A SYSTEM FOR RECORDING AND INTEGRATING PHYSICAL MEASUREMENTS*

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Introduction

Many occasions occur when it is required to make recordings of one or more fluctuating physical quantities. When the measurements to be made, either of the same quantity at a number of positions or of various quantities at one position, exceed quite a small number, continuous recording is not a practical proposition. In any event it may not be necessary. The frequency with which it would be desirable to record a particular measurement will depend on : (*a*) the expected rate of fluctuation of the quantity concerned having regard to smoothing that may be introduced by the primary sensing device and the recorder in use ; (*b*) the magnitude of the expected fluctuations, again almost certainly modified by the apparatus ; (*c*) the resolution available in a single measurement ; (*d*) the accuracy to which a time mean value is required together with the time over which the mean is to be taken.

Very often the frequency with which individual readings can be made is dictated by the number of different observations required together with the characteristics of the available recording system. Recordings are normally made with appropriate sensing heads working in conjunction with multichannel recorders. The record finally obtained is a representation of the spot values of the quantities at time intervals depending on the switching cycle of the particular recorder. Effective multiplication of the number of recording channels with a decrease in the frequency of recording of a single variable can sometimes be achieved by external switching which is synchronized to any internal switching in the recorder. Various devices have been reported (e.g. McHugo 1959) which will provide an integrated value of at least one variable which is working into a single-channel recorder. A limit to the number of different channels that may be used on one recorder is often set by the chart record itself as this becomes too confused for convenient analysis. In all cases the chart has to be subsequently measured before the desired numerical values are available. This is often tedious and time consuming and provides opportunity for subjective error. The system

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to be described is fully automatic and no error of this type is possible, the individual measurements and their totals over any desired period being presented on counters. Moreover, the initial signals themselves need only be of the order of a fraction of a microvolt and, since reflecting galvanometers provide the initial signal sensing elements, the system is very flexible. It may be made to cater for a wide range of signal magnitudes. To make what is to follow specific the system as constructed to record and integrate the dry- and wet-bulb temperatures from 20 positions will be described. Modifications for other applications will readily suggest themselves.

The System in Outline

The basic idea was first developed by House, Rider, and Tugwell (1960) for use in their surface energy balance computer in which it was necessary to digitize the deflections of a reflecting galvanometer. It has not been described previously and the present system is a further development to more general use. The usual semitransparent scale of a reflecting galvanometer is replaced by a long photovoltaic selenium cell which is covered with a grid consisting of alternate opaque and transparent bands of equal width. The width of the image of the projection lamp slit at the scale distance is made the same as that of these bands. As the image of the slit moves across the photocell scale a series of pulses is produced by the cell. The number of pulses is a measure of the distance swept out by the slit image. If these pulses are applied to an electromagnetic counter via the necessary pulse amplifier a record of the change in galvanometer deflection is obtained. When a current passes through a galvanometer it takes up a position defined by the magnitude of the current and its closed circuit zero position. If the galvanometer is disconnected from the circuit in which this current originates and connected to another circuit, the bias circuit, from which a small current flows which is sufficient to move the image of the projection lamp slit off one end of the scale, the number of pulses produced will be a measure of this position with respect to the end of the scale concerned. Repetition of the operation with the galvanometer connected to its critical damping resistance in place of the signal circuit yields a measure of the zero position of the galvanometer with respect to the same end of the scale. This position is recorded on a second counter. The difference in the counter readings is then a measure of the original current which it is desired to measure and record. Suitable switching enables a sequence of signals to be applied to the one galvanometer and the resulting pulses to be passed to individual counters. The accuracy of recording will be determined by the galvanometer *v.* signal characteristics and the size of the grid spacing used. If the galvanometer and its associated circuits are allowed to pass through a number of cycles of operation the integrated deflections are obtained on the counters, which can then be photographed, or the indications can be printed out, at desired intervals.

Application to Temperature and Humidity Recording

In our present research programme we wished to record a two-dimensional grid of temperature and humidity. Absolute accuracies were relatively unimportant, but temperature and humidity differences in the vertical and horizontal were required to be as accurate as possible consistent with the use of a reasonable amount of apparatus. Fine wire thermocouples of copper/copper-nickel were used in psychrometer units mounted on masts, there being five such units on each of four masts. Since the dry- and wet-bulb circuits are identical it is only necessary to consider one set, the addition of the other set merely requiring a duplication of the facilities to be described. The arrangement of the masts and wiring (dry bulbs only) for masts 1 and 2 is shown in Figure 1.

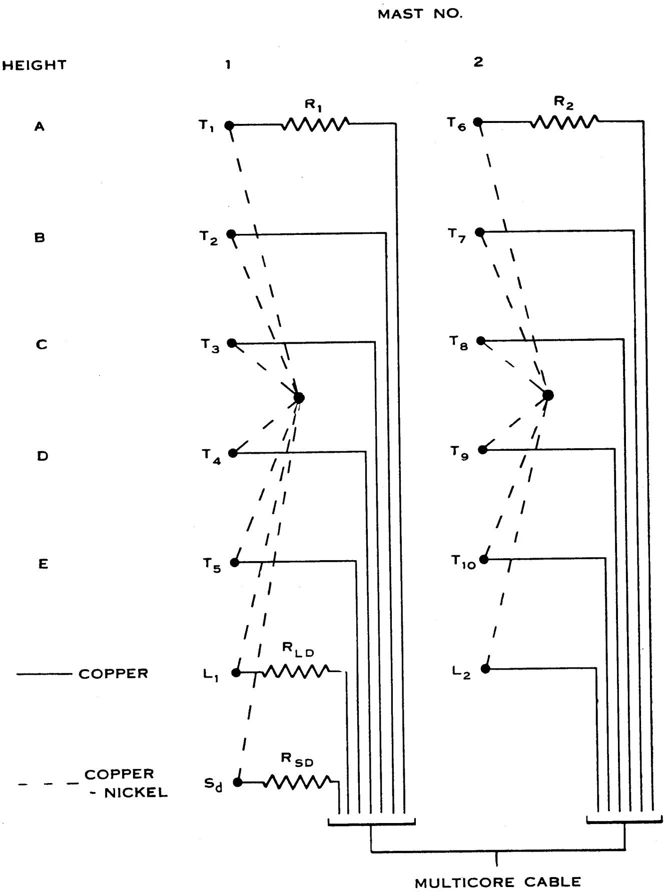

Fig. 1.—Schematic diagram of dry-bulb thermocouple circuits for two masts.

On mast No. 1 it will be seen that, as well as the five thermojunctions at heights from A to E inclusive, a standard junction (S_d) and link junction (L_1) are provided and that all the copper-nickel leads are connected together in one point. Masts Nos. 2–4 are identical and differ from the first in that they have no standard junctions. All the link junctions and the one standard junction are maintained in melting ice. Selection of any pair of copper leads from one mast provides an e.m.f. which is a measure of the small temperature difference existing between the corresponding junctions. These dry-bulb circuits use five galvanometers and switching arrangements, to be discussed later, enabling connections to be made according to the programme given in Table 1. The time interval of 7 sec is allowed in each circuit since the galvanometers used (Tinsley type 4500, 2 sec periodic time, resistance and sensitivity approximately 50 Ω and 10 cm/μA at 33 cm scale distance respectively) required this time to take up full deflection with the fairly low resistance circuits employed, themselves necessary to obtain the required deflection per degree of temperature difference between junctions. The times not accounted for in Table 1, i.e. 8 to 11, 20 to 23 sec, etc., were occupied in sweeping the slits of the galvanometers off the ends of the scales to obtain records on the deflections at 7, 19, 31, 43, and 55 sec. With this schedule a spot value of the temperatures at each position of exposure is obtained once per minute. A faster schedule would be possible if (*a*) shorter period galvanometers, or (*b*) more galvanometers, or (*c*) higher external circuit resistances were used.

TABLE 1

SCHEDULE OF GALVANOMETER OPERATIONS FOR DRY BULB CIRCUITS

Time (sec)	Galvanometer No.				
	1	2	3	4	5
0–7	T_1 *v.* T_2	T_6 *v.* T_7	T_{11} *v.* T_{12}	T_{16} *v.* T_{17}	zero
12–19	T_1 *v.* T_3	T_6 *v.* T_8	T_{11} *v.* T_{13}	T_{16} *v.* T_{18}	T_2 *v.* S_d
24–31	T_1 *v.* T_4	T_6 *v.* T_9	T_{11} *v.* T_{14}	T_{16} *v.* T_{19}	T_2 *v.* T_7
36–43	T_1 *v.* T_5	T_6 *v.* T_{10}	T_{11} *v.* T_{15}	T_{16} *v.* T_{20}	T_2 *v.* T_{12}
48–55	zero	zero	zero	zero	T_2 *v.* T_{17}

However, the present arrangement compares favourably with what could be achieved with a reasonable number of multichannel recorders, both from the point of view of the resolution available in a single record and in the frequency of measurement at one point. It will be noted that one operation of each galvanometer is occupied in recording its zero position and that the total of 25 operations requires the use of the same number of electromagnetic counters. The link junctions are required in order to avoid the use of long lengths of copper-nickel wire between masts which would otherwise be necessary so that galvanometer No. 5 could execute its last three operations in the schedule. Since the accuracy required in the T_2 *v.* T_7, T_2 *v.* T_{12}, and T_2 *v.* T_{17} temperature difference is the same as in the T_1 *v.* T_2, T_1 *v.* T_3, etc. determinations the additional resistance that would be included in the former circuits by long lengths of copper-nickel wire would not be admissible. The link junctions would not be necessary if all measuring points were in close proximity. The resistances which have been shown in Figure 1 are provided to allow adjustment of the temperature difference *v.* galvanometer deflection characteristics of the various galvanometers and circuits. Actually they are not mounted at the masts but at the recording apparatus. These resistances are adjusted so that the sensitivity of all circuits is the same, with the exception of the T_2 *v.* S_d circuit which has a sensitivity of about one-fifth of the other circuits.

Details of Circuit Arrangements

The basic timing device which controlled the whole cycle of operations was a geared down synchronous motor which operated a 1 sec cam, this cam in turn operating a mercury-in-glass switch which energized the coil of a miniature uniselector. The uniselector had 30 output contacts per level, there being seven levels with provision for inter-level switching. This device provided the means whereby relays could be energized in time intervals down to 1 sec in the cycle of operations lasting 1 min. By grouping the uniselector output contacts any relay could be made to remain energized for any desired period during the cycle.

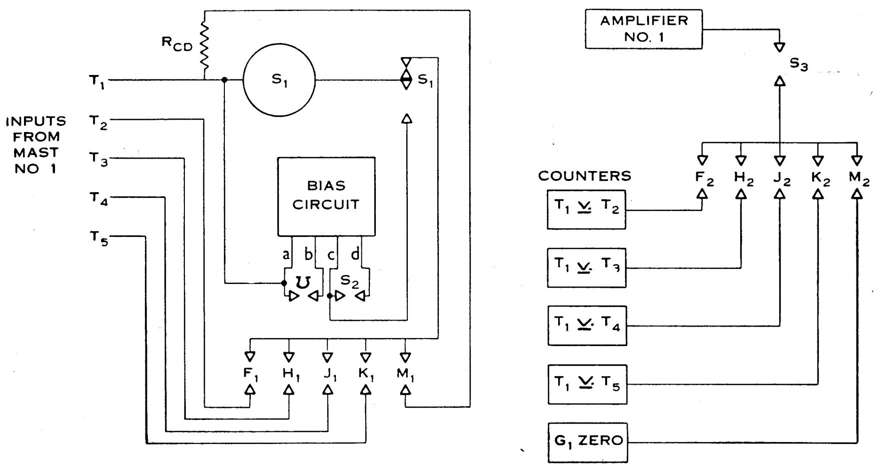

Fig. 2.—Switching circuits for galvanometer and amplifier No. 1. The contacts are shown in their normal positions. The times when they are not in the positions shown are given in Table 2.

We require that the switching arrangements should connect the correct circuits to the galvanometers at predetermined times, apply the currents required to generate the galvanometer sweeps, and select the correct electromagnetic counters to receive the outputs of the pulse amplifiers. Several other functions are also required and were arranged quite easily. The shutter of the automatic 35 mm camera used to record the counter indications must be operated at the correct time in the cycle and after the desired number of cycles have been completed, and the field illumination must be similarly controlled. If, as in the present case, the counters are fitted with reset coils these must be energized immediately following the film exposure. To cater for these operations a second uniselector of the same type as the first is driven from the latter in such a way that it moves on one step per half minute. Many arrangements are possible with these uniselectors according to the requirements of the particular application. In our case an integrated total was required after 20 cycles of operation and arrangements were made for this. We also wished to obtain on occasions an individual record of each cycle of operation and change over to this type of operation was provided for. Further, times occurred when, owing to some emergency, it was necessary to stop a run and restart. This facility was incorporated by the use of homing arcs on the uniselectors. So many arrangements are possible that it is thought not to be worth while to detail the uniselector and relay energizing wiring and we shall confine ourselves to giving some account of the type of switching that is used in the circuit of one galvanometer (G_1) which is illustrated in Figure 2. Referring to this figure it will be seen that the copper lead from the T_1 junction is connected to one side of G_1 and that the other side of

TABLE 2

TIMES OF OPERATION OF RELAY CONTACTS SHOWN IN FIGURE 2

Contact	Time of Operation (sec)
S_1, S_2, S_3	7–11, 19–23, 31–35, 43–47, 55–59
F_1, F_2	0–11
H_1, H_2	12–23
J_1, J_2	24–35
K_1, K_2	36–47
M_1, M_2	48–59
U	8–11, 20–23, 32–35, 44–47, 56–59

the galvanometer is connected via the change-over contact S_1 to one side of a series of relay contacts marked F_1, H_1, J_1, K_1, and M_1, the other sides being connected directly to T_2, T_3, T_4, T_5, and R_{cd}, the galvanometer critical damping resistance, respectively. The times during which these and all other contacts are not in the positions shown in Figure 2 are given in Table 2. We see, for example that contact F_1 is closed in the period 0–11 sec so that G_1 is in the T_1 v. T_2 circuit until S_1 changes over at 7 sec, thus connecting the galvanometer into its

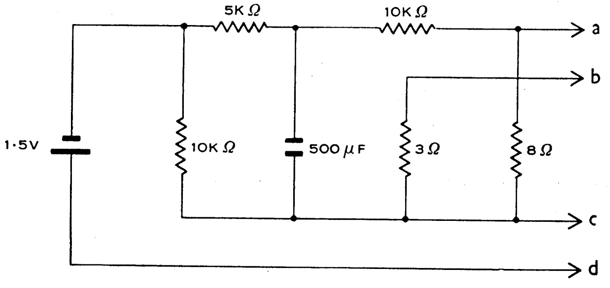

Fig. 3.—The galvanometer bias circuit.

bias circuit which produces the sweep of the slit across the cell. During the period up to 7 sec contact S_3 is open so that although F_2 is closed and the T_1 v. T_2 counter is in circuit no pulses which may be produced by the cell and amplifier due to fluctuations in the deflection of the galvanometer will be passed to the counter, only those arising in an actual sweep being recorded. Similar switching circuits are provided for each galvanometer and its associated amplifier and counters and each has its own bias circuit, illustrated in Figure 3, which should be considered in conjunction with Figure 2. The bias circuit consists of a 1·5 V dry cell and a delay line which is designed to limit the rate at which the bias current rises through the galvanometer, thus ensuring that the sweep commences slowly and later speeds up. On first making contact S_2 all the current flows into the condenser and the current rises through the galvanometer and its parallel resistances as the condenser charges. This arrangement by itself was found to be insufficient to exercise enough control on the sweep speed and so two parallel resistances were used as shown, having values of around 3 and 8 Ω. At first these are both in parallel across the galvanometer but 1 sec after the start of a sweep contact U opens to increase the parallel resistance from about 2 to 8 Ω. The exact values of these two small resistances are adjusted to suit the particular galvanometer. All these bias circuit arrangements were necessary since the photovoltaic cells appear to have an initial lag to changes in light level but once they commence to operate they may be pulsed satisfactorily at speeds up to a few kc/s. The highest speed here is governed by the maximum counting rate of the electromagnetic counters used.

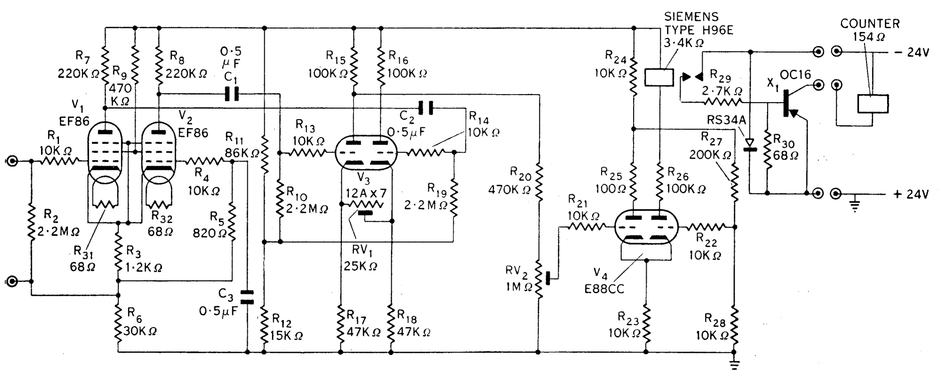

Fig. 4.—The pulse amplifier circuit.

One pulse amplifier was used with each galvanometer. Although photovoltaic cells do not lend themselves very readily to incorporation in electronic circuits (owing to their low internal impedance and small output at the low light levels used here) a satisfactory amplifier design was finally produced and is shown in Figure 4. Very briefly it consists of two EF86's connected as a long tailed pair, followed by a double triode (12AX7) to give further amplification, and the last stage is a Schmitt trigger circuit (Schmitt 1938) which operates a high speed relay. A voltage gain approaching 10^4 is obtained. RV_1 is the gain control and the relay firing point is set with RV_2. The frequency range over which the amplifier will operate is from less than 1 c/s up to a maximum determined by the relay used, in our case about 80 c/s. However, the sweep speed of the galvanometer slit must, as has already been indicated, be kept below the maximum working speed of the counters which in our case was around 35 counts/sec. Precautions have to be taken in the amplifier against oscillation at mains frequency. The valve heaters are connected in series and supplied with 24 V d.c., this supply being also required for the uniselectors, relay coils, and projection lamps. The 300 V h.t. supply must be taken from a good quality power pack. The contacts of the high speed relay are conveniently protected by the power transistor which is shown in Figure 4. Here, with 24 V counters, the current passed by the relay contacts is completely non-inductive and is less than 10 mA, while virtually the full 24 V is dropped across the counter coil when the relay makes.

The photocells used had the dimensions 15 by 2·5 cm and the metal grids passed five pulses per 1 cm of light movement. Since the cells tend to have small weak areas it is convenient to replace the single band of light from the projector lamp by a double slit or small grid of light the image of which has the same spacing as the grid covering the cell at the scale distance.

It will be clear that the records obtained are independent of long-term galvanometer zero drift. It is only necessary for the zeros to remain fixed for the period occupied by one cycle of operation to eradicate any error which might arise on this account.

Conclusion

The particular form of the system described has been in use in a mobile laboratory for some time where it has been subjected to unusually rough treatment in travelling. All faults that have occurred can be traced to damage in transit and as a static installation the system should prove as reliable as one based on conventional recorders. If the latter had been used it is estimated that several days' work would be involved in chart analysis before a grid of temperature and humidity could be constructed for a single 30 min period. Here the basic information is immediately available in numerical form and such work as is necessary is limited to the use of the psychrometric equation to arrive at values of vapour pressure. It is not necessary to list other possible uses for the system—any application to which photographic, multichannel potentiometric or thread recorders, or pen recorders have hitherto been appropriate could be suitably served. The cost of the system is less than that of potentiometric recorders which would provide the same facilities.

References

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