In the Naval case, the existence of a well-developed technical reporting organization, with adequate engineer supervision down to small ship level, enabled this further reporting to be taken on with some confidence that it would reflect the true rates of failures under operational conditions.

Some early analyses of a general nature served to confirm on sea experience the findings of other authorities concerned with component reliability, and to highlight the generally unsatisfactory behaviour of many components still current at the time of the exercise. For example, of the total of fixed capacitors reported as being used for maintenance, 40% were electrolytics of one kind or another. Bearing in mind that electrolytics, as a class represented only a small fraction of the total capacitor usage in equipments this represented a very high incidence of failure. The most troublesome types accordingly came in for technical examination and subsequent replacement by more reliable types. Component failure rates of the order of 2% per annum of the numbers exposed to risk were seen to be quite unacceptable in future large weapon systems of the "series" type, where the component population might number tens of thousands. Failure rates of under one hundredth of this figure are looked for to-day.

Analysis of usage data also served to pinpoint whole units of equipment which were responsible for an undue maintenance load. In the case of one Display Outfit having a component population of eighty, ships' staffs had fitted into 480 outfits some 1300 replacement parts in six months, excluding valves. In addition to the man-hours involved, this represented an operational breakdown per ship once every ten days due to random component failures alone.

The random nature of the spares usage was of particular interest from the logistic viewpoint. Many hundreds of items were reported as having been used only once or twice each in the whole Fleet over one year. At the other end of the scale less than ten items had each been used more than 100 times in a year, excluding valves, lamps and fuses. The opinion was formed, and is still held, that if all equipment could be so designed as to eliminate *repetitive* failures caused by a definite manufacturing fault or circuit error, the resulting component failures would be :

(a) negligibly small, as a percentage of the numbers fitted, and

(b) quite random over the range of descriptions used.

The extent to which (a) is being achieved is a matter of concern to designer and user alike. Having achieved it, one is left with the random pattern of chance failures for which the spares insurance needs to be as *rational* as possible.

5. Component Variety

Consider the case of a simple composition resistor of value say 100 kilohms and power rating $\frac{1}{2}$ watt. Taken by itself, the item is so tiny and so inexpensive in direct cost that its existence is merely taken for granted. Yet in the aggregate it can cost many times its material value in terms of paperwork and man-hours in general. It has to be developed, drawn, specified, controlled in manufacture, tested, packed and transported, meanwhile being accounted for at each stage of its progress. It must not sustain damage due to mechanical vibration, it must not overheat in operation nor crack if subjected to extreme cold; it must not absorb moisture nor support mould growth, and it must not only satisfy these requirements when it is first manufactured but continue to do so when removed from its envelope in the jungle or in the Arctic regions perhaps five years later.

Of the range of items under the common description "Resistors, Composition, 100 K" there were to be found in stock the following principal varieties:

Pattern A	Grade 1,	insulated,	1%	tolerance
,, B	,,	,,	2%	,,
,, C	,,	,,	5%	,,
,, D	,,	non-insulated,	1%	tolerance
,, E	,,	,,	2%	,,
,, F	,,	,,	5%	,,
,, G	Grade 2,	insulated,	5%	tolerance
,, H	,,	,,	10%	,,
,, I	,,	,,	20%	,,
,, J	,,	non-insulated,	5%	tolerance
,, K	,,	,,	10%	,,
,, L	,,	,,	20%	,,

(12 basic patterns, permuting three selection tolerances and two styles on one ohmic value)

The above basic technical variants were held in a further variety of patterns according to their sources of supply as follows:

(1) Joint-Service Standard Items (for modern equipments)

(2) Admiralty Pattern Items (for older equipments)

(3) War Office Patterns (as spares for Army equipments adopted for Naval use)

(4) Air Ministry Items (as spares for Royal Air Force equipments adopted for Naval use)

(5) American Items (as spares for equipments supplied under the Mutual Defence Aid Programme, and for wartime "lease-lend" equipments still in R.N. use)

(6) Proprietary Items (as spares for equipments of commercial design).

There were in fact some 135 patterns of "100 K" composition resistors in use for Naval maintenance at the time of the exercise, many of which were fully interchangeable for purposes of field repairs. The difficulty of course was not so much the existence of so many patterns but in the fact that nobody knew which were acceptable alternatives. Added to the common standard ohmic values and power ratings were patterns whose style and advertised characteristics did not correspond to any regular series and it was thus not surprising to find that the total range of composition resistors numbered over 8000 types. What was perhaps more important, the *potential* range was clearly many times this figure, if nothing was done to limit the intake of similar items under dissimilar names. Proportionate figures applied with other common spares such as capacitors, potentiometers, valveholders etc., the total range of items coming under review being approximately 14 000.

6. The Impact in Ships

Of this total variety of spares, the proportion needed to be carried in the individual ship naturally varied according to the equipments fitted. In a large ship a fair proportion of the overall range was represented in varying quantities; in small ships there were reduced holdings, but not in direct proportion because, although the total amount of electronic equipment was much less, the variety of spares was still large, as the following examples show:

AIRCRAFT CARRIER

Spares Carried	*Variety*	*Quantity*
Capacitors	832	4938
Resistors	1002	8740
Miscellaneous	1456	7352
	3290	21 030

FRIGATE

Spares Carried	*Variety*	*Quantity*
Capacitors	475	1270
Resistors	786	2289
Miscellaneous	739	1932
	2000	5491

It will be seen that the variety of spares remained large even in the small ship. If she carried only one spare of each item, which in many cases would be inadequate, she would still need to carry 2000 stock items, excluding "consumable" items such as valves, lamps and fuses. This followed from the very nature of the component usage in the equipments themselves—it seemed that as soon as two or three fairly complex equipments were installed in the ship virtually the full range of component values, ratings and tolerances had to appear in the maintenance outfit.

7. Spares as an Insurance

Most of these spares were essentially insurance spares, not normally expected to fail but nevertheless essential because they could not, in the main, be extemporized on board ship or at some remote Base if and when they did fail. This insurance aspect was brought out most markedly when the spares being carried in representative ships were compared with the components which the usage data on replacements showed to have actually failed over a typical six months period:

AIRCRAFT CARRIER

Type of Spare	*Quantity Carried*	*Used in Six months*
Capacitors	4938	45
Resistors	8740	74
Miscellaneous	7352	82
	21 030	201 (≯0·1%)

FRIGATE

Type of Spare	*Quantity Carried*	*Used in Six months*
Capacitors	1270	9
Resistors	2289	12
Miscellaneous	1932	20
	5491	41 (≯0·75%)

It appeared that on a quantitative basis alone, very large reductions could be made. Unfortunately any reduction based on pure quantity grounds was dangerous because of the variety aspect just discussed, and it was clear that a workable simplification could only come out of a technical appraisal on the number of different *kinds* of spares to be carried. Furthermore, any reduced ranges of spares must not only satisfy the circuit requirements in the existing equipments but must continue to do so as far as possible in future equipments for there to be any long-term advantage.

A degree of adaptation was acceptable, for example the use of series/parallel arrangements to replace non-standard values, the use of wire-ended components in lieu of similar items with tag ends, and the use of adapting clamps to enable selected standard items to replace items of odd sizes and shapes. The degree of adaptation permissible needed careful consideration however, or the interchangeability of equipment after repair would have been adversely affected and the maintenance staffs called upon to effect substitutions requiring either too many man-hours to complete or requiring more information than was available in their published maintenance instructions.

8. Examples of Duplication

With these points in mind the main ranges of common spares were examined in detail using their specifications and, where necessary, production samples and examination of their circuit applications in actual equipment. Some anomalies were revealed which it is thought would not occur in present-day equipment: the association, in the same circuit network, of close-tolerance high-stability capacitors together with low-stability composition resistors subject to substantial random drift; the requirement, in an equipment in quantity production, for 498 pF capacitors, obtained by expensive selection from nominal 500 pF capacitors; the insistence on the use of a nominal 14 μF (as opposed to 16 μF) electrolyic capacitor as one element of a smoothing filter, the production tolerances of the components being $+100$, -25%; the addition of an extra colour mark to components on passing from the component manufacturer to the equipment manufacturer, the components thereby assuming an apparent new identity; and so on. On the other hand some interesting examples of very close liaison between designer and maintainer were brought to notice. From the "Table of Replaceable Parts" for a telephony transmitter, in this instance of transatlantic origin, it was seen that *the same* capacitor had been successfully applied in twelve circuit positions in the equipment and furthermore the designer had seen fit to add after the specification for the component the words "or any equivalent capacitor within the range 6000 to 10 000 pF." There are of course many circuit positions where no laxity in the choice of replacements can be permitted but it is a useful gesture to indicate alternatives where they are appropriate.

8.1. *Capacitor Spares*

Figure 1 shows a range of rectangular-cased paper-capacitors of the foil type. All are of nominal capacitance value 1 μF, with an effective voltage rating not exceeding 600 V d.c. at 70° C ambient temperature. There are three main structural differences, namely upright with feet, inverted with feet and those without feet, intended for clamp mounting either way up. Other minor physical differences are in the type of terminations, the terminal bushing arrangements, the method of sealing and the quality of finish and markings. Regarding the electrical

Fig. 1. Rectangular metal cased paper foil capacitors–all 1 μF.

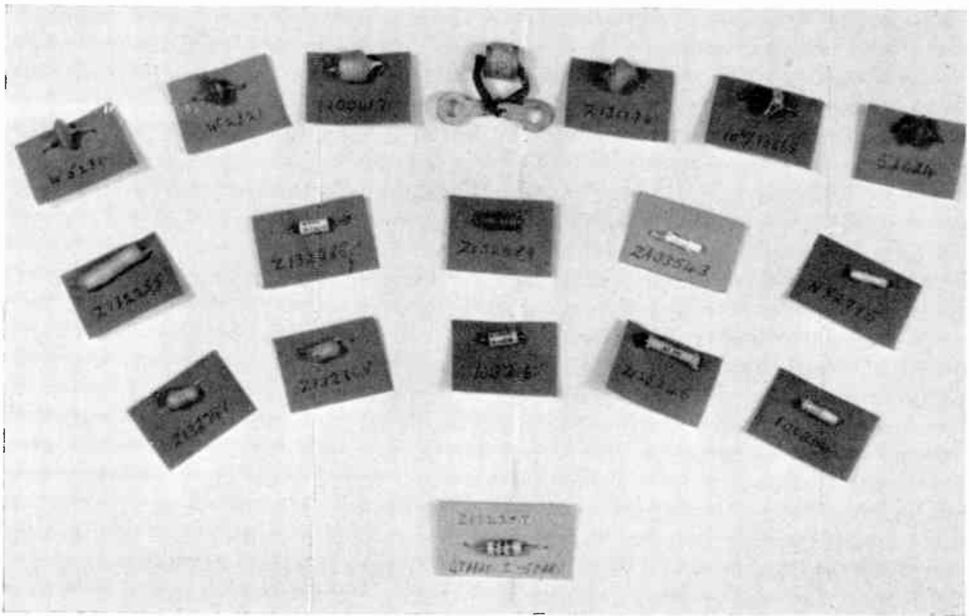


Fig. 2. Ceramic capacitors–all 47 pF.

characteristics, no item was found to be superior in respect of working voltage, power factor and current carrying capacity, to the Selected Item shown below, and this could be chosen in a selection tolerance and with a long-term stability at least equal to the best of the non-preferred patterns above. We have, in fact, for maintenance purposes one item doing the job of thirty-seven others in this commonly used capacitance value. Proportionate reductions applied in other values in the range. With the aid of its claw-type clamps the Selected Item replaces the others in either the upright or inverted position, any minor adaptations necessary being well within the capabilities of maintenance staff using normal sound engineering practice. In a small number of instances in very old equipments it was necessary to verify the substitution in the actual circuit position; in most cases substitution was direct. This again, bears testimony to the technical work of the Radio Components Standardization Committees concerned in providing the short lists in the first instance, from which these Selected Spares were taken.

Figure 2 shows a variety of styles amongst small ceramic capacitors of the so-called cup, hat, disc and bead types, in this example in the 47 pF value. Manufacturing techniques for ceramic capacitors have been less stabilized than other capacitor types and there has been a wide range of physical styles and finishes. These are "non-temperature compensating types" and it was found that by selecting a preferred component having a temperature coefficient of -750 parts in 10^6 per deg C in the closest tolerance readily available, the permitted temperature coefficients of a much larger number of non-standard patterns could be covered. The permitted temperature coefficients of the items in the top row were by specification allowed to be to the limits of -830 parts and $+120$ parts, so that the Joint-Service standard item must necessarily satisfy the circuit conditions. The replacement of some of the older styles is good for the equipment in fact, as the behaviour of some of these items under arduous Service conditions was inclined to be erratic. This observation is true of other types of the older components but probably more so in the case of the ceramic capacitors.

Although the preferred spare is of a different shape to some of the others, its effective overall dimensions are not greater. In the case of the cup and bead types the space required to accommodate the capacitor comprises the body length plus lead length, on which there is a practical limitation imposed by the soldering-in process. These particular substitutions were not employed below a limit of capacitance value at which the changes in stray capacitance and inductance were significant and in some applications special spares continue to be carried for particular circuit positions. The number of occasions on which these very minor variations are significant in field repair work are very few and far between however.

Figure 3 shows a variety of paper tubular capacitors of the foil and metallized foil types, all of $0{\cdot}1$ μF value, in d.c. voltage ratings up to 350 V at 70° C. The Selected Spare is a plain foil type having an r.m.s. current rating at least equal to those of the remaining patterns, and a stability of capacitance also at least equal. Excepting certain special types made for video applications the metallized paper capacitors of small capacitance value had no particular advantages over the best foil types except for cheapness and a marginal difference in size and there was generally no purpose in carrying them as spares in ships. It is worth noting, apropos of voltage rating, that the marking on the capacitor was not necessarily indicative of its performance *vis-à-vis* the Selected Item. For example, some items specified and marked "500 V d.c. test" had an effective working voltage at 70° C of only 200 volts and it is doubtful if they would in fact have performed at this temperature without serious losses. It was seen that many of this type of capacitor were liable to failure owing to ingress of moisture through imperfect sealing, making it even more desirable to replace it with the preferred spare and in some cases whole batches of these capacitors were replaced retrospectively in older equipments thus removing a prevalent source of breakdown.

The three items in the upper row are examples of "odd men out" in this style and capacitance range. From the maintenance repair aspect it is better that complete "tidy" ranges are used, with a definite turnover of style at some arbitrary capacitance value. If it is not desired to use the tubular style suspended in wiring it can be secured to the chassis with a suitable clamp.

Outside the common-range components replaceable by Selected Standards were a variety of special items some of which were by virtue of their specifications quite genuinely irreplaceable by anything other than the specified component. Transmitting type mica plate capacitors are an example being usually designed for a particular circuit application for which the precise operating cycle, frequency, peak voltage and waveform must be known. On the other hand some of the "spares peculiar" were found to be "special" only by virtue of some structural feature invoked either by the equipment designer or the component manufacturer, which made them very difficult to deal with from the replacement angle. Figure 4 shows some examples, mainly of an obsolescent nature, but useful to illustrate what has happened and could easily be perpetuated.

To give an assembly of ordinary components a special identity, therefore needing to be provisioned as a special spare for the equipment, is unnecessary, since the individual items are replaceable by the maintainer from his outfit of standard spares, assuming of course that standard styles have been used in the first place. However two tubular paper capacitors are seen to be assembled into a wire cradle and secured with rubber bands, the whole becoming a special component spare. In practice the only items likely to fail in service are the electronic components or their connections, and these are readily replaceable from standard component spares.

The use of the capacitor blocks is not preferred, as the probability is that only one section is likely to fail at any one time and it means carrying "spares peculiar" for each application. Replacement is usually a lengthy operation, involving disturbance of wiring harness, and there is often insufficient spare

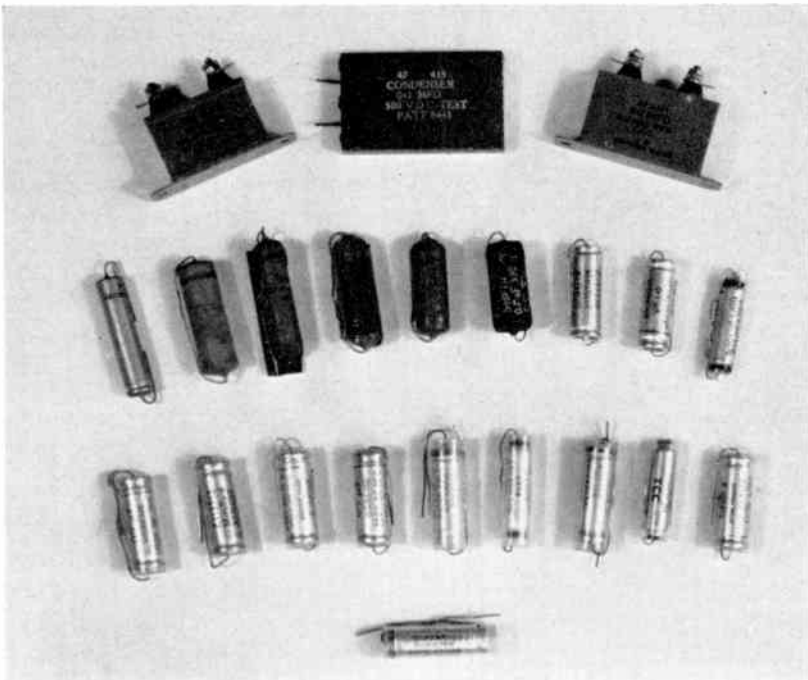


Fig. 3. Paper tubular capacitors–all 0·1 μF.

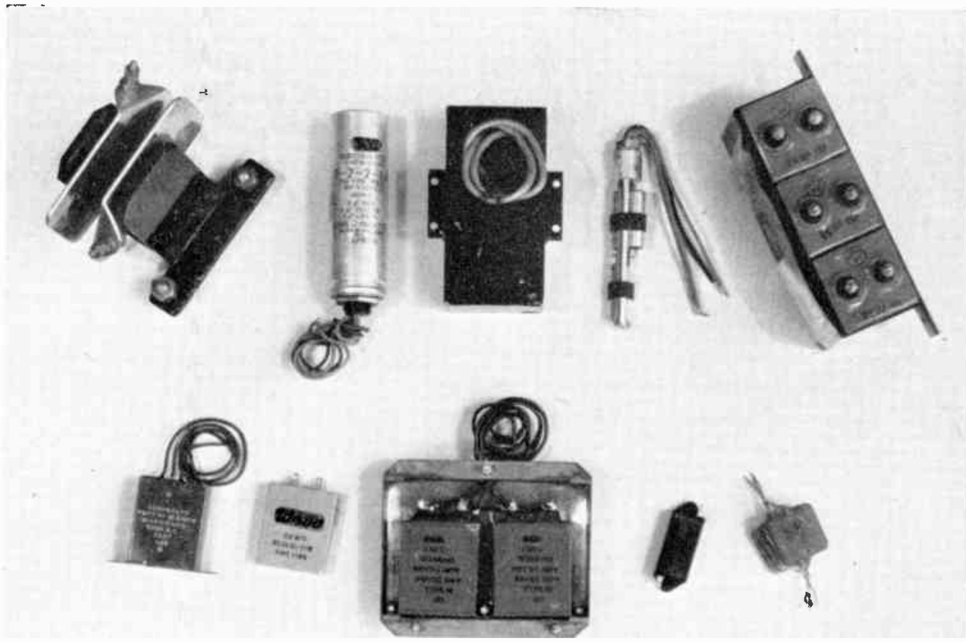


Fig. 4. "Spares Peculiar".

room to replace the failed section tidily with a standard spare as a temporary expedient.

The flat metal-cased capacitor is one designed to be secured to the carcase of a rotating machine for interference-suppression purposes. It would be better in such cases if the requirement was made up by a parallel arrangement of standard tubular capacitors.

It is also undesirable to package standard combinations of R and C (the example shows a component of "$0{\cdot}5\,\mu F + 50\ \Omega$") unless there are other very sound design reasons for doing it, since it means a special spare and also hinders fault diagnosis. Where whole circuits are assembled in microminiature technique and essential to be replaced *as a unit* it is of course a different matter.

The air-dielectric capacitor in the top left corner of the illustration is of course a genuine "spare peculiar" but one not normally expected to fail!

The making up of a non-standard capacitance values by parallel stacking of standard values is a useful practice provided that the maintenance documentation specifies what are the standard items and does not disguise them under a special name.

8.2. *Resistor Spares*

In the reduction of resistor spares, it was apparent that certain direct methods could be employed, based mainly on paper specifications, and without the need for reference back to particular circuit applications. What was needed, within each particular technical description, was a selected item which by virtue of its specification could be guaranteed to be "at least as good as" any other in all significant respects and not be larger in any dimension. By extracting close tolerance items in preferred styles from amongst the Joint-Service Standards there was built up a "short list" of "Selected Spares" for ship use, to replace the much wider variety then being carried. In practice, the $\pm$ 2% selection tolerance was chosen as the preferred spare in the Grade I series and the $\pm$ 10% in the Grade 2 series.

Where dimensional tolerances and power ratings permitted, reductions were effected in the actual styles of resistors needed to be kept as spares; in some cases insulated versions were found, in certain ohmic ranges, to be not significantly larger than non-insulated versions for the same power rating and proof voltage between terminations. It was appreciated that minute variations in maximum specified dimensions, which were quite acceptable for field repair purposes, might not be practicable on a manufacturing basis; it has nevertheless proved entirely practicable to implement many of these substitutions in production and in development work.

From the maintenance spares aspect, the "2%" resistor is clearly a satisfactory replacement for $\pm$ 5% and $\pm$ 10% samples in the same general style and for the purpose of field repairs is an acceptable substitute for the $\pm$ 1% resistor. With further development towards closer tolerances and (more significant) closer orders of long-term stability, it becomes necessary to revise the "short lists" of preferred spares, but the principle remains the same.

9. Financial Advantage

The financial aspect of the matter is interesting and largely self-evident. The holding of x in number high grade components at even two or three times the individual cost of the equivalent low grade components give "better than standard" spares insurance at a much lower premium than is represented by holding all the items originally specified in production. Furthermore the use of Joint-Service standard components, subject to rigorous specification and quality control, has a salutary effect on the actual reliability of the equipment after repair. This is a most important indirect advantage of using selected spares, since nothing is more unsatisfactory operationally, nor discouraging to the maintainer, than to have equipment fail successively for the same reason.

10. Substitution and Cataloguing

Table 1 is an extract from the documentation coming out of the spares exercise and shows how the information on substitutions was presented to the maintainer. The description at the top of the page fits the Selected Spare, in this example ½ watt Grade 2 composition resistors. The Selected Ship's Spare is quoted for each standard ohmic value, together with all the "non-preferred" patterns known to be extant. Those familiar with cataloguing will recognize the various sources of supply. The information, prepared in the form of a "Substitution Guide" was cross-referenced by pattern number and technical description, thus the store-keeper who deals solely in pattern numbers is helped, whilst the maintainer (who is really looking for a technical description) can see what he wants. The value of such a book to the maintainer is of course very substantial, particularly during the inevitable rundown period involved in reducing from the large variety of patterns down to the selected outfit.

Not all of the substitutions were of course justified in equipment manufacture, a "Preferred List" being used for development and production which allows much wider choice than the "Short List" used for ship's maintenance.

As an example of the overall reductions achieved the initial exercise reduced some 6290 patterns of fixed resistor to 1490 patterns for spares purposes, and some 2420 fixed capacitors to 277 patterns. Similar reductions applied with other common spares such as potentiometers and valveholders. The reduction in resistor types was limited owing to the existence of the basic "Grade 1, Grade 2" requirement. It was considered unfortunate that development had not yet achieved a single type of low-power resistor combining the qualities of close tolerance, good long-term stability, low noise and self-inductance.

The Naval "Substitution Guide" continues to be revised from time to time in the light of new component developments, amendments being carried out for preference when complete ranges can be superseded. In this connection it is desired to make a plea to those concerned with component development to consider, when engineering new components, the versatility of the new style for physically replacing those it renders obsolete in terms of electrical characteristics. Generally speaking, improvement in the chemistry and metallurgy of components should and does result in equal or superior characteristics in rather smaller space. It seems however on reviewing the past history of component development in this considerable detail that in many cases the new item has turned out just that small amount different in style that it cannot be used to directly replace anything else.

The natural consequence of this exercise on spares was a "new look" at component usage at the equipment design stage since it is during development that the maintenance pattern is set. Once a non-preferred component has been used at the "breadboard" stage it can become extremely difficult to change it. The Admiralty method is to make it easy for laboratory staff to obtain the preferred components and difficult inadvertently to make use of the non-preferred. What comes readily to hand and is clearly specified in easy-to-use catalogues is likely to receive first consideration.

In this connection the current instructions taken from the appropriate Admiralty Code of Practice are considered worth quoting as an example of the importance attached to component usage in its impact on equipment reliability.

Table 1

Extract from "Substitution Guide"

Description Applicable to Ship's Spare: Resistor, Fixed, Grade 2, Composition, Insulated, ½ W @ 70°C Tolerance ±5%		G
SHIP'S SPARE	ITEMS REPLACEABLE BY SHIP'S SPARE	VALUE in Ohms
Z223131	Z223134, W8265	560K
Z223140	Z223143, W8266, 100218, Z223146, W8808	680K
Z223152	52323, 10W/8932, Z223155, W8267	820K
Z223161	W4798, Z223164, W2644, ZA3833, ZA19265, 10W/11384, Z223167, W3352A, 10W/6962	1 M
Z223173	Z223174, ZA15410, Z223176, W8810, 10W/6909, Z223177, W7241, Z223320, Z213340	1·2M
Z223182	Z223183, 51995, Z223185, W8268, Z223188, W8812, Z223186, W7242, Z223189, W8575, Z223321, Z213341	1·5M
Z223194	Z223195, 51937, Z223197, W5230, 10W/549, 10W/7166, Z223198, W7243, Z223322, Z213342	1·8M
Z223203	Z223204, 51999, 10W/6415, Z223206, W2260A, ZA12826, 10W/553, Z223209, W3074A, 83080, 10W/996, Z223207, W4606, 10W/1592, Z223210, W8576, Z223323, Z213343, 10W/7669	2·2M
Z223215	Z223216, W7917, Z223218, W8813, Z223219, W7244, Z223324, Z213344	2·7M
Z223224	Z223225, 52001, Z223227, W8814, Z223230, W8815, 10W/1891, Z223228, W7245, Z223231, W8577, 10W/9593, Z223325, Z213345	3·3M
Z223236	Z223237, 52003, Z223239, W5722, Z223240, W9041, Z223326, Z213346	3·9M
Z223245	Z223246, 52005, Z223248, W5646, 10W/9515, Z223251, W8599, Z223249, W7246, Z223252, W8578, 10703D, Z223327, Z213347, 10W/1722	4·7M
Z223257	10W/6556, Z223250, 52007, Z223260, W8269, Z223261, W7247, Z223328, Z213348, 10W/8093	5·6M
Z223266	Z223267, 52009, Z223269, W8817, Z223272, W8818, Z223270, W7248, Z223273, W8579, 10W/8923, Z223329, Z213349	6·8M
Z223278	Z223279, Z223281, W8620, Z223282, W7249, Z223330, Z213350	8·2M
Z223287	Z223288, 52013, Z223290, W3075, Z223293, W8600, Z223291, W4605, Z223294, W8580, Z223331, 10W/1190, Z213351	10M

"(a) In view of the fact that Naval equipment is required to operate continuously for long periods in conditions of high relative humidity and/or high temperature, it is essential that only good qualtity components shall be used and that they be selected with due regard to selection tolerance and drift.

"(b) The normal standard of component shall conform to R.C.S. 11, Category H2–40/70, but this does not preclude the use of the higher category H1, 40–100 components where these are the normal standards for the particular range or where working conditions justify the higher category e.g. exposed equipment.

"(c) No component shall be loaded beyond the rating given in the relevant component specification and in general derating shall be employed in order to enhance reliability.

"(d) Electronic components shall be selected from the range of Joint-Service approved standards given in DEF Specifications and Lists and in R.C.S.C. documents. Preferred values of N.A.T.O. standard styles shall be used where possible. Series/parallel combinations of preferred values should be considered where non-standard values of resistance and capacitance are required.

"(e) When a Joint-Service Approved Standard is not available reference should be made to lists of selected Admiralty Pattern articles and use made of any that are suitable.

"(f) All components intended to be embodied in the *laboratory model* shall be listed and referred for approval."

A final word on the subject of N.A.T.O. cataloguing is appropriate. The N.A.T.O. system classifies all warlike stores into some 550 Class/Groups under 13-digit numbers, signifying the nature of the article (e.g. electronic component), the general description (e.g. capacitor, resistor etc.), the country of origin, and a sequential catalogue number which describes the item uniquely. This enables other Service authorities to determine if the item about to be introduced has been catalogued already and satisfy themselves that the characteristics are acceptable and they can safely use the existing catalogue number. The distribution of the cataloguing slips is very well organized and copies go to every Service cataloguing agency in the United Kingdom. At headquarters there is a screening process to stop any inadvertent duplications. This should go a long way towards preventing actual duplications and unnecessary minor variations in Service practice in future.

As a suggestion, it would seem desirable that where an Internationally-used number is in existence for a specific article individual organizations should adopt it.

11. Conclusion

It will have been seen from this paper what led to a "new look" from the Naval angle, at component development, manufacture and use. It has been said that standardization is the enemy of progress but in many ways this need not necessarily be so, provided that this all-important aspect of the *replacement* value of the new component is taken into account as well as its exciting new characteristics for the designer.

12. Acknowledgments

I would like to thank Mr. N. G. Sykes, and Mr. F. E. Parr, for suggestions on this paper, and also Captain Lucien Hix, Past Chairman of the South Western Section, for suggesting it as a subject for this address.

Finally, I have to state that whilst the factual content of the paper is published with the permission of the Admiralty, any opinions expressed are my own.

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Overall System Requirements for Low Noise Performance

By

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Summary: The limit of system performance with low-noise amplifiers will probably not be receiver noise, but rather the ambient noise background against which the signal is sought and the noise which is generated by the aerial, transmission lines or other components of the complete system. For a ground based system receiving signals from a satellite, considerations of galactic noise and atmospheric attenuation lead to a choice of wavelength in the centimetric band, as the optimum with regard to source noise. The optimum frequency for satellite-to-satellite communication would be much higher. The practical limits which may be achieved in the various components of a microwave system are discussed and the overall performance is assessed.

1. Introduction

The smallest signal power that can be detected depends upon the noise output of the signal source and on the additional noise contributed by the receiving system. The concept of noise factor, F, implies a source temperature of 290° K, with the associated source noise $kT\Delta f$ equivalent to 4×10^{-15} watts per Mc/s bandwidth. However, microwave receiving systems employed to detect signals incident from directions of reasonable elevation are used with source temperatures much lower than this. Therefore the noise factor criterion is no longer the best measure of comparison between the performance of various systems, and the concept of input noise temperature of a receiver will be used. The input noise temperature T_i of a single channel receiver is equal to the increase in source temperature required to double the output of the receiver when originally connected to a noise-free source. It follows that the two concepts are related by

$$T_i = (F-1) \times 290^\circ \text{ K} \qquad \ldots\ldots(1)$$

The equivalence of thermal radiation and electrical Johnson noise is well established, as is also the relation between the emissive and absorptive properties of a medium. Thus any absorptive medium at a temperature above 0° K, between the signal source and the receiver, will introduce additional noise and degrade the system performance.

The contributing factors relevant to low noise system performance are:

(1) source noise,

(2) the attenuating medium between the source and the aerial,

(3) the efficiency of the aerial,

(4) the attenuating transmission lines between the aerial and the receiver,

(5) the input noise temperature of the receiver,

and these, which will be considered in turn, are shown in Fig. 1.

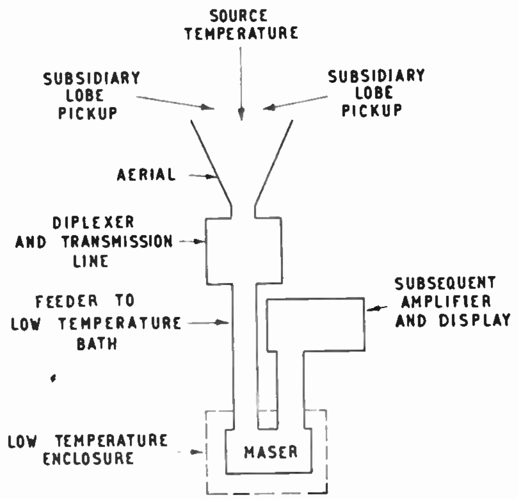

Fig. 1. Thermal noise sources in a receiving system.

2. Source Noise

For any receiving system, either on the ground or on a space vehicle, whose aerial is directed away from the earth the source temperature is markedly dependent on the frequency used. This galactic noise is to some extent dependent on the direction considered, but can be taken as having a value of about 1000° K at 200 Mc/s, falling to 5° K at 2000 Mc/s. Thus a

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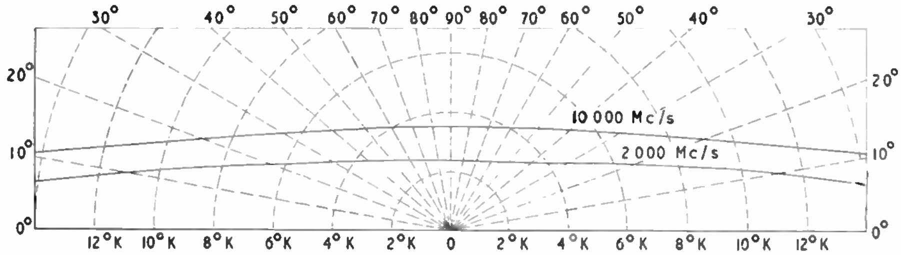

Fig. 2. Polar plot of sky temperature for frequencies of 2000 Mc/s and 10 000 Mc/s.

communication system intended to have really low noise performance should operate in the microwave band, i.e. at frequencies above 2000 Mc/s.

3. The Sky Temperature

When radiation, appropriate to a temperature T_1° K, passes through an absorptive medium of power transmission coefficient x the attenuated noise power is $xkT_1\Delta f$. In addition to this, the medium will emit noise appropriate to its temperature T_2 and its emissive coefficient $(1-x)$,

i.e. to an extent $(1-x)kT_2\Delta f$.

The output temperature of the medium is thus

$$T_0 = [xT_1+(1-x)T_2]^\circ \text{ K} \qquad \ldots\ldots\ldots(2)$$

The atmosphere is such an attenuating medium, because of its oxygen and water vapour content. Thus, whilst the sky temperature in outer space is prescribed by the source noise discussed in Section 2, the sky temperature for a ground-based system is more complicated. For an aerial pointing at the zenith the total vertical attenuation at 22 000 Mc/s is about 0·6 dB, corresponding to $x = 0{\cdot}87$. This attenuation is almost entirely due to water vapour, which has a resonance peak at this frequency. Still higher attenuations can occur in the millimetre waveband, particularly at about 60 000 Mc/s where there is an oxygen resonance. The total vertical attenuation decreases as the frequency decreases, being less than 0·1 dB at 10 000 Mc/s. Most of the water vapour occurs at fairly low altitude, i.e. less than 15 000 feet, and thus is at a temperature of near to 270° K. Therefore the noise contribution due to water vapour will vary from about $0{\cdot}13\times 270 = 35$° K at 22 000 Mc/s to about 1° K at 10 000 Mc/s, for a vertically pointing aerial. In addition to this there is a contribution due to the oxygen content which is fairly constant, between 2° and 3° K, for frequencies from 1000 Mc/s to 20 000 Mc/s.

The length of the absorbing path through the atmosphere will increase as the aerial moves from the zenith, being approximately proportional to cosec γ where γ is the angle of elevation. However γ has to be quite small for the effect to be significant and between 2000 Mc/s and 10 000 Mc/s the total sky temperature, including the atmospheric emission and the small galactic effect, is below 20° K for angles of elevation above 10 deg. These effects have been discussed by many authors the most recent contribution being due to Hogg.[1] Figure 2 shows a polar plot of sky temperature for the extreme frequencies of the above band.

4. The Aerial Temperature

If the aerial were perfect and had only one beam, pointing only in the direction of the signal, the aerial temperature would be the same as the sky temperature, assuming no resistive loss in the aerial. In practice, in addition to the main beam there are forward-looking side-lobes and, more serious from the noise viewpoint, also back lobes or spillover. As the gain and sky temperature, T_s, are both functions of angle, the aerial temperature T_A is given by integrating with respect to solid angle:

$$T_A = \frac{\int G(\theta\phi)T_s(\theta\phi)\mathrm{d}\Omega}{\int G(\theta\phi)\mathrm{d}\Omega} = \frac{\int G(\theta\phi)T_s(\theta\phi)\mathrm{d}\Omega}{4\pi} \qquad \ldots\ldots(3)$$

This is difficult to evaluate from polar diagram measurements, because it demands measurements of perhaps 100 dB down on the power in the main beam. An experimental determination involves the use of either a very low noise amplifier or radiometric techniques.

A simplified numerical example illustrates the low side-lobe level required to achieve a low aerial temperature. If we consider a paraboloid illuminated by a horn at its focus, the illumination is usually tapered to about 10 dB at the edge of the paraboloid. This results in about 20% of the feed power falling on the ground behind a skyward looking aerial. By reciprocity this means that about 20% of the ground temperature is fed into the aerial, resulting in an aerial temperature of about 60° K. This is much too high for a low-noise system; even a sacrifice of aperture efficiency, by arranging for all the main lobe of the feed horn to be intercepted by the paraboloid, is only a partial solution, as the side-lobes of the feed horn will still fall on the ground. It may be possible to constrain the energy between the horn

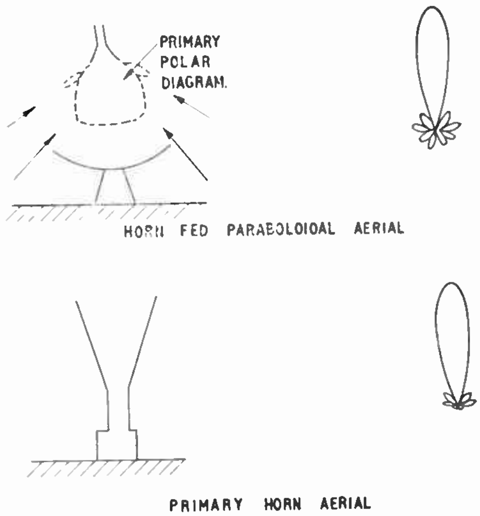

Fig. 3. Comparison between rear lobes of paraboloidal and horn aerials.

and the paraboloid, whilst still allowing the forward beam to be unimpaired, but a satisfactory solution to this problem has not appeared. In any event the aerial should be designed for best signal/noise performance and not maximum gain.

Consequently the best low-noise aerial at present is a large horn, which does not have this problem of large rear lobes caused by spillover, the two types of aerial being shown schematically in Fig. 3. To simplify the mathematics we will consider such an aerial directed at the zenith, with a main beam of solid angle 10^{-4} steradians ($\theta \simeq 0{\cdot}65^\circ$) and a gain, referred to an isotropic aerial, of 10^5, giving an aperture efficiency of 80%. The forward side-lobes will be assumed to have an effective mean gain of 0·4, referred to an isotropic aerial, and to receive energy from a mean sky temperature of 5° K, whilst the rear lobes have an effective mean gain of 10^{-2}, defined as before, and receive energy from a ground temperature of 300° K (Fig. 4). Using a summation rather than the integral form of eqn. (3), the aerial temperature, with the main beam directed towards a temperature T° K, is given by

$$\frac{10^5 \times T \times 10^{-4} + 0{\cdot}4 \times 5 \times 2\pi + 10^{-2} \times 300 \times 2\pi}{4\pi} = (0{\cdot}8T + 2{\cdot}5)^\circ \text{ K}$$

If we take T as 3° K the aerial temperature is about 5° K, which is a reasonable value. With the aerial at a small angle of elevation, such that the main beam does not intercept the ground, the aerial temperature is increased to

$$\frac{10^5 \times T \times 10^{-4} + 0{\cdot}4 \times 5 \times \pi + 0{\cdot}4 \times 300 \times \pi + \\ + 10^{-2} \times 300 \times \pi + 10^{-2} \times 5 \times \pi}{4\pi} = (0{\cdot}8T + 31{\cdot}3)^\circ \text{ K}$$

With T equal to 17° K this gives an aerial temperature of 45° K at an elevation of about 7 deg.

The main contribution to these aerial temperatures is the ground radiation at 300° K. This could be decreased by use of a reflecting screen, such as wire mesh (but the area which would have to be covered may be quite large) or by siting the aerial over the water, resulting in the rear lobes seeing a temperature much nearer to the cold sky.

Discrete sources, such as the sun, do not contribute a great deal to the aerial temperature, unless they fall within the main beam, because they subtend only a small solid angle. For example the effective increase in temperature due to the sun (subtending 0·5 deg, and at a representative temperature of 3×10^4 °K) is

$$\frac{3 \times 10^4 \times G'}{1{\cdot}65 \times 10^4 \times 4\pi}$$

where G' is the gain of the aerial in the direction of the sun, which even at the peak of a side-lobe of the above aerial, may only be about 10. Hence the sun will contribute less than 1·5° K.

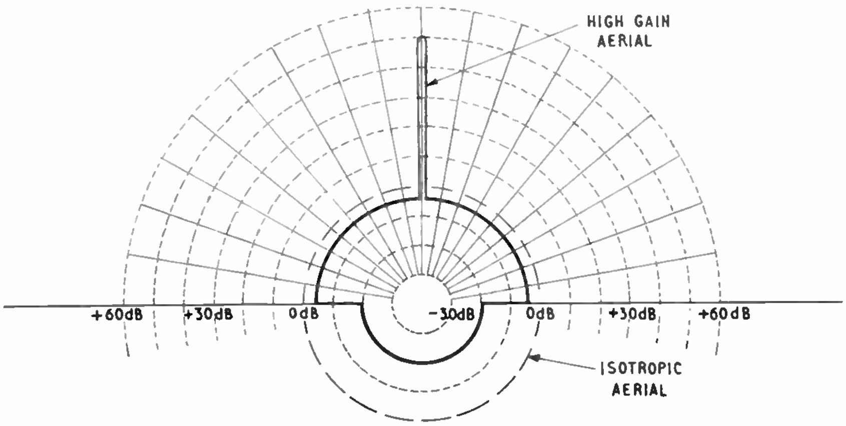

Fig. 4. Simplified directivity pattern of low-noise high-gain aerial.

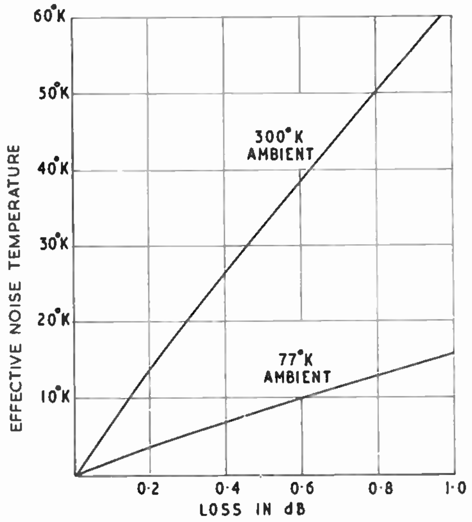

Fig. 5. Thermal emission as a function of insertion loss and ambient temperature.

Thus the aerial considered has the characteristics shown in Table 1:

Table 1

Beam angle	$\theta \simeq 0{\cdot}65°$, $\Omega = 10^{-4}$ steradians
Main beam gain	10^5
Aperture efficiency	80%
Side-lobe gain	<10 (>40 dB down on main beam)
Mean forward gain	0·4 (54 dB down on main beam)
Mean backward gain	10^{-2} (70 dB down on main beam)
Aerial temperature at zenith	5° K
Aerial temperature near horizon	45° K

5. Transmission Line Loss

This can be treated mathematically in a manner similar to that used for the attenuating atmosphere; for small losses at room temperature, each 0·1 dB of loss contributes about 6° K to the system temperature. It is essential therefore to mount the receiver at the focus of the paraboloid, or at the throat of a horn aerial, if at all possible. If any lossy component, such as a diplexer, has to be placed between the aerial and the receiver it may well be worth cooling this by liquid nitrogen, thus reducing the noise contribution by a factor of 4. Figure 5 shows the noise emission as a function of ambient temperature and insertion loss.

6. The Receiver Input Noise Temperature

It is doubtful whether a reliable parametric amplifier is available at present for the frequency range considered, i.e. 2000 to 10 000 Mc/s, which can give an input noise temperature much below 100° K. On the other hand a number of maser designs exist, in either a cavity or travelling-wave form, which operate satisfactorily at these frequencies.

The effective input temperature of a high gain travelling-wave maser, at its low temperature terminals, is

$$T_{\text{eff}} = \frac{\alpha_m\,|T_m| + \alpha_c T_c}{\alpha_m - \alpha_c}$$

where α_m and α_c are the incremental gain and attenuation apertaining to the sample and structure respectively and T_c is the structure temperature.[2] It should be noted that $|T_m|$, the magnitude of the spin temperature of the active material, may be several times lower than the ambient temperature. A similar expression for a reflection cavity maser is

$$T_{\text{eff}} = \frac{T_c}{|\beta_3| - 1} + \frac{|T_m|}{1 - \dfrac{1}{|\beta_3|}}$$

where β_3 is the ratio of the unloaded cavity Q to the magnetic Q of the sample. With good design $\alpha_m \gg \alpha_c$, or $|\beta_3| \gg 1$ and the effective input temperature is then equal to the spin temperature, which, for a helium temperature maser, will only be one or two degrees. It is possible that further extension of maser techniques may result in small values of $|T_m|$ even at higher operating temperatures, but, in any event, the development in the U.S.A. of small closed circuit helium liquefiers, which can be integrated into the maser design, will largely remove the practical disadvantage of helium temperature working.

In addition to the low temperature maser noise, there will be a contribution due to the feeds from the high to the low temperature terminals. Assuming a loss of 0·2 dB at a mean temperature of 100° K this contribution will be 4° K.

7. Overall System Performance

Considerations of attenuation through a clear atmosphere and galactic noise indicate that a low-noise system, for use in a communications role for example, should operate between 2000 Mc/s and 10 000 Mc/s. The effect of cloud and, more particularly, rain will give a bias towards the lower frequency range, whereas considerations of aerial size for a given beam width operate in the opposite direction. A compromise frequency of about 4000 Mc/s, will serve for illustration.

The sky temperature is about 3° K at the zenith, increasing to 17° K at about 7 deg elevation. To this must be added the ground emission accepted by side-lobes which is 2° K at the zenith increasing to 30° K near the horizon. The transmission loss may contribute about 6° K (0·1 dB at room temperature or 0·4 dB at 77° K) whilst the maser amplifier contributes 5° K total. Thus the system temperature, including the aerial, varies from 13° K at the zenith to 41° K near the horizon, whilst the total noise, including sky noise will vary from 16° K to 58° K.

It may be noted that a simplified expression has been used to evaluate system noise temperature, i.e. the sum of the individual contributions. A more precise expression, derived with ease from the expressions of Section 2, shows the degradation of system performance due to signal loss as well as the effect of increased input temperature. However for small losses in transmission lines the approximate formula is adequate for the present purpose.

The only really low noise system known to the author is that used by the Bell Telephone Laboratories in their atmospheric attenuation and *Echo* experiments.[3] The cornucopia or sugar scoop aerial used is a modified form of horn and Table 2 illustrates the performance achieved, which is thought to be capable of further improvement.

Table 2

Sky noise at zenith	2·5° K
Subsidiary lobe pick-up	2° K
Antenna and rotating joint loss	1·5° K
Waveguide and coupler loss	2° K
Maser feed loss	8·5° K
Maser noise	2° K
	18·5° K

8. Conclusions

With present day techniques there is a possibility of building a low-noise system of effective noise temperature about 10° K. This compares with a noise input of perhaps 2000° K, using a conventional amplifier in a conventional system, or about 100° K to 200° K using a low-noise amplifier in a conventional system, i.e. parabolic aerial with long transmission lines. Because an improvement of system temperature by a factor of 10 reduces the output power requirements of an active satellite by a similar amount, with enormous decrease in weight and increase in reliability, there is considerable advantage to be obtained by extending low-noise techniques to the whole system.

9. References

1. D. C. Hogg, "Effective antenna temperatures due to oxygen and water vapour in the atmosphere", *J. Appl. Phys.*, **30**, pp. 1417–9, September 1959.
2. C. R. Ditchfield, "Noise in Quantum Mechanical Amplifiers", Low Noise Receiver Symposium, Lincoln Laboratory, M.I.T. 1960.
3. R. W. DeGrasse, D. C. Hogg, E. A. Ohm and H. E. D. Scovil, "Ultra-low noise measurements using a horn reflector antenna and a travelling-wave maser", *J. Appl. Phys.*, **30**, p. 2013, December 1959.

Manuscript received by the Institution on 26th May 1961 (Paper No. 657).

POINTS FROM THE DISCUSSION

Mr. M. Telford: What are the noise contributions from a radome at 4000 Mc/s for an elevation of 7 deg? Also what effects may be expected from heavy rain, particularly in tropical regions?

Mr. C. Williams: Figure 2 is a very interesting presentation of temperature as a function of zenithal angle, and presumably the values given are average values. I would like the author to give some indication of the order of deviation from mean sky temperature. This is important because the existence of large deviations from the mean values given will be sufficient to cause temporary loss of communication signals, while the receiver is tracking the satellite along its path.

Mr. C. R. Ditchfield (*in reply*): The resistive loss in a radome at 290° K will contribute about 6·6° K noise temperature for each 0·1 dB loss (see Fig. 5). It may also reflect ground noise into the aerial; this can be minimized by the optical technique of blooming (cf. quarter wave transformer matching).

I have no figures for the tropics but the first satellite communications ground station will be established in temperate climates. Dr. Hogg of B.T.L. has measured an increase of 90° K sky temperature at 6000 Mc/s for a rainfall rate of 50 mm/hr, and predicts that at 3000 Mc/s the comparable rise would be 6° K, implying about 15° K at 4000 Mc/s. This rainfall rate is termed "very heavy", persisting only for a few minutes, and in temperate climates will only total perhaps 30 minutes per year.

At 4000 Mc/s galactic noise is very small even in the hotter regions of the sky. Hence only on very rare occasions will the sky noise deviate significantly from the values quoted if the frequency is about 4000 Mc/s.

INSTITUTION NOTICES

Appreciation

As this *Journal* was prepared for printing messages were being received from members expressing appreciation of the news that the Institution had been granted a Royal Charter.

The General Secretary hopes that members will understand that there may be some delay in acknowledging all the kind messages and donations which have been sent to the Institution. Meanwhile, however, all such contributions are being put towards a purpose which so many members seem to have at heart "... the acquisition of a building for the Chartered Institution."

The Institution in Canada

Reference was made in the January *Journal* (page 40) to the forthcoming visit to Canada of the General Secretary of the Institution. Mr. Clifford is due to arrive in Montreal on Wednesday, 4th October, and may be contacted there, c/o the Mount Royal Hotel, until Monday, 9th October. The Secretary then leaves for Toronto where he will be holding a meeting of members at the Royal York Hotel. Before returning to Montreal on 18th October, Mr. Clifford will visit Ottawa.

Among the matters which are to be discussed with the Canadian Advisory Committee and other members, are arrangements for the regular publication of *Canadian Proceedings of the Brit.I.R.E.* The first issue of this new venture in Institution publications is currently under preparation in London. Copies will be despatched during September to members in Canada and the U.S.A., as well as to subscribers in government departments, universities and industry.

Following his stay in Canada the General Secretary will visit the United States toward the end of October. An itinerary is being worked out which will enable Mr. Clifford to take advantage of the many invitations which have been received since his tour was announced. Further details of the General Secretary's arrangements will be notified to members in Canada and the United States and Mr. Clifford hopes to meet the majority of these members during the course of his six weeks' visit.

Radar Group Visit to T.E.E.

On the evening of 13th June last, some 40 members of the Institution's Radar and Navigational Aids Group visited the Telecommunications Engineering Establishment of the Ministry of Aviation at Gatwick Airport, Surrey. The visit was made at the kind invitation of the Superintendent of T.E.E., Mr. William P. Nicol (Member), who welcomed members and told them about the purpose and activities of the Establishment, which had only been opened a week beforehand.

Briefly, T.E.E. is responsible for the field engineering of civil ground radio, radar and navigational services of the Ministry of Aviation. This function embraces certain aspects of specification, model and prototype production, installation, and major overhaul and repair. The facilities therefore offered much of interest to radio engineers. Following Mr. Nicol's talk and supplementary details given by senior members of his staff, the tour of the workshops and laboratories provided ample material to involve members in discussion until late in the evening.

Further Insignia Awards to Members

The City and Guilds of London Institute has recently announced that the City and Guilds Insignia Award has been granted to two members of the Institution.

Mr. William T. Warnock (Associate Member) has received an Award in the field of telecommunications, his thesis being on the subject of "The Director System of Automatic Telephony". Mr. Warnock is Deputy Principal at the Post Office Central Training School where he has general responsibility for the courses on audio frequency, telegraph, high frequency, radio and electronic equipment. He was transferred to the grade of Associate Member in 1945.

Mr. John F. Young (Associate Member) receives the C.G.I.A. for work which has led up to a thesis entitled "Non-Mechanical Switching Devices". Mr. Young, who was elected an Associate Member in 1953 is currently manager of the Electronics Division of Donovan Electrical Co. Ltd., Birmingham; he previously held appointments with Lancashire Dynamo Electronic Products Ltd., and the General Electric Company Ltd.

Proceedings of the Symposium on "New Components"

The formal papers read at the Symposium on "New Components" held in London on 26th–27th October last have now all been published in the *Journal*. Sets of the Proceedings of the Symposium are available price £2 10s. complete from the Publications Department, 9 Bedford Square, London, W.C.1. Reprints of individual papers may be obtained price 3s. 6d. each. A list of the papers was given on page 13 of the July *Journal*.

U.D.C. 618.2.085

An Electro-Mechanical Indicator

By

IR. J. A. VAN STUYVENBERG†

Presented at the Computer Group Symposium on Alpha-Numeric Display Devices held in London on 18th January 1961.

Summary: The principles of the construction and operation of the indicator which employs an endless band driven by a stepping motor are described. Some details are given about the driving circuitry, including that developed for multiple driving of indicators in display boards.

1. Introduction

This indicator was developed to meet the need for display equipment in the Signaal Automatic Air Traffic Control System (SATCO). In the automation of air traffic control, flight progress boards are required from which a traffic controller can obtain an overall view of the traffic situation. The requirements to be met by the display boards for this purpose have been described elsewhere.‡

Reliability considerations, especially the requirements that the stored information should not be lost in case of power failure, led to a mechanical solution for the display demands.

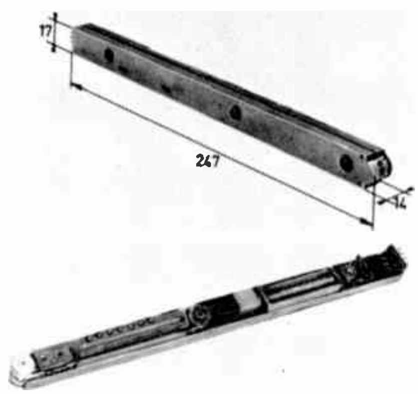

Fig. 1. The SATCO electro-mechanical indicator. External view and with one side cover removed. Dimensions in millimetres.

The basic components of the boards are electro-mechanical indicators, each displaying one character. The indicator should have small front dimensions, while the length was of little importance. This indicator is shown in Fig. 1. In the upper part of the diagram the device is shown completely assembled, in the lower part one side cover has been removed. It is capable of displaying 40 characters, e.g. the 26 letters of the alphabet, the figures from 0 to 9 and four other characters. A further feature of the device is its memory function, since the displayed character is always available in electrical form.

2. Construction and Operation of the Unit

The principle of operation is shown in Fig. 2. The characters to be displayed are printed upon an endless band, which passes over two rollers. One of these rollers is at the front side, where the characters are read off, the second roller is a sprocket wheel and drives the band. This roller is driven by a stepping motor, consisting of a plunger-type magnet, and a ratchet mechanism.

To move the band one position the plunger has to be attracted and released, so one current pulse must be applied to the coil. A half sine wave of 50 or 60 c/s can be used for this purpose.

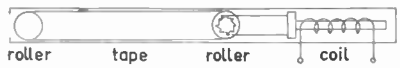

Fig. 2. Method of operation of the indicator.

Fig. 3. The band showing the code track.

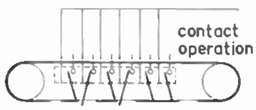

Fig. 4. Method of sensing the code notches.

The position of the band can be read back electrically. For this purpose the two edges of the band are provided with notches. Figure 3 shows a part of the band. Above one of these code tracks six contacts are mounted. These are equipped with feelers which sense the notches in the band (Fig. 4). If a feeler is on a notch, the contact is closed, if there is no notch the contact is open. With these six contacts the 40 positions of the band can be recognized.

† N.V. Hollandse Signaalapparaten, Hengelo, (O), Netherlands.

‡ C. G. H. Scholten, "An electronic computing system for air traffic control", *Proc. Instn Elect. Engrs*, **107B**, Supp. 19, pp. 12–18, 1960 (I.E.E. Paper 3240E).

There is a seventh contact, which is operated by the code track on the other side of the band. The code of this track has such a form that the number of 1's in the total code combination is always odd. This redundancy information may be used for checking purposes.

In order to increase the reliability of the indicator, the contacts are contained in a hermetically sealed box. The design and test requirements are for an expected servicing period of two years when used in SATCO equipment.

3. Application

Figure 5 shows a display board, housing 90 strips of indicators, with 29 indicators in each strip, which makes a total of 2610 indicators.

A layout of one strip is shown in Fig. 6. In each strip there are two rows of indicators. They are stacked immediately next to and above each other. Special double connectors have been designed to make this possible.

The construction is shown in Fig. 7. Between the different strips a small separation is left for providing

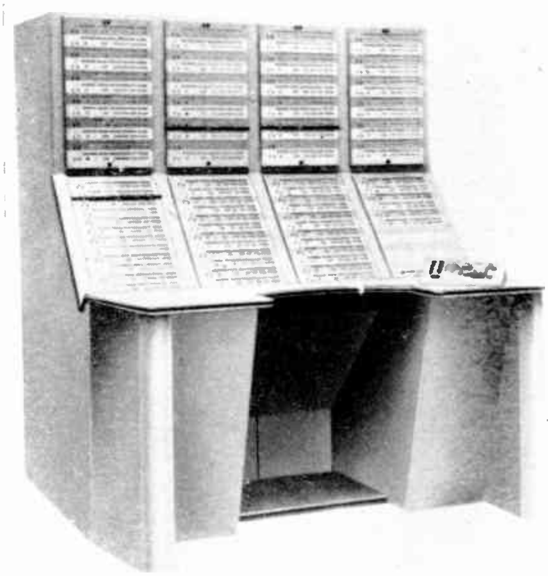

Fig. 5. A complete display board.

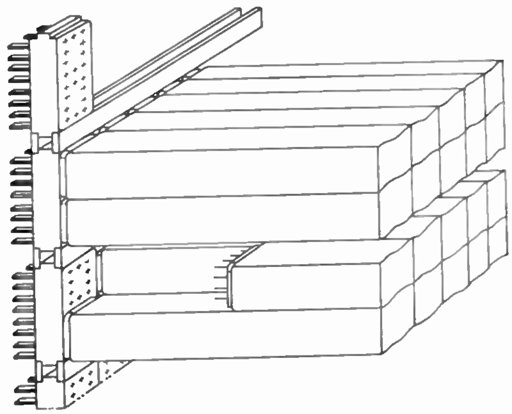

Fig. 7. Mounting arrangements for the indicators.

supports. In this way the indicators can be densely packed together. The perspex front cover as seen in Fig. 6 has three functions:

(1) it protects the indicators against outside influences;

(2) by proper masking it groups the indicators;

(3) by proper shaping it acts as a cylindrical lens for every indicator to increase its readability.

Internal lighting of the indicator has been considered but has not been adopted, the readability being excellent in normal ambient lighting.

4. Driving

Figure 8 shows the electrical connections of the indicator. In series with each contact and in series with the coil, diodes are inserted. The function of these diodes will be explained later.

A method for reading the contact code is indicated in the diagram. A high voltage denotes a closed contact, a low voltage an open contact.

A driving method is shown in Fig. 9. The code to which the indicator must turn is offered in the form of a set of low and high voltages.

In the equivalence circuit this code is compared with the contact code. This equivalence circuit operates a switch, which controls the coil current. The switch is kept closed as long as there is no equivalence. When equivalence is reached the switch is opened, and the indicator stops at the desired position.

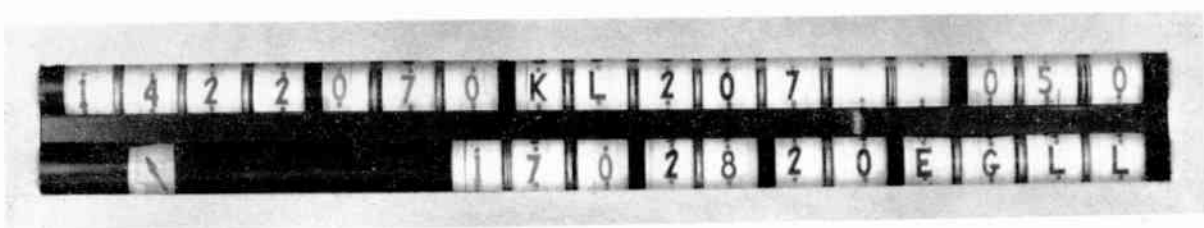

Fig. 6. A strip of indicators.

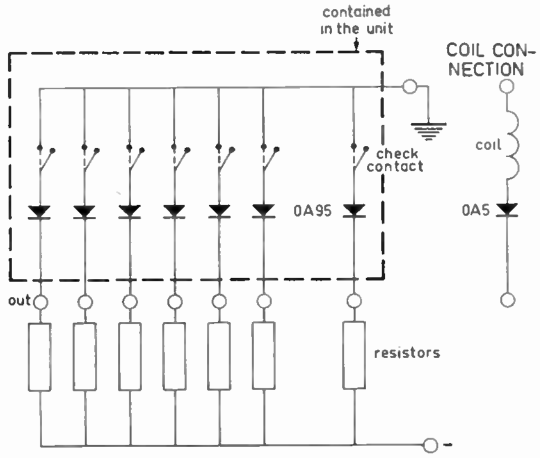

Fig. 8. Method of reading the code from the contacts.

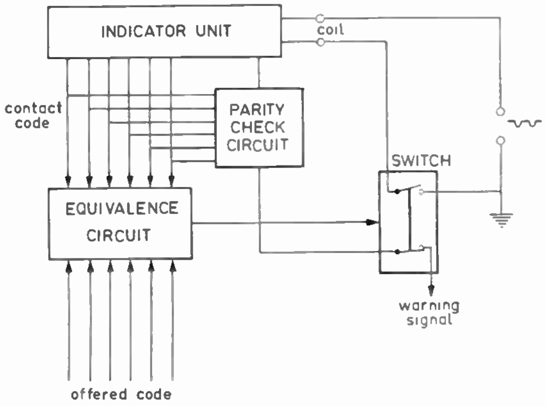

Fig. 9. Driving circuit for a single indicator.

Furthermore there is a parity check circuit, which delivers an alarm signal if there is an even number of 1's. This alarm signal is controlled by a normally closed contact of the switch which opens when the indicator starts, thus avoiding erroneous fault indication while running, when the parity may be disturbed by non-synchronous change-over of the contacts. The circuit here described is applicable when only one indicator needs to be driven.

In this case the use of relay circuitry may prove advantageous. In most other applications the use of electronic circuitry will be preferred and for control of the coil current a transistor can be used. The supply voltage may be a direct voltage, the pulsing being done by switching the transistor on and off.

However this method puts strong demands on the transistor, as the magnetic energy in the coil will produce high transient voltages. The use of a half-wave rectified sinusoidal voltage proves very advantageous for this purpose.

The switching-off of the coil can then be done during the non-conducting half period. A very useful device for the driving method described below is the silicon controlled rectifier. In the previous arrangement the equivalence was examined continuously. In most applications however, especially when a number of indicators need to be driven simultaneously, another driving circuit is preferred.

Since the motion of the band is discontinuous, there is a period of standstill between two successive steps. In this period the equivalence and the parity check may be read off with a short read pulse. This method leads to the circuit of Fig. 10.

A flip-flop controls the electronic switch. The switch closes when the output is in the "low" state and it opens when the output attains the "high" state.

To drive the indicator to a certain offered code a start pulse must be applied to the start-stop flip-flop which changes its state and closes the electronic switch. The indicator then starts running. After each step of the indicator the equivalence is read out with a pulse. The read pulse generator is triggered by the supply voltage and it must be adjusted to have such a delay that it coincides with the standstill period of the band.

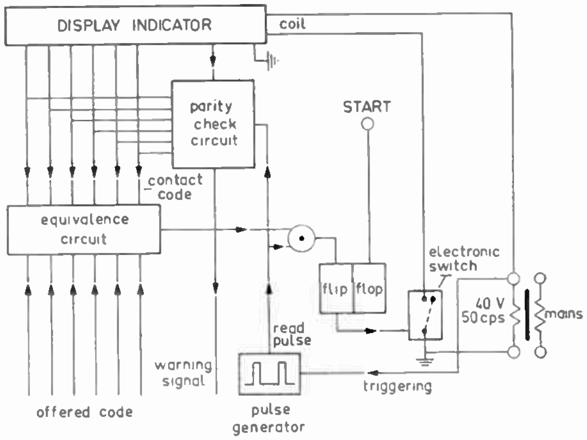

Fig. 10. Driving circuit with a read pulse.

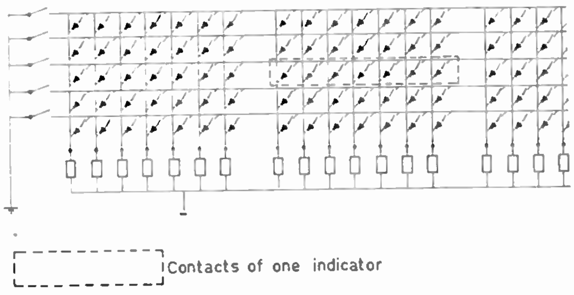

Fig. 11. Matrix of indicator contacts in a multiple driving arrangement.

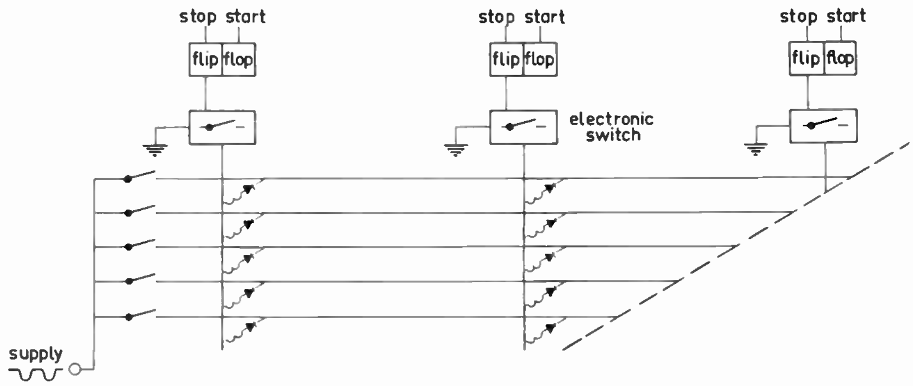

Fig. 12. Matrix of coils for multiple driving arrangement.

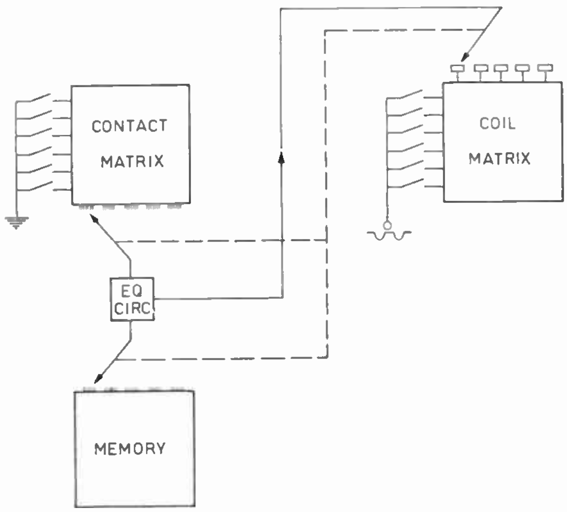

Fig. 13. Arrangement for simultaneous driving of a number of indicators.

When equivalence is reached the equivalence signal becomes high, and the read pulse can pass through the AND gate, thus changing the state of the flip-flop, which opens the electronic switch and stops the unit.

5. Multiple Driving of Indicators

In the SATCO display boards it is desirable to have the data of the indicators in a strip all changed at one time.

For this driving method the contacts of the indicators are arranged in a matrix. A part of such a matrix is shown in Fig. 11. The contacts belonging to one indicator are enclosed by a dashed line.

If for instance the information on the third strip should be known, the third line switch on the side of the matrix is closed and the code appears on the resistors at the bottom of the matrix. The diodes in the indicator unit in series with each contact prevent interference with indicators on other lines.

As seen in Fig. 12 a similar matrix can be built up of the coils, the diodes for which already form a part of the circuit in the indicator unit. Driving a certain indicator can be achieved by closing the appropriate line switch and setting the start-stop flip-flop at the top of the column concerned in the start state. With these matrices it is possible to form an arrangement for driving a complete strip. This is shown in Fig. 13.

The line switches in the contact and coil matrix for the strip concerned are closed and all start-stop flip-flops on top of the coil matrix are set to the start state. After each step the codes of the indicators are switched successively to a common equivalence circuit, where they are compared with the codes that are read out synchronously from a memory device.

The output of the equivalence circuit is switched in the same order along the stop inputs of the start-stop flip-flops. Thus the indicators having reached the desired position are stopped. This scanning is continued until the last indicator has stopped.

Manuscript received by the Institution on 18th January 1961 (Contribution No. 36).

U.D.C. 621.387

A Gas-filled Glow Discharge Character Display Tube

By

G. HIGGINS, B.Sc.†

Presented at the Computer Group's Symposium on "Alpha-Numeric Display Devices" held in London on 18th January 1961.

Summary: The construction of a gas-filled glow discharge display tube and its limiting operating conditions are discussed. A graphical method is described for determining the correct working point in a typical simple circuit. A number of circuits are described which show the application of the tube to typical counting systems with counting speeds ranging from a few cycles/second to 2 Mc/s. It is shown that, provided suitable precautions are taken, end of life can be predicted and failure in service is unlikely.

1. The Gas-filled Glow Discharge Tube

Cold cathode character display tubes are a relatively new application of a phenomenon which was observed around 100 years ago, namely, the glow produced by an electrical discharge through a gas at low pressure.

If a potential difference is applied to a pair of electrodes sealed into a glass tube which contains a gas at a pressure of a few millimetres of mercury, then a glow pattern, similar to that shown in Fig. 1, can be observed. The cathode glow follows the profile of the cathode very closely and is separated from it by the Crookes' dark space. Between the cathode glow and the anode is the positive column, made up of a number of luminous striae. The dark space between the cathode glow and the first of the striae is known as the Faraday dark space. For a fixed potential difference the position and spacing of the striae is dependent mainly on the gas pressure. If the anode is moved towards the cathode the number of striae will be reduced but the positions of those remaining will be relatively unaffected. The anode can in fact be moved into the Faraday dark space so that the only visible glow in the tube is the cathode glow. This is the condition of operation for a display tube.

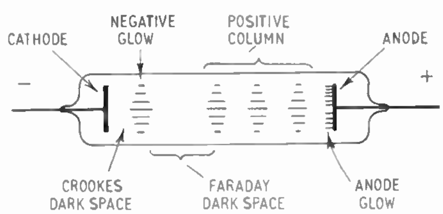

Fig. 1. Typical appearance of glow discharge tube.

2. Construction and Operation of the Digitron

A typical tube is shown in Fig. 2. It can be seen that it has a number of separate cathodes surrounded by a common anode structure. The cathodes are formed in the shape of the required display, in this case the digits 0–9, and are in line, one behind the other, stacked closely together to reduce the three-dimensional appearance which may be apparent in a multi-tube display. Any one of these cathodes may be selected by the associated circuitry or switches and connected to the negative pole of the supply. The cathode glow will surround the selected cathode, increasing its apparent thickness by a factor of 4 or 5. The required display is thus not appreciably obscured by any other cathode shapes which may be in front of it. In a typical tube the cathode cross-section would be about 0·25 mm thick by 0·4 mm wide. The glow would have a width of about 3 mm. The gas mixture and pressure are chosen so that the Crookes' dark space is not apparent, the glow having a uniform appearance with clearly defined edges.

The unused cathodes must be left disconnected from the circuit or biased positively with respect to the selected cathode. If this is not done the glow will tend to spread on to the unwanted cathodes and a confused display will result. As will be seen later when suitable drive circuits are described, it is desirable that the bias required is small.

Cathodes can be made in a great variety of shapes and tubes are available commercially which will display the digits 0–9; letters of the alphabet; fractions $\frac{1}{4}$, $\frac{1}{2}$, $\frac{3}{4}$, and + and − signs. It has not been found practicable to include more than 16 cathodes in any one tube and for this reason the alphabet must be covered in two tubes. Various mechanical construc-

† Ericsson Telephones Ltd., Beeston, Nottingham.

tions are used and Figs. 2 and 3 show examples of side-viewing and end-viewing constructions. The larger side-viewing tube has characters 30 mm high and can be read at a distance of 50 ft over a wide viewing angle under normal conditions of lighting. Figure 3 shows an example of a smaller end-viewing tube. In this case the characters are 19 mm high and the tube has particular application in compact portable equipment.

In general the current required by a tube increases as the character size increases. For the two examples given the currents are 6·5 mA and 2 mA. The running and striking voltages are not directly related to character size and will normally be in the region 150 V to 200 V.

During the normal operation of a tube, sputtering of the cathode material takes place, i.e. material is removed from the surface of the cathodes and deposited on other parts of the electrode structure and the glass bulb. A certain amount of sputtering is inevitable and the design of the tube and its operating conditions must be arranged to keep its effects to a minimum. To prevent material being deposited on the glass and so obscuring the display, the anode is usually made in the form of a wire mesh surrounding the cathode assembly. This intercepts a large proportion of the sputtered material but does not obscure the display to any great extent.

Fig. 3. End-viewing Digitron.

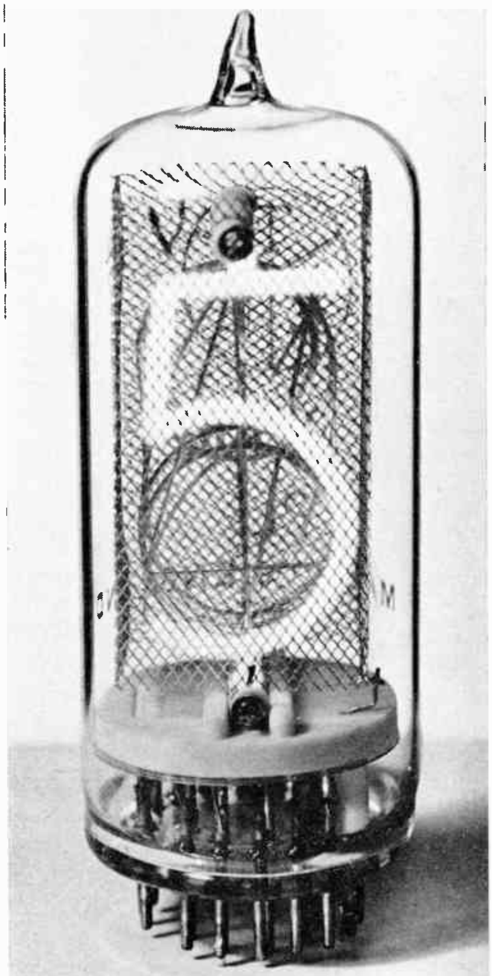

Fig. 2. Side-viewing Digitron.

The rate of sputtering and the minimum current required to cover a cathode are dependent on the gas pressure. A tube can be made to have very low current requirements but this would be obtained at the expense of short life due to the increased sputtering rate.

3. Tube Characteristics

A graphical method of determining the design centre working point is shown in Fig. 4. The two near horizontal lines represent the upper and lower manufacturing limit of running voltage. The minimum and maximum values of current are indicated by two vertical lines. The enclosed area is the working range of the tube. The upper, lower and left-hand boundaries represent the manufacturing limits and the right-hand boundary is obtained from the results of life tests. This information is normally supplied by the tube manufacturers.

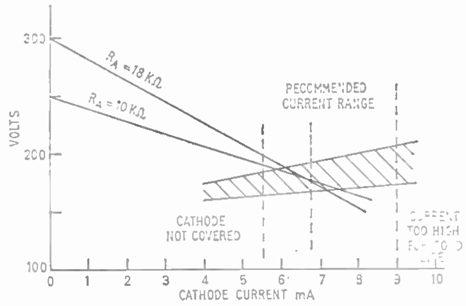

Fig. 4. Typical Digitron characteristics.

Consider the simple circuit shown in Fig. 5, the tube current is given by

$$I = \frac{V_B - V_R}{R_A}$$

where V_B is the supply voltage and V_R is the tube running voltage.

A load line corresponding to R_A can be constructed on Fig. 4. This line must intersect the running voltage limit lines at points between the current limit lines. A series of such load lines can be drawn to determine the permissible tolerances of V_B and R_A. The voltage supply V_B must always be in excess of the tube striking voltage.

The running voltage and minimum and maximum values of current may vary from digit to digit with certain tube types. For example, the digits 1 and 7 have a smaller area than the remainder and may require less current. It may therefore be necessary to include compensating resistances in series with these cathodes. In certain tube types this effect has been controlled by the tube design and no compensation is necessary in these cases.

The simple circuit discussed is not suitable for all applications but the method of approach can be adopted to any other circuit configuration.

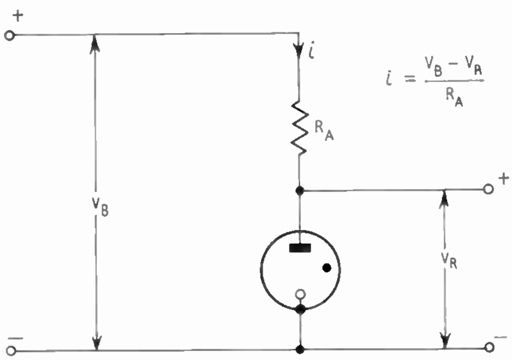

Fig. 5. Basic discharge tube circuit.

Although the Digitron is a gas-filled device and requires a certain amount of time to ionize and de-ionize it need not impose any limit on the speed of the circuit with which it is used. At switching speeds in excess of about 200 kc/s the tube will extinguish but will re-strike and register the correct count when the counter slows down or stops. In the interval between the potential being applied and the tube striking, the tube presents a high impedance to the drive circuit; after striking it becomes a constant-voltage load. The drive circuit design must be arranged so that the switching or counting is not upset by this variation in load.

4. Circuit Applications

As the numerical Digitron is a scale-of-ten read-out device it is naturally more convenient to use it in conjunction with scale-of-ten counters rather than with

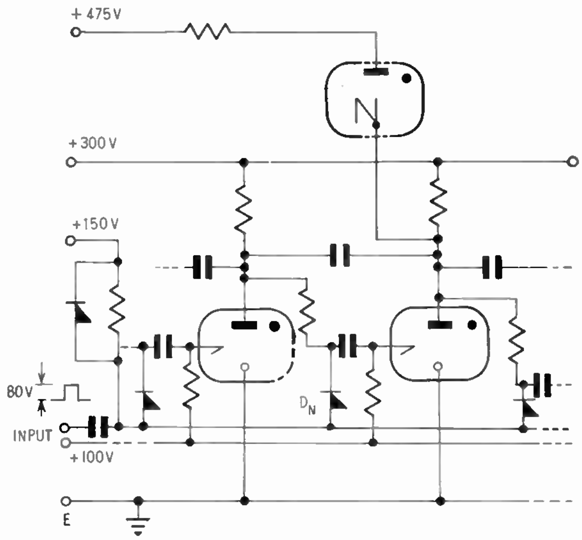

Fig. 6. Digitron read-out of cold cathode trigger tube ring counter.

binary systems. The examples of drive circuits which follow are mainly based on various scale-of-ten counting devices although one method is shown for obtaining read-out from a decimal coded binary system. The systems discussed cover a wide range of operating speeds up to a maximum of 2 Mc/s.

The simplest and most obvious way of driving a Digitron is by the use of mechanical switching devices such as relays and uniselectors. These systems are relatively slow but have many applications in industrial process control systems.

Figure 6 shows a typical cold cathode tube ring counter. This type of circuit is relatively inexpensive and can be used at counting speeds up to a few hundred cycles a second. Ten trigger tubes are used

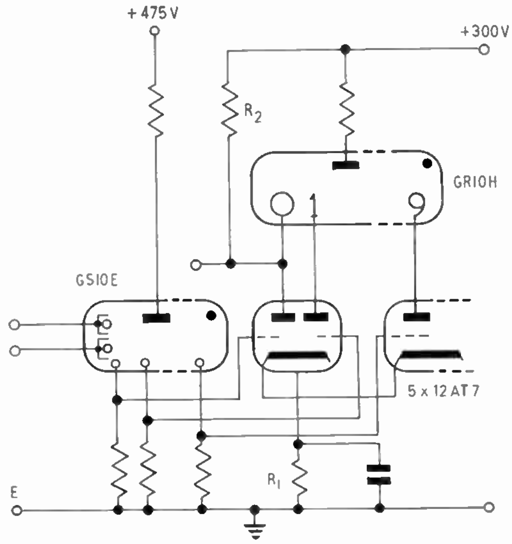

Fig. 7. Digitron read-out from Dekatron using triode coupling.

only two of which are shown in the diagram. The mode of operation is as follows.

If we assume that the left-hand trigger tube is conducting its anode voltage will be sufficiently low to enable the diode D_N to conduct when a trigger pulse is applied to the input. The anodes of the remaining tubes will be at h.t. potential, biasing the other diodes sufficiently to prevent conduction during the pulse. The right-hand trigger tube will therefore receive a positive pulse on its triggering electrode causing it to conduct. The anode voltage of this tube will fall and a negative pulse will be applied to the anode of the left-hand trigger tube, returning it to the non-conducting state.

It can be seen that successive pulses will cause each trigger tube to conduct in turn and that only one tube at a time can conduct. The trigger tube anode presents a constant voltage source to the Digitron cathode and the Digitron current must be controlled by means of an anode resistance.

The Dekatron would appear to be the logical companion tube to the Digitron; both are scale-of-ten cold cathode devices and require voltages and currents of the same order of magnitude. Unfortunately the conventional Dekatron and Digitron are not completely compatible and it is necessary to introduce rather a lot of components to obtain the digital read-out. Figures 7 and 8 show two suitable arrangements.

The circuit shown in Fig. 7 uses 10 triodes to supply the current to the Digitron cathodes. The triodes are switched on in turn by the positive voltage appearing at the Dekatron cathodes. The Digitron current can be controlled by the common cathode resistance R_1. If a carry pulse is required from the "O" cathode, the resistance R_2 should be included to make the leading edge of this pulse independent of the ionization time of the tube.

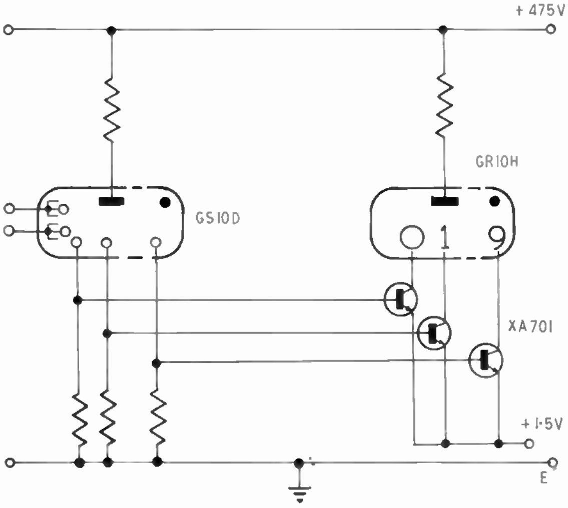

Fig. 8. Digitron read-out of Dekatron using transistor current amplifier.

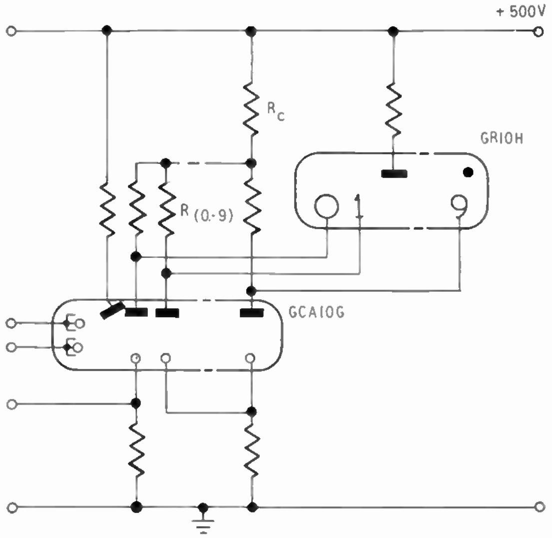

Fig. 9. Digitron read-out from auxiliary anode Dekatron.

Transistors may be used to replace the triodes as shown in Fig. 8. To obtain the necessary current amplification it is necessary to use the transistors in the grounded emitter configuration and, as the output voltage of the Dekatron is positive going, an *n-p-n* type of transistor must be used.

The current to the cathodes which are "off" must not exceed about 100 μA per digit to avoid confusion of the display by spurious glows. At this current the voltage appearing on these cathodes will be about 40 V, so that relatively high voltage transistors must

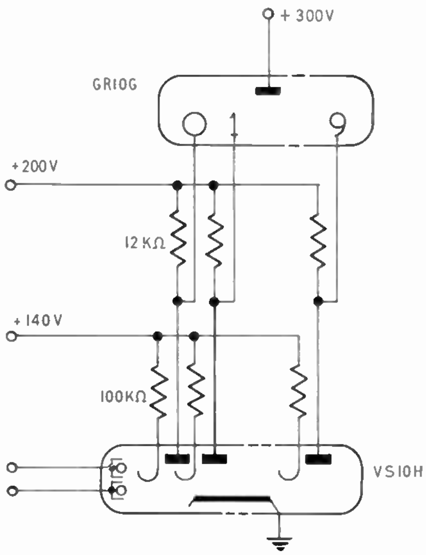

Fig. 10. Digitron read-out of Trochotron.

be used. These are not very cheap although the situation is improving rapidly.

A new type of Dekatron has recently been introduced which is designed for Digitron read-out. It incorporates ten auxiliary anodes in addition to the normal Dekatron electrodes and an electron current of up to 2 mA can be obtained from these anodes without affecting the normal Dekatron operation. The circuit arrangement for this tube and its read-out is shown in Fig. 9. The output of the auxiliary anodes is at constant voltage so that the Digitron current must be controlled by its anode resistance. The Digitron bias is obtained by returning the auxiliary anodes and Digitron cathodes to the h.t. supply via the resistances $R_{(0-9)}$ and R_C, its value being determined by the ratio of R/R_C.

The Dekatron based systems discussed above will have maximum counting speeds of up to 20 kc/s depending on the tube types chosen. Speeds of up to 2 Mc/s can be achieved by using Trochotron type tubes.† These are hot cathode electron beam switching tubes, which, as they have a constant current output characteristic, are particularly well suited to driving a Digitron. Tube types are available which can supply up to 18 mA which is more than enough to drive the largest Digitron. Figure 10 shows a typical arrangement. Because of the constant current output of the Trochotron, a Digitron anode resistance is not required and the h.t. voltage can be correspondingly lower.

† D. Reaney, "Trochotron high-speed beam switching tubes". Paper read at Brit.I.R.E. Symposium on "Electronic Counting Techniques", 26th April 1961. *J. Brit.I.R.E.*, 22, 1961. (To be published)

Digitron read-out is not necessarily confined to devices operating on a scale-of-ten. Figure 11 shows a typical arrangement for obtaining decimal read-out from a binary counter. A diode matrix, operating at low voltage, is used to perform the decoding operation. The output signal from this is amplified by means of a high voltage *n-p-n* transistor, to provide the drive current for the Digitron. Using the circuit arrangement shown, the output voltages of each binary stage must swing between earth and $-1{\cdot}5$ V.

5. Reliability and Life

The life of a Digitron is determined primarily by the rate at which material is sputtered off the cathodes. This sputtering may eventually weaken a cathode sufficiently to cause a mechanical failure, or alternatively deposits on the internal insulation may cause short circuiting. The time required to reach this condition is predictable if the operating conditions and duty cycle are known.

A proportion of the sputtered material is deposited on the glass bulb and, with experience, this can give a useful indication of the age of a tube. A regular maintenance schedule should therefore enable tubes to be replaced before actual failure occurs and so increase the overall reliability of the equipment.

Figure 12 shows a typical failure distribution curve. The initial failures are due to manufacturing defects and these tubes are detected and discarded during the conditioning processes and subsequent factory tests.

The time taken to reach the end of life will depend on the duty cycle of the cathode switching. The

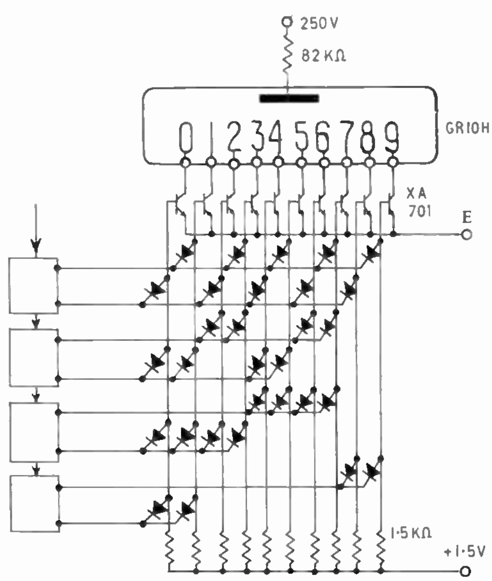

Fig. 11. Digitron read-out of binary counter.

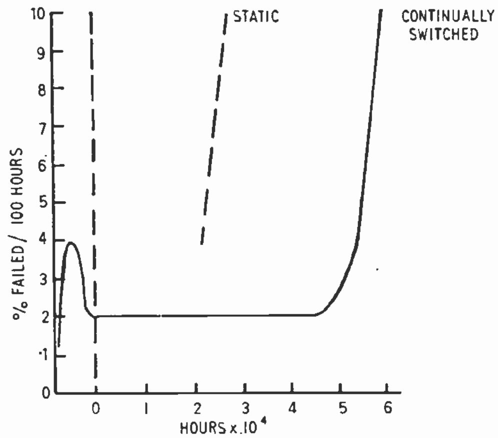

Fig. 12. Typical Digitron failure rate.

worst possible conditions are obtained when one cathode is used continually. The life will then only be about half that obtained when all cathodes are switched regularly.

A considerable improvement in life can be obtained, where circuit conditions permit, by operating the Digitron from an unsmoothed, half-wave rectified, anode voltage supply. If the voltage and anode resistance are chosen so that the peak current does not exceed the recommended maximum, then the life of the tube will be approximately doubled. A slight loss of brightness is incurred but this effect is negligible except where the equipment has to be operated in bright sunlight.

With currently available tubes lives up to 5000 hours can be obtained from a tube which is regularly switched and operating from a d.c. supply. "Long life" Digitrons are being developed which will have lives of 10 000 hours or more under the above conditions of operation. These tubes include a small amount of mercury in the gas filling which has the double effect of reducing the "current to cover" and for a given current, reducing the rate of sputtering. These effects combine to give at least a 2 : 1 increase in life. Because of the presence of mercury vapour in these tubes a faint blue haze surrounds the glowing cathode. If this is objectionable an orange or red filter may be placed in front of the display.

6. Conclusion

It can be seen that the Digitron provides a read-out system with good brightness and definition which can be combined with the majority of the counting systems in use by industry. The size of the characters makes them suitable for use in large control panels and their small overall size permits their use in compact bench instruments. Sudden, unexpected failures are unlikely, and provided that proper maintenance is carried out, the overall reliability of a system is not impaired by their inclusion.

7. Acknowledgments

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C.R.T. Display of Alpha-Numeric Information Applied to Radar Data Handling

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Presented at the Computer Group's Symposium on "Alpha-Numeric Display Devices" held in London on 18th January, 1961.

Summary: The problem of extracting and classifying the large volume of information presented by a long-range radar is discussed, and the types of information an operator may require to have displayed to him in alpha-numeric form on the radar c.r.t. are detailed. The necessity to time-share the beam deflection circuits between many signal sources makes a high speed writing method essential. Several methods are considered, and one using digital techniques is examined in detail. The writing speed attainable is a function of the screen positions in which consecutive digits are to be presented, but may reach 3×10^4 characters per second.

1. Introduction

A modern long-range radar collects information from a very large volume of air space; much of this information is redundant and some of it, echoes representing static objects, factory chimneys, etc., can be removed by static target cancellation techniques. Even when this is done there may remain a very considerable amount of information which requires classification. To particularize, a surveillance radar with a range of 100 miles situated at London Airport will have within its coverage aircraft operating to and from London, Gatwick, Blackbushe, Southend, Lydd, Birmingham and Southampton Airports apart from a considerable number of private and military airfields. As a result there are usually about 100 aircraft echoes visible on the display and frequently a considerably larger number. In the case of military radar where longer ranges are in use, this problem is even more marked and naturally the urgency of the data handling problem is greater.

It is obviously desirable that at the earliest possible stage of human intervention in the data handling process, all targets which have already been classified should be marked in some way on the operator's radar display, leaving him free to concentrate on those not yet accounted for.

Much of this can be done without the use of alpha-numeric characters, for example, incoming aircraft echoes might be enclosed by square symbols, outgoing by circles while those being handled by other airports might be indicated by triangles; these simple symbols may readily be written by a combination of suitable waveforms using Lissajous' figure techniques.

† Formerly of Decca Radar Ltd.; now with Research & Engineering Controls Ltd., Kingston-upon-Thames.

Once the particular class of track in which the operator is primarily interested has been identified, however, he will require more detailed information on these tracks to be presented to him. This information may include vector lines, showing the direction of flight, and predicted positions after the passage of some chosen time interval, but in most cases it will be necessary to print alongside each target some information in the form of letters and numerals.[1, 2]

This information might be one or more of the following items:

(i) *Track Number.* A number indicating which particular tracking circuits in the data processing unit are associated with that target.

(ii) *Target Height.* In congested airways, decisions on the possibility of conflict between the tracks of two aircraft may require this information.

(iii) *Aircraft R.T. Call-sign.* This may be required by the operator so that information passed by r.t. may be correlated with the relevant echo.

(iv) *R.T. Frequency.* May be required if several frequencies are in use.

(v) *E.T.A.* Normally a four-figure group in hours and minutes.

(vi) *Other Information.* Various other items of information may be required by particular users of the equipment for their own special purposes.

While it may be argued that some of this information at least, could be presented on paper flight strips or on other forms of digital indicator, rather than on the radar display, the spatial inter-relation of the various targets makes it very desirable that as much as possible of this information should be written on the radar display screen itself. The other important advantage lies in the reduction of the number of instruments to which the operator must give his attention.

The methods which will be described in the paper for data display are not restricted to radar problems, and their use in computer output applications will be mentioned later.

2. Display Methods

Since radar displays normally employ single-beam electromagnetically deflected c.r.t.s, the beam deflection circuits have to be time-shared between all the various information sources, that is to say between the incoming radar scan information, the vector lines, squares, circles and triangles; information about fixed beacons, reporting points, runways in use and the alpha-numeric character generators. Of these the writing of the radar information may occupy say 75% of the total available time, while additional time is lost in waiting for various circuits to recover to their normal condition after some deflecting signal has been removed.

In any large radar system a single data processing unit would normally be shared between many operators. The information appropriate to all their separate displays must be handled in turn and correctly collected from and distributed to these operators. Thus although the total amount of alpha-numeric information to be displayed at a particular operating position may be small by computer output standards, the short time available for its presentation, together with the requirement that it be re-written say 10 times per second to avoid flicker, makes it essential to employ a very fast method. In calculating the speed required it is necessary to allow a safety margin to ensure that the station's handling capacity can never be over-saturated at peak periods. These requirements have been detailed for the particular case of radar data processing which is the subject of this paper, but very similar criteria apply to any process in which a computer is used in an "on-line" application, and the methods to be described could equally be used as a high speed output medium in many other computing processes. In these other applications it may be more convenient to arrange the characters in lines like a page of typescript.

2.1. *Digit Coil*

Since it is inconvenient to produce a single electromagnetic deflection system which has both the high sensitivity, required in order to paint the radar scan information, and also the high bandwidth necessary to handle alpha-numeric characters, two separate deflection coils are provided on the neck of the c.r.t., one being used for radar information and the other for character writing.

2.2. *Synthesis of Waveforms to Form Characters*

This method is a variant on the well-known Lissajous figure technique and, by selection and addition of suitable portions of sinusoidal, triangular and square waveforms in the correct time sequence, a wide variety of shapes and symbols can be produced. The method has some disadvantages when used at very high writing speeds which arise from the difficulty of switching the various waveforms accurately and cleanly; this problem is increased by the high bandwidths needed to describe very angular characters.

The method is particularly useful in generating the various geometrical shapes (circles, squares, triangles, etc.) mentioned above.

2.3. *Raster Methods*

2.3.1. Optical flying spot scanner

The characters to be presented are printed on a transparent mask placed between the c.r.t. screen and a photo-cell; an unmodulated television raster is produced on the c.r.t. screen and a signal obtained from the photo-cell as the spot traverses the characters. This signal is used as a brightness modulating signal on the operator's display, while a similar raster is produced by the display deflection circuits. This method gives the ability to change the selection of characters or shapes available at will. Considerable problems appear, however, in the optical registration of the apparatus, particularly if a single mask comprises a large number of different symbols. A further complication in this case is that the raster, when scanning a particular character on the mask, occupies only a small part of the field view of the photocell. A variant on this method used separate 1-inch c.r.t.s, one for each character and having a transistor photocell to each tube. This system, while overcoming the difficulties mentioned above, is obviously unacceptably bulky if a very large variety of characters is required.

2.3.2. Monoscope tube[3]

Optical raster methods were eventually abandoned in favour of the monoscope tube, which avoids many of the problems described above. In the monoscope tube an electron beam is made to produce a raster over characters printed on a target inside the tube which has areas of varying secondary emission coefficients. A video output is obtained from a load resistor connected to this target plate and is used to modulate the operator's c.r.t. in exactly the same manner as the signal from the photocell in the optical method. A difficulty with all raster methods lies in phase shifts encountered by the deflecting signals which may well be generated in equipment remote from the operator's display. To minimize the effects of these phase shifts it was found convenient to use a decreasing spiral raster instead of the more usual television scan. This method of character generation has been extensively used in spite of a number of difficulties. The method is not very flexible, since if a new set of characters has to be specified, the tube must be dismantled, or replaced by a new one, in order to include a new target plate. In addition, the monoscope tube requires a complete deflection system similar to that required by a normal radar tube, and if characters are selected at random, the method becomes slow because of the recovery time that must be allowed for its deflection system to settle on the next digit. To some extent this can be minimized by having the digits on the target plate arranged in the groups in which they are to be used; thus if the character groups in a particular equipment could be any number from 0 to 99 the digits could be grouped in pairs on the target plate.

2.4. *Quasi-Digital Methods*

The foregoing methods have been used in radar systems employing almost entirely analogue methods for data processing. The next two methods are more immediately applicable to digital data handling.

2.4.1. Delay line technique

In this method, a pulse is launched into a normal delay line and signals available at the various taps of the line are amplified to standard digital pulses. A pulse therefore, appears at the output of each of these amplifiers in turn. These amplifier outputs are connected to resistors having various values which determine the deflecting currents to be passed to the digit coil as each pulse appears. In this way, by suitable choice of resistor values, it is possible to produce a current waveform which, in association with the corresponding one generated for the other axis, will cause the spot to trace out the character required.

Character writing by this method may be very rapid; a model was produced in which a complete character could be traced out in 5 μs.

If a very large number of characters is to be produced, however, the method is rather cumbersome in equipment and involves a considerable amount of switching of actual deflection waveforms. Its chief merit, therefore, lies in its use in systems requiring a small number of different characters.

2.4.2. Method using computer logic

The increasing use of digital methods in radar data handling has led to the use of these digital techniques in character writing in a form which has to be compatible in speed and design with the computer in use. As this method promises to be the most useful for large digital data processing systems, its operation will be described in some detail.

2.5. *Digital Character Generator*

This equipment has been designed to work in conjunction with a single-address, parallel computer capable of outputing words of 18 bits, at intervals of 14 μs and having a basic clock rate of 1 Mc/s. It has, however, also been used with slight modification on a slower serial machine.

The detailed operation will depend to some extent on the format of the display required and so a particular case is considered in which a three-character group is to be associated with particular radar echoes.

In this case, three words are needed for each group of characters; two of the words represent the cartesian coordinates of the position on the screen in which it is to be written, while the third specifies which characters, from a repertoire of 64, the group is to comprise. These three words are placed in three output registers in a time slightly in excess of 42 μs.

Once the three words are available, those representing the character position are converted into the component beam deflection currents by a digital-to-analogue converter (di-an). Then, before the characters can be written, it is necessary to allow a period of time to elapse during which the deflecting field builds up to its final value. This time will vary with the design of the radar display, but in a particular case the figure was about 200 μs.

The three characters are then written in sequence (in a time of about 50 μs), with a minor shift between them so as to space them along a horizontal line.

2.5.1. Character writing circuitry (Fig. 1)

Each character is formed by a maximum of 15 bright dots chosen from the 225 possible positions of a 15×15 array.

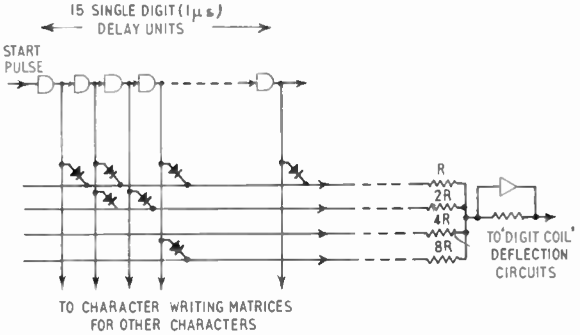

Fig. 1. Character writing circuitry.

The number 15 is arbitrary, and is based on the appearance of the characters on the front of the c.r.t.; it will depend on the ratio of the spot size to the linear dimensions of the complete character. The choice of a square array gives the ability to describe symmetrical geometric figures such as squares and circles as well as letters and numerals.

A start pulse is fed into the chain of single digit (1 μs) delay circuits so that a "1" appears on each of the lines P0 to P14 in turn; the diode matrix decides to which input or inputs of the digital to analogue converter each pulse will be routed. Thus during any one of the time intervals P0 to P14, any desired binary number in the range 0 to 15 can be routed to the di-an which converts this succession of numbers into voltage deflection waveforms. The same pulses are simultaneously operated upon by another corresponding diode matrix and di-an to form the waveform needed in the other axis.

The combined effect of these deflecting signals causes the spot to trace out the digit on the output cathode-ray tube.

2.5.2. Character generating system (Fig. 2)

The writing cycle begins with the computer filling the three registers at the extreme left with the positional coordinates and the group of characters to be written. The positional coordinates are immediately transformed to analogue form and these signals perform the main deflection of the c.r.t. beam.

After the waiting period for the deflection system to settle, a "start" pulse is fed into the writing system. This sets the bi-stable A at the top right hand corner of the diagram and this in turn routes the first character to be written from the computer output register to one of the 64 character writing matrices via the character decoding matrix.

The character writing matrix is of the form shown in Fig. 1, and, since the same start pulse which sets the bi-stable is used to initiate the action of the chain of delay units, the appropriate sequence of numbers to describe the dot positions of the selected character is produced and passed to the character writing di-an.

The last pulse out of the delay chain resets bi-stable A and sets B. This adds a "minor shift" voltage to the character-writing di-an displacing the second character one place to the right. The last pulse is also fed back to the start of the delay chain so that the whole process repeats, this time of course writing the second character.

In the same way the third character is presented but at the end of this cycle the last pulse from the delay chain is not returned to the start, and the writing sequence is complete.

For the sake of clarity, only the character matrices and di-an appropriate to the x axis have been shown in Fig. 2.

2.5.3. Brightness modulation

In order to avoid displaying the inevitable spurious transient signals that would appear during the switching of the inputs to the di-an, the operator's c.r.t. is brightened only for a portion of the time for which a particular spot position is selected.

With a brightening pulse of duration 0·1 μs and assuming the characters to be written say 10 times per second, the duty cycle is only one in 10^6. To get acceptable brightness from the display, quite high beam currents have therefore to be used, and there is a tendency to defocusing of the spots. A typical

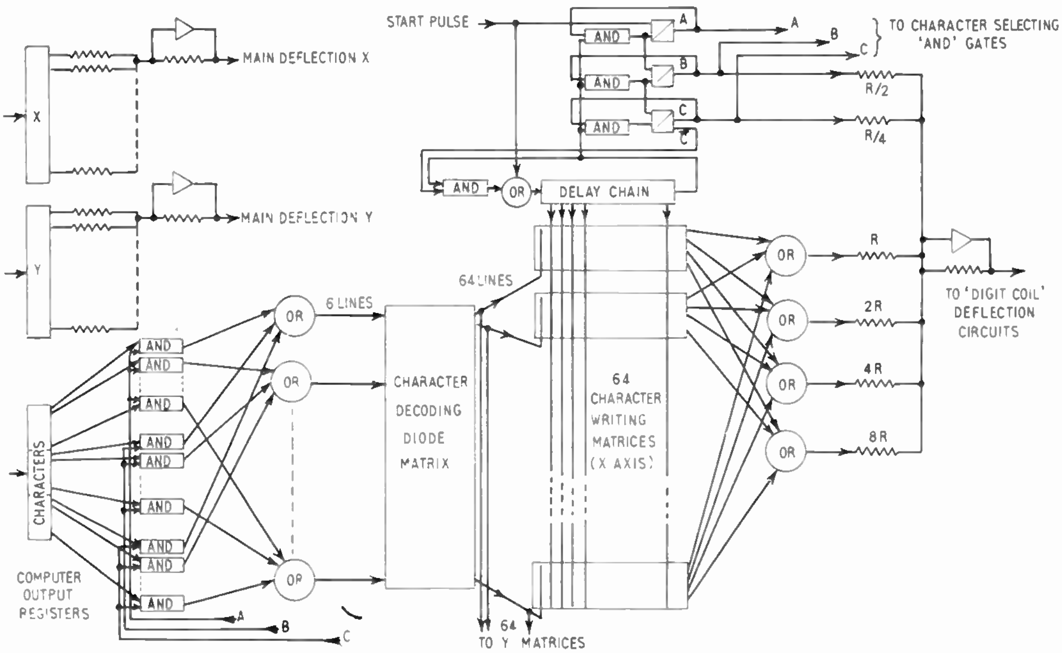

Fig. 2. Schematic diagram of complete character generator.

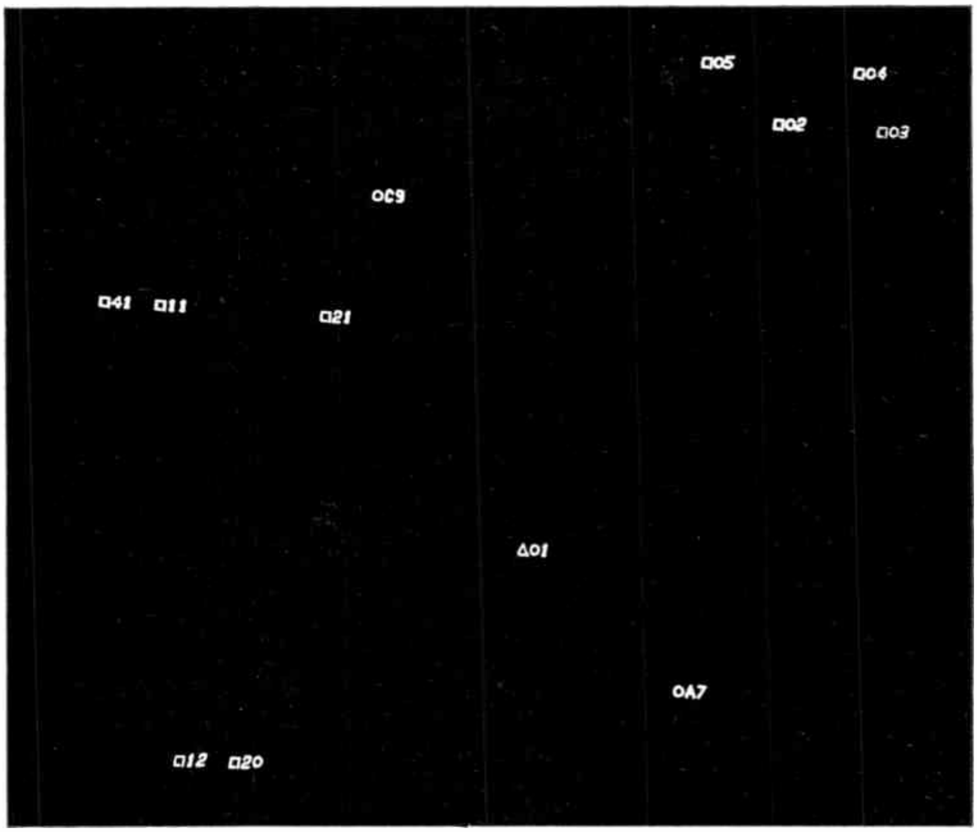

Fig. 3. Photograph of display. The height of the symbols is approximately 3 mm and they are shown here on a 12-inch c.r.t. (CV 429).

radar tube, such as the CV429 with a long persistence phosphor, produces acceptable characters at the speeds indicated here (Fig. 3) but if still higher writing speeds were attempted, it might be necessary to use tubes specially adapted to this type of display.

In order to give the freedom to use less than 15 spots if this is more convenient, no brightening pulse is produced if the digital number representing the spot position in either axis is zero.

3. Conclusion

The need for presenting information to a radar display operator in the form of letters and numerals on the screen of a cathode-ray tube has led to the evaluation of various methods of high-speed character writing. The digital method described in detail provides a computer output medium which comes close to following the high speeds of current machines.

In a particular example of its use in radar systems a group of three characters can be taken from the computer store and displayed in about 300 µs. Writing in page format the equipment would be capable of output speeds reaching, say, one character every 30 µs.

An important advantage of the digital method in large radar display systems lies in the possibility of placing a character-writing di-an at each viewing position. This means that the character-writing signals may be transmitted to each operating position in digital form, and regenerated before application to the di-an. In this way the effect of attenuation and distortion in the signal lines may be minimized.

4. Acknowledgments

The author wishes to thank Mr. R. F. Hansford of Decca Radar Limited for permission to publish this paper, and gratefully acknowledges the helpful discussions with the various members of the Display and Data Laboratory who have been particularly concerned with the different character generating methods described.

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OBITUARY

Archibald Gerald Egginton was before the last war one of the most active members of the Institution. He first joined the Institution soon after its formation in 1925 but strongly opposed the decision to change its name—a subject explained more fully in the Institution's official history.

"Gerry" Egginton campaigned for a reversal to the present name of the Institution and then secured reinstatement and transfer to the class of Member in 1935. The establishment of the Institution's North Western Section before the war was mainly due to his initiative.

He was very proud of his family's ancestry in Lancashire and Cheshire and was associated with a number of activities in those counties. He had been a keen cricketer and was a member of several masonic lodges. His main county affinity was to Cheshire where he was born on 25th June, 1901, and it was the masonic provincial lodge of that county which honoured him with high office just after the war.

As a young boy "Gerry" Egginton had shown interest in radio matters by becoming a registered amateur transmitter. After industrial experience in Trafford Park, he joined his father's business which originally started as a small wireless assembly company. This developed into a thriving concern not only for the distribution of domestic equipment, but for public address systems and radio relay services.

Commissioned in the Royal Air Force on 2nd May 1941, he had a varied Service career in signals operations and in radar development. He retired at the end of the war with the rank of Squadron Leader.

In more recent years Mr. Egginton's activities had been curbed by heart trouble. His main interests became concentrated on freemasonry activities and he was one of the prime movers in the formation of the Clerk Maxwell Lodge No. 7382, in which he was one of the first senior officers.

He died on 20th May, from coronary thrombosis, only a few days after admission to hospital.

"Gerry" Egginton made a host of friends, not only in the Institution but throughout the radio industry, and he will be greatly missed.

G. D. C.

Frank J. Forbes died in July 1961 at the age of 45 years. He was registered as a Student of the Institution in 1949 and by succeeding in the Graduateship Examination in November of that year qualified for transfer to Graduateship in 1950. He was subsequently elected an Associate Member in 1953.

He received his technical education first at the Northampton Engineering College and later at the Northern Polytechnic, and joined the B.B.C. as a Maintenance Engineer in 1942.

Crippled from birth, Mr. Forbes constantly battled against ill-health. This prevented regular employment, but he held several appointments in the radio industry and was, in fact, in active employment with Mullard Ltd. up to the time of his death.

He leaves a widow.

Arthur Frederick Norman Blackburne died on 25th August 1960 at the age of fifty-eight years. He was elected as Associate Member in 1931 and was transferred to full Membership in 1937.

Mr. Blackburne was educated at Hastings Grammar and Municipal Science Schools. In the very early days of broadcasting he started a small wireless assembly business, but in more recent years his interests had been associated with a radio and television distribution business in Sussex.

He leaves a widow.

Charles Nathaniel Albury was born in the Bahamas in February 1912. He registered as a student of the Institution in 1948, and was transferred to the grade of Associate in 1955.

Mr. Albury worked in the Telecommunications Engineering Department of the Bahamas all his life but came to the United Kingdom for practical training in 1947–48. On his return to the Bahamas he was appointed engineer in charge of all radio facilities in the Bahamas, including aeronautical, police, other mobile services, marine and external services.

Mr. Albury died recently whilst visiting some of the outer islands of the Bahamas Group.

Stanley George Turner was born in London in December 1897. He was educated at Aske's Hatcham School and the Borough Polytechnic. During the period 1917 to 1921 he served in the Royal Engineers Signals Service and then joined Burne-Jones & Co. Ltd. as their Chief Technical Engineer.

During the last war Mr. Turner served with the Scientific Experiment and Research Department of the Royal Navy in Cambridge, and for the past eight years held an appointment as Senior Development Engineer with Clarke & Smith Mfg. Co. Ltd. Whilst with this Company he was primarily concerned in the development of the tape talking book cassette for the Royal National Institute for the Blind.

Mr. Turner was elected an Associate of the Institution in January 1934.

He died from a heart attack on the 27th May 1961, and leaves a widow.

U.D.C. 629.136.3 : 629.19

The Engineering Aspects of Satellites and their Launching Rockets

By

G. K. C. PARDOE,

B.Sc., D.L.C.†

Presented at the Convention on "Radio Techniques and Space Research" in Oxford on 5th–8th July 1961.

Summary: The paper discusses the different engineering problems associated with satellites and probes, and their launching rockets. The different set of operating conditions encountered in these two main areas of space technology are examined and the motive power and control problems which arise are dealt with. The basic requirements for the multi-stage launching rockets are discussed; rocket equipment at present under development is then reviewed, noting the limitations imposed by present rocket techniques and launching facilities. Future trends of rocket development are mentioned in relation to possible payloads. The composition of a typical satellite or space probe is then considered, with some attention being given to each of the different systems, such as structure, power, attitude and speed control, instrumentation and communication equipment, etc. Critical design criteria such as weight, and electrical power requirements are highlighted. The operating environment is then related to the choice of design of the various systems. Particular consideration is then given to several specific types of satellites and space probes, examining the differences which arise from the varied requirements, and assessing what integration may be achieved by the design of common systems for the various applications.

1. Introduction

The subject of Space Technology embraces a very diverse number of branches of science and engineering. It brings together in one project a greater range of techniques than ever before and, as so often happens, the dramatic end product on which everyone's attention is so keenly focused is but one small part of the overall system. Indeed, much of the effort, and certainly the money, of such a project is devoted to ground support equipment in factories and on the test sites.

The satellites and space probes and their launching rockets are essentially complementary—neither is of ultimate value without the other. It is true of course that the actual payload in space gives the direct benefit of the experiment—be it for civil, research or for military purposes. It is just as essential, however, that the means to launch such a payload by multi-stage rocket vehicle be developed, and satisfies those people interested in the design of the satellite.

This paper will review some of the engineering aspects concerned both with the launching vehicles and the payloads that they carry into space, and in particular highlight some of the most important and interesting of the new developments required in this technology.

† The De Havilland Aircraft Co. Ltd., London, E.C.1.

2. Launching Rockets

2.1. *General Comments*

Let us initially consider the basic principles involved. The requirement is to accelerate a payload from the surface of the earth up and out of the atmosphere until such a speed and direction is reached that centrifugal force balances the pull of gravity. Figure 1 shows the three different categories of vehicle graded by different velocities. If the take-off speed is below 25 000 ft/s approximately, a steady orbit will not be reached and the vehicle will fall back to earth as a ballistic missile. Between 25 000 and 37 000 ft/s various conditions can be reached, which will determine the precise shape of the orbit. Below the top level of this bracket the speed will be insufficient to create escape conditions from the earth, and the payload will always revolve around our planet. Above 37 000 ft/s, however, the decreasing deceleration effect of the earth's gravitational field is such that the payload will still have a positive velocity away from the earth at infinity, i.e. escape conditions have been generated and the space probe will go into orbit around the sun, the major centre of the extra-terrestrial solar system. We are of course therefore interested in payloads which have been given speeds in excess of about 25 000 ft/s.

The most simple concept is a single large rocket which should be able to take off and accelerate until

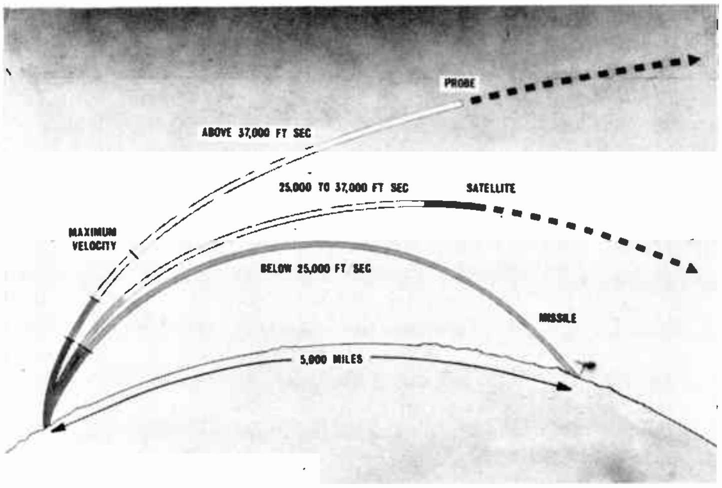


Fig. 1. Ballistic trajectories.

the appropriate speed is reached. At this point the payload is separated from the front end. However, with present limitations of engineering techniques, insufficient rocket engine thrust is available to lift off a single rocket with a tank full of propellant adequate to keep the engines burning long enough to achieve the desired velocity. We are therefore forced to stage the rocket, in other words a large heavy booster first stage provides enough thrust to lift the whole assembly from the ground and accelerate it to a reasonably low speed (say in the region of 12 000 to 15 000 ft/s) through the lower parts of the atmosphere. (This, for the purposes of discussion, ceases to become very embarrassing from a drag point of view at an altitude of 40 nautical miles.) The first stage is then discarded and the second stage with a lower thrust takes over to continue the acceleration. The efficiency of the whole operation depends to a large degree on the staging mass ratios, i.e. the ratios between the mass of the rocket before its engines start burning and the residual mass after the engines stop burning. Ideally the mass ratio of each rocket stage is the same but, in practice, this is often difficult to achieve, either by virtue of the limited choice of rocket engines under development or in the basic difficulties of manufacturing techniques associated with the propellants available. For a typical three-stage vehicle such as the proposed *Blue Streak* combination, with a first-stage mass ratio of nearly 6, the second-stage mass ratio is about 3 and the third-stage ratio of the order of $2\frac{1}{2}$. Velocities attained at the end of each stage are about 12 800 ft/s after the first stage, 19 400 ft/s after the second stage and nearly 25 000 ft/s at the end of the third stage, this being appropriate for a 300-mile circular orbit. Since the first and second stage both have sub-orbital velocities at separation, they will return to the earth and therefore the choice of staging will clearly influence the part of the range in which they fall in relation to the launching point. Population distribution round the world obviously cannot be adjusted to avoid rocket debris from satellite launchings and staging must be selected to some degree to suit the geographical requirements. This is but one example of external factors which influence the choice of launcher design.

Clearly with the large chemical rockets at present in use, engineers are always aiming for minimum vehicle dead-weight and maximum efficiency from the rocket engine and propellants. At present liquid propellants offer greater efficiency in terms of specific impulse than solid propellants. The first generation of ballistic rockets which use liquid oxygen and kerosene—with a specific impulse at sea level of about 245 seconds—are being augmented by other rockets (such as *Centaur*) which have liquid oxygen and liquid hydrogen propellants giving a specific impulse of some 350 seconds. So far as dead weight is concerned the empty weight of a first stage compared with its full weight can be less than 10%, and contains all the structure of the tankage, rocket engines, propellant systems, control, guidance, electrical power generation, etc. This has introduced some very novel design techniques to achieve high strength/weight ratios compared with orthodox aircraft construction. One method has been to produce tanks with single wall thicknesses as low as 15 to 20 thousandths of an inch and made of high tensile stainless steel—stability of these tanks, perhaps 10 ft diameter, being achieved by internal pressurization. In some cases the structural integrity is achieved not only by pressurization but by structural members. Such supplementary structures may well be dictated in certain circumstances by handling or ground running conditions, rather than by flight conditions. Some 70% of the volume of the whole first stage vehicle may be taken up by propellant space, and the actual tanks themselves (which may be in the

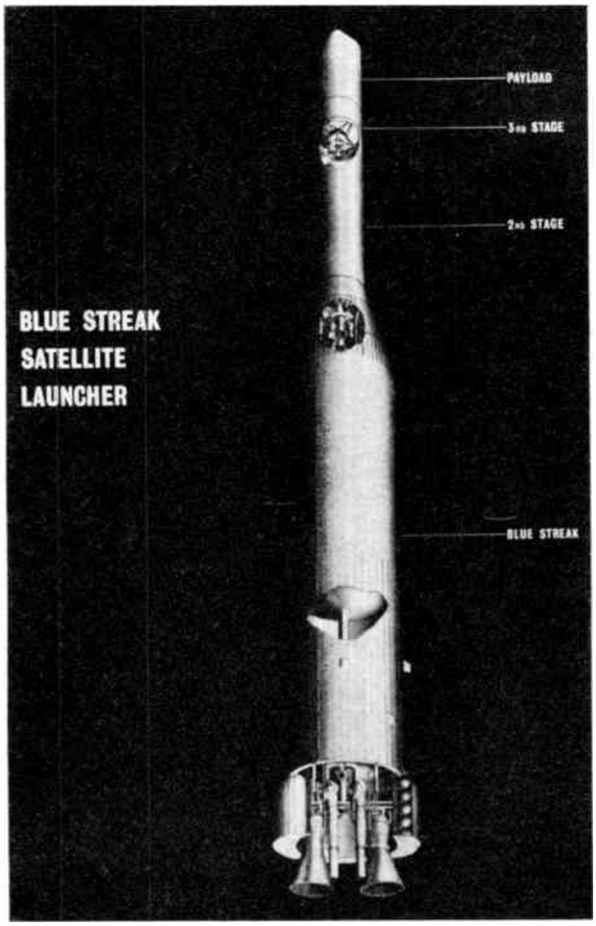


Fig. 2. Cut-away diagram of a *Blue Streak* satellite launcher.

order of 45 or 50 ft long and 10 ft in diameter) may only weigh about one ton.

The main elements in a typical staged rocket vehicle are as shown in Fig. 2. The importance of cutting down dead weight can be seen if one considers that on this typical first stage, every 10 lb of added dead weight causes a reduction in terminal velocity of 2·5 ft/s. The need to reduce dead weight increases in importance as we move up the stages. For example, every added 10 lb weight in the second stage reduces its end velocity after first and second burning by 8·0 ft/s, and every 10 lb weight in the third stage reduces its terminal velocity by 30·5 ft/s. The same penalty applies to weight in the payload. Looked at in a different way, every added 1 lb in weight in the payload of a typical configuration in the present generation of space vehicles requires an extra 25 lb in weight of the whole vehicle standing on the launcher ready to take off in order to achieve the same velocity and therefore orbit capability. The benefits to be reaped both in terms of size and cost of the whole rocket vehicle by minimizing the weight of the payload in particular as well as of the third stage can easily be recognized.

So far as a particular rocket stage is concerned the velocity of burn-out (v_b) is related to the effective exhaust velocity (c) of the rocket and the mass ratio (r_m) by the equation:

$$v_b = c \log_e r_m + v_0$$

where v_0 is vehicle velocity at ignition of the stage considered.

Typical values for liquid fuel rocket exhaust velocities at present are 8000 to 11 000 ft/s, and Fig. 3 shows how the burn-out velocity varies with mass ratio for several exhaust velocities.

The performance that one can derive from a particular design of vehicle is therefore related to the efficiency of the propellant (and by implication the rocket engines together with the structural efficiency and staging ratios). Current generations of rocket launching vehicles are far from ideal since they are largely derived from military vehicles designed initially for ballistic operations, and therefore it often happens that present space vehicles are a combination of optimization and compromise using existing techniques.

The above simplified formula to establish the burn-out velocity of different stages must be reviewed in relation to environment in the sense that the vehicle is lifting off against the full deceleration of gravity in the first part of its ascent before turning over. Indeed during lift-off the first part of the trajectory is vertical to penetrate the dense regions of the atmosphere as quickly as possible, but thereafter in order to reduce the gravity component the vehicle turns over (a typical rate being 0·7 deg/s) and begins to accelerate more in the orbital direction. The rate of turnover

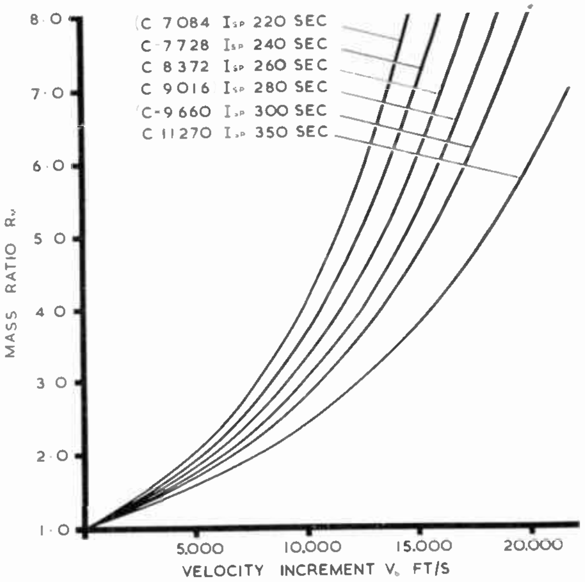


Fig. 3. Variation of velocity with mass ratio and I_{sp}. No losses.

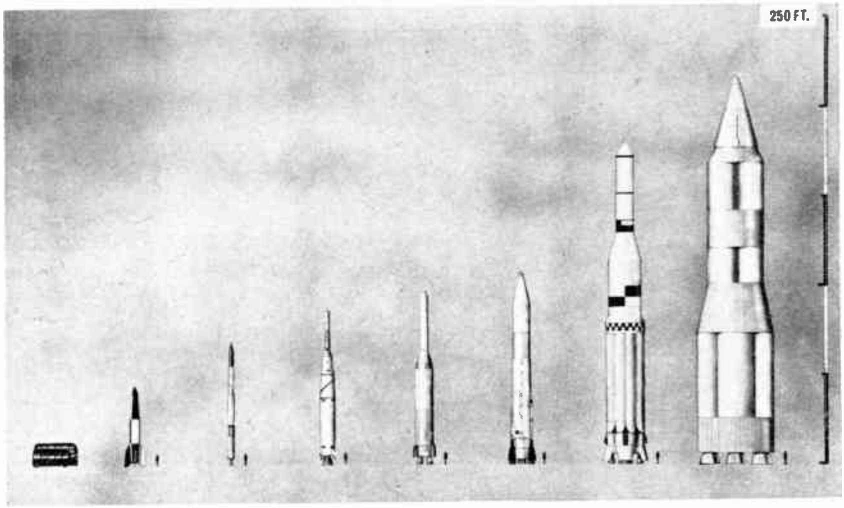


Fig. 4.
Space vehicle evolution.

	V2	Vanguard	Thor Able	Blue Streak	Atlas-Centaur	Saturn	Nova
Launch Weight lb	28 500	22 600	105 000	210 000	300 000	1 160 000	4 500 000
Engine Thrust lb	56 000	28 000	150 000	274 000	360 000	1 504 000	6 000 000
Single Engine Thrust lb	56 000	28 000	150 000	137 000	150 000	188 000	1 500 000

must be related to the physical design of the weapon by virtue of the acceleration loads imposed on a structure which is basically fragile in the lateral direction. It must also be related to the control available from the rocket engines since it is by swivelling these engines that control can most conveniently be achieved outside the atmosphere.

In a typical flight of a rocket into a low circular orbit (say 300 miles) some 2600 ft/s must be considered as gravity loss, in other words the theoretical velocity of the multi-stage rocket must be 2600 ft/s greater to allow for the loss due to gravity during the take-off and turnover before injection into orbit.

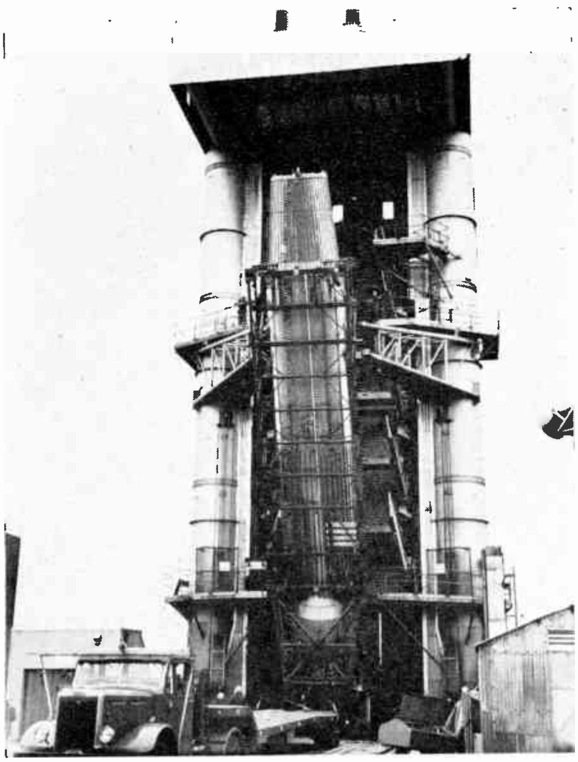
The direction of launch will obviously have a further effect since if the rocket is launched and turns over into an easterly direction, it will receive an appropriate component of the earth's rotational speed. Since it is velocity in relation to space axes which determines the orbital condition, clearly it is of value to take advantage of the earth's rotational speed which on the Equator is about 1500 ft/s. Conversely if one launches in a westerly direction or with a westerly component the effective injection velocity is reduced which means that the size of the rocket must be increased to put a given payload into the same orbit. Often the payload and spent rocket case are separated by the use of springs or small gas jets and are referred to as "mass in orbit". This "mass in orbit" is affected by some 25% from "still earth" conditions as represented by launching into a polar orbit (an orbit which contains the plane of the North and South Pole), i.e. it is 25% greater if fired in an easterly direction, or 25% less if fired in a westerly direction.

2.2. *Practical Cases*

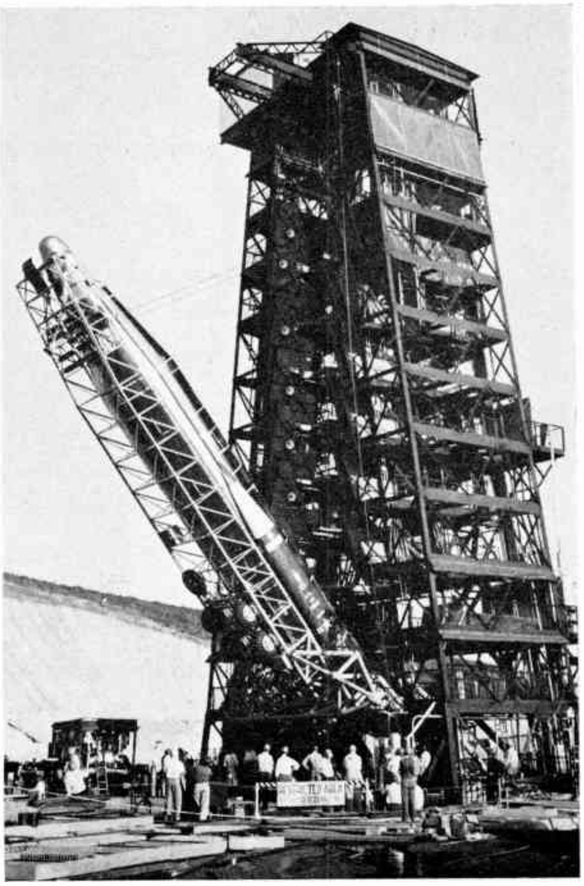
The forerunner of the present rockets was of course the German V2, but this could only achieve a total velocity of some 5000 ft/s. This is clearly far short of orbital capability, even if the payload of a ton warhead were removed and the difference made up with additional fuel. The trend since the V2 days has been one of increasing thrust and improvement in specific impulse of the propellants, together with improvements in the structural overall weight ratio. Figure 4 shows the vehicles of the Western World, some of which have been used to date for space work, together with an indication of their total rocket thrust and how this is composed in terms of single rocket chamber thrust.

Let us consider the sort of environmental conditions that the present generation rockets experience during their life.

These must be considered from the time that they are constructed in the factory. Such large and comparatively fragile devices, until pressurized in the vertical position, must be handled carefully in special frames and transporters from the time the tanks are lifted off the manufacturing track. Two examples of such frames are the *Blue Streak* handling frame and the combined handling frame and road transporter for the *Atlas* missile (Fig. 5). The tanks (and often the complete missile) live for the most of their life horizontally in these special frames and can only be isolated after being raised into the vertical and either supported from servicing towers or pressurized. During their horizontal life the tanks are usually slightly pressurized (at about 5 lb/in.^{2}) to provide local stability and to discourage the entry of contami-



(*a*)



(*b*)

Fig. 5. (*a*) *Blue Streak* in handling frame being raised into a test tower at Spadeadam.
(*b*) *Atlas* missile and its transporter at the Sycamore Canyon test stand, showing the "A" frame pivoting structure required.

nating matter. Indeed this question of cleanliness within the propellant and pneumatic systems of a typical space vehicle is extremely important, and it has been said that a very high percentage of the cost of manufacturing and subsequent checking of a missile, is devoted to the thorough cleaning and inspection of those parts of the system which will contain fluids. Certainly the required degree of cleanliness demands special purging systems which are incorporated as permanent parts of the system, during the long cycle of activity on test and launching sites. During transportation (which in the case of British rockets involves carriage by land, sea and air to Woomera) different loading conditions are experienced by the components from those encountered in flight. For example, problems arise due to the fact that transportation time for a tank to Australia can be several months and means must be provided for maintaining a small internal pressure in the tank. This must not exceed certain limits and must not reverse any of the pressure differentials which occur across the critical parts of the structure.

Now, what of the applications of the rockets presently in use? The relatively small *Vanguard* rocket (length 72 ft, lift-off weight 22 600 lb), was designed principally for space exploration work and in particular for activity during the International Geophysical Year 1957–58. It did not have military priority and therefore was not subjected to the same intensive development drive more generally associated with military rockets. It was not particularly successful in its early days although it eventually placed three satellites into orbit during 1957–59. Its payload, however, was limited to a few tens of pounds in weight in elliptical orbits (typically 300–2300 miles) and it has not been used for space experiments since September 1959.

The present American booster for small payloads is a four-stage solid-fuel rocket, designated *Scout*, also designed exclusively for space work. This rocket is of particular interest to this country as it is, of course, the means of launching the American Satellites carrying British instrumentation. The first of these, which we designate *U.K.1* and the Americans designate S51 is programmed to be launched into space early in 1962. *Scout* weighs 36 100 lb at launch and is a total of 72 ft in height. The payload is limited to about 150 lb into a 300-mile circular orbit around the earth.

Table 1
The Payload Capabilities of Several American Satellite Launching Vehicles

VEHICLE	TYPICAL PAYLOAD – LB					
	CIRCULAR EARTH ORBIT				ESCAPE	LUNAR MISSION
	300 MILE	500 MILE	1000 MILE	24 HOUR		
VANGUARD			50 – 100			
SCOUT	150 – 200			32		
JUNO I			30			
THOR - ABLE	300			120	95	
THOR-ABLE STAR		265 — 500				
THOR - DELTA	500-600		130 – 150		60 - 65	
THOR -AGENA A	1700					
THOR-AGENA B	2100		1000			
JUNO 2	100	90			15	
ATLAS-AGENA B	5800		3000		800	200 - 800
ATLAS-CENTAUR	8500		6000		1450	
SATURN C-I	20 000 -25 000				6000 - 9000	1000 -2000
SATURN C-2	45 000				15 000	
NOVA SERIES 6-12 MILL. LB. THRUST	150 000 290 000			60 000		15 000 20 000

It is specifically associated with research experiments as opposed to broad direct applications of use of space. More recently there have been some proposals to increase the payload capability of *Scout* to some degree (about 40%) by the use of improved propellants in the third and fourth stages. There has, however, been a proposal by the Hughes Corporation of America to use a modified *Scout* rocket with two further stages as a means of placing a 32 lb communication satellite into a 24-hour equatorial orbit. This appears to be rather a marginal proposition, as with the low power of *Scout* a tremendous amount of development would have to be put into such a light-weight satellite in order to achieve reasonable reliability and capacity. Moreover, so marginal is the *Scout* capability in this case that the proposal is inherently based on creating a new launching site on the Equator. Any launching site away from the Equator becomes very embarrassing in terms of using energy, since, after take-off, one of the upper stages must induce a large lateral velocity to change the launching orbital plane into the required Equatorial orbit plane. This process is expensive in terms of energy and imposes a reduction in payload. It would seem therefore that apart from this one specific ingenious but marginally valid case, this order of size of rocket is limited to scientific applications.

The modified military *Jupiter C* rocket has become a very successful space probe and satellite launcher designated *Juno I*, and later *Juno II*. Up to May 1961 it had launched seven satellites into orbit and one probe into space. Again, however, it is not of large capability. *Juno II* has a total height of about 76 ft and its lift-off weight equipped with small upper stages is 122 000 lb. Into a nominal 300 miles circular orbit around the earth, it is capable of placing a payload in the order of 100 lb and into space payloads of 13·4 lb can be contemplated.

The next space launcher in the American arsenal is *Thor* which by itself is not capable of placing payloads into orbit. However, when equipped with various stages such as *Able*, *Able Star*, or *Agena B* it has been used for a variety of missions. Its capability is again limited to payloads in low circular orbits in the order of hundreds of pounds in weight and Table 1 shows how this capability fits in with the others previously referred to.

The remaining vehicle with orbital capability at present in use in America is the *Atlas* missile; this when stripped down can actually place itself in orbit and did so in the course of project SCORE. This was the exercise in which it carried aloft a receiver, tape recorder and a transmitter which beamed a pre-recorded message by President Eisenhower from orbit for the first time. Subsequently as many as seven teletype messages were transmitted to the vehicle and later relayed on command during its month in orbit. However, *Atlas*'s more general application has been when fitted with *Agena B* or *Able Star* as a second stage.

It is of interest to consider the general state of reliability which these various rocket vehicles have achieved. Figure 6 shows this broken down, project by project, and it can be seen that the *Juno II* and *Thor-Agena* series have reached by May 1961 reasonable states of reliability, being represented by a fairly high percentage of success of placing payloads in orbit : in the case of *Juno II* 43% success, in the case of *Thor-Agena* 70%. The merit of concentrating development on a single launching vehicle can readily be seen from such an analysis.

In the same way there is every confidence that in Britain the 100% success so far experienced by the nine *Black Knight* firings to May 1961 will be repeated to the same degree with the *Blue Streak* firings when they are approved. Thus in concentrating the development on a single type of launching vehicle there is every indication that one can achieve reliability figures much higher than the average experienced to date in the Western World's space attempts.

2.3. *Future Trends of Rocket Vehicle Development*

Since this paper is discussing the engineering aspects of rocket vehicles it is not appropriate to go into a full review of the vehicles under development in the Western World for the next ten years. However, it is significant to examine again this chart (Fig. 4) which includes the anticipated overall growth of rockets with particular reference to the *Saturn* project previously mentioned. In its first C1 configuration *Saturn* still uses present generation techniques of propellants and rocket engines, its lift-off thrust is achieved by grouping eight engines of a similar type to that used in the single engined *Thor* using liquid oxygen and kerosene as propellant. However, upper stages take advantage of later developments and for the C1 configuration the liquid oxygen/liquid hydrogen second and third stages will provide very high capabilities for payload injections into orbit or space probes. This vehicle will be extended by the insertion of an additional stage between the first and second stages which will produce the C2 configuration which will come into operation in 1967–1970. This for the first time will represent a capability approaching that necessary to land reasonably large capsules on to the moon and return them again to earth. It is the C2 configuration of *Saturn* which holds the first promise to the Western World of sending a man to the moon. Its lift-off thrust is 1½ million pounds and its total height is 240 ft.

The final rocket on the right is worth mentioning, for one of its engineering features (apart from its massive size and weight), namely the advent of four single chambers each producing 1½ million pounds of thrust. This will be derived from an engine designated F1 being developed by the North American Aviation Company and represents an order of improvement in single chamber thrust from contemporary engines.

As a point of interest the consumption of each engine is in the region of 3 tons of fuel per second, and the associated turbo-pump is rated at 60 000 horse-power (equivalent to the engine capacity of a small cruiser). The first tests on this engine took place in February this year. The design thrust was slightly

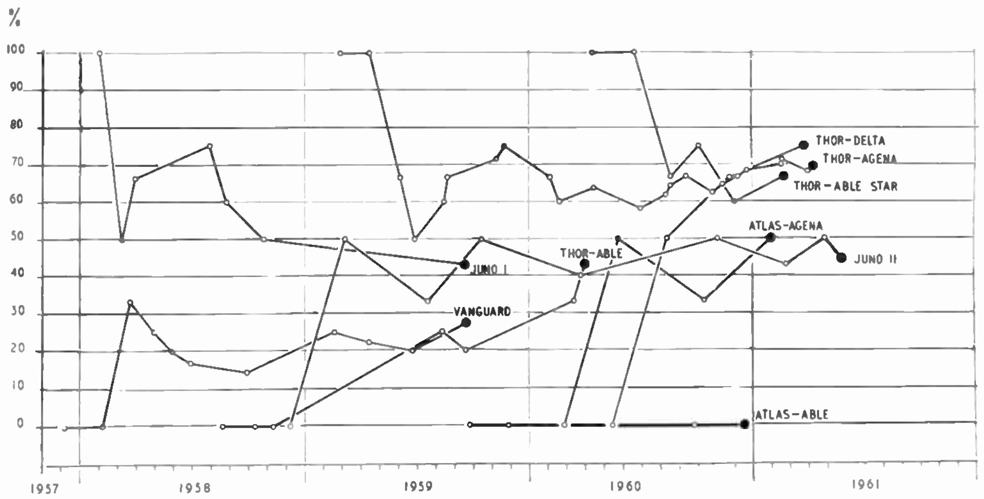


Fig. 6. Rocket vehicle reliability expressed as a percentage of successful orbits in number fired.

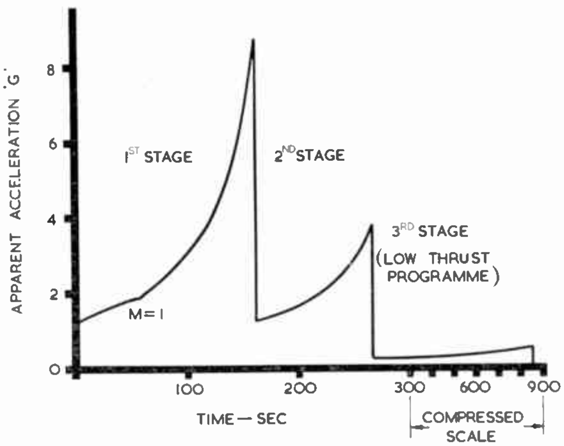


Fig. 7. Typical longitudinal acceleration against time for a three-stage vehicle based on *Blue Streak*.

exceeded, a figure of 1 550 000 lb being delivered for a few seconds. It does, however, still use liquid oxygen and kerosene as its propellant and one wonders therefore whether this *Nova* project as such will ever be used, since the new generation of propellants such as liquid hydrogen/liquid oxygen and the various boron derivatives would seem to be a far better choice for the later developments in this decade. It may well be therefore that the F1 engine development will represent a little too much stretch in contemporary techniques.

Future propulsion systems would seem to be veering away from conventional chemical techniques. The first and largest of these is the nuclear propulsion system of which the American project ROVER is a prime example. In this case heat for thrust generation is derived by a nuclear heat exchanger using liquid hydrogen raised to 4000° F as a working fluid. Thrust levels in the order of 50 000 lb weight are contemplated. Clearly project ROVER is the forerunner of a long line of developments of this type of rocket motor which does certainly combine reasonably high thrust levels with high specific impulses, the later being of the order of 800 seconds.

Even further into the future come the electric drive engines, typified by the ion type motor which depends on the acceleration of charged particles for the generation thrust. The efficiency of these engines is extremely high, as represented by specific impulses which are now in the region of 2000–3000 seconds, but unfortunately the thrust levels available are extremely low, being measured in terms of 10^{-2} lb. For the moment these ion engines are strictly limited to very low acceleration of vehicles already under zero gravity conditions outside a planet's atmosphere, and as such could be useful once a space probe is on the way. They are also of course potentially available for orbital work where small speed attitude corrections are required.

Looking even further into the future it does seem that a major break through must be contemplated in the basic techniques of energy transformation since all contemporary techniques, including the electric drive, depend on accelerating mass and producing momentum change. This has inevitably involved carrying large propellant masses for a given rocket mission.

2.4. *Some Engineering Features in the Current Generation of Rocket Vehicles*

Some idea of the typical orders of acceleration and environment within the rocket vehicle is given in Figs. 7 and 8. Elements in a rocket vehicle are subjected to rough treatment. However, the sheer size of the vehicle provides considerable attenuation in certain areas remote from the engines and thus particularly sensitive components can be carried in fairly comfortable conditions.

Injection of a payload into certain orbits demands that the motors of the various stages of the missile are not burned continuously or consecutively from the time of take-off. They require to have what is termed "interrupted burning capability", that is to say one particular stage may be required to burn for some time then shut down and coast, possibly for many hours, and then light up again. Within present techniques this can only readily be done with liquid fuel engines and the very fact that they are liquid fuel engines generates certain difficulties. The coasting phase clearly is in a weightless condition, and experiments have been carried out to show that propellants fairly rapidly dissociate into a froth-like composition, mixing with the ullage content of the fuel tanks. This process starts within a few seconds of

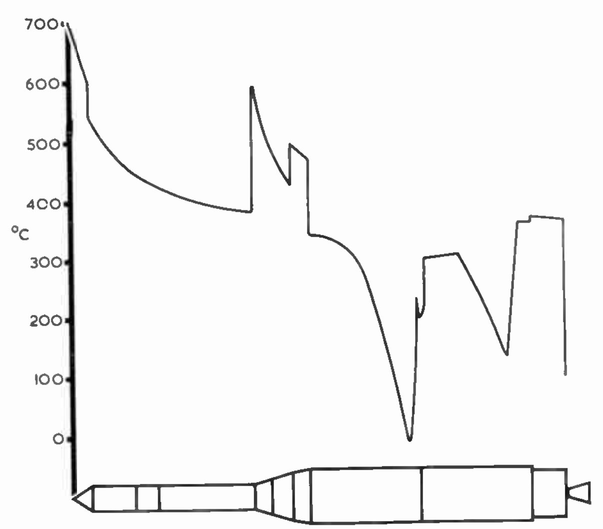


Fig. 8. Typical enclosure of maximum skin temperatures based on a three-stage vehicle.

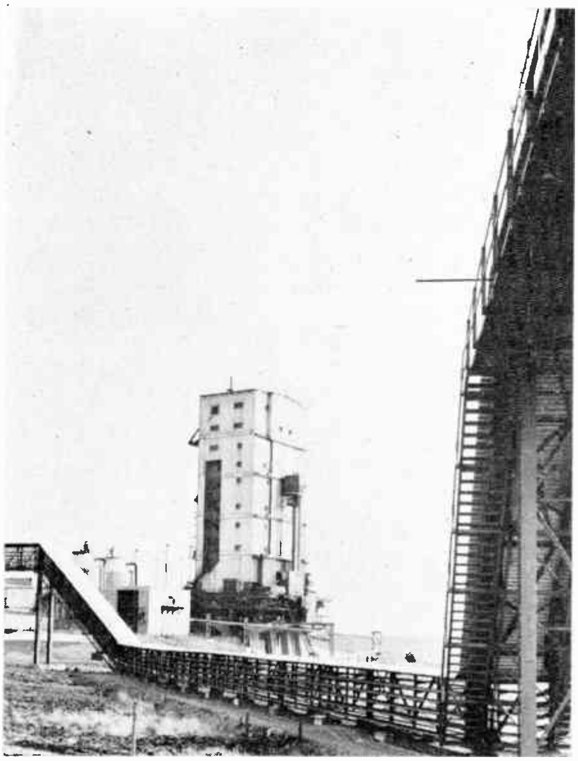
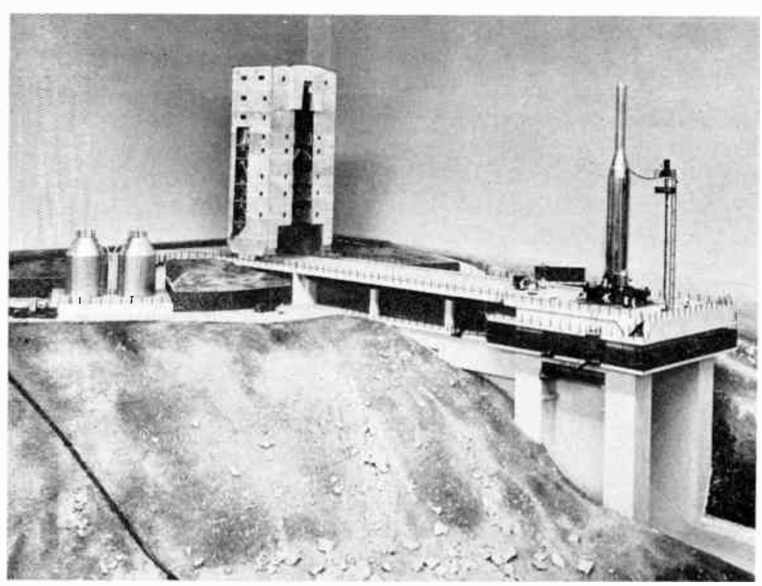


Fig. 9. Spadeadam C site. In the foreground is part of the cable ducting required for instrumentation purposes.

zero *g* and certainly complete dissociation into the froth-like composition is achieved before the engine is required to be re-lit. This frothy state is worsened if the propellants are of high energy such as liquid oxygen or liquid hydrogen, which are also boiling off. Such a froth is completely unsatisfactory to feed the engine thrust chambers when they need to be re-lit. This poses an interesting problem and various solutions have been suggested. One is to use small solid rocket engines to provide an acceleration period before relighting the liquid fuel engines, the acceleration tending to re-generate the liquid at the bottom of the tank which will at least get the rocket engines started. However, this can be very difficult if dissociation is complete, since the size and length of firing of these regeneration rockets is such that they constitute a severe embarrassment. Another method considered uses electrically driven centrifugal liquid regenerators to provide enough priming liquids for the rocket engines to start. A third method is to store a limited amount of fuel in a fluid accumulator; since there is no ullage space in such a device, no frothing will occur and liquid fuel is thus available for instantly restarting.

A further word on launching sites associated with these rockets. Mention has already been made of the American proposal for a new site on the Equator for launching satellites into Equatorial orbit. It is of interest to note that Americans are approximately 28 degrees North of the Equator at the nearest point with their Cape Canaveral site, and the Commonwealth has its Woomera site in Australia some 31 degrees South of the Equator, both of which have the same order of penalty or, alternatively, the same order of assistance in relation to the Equatorial surface speed. As well as the American suggestion of Jarvis Island which is 2 degrees away from the Equator, there are further suitable islands in the Commonwealth, which are also being considered as possible launching sites. Unfortunately these launching sites for space work are highly complicated and expensive, certainly as far as launching liquid fuel rockets are concerned. It is

Fig. 10.
A model of the *Blue Streak* launching stand at Woomera.



not only the actual site itself, but all the range facilities must be considered which are required to enable the rockets to be suitably tracked after their take-off, turnover, and transition phase before going into orbit. For range safety measures, impact areas for first and possibly second stages must be allocated and a fool-proof remote destruction mechanism with a radio-command link installed.

Typical arrangements for a possible *Blue Streak* launching from Woomera would allow the first stage to impact nearly 1000 nautical miles from the launcher (i.e. the Gulf of Carpentaria) and the second stage would land in the Pacific Ocean some 2750 nautical miles from the launcher. There seems little doubt though that before the next decade is past some more advanced plans will be forthcoming for the creation of Equatorial launching sites, possibly for international use in some instances. It should be emphasized that the majority of effort in space activity goes into the building, equipping and operating of a launching site. Typical examples of such facilities are shown by these photographs of some of the test stands at Spadeadam, Cumberland, used in the *Blue Streak* development and one of the launching pads at Woomera, Australia, intended for *Blue Streak* (Figs. 9 and 10). Not only the creation of the launching and range facilities but also the necessary industrial support, provision of water, electricity, the generation of propellants on site, etc., play a very important part in the logistics of space activity.

We have touched on the developments we may see in terms of propulsion systems; a further derivation of this may well be the advent of recoverable rockets principally in the booster stage. A considerable amount of work is going on in America on the design of such vehicles which may well be manned and piloted back to earth in what can best be described as a relatively conventional manner. Clearly the work which will be done on the manned *Dyna-Soar* space vehicle project which will be flight tested on the *Titan II* vehicle in about 1963 will yield tremendous experience in the problem of aerodynamic controlled re-entry as opposed to the ballistic type re-entry experienced by the Americans in their project MERCURY, and previously achieved by the Russians with Major Gagarin's flight in *Vostock*.

It will readily be appreciated that the problems involved in recoverable boosters are immense. The vehicle involved may well be up to 100 ft long and 30 ft diameter and weigh 40 to 50 tons. The system employed must not impair the performance during the launching and separation phases and the final landing must be sufficiently gentle to avoid any serious damage. Since the landing may generally be in sea-water, great care must be taken in the choice of construction materials to minimize corrosion.

The question is, above all, one of economics, as a system to meet these requirements will undoubtedly prove extremely costly to develop and operate. Before the unit can be used again it will be necessary completely to strip, inspect and re-assemble the entire assembly, having replaced any damaged components. Since labour costs are, in general, far higher than material costs, the system will only prove economic for relatively large units and high rates of launching.

Once orbiting space stations exist, the higher rate of firings involved will render the prospect of recoverable boosters far more attractive.

3. Satellites and Space Probes

3.1. *Basic Requirements for a Satellite or Space Probe*

We define a satellite as a body describing a closed orbit round the earth, as against a space probe which leaves the gravitational zone of this earth and goes into orbit around the sun before perhaps joining an orbit around another planet or one of its moons. One essential difference between present generation satellites and space probes is that the probe will be of a scientific nature for many years to come whereas satellites are already being considered for direct civil, commercial and military applications.

A space probe must be equipped with a communication system suitable for the transmission of data over many hundreds of millions of miles during transition times between planets measured in terms of months or years. Earth orbiting satellites will never be more than thousands or at the most hundreds of thousands of miles from the earth, thus the transmission problem is eased although a longer service life may well be required. A space probe and a typical satellite are similar, in the sense that they have an overall structure which contains or supports an electrical power generation system. The power so created feeds electronic equipment, e.g. radio receivers and transmitters, and may also serve electronic equipment controlling attitude stabilization or speed control rocket gear.

If a satellite needs to be recovered or a space probe needs to be landed on another planet, then it is equipped not only with low thrust capability attitude control, or speed control equipment but also with larger thrust producing systems. In the case of the space probe these serve to inject the probe into orbit around the planet or its moon, and then to perform a controlled descent to the surface of the planet. This requirement for a space probe becomes even more complicated if the probe is required to take off again, since its descent and landing attitude must be held to more rigorous limits.

The comparisons between the systems required in a space probe or satellite is shown in Table 2. Considering the various systems in rather more detail:

Table 2

SPACE-PROBE AND SATELLITE SYSTEM REQUIREMENTS

N = NECESSARY P = POSSIBLE

FUNCTION		SPACE PROBE	HARD LANDING PROBE	SOFT LANDING PROBE	RECOVERABLE LANDING PROBE	REAL TIME COMMUNICATION SATELLITE	DELAYED TIME COMMUNICATION SATELLITE	NAVIGATION SATELLITE	METEOROLOGICAL SATELLITE	ASTRONOMICAL SATELLITE	RECONNAISSANCE SATELLITE
TELEMETRY		N	N	N	N	P	P	P	N	N	P
POWER		N	N	N	N	N	N	N	N	N	N
ATTITUDE DETECTORS		P	N	N	N	P	P		N	N	N
COMMAND LINK		N	N	N	N	P	N	N	N	N	N
LONG RANGE OPTICS		P								N	N
TV LINK		P	P	N	N				N	N	N
STABLE FREQUENCY REFERENCE SOURCE								N			
ENGINE RE-START OR RETRO ROCKETS		P	N	N	N	P	P			P	P
GAS JETS OR REACTION WHEELS		P	N	N	N	P	P		N	N	N
AERIAL SYSTEM	DIRECTIONAL					N OR N	N OR N				N
	OMNI-DIRECTIONAL	N	N	N	N			N	N	N	
DE-SPIN		P	P	N	N	P	P	N	P	N	P
INSTRUMENTATION		N	N	N	N	P	P	P	N	N	P
RECORDING SYSTEM	DATA				P		N	N	N	P	N
	VIDEO				P				N		N
	PHOTO-GRAPHIC				P						P
RE-ENTRY SYSTEM					N						P

3.1.1. Telemetry

The American f.m./f.m. and f.m./a.m. systems with radiated powers up to 60 mW have given excellent results for ranges up to 3000 miles. Another system employed used digitally modulated sub-carriers and phase modulation in the transmitter together with phase-locked-loop receivers on the ground.[1]

3.1.2. Power

At present the silicon solar cell is pre-eminent in the field of space power supplies. However, due to the low conversion efficiencies obtainable large areas are required for even moderate powers. Since output power varies approximately as the cosine of the angle of incidence of the radiation, the most common methods of dealing with the changing direction to the sun are: (1) cover the whole surface of the satellite with cells, or (2) provide paddles which are so angled as to provide a certain proportion of the cells normal to the incident radiation. Both schemes have a maximum effective area/total area ratio of 25% and have been frequently described.[e.g. 2,3,4,5]

An obvious improvement would be to employ a single sided panel which is held perpendicular to the incident radiation by simple position servos. However, the mechanical reaction problems are considerable and one must also balance the increased power available against the consumption of the servo units; long life requirements are also made more difficult. Much work is proceeding on these problems in America and to some extent in this country. One view which has been expressed holds that the break-even point for orientation is for powers in the region of 200 W.

Temperature rise of the cells due to incident energy which cannot be converted tends to lower efficiency. Various coatings have been proposed[6, 7, 8] in order to improve the cell characteristics and afford some additional protection against radiation and micrometeorite bombardment.

The values quoted in Table 3 give some idea of the levels of radiation expected. Work on measuring these levels is still proceeding in America and the majority of authorities are rather cautious about quoting firm figures. Glass slides 0·038 in. thick will stop 12 MeV protons (compare 0·0035 in. for 3 MeV protons). Electrons up to 800 keV require 0·065 in. of glass. Photographs have recently appeared in the press of satellites embodying synthetic sapphire cover glasses, but figures showing the effect of these on solar cell life in a true space environment are not yet available.

In general it seems that it is possible to protect cells against radiation other than that present in the inner Van Allen belt. *Vanguard I* is still orbiting through the lower belt and functioning but it is believed that the conversion efficiency of the cells employed has now dropped from an initial 10% to 2½%.

It would thus seem that the only available method of coping with inner belt conditions is to increase the size of the solar array in order that the deteriorated output is still adequate.

General erosion of the paddle surfaces by micrometeorites presents some problem but this may be alleviated by oxide coating the cover glass surface. This finish may usefully be combined with the emissivity control coating.

Work is proceeding on a variety of alternative methods of obtaining electrical power including nuclear, thermoelectric, thermionic and photochemical processes.[9]

3.1.3. Attitude detectors

When required for earth orbiting satellites, horizon detectors employing infra-red sensitive cells would seem to be the obvious choice and most schemes so

Table 3
Satellite Environmental Conditions

Temperature:

(a) During launch mean temperatures of up to 70° C with short term peaks of up to 475° C may be encountered.
(b) During orbit the temperature encountered is a function of satellite design and will most likely lie in the range 0 to +45° C.

Vibration:

(a) During launch vibration at frequencies up to 2000 c/s may be experienced with amplitudes up to 14*g*.
(b) During orbit it is anticipated that vibration, if present, will be of a transient nature and of negligible amplitude.

Steady Acceleration:

During launch, the satellite should survive acceleration of the following orders:
(a) longitudinal (fore-aft) 20*g*
(b) longitudinal (aft-fore) 5*g*
(c) transverse 5*g*

Vacuum:

The satellite must function under a continuous vacuum of 10^{-12} mm of mercury.

Spin at Injection:

It is common for the satellite to be spinning immediately prior to entry into orbit. A typical figure is 120 rev/min.

Micrometeorites:

Let mass of micrometeorite be m

where 10^{-13} grammes $< m \leqslant 10^{-3}$ grammes

Two types may be encountered:
(1) Sporadic (velocity 10–70 km/s)
(2) Micrometeorite streams (velocity approx. 35 km/s)

For type (1)

$$\text{Space density} = \frac{4\times 10^{-22}}{m}\ \text{cm}^{-3}$$

For type (2)

$$\text{Space density} = 4\times 10^{19}\left(\frac{10^{-3}}{m}\right)^{0\cdot 66}\ \text{cm}^{-3}$$

Radiation:

Typical figures for an orbit passing through the the outer and inner Van Allen belts with more time in the latter are:

	Protons ($E > 40$ MeV)	Electrons ($E > 600$ keV)
Average intensity	2×10^{4} cm^{-2}. s^{-1}	10^{8} cm^{-2}. s^{-1}
Integrated flux per week	$8{\cdot}5\times 10^{9}$ proton. cm^{-2}	5×10^{13} electron. cm^{-2}

far proposed or employed have used this technique which can resolve 1 deg of arc without difficulty.

Closely coupled with the question of attitude detection is the problem of correcting attitude if it should be other than that desired. Two methods are in common use. The first uses a jet of gas expelled from a suitable orifice on the satellite's surface, the reaction so produced rotating the satellite. In order to bring the satellite to rest again, a second correction in the opposite direction is necessary.

The second method uses reaction wheels. These are flywheels arranged to cover the three principal areas. The angular momentum of the satellite is constant and thus any variation in the rotational speed of the flywheel (i.e. change in angular momentum) produces a corresponding change in the angular momentum of the satellite. The induced angular velocity is, of course, inversely proportional to the ratio of the moments of inertia. Such a scheme has a tendency to saturate if confronted with cumulative rotational errors and the two methods are often combined, the reaction jets serving to de-saturate the flywheels when this is necessary.

A rather ingenious reaction wheel system has been proposed by Bendix Aviation Corporation.[10] This employs a steel sphere rotated by the torque produced by three mutually perpendicular windings. The system has no bearings and no gyroscopic moments are introduced to the vehicle. The single sphere will correct for all three axes.

A further scheme is being considered using the earth's gravitational field as the control medium. A body orbiting the earth will tend to settle with its principal axis along the local vertical as demonstrated most forcibly by the moon. Any tendency to depart from this position will produce a torque acting on the lever arms in such a manner as to restore the original state. By producing a "dumb-bell" shaped satellite with the heavy items located at the extremities, this effect can be enhanced.

3.1.4. Command link

The functions of this system are often interlinked with the telemetry system. A good example of this is quoted by Taber.[1]

3.1.5. Optical system

This system will generally operate in conjunction with a television link back to earth. The elements will, in general, form a telescope which will, in the case of the astronomical satellite be focused on a heavenly body, and in the case of a reconnaissance satellite be focused on the ground. Present day telescope size limits appear to be about 18 in. diameter and satellites for these have yet to be launched.

3.1.6. Television link

This should follow conventional lines except that the resolution required will be of a far higher order. In the case of the reconnaissance satellite a compromise must be reached between the lines of successive tracks and the field of view of the camera optical system should anything approaching continuous coverage be contemplated.

3.1.7. Stable frequency reference source

This is most necessary in the case of the navigational satellite. Two schemes have been proposed.[11, 12, 13] The first of these is the *Transit* system. Here the Doppler shift of the transmission is measured and corrected for ionospheric refraction. This information together with an approximate idea of the observers position will provide a position fix to better them one half mile. The basic transmission frequency must be held to one part in 10^8 during the pass of the satellite in order to obtain this accuracy.

The second scheme measures the received delay between two homologous pulses, one transmitted by the satellite and the other developed by a clock at the position of the observer. The desirable clock stability is also one part in 10^8. The positional calculation is somewhat similar.

3.1.8. Retro-rockets

These are required where some form of entry or re-entry into a planet's atmosphere is contemplated. Their action is to provide an impulse in opposition to the direction of travel of the satellite and to lower the re-entry speed through the upper levels of the atmosphere.

3.1.9. Aerials

To date the omni-directional aerial has normally been employed. Simple rod aerials using the satellite as a ground plane have been widely used with excellent results. Their use is by no means restricted to v.h.f.

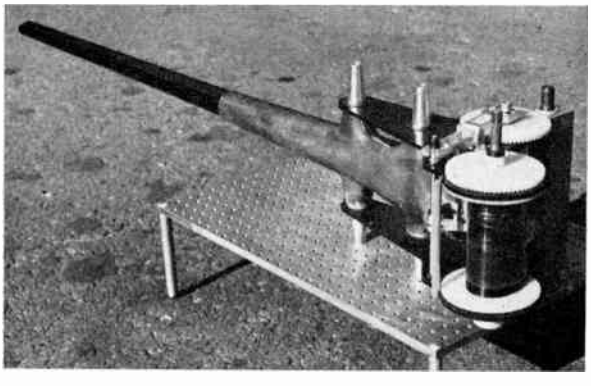


Fig. 11. An antenna erection unit for the Canadian topside sounder satellite, S-27.

work since by the use of a rather ingenious device light-weight, self-erecting aerials up to 100 ft. in length may be employed.[14] Figure 11 shows such an aerial (75 ft. long) developed by De Havilland Aircraft of Canada Limited. The aerial (dark tube on left) is in the process of being erected. The basic unit is 20 in. long. Another technique employed[15] has been to produce a slot aerial by spraying metal on the surface of the satellite in such a manner as to leave an equi-angular spiral slot.

The majority of proposals for communication satellites have involved the use of some form of directional aerial usually a horn or parabolic dish. The extra complexity involved in orientation is more than compensated by the consequent permissible reduction in transmitter power.

3.1.10. Engine re-start

This function is really part of the command link system and the difficulties associated with propellant feed have previously been covered.

The *Agena B* series of satellites incorporate engine re-start facilities which have functioned successfully. The propellants employed are unsymmetrical dimethyl hydrazine and inhibited red-fuming nitric acid, which feed a single chambered, gimballed, engine. Re-start has been accomplished by using solid propellant charges to spin the turbo-pump and also provide a small kick to coalesce the weightless fluids.

The use of such techniques in transfer orbits has been previously mentioned. The method may also be employed in conjunction with reaction jets to provide the velocity corrections required to ensure station keeping in the required orbit. In other cases such corrections are provided by reaction jets alone.

3.1.11. De-spin

In order to remove any residual spin several systems have been successfully employed. A typical method used in *Transit 1B* employed weights attached to the ends of two short cables. These were wrapped round the satellite's mid-section. On command the weights were released and centrifugal force caused them to fly outwards to the length of the cables thus arresting the satellite's spin. At the extreme position the end of the cable was unlatched to prevent rotation being developed in the opposite direction. A second scheme used eight thin nickel iron bars mounted across the satellite. The material had a high permeability and also a large hysteresis loss. The bars, being acted upon by a component of the earth's field, became magnetized and the high hysteresis opposed any effective reversal of the earth's field produced by spin. In a typical case a spin of 2·6 rev/s was reduced to 0·04 rev/s in seven days. This scheme has now replaced the weight method since it is so simple, reliable and effective.

3.1.12. Instrumentation

Great progress in this type of work has been achieved in the United States and work in *U.K.1* will surely yield most rewarding results.

4. Integration of Equipment

It can be seen that various systems are indeed common to most applications, principally electrical power generation, radio transmitter and attitude control gear. It would therefore be most desirable if, within an integrated space programme, a common carrier concept could be conceived whereby a basic structure, electrical power generation system, attitude speed control system, and data transmission equipment, together with the antenna arrays could be produced for different payload content as applied to research, communication, meteorology, etc. Unfortunately more careful consideration of the requirements for each of these missions often suggests that while certain sub-systems can undoubtedly be shared between different applications, the accuracy dictated by specific requirements is such that only a limited measure of integration can be contemplated. There is no doubt, however, that techniques developed for attitude stabilization and speed control will have broad application, but for example the attitude control required for a communication satellite with directional antenna beam down towards the earth may be measured in terms of a few degrees accuracy of stabilization, whereas for an astronomical laboratory, certainly the optical system looking out into space would be required to be stabilized to a few seconds of arc.

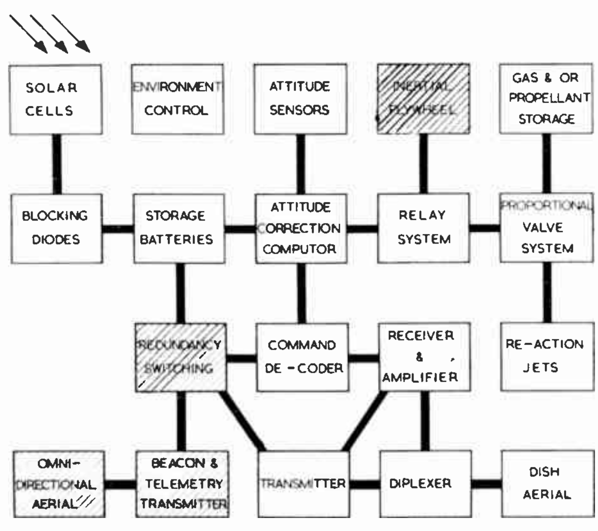


Fig. 12. Block diagram of an hypothetical communication satellite. The shaded areas indicate systems that may be eliminated.

Figure 12 shows a block diagram of a hypothetical communication satellite illustrating a typical combination of systems. Two systems of attitude control are shown as are telemetry and redundant (i.e. reserve) equipment. The arrangement may be considerably simplified as shown by the non-shaded area which indicates the minimum standard. As may be seen, attitude control is now by reaction jets (a well tried and proven system). The satellite beacon transmitter (for ground tracking stations) can be dispensed with if the unmodulated carrier of the satellite is used for tracking. Since ground reception of the satellite in use will be via a narrow-beam orientated aerial there should be no interference between the two carriers thus removing any necessity for muting. The simplified scheme, however, involves the penalty of total failure should any one item malfunction.

Certain factors have considerable influence in the design and choice of these systems. The first is the ever-present need to minimize weight. It is worth recalling the relationship mentioned earlier that, for *Blue Streak* every pound of satellite to be placed in (say a 300 mile circular) orbit an added 25 lb of total rocket vehicle take-off weight is required. It can therefore be seen that, as well as struggling for efficiency in launching vehicles, tremendous dividends can be obtained from minimizing weight in the satellite. As has been shown in certain instances elimination of whole systems is feasible by the use of specific techniques. As a rule of thumb it may be taken that about 20% of the total permissible weight of the satellite is available for the communication equipment (including aerials). In the simplified type of satellite the proportion would be somewhat greater.

The second critical factor in contemporary space probes and satellites is the electrical power generation system. The solar cell systems at present widely used demand large and relatively heavy arrays (possibly solar seeking, thus involving attendant drive requirements) and at the moment it costs approximately £500 per watt for power generation by non-orientated solar cell systems. It is clear that a long life high efficiency/weight ratio system will pay handsome dividends in terms of payload capability.

Consider the environment that a satellite and its equipment experience. After the stresses encountered during the launching phase as discussed in a previous section, a satellite in orbit is in an extremely steady state so far as physical loads are concerned: these will be zero except perhaps at such time as attitude stabilization or speed control systems may be operated. It is, however, possibly subjected to a varying temperature environment, caused by any rotation it may have when in direct vision of the sun. This temperature cycling will again be influenced as the satellite in orbit goes into the shadow of the earth and various systems have been proposed and indeed employed for establishing heat balance in the satellite.[16, 17] One of these is typified by the *Able V* system[18] which consists of many vanes covering or exposing different painted areas of the surface of the satellite, the coverage of the vanes being related to the surface temperature reached. Further insulation inside the vehicle establishes a reasonable environment for some of the more critical parts of the equipment. Table 3 gives typical environmental conditions within a satellite established in an earth orbit.

5. Final Comments

We have reviewed therefore various aspects involved in the whole wide spectrum of engineering activity involved in space technology. Most of these different aspects are interdependent in a complex manner and as always happens, some are far more advanced in technique than others. At the moment certain aspects seem out of proportion perhaps, one example being the cost of producing a very modest amount of electrical power for a satellite; for example in a three-stage vehicle which may well cost something in the order of £1 000 000 including the satellite, the solar cells account for almost an eighth of this sum. There would thus seem to be a very good case for the develoment of more efficient and cheaper electrical power sources for use in space. Low weight high reliability electronics particularly that concerned with radio communication will play a vital part in the evolution of space equipment for satellites and space probes and to some degree in the development of launching vehicles. Control system engineering will clearly also be of importance in both vehicle and satellite design, particularly in the case of communication satellites where long life and high reliability coupled with low weight and power requirements are essential in a system destined to play a paramount part in world communication. This will undoubtedly be the first direct use of space by the world at large and will also be the first example of how this new space technology will yield large financial returns to support and justify the enormous investment which will be necessary to establish such new engineering techniques.

The requirements of space have already stimulated great advances in techniques associated with electronics in particular, quite apart from the "rocketry" in general. In the electronic field for example no mention has been made of the microminiaturization of equipment which, although it was started in principle as a result of guided weapon requirements, has become a vital part of space electronics. There are many other points which in the time have had to be ignored. In any case the whole field of activity is so rapidly expanding we may look forward to many new directions of progress within this space era.

6. Acknowledgments

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A report of the discussion which followed the reading of this paper will be published in a subsequent issue of the *Journal*.

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Solar Cells for Communication Satellites in the Van Allen Belt

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Presented at the Convention on "Radio Techniques and Space Research" in Oxford on 5th–8th July 1961.

Summary: The power output of solar cells on satellites passing through the Van Allen belt is constantly degraded due to the radiation damage. It thus becomes necessary to optimize the power output of the solar plant not initially but at a later time in the satellite life.

The effect of the radiation environment on the expected life of solar cells has been investigated by electron and proton bombardment studies. Based on these experiments *n*-on-*p* solar cells have been specially developed for communication satellites. These cells have a moderate initial efficiency and are made very blue-sensitive, since the response to short wavelength light is considerably more resistant to radiation than the response to long wavelength light.

A shielding of 0·25 g/cm^2 has been found to eliminate the effect of electron irradiation with energies up to 1 MeV. Since most, if not all, electrons in the Van Allen belt have energies of less than 1 MeV, a transparent protection of moderate weight can eliminate radiation damage due to electrons. For a typical orbit passing through the inner Van Allen belt, studies under proton bombardment indicate conversion efficiencies of approximately 8% after one year and on the order of 5% after 10 years. With such conversion efficiencies, long life communication satellites appear feasible with presently available solar cells.

1. Introduction

The communication satellites presently planned by the A.T.&T. Company are designed as real time repeaters for transoceanic telephone and television transmission. Sufficiently long periods of mutual visibility between Europe and America set lower limits to the altitude of these satellites at several thousand miles. At these altitudes the satellites are exposed to the radiation environment of the Van Allen belt.

The high energy electron and proton radiation in the Van Allen belt produces defects in semi-conductors which decrease the minority carrier lifetime and alter the conductivity of the material. After sufficient bombardment, these effects cause a reduction in transistor current-gain, diode rectification efficiency, and solar cell power output. The most pronounced changes occur in devices requiring a high minority carrier lifetime for their performance. Silicon solar cells require a high lifetime and are the most sensitive semi-conductor components in a satellite. The degradation with radiation will set a limit to the available power as a function of time. The solar plant has to be designed with radiation damage in mind, and it becomes necessary to optimize the power output of the solar plant, not initially but at a later time in the satellite life.

This paper discusses in detail the considerations entering in the design of a solar plant for long life satellites exposed to the radiation environment of the Van Allen belt. In Section 2 data on Van Allen radiation are interpreted, Section 3 reviews solar cell theory, Section 4 describes the design of the solar cell developed for satellite application at Bell Telephone Laboratories, and in Section 5 the bombardment studies on these solar cells are given. These studies, in combination with the radiation environment assumptions given in Section 2, permit prediction of the solar cell performance in time as a function of exposure to Van Allen radiation.

2. The Van Allen Radiation

Since the damage rate in semi-conductors depends critically upon the energy as well as the flux of the incoming particles, the energy distribution both for electrons and for protons must be known. Available information on the energy dependence of electron and proton flux is still meagre.

† Bell Telephone Laboratories Inc, Murray Hill, New Jersey.

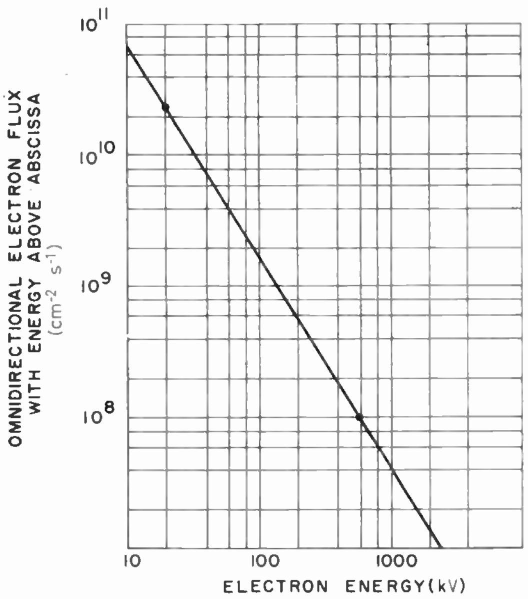

Fig. 1. Electron spectrum in inner Van Allen belt.

The best estimates given by Van Allen for electrons in the heart of the inner Van Allen belt are:[1]

(1) Electrons with energy > 20 keV maximum omni-directional intensity approximately $2{\cdot}5 \times 10^{10}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$.

(2) Electrons with energy > 600 keV maximum omni-directional intensity approximately $1 \times 10^{8}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$.

A crude approximation to the electron spectrum encountered in the inner Van Allen belt is derived by plotting these two points on log-log paper and connecting them by a straight line. This is shown in Fig. 1. Recent experiments by Holly and Johnson[2] indicate that the spectrum at the high energy end falls off even more rapidly. This lends support to the prevailing theory that the origin of these electrons is in the radioactive decay of the neutron albedo. Electrons of such origin should show a cutoff in their spectrum at 780 keV. For the present study, however, a spectrum of the electron component in the inner Van Allen belt as given in Fig. 1 is assumed. The spatial distribution of the electrons has been obtained by Van Allen and is shown in Fig. 2.

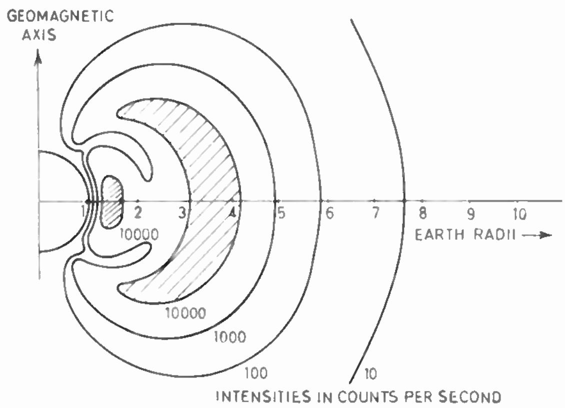

Fig. 2. Electron intensity contours.

The proton flux for energies above 40 MeV was reported by Van Allen from satellite counter measurements.[1] He gives a value of 2×10^{4} protons $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ in the heart of the inner belt. The energy dependence of the proton intensity has been measured by analyzing nuclear emulsions flown in rockets. The first such experiment was performed by Freden and White,[3] and a recent experiment has been reported by Naugle and Fichtel.[4] In both cases, the trajectory of the rocket took the nuclear emulsions only into the lower fringes of the Van Allen belt. Figure 3 shows the differential spectrum observed in these two experiments. The dashed portion of the curve marked " Freden and White " represents a theoretical extrapolation.

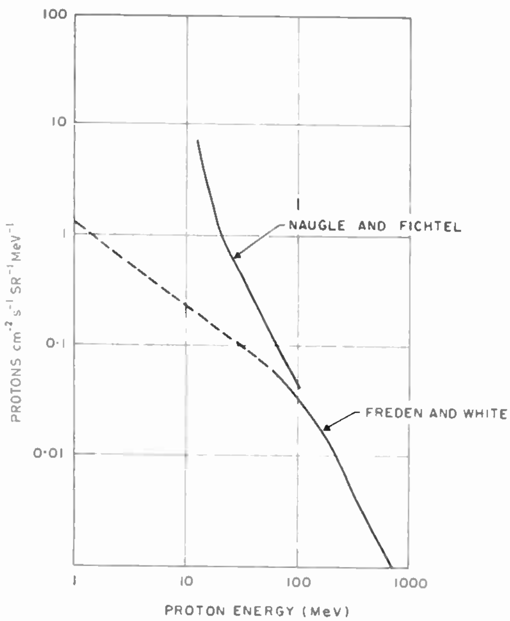

Fig. 3. Experimental proton spectra.

Combining the experimental sections of the two curves and constructing the integral spectrum results in the distribution shown in the lower curve of Fig. 4. This figure gives an omni-directional flux under the assumption that the proton flux is isotropic. As can be seen, the integrated flux at 40 MeV is below the counter measurement of 2×10^{4} protons $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$. This, however, can be expected, since the nuclear emulsions were carried only into the lower fringes of the Van

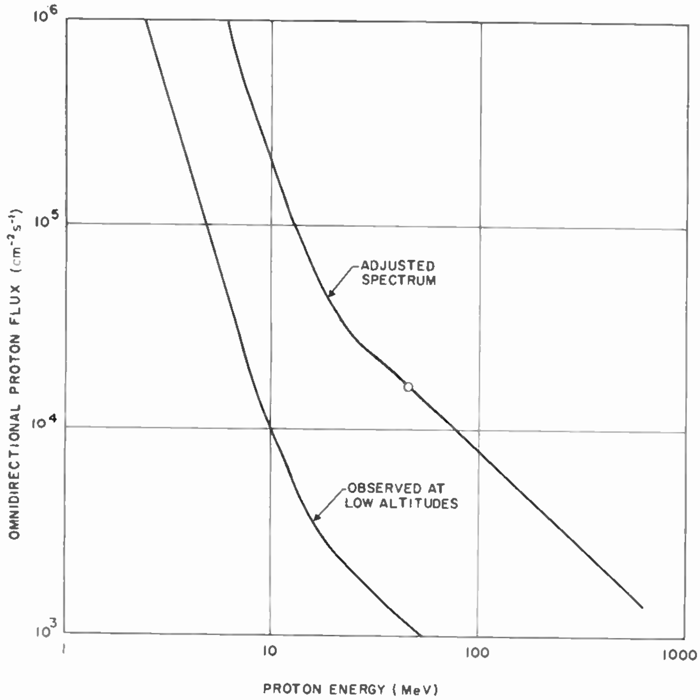

Fig. 4. Integral proton spectrum in inner Van Allen belt.

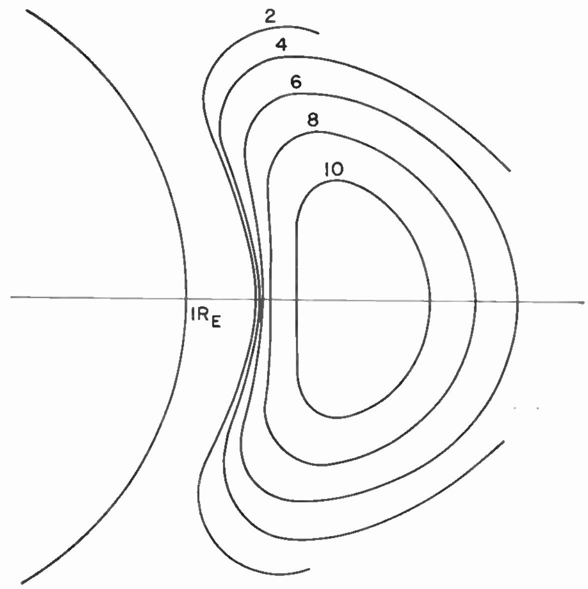

Fig. 5. Theoretical proton contours.

Allen belt. To estimate the energy dependence of the proton flux at higher altitudes, one is forced to assume a spectrum similar to that observed at the lower altitudes, but with the intensity increased by a factor of 12·5 at each energy so that the curve will pass through the point determined by counter measurements at higher altitudes. Such a curve is shown in Fig. 4 as the upper curve.

The spatial variation of the proton flux, at present, can only be deduced from theory. Figure 5 gives the dependence according to Singer.[5] The intensity ratio between the nuclear emulsion results and the satellite measurements are in approximate agreement with this spatial dependence.

3. Review of Solar Cell Theory

An extended theoretical review of solar cells can be found in a paper by Kleinman.[6] Following the main points of his description, the solar cell and the power losses within the solar cell can be described as follows:

(1) Some solar radiation incident upon the surface is reflected without entering the cell. This reflection can be a very important loss, since the reflectivity of clean silicon is about 34 per cent in the wavelength range of interest. The application of anti-reflection coatings reduces this loss. The angle of incidence of illumination is an important parameter in the design theory of anti-reflection coatings. This must be taken into account for satellites, since most solar cells are not irradiated at normal incidence, unless a steerable array is used.

(2) After the light enters the cell, some is absorbed by the intrinsic absorption process in which a hole-electron pair is created and a photon is destroyed. The light absorbed in this way is the useful light. Light of wavelength longer than the intrinsic absorption edge cannot produce a hole-electron pair and is wasted. There is further waste of energy when hole-electron pairs are produced by photons with more than the minimum energy, since the excess energy is transferred in a very short time to the semi-conductor lattice in the form of heat. Both of these losses may be ascribed to the spectrum of the solar radiation, since they would not occur if the radiation were monochromatic at the wavelength of the absorption edge. For silicon, the losses due to the wide range of wavelengths in the solar spectrum are about 53 per cent of the energy which enters the cell.

(3) Some of the minority carriers, produced by the light, flow by diffusion to the *p-n* junction and contribute to the output current of the cell. Other carriers diffuse away from the junction and recombine at the surface or deep inside the cell. The percentage of minority carriers contributing to the current is called the collection efficiency. Long wavelength (red) light generates carriers up to hundreds of microns inside a semi-conductor. Collection of these minority carriers at the *p-n* junction requires that they diffuse to the

junction before they recombine. They must therefore have a very long diffusion length and a correspondingly long minority carrier lifetime.

As mentioned before this lifetime is very susceptible to radiation damage. Thus, the radiation damage is expected to affect primarily the response to red light. In order to minimize the effect of radiation damage, an attempt can be made either to minimize the effect of reduction in minority carrier lifetime or to maximize the carrier mobility. Because the electron diffusion coefficient is about three times that for holes, the latter condition suggests electrons as the minority carriers; in other words, it calls for an *n*-on-*p* rather than a *p*-on-*n* solar cell, provided that the first condition does not dominate.

Under short wavelength (blue) light illumination, the carriers are generated very close to (less than one micron from) the surface and thus are most susceptible to surface recombination. To increase the collection efficiency for these carriers, very shallow junctions are desirable. Since these carriers have to travel only short distances, the collection efficiency for them is relatively radiation independent. Thus, it becomes apparent that solar cells with a predominantly blue response are less radiation sensitive.

(4) Diffusion maintains an excess concentration of minority carriers on both sides of the junction. The voltage developed by the solar cell is due to this excess concentration of minority. This voltage, however, is considerably less than the energy (in units of electron volts) required to create a hole-electron pair in the semi-conductor. The latter may be taken to be the energy gap, which in silicon is 1·2 volts. The voltage of the silicon solar cell in full sunlight under maximum power conditions is only about 0·45 volt. Therefore, the cell is able to convert only a portion of the energy stored as hole-electron pairs into electrical work. This loss may be referred to as the junction loss.

(5) Finally, there is the loss due to the resistance of the very thin surface layer above the junction and to the resistance of the contact to the surface. Because layer resistance rises as the layer becomes thinner, this loss will increase as the junction is made closer to the surface. As discussed before, for a radiation-insensitive, blue-sensitive solar cell, a very shallow junction is desirable. A proper compromise must therefore be found between the resistive losses and the blue sensitivity. The application of contact " fingers " to the solar cells substantially reduces this loss.

The first-order effect associated with particle radiation damage is a significant reduction in collection efficiency. The junction loss also increases with exposure to nuclear radiation. However, its dependence on the bombardment flux is not as pronounced as the dependence of the collection efficiency. Accordingly the design of radiation resistant solar cells has to concentrate on minimizing the degradation in short circuit current, which is proportional to the collection efficiency.

4. Specific Solar Cell Design

Understanding of the cell operation and the effect of radiation damage on spectral response must be taken into account in the specific cell design. Subject to constraints imposed to minimize radiation damage effects, the power output of the cell is made as large as possible. As discussed previously, the short wavelength (green to ultra-violet) performance is most important in determining power output after prolonged radiation exposure, while the response in the red is found to be less radiation sensitive for *n*-on-*p* cells than it is for *p*-on-*n* cells. This difference was first pointed out by Mandelkorn[7] and is now firmly established. Thus an optimum silicon solar cell for longlife service in a radiation environment incorporates the following design features:

(1) *n*-on-*p* structure.

(2) Maximum power conversion of solar energy received in the blue-green region of the spectrum.

(3) Optimum features of the design which are not radiation sensitive.

(4) Coordinated over-all design of the cell, including protective cover, mounting arrangements, and operating load voltage, to provide maximum performance at end of life, after prolonged radiation exposure.

Feasibility development of satisfactory *n*-on-*p* cell structures has required consideration of material requirements, diffusion technology, and methods of contact application. Optimization of blue-green response has been achieved by using a very shallow (0·25 micron) diffused *n*-layer, by careful attention to the quality of the silicon surface, and by optimizing the anti-reflection coating for the spectral region of importance.

Optimization of features in the structure which are not radiation sensitive is of great importance. This is because a gain in response by such design is fully effective throughout the life of the satellite. Optimization of these features is accomplished in the following ways:

(1) Maintenance of " good " cell surface structure to minimize surface recombination losses.

(2) Design of optimum contact arrangements to minimize series-resistive losses introduced by high *n*-layer sheet resistance. The high sheet resistance results from the very shallow layer required for good spectral response.

(3) Choice of best semi-conductor body resistivity.

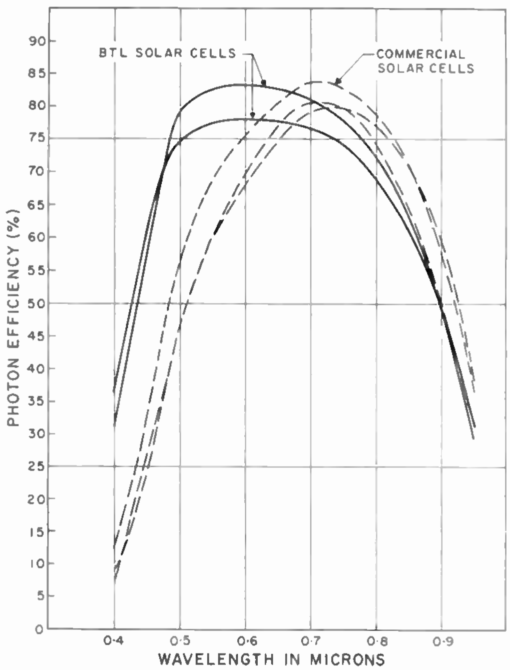

Fig. 6. Spectral response of solar cells.

(4) Minimization of reflection and transmission losses exterior to the cells.

The *n*-on-*p* solar cell developed at Bell Telephone Laboratories has a width, length, and general contact arrangements as previously used for *p*-on-*n* cells for satellites.

The cell is fabricated from a slab of single crystal *p*-type silicon, of resistivity near 1 ohm-cm. It has been found that, in the neighbourhood of this resistivity, the highest efficiency solar cell can be made. The reason for this is that the general trend for the junction loss is an increase with increasing resistivity. For the collection efficiency, the general trend is the opposite; that is, the collection efficiency is more likely to be high in high-resistivity material and low in low-resistivity material. Thus, an optimum power conversion is expected in a medium-resistivity cell.

The performance of these cells, in sunlight and at ground level, is about equivalent to that of the better *p*-on-*n* commercial cells. The acceptance limit in the fabrication of the cells is such that the solar cells can be fabricated with reasonable yield. A comparison of the spectral response of these cells with high efficiency commercial *p*-on-*n* cells is shown in Fig. 6. The superior performance at short wavelength becomes apparent.

A proper assessment of a solar cell under outer space illumination can not be made by just stating the conversion efficiency, measured inside the atmosphere, since the increase in response in leaving the atmosphere depends on the spectral response of the solar cells. Blue sensitive cells in particular will show a relatively higher increase in response than do the red sensitive cells.

To avoid this uncertainty it is preferred to quote the actual power output per solar cell under outer space illumination. This power can readily be obtained from measurements under any illumination, once the short-circuit current under outer space illumination is known.

For a determination of the short-circuit current of solar cells under solar illumination outside the atmosphere, the short-circuit current of solar cells has been measured concurrently with spectral recordings of the solar spectrum at the Table Mountain installation of the Smithsonian Astrophysical Observatory. From prior measurements of the solar spectrum through various airmasses, the zero airmass solar spectrum can be obtained in a well established manner. These measurements, combined with laboratory measurements of the spectral response of solar cells, permit an accurate extrapolation of the short circuit current for zero airmass illumination.

A number of solar cells having widely different spectral response curves have been calibrated by this method. Using these cells as reference it has been found that the median of 92 cells selected at random from a group of 1000 cells delivers 19·2 mW without anti-reflection coatings. Application of an anti-reflection coating raises this number by at least 25% to 24 mW. The active area of these cells is 1·78 cm^2. The conversion efficiency evaluated under solar illumination corresponds to 8·6% and 10·7% respectively.

These measurements and the bombardment studies to be reported in the next section were carried out on cells without anti-reflection coating.

5. Bombardment Studies

A quantitative determination of the damage rate of ionizing irradiation on the collection efficiency is ordinarily carried out by evaluating the degradation of the short-circuit current measured under constant illumination. Using this method, it is important to recognize the dependence of the results on the spectral composition of the illumination. Hence, in order to evaluate the rate of degradation, it is necessary to illuminate the cell with the light under which the cell is going to be used or with calibrated sources of monochromatic light of various wavelengths, a method heavily relied on in the studies to be reported in this section.

As pointed out before the diffusion length is the most important parameter controlling the collection efficiency. A measurement of the diffusion length is easily done under electron bombardment. Electrons are a very penetrating radiation that not only introduces radiation damage but also produces hole-electron pairs. Since the radiation is very penetrating, the hole-electron pairs are generated essentially uniformly throughout the active region. The short-circuit current collected under electron bombardment accordingly is proportional to diffusion length, provided the diffusion length is large compared to the layer thickness. In these studies this condition was always met.

5.1. *Electrons*

In the first set of electron bombardment measurements, the change in the significant characteristics of the aforementioned 92 solar cells was investigated. By moving the cells through the electron beam 23 cells were bombarded simultaneously, thus assuring uniform bombardment dose. Before and between each bombardment step the following quantities were measured in an automatic testing installation:

(1) Short-circuit current response with monochromatic illumination of eight different wavelengths.

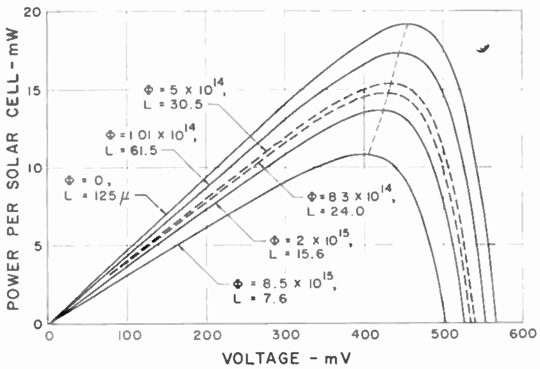

Fig. 7. Solar cell characteristics under electron bombardment (Median of 92 cells, except dashed curves which are the median of 46 cells).

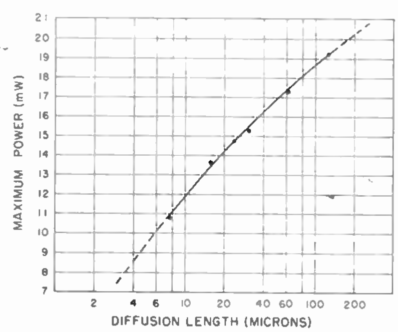

Fig. 8. Dependence of maximum power on diffusion length.

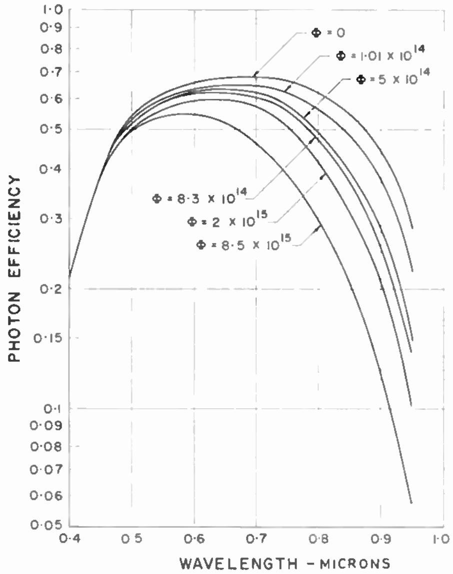

Fig. 9. Spectral response under electron bombardment.

(2) Short-circuit current response under tungsten filament illumination, filtered by heat absorbing glass.

(3) Current delivered into 0·45 V under illumination as in (2).

(4) Current delivered into 0·35 V under illumination as in (2).

(5) Open-circuit voltage under illumination as in (2).

From these measurements the median power output versus voltage under outer space illumination was constructed and is shown for the various bombardment levels in Fig. 7. Besides the electron fluxes the corresponding diffusion lengths are marked. The reduction in the maximum power point and its shift to smaller voltages becomes apparent. The relation between maximum power and diffusion length is shown in Fig. 8. With this relation simple diffusion length measurements under radiations other than electrons can be interpreted in terms of actual solar cell performance.

Figure 9 gives the spectral response curves corresponding to the various bombardment steps. It very clearly demonstrates that the long wavelength response is most sensitive to radiation.

In a further experiment, electron bombardments were carried out at four energies, 0·4, 0·6, 0·8, and 1·0 MeV according to a schedule which simulated the inner Van Allen belt as given in Section 2. The irradiation at the first three energies was given in dosages which were in proportion to the fluxes in the 0·2-MeV interval they represented. The 1-MeV irradiation was given in such a proportion as to represent the entire flux above 0·9 MeV. For these

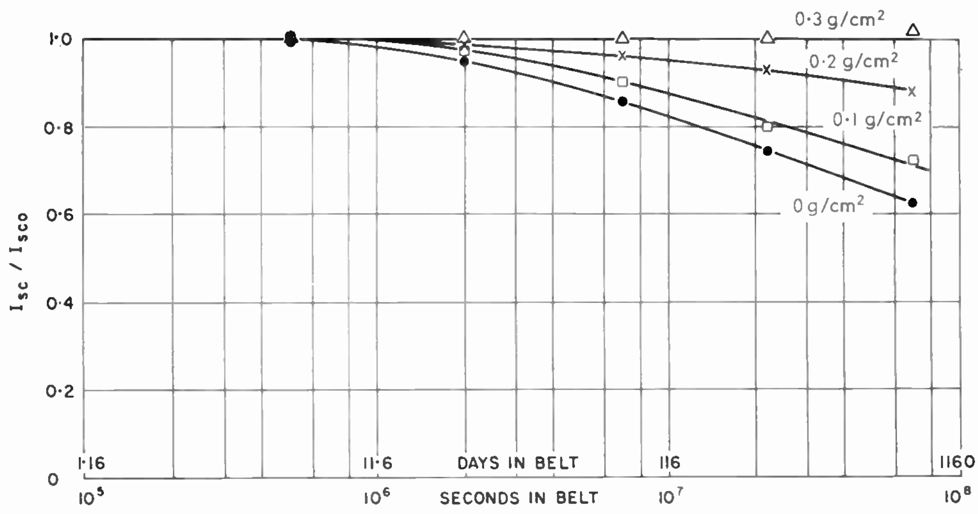

Fig. 10. Degradation of short-circuit current as a function of shield thickness.

experiments, four essentially identical 1-cm² samples were used. Three of the four cells were covered by sapphire covers of thicknesses corresponding to 0·1, 0·2, and 0·3 g/cm²; the fourth cell remained uncovered. The results are shown in Fig. 10, which is a plot of the short-circuit current existing under tungsten illumination normalized to the initial short-circuit current versus the log of time in the inner Van Allen belt.

This experiment permits a correlation between the damage of the Van Allen belt mixture under various shield thicknesses and the flux of 1-MeV electrons producing damage in unshielded solar cells. For this experiment an evaluation under tungsten light is meaningful, since one is interested in establishing for various thicknesses of protection the relative flux levels to produce identical damage.

The result of such an evaluation is shown in Fig. 11. The equivalent 1-MeV flux drops to zero for a shield thickness corresponding to ~ 0·25 g/cm². The question of having properly represented the Van Allen spectrum remains. If there should be significant fluxes above 1 MeV, electron radiation damage is expected with 0·3 g/cm² shield thicknesses also. Furthermore, the results for the thinner shields would be modified also. However, if there are no electrons of energies above 1 MeV in the Van Allen belt, then moderate shield thicknesses will entirely eliminate radiation damage effects due to electrons. If the origin of these electrons is the radioactive decay of the neutrons, the maximum energy, as mentioned previously, will be below 1 MeV. In this case a shielding of even less than 0·25 g/cm² will eliminate the radiation damage effects due to electrons.

5.2. *Protons*

The experiments performed under proton bombardment concentrated on a study of the diffusion length degradation for various proton energies. The details of this study would lead beyond the scope of the present paper and only the pertinent results of this work will be quoted here.

By determining the rate at which the diffusion length is degraded under various proton energies, the solar cell performance under a mixed radiation can be calculated from the results obtained under electron bombardment (Fig. 8). For such analysis to be valid it has been assumed that:

(1) The effects of the various radiations are additive.

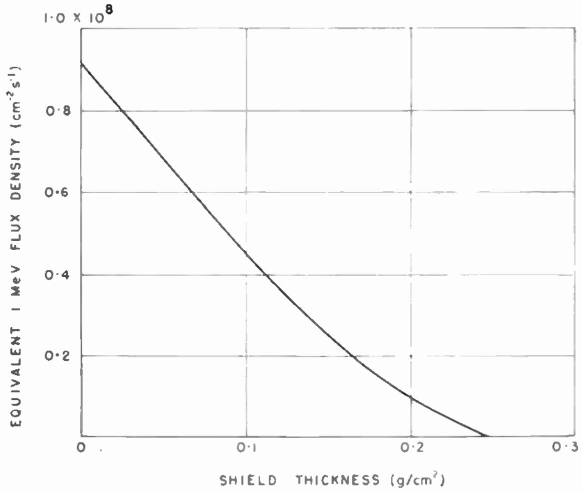

Fig. 11. Equivalent flux versus shield thickness.

(2) For a given solar cell structure the performance is a unique function of the diffusion length, no matter by what radiation he diffusion length was reduced.

Both assumptions have been carefully checked and found to be valid.

The actual bombardment experiments were carried out with protons of energy between 16·5 MeV and 135 MeV. For protons of 16·5 MeV energy the rate of damage introduction is 4500 times the rate observed for 1 MeV electrons. This implies that 4500 electrons of 1 MeV energy have the same effect as one proton of 16·5 MeV energy. With increasing energy the damage rate falls off as (log E)/E, a functional relation expected from Rutherford scattering.[8]

5.3. *Van Allen Radiation*

With the information on electron and proton damage, the degradation of solar cells in the Van Allen belt can be determined.

Any protection of the solar cells reduces the energy of all protons. Since the radiation in space is omni-directional, a great fraction of the radiation will pass through the protection at less than normal incidence. For an evaluation of the effect of the Van Allen spectrum as given in Fig. 4 one first calculates the omni-directional proton spectrum expected behind the protection. Next the energy dependent damage rate is multiplied into the resulting spectrum and the integral is formed. By then incorporating the damage rate due to electrons one can derive the expected rate of diffusion length degradation. Using the results given in Fig. 8 the maximum power as a function of time can be obtained (not counting light losses in the protection).

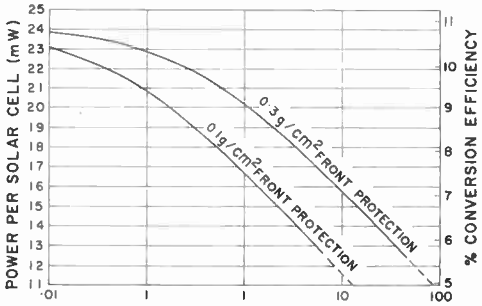

Fig. 12. Maximum power versus time in inner Van Allen belt.

The results of such calculations are shown in Fig. 12, which includes a 25% correction for anti-reflection coating. The thickness of the front protection was assumed to be 0·1 and 0·3 g/cm² respectively while a back protection of 1 g/cm was assumed in either case. The ordinate gives the power per cell and the conventionally defined efficiency. The times in Fig. 12 correspond to an exposure in the heart of the inner Van Allen belt which would only be encountered in a circular equatorial orbit of 2000 miles altitude.

In all other orbits the exposure would be only a fraction of the exposure in the inner Van Allen belt. The time scale in Fig. 12 accordingly can be extended by the inverse of the fraction.

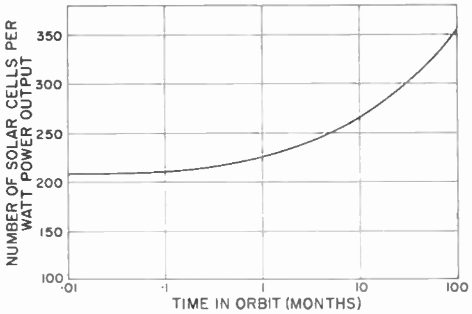

Fig. 13. Number of solar cells required per watt power. (Spherical satellite in elliptical orbit, *n*-on-*p* cells, 0·3 g/cm² protection).

Having determined this fraction, Fig. 12 can readily give the number of solar cells required to provide a given amount of power a predetermined time after launch of the satellite. Into this number enters the " aspect ratio ", which accounts for the geometry of the solar cell array and the losses in the cover plates. For a full evaluation, the temperature distribution on the satellite has to be applied to the temperature dependence of the solar cell parameters. Since the temperature distribution problem is not directly relevant to the present topic, it will not be considered here.

As an example a spherical satellite is considered with a uniform temperature equal to room temperature. The solar cells are assumed to be covered with artificial sapphire of 0·3 g/cm thickness. For such a configuration the aspect ratio was found to be approximately 20%, e.g. on the average the power delivered per solar cell is 20% of the power delivered by an uncovered cell, exposed to the sun under normal incidence.

Evaluating the previous information for an assumed orbit of 4000 nautical miles apogee—600 nautical miles perigee—and 45 deg inclination leads to the plot shown in Fig. 13 giving the number of solar cells that will provide 1 W of power as a function of time after launch. For this particular orbit, the average radiation exposure corresponds to 22% of the exposure in the heart of the Van Allen belt.

By inspection of Fig. 7 it can be seen that the voltage at the maximum power point changes with bombardment. To utilize fully the potentially available power at a given level of degradation requires that the load chosen is such that at that moment the plant operates at the maximum power point. The power actually available at any other time will be necessarily less than the potentially available power at that time.

It has to be emphasized that all estimates given in this paper are based on rather uncertain radiation levels in the Van Allen belt. In as much as these levels are uncertain by at least a factor of two,[9] all time scales quoted carry the same uncertainty. Nevertheless the results quoted in this paper make it apparent that, with the type of solar cells described, long life satellites are indeed feasible.

6. Acknowledgments

The authors are very grateful for the cooperation of several individuals in particular W. G. Ansley, D. F. Ciccolella, H. K. Gummel, M. P. Lepselter and W. Rosenzweig.

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(*Paper No. 661*)

A report of the discussion which followed the reading of this paper will be published in a subsequent issue of the *Journal*.

APPLICANTS FOR ELECTION AND TRANSFER

As a result of its meeting on 27th July 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

MOORE, Air Commodore Lawrence Patrick, R.A.F. *Hereford.*

Transfer from Associate Member to Member

SMITH, David Heseltine, B.Sc.(Eng.). *Lagos, Nigeria.*

Direct Election to Associate Member

BAIRD, Lt. Cdr. John Wishart, B.Sc., R.N. *Fareham, Hampshire.*
BHALOTRA, Capt. Talik Raj, M.Sc., Indian Sigs. *New Delhi.*
BIDGOOD, Peter Francis, B.Sc.(Eng.). *Plymouth.*
CORRIS, Major Philip Geoffrey, R.A. *Redhill, Surrey.*
DAVIES, Arthur John. *Liverpool.*
HEARD, Major John Lennoy, R.Sigs. *Lee-on-Solent, Hampshire.*
MANNING, Frank Neville, B.Sc.(Eng.). *Chelmsford, Essex.*
POLL, Instructor-Commander Peter John, B.A., R.N. *Lee-on-Solent, Hampshire.*
SAWHNEY, Capt. Harwant Singh, B.Sc.(Eng.), Indian E.M.E. *Reading, Berkshire.*

Transfer from Graduate to Associate Member

KAIWAR, Flight-Lieutenant Badri Nath, B.Sc.(Hons.), I.A.F. *Madras.*
MACHIN, John Willis, B.Sc.(Hons.). *Stoke-on-Trent.*
MORGAN, Charles Thomas. *Liverpool.*
ROY, Ashutosh, B.Sc. *London, N.4.*
WRAY, Robert William, B.Sc. *Sutton, Surrey.*

Transfer from Student to Associate Member

SOOD, Shiv Dutt. *Edgware, Middlesex.*
VAN DEN HAAK, Willem. *Oegstgeest, Holland.*

Direct Election to Companion

GRANT, Rear Admiral John, C.B., D.S.O. *London, S.W.10.*

Direct Election to Associate

BUCHANAN, John Scott. *Geneva.*
COX, Anthony. *Shoreham-by-Sea, Sussex.*
FULLER, Gordon Hardy. *Kingston, Jamaica.*
HOLTON, Capt. Harold Wilfred, R. Sigs. *Bideford, Devon.*
OATES, Lionel Harley. *Eccles, Lancashire.*
RAYER, Francis George. *Upton-on-Severn, Worcester.*
SMITH, Douglas Sydney. *London, S.W.20.*

Transfer from Student to Associate

HARDWICK, George Thomas. *Watford, Herts.*
SEAMAN, John Alan. *Dorval, Canada.*

Direct Election to Graduate

BACCHUS, Jerome Stanislaus, B.Sc. *Edinburgh.*
BELL, Malcolm Alexander. *Hatfield, Hertfordshire.*
BROWN, Thomas David. *Blackburn, Lancashire.*
DAVIS, Barry Rous, B.Sc.(Eng.). *Havant, Hampshire.*
EVANS, Christopher David Ian. *Fareham, Hampshire.*
HOWE, Kenneth Gilbert. *Harlow, Essex.*
JACOBS, Jack Solomon. *Harlow, Essex.*
KNIGHT, Peter. *London, S.E.27.*
MATTHEWS, Alan Henry. *Chelmsford, Essex.*
ROGERS, Bryan Charles. *Reading, Berkshire.*
ROUGHLEY, Derek Peter. *Wallasey, Cheshire.*
SAMAD, Mohammed Abdus. *Akora Khatlak, Pakistan.*
SIDERAS, Christokis Stavros. *Hounslow, Middlesex.*
STRAFFON, Alan Edward. *Sutton, Surrey.*
WALKER, Kenneth. *North Shields, Northumberland.*
WINTERBOURNE, William Edward John. *Warminster, Wiltshire.*

Transfer from Associate to Graduate

CHITTY, Arthur Richard. *Preston, Lancashire.*

Transfer from Student to Graduate

HUGHES, Thomas George. *Accra, Ghana.*
LEA, Arnold Trevor. *Bracknell, Berkshire.*
STRONG, Adrian Harold. *Bath, Somerset.*

STUDENTSHIP REGISTRATIONS

The following students were registered at the 27th July meeting of the Committee.

ADEKUNLE, Oyegbola. *Lagos, Nigeria.*
BARNES, David William, B.Sc. *Cheltenham, Gloucestershire.*
BAWN, Martin Russell. *Larne, Northern Ireland.*
BEWSHER, Pat. *Bern, Switzerland.*
BRIGGS, Terence. *Ramsey, Huntingdonshire.*
BUCKLEY, Brian. *Wolverhampton, Staffordshire.*
CHAKRABORTY, Narayan Chandra. *Kanpur, India.*
CHAN, Cecil Shu On. *Hong Kong.*
DAS, Tapan Kumar, B.Sc. *Bangalore.*
DORE, Brian Leslie. *Plymouth.*
GEORGE, Frederick Ralph. *Wolverton, Buckinghamshire.*
GHOSH DASTIDAR, Bikas Kusum, B.Sc. *Calcutta.*
JONES, Michael John. *Swindon, Wiltshire.*
KERNICK, John Humphrey. *Gwelo, Southern Rhodesia.*
LOVELL, Brian William, *Bletchley, Buckinghamshire.*
NASH, John Alan. *Penzance, Cornwall.*
PARKINS, Trevor Williams. *Birmingham.*
PINTO, Anthony Francis, B.Sc. *Bangalore.*
RAINEY, William Francis. *Limavady, Northern Ireland.*
RAMAMURTHY, Dandin, B.Sc. *Bangalore.*
RAY, Robinkumar, B.Sc. *London, S.E.8.*
RICHARDS, William Cyril Desmond. *Droitwich Worcestershire.*
ROSE, David John. *London, E.11.*
SCHMIT, Hugo. *Oranjemund, South West Africa.*
SEAR, Mubarak, B.Sc. *London, S.E.18.*
SODHI, Inder Jeet Singh. *London, W.2.*
STA-MARIA, Jeffrey Anthony. *Kuala Lumpur, Malaya.*
SUBRAMANAYAM, Sulur Rangaswamy, B.Sc. *Bangalore.*
TUNSTALL, Anthony John. *Reading, Berkshire.*
VALLANCEY, Gerald Charles. *Hamilton, Bermuda.*
VASAN, Jeevanna, B.A. *Tanjore, South India.*
WIJESINGHE, Mahendra Punsiri, B.Sc. *London, W.8.*
YAWSON, Andrew Eshun. *Bristol.*

U.D.C. 523.72 : 621.386

Measurement of Solar X-radiation

By

K. A. POUNDS,

B.Sc., Ph.D.†

Presented at the Convention on "Radio Techniques and Space Research" in Oxford on 5th to 8th July 1961.

Summary: The vertical-sounding *Skylark* rocket and the small Earth satellite, *U.K.1*, provide vehicles from which the short-wavelength solar x-ray emission may be studied under varying conditions of solar activity. Equipment has been developed compatible with these relatively small vehicles, to provide a measure of the x-ray flux *and* the spectral shape in this very important and little-known part of the solar spectrum.

1. Introduction

Rocket studies, largely by a group at the U.S. Naval Research Laboratories led by H. Friedman, have shown that the bulk of solar x-ray emission lies in the "soft" wavelength region, from 10–20 Å to about 200 Å. The ease of absorption of this radiation results in its complete removal from the solar spectrum in passage through the extremely rarified atmosphere, 100–150 km above the Earth. It was for this reason that direct study of solar x-radiation had to await development of the high altitude sounding rocket.

Since the first successful detection of solar x-rays in 1948, rocket-borne photon counters, sensitive to certain narrow wavelength bands in the x-ray region, have provided a quantitative study of the Sun's x-ray emission over a complete sunspot cycle and, also, during a number of large solar flares.[1, 2] The Sun is revealed as an extremely variable star in the x-ray region, the total emission varying by more than an order of magnitude with degree of solar activity. The most pronounced variations appear to be in the short wavelength "tail" of the spectrum, below 20–30 Å, and British research‡ in this area is concentrated on a closer study of this variable short wavelength radiation.

The primary means with which data on this x-ray "tail" emission have been obtained, employs a photon Geiger counter as the x-ray detector, with simple rate-metering of the resulting counter pulses. Whilst providing a valuable indication of the amount and variation of the x-ray flux, no direct information of the shape of the spectral tail is yielded. This information is of considerable astrophysical interest, as it concerns directly[3] the kinetic electron temperature in the solar atmosphere ("corona") where the x-ray emission originates, a matter at present in dispute.[4, 5] In addition, computation of the incident x-ray flux from the Geiger counter data requires the assumption of a suitable spectrum. Owing to the rapid change of detector sensitivity with wavelength, the flux value obtained is a quite sensitive function of the actual spectral shape assumed.[6]

In this paper, an x-ray spectrometer will be described which has been developed to obtain more precise measurement of the short-wavelength x-ray spectrum.

A considerable amount of associated electronic circuitry has been required to achieve this increased precision. The experimental requirements of this instrumentation, balanced against the environmental limitations of a small space vehicle, are discussed in this and a following paper.[7] Emphasis will be placed, in this paper, on the limitations on the spectral measurement imposed in part by the detector, part by the associated electronics, and in part by the vehicle itself.

It is intended to fly the x-ray spectrometer in a number of *Skylark* rockets over the next two years, and also in the first U.S.–U.K. *Scout* satellite, due to be launched early in 1962.

2. The Photon Counter Spectrometer

The energy in the whole x-ray spectrum of the Sun, though sufficient to account for a large part of the heating, ionization, dissociation and excitation of the upper atmosphere at the levels of its absorption, is quite small, being about one millionth of the energy in the whole solar spectrum. Of this x-ray flux only about 1% may be found below about 20 Å, in the spectral "tail". This is too weak for high resolution spectral analysis by a crystal or grating spectrometer without lengthy exposures, and a stabilized space platform.

A much more sensitive spectrometer may be designed making use of the wavelength resolution of a proportional gas counter, the high sensitivity being obtained by arranging for a high probability of x-ray photon absorption in the gas filling of the counter. Detection of pulses in this way is virtually 100%. The photon absorption releases a small

† Department of Physics, University of Leicester.
‡ Started at University College London in 1958 and now extended in cooperation with the University of Leicester.

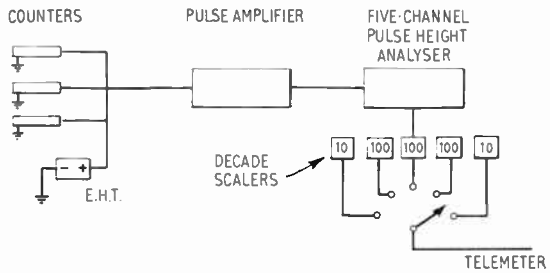

Fig. 1. Block diagram of instrumentation of x-ray counter spectrometer.

primary charge in the counter body. This charge is amplified in a controlled avalanche in the vicinity of the counter anode (Fig. 2), resulting in a final charge at the wire being some fixed multiple of the primary charge. Thus, for initial x-ray photons of differing energies, current or voltage pulses are available at the counter anode, linearly related, or proportional, to the respective incident photon energies.

Incident solar x-radiation will result in a random "train" of such pulses from the photon counter. The block diagram of Fig. 1 indicates how this pulse spectrum is further amplified, sorted into amplitude channels, and counted in the rocket or satellite vehicle, before relay to ground, via the vehicle telemetry.

A quite high level of charge multiplication, or gas gain, in the photon counter is required in order that these pulses may be suitably larger than the noise level at the input of a wideband transistor amplifier.

In the following sections, it is seen that working at very high levels of gas gain impairs the properties of the photon counter; this must be considered with amplifier signal/noise ratio. The degree of wavelength resolution obtainable and the dynamic range of the whole instrumentation must be considered in terms of both rocket and satellite experiments.

3. Experimental Limitations of the Photon Counter

The photon counter, shown in Fig. 2, consists of a cylindrical aluminium tube, with a thin axial anode wire of tungsten. The tube, of standard commercial design, is filled to strict specifications and a special, collimated photon entry window is supplied to and fitted by the tube manufacturers.† In operation, a stable high voltage is applied to the anode, the outer cylinder being earthed. Photo-electrons, formed in the initial absorption process, are drawn to the anode, where the high electric field results in further collisional ionization, to produce the required charge "avalanche".

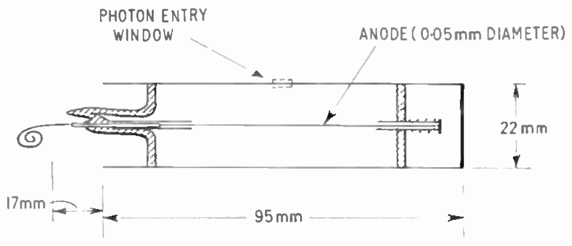

Fig. 2. Dimensions of the photon counter.

3.1. *Narrow-band Detection*

The detection efficiency of the photon counter‡ is a product of the fractional window transmission and gas absorption, as functions of photon energy or wavelength, and high efficiencies can be achieved over particular narrow wavelength bands by proper choice of these parameters. The p.d.e. curves of two counters developed for use in the *Skylark* and *Scout* programmes are shown in Figs. 3 and 4. The aluminium window counter will be used in *Skylark* to

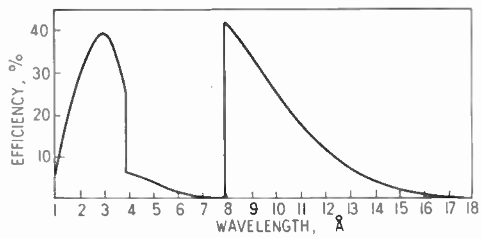

Fig. 3. Photon detection efficiency of the aluminium window counter with gas absorption path 2 atmos-cm argon.

Mass absorption data:
for Al$\lambda < 7{\cdot}9$Å, Compton and Allison (1935).
Al$\lambda > 7{\cdot}9$Å, Unpublished measurements.
Argon, Compton and Allison (1935).

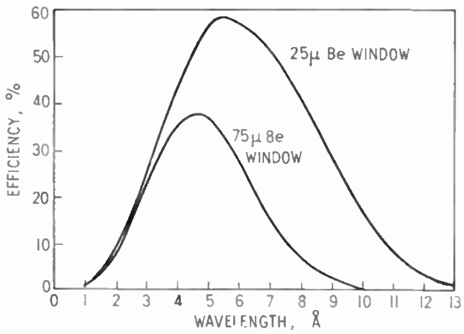

Fig. 4. Photon detection efficiency of two beryllium window counters with gas absorption path 2 atmos-cm neon. Mass absorption data—Compton and Allison (1935).

† 20th Century Electronics Ltd., New Addington, Surrey.

‡ The photon detection efficiency (p.d.e.) is defined as the fraction of the photon flux incident on the counter window that result in detectable pulses or "counts".

study the short wavelength tail of the solar spectrum during normal or "quiet" solar conditions, whilst the beryllium counter is to be used in the satellite *U.K.1*, to investigate the flux increase and short-wavelength extension of the spectrum at times of solar activity. The satellite provides an ideal vehicle for study of such transient phenomena.

3.2. *Proportionality*

The photon counter, shown in Fig. 2, has entry windows along the central circumference and, with beam collimation usually to within 30 deg of the normal to the windows, photon absorption always occurs well away from the ends of the counter; together with strict precaution against electronegative gas impurities during preparation of the counters, this ensures no geometrical limitations on linearity of gas multiplication, or proportionality, of the counter. (A second advantage is the resulting uniformity of pulse shape, enabling a fast clipping time to be used in the following amplifier with no resultant loss of linearity.)

The real detector limitation affecting proportionality is due to space charge effects. Experiment has shown that when a sufficiently large positive ion density exists in the counter body the full gas multiplication, appropriate to the applied counter e.h.t., is not achieved. The gas multiplication deficiency, moreover, is greater for larger pulses, i.e. those resulting from the higher energy photons in the spectrum, and thus exact proportionality is impaired.

This "self saturation" of counter pulses is increased at the extremely high count rates possible with a proportional gas counter, by a "mutual saturation" effect, occurring with the coincident development of a number of pulses in the counter. Figure 5 shows the gas gain as a function of counter e.h.t. for a number of

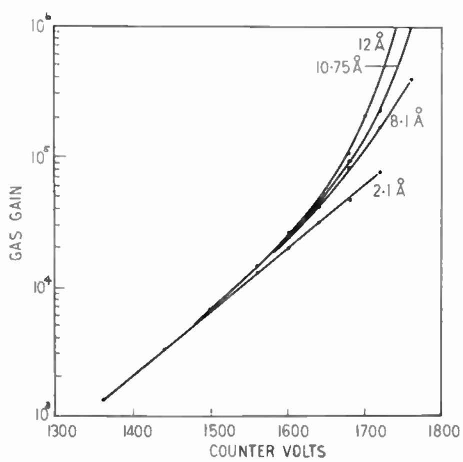

Fig. 5. Gas multiplication-voltage characteristic for the photon counter (argon filling).

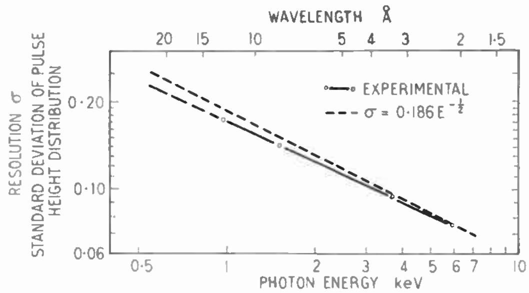

Fig. 6. Photon counter wavelength resolution (argon filling)

x-ray wavelengths. The splitting of the curve at high gas gain values indicates the onset of "self saturation" and the separation of respective curves gives the degree of proportionality loss in a given wavelength region.

In the solar spectrometer, wavelength distortion of the spectrum is reduced to a minimum by working at the lowest gas gain permitted by signal/amplifier noise consideration (compare Section 4.1) and choosing detector window apertures to give normal counting rates of less than 10^3 per second. Corrections will be applied to intense spectra from the satellite spectrometer occurring during solar flares.

3.3. *Resolution*

Some variation of pulse height occurs with monochromatic radiation incident on the counter, due to the statistical nature of both the initial process of gas ionization and the ensuing gas multiplication. The measured wavelength resolution of the present photon counters, as a function of wavelength, is shown in Fig. 6, and compares favourably with the theoretical relation computed for a "perfect" gas counter, i.e. uniform wire diameter, no negative ions, etc.

Wavelength resolution is found to deteriorate with the effects of space-charge saturation, though the effect is less marked than on the proportionality.

4. The Spectrometer Electronics

It is the function of the spectrometer electronics to amplify the detector pulses to such a level that they may be sorted and counted and then to sort them into different amplitude channels and register the count rate at each channel. It is essential that this processing is performed with as little count loss and distortion of the spectral shape as possible, within the limitations of space, weight and power set by the vehicle. Economy in equipment weight, size and, particularly, in power drain is needed in both rocket and satellite instrumentations; the limitations in a long-life satellite, powered by its own solar batteries, are considerably more severe, however. Some general considerations of the electronics system will be made in this section, for both rocket and satellite-borne spectrometers, and in relation to the previously noted photon counter performance. Further detail of the complete, low-power, electronics for the spectrometer is given in the companion paper.[7]

4.1. *Amplifier*

Absorption of a solar x-ray photon in the argon gas counter releases, on average, about 36 ion pairs per keV. Thus, in the 8–16 Å spectrometer, for example, with photon counter gas gain of M_c, the signal at the amplifier input ranges from 27 M_c to 54 M_c. This is to be compared with amplifier noise, related to the input stage, of about 2×10^4 ion pairs r.m.s. For a maximum of 1 noise count per second equal to or greater than a 16 Å photon pulse, the required signal/r.m.s. noise ratio is 7·5 (Gillespie[8]). At this level, superimposition of noise on the pulse spectrum will result in some loss of resolution. With a short wavelength limit of 8 Å, for the spectrum under study, the upper limit of counter gas gain for no loss of proportionality is seen (Fig. 5) to be about $1{\cdot}5 \times 10^4$. With this value for M_c the effective signal/noise ratio, for a 16 Å photon becomes 20 and the added loss of wavelength resolution is small compared with that due to the inherent resolution of the photon counter, which, at 16 Å, is about 19%.

A current gain of about 72 dB is required to bring the signal pulses up to the pulse height analyser channel levels. This gain is obtained, in both *Skylark* and *U.K.1* electronics, by three cascaded stages of a ring-of-two transistor amplifier loop, negative current feed-back defining a stable gain level and ensuring gain linearity. The measured gain stability for a 10% supply voltage change is better than 3%.

The final amplifier consideration deals with resolving time. In the event of a mean count rate from the photon counter of 10^4 per second, a resolving time of 1 microsecond is required in order that there be only a 1% probability of pulse overlap, with random count rate. This is possible here (compare Section 3.2), since the present photon counter provides pulses of unique shape and these fast clipping times introduce no amplitude modulation. The *real* amplifier limitation, at high counting rates, is not the loss of some counts, but rather the spectral distortion resulting from overlap of two small pulses, giving a single larger pulse at the output. This is significant in the present studies, where the incident solar spectrum falls off rapidly at the higher photon energies.

4.2. *Pulse Height Analysis*

The total number of pulse height channels necessary to read the spectrum without loss of resolution is quite small. Kelley[9] shows that only three or four

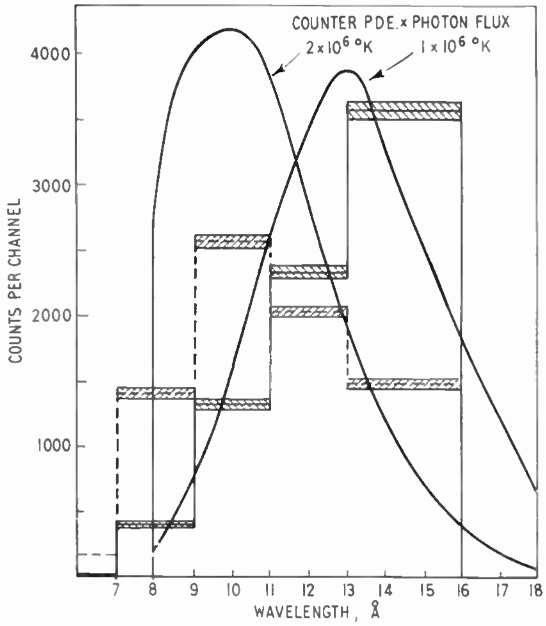

Fig. 7. Count histograms for two assumed x-ray spectra.

A total count of 7500 is shared by the five pulse height channels in each histogram; the hatched areas represent the statistical inaccuracy in this record.

channels need be allotted to a spectral peak between points of half counting rate for the analyser without markedly affecting the resolution. The full-line curves in Fig. 7 show the count spectra from the amplifier for incident x-ray spectra of, respectively, 10^6 and 2×10^6 °K colour temperature. Since the photon counter resolution (Fig. 6) in this wavelength region will further broaden this peak, five channels are considered sufficient to cover the significant wavelength range.

There are some differences in the pulse height analyser systems used in the *Skylark* and in the *U.K.1* spectrometers. In the satellite equipment the time available for scanning the solar spectrum is comparatively long and since power, space and weight are at a premium, a stepped single-channel analysis, over five equal (energy) intervals, is used. The vertical sounding rocket, on the other hand, allows much less time for spectral scanning whilst more electrical power is available, and here multi-channel analysis is preferred. Figure 7 refers to the multi-channel rocket analyser, with four variable-width analysis channels and a fifth simple discriminator level to count all pulses higher than the fourth channel.

4.3. *Pulse Counting, Storage and Transmission*

Some reduction of the count rate histogram is necessary in the vehicle in order to limit the amount of data to be telemetered to a ground station. This problem is much more severe in the satellite equipment, which must cater for a large dynamic range of count rate and where the available telemetry capacity is considerably more limited.

4.3.1. *Skylark*

As indicated in Fig. 1 the pulse rates are continuously fed from the multi-channel analyser into a bank of commercial decade scalers. The five scaling units are sampled by the round telemetry 80 times per second, to give ample cover of a "quiet" solar x-ray flux rate of 500 counts per second. Unambiguous counting is provided by the above system of counting rates up to an order of magnitude higher. The telemetry load of this system is high, however, with continual use of five telemetry channels and approximately 1600 information bits per second.

4.3.2. *Scout*

A 5-digit binary counter of capacity 32 767 provides the dynamic range factor of several thousand, necessary for coverage of x-ray spectra from the "quiet" to the "flare active" Sun. A single counter is used and this is applied sequentially, for alternate 1 second periods, to each of the five pulse-analyser bias settings. The counting system power-drain is 42 milliwatts as compared to 1·3 watts for the original *Skylark* system.

A "gating" pulse opens the counter to a pulse height channel for 1 second, following which the "gate" is closed for a further second. During this time the satellite encoder thrice samples the 15 digit counter. A total period of 10 seconds is necessary for scanning the complete spectrum. In this time the rocket spectrometer yields 200–300 spectra of similar precision, the speed factor being largely a result of the different telemetry capacity available.

5. Conclusion

A proportional photon counter operating at a fairly high level of gas multiplication, in combination with a linear transistorized pulse amplifier, provides the basis for a rocket or satellite-born spectrometer to measure the short-wavelength solar x-ray spectrum. The resolution of the spectrometer is largely determined by statistical pulse height variations inherent in the photon counter.

Adequate precision of sorting the amplified pulse spectrum is provided by about 5 pulse height channels. Choice of sequential, or coincident counting over this 5-channel analyser depends on the space and power available in the rocket or satellite vehicle. Only in the rocket-borne spectrometer is multichannel analysis possible, but against this the satellite provides much longer spectral scan times.

The spectrometers will be set for a fairly low total counting rate, by suitable choice of photon counter window aperture. Spectral distortion and counting loss, which will occur at high count rates during periods of intense solar "activity", are predictable and corrections may be applied to the measured spectra.

6. References

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   H. Friedman, *Mém. Soc. Roy. Sci. de Liège* (Series 5), **4**, p. 228, 1961.
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8. A. B. Gillespie, "Signal, Noise and Resolution in Nuclear Counter Amplifiers", Chap. 5 (Pergamon Press, London, 1953).
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GRADUATESHIP EXAMINATION—MAY 1961—PASS LISTS

These lists contain the results of all successful candidates in the May Graduateship Examination. A total of 480 candidates entered for the Examination which was held at seventy-one centres.

LIST 1: The following candidates have now completed the Graduateship Examination and thus qualify for transfer or election to Graduate or a higher grade of membership.

ASHEN, David John (S) *London, E.17.*

BLAIR, Desmond McGavock (S) *Bedford.*
BRAVINSKY, Gary (S) *London, N.W.3.*
BROWN, Thomas David, *Blackburn, Lancs.*

CHAN, Ping Cheung (S) *Hong Kong.*

DALE, Collis Seymour (S) *R.A.F. Feltwell, Norfolk.*
DAWSON, John Sydney (S) *Wallsend-on-Tyne, Northumberland.*

FIRTH, Peter Thomas (S) *Huddersfield, Yorks.*
FRASER, William Morrison (S) *Weston-super-Mare, Somerset.*

GIBBS, Ian Grenvill (S) *Coulsdon, Surrey.*
GRICE, William George (S) *London, W.13.*

HOWE, Kenneth Gilbert, *Harlow, Essex.*

JACKSON, Brian David (S) *London, N.4.*

KAPOR, Onkar Nath (S) *Ludhiana, India.*
KARTHIKEYAN, Muthukumarasany (S) *Madras.*
KEEBLE, Ronald Sidney (S) *Holmer Green, Bucks.*
KENNETT, Barrington George (S) *Paignton, Devon.*
KENT, Derek Wilfred (S) *Enfield, Middlesex.*
KNIGHT, Peter, *London, S.E.27.*
KUMAR, Ramesh (S) *Walton-on-Thames, Surrey.*

LEWIS, Arthur Dennis (S) *Berbera, Somalia.*
LING, Shun Ki (S) *Hong Kong.*

McQUIRE, Adrian Frank (S) *Romford.*
MADAN, Rusi Sorabji (S) *Bombay.*
MARSDEN, Norman Wain (S) *Sheffield.*
MILLS, Raymond Hugh (S) *Cambridge.*
MITCHELL, Robert (S) *Stevenage, Herts.*
MOSLEY, John Malcolm (S) *Keighley, Yorks.*

NAIR, Bala Krishna Sreekumar (S) *Lonavla, India.*
NEUMAN, Shimon Siegfreid (S) *Rannat Gan, Israel.*

OGBU, Christian Okonkwo (S) *London, N.5.*
ONG, Tat Lim (S) *Kuala Lumpur, Malaya.*

PARRIS, Charles Deighton, *Jamaica.*
PHILLIPS, Edmund (S) *Cambridge.*

RADHAKRISHNAN, Gopalaswamy (S) *Bombay.*
RAO, Gadiyara Prabhakara (S) *New Delhi.*

SAUNDERS, George Brian (S) *Nuneaton, Warwicks.*
SCURRAH, Robert Eric (S) *London, S.W.16.*
SHARMAN, Harold (S) *Edinburgh.*
SPALDING, James Melville Ferguson (S) *Cambridge.*

TALGERI, Gurudutt Shripadrao (S) *Bombay.*
TALMACIU, Josef (S) *London, N.4.*

LIST 2: The following candidates have now satisfied the requirements of Section A.

ALBACH, Gilbert David, *London, N.W.11.*
ARMSTRONG, John Patrick (S) *Basingstoke, Hants.*
ASPINALL, Charles Deacon, *Nairobi.*
ASWATHANARAYANA, K. R. (S) *Bangalore.*
AZUBUINE, Linus Okafor (S) *Lagos.*

BANERJEE, Gour (S) *Bombay.*
BATES, Arthur Owen (S) *Slough, Bucks.*
BIEGUN, Ephraim (S) *Tel-Aviv.*
BINENSTOCK, Joseph (S) *Brei Bray, Israel.*
BLACH, Robert Renee, *Akazienhof, Austria.*
BLAND, Cecil Allan (S) *Wellington, Shropshire.*
BURDEN, Peter, *Liverpool.*

CALDICOTT, Jack Richard (S) *Coventry, Warwicks.*
CARTER, Reginald Lewis, *London, N.1.*
CHAPMAN, Christopher John (S) *London, S.E.22.*
CHUNG, Yook Kei (S) *Hong Kong.*

DARE, Isaac Oluwole (S) *London, E.9.*
DARSHAN SINGH (S) *Chandigarh, India.*
DAVIES, Bryan Francis (S) *London, N.20.*
DAVIES, Garnet Burne (S) *London, N.1.*
DAWSON, Albert Thompson (S) *Albrighton, Staffs.*
DESAI, Shrihari Baboorao (S) *Bombay.*
DEVGON, Harbans Lal (S) *Madras.*

FARBEY, Michael Ian (S) *London, E.5.*
FENSOME, David Arthur (S) *Potters Bar, Middlesex.*
FERBRACHE, Rex Reginald (S) *Cardiff.*
FLANAGAN, Robert Gerald (S) *Stillorgan, Ireland.*
FORESTAL, Peter (S) *Hong Kong.*
FRY, Anthony Jack (S) *Worcester Park, Surrey.*

GHALLEY, Jaspal Singh (S) *London, S.E.27.*
GILBERT, Victor Staniford (S) *Selsdon, Surrey.*
GOODALL, George (S) *London, W.5.*
GOPAILLON, Peron (S) *London, N.1.*
GOTHAM, Peter Frederick (S) *Wells, Somerset.*

HACKING, John Bellamy (S) *Penzance, Cornwall.*
HACKENEY, Joseph Michael, *Birmingham, 13.*
HAKHVERDIAN, Armik A. (S) *Tehran.*
HALE, Derek Stanley (S) *Jersey, Channel Islands.*
HAMBELTON, David Robert, *New Malden, Surrey.*
HARTLEY, William (S) *London, S.W.15.*
HASAN, Ghulam (S) *Karachi.*
HILL, Eric Sylvester (S) *Wells, Somerset.*
HILL, Michael Edward (S) *Birmingham.*

IVATT, Kenneth Raymond (S) *London, N.6.*

JONAS, Malkiel (S) *Jerusalem.*

KAPONIDES, Aristides (S) *London, N.4.*
KATE, Zvi (S) *Haifa, Israel.*

LAMPREAO, Manuel Redro Ferreira, *Lisbon.*
LEARMONTH, William George (S) *Plains, Lanarks.*
LESS, William Victor (S) *London, N.16.*
LLOYD, Lionel Edward (S) *London, N.W.1.*
LODGE, John William (S) *Didcot, Berks.*
LYE, Khay Fong (S) *Singapore.*

MAHAJAN, Prabhakar Shankar (S) *Bombay.*
MAIN, William (S) *Wolverhampton, Staffs.*
MANCHESTER, John Kay, *London, W.4.*
MEINTJES, Jeffery Ayton (S) *London, E.4.*
MUKHERJEE, Sudhendu Kumar (S) *Kanpur.*
MULCAY, Michael (S) *London, N.9.*

NAGESH, Jai Ram (S) *Rohtak, India.*
NG, Song Kang (S) *Singapore.*
NORRIS, Alan Richard Bradley, *Bristol.*

OAIYA, Frederic Akhamiator (S) *Southampton.*
O'BRIEN, Bernard (S) *Whitechurch, Glam.*
OLOMU, Solomon Ovenseri (S) *Lagos.*
ONUKWUBE, Lawrence Chilaka (S) *Lagos.*

PARK, Kenneth Charles (S) *Shepton Mallet, Somerset.*
PARKIN, Oswald Theodore (S) *Bedhampton, Hants.*
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RAJAN, Krishnaswamy Pothi (S) *Poona.*
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ROBERTS, Brian Gordon, *Rayleigh, Essex.*
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SRIVASTAVA, Verendra Prasad (S) *Kanpur.*

TEN BROEKE, Bunardus Johannes (S) *The Hague, Holland.*
THOMAS, Philip Wilfred (S) *Bristol.*
TIDSWELL, Anthony (S) *Grays, Essex.*

UKO, Okon Nathaniel (S) *Lagos.*

VEERANKUTTY, Karalamkunnath (S) *Madras.*

WHEELER, Edwin Ernest (S) *Cobham, Surrey.*
WIENER, Eliezer (S) *Magdiel, Israel.*
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WINDLE, Kevin Joseph (S) *Belfast.*
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