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# An Electronic Actinometer for measurements in narrow spectral ranges

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ABSTRACT. This paper describes the use of capacitance bolometers for special measurements of the direct solar radiation. Electronic and optical design factors are outlined, followed by constructional and operational details. Indicating methods for capacitance bolometers are discussed with particular reference to this electronic actinometer.

## 1. Introduction

Measurements of solar radiation in specified spectral bands are of considerable importance, particularly for the determination of atmospheric water vapour by actinometric means. The use of ordinary actinometers is often unsatisfactory, because their radiation-sensitive elements consist of resistance bolometers cr thermo-piles; both are not sufficiently sensitive if connected to normal indicators, *e.g.*, pointer-type galvanometers. On the other hand, large sensitivity is required because of the small radiation intensities available in narrow spectral bands.

Adequate sensitivity may of course be obtained if a mirror-galvanometer, of portable or laboratory type, is used in conjunction with an ordinary actinometer. However, such indicators lack operational convenience under daylight conditions and are absolutely useless wherever physical vibrations are encountered (*e.g.*, measurements in aircraft).

The only possible solution appears to be the use of the capacitance bolometer which was developed by the author sometime ago (Albrecht 1955). This bolometer's principle is based upon the temperature coefficient of the dielectric of ceramic condensers, and their measurement by means of a superimposition of two frequencies, one being governed by an unexposed temperature-sensitive capacitor and the other by an identical element being exposed to the radiation to be measured. If both frequencies are selected and adjusted as suggested in the author's previous publication on this subject, the capacitance bolometer can be used for convenient measurements of all possible types of heat radiation, because the resultant frequency is automatically compensated for effects of the ambient temperature and thus gives an accurate and reliable indication of the *actual* radiation intensity.

## 2. Electronic Design

Fundamentally, the design of capacitance bolometers is based upon the selection of operating frequencies for both, the temperature-compensating and the radiation-sensitive oscillator. This is governed by the distance within which the readings are to be taken. In the case of actinometers, the indicator should either be housed in the cabinet of the actual actinometer, or be in a separate unit situated close to the actinometer for convenient operation by one observer. Thus the distance is extremely small and a low radio-frequency can be utilized.

To illustrate the importance of the above considerations, it may be mentioned that the author has designed and manufactured tele-apparatus, *e.g.*, tele-pyranometers, with distances of more than thousand miles between the positions of detector and indicator (Albrecht 1955). In such cases, the resultant frequency has to be chosen with regard to the ionospheric propagation at the times of operation; in other words, frequencies of the order of 3 to 7 Mc/s have to be used.

However, small distances such as required for the actinometer under discussion result in a considerable simplification because the number of amplifying stages can be reduced to a minimum. Furthermore, a low resultant frequency allows the components of both oscillating circuits to be of very similar type if the oscillators operate on high frequencies. No additional capacitor combinations for compensation of different frequency coverages of both capacitance variations are necessary, as oscillator and resultant frequencies are not of the same order of magnitude.

Consequently, an operating frequency of 4·4 Mc/s (at ambient temperature 20°C) was chosen for the radiation-sensitive oscillator, while the temperature-compensating oscillator oscillates on 4·3 Mc/s (also at 20°C). The resultant frequency is, therefore, 100 Kc/s, if the same temperature acts upon both oscillators. The radiation-sensitive oscillator increases its frequency if radiation is allowed to fall on to its capacitor, thereby increasing the resultant frequency. The following relation exists between the oscillator and resultant frequencies—

$$F = \frac{f_T}{\sqrt{1 + TK_T \triangle t_T}} - \frac{f_R}{\sqrt{1 + TK_R \triangle t_R}} \quad (1)$$

where $F$ =resultant frequency

$f_T$ =temperature-compensating freq.

$f_R$ =radiation-sensitive freq.

$TK_T$ =effective temp. coeff. - - - temp.-comp. circuit

$TK_R$ =effective temp. coeff. - - - rad.-sens. circuit

$t_T$ =temp. of compensating element

$t_R$ =temp. of radiation-sensitive element

Due to the low resultant frequency, both oscillators may be very similar as far as their circuits are concerned. As in the author's original form of capacitance bolometer, a kind of electron-coupled oscillator is used for both circuits, as is apparent from the circuit diagram (Fig. 1).

The resonant circuit of the radiation-sensitive oscillator contains a fixed inductance and four temperature-sensitive capacitors which are alternately connected into the circuit by means of a selector switch. Each of these capacitors is mounted behind a special combination filter (see Sec. 3, Optical Design). Thus the elements measuring radiation intensity in four different spectral bands may be exposed simultaneously and switched in the order desired. Theoretically, there is no limit to the number of elements, *i.e.*, the number of different spectral bands, as long as constructional requirements with electronic instruments are observed. One criterion is the quality of the multi-position switch used for selecting the elements. Its contacts must be of good construction and its insulation material should have very low losses. A ceramic rotary switch of good quality should meet all requirements, although a bakelite rotary switch may be substituted.

The temperature-compensating oscillator uses an identical type of capacitor as temperature-sensitive element. No switch is necessary and the circuit is the same as that of the other oscillator (see Fig. 1). The inductance of the resonant circuit is adjusted so that the operating frequency differs by 100 Kc/s from that of the above-mentioned oscillator (no element exposed to the radiation).

Capacitors suitable for capacitance bolometers have been discussed at length in the author's previous publication (Albrecht 1955). A so-called medium-K capacitor (240 $pF$; $K$=250; temperature coefficient: $-2800 \times 10^{-6}$ $\triangle C/C$) was utilized in the instrument being described. All temperature-sensitive capacitors, *i.e.*, four in the radiation oscillator (painted black)

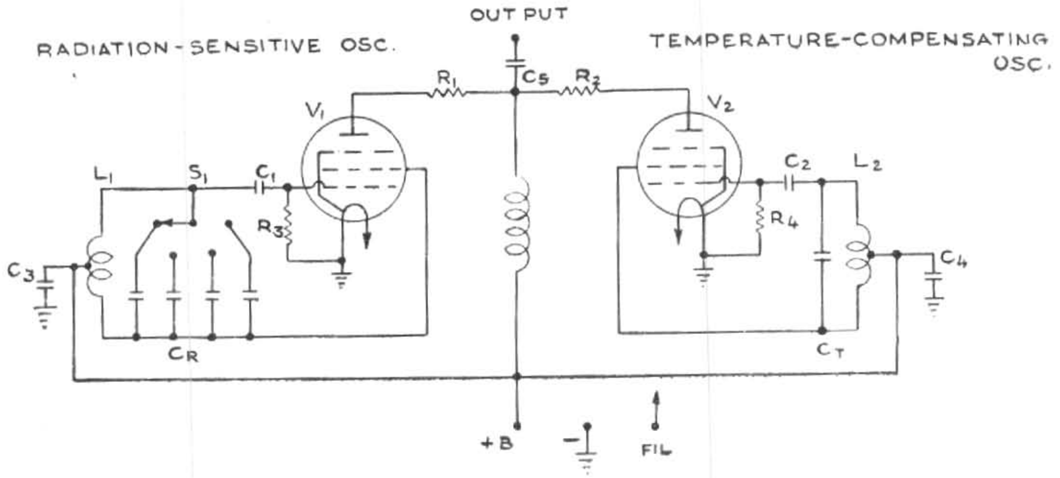


Fig. 1

$C_R$ — radiation-sensitive capacitor (four separate capacitor)
$C_T$ — temperature-compensating capacitor
$C_1$, $C_2$ — 100 $pF$
$C_3$, $C_4$ — 0·002 $\mu F$
$C_5$ — 0·1 $\mu F$

$L_1$, $L_2$ — circuit inductances
$L_3$ — radio-frequency choke for 100 Kc/s
$R_1$, $R_2$ — $10k\,\Omega$
$R_3$, $R_4$ — $15k\,\Omega$
$V_1$, $V_2$ — valves I T 4
$S_1$ — rotary switch (four positions)

and one in the compensating oscillator, should preferably have the same value of capacitance and temperature coefficient. For convenient operation, the zero frequency, *i.e.*, the reference frequency, should be the same in all switch positions. This is purely an operational advantage and can be achieved without much trouble even if the capacitors differ slightly in their capacitances. In any radio-frequency equipment, the stray capacitances of components and the inter-electrode capacitances of valves result in an additional capacitance across the resonant circuit. Due to the relative unpredictability of its actual value which, however, can be regarded as constant, a certain figure (normaly 30 $pF$) is generally assumed in the theoretical design. Of course, the stray capacitance cannot be expected to be the same for all radiation-sensitive capacitors, as the lengths of their leads may differ appreciably. It may here be mentioned that all leads must be kept as short as possible, following normal practice in R.F. constructions.

Ceramic trimmers may be used to bring all effective circuit capacitances to the same value, which means that the zero frequencies of all elements are the same. Usually, trimmers of approximately 10 $pF$ maximum capacitance should suffice. Under ideal conditions their temperature coefficient should be zero, because they are not exposed to the radiation but to the ambient or instrument temperature. Such trimmers are readily available. The reduction in radiation sensitivity due to trimmers and stray capacitances, whose temperature coefficient is slightly positive, is negligible, although they are connected in parallel to the temperature sensitive capacitor in the resonant circuit. This is so because their total capacitance does not amount to more than ten per cent of that of the temperature-sensitive capacitor. In any case, the effect can be taken into account when calibrating the instrument.

The coils in the actinometer should be wound on formers of suitable material, *e.g.*, polystyrene. With the circuit constants mentioned earlier $4 \cdot 67\ \mu H$ and $4 \cdot 9\ \mu H$ are required as inductances for the radiation oscillator and the compensating oscillator, respectively. Values of frequencies capacitors, and inductances can of course be changed with capacitance bolometers of any description, and handbooks of electronic engineering should be consulted for the design of ordinary circuit components. However, the constants used in the actinometer being described appear to be most suitable for this application.

The design of the entire circuit is such that alterations of output loading and changes in supply voltages have a negligible effect on the *resultant* frequency, which is the only important frequency as far as the actinometer reading is concerned. As in the tele-pyranometer (Albrecht 1955), electronic coupling is achieved by allowing oscillations to take place between filament, control grid and screen grid of each valve. Strictly speaking, capacitive coupling is also involved to a certain degree but this can be neglected for the purpose of this actinometer. The output is taken from the plate of each valve. As the actual output power is of no consequence as long as distances of a few feet can be covered, a radio-frequency choke for the resultant frequency serves as common plate load. The plates of both valves are connected through $10\ k\Omega$ resistors, in order to avoid possible interactions between the oscillators. The actinometer output is capacitively coupled to the choke.

The valves being battery-operated, power for the filaments and the high tension are supplied by dry batteries. These may be housed in the base of the actinometer stand. If the actinometer is to be used for recording purposes a permanent mains power supply can be substituted. The valves can easily be replaced by cathode-type penthodes (*e.g.*, 6AC7, 6AU6, 6CB6, etc). However, for normal actinometer measurements, the portable version appears to be far more practicable.

### 3. Optical Design

As mentioned in the previous section, all radiation sensitive elements are exposed simultaneously. This requires four identical systems of diaphragms.

Type and quality of narrow band filters are of major importance in the actinometer under discussion. Combinations of two Schott-filters (manufactured by Schott & Gen., Mainz, West-Germany) are used for each of the following bands:

| | | | |
|---|---|---|---|
| Band Nr. | 1 | 330—470 $m\mu$ | blue |
| | 2 | 525—685 $m\mu$ | yellow minus red |
| | 3 | 760—1060 $m\mu$ | "near" infra-red |
| | 4 | 1700—3000 $m\mu$ (approx.) | "far" infra-red |

This selection of the bands is based on the optical design of the differential actinometer described by Fritz H.W. Albrecht (1954). Using pulse-operated normal resistance bolometers, the differential actinometer was designed before the author completed work on his capacitance bolometers. The sensitivity of the differential actinometer was found to be inadequate for reliable investigations of the atmospheric water vapour. Capacitance bolometers have proved to be far more sensitive radiation detectors. However the optical design of the electronic actinometer being described in this paper is very similar to that of the differential actinometer.

Using the manufacturer's characteristics (Schott and Gen. 1952), simple calculations lead to the filter combinations:

| | | |
|---|---|---|
| Band Nr. | 1 | 2 mm BG 25 plus 3 mm BG 19 |
| | 2 | 1 mm OG 1 plus 3 mm BG 19 |
| | 3 | 1 mm RG 2 plus 3 mm BG 3 |
| | 4 | 1 mm BG 18 plus 1 mm RG 10 |

### 4. Constructional Details

The prototype of this electronic actinometer is housed in a metal case (standard size $6 \times 4 \times 2$ inches). Diaphragms, filters and radiation-sensitive capacitors from one unit, which can be separated for constructional purposes, inserted into the case when completed, and aligned with respect to four corresponding openings in one $4 \times 2$ side. Viewing from outside, components are arranged as follows—opening, filter, and diaphragms of progressively smaller diameters, the last diaphragm being one wall of the element chamber. The capacitors used are of the disc type with an approximate diameter of 8 mm. Each capacitor is held in position by its connecting wires which are soldered to a mounting strip. This strip is fixed to the element chamber.

The other side of the metal case contains all other components, *viz.*, two valves 1 T 4, two inductances, the rotary switch, output choke and additional components. A shield is placed between both oscillators such that stray coupling is reduced to a minimum without seriously affecting the temperature distribution within the case. This is important because the circuit capacitor of the temperature-compensating oscillator should be at an ambient temperature representing the instrument temperature as well as possible. This capacitor is placed close to its inductance and yet thermally shielded as much as possible from the glass section of the valve, which assumes a certain temperature due to the heating of its filament. By observing both, electrical and thermal, requirements a satisfactory compromise can be achieved without much difficulty. To further reduce stray coupling, the inductances of both oscillators should be situated at right angles to each other.

As is usual practice in actinometer construction, the instrument case must be closed tightly so that wind effects do not exist.

Outside the case, a lid covers the four openings when no observations are being taken. The actinometer sight is of the normal black-spot type. The only control is the four-position switch.

The case may be mounted on a spherical joint, or other means of universal adjustment may be employed. The base of the actinometer stand contains all supply batteries and the on-off switch.

### 5. Indicators

Indicators for capacitance bolometers are required to be of the highest possible accuracy. As outlined in the author's previous publication on this subject (Albrecht 1955), the accuracy usually obtainable with ordinary frequency meters, namely one part in 10,000 is sufficient for most meteorological applications of capacitance bolometers. The *relative* accuracy of good communications receivers may be assumed to be of the same order of magnitude and only *relative* accuracy is important for the electronic actinometer, unless automatic recordings are contemplated.

Thus a communications receiver, the resultant frequency (approximately 100 Kc/s) being within its range of operation, has been used as indicator and can be recommended. The receiver is an ex-war type, Marconi R 1155A, which includes a range of 75 to 150 Kc/s. This receiver requires a mains power supply and it may, therefore, be advisable to replace it with a portable battery-powered receiver for the range in question. The stability of any receiver should be adequate because the frequency is comparatively low.

Very successful investigations have also been made with a frequency meter especially built for the frequency range concerned. The author designed it on the basis of the temperature-compensated variable-frequency oscillator mentioned in connection with the tele-pyranometer (Albrecht 1955). This oscillator may be modified such that a battery powered valve can be used, which results in an entirely portable indicator for the portable actinometer.

Operational requirements of the above indicators for capacitance bolometers are unusual, to some extent, if compared with indicators normally used for meteorological instruments. The observer has to possess practice and a "sense of touch" in tuning the receiver or frequency meter with adequate care. As is usual in communications practice, the unknown frequency (here the bolometer freq.) is measured by varying the known frequency of the indicator until "zero-beat" is indicated by an absolute beat-frequency null (adjustments to within one cycle are possible with ordinary equipment). The indicator dial having been read for the reference frequency—elements at instrument temperature and unexposed—the elements are exposed for a certain period (one or two minutes are more than sufficient) and the new frequencies are read. Audible zero-beat indication can simply be achieved by headphones or loudspeaker at the output of the receiver or frequency meter. A useful operating aid is a tuning indicator, *e.g.*, a strength meter or small cathode-ray tube, connected to the receiver.

The method of indication just described may be replaced by a direct indication on a pointer-type galvanometer. Good results have been obtained by applying pulses formed in accordance with the audio frequency to an electric integrating circuit whose output is connected to the galvanometer. However, optimum accuracy can more simply be achieved with the tone indication described above. A portable, economic and stable indicator, using a pointer-type galvanometer, is in the process of being designed by the author.

### 6. Conclusions

The application of capacitance bolometers for measurements of solar radiation in narrow spectral ranges is another proof for the universal usefulness of these new radiation detectors. Their sensitivity exceeds that of ordinary detectors by a considerable factor. Assuming an effective temperature coefficient of $-2 \cdot 7 \times 10^{-3}$ $\Delta C/C$ per °C, a radiation increase of 1°C in element temperature causes a frequency change of 6·1 Kc/s, according to eq. (1); with a normal indicator accuracy of one part in 10,000, the theoretical limit would be 0·0016°C. Of course, this sensitivity can only be reached by special selection of the capacitors to be used as elements, and by a stable type of oscillator. Although such a sensitivity is obviously not required in the case of the actinometer described in this paper, its mention helps to illustrate the extreme usefulness of capacitance bolometers in radiation investigations. It should, for instance, be possible to simplify apparatus using interference filters, which require a considerable element sensitivity. Furthermore, the use of the new bolometers for spectrographic investigations may be possible. If high-K capacitors are used, the ratio of barium titanate ( $BaTi0_3$ ) to strontium titanate ( $SrTi0_3$ ) and possible additional mixtures in the dielectric governs the position of the Curie temperature (in analogy to ferromagnetism) of the sensitive element and the bolometer has to be designed accordingly (Albrecht 1955). Considering that normal industrial types of capacitors have been utilized by the author, it appears to be promising to experiment with specially made types in order to further improve the sensitivity.

Turning to the use of this electronic actinometer for investigations of atmospheric water vapour, an obvious conclusion is that this is an ideal instrument for it. The type described in this paper allows special accurate measurements in each of the four spectral bands. In fact, its use in radiation networks should be possible because the only maintenance work likely to be necessary is the occasional replacement of batteries and valves and thus well within the capabilities of scientific and technical personnel.

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