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THE MEASUREMENT OF ATMOSPHERIC TURBULENCE
AT SEA.

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1. Introduction

The instrumentation used during ATEX in 1969 was briefly described in TDN 11, where it was pointed out that various shortcomings were encountered. Much of this instrumentation had now been extensively redesigned, and a description of its revised form is the substance of this note.

The equipment is intended to measure (directly or indirectly) fluctuations of horizontal and vertical wind speed, temperature and water vapour, and it is normally used at heights above about 50 m. This height is taken to be the lowest at which the influence of the ship might be neglected if lying broadside to wind. When headed into wind it is certainly incorrect to use such a low level and measurements have not been made below 100 m in these circumstances. There are two advantages which result from the comparatively large minimum height above the surface. First, instrumental time constants can be relatively large if measurements of fluxes rather than the high-frequency part of the turbulence spectra are the prime objectives (McIlroy (1961) suggested that the effect of finite exponential time constant τ on the measured flux was small for $\tau \bar{U}/z \approx 0.1$, giving $\tau \approx 1$ sec for $u = 5 \text{ m sec}^{-1}$ and $z = 50$ m. This is to be compared with results quoted by Miyake et al (1970) who suggest that a high frequency cut-off of about \bar{U}/z is adequate for momentum and moisture flux determinations, but possibly several times larger for the heat flux: equivalent time constants would be around 2 secs and perhaps rather less than 0.5 sec respectively, for the height and wind speed already cited). Secondly, the frequencies making the major contribution to the required cross-spectra decrease as height above surface increase. This means that above some level the influence of ship motion, which produces highly distorted measured spectra over the frequency range of the motion, probably can be subjectively eliminated from the desired cross-spectra (by low pass filtering) without introducing significant errors in the computed fluxes.

Techniques for measuring atmospheric turbulence already in use within Met O 14 have facilitated some aspects of the airborne system design, but for reasons of compactness and because of the use of radio telemetry the end product differs very substantially from those at present being used at Cardington. The system which has evolved uses conventional electronic circuits for signal conditioning but it has been the aim (not necessarily realized) to achieve a reasonable absolute accuracy in the case of temperature and moisture measurements in particular. This has been facilitated by constructing a simple calibrating system which can be easily used on board ship. The remainder of this note describes the airborne and ground equipment in some detail. (A description of the associated balloon and tethering system is given in TDN 11).

2. Sensors

a. Inclinometer. This uses a double 'V' configuration of hot-wires described by Jones (1961). Wind tunnel tests of the output sensitivity variation with wind speed have shown less than $\pm 4\%$ for inclinations up to $\pm 30^\circ$ and speed range 3 to 15 m sec^{-1} , when used in conjunction with the circuit described in § 4(b) below. Routine calibrations are made at 8 m sec^{-1} and are applied to all experimental data. Tunnel tests have also been made to assess the output variations for fixed inclination but varying azimuth:

up to ± 20 degrees azimuth and ± 30 degrees inclination the indicated errors are less than ± 3 degrees inclination: there are significant differences between inclinometers, presumably due to the difficulties of obtaining exact geometry during manufacture, and a tendency towards asymmetry, ie inclination errors for azimuth of different sign themselves usually have different sign. In the practical application of measuring inclination for subsequent eddy-flux calculations these errors would tend to cancel out since the bulk of the fluxes are associated with eddies of periods much longer than the natural period of the vane supporting the sensor system (2 to 3 seconds in moderate winds).

b. Anemometer. The design is based on one due to D Tribble (Imperial College), which incorporates a 3-cup rotor with photo-electric sensing of rate of rotation. The photo-cell system works satisfactorily without shielding from ambient light and the optical alignment is uncritical. The cups are pressed from plastic sheet which is stretched to produce the desired thickness: this thickness increases from tip to base of the cups to give greater rigidity. The shaft of the rotor is stainless steel, running in jewelled bearings. Two versions of the anemometer have been made, for light ($< 10 \text{ m sec}^{-1}$) winds and stronger winds ($\sim 15 \text{ m sec}^{-1}$): these differ only in thickness of the cup material. Distance constants for the lower speed version is 0.5 m with an increase of about 50% for the higher speed anemometer.

c. 'Dry Bulb' thermometer. This is an open helix of 25μ platinum wire which is non-inductively wound on a transparent plastic former. The wire is heat treated by passing a high current through it for a few seconds (roughly doubling its resistance) and repeating this until an unchanging cold resistance is obtained. The operating current is restricted to keep the calculated self-heating to less than 0.01°C in a 5 m sec^{-1} wind (Taylor 1963). The sensor is used unshielded at present (the calculated radiational heating, assuming 80% of the incident radiation is reflected, is less than 0.02°C in a 5 m sec^{-1} wind). The resistance is a nominal 128 ohms at 0°C , with a resistance change almost exactly 0.5 ohms for each degree C. Trimming is done with metal-oxide shunt resistors. Matching and calibrations are carried out in an air chamber immersed in a water bath, the measurements being made with a precision autobalance bridge.

d. Wet-bulb sensor. This is constructed with 25μ platinum wire from the same batch used in (c). Two very fine cotton threads (each is one of the three cords that make up the standard 'machine' cotton used in dressmaking) are wound in opposite helices on the wire: the result is then twisted with a length of machine cotton and wound in the form of an open helix on to thicker parallel cotton wicks joining the peripheries of two discs. The sensor is mounted with the wicks vertical and is fed at both top and bottom from a reservoir containing deionised water. Wind tunnel tests have demonstrated some drying out of the system at winds of 15 m sec^{-1} when the air was dry and warm (wet bulb depression around 8°C), but for depressions of 4 or 5°C the variations of indicated temperature were less than $\pm 0.02^\circ\text{C}$ over the speed range 2 to 15 m sec^{-1} . Calibrations were made with the sensor dry, but measured wet bulb temperatures then disagreed with those obtained by a conventional wet bulb thermometer, the difference being around 1°C , probably due to shunting of the resistance wire by the water film. Future sensors will be constructed with insulated wire.

3. The Vane (figs 1(a), 1(b))

The basic frame is a horizontal tube attached near its midpoint to the balloon cable by a bearing which allows rotation about the cable and also damped rotation about the tube's axis. Adjustments can be made to keep the tube approximately horizontal for any cable angle up to 40° . The inclinometer is mounted at the forward end on a damped pendulum which is aerodynamically

balanced. Aft of this a cross-arm supports the anemometer and the two temperature elements. The wet bulb sensor is shielded from direct solar radiation, and its height with respect to the reservoir is adjustable. All electronics except the transmitter are contained in the box immediately to the rear. The rear half of the vane tube supports batteries, the transmitter and the antenna (a simple half wave dipole and reflector). Total weight is about 3.5 kg and its length is 1 m.

4. Circuits

These are illustrated diagrammatically in figure 2. The circuits serve essentially as interfaces between sensors and the telemetry system. All have gain options to cover realistic ranges of meteorological parameters (over the sea) because it is essential that the turbulence signals produce the maximum possible variations in output frequency of the voltage-controlled oscillators (within the allowed frequency range) in order to achieve the highest possible signal-to-noise ratio.

- a. Voltage stabilizer (figure 3). Power is provided by rechargeable silver-zinc accumulators of 1.5 AH capacity and high power/weight ratio. Cells are series-connected in banks of six and in conjunction with the stabilizer produce two outputs (- 6 to 0, 0 to 6V). The output impedance of the stabilizer does not have to be very low because the current drawn by the various circuits varies comparatively little during an experiment: the actual impedance is about 0.02 ohms. The circuit is designed to give only small output variations for the large input variations as the accumulators discharge: output changes are about 10 mV for input voltage variation between 14 and 7.5V. Temperature stability is approximately 0.01% per degree C over the range 0 to 30 degrees C.
- b. Inclinometer bridge (figure 4). This follows a design first used at Porton a decade or so ago. The 10 ohm resistors in series with the sensors reduce the sensitivity changes that occur with changes of wind speed. Switched output attenuators provide nominal range of ± 30 and ± 45 degrees.
- c. Anemometer (figure 5). A chopper disc attached to the rotor lies close to a segment of a similar disc attached to the anemometer frame, and behind this is located the photo-transistor. The light source is a miniature 6V bulb. The photo-transistor is connected in a pulse circuit which is followed by a shaper producing a sharp leading edge. The shaped pulse-train is fed to a $\div 2$ module (a further $\div 2$ module is used in high winds). A simple 3-stage low-pass filter removes harmonics which could otherwise interfere with signals from the VCO's. The first divider ensures that the filter is offered a constant source impedance, whether or not the high speed option is used. The photo-transistor's performance remains satisfactory in temperature below 0 degrees C and the other electronics function properly over the range 0 to 30 degrees C.
- d. Temperature bridges (Figure 6). A 2.9 kHz oscillator powers the bridge containing the two temperature sensors (the frequency is selected to minimise interference with the VCO system). The AC outputs representing Td and Td-Tw are directly coupled to amplifiers with gains of 100, and the amplified signals are fed to phase-sensitive detectors (PSD's). Outputs from these are led via low-pass filters to attenuators giving ranges of ± 1.5 to ± 3 degrees C for Td and ± 1 to ± 3 degrees C for Td-Tw. The Td signal is also led via a buffer amplifier to an active high-pass filter (figure 6a) with

cut-off at 0.1 Hz. Its output is also controlled by an attenuator providing full scale output ranges between ± 0.25 and ± 1 degrees C. Binary-scaled resistors switched by low contact resistance toggle switches are used to offset ambient temperatures to the nearest 0.5 degree C. Useable ambient range is 0 to 31.5 degrees C.

e. Voltage-controlled oscillator system (Figure 7). The VCO's have a nominal sensitivity of ± 10 mV for ± 250 Hz deviation, and centre frequencies of 4375, 5312, 6250 and 7187 Hz. RV1 and RV2 provide gain and centre-frequency adjustments when required. Departures from linearity are about $\pm 2\%$ from best fitting straight line. Common-mode rejection is around 60 db. The output is summed via a resistor R1 with those from the other VCO's. The output frequency from the anemometer is also fed to the summing amplifier.

The VCO's have a drift with temperature up to about 3Hz per degree C and to reduce this effect of variations in ambient temperature the oscillators are mounted side by side in an oven. This consists of a metal cap round which is wound a heating coil: temperature is sensed by an attached thermistor. The whole is surrounded by expanded polystyrene. The heater and thermistor are connected in a simple control circuit (figure 8). Switching temperature can be set to within ± 0.5 degrees C by selecting the value of R1. At present it is not clear what is the most suitable excess temperature ($T(\text{oven}) - T(\text{ambient})$): Probably 5 to 10 degrees C is satisfactory, though care has to be taken to allow the instrument to cool for some minutes before being winched up when ambient temperature is appreciably lower than that in the laboratory. In any event, because of conduction down the leads from the VCO's to the underlying printed circuit board, there are always temperature gradients across the VCO's and it is difficult to achieve very high stability.

f. Transmitter. Interception of radio-frequency signals from this by the VCO's during ATEX resulted in poor quality data on that expedition, but the effect has been much reduced in the present equipment. It was found that the main interference was due to feedback of a 4 MHz signal from the mixer stage of the transmitter into the VCO's: the effect has been made negligible by using small RF chokes with bypass condensers on all lines to the transmitters, and also chokes on lines between accumulators and the voltage stabilisers.

g. Circuit Layout. Where feasible the circuits are built on plug-in printed-circuit boards. The boards are connected to the appropriate sockets by very low resistance pin connectors (Smith's 'Hypertac').

5. Calibration Unit

This consists essentially of a trolley which supports the vanes, auxiliary power supplies and various items of test equipment, and is designed specifically for easy use on board ship. The auxiliary power is connected to the vanes during the test programme, and is also used to supply the VCO ovens so that thermal equilibrium can be reached when on deck prior to an experimental run without draining the vanes' internal power supplies. A test-box containing sets of dummy sensors is connected to each probe in turn and two or three calibration points are obtained for each circuit. These are used subsequently in conjunction with more elaborate laboratory calibrations (carried out at Bracknell) to evaluate the various calibration factors.

6. Ground receiving and recording equipment (Figure 9)

This differs in only a few details from that outlined in TDN 11 . The output from a phased, cross-dipole receiving antenna is fed via low-loss cable to the receiver whose output is summed with a 12.5 kHz reference signal before being recorded on magnetic tape. The recorder is an Ampex FR 1300, used at a recording speed of 3.75 ips which gives a maximum continuous record length of rather more than 3 hours. The recorded signal is continuously monitored by feeding it to a discriminator system which provides band-pass filtering, frequency-to-voltage conversion and tape-speed variation compensation. A low-frequency (150 to 650 Hz) discriminator is used to convert the anemometer signal to a voltage proportional to wind speed: if the wind speed falls to such a low value that the anemometer output signal frequency becomes less than 150 Hz the signal cannot then be monitored, though it can be recovered readily during subsequent data analysis. In practice, when the wind falls very light at sea it becomes almost impossible to measure because of the effect of ship motion which can produce speed variations larger than the actual wind, and so these limitations of the associated electronic system are not very serious. The ship would normally make way in these conditions to produce sufficiently large measured winds.

A unit constructed from two recycling timers is used to provide time marks for the UV recorder and tape recorder.

7. Future developments

At present the system has been used with only 1 transmitter, necessitating the addition of cable telemetry for multilevel measurements; four transmitters are now available and are being incorporated in the vanes. Apart from this only minor modifications are being made to the vanes.

A brief design study of systems to reduce the effect of ship motion on the shape of the balloon cable catenary and hence to reduce ship-induced sensor motion has been completed and the possible alternatives are being considered. The most likely system involves an accelerometer-controlled servo device with hydraulic drive.

It is hoped that measurements of turbulence parameters will also be made in future using an instrument similar in many respects to the vane described above but attached at the end of a boom mounted at the bows of a ship: extra equipment (accelerometers, rate gyro and precision integrators) will also be needed to measure the ship motion in this case. The design of such a system is now in progress.

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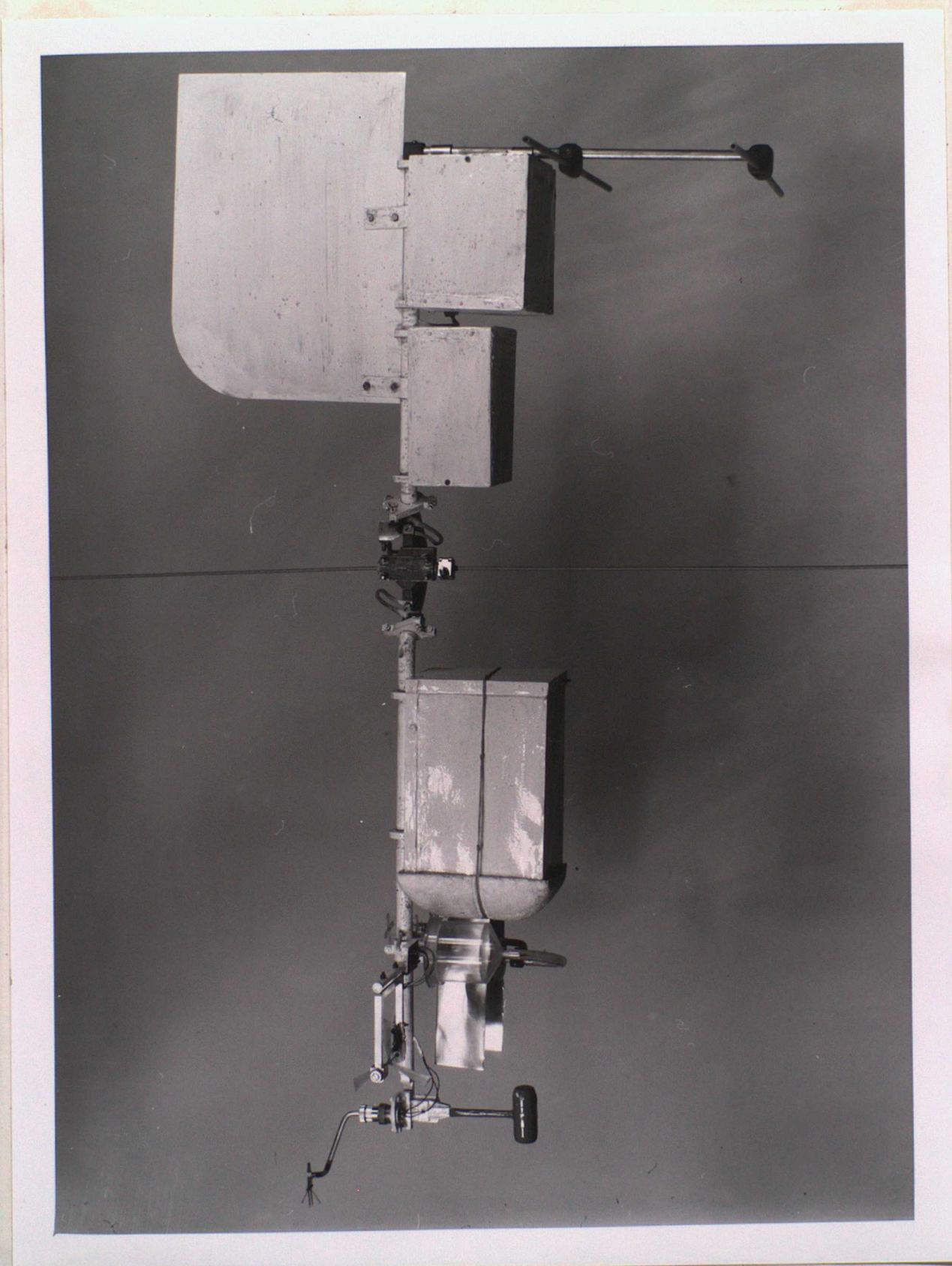


Figure 1a

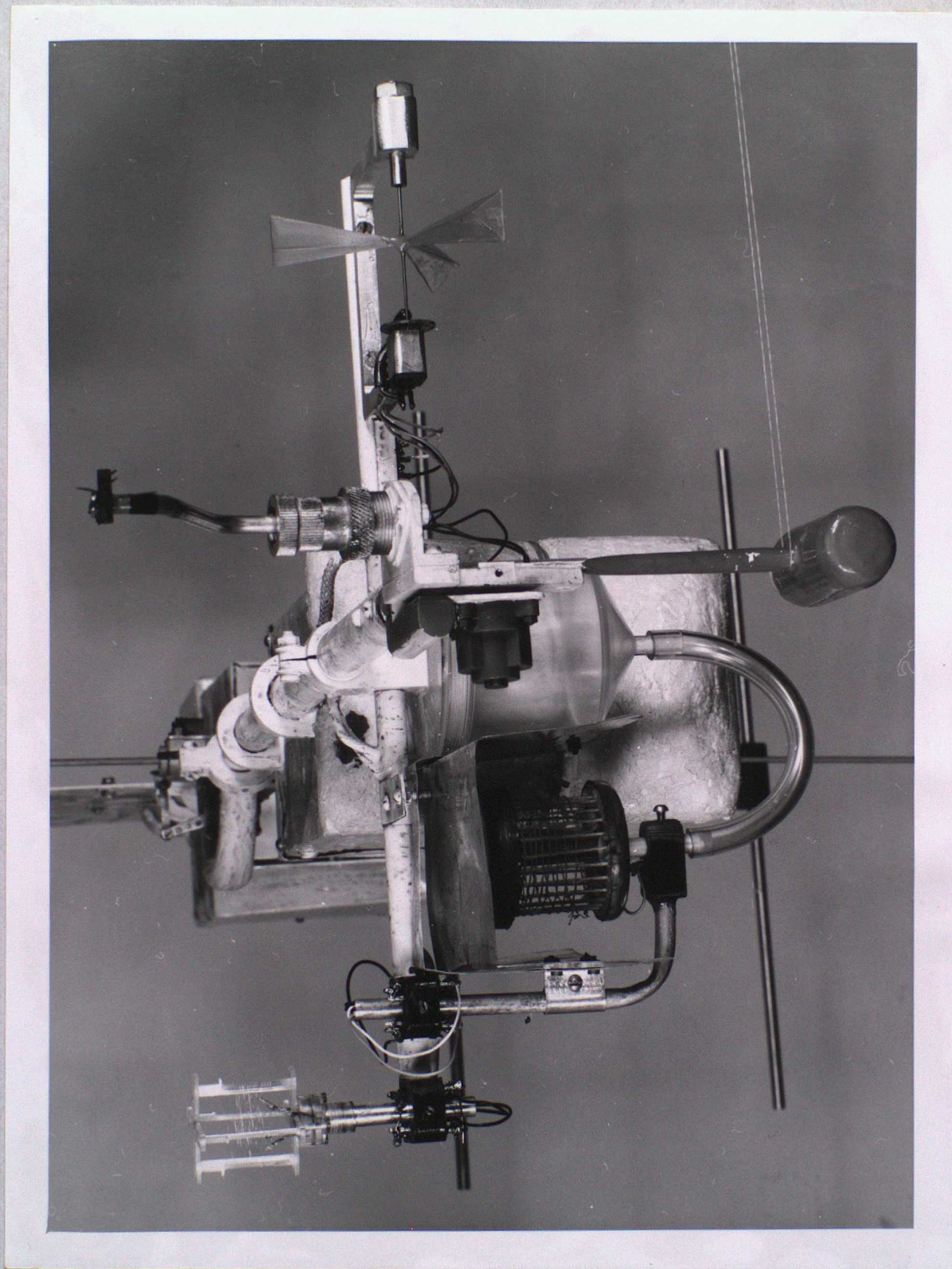


Figure 1b

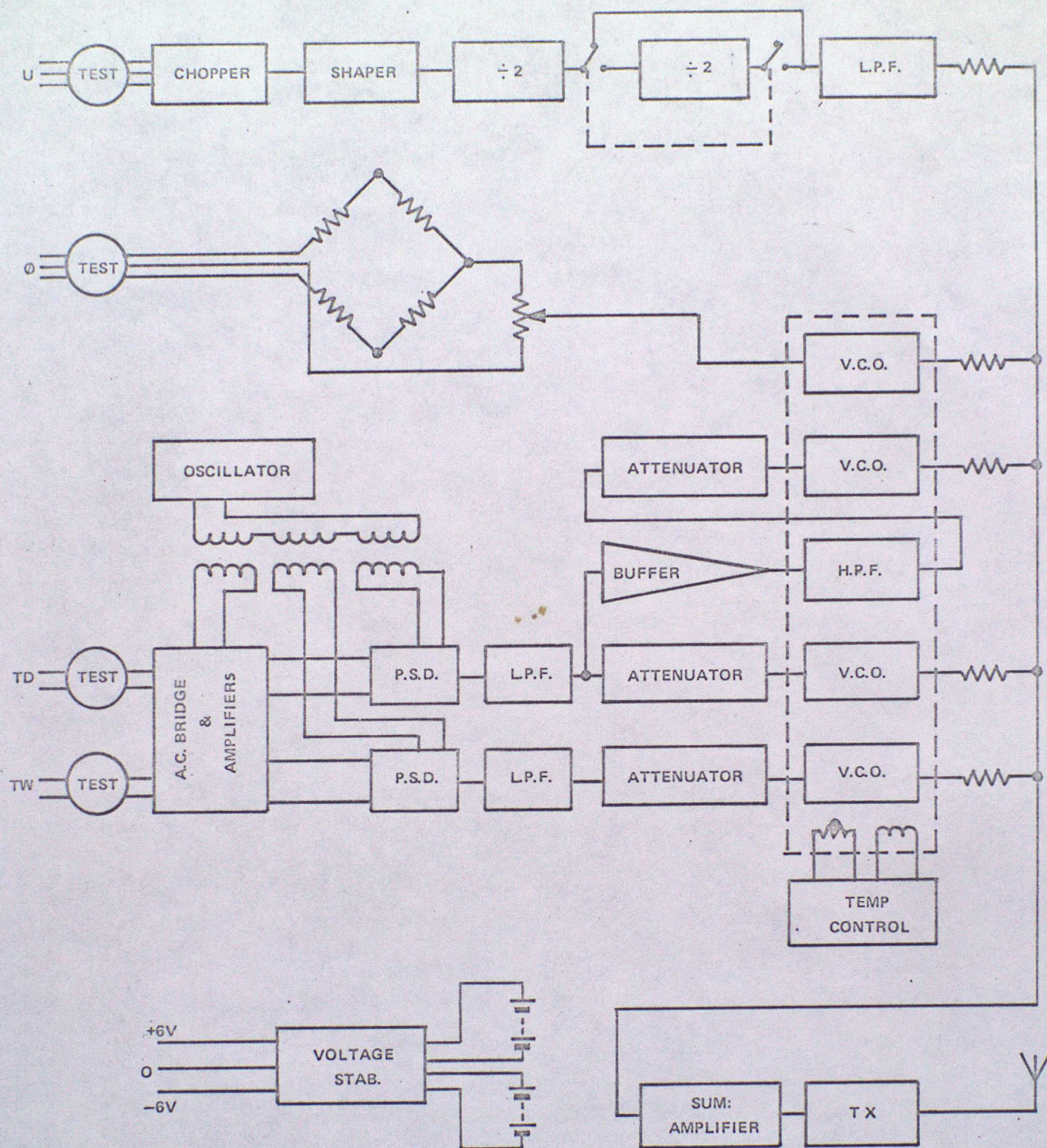


FIG 2 VANE ELECTRONICS

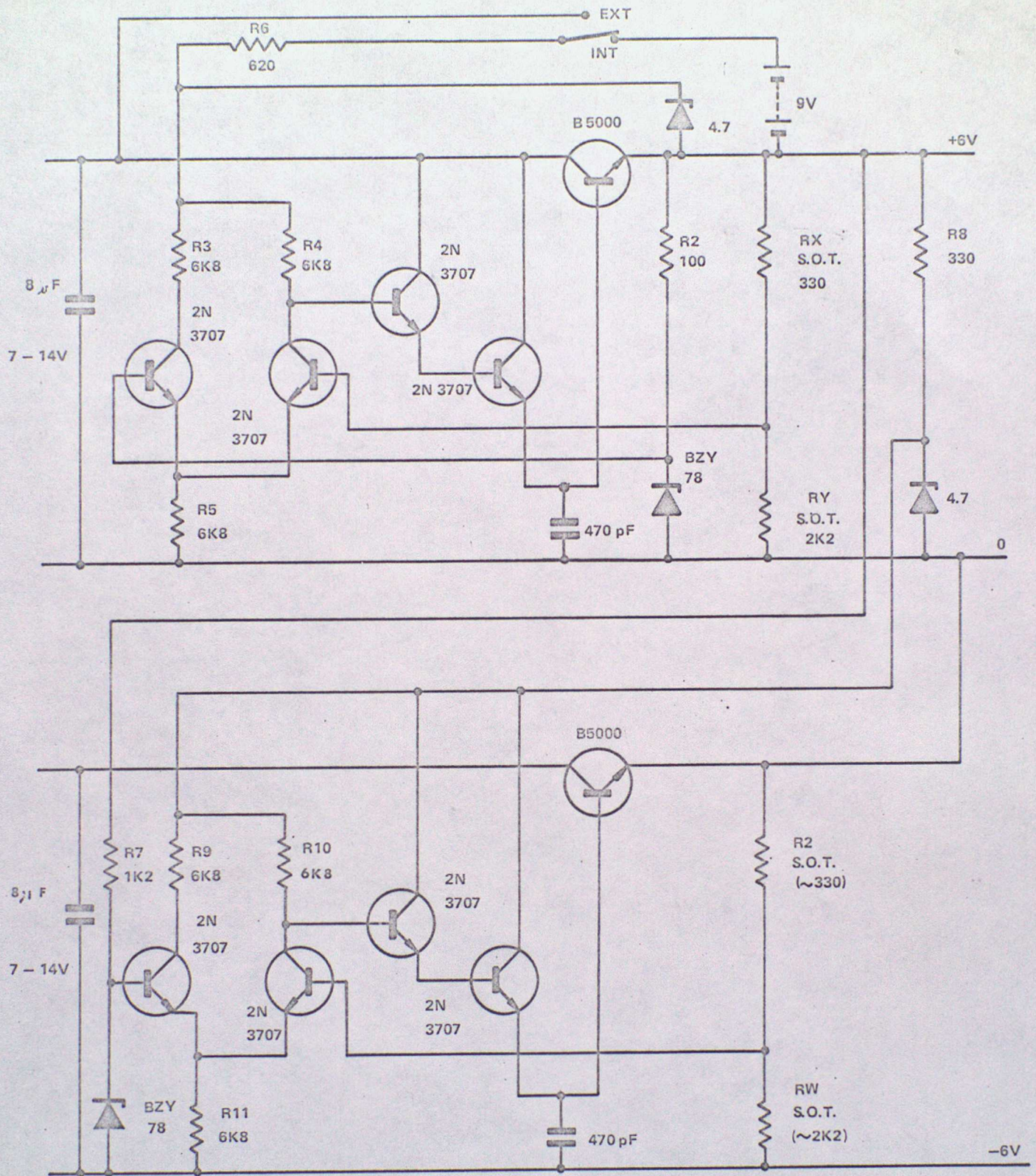


FIG 3 VOLTAGE STABILIZER

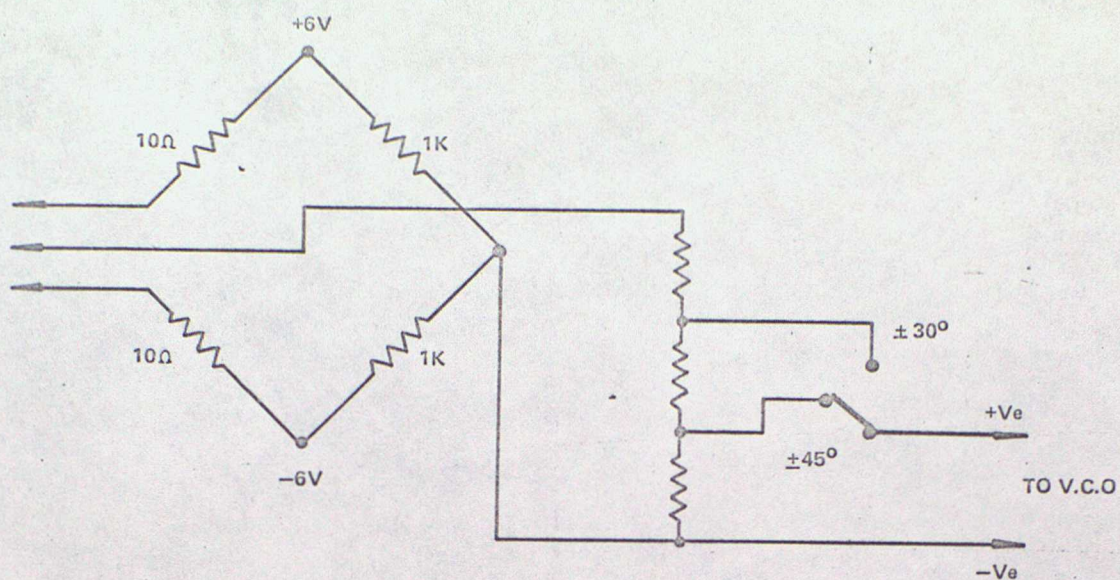


FIG 4 INCLINOMETER BRIDGE

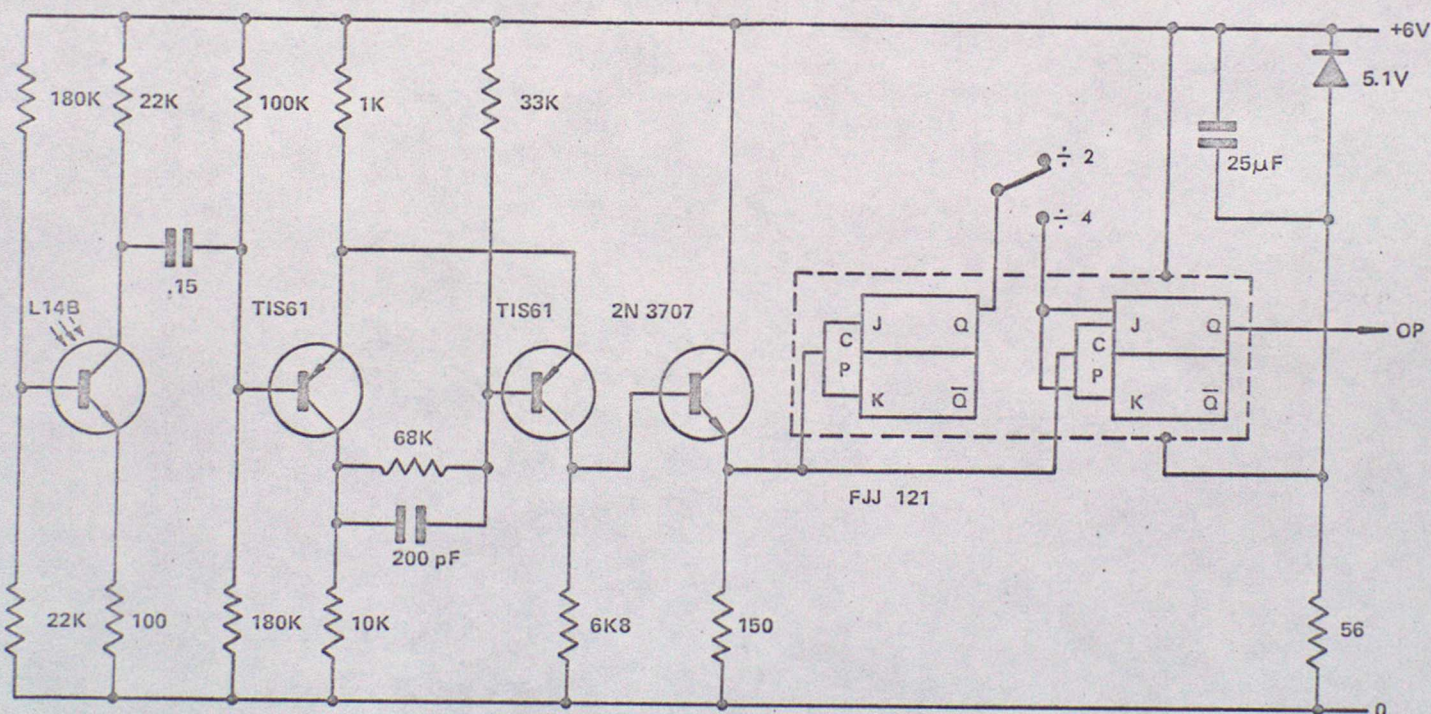


FIG 5 ANEMOMETER CIRCUIT

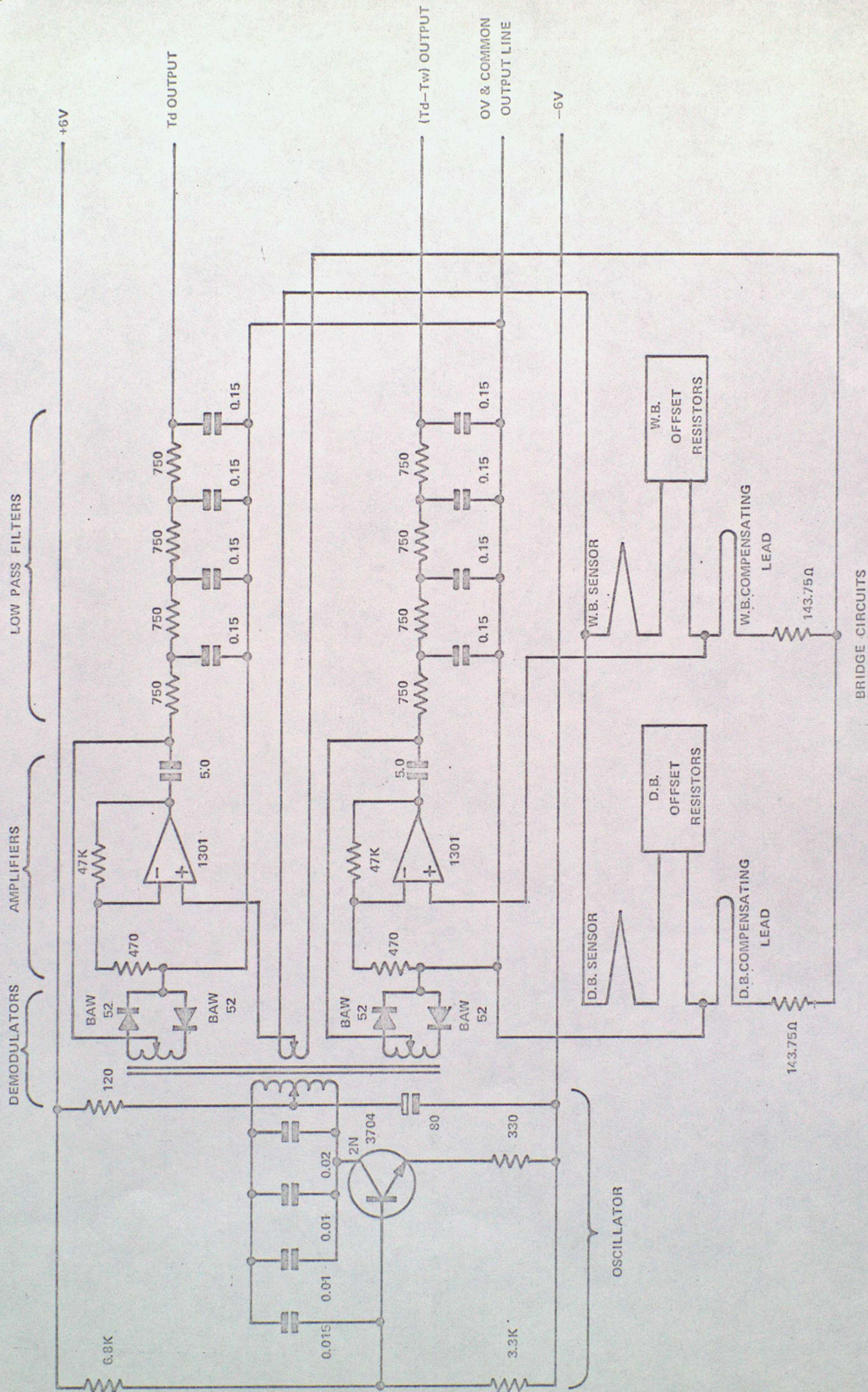


FIG 6 TEMPERATURE BRIDGES

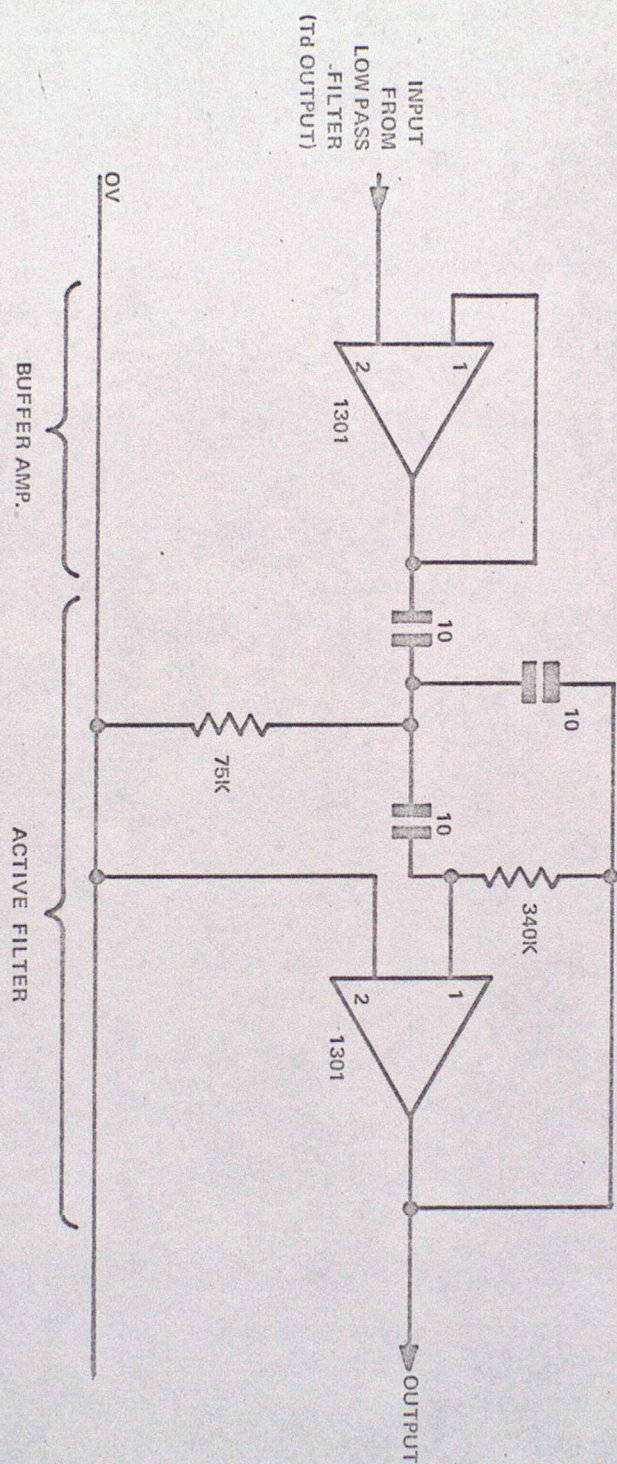


FIG 6A Td HIGH-PASS FILTER

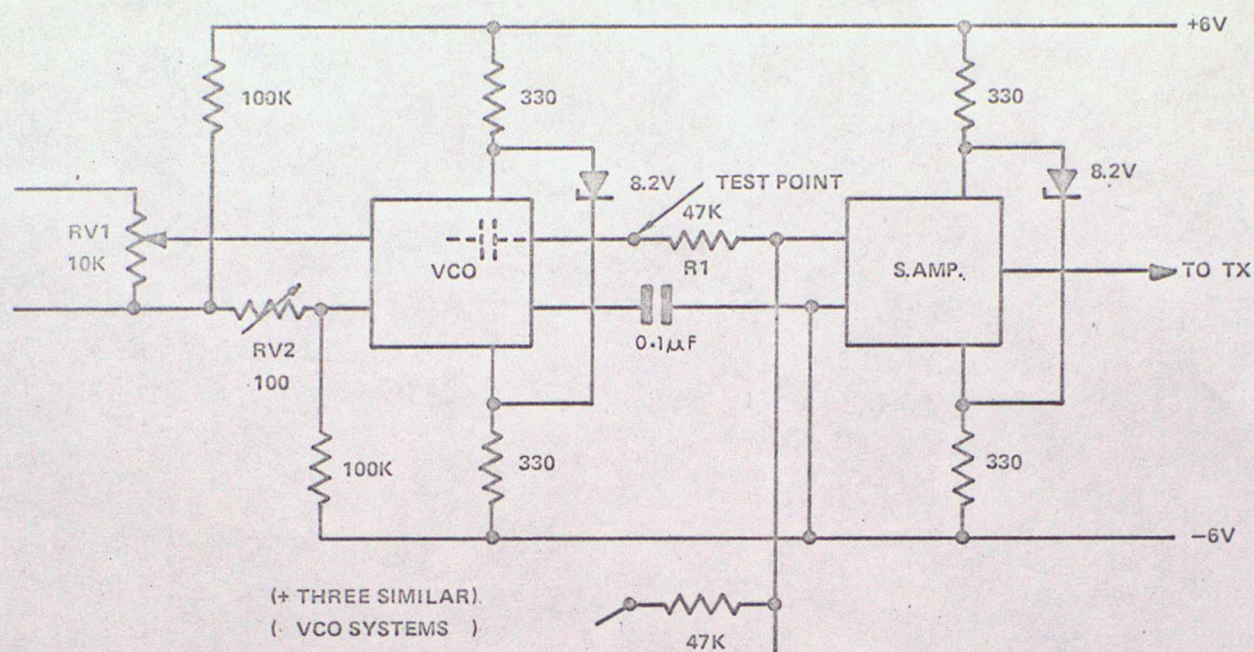


FIG 7 V.C.O. SYSTEM

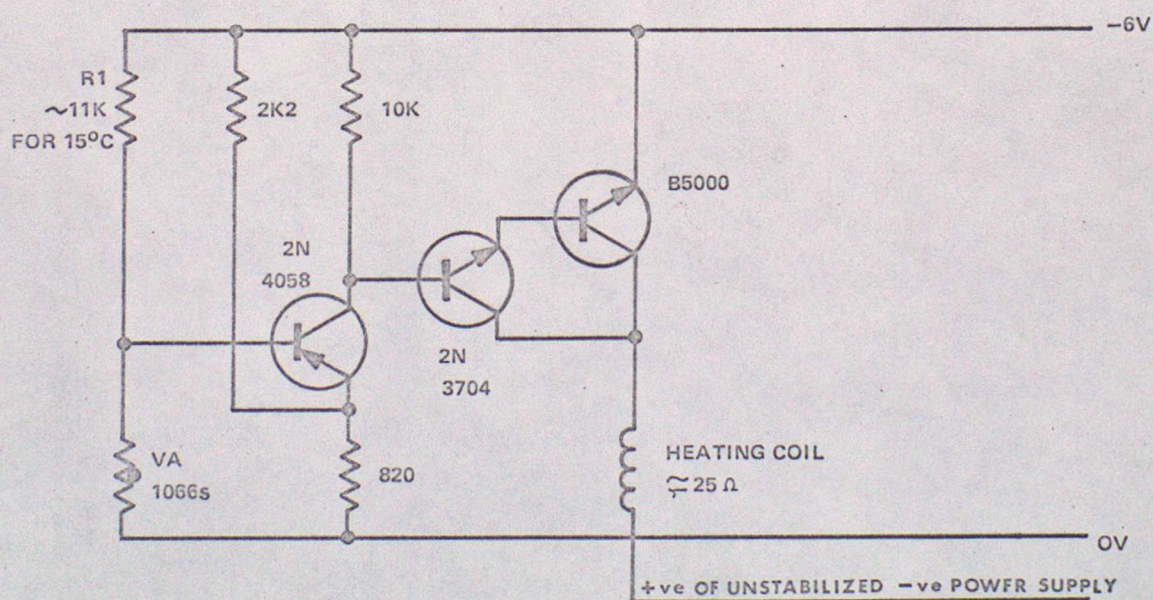


FIG 8 THERMOSTAT SYSTEM

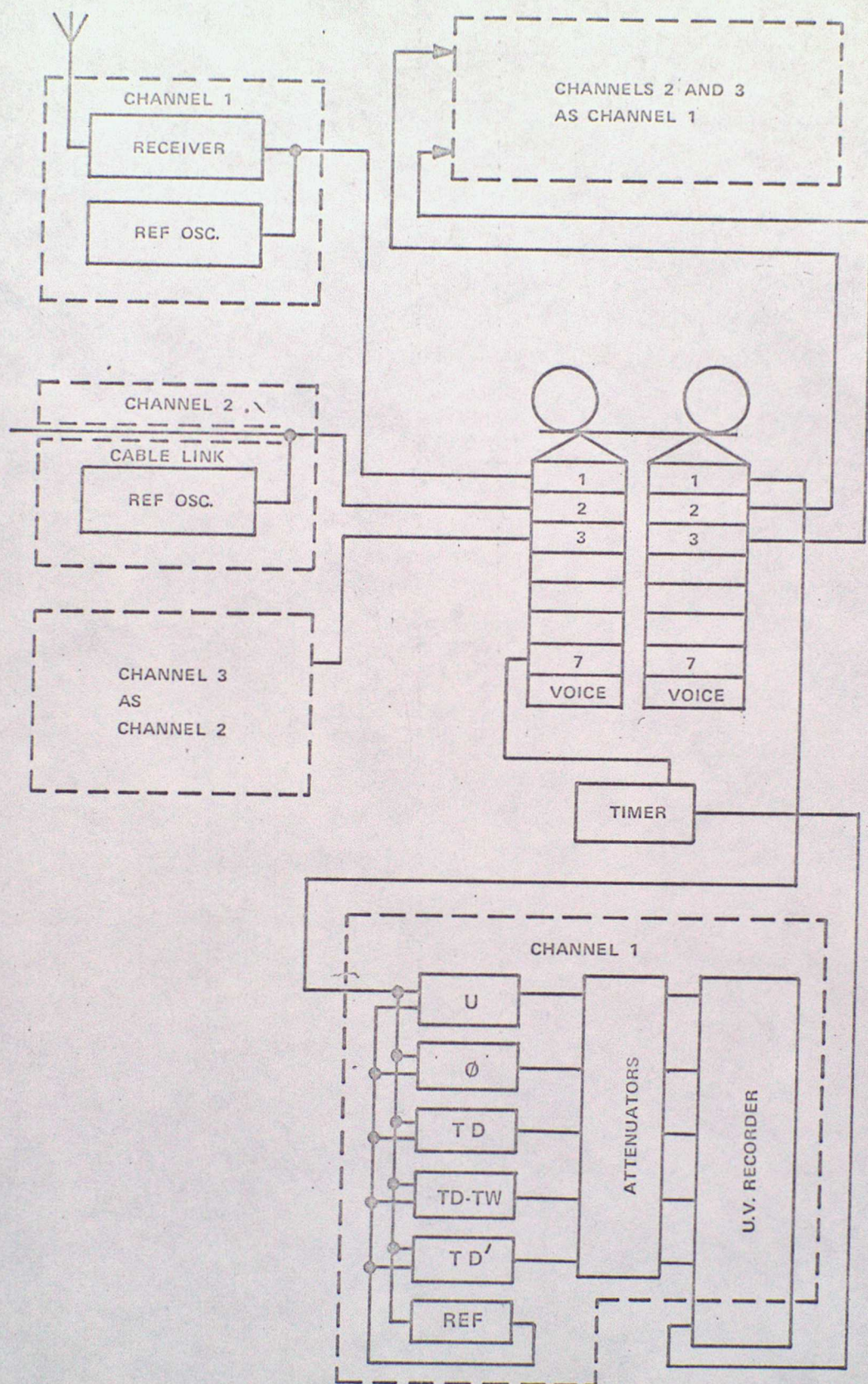


FIG 9 GROUND EQUIPMENT