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AUXILIARY EQUIPMENT OF AN ASTRONOMICAL PHOTOMETER

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This paper discusses an instrumental system for efficient photo-electric photometry of large numbers of stars; Leiden Observatory's 36-inch light-collector and the simultaneous five-colour photometer designed by Walraven are used as a concrete example. Simultaneous multi-band photometry can yield colours more accurate than the magnitudes contributing to them; this leads to the extra requirement that the response of the measurement system to undetected accidental disturbances be "grey". After a brief description of the telescope and photometer (section 2), the design of the following components is discussed in more detail: coldboxes (section 3), analogue integrators (section 4), digital recording equipment (section 5) and computer programmes (section 6). All items described have been in use for at least one observational season of six months.

1. Introduction and general description

The need for large quantities of photometric data of photo-electric quality has led to the design of specialized telescopes for this purpose, with simple optics (narrow field of view only), but with high efficiency in star-acquisition [see, for instance, JOHNSON (1968) for a very thorough-going application of this approach]. Many such telescopes are in operation, but not all of them have a photometer that even approximately matches its telescope in efficiency. The Leiden Observatory Southern Station (at the Republic Observatory Annexe near Hartebeestpoortdam in South Africa) has for several years had in operation a system that goes some way towards matching its telescope; the principle of the simultaneous five-colour photometer has been described by WALRAVEN and WALRAVEN (1960), but the system has been extended considerably since that paper appeared. Since in astronomy the requirements are often such that available commercial equipment is not really suitable, and since development work usually accounts for most of the time and cost of custom-built equipment, it has seemed worthwhile to save others at least some of their development effort by publishing a rather detailed description of our system. It is of course only one of many possible solutions, but it has the merit of on the whole working satisfactorily.

Experienced photometrists will find much that is familiar amongst the design considerations raised in this article. We have intended our article at least as much for the inexperienced and have therefore felt it worthwhile to include this background material. We may seem to have had an exaggerated concern for reliability; the reason for this is that the system has to operate at a self-supporting field station and for long periods has to survive with only a little specialist attention.

A photometric instrumental system may conveniently be divided into a telescope, photometer, amplifiers (or integrators), a (usually recording) voltmeter and various indicators or recorders of auxiliary quantities such as time, coordinates, instrumental settings and star identification. In a simple system most of the indicators are control knobs or pointer instruments, the operator noting down the reading in a logbook. The system used at our Southern Station started as such a simple one, the only "luxuries" being a recorder rather than a voltmeter, and star-acquisition by preset coordinates rather than by operator control. Practical experience with the five-colour photometer soon showed that with these methods reduction could not possibly keep pace with the observations; plans were accordingly made to eliminate as much as possible of the reading-off and to make the output suitable for computer reduction. The present equipment includes auto-ranging (i.e. adapting their sensitivity to the size of the input signal) integrating amplifiers, a digital voltmeter and automatic digital recording (typed and on punched paper tape) of all quantities thought significant for the reduction. The computer programmes necessary for standard reduction are considered an essential part of the system; a good digital readout system without computer programmes would be a very lopsided investment.

Simultaneous multi-band photometry imposes extra demands on the system because of its superior capabilities. Experience has shown that the smaller variations in extinction, on a short time-scale, are to some extent "grey", i.e. they affect all bands in the same proportion. This makes it possible to obtain photometric colours (which contain the astrophysical information we want) more acccurate than the magnitudes contributing to them, but only if the whole photometric system is also built to be "grey" with respect to all disturbances. For instance, the effects of scintillations should be grey, the effect of small accidental variations of the voltages on the photomultipliers should be grey, the gain variations of the amplifier/attenuator chains should be grey and so on. We have tried to achieve this by using one timer, one dynode resistor chain, one optical attenuator, one set of resistor attenuators and one recording instrument in common to all five channels.

The old system at our Southern Station used a Brown recorder in conjunction with a calibrated resistive attenuator common to all channels. With care, the reading accuracy obtainable with the recorder was about 0.3 per cent (a back-off voltage properly applied could have been used to give greater accuracy, but this would have complicated registration, calibration and reduction too much). As it seemed that this limited the accuracy found for the colours of bright stars on good nights and therefore some potentially important astrophysical data were perhaps being lost, a new accuracy of 0.1 per cent was set as the design goal for the new system. At the same time, we tried to make attainment of this accuracy reasonably independent of the operator's detailed understanding of the system.

The dynamic range of a photometric system should be as large as possible. The upper useful limit is set by the very brightest stars, the lower useful limit by the sky reading in wide or medium-band photometry or the dark current in narrow-band photometry (both these latter are of course partly the result of instrumental design). The system at our Southern Station has always had a useful range from magnitude about 1.5 to about 15. The brightest 9.5 mag of this range has, as far as we know, full accuracy, i.e. the accuracy is limited by the extinction variations and scintillation. The linearity is determined entirely by the photocells; the integrators and readout equipment have a sufficiently large linear range. The dynamic range is achieved with an optical attenuator, a choice of integrating condensors (formerly two, hand-operated, now three, auto-ranging) and resistive attenuators (formerly hand-operated, now part of the auto-ranging digital voltmeter).

When the digital readout system was planned, it was foreseen that other photometers would be used with the telescope in the future. The telescope itself, however, is limited to observing essentially only one star at a time ("light-collector" optics), which puts a limit to the information-flow to be expected. Within this limitation, photometers with up to 20 simultaneous channels can be accommodated, as can photometers with repeated readings of one or more channels, such as a spectrum scanner. Leiden Observatory plans include a radial-velocity meter, an eleven-channel simultaneous photometer and a polarimeter, each of which can be accommodated with a few minor adjustments. Most of the computer programmes will need only relatively minor changes for other types of photometer; their logical structure can generally remain the same.

Figure 1 shows the main features of the instrumental system, as it is at present.

Many people have played a part in achieving the present state of the equipment. The photometer, the coldboxes and the original integrators were designed by Walraven; in constructing some or all of these he was greatly assisted by Mrs. J. H. Walraven, Mr. A. Meester, Mr. I. Starre, Mr. A. P. M. de Jong and staff of the Observatory workshop. After consultations with Walraven, the requirements for the digital system and its general form were worked out by Rijf and Tinbergen; the equipment was designed in detail by Rijf and built by Rijf, Mr. J. M. Kriest and Mr. A. J. van der Helm. The new integrating amplifiers, with auto-ranging by condensor-switching as proposed by Walraven, were designed and built by Rijf and Van der Helm. The computer programmes were written by Tinbergen; the computer used is the IBM 360/50 of Leiden University's Central Computing Institute. The equipment at the Southern Station is in the care of Mr. D. F. Stevenson.

Observations with the Walravens' photometer, but

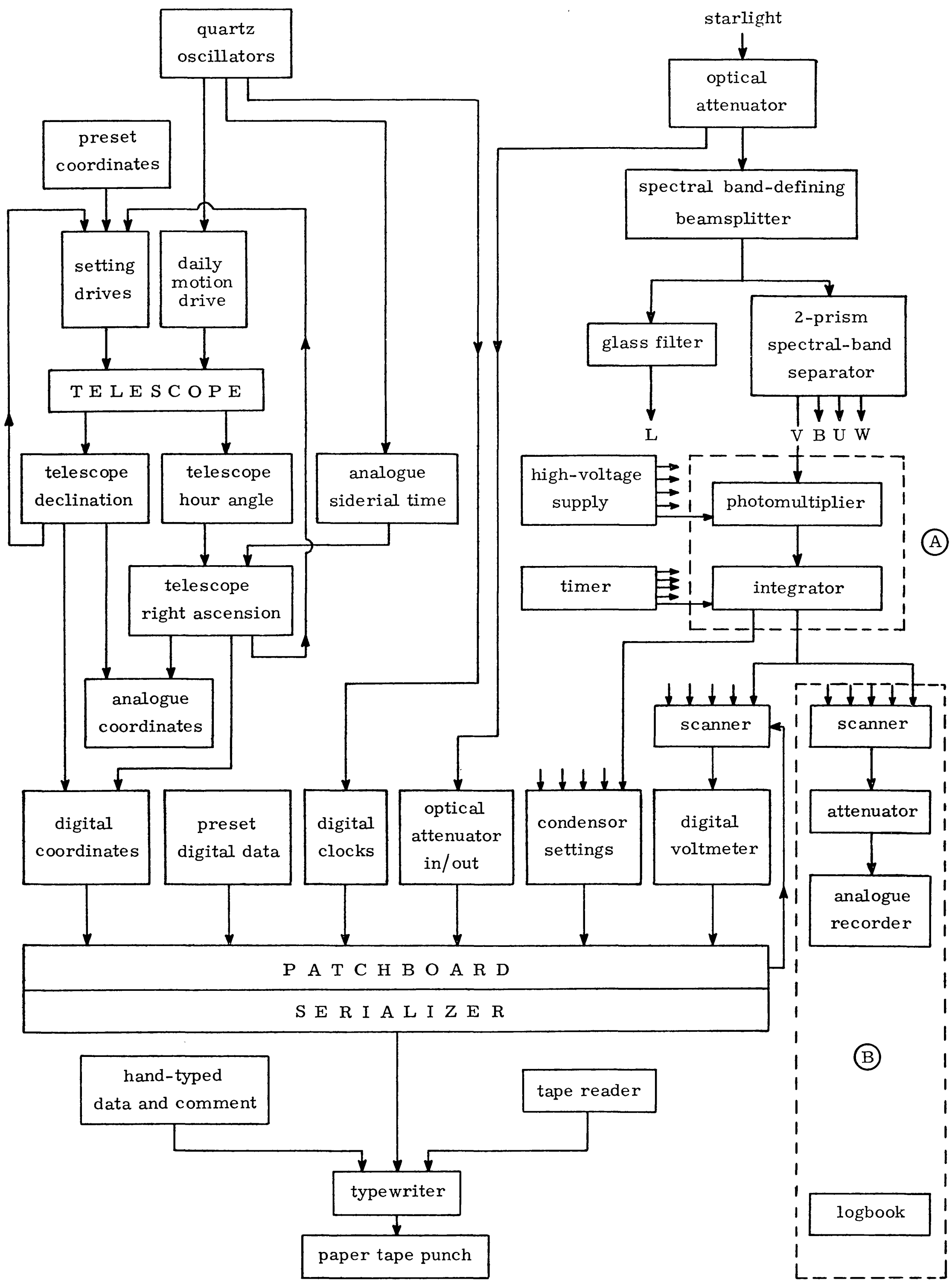


Figure 1. Block diagram of the telescope and its peripheral equipment. Block A is present once for each photometric channel. Block B is used for monitoring, during breakdown of the digital equipment and for adjustment of the photometer; it is operated by hand.

without the digital system, have so far been published in the following papers: WALRAVEN and WALRAVEN, 1960; PONSEN, 1963; WALRAVEN and WALRAVEN, 1964; WALRAVEN, TINBERGEN and WALRAVEN, 1964; GRAHAM 1966; OOSTERHOFF, 1966; OOSTERHOFF and PONSEN, 1966; OOSTERHOFF and WALRAVEN, 1966; PONSEN and OOSTERHOFF, 1966; WALRAVEN, 1966; BRAES, 1967; VAN GENDEREN, 1967; GRAHAM, 1967; LEOTTA-JANIN, 1967; GRAHAM, 1968. A very large programme of O and B stars by the Walravens is still being reduced.

2. Telescope and photometer

The telescope at our Southern Station is a fork-mounted 36-inch (91 cm) reflector with "light-collector" optics, with a large clearance (80 cm) behind the main mirror to allow fairly bulky photometers to be mounted there. The roof of the telescope building slides off. The maximum slewing speed of the telescope is about 75 degrees per minute in each coordinate and the setting accuracy is about 30 seconds of arc, sufficient for direct identification without finding charts in almost all cases (the differential setting accuracy, determined by the accuracy of the drive, is about 10 seconds of arc. The actual absolute accuracy is sometimes degraded by misalignment of the polar axis due to movement of the foundations of the telescope). The declination and right ascension can be preset at a console, which also contains the controls of the photometer electronics and the digital equipment. When the required preset position has been reached, the drive switches over to hand operation, for final positioning by a "joystick" control near the eyepiece. Limit switches are fitted in hour angle, declination and elevation to eliminate the more disastrous effects of operator errors. Quartz-derived frequencies are available for both civil and sidereal time, and for the stepping motor of the daily-motion drive. The original coordinate indication and presetting mechanisms are analogue devices; the digital indication was added later for registration only and is independent of the analogue system. A guiding telescope is fitted, but the eyepiece on the photometer on the main telescope is used most of the time. The telescope can be offset by up to 80 arc-seconds using the photometer eyepiece, and much more by using the guiding telescope. The standard diaphragm is 16 arc-seconds in diameter; a small inspection telescope can be inserted behind the diaphragm to verify alignment of the diaphragm with the eyepiece crosswires.

The photometer has been described by WALRAVEN and WALRAVEN (1960). It is a medium-band simultaneous five-colour photometer using polarization optics for definition of the bands and two spectral prisms to separate them in space. Most of the optics are either fused or crystal quartz, or calcite; the estimated light loss is less than 30 per cent in all five bands. The shape of the passbands is almost unaffected by changes in ambient temperature, by scintillation, or (except in the case of band V) by changes in photocell characteristics; the short-wave flank of band W is slightly affected by atmospheric extinction. Figure 2 shows the passbands.

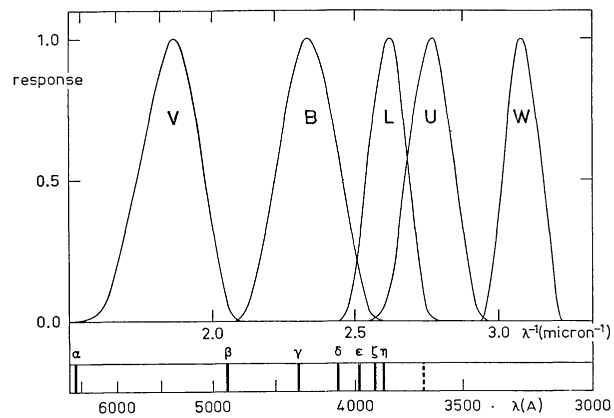


Figure 2. The passbands of the photometer, with the Balmer lines shown for comparison. The curves represent the response for an unreddened O star in the zenith and were determined by moving a slit through the spectrum in the photometer; the colours predicted by applying these bands to spectral scans by WILLSTROP (1965) agree even in detail with those observed. A forthcoming article by Th. and J. H. Walraven will discuss this more fully.

An essential part of the photometer is the slotted-drum optical attenuator (figure 3), which produces about three magnitudes of attenuation. If this attenuator were placed at the focus of the telescope, it would chop the light into pulses. If it were placed at an image of the entrance pupil, it would sweep a bright region across the photocathode and the total light would be attenuated but constant. In practice, the attenuator is in neither position and the effect is a mixture: rather fuzzy strips of light move across the cathode, the total light varies in synchronism with this, but is at all times attenuated. The time-average of the effect of the at-

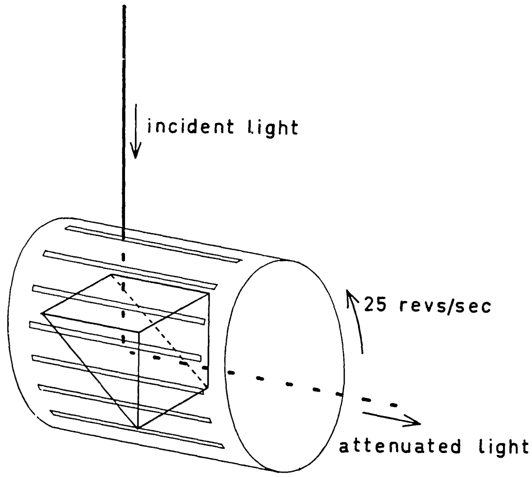


Figure 3. Slotted-drum optical attenuator. It is represented as placed at the focus of the telescope (see text for explanation); to remove the attenuator from the beam, it is pulled back along the cylinder axis.

tenuator should be the same in all channels; in practice the measured *V* attenuation is about 0.008 mag more than that in the other four channels. We have not found a satisfactory explanation for this. The *V* photomultiplier, however, is a 931A, not a 1P21 as in the other channels, and was constructed more than 20 years ago; we are inclined to ascribe the abnormal attenuation to the properties of the photomultiplier. In any case, the attenuator is sufficiently "grey" for the effective wavelengths not to be influenced by it. The attenuator is calibrated by observations of suitable (not too bright) stars alternately with and without attenuator.

The photomultipliers used are four 1P21's and a 931A, all cooled by dry ice. Since the region of highest sensitivity is narrow, the light spot has to be narrow, too. In front of the photocathode there is a wire screen, which obstructs some of the light. Slight unintentional movement of the light spot would therefore result in sensitivity variations; in order to minimize these, the light spot has to be as large as possible along the length of the photocathode. We use a spot of approximately 9 × 2 mm (see figure 4, inset c).

An important feature of the high-voltage supply for the photomultipliers is that all five tubes are fed in parallel from a single resistance chain mounted *outside* the coldbox. The most important reason for this is that the resistance chain is a source of considerable heat and must not under any circumstances be in close thermal contact with the photocathode. The base pins of the photomultiplier form a very efficient thermal connection between the photocathode and the outside world and must not be thermally connected to a resistance chain dissipating about 1 Watt. A further consideration is that the gain of a photomultiplier is critically dependent on its supply voltages. If separate dynode chains were to be mounted inside the coldboxes, the photomultiplier gains would depend on the coldbox temperatures and the temperature coefficients of the resistors. When a single chain is used, the voltage variations are at least the same on corresponding dynodes of all five photomultipliers and the gains will vary roughly proportionally (i.e. in a "grey" manner).

The high-voltage unit must be of high quality. The short-term stability (less than 1 hour) of the unit used at our Southern Station is better than 0.005 per cent; long-term stability is not critical, because of frequent calibration by standard star observations.

The photomultiplier supply voltage is never varied. Although some photometrists adjust the gain of photomultipliers by changing the supply voltage, this is dangerous practice for two reasons. In the first place, the apparent sensitivity distribution over the photocathode changes as the voltage is changed. Since the spectral sensitivity distribution is not the same everywhere on the cathode, one may be changing the passbands of the system at the same time as the gain. The second reason is that after a change of the supply voltage the dark current changes only slowly (this is of course unimportant if the photocurrent is much larger than the dark current).

Since condensors are in general much more stable than the very high resistors needed in photometric feedback amplifiers, the photometer has at all times been equipped with integrators. These are described in a separate section.

3. Coldboxes

A coldbox seems a simple, easily constructed, piece of equipment. In practice it often turns out to be a source of errors and irritation; for this reason we describe a design which has proved itself by about ten years of successful and convenient operation. The design is illustrated in figure 4.

In order to have the photocathode at a low temperature which is also as stable as possible, the guiding principle of the design is to keep the thermal resistance

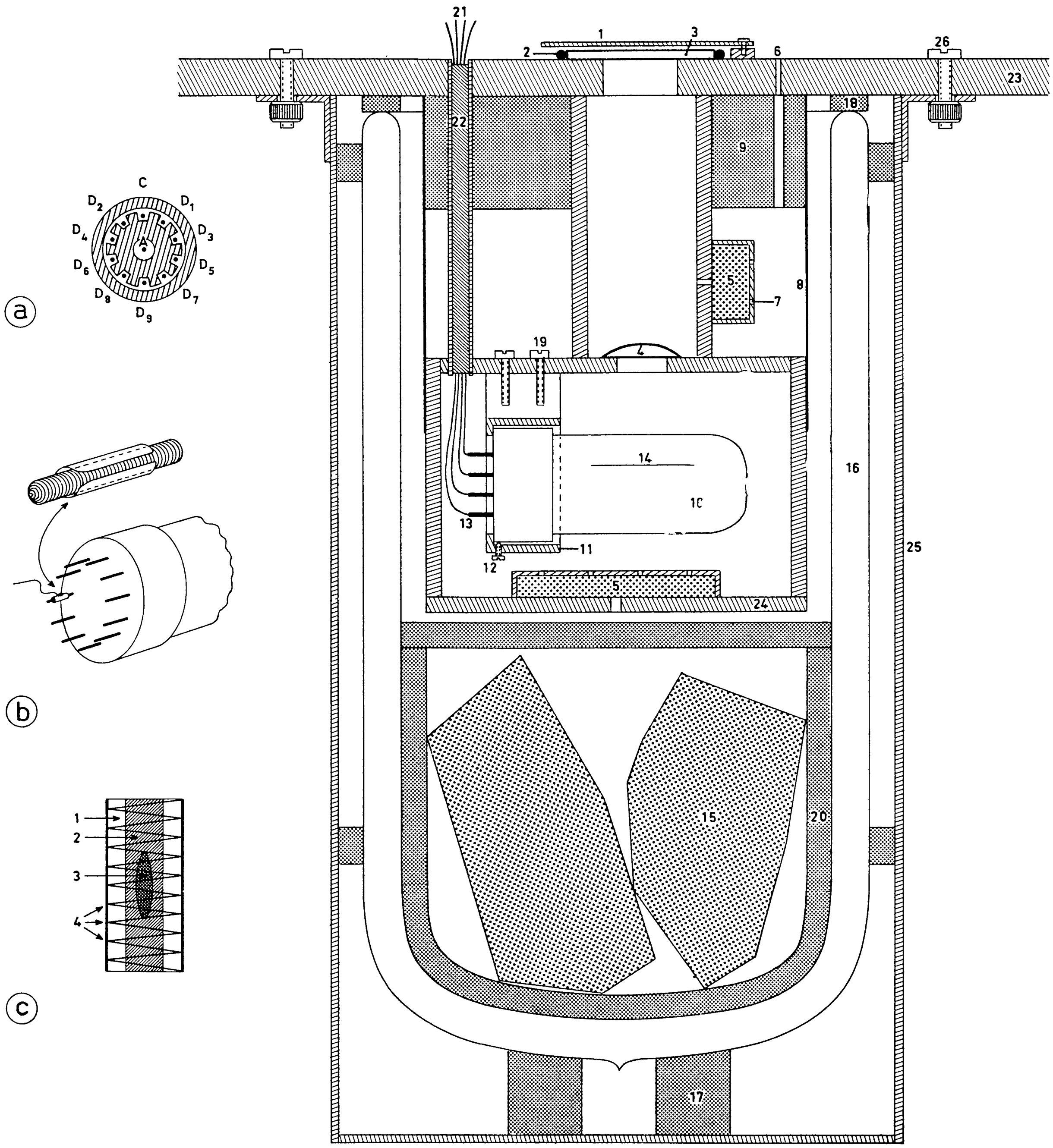


Figure 4. Schematic representation of a coldbox. The most essential features are the felt ring (18) and the single exit hole for the gas (6); they cause the slight excess pressure which is essential for proper functioning of the coldbox. There are two closed chambers that can be expected to "breathe" as the coldbox is alternately cooled and heated again during weeks of continuous operation. As hermetic sealing is very difficult to achieve, these chambers are allowed to breathe, but through a silica gel container to keep the gas inside them dry. The light-tight plastic shield (8) allows filling while the photomultiplier voltage is switched on. The distance between photocell and earthed container should everywhere be large enough not to influence the internal electric fields. 1: Shutter. 2: Window heating. 3: Filter/entrance window. 4: Fabry lens. 5: Silica gel. 6: Exit hole for CO_2 gas. 7: Breathing holes. 8: Light-tight, but not gas-tight, shield (black PVC). 9: Polystyrene foam. 10: 1 P 21. 11: 1 P 21 holder. 12: Clamping

between the cooled space and the outside world as high as possible and to eliminate all sources of heat inside the cooled space (e.g. the dynode resistors, see section 2). It is not necessarily good practice to reduce the thermal resistance between coolant and photocell, since the cell can easily be damaged by severe thermal shock.

Our guiding principle suggests the use of a Dewar flask as the main container of the cold space, since Dewar flasks provide the highest thermal insulation for a given size of coldbox. It also suggests that the photocells be mounted deep inside the Dewar, with cold gas flowing round in front of the photocell enclosure. The baseplate covering the Dewar entrance should be a good insulator; in our case it is made of Celeron (a composition of cloth and phenolic resin), lined on the inside with polystyrene foam and on the outside with black PVC (Celeron is slightly transparent). An important heat leak, especially when the dynode voltages are generated outside the coldbox, is by conduction along the supply wires. To reduce this leak, we have tried both resistance wire and thin steel wire in the past, but have recently come across an ideal material for this purpose, viz. the flexible cable used in hearing-aid leads, consisting of a very thin copper strip, wound in a helix on an insulating core. The heat conduction of this cable is small, yet it is strong and flexible and can be soldered without any risk of dry joints.

The entrance window for the light must be heated in order to prevent dewing on the outside. However, a heated quartz window radiates enough infrared to affect the dark current of a cell placed immediately behind it and the distance between entrance window and photocell should therefore be as large as possible.

A convenient place for the dry-ice reservoir is immediately behind the photocell enclosure. In order to refill the reservoir, it is necessary to remove the Dewar, but this has not proved troublesome in practice (it takes about 15 minutes to load the three coldboxes on our telescope with sufficient dry ice for more than 24 hours; loading is done in the afternoon, so that the temperature is stable again long before the observations start).

A persistent problem in coldbox design has been to stop moisture from the surrounding air getting in and condensing in all sorts of awkward places, causing high dark currents, or even danger to the observer if the enclosure is not properly earthed. A foolproof method of solving this is to seal all possible entrances to the cold space, except for one small hole. The gas generated by the evaporating dry ice streams out at high speed, preventing any air from coming in (the carbon dioxide gas is so dry, that it even sweeps any moisture initially present out with it). The Dewar-and-baseplate construction of the coldbox is particularly suited for this method of moisture-proofing, since all that is necessary is to seal the joint between the Dewar and the baseplate by a felt ring, and to seal any holes made through the baseplate. It is desirable to include some sort of safety valve, in case the exit hole should become blocked; in our case the Dewar is spring-loaded in its container, and would lift off as a whole if the pressure built up too much.

The contact strips in a 1P21 socket are wider than necessary and often have unnecessarily sharp edges; in a 1P21, where anode and cathode pins are close together, this can lead to appreciable contributions to the dark current noise by discharge currents between the contact strips. For this reason a 1P21 should preferably not be mounted in a socket, but clamped, with the connections to the pins made by (for example) thin, silver-plated phosphor-bronze tubes, split along one side and of slightly smaller diameter than the pins (see figure 4, inset b). A further point, often stressed but as often sinned against, is that for proper functioning of a photomultiplier it is essential to have sufficient distance between the tube and the earthed container so as not to influence the internal electric fields too much.

A coldbox constructed along the above lines is shown schematically in figure 4. Coldboxes of this general type have proved so convenient and reliable that we have

screw on strongest part of base. 13: High-voltage leads direct to pins. 14: Photocathode. 15: Dry ice. 16: Dewar flask. 17: Foam plastic ring (to act as spring of safety value). 18: Felt ring. 19: Photomultiplier adjustment (no realism attempted). 20: Felt for protection of Dewar and photocell container. 21: High voltage leads. 22: Seal. 23: Baseplate (Celeron lined with black PVC). 24: Earthed photocell container (metal). 25: Earthed outer case (metal). 26: Fixing bolts.
Inset a: Cross-section of lead-through of photocell connections. C: Cathode. A: Anode. D_1–D_9: Dynodes. Inset b: Connection of leads to base pins. Inset c: Rough sketch of photocathode. 1: Photocathode. 2: Most sensitive part of cathode. 3: Light spot. 4: Wire screen in front of cathode.

no immediate plans for experimenting with other methods, such as thermo-electric cooling or miniature refrigerators. We have used such coldboxes with both one and two 1P21's; for the new 11-channel photometer we again plan to use such a coldbox, this time to contain 11 photomultipliers of three different types.

In our experience it is possible to obtain cathode dark currents of 3 to 10 electrons per second from 1P21's cooled by dry ice. Almost all 1P21's seem to fall within this range, although some cells may take hours or even days to reach the lowest dark currents (therefore, when testing photocells for dark current, one should keep them cold for several hours before making any measurements; for the same reason, coldboxes which need refilling with dry ice every few hours will probably not yield the lowest dark currents). We wish to stress that, with thorough and prolonged cooling, there is usually little reason to go to great trouble to select the best cells out of a batch of 1P21's, since cathode sensitivity varies by a factor 2 at most, gain is irrelevant as long as it is constant, and dark currents are sufficiently low for the sky photocurrent to dominate in all but the narrowest-band work.

4. Integrators

The integrators are of the multi-stage Miller-integrator type. The original ones, in operation from 1958 to 1967, used vacuum tubes; the input stage used a type 954 acorn tube, operated under somewhat special conditions so that its grid current was less than 10^{-14} A (Gabus and Pool, 1937). These acorn tubes are less attitude-sensitive and less microphonic than normal electrometer tubes and can be mounted on the telescope (the Philips EF98, intended for car radios, is even better in this respect and would be our choice now). The new integrators (plate 1), used for the first time in the 1968 season, are solid-state; they use a balanced MOSFET input stage, followed by an integrated-circuit amplifier. The leakage current of the MOSFET is about 5×10^{-14} A. This is satisfactory, since the smallest current we wish to measure at full accuracy is about 10^{-10} A, corresponding to roughly 50000 incident photons per second, or, in the V channel, to a star of about the 11th magnitude.

An important point in the design of an amplifier for photometric work is that its input should remain close to earth at all times. Even at voltages as low as 1 V, the

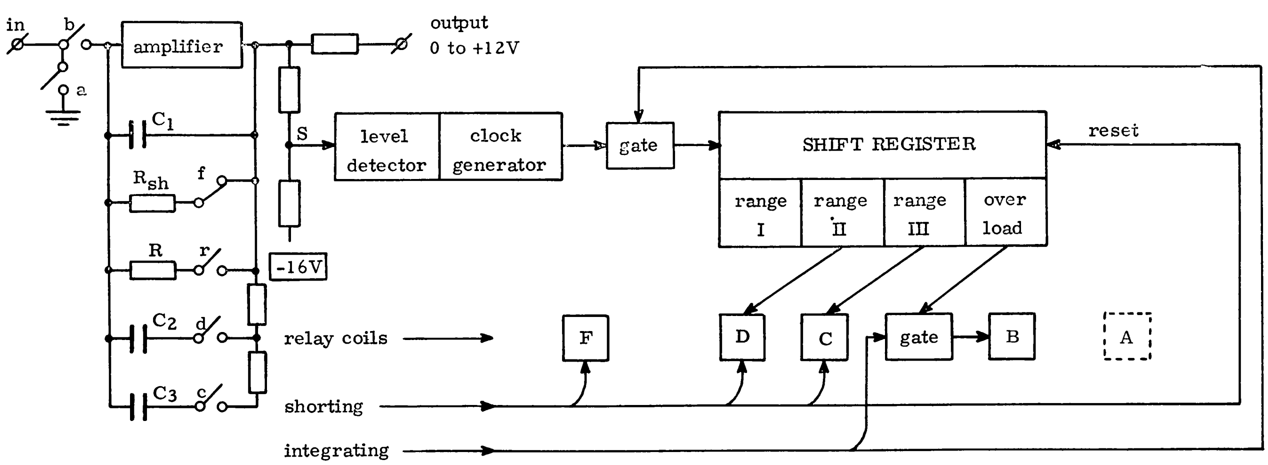


Figure 5. Schematic representation of a complete auto-ranging integrator. When the output exceeds 12 V, the clock generator is enabled. The state of the shift register determines the condensor combination in use. If, after switching in an extra condensor, the voltage still exceeds 12 V, the next pulse of the clock generator moves the shift register one more position. The overload position of the shift register ends integration prematurely. When integration starts, relay a is opened before b is closed; at the end of integration, b is opened before a is closed. For the logic we used Philips TTL and DTL integrated circuits. For low-leakage switching we used Hamlin MRG 15 reed switches, which have a minimum insulation resistance of 10^{15} ohm. The polystyrene capacitors are Philips type C 295. Critical parts of the circuit are mounted on Pressfit ST250SL/P60 stand-off Teflon PTFE insulators. Complete diagrams and parts lists can be supplied to those seriously interested.

input cable can act as a Geiger counter and degrade the measurements. Amplifiers using an input resistor to earth in order to generate an input voltage suffer from this, as do feedback amplifiers with a zero-point not at earth potential.

The zero-point of both the old and the new integrators is adjustable and is never more than a few millivolts from earth potential.

Integration (relay b, figure 5) always starts with a 5000 pF feedback condensor (C_1). If the output voltage exceeds about 12 V, a 0.05 μF condensor (C_2) is switched in parallel with the first. The charge redistributes itself (the current being limited by a resistor of 100 KΩ) and integration continues with the combination. If the output voltage again exceeds 12 V, a third condensor (C_3, 0.5 μF) is switched in. If the output exceeds 12 V once again, the input is disconnected in order to protect the amplifier. The relays can only be switched during integration, in order to avoid spurious results due to accidental range-switching during readout. Relays in parallel with c and d (figure 5) allow external determination of the condensor combination in use.

Normally, when relay b is open, relay a is closed, to prevent the input cable capacity being charged by the photomultiplier (this charge would be added to the integrated photocurrent and in addition would influence the voltages applied to the photomultiplier, which might have after-effects on its sensitivity; for a similar reason, photometrists generally use feedback amplifiers, whose input voltage remains nearly constant irrespective of the input current). Relay b is delayed by 4 msec relative to relay a at the start of an integration. This delay is necessary to prevent the amplifier input being connected to earth accidentally. Before the start of an integration, the three condensors are connected in parallel and shorted for a certain time (through R_{sh}). Relay f is normally closed (by permanent magnet), so that the integrator is protected when it is switched off.

Operation as a feedback amplifier is possible by switching in the resistance R. The combination of R with C_1 yields a time constant of 0.5 second. The output voltage is 1 V for an input current of 10^{-8} A.

The condensors are mounted on Teflon (PTFE) standoff insulators, which are surrounded by an earthed plane. Since the input is at earth potential, leakage between output and input via the insulators is virtually eliminated in this way; any leakage remaining is through or over the components themselves. Leakage to earth takes place only at the output, where it is harmless.

Stray capacities can cause output changes of several millivolts if the orientation of the integrator is changed during integration. These changes are completely reversible and do not influence results if the integrators are rigidly mounted on the telescope (therefore virtually do not move between the moment of discharging the condensor and the end of the integration period).

Plate 1 shows an integrator assembled, but with the case opened for inspection. The components are mounted on a single printed-circuit card and the integrator has outside dimensions of $260 \times 129 \times 26$ mm. The cost of components and materials for a complete integrator is about fl. 600, of which the amplifier alone accounts for about fl. 250.

A circuit diagram of the amplifier is shown in figure 6. The long-tailed pair input, one side of which is used for zero adjustment, feeds the balanced input of an integrated amplifier. The balanced configuration was chosen for its low zero-point drift. The complete amplifier has a gain of about 25000, which is enough for good linearity and leads to less than 0.5 mV change in input voltage over the entire range of output voltage. The supply voltage (45 to 70 V) is split into two stabilized voltages by zener diodes actually on the amplifier. The amplifier has short-circuit protection on its output and cannot be permanently damaged by short-circuiting the input, though measurements do suffer for a short time afterwards. After first switching on, about 15 minutes' wait is necessary before the zero-point is stable to better than 1 mV. After short supply interruptions, the zero-point is stable immediately.

A very important part of an analogue integrator is the charge storage condensor used in the feedback circuit. Most dielectrics show "dielectric absorption", i.e. they "soak up" a certain amount of charge, which is released only slowly on shorting the condensor. In practice, only Teflon (PTFE) and polystyrene capacitors are suitable for integrators. We have chosen polystyrene; under typical operating conditions, the charge retained in this material may be of the order of 0.01 per cent of that contained before shorting (in other words, any integration has an error component of 0.01 per cent of the previous integration). If with each conden-

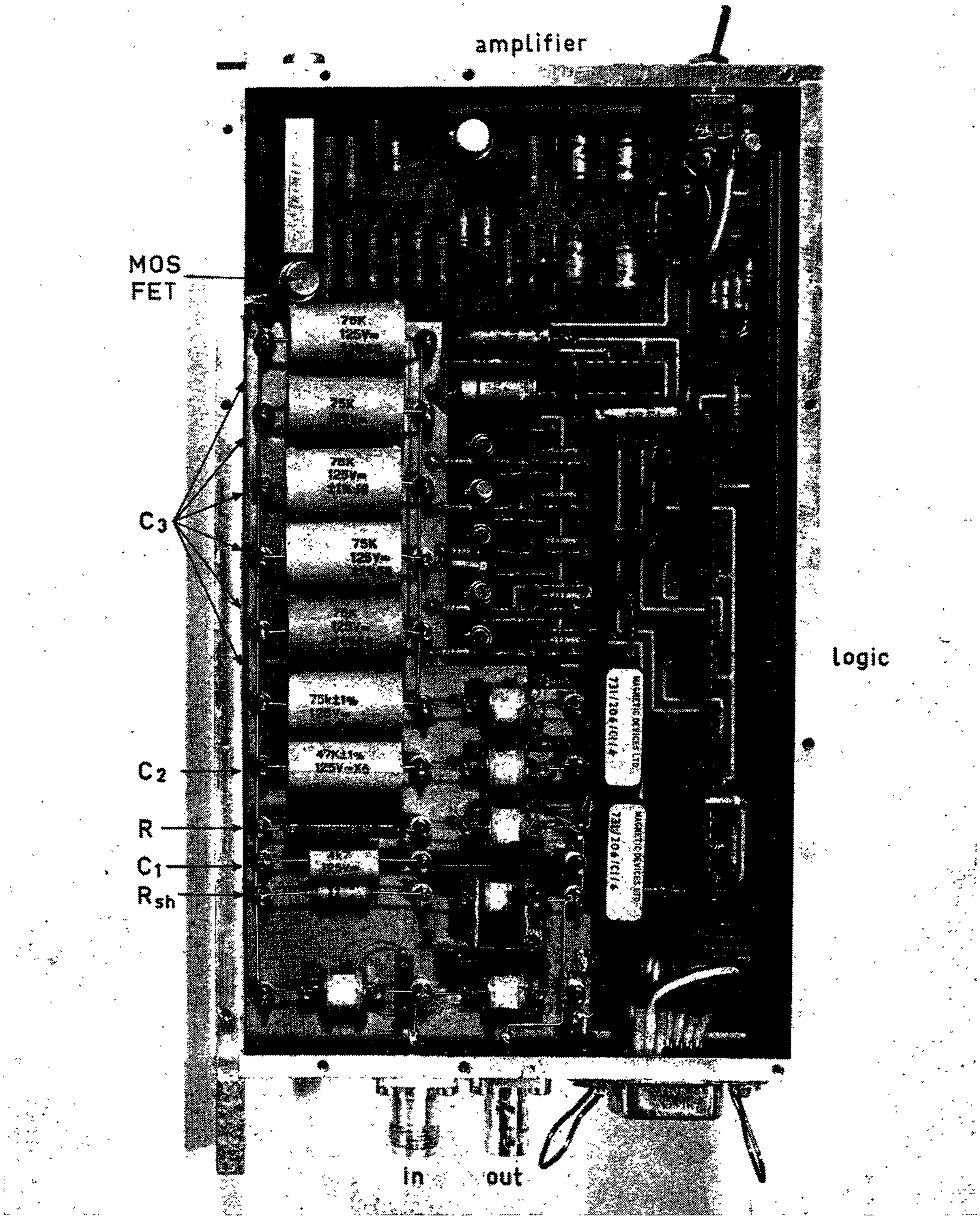


Plate 1. Integrator unit, with covers removed. The dimensions are 260 × 129 × 26 mm. The switch at the top has 3 positions: remote control, resistor (R) feedback, and a "safe" position (condensors shorted).

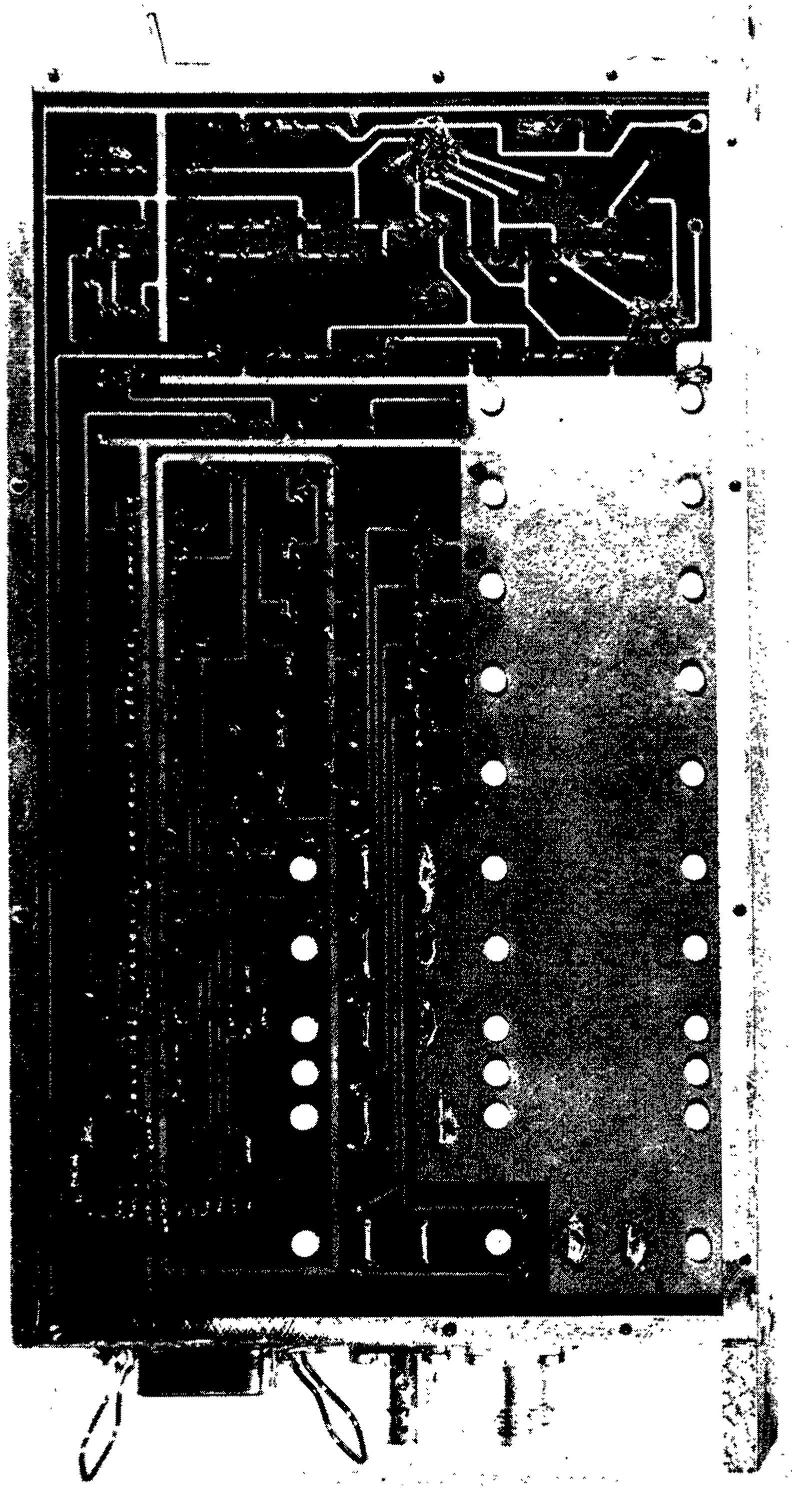


Plate 1 *(continued)*.

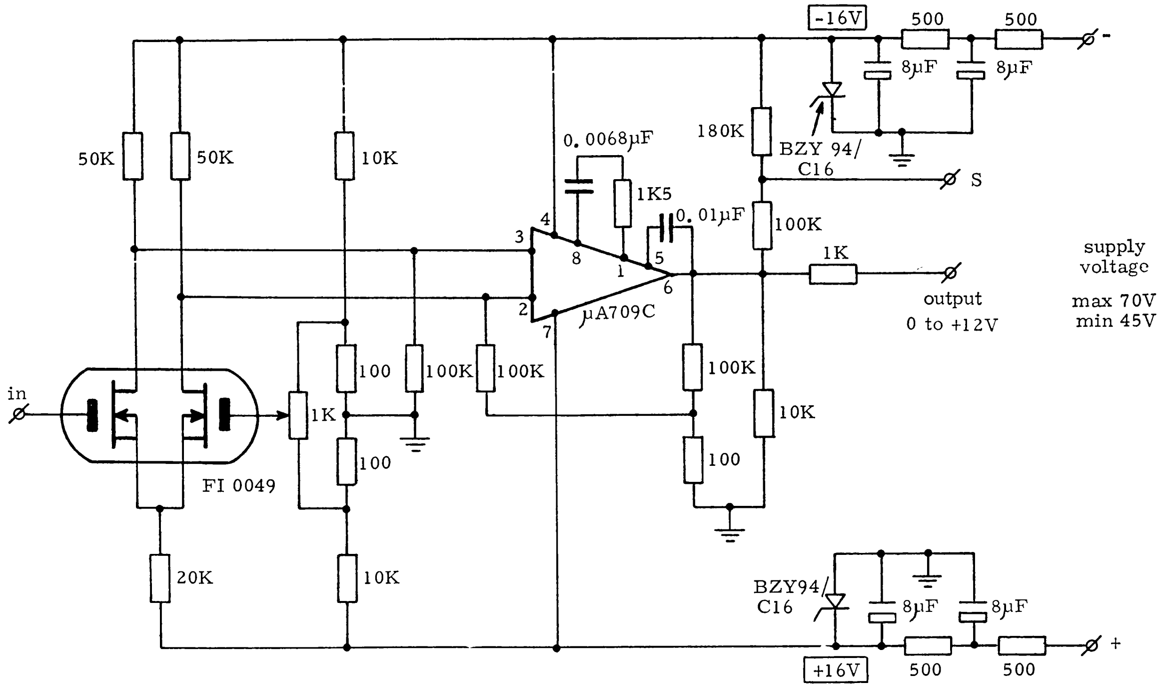


Figure 6. Circuit diagram of the solid-state amplifier. Resistor values are given in ohms. The integrated amplifier has a feedback loop to give it a gain of 1000. The auxiliary output at the point S is the input to the auto-ranging logic. The dual MOSFET and the integrated amplifier are manufactured by SGS Fairchild. The resistors are made by Welwyn (Welmet metal film resistors) and have a temperature coefficient of 0.005 per cent/°C.

sor one wishes to serve a dynamic range of 10 to 1, then the effect of dielectric absorption on the measurements may sometimes amount to 0.1 per cent and the phenomenon must obviously be investigated in detail. Not all brands of condensor show the same amount of absorption; the results of our tests can be made available on request. With a 30-second integration time and a 3-second discharge time, there are polystyrene condensors in existence which permit the desired 0.1 per cent accuracy over a 10 to 1 voltage range.

The arrangement used to test the integrators is shown in figure 7. It allows us to charge the condensors with a constant current for a measured, but variable, time. The combination of step-variable backing-off supply and vacuum-tube voltmeter can of course be replaced by a single instrument, preferably a high-accuracy digital voltmeter, since this would speed up the measurements by a large factor. Since the input current is determined by the resistance R, this resistance is critical. Even very good resistors at the required value (of the order of 500 MΩ) are only just stable enough; in practice all measurements were done relative to some standard integration time to take account of drift in R. The voltage V has to be large enough to prevent variations in the amplifier zero-point from influencing the input current too much.

The following results were obtained from tests made on all integrators; tests b to e were made at two temperatures (15 °C or 20 °C, and 40 °C), test a only at 20 °C:

a) The variation of the condensor capacities with voltage is certainly less than 0.05 per cent between 1 V and 10 V.
b) The dielectric absorption is marginally small enough if shorting times of a few seconds are used. The absorption at 40 °C ambient temperature was twice as large as at 20 °C (at least in our brand of capacitor). Careful selection of the brand of capacitor used is worthwhile.
c) The worst of 12 integrators had a zero-point drift of 0.4 mV/°C, the rest less than 0.15 mV/°C. As the sensitive components are totally enclosed in the integrator case, the thermal time constant is large. On the telescope the zero-point drift is almost always less than 0.5 mV/hour.

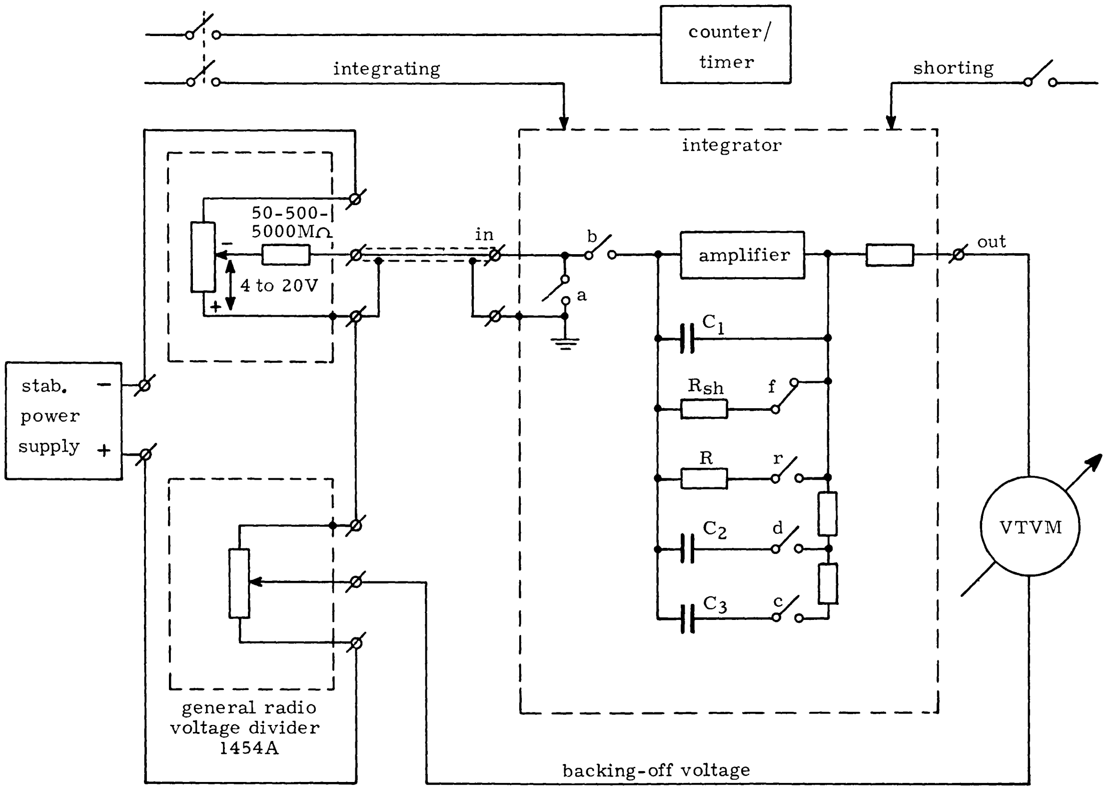


Figure 7. Laboratory situation for tests on the integrators. Each series of tests used a constant input current, the integration time being varied.

d) Any change in the ratios C_2/C_1 and C_3/C_2 is less than 0.1 per cent between 15 °C and 40 °C. We have no data yet on aging of the condensors, but, as long as the ratios are recalibrated now and again by special star observations, aging is of no importance in practice (see Note on p. 299).

e) The output drop due to leakage was always less than 0.02 per cent per minute, which is at least a factor 100 less than could be just tolerated under our observing conditions. This we consider sufficient, even for such an unpredictable thing as leakage.

5. Digital equipment

After the five-colour photometer had been brought into operation, reduction of the results soon proved to be a serious bottleneck. Particularly the repetitive operations of subtracting sky readings, taking logarithms and computing the air mass were felt to take up time which could be saved in a properly organised computer reduction. We realized from the beginning that such a machine reduction could only be fully successful if *all* the data needed for the reduction were made available in machine-readable form. We required that the digital system be capable of recording the following items:

A: Photometer output in one or more channels, as given by analogue integrators.
B: Positions of switches controlling attenuator or gain settings (e.g. optical attenuator, condensor values).
C: Accurate coordinates, taken directly from the telescope.
D: Sidereal and civil time.
E: Star identification.
F: Reduction programme identification.
G: Type of observation, e.g. "star", "sky", "dark current", or "integrator zero".
H: Information as to which sky observation is to be used in the reduction of a star observation.
I: Weight of the observation (after inspection).
J: Anything not thought of in time to be incorporated into the present scheme.
K: Comment in words.

Item H is crucial to the success of machine reduction. Most of the work one wants the machine to do can only start after subtraction of the sky reading, yet one does not always want to observe the sky after *every* star observation, nor does one want to construct only photometers with automatic sky subtraction. Our solution to this problem is described later in this section. Item K implies some sort of keyboard coupled to the output medium. Item J has been catered for by providing a number of decade pushbuttons, which can be used to feed "preset" numerical data to the output. At the end of a measurement one is also free to use the keyboard to add further information.

The general requirement that the digital system be suitable for different kinds of photometers led to the use of a patchboard for controlling the choice of data and the order in which they are read out. Further demands on the system were that it be foolproof in operation (or, rather, "astronomerproof", a more stringent requirement), that the digital devices be provided with suitable readout on the control panel, that the stray light from these readouts be as faint as possible, that a defective piece of equipment can be switched off without affecting the rest, that the observer be able to monitor his observations in complete detail, and that output format be such as to allow convenient hand-reduction. However, no attempt need be made to make the equipment light enough to be portable, as it is part of a fixed telescope installation.

A description of the digital sytem now follows; a more detailed description, which is part of the telescope manual, can be made available to those seriously interested. Figure 1 shows the principal parts of the equipment. The data sources are scanned by the serializer (an elaborate stepping switch), which feeds the data digit by digit into the typewriter. The typewriter keys (whether driven by a data source or by hand) in turn drive the tape punch. The tape reader can be used for reading and copying tapes. The patchboard allows full control of the layout by connecting any given data socket to any desired column socket. All sockets are duplicated; this allows typing out the same data digit in a number of columns without splitting the connection cables. Instead of data digits, one may connect permanent digits, or the space, decimal point, carriage return and tabulation to any given column.

The control panel of the digital equipment, located close to the telescope controls and the typewriter, contains a start button, hand controls of the integration and condensor shorting relays, and various indicator lamps for error-detection purposes. Single-step operation of the serializer and typewriter is also controlled from this panel.

A fundamental requirement of successful machine

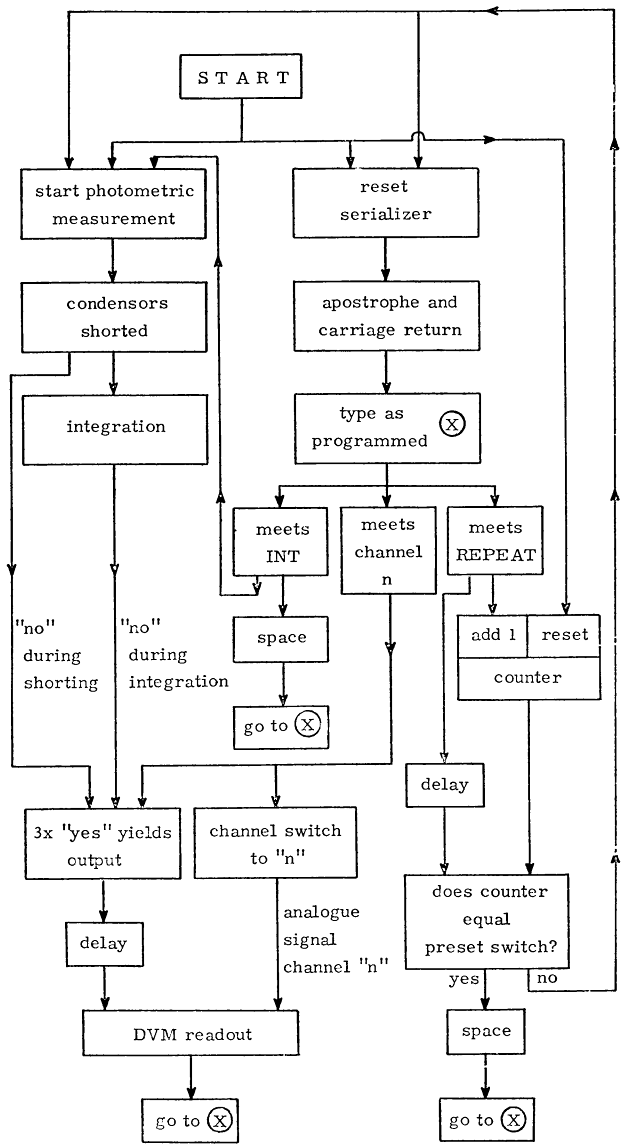


Figure 8. Logical flow diagram of the action of the digital system. If nothing is programmed in a given column, action stops there until the start button is pressed again or something is typed in by hand. Readout of the digital voltmeter is prevented until after completion of the integration.

reduction is the ability to recognize the start of a measurement; if *this* is made foolproof, then any single error can only cause the loss of a single measurement. We have reserved the apostrophe for such resetting duties. Columns 1 and 2 are connected on the patchboard to the apostrophe and the carriage return. Pressing the start button causes the serializer to reset, which in its turn causes an apostrophe to be typed in the current column, followed by a return of the typewriter carriage and the rest of the programmed readout. In order to prevent accidental touching of the apostrophe key on the typewriter, we have fitted a guard over it; however, since we also use three apostrophes as the starting code for a date specification, we have pierced the guard with a hole large enough to allow a pencil through for deliberate actuation of the key.

A feature of some convenience to the observer, when observing faint stars, or when the conditions are bad, is the "number of measurements" pushbutton switch. This provides for automatic resetting of the serializer at the end of a measurement until the specified number of measurements has been completed; we prefer this to a variable integration time, even though it consumes a little extra readout time. The typewriter column at which the resetting takes place is determined by a patchboard connection of this column to the REPEAT socket. A space is typed in this column after the last measurement.

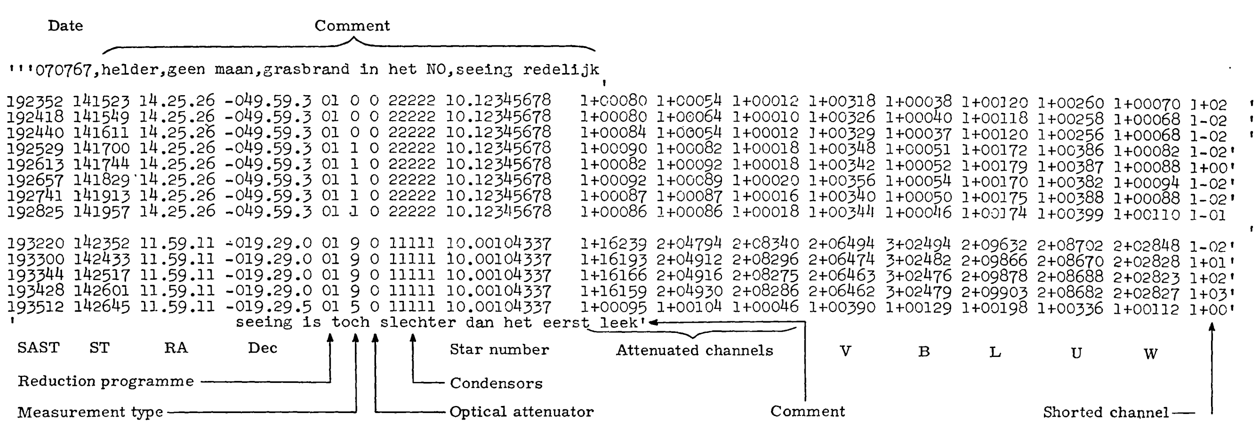
Resetting the serializer always shorts the condensors for a few seconds, then starts the integration. These actions can also be performed without resetting the serializer, by connecting the integration (INT) socket to a given column; this feature can be useful for a photometer that makes repeated measurements in a single channel, such as a spectrum scanner.

At the input to the digital voltmeter there is a 20-channel switch, commanded from the patchboard by connecting the desired channel socket to the column that is to contain the first digit of the voltmeter output. The voltmeter range is typed into this column, followed by whatever has been programmed into the next few columns, usually the sign and five digits of the voltmeter output.

A logical diagram of the action is shown in figure 8. The REPEAT and INT functions can be understood by following the logical flow. The arrangement works satisfactorily in practice.

A specimen of typed output is shown in figure 9. The paper tape contains a code for each action performed by the typewriter, including carriage return and space. Figure 10 shows the timing of one observation. The observer's schedule for a single observation is as follows:

1) During integration, preset telescope coordinate controls and decade pushbuttons.
2) Inspect observation on typewriter.
3) Start the acquisition mechanism of the telescope.
4) Type weight, if required.
5) Type "where is sky?" information, if required.
6) Type comment, if required.
7) Go to the eyepiece, centre the star by hand and press the start button (a duplicate of the one on the control panel).
8) Go to the typewriter and inspect typed auxiliary data.
9) As 1).



```
'''070767,helder,geen maan,grasbrand in het NO,seeing redelijk
                                                               '
192352 141523 14.25.26 -049.59.3 01 0 0 22222 10.12345678  1+00080 1+00054 1+00012 1+00318 1+00038 1+00120 1+00260 1+00070 1+02  '
192418 141549 14.25.26 -049.59.3 01 0 0 22222 10.12345678  1+00080 1+00064 1+00010 1+00326 1+00040 1+00118 1+00258 1+00068 1-02  '
192440 141611 14.25.26 -049.59.3 01 0 0 22222 10.12345678  1+00084 1+00054 1+00012 1+00329 1+00037 1+00120 1+00256 1+00068 1-02  '
192529 141700 14.25.26 -049.59.3 01 1 0 22222 10.12345678  1+00090 1+00082 1+00018 1+00348 1+00051 1+00172 1+00386 1+00082 1-02'
192613 141744 14.25.26 -049.59.3 01 1 0 22222 10.12345678  1+00082 1+00092 1+00018 1+00342 1+00052 1+00179 1+00387 1+00088 1+00'
192657 141829 14.25.26 -049.59.3 01 1 0 22222 10.12345678  1+00092 1+00089 1+00020 1+00356 1+00054 1+00170 1+00382 1+00094 1-02'
192741 141913 14.25.26 -049.59.3 01 1 0 22222 10.12345678  1+00087 1+00087 1+00016 1+00340 1+00050 1+00175 1+00388 1+00088 1-02'
192825 141957 14.25.26 -049.59.3 01 1 0 22222 10.12345678  1+00086 1+00086 1+00018 1+00344 1+00046 1+00174 1+00399 1+00110 1-01
                                                                                                                                  '
193220 142352 11.59.11 -019.29.0 01 9 0 11111 10.00104337  1+16239 2+04794 2+08340 2+06494 3+02494 2+09632 2+08702 2+02848 1-02'
193300 142433 11.59.11 -019.29.0 01 9 0 11111 10.00104337  1+16193 2+04912 2+08296 2+06474 3+02482 2+09866 2+08670 2+02828 1+01'
193344 142517 11.59.11 -019.29.0 01 9 0 11111 10.00104337  1+16166 2+04916 2+08275 2+06463 3+02476 2+09878 2+08688 2+02823 1+02'
193428 142601 11.59.11 -019.29.0 01 9 0 11111 10.00104337  1+16159 2+04930 2+08286 2+06462 3+02479 2+09903 2+08682 2+02827 1+03'
193512 142645 11.59.11 -019.29.5 01 5 0 11111 10.00104337  1+00095 1+00104 1+00046 1+00390 1+00129 1+00198 1+00336 1+00112 1+00'
'                        seeing is toch slechter dan het eerst leek'
```


Figure 9. Example of typed page. The paper tape contains a code for every action performed by the typewriter.

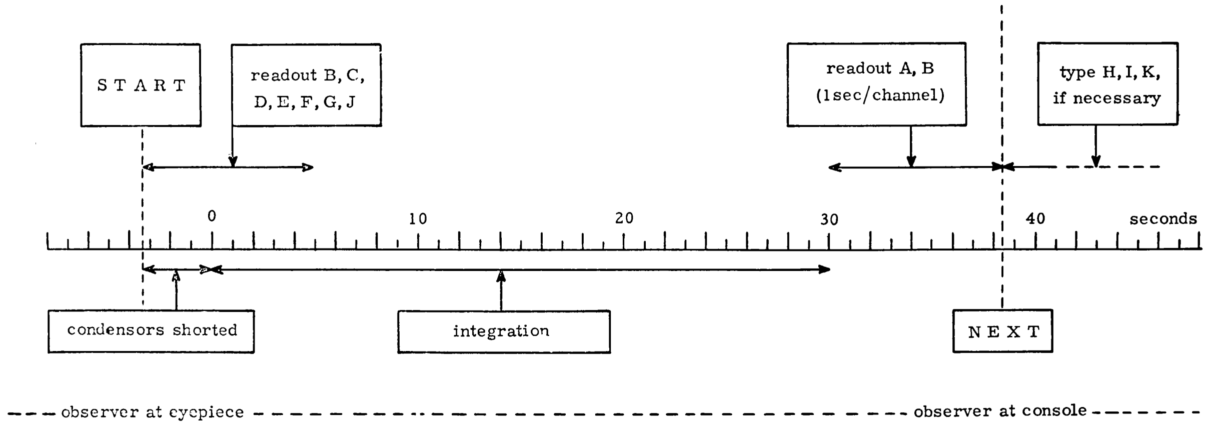


Figure 10. Timing of one measurement. The letters refer to the data items mentioned in the text. After readout of the immediately available data in the first few seconds of the measurement, the observer may preset data such as E and G for the next observation. Soon after "NEXT" he will usually start the star acquisition mechanism.

Experience has shown that the integration time is long enough to perform all the necessary actions in almost all cases. Observing with the digital equipment is somewhat faster than by the older recorder and log-book method, and much less tiring. The latter is an important factor, as rather long observing nights are usual in our case and the observer has no assistant at the telescope.

Points 4 and 5 require some comment. We have reserved one column for an optional weight, to be typed in by the observer after inspection of the observation. For the "where is sky?" information we have reserved two columns, into which the observer may type "+n", "−n", "00", or nothing at all. The interpretation is as follows: "+n" or "−n" indicate that the sky observation will be made n observations later, or was made n observations earlier, than the present observation; "00" indicates that the sky is to be computed at the time of the observation, i.e. interpolated from the last preceding and first succeeding sky observation; finally, if no information is typed, the computer uses the first sky observation it comes to when scanning forward in time. This system has so far satisfied all observers.

The observer is free to type in any comment he wishes after the end of an observation. This may contain data on observing conditions and equipment performance, and editing or reduction instructions.

In addition to his programme of field star, standard star and sky observations, the observer has to include in his schedule observations of the integrator zero-points (time required: about 1 minute per hour) and observations to calibrate the condensor ratios and the optical attenuator (about 2 hours per month). The digital voltmeter is calibrated automatically in the following way: we have short-circuited one input to the 20-channel switch. Into three other inputs we feed three of the five photometric signals, attenuated by factors of about 2, 3 and 4. The shorted channel serves as an immediate check on the stability of the zero-point of the digital voltmeter, the three attenuated channels, together with their respective unattenuated channels, allow one to determine any curvature of the DVM characteristic and the factors (approximately 10 and 100) that convert readings on higher ranges of the DVM to the lowest range. A computer programme that makes these determinations is described in section 6 (programme d). We are satisfied that we can in general determine the relative sensitivity of the DVM to an accuracy of better than 0.05 per cent over the entire operating range (0.2 V to 12 V). The stability of the three resistive attenuators is crucial in this method. We have used assemblies of identical wire-wound resistors in both parts of each attenuator, thermally in good contact with one another; ambient temperature changes will therefore not influence the attenuation factors very much.

It is, of course, essential that readout of the photometric data be prevented until the integration has been completed. We have done this by blocking the DVM readout command while the photocells are connected to the integrators and while the condensors are shorted. Since we do want to read out all the preset data during the integration time, the preset data must be programmed in earlier columns than the photometric data.

A somewhat random collection of remarks now follows, mostly concerned with constructional details:

— A single integration timer is used, driven by pulses from one of the quartz clocks. A master mercury-wetted relay drives dry-reed relays on the integrator units. The condensors are shorted from the moment the start button is pressed until the second 2-second pulse from the clock comes along; the minimum and maximum shorting times are therefore 2 and 4 seconds respectively. The integration time is 30 seconds.

— For ease of hand-reduction, we have chosen to record the civil and sidereal times, and the right ascension, in the form of hours, minutes and seconds rather than in degrees or in decimal fractions of a revolution; the declination is recorded in degrees, minutes and tenths of minutes, to agree with the analogue scales on the console. The digital position indicators are of the bidirectional pulse-counting type; they do not, therefore, have an absolute zero-point, but they have built-in error-detection facilities and have proved reliable enough in practice. We have chosen to record right ascension rather than hour angle because the right-ascension shaft is stationary during an observation and because the right ascension is needed for star identification.

— The clocks for the sidereal and civil time consist of quartz-controlled oscillators (the quartz crystals enclosed in simple proportional ovens) followed by frequency-dividing and counting stages. During readout of the time, the counter indication must not change if we are to avoid occasional gross errors; to accomplish this, the readout is blocked until the arrival of a 1-second pulse, after which the typing of six figures is completed in about 0.8 second.

— As the mains supply is not very reliable in our case, and even short interruptions could cause errors or damage, the mains supply remains off after any interruption until restored deliberately by observer action. This increases the amount of time lost after an interruption, but diminishes the chance of errors. Recently the most critical circuits have been put on a battery-and-inverter supply, so that they can continue to operate throughout a mains interruption.

— Those data sources that have to be checked regularly by the observer (e.g. clocks, coordinates, star number) have displays with characters large enough to be seen from several metres' distance. The displays are self-luminous, so that they cause a minimum of ambient light for a given visibility; the intensity of the displays has been kept as low as possible (and has been made adjustable to some extent) in order to disturb the dark-adapted eye as little as possible.

— The data sources are independent of one another; failure of one does not in general affect the others. If a data source fails, but the data themselves are available, the observer can type the data in by hand (examples of this situation are when the electrical output of a unit has failed but its display still works, or when the corresponding analogue indicator functions normally). One clock is redundant, as, to some extent, are either the coordinates or the star number. If the digital voltmeter or the punch should fail, the old system of calibrated attenuator and Brown recorder can be reactivated within minutes. Something really drastic has to happen to make observations completely impossible. This, of course, is an entirely reasonable demand to make, but in such a relatively complex system it has to be one of the most important design considerations if one is to achieve it in practice.

— The tape punch is capable of punching two tapes at once. We normally in fact do this and send one tape to Leiden, together with a carbon copy of the typed record.

— There is electrical interlocking between serializer and typewriter, but no mechanical connection.

— If more than one key is depressed in any decade of the preset pushbuttons (sources E, F and G), the typewriter stops when that column is reached and an alarm light comes on.

— The time for a single five-colour observation is 41 seconds if it is one of an automatic series on a single star (no setting necessary). In a cluster the average time for a single observation (not part of an automatic series) is about 75 seconds, while for all-sky work the average time for an observation of star and sky is 3 to 4 minutes.

— The cost of equipment and materials for the digital system was about fl. 55000. The yield in extra observations is between 30 and 50 per cent. The speedup of the reduction is difficult to estimate, but in some cases is as much as a factor 10 with the computer programmes available at present. Errors in reading-off have been virtually eliminated and we feel that in general few errors remain entirely undetected (although correction of those that do remain can be laborious).

6. Computer programmes

A digital recording system is an expensive luxury if the results cannot be analysed by computer. Since in our view suitable programmes are an essential part of the instrumental system, we shall describe them at some length, even though there is nothing new in the techniques employed. As is the case when designing an instrument, considerable time has to be invested in programming before it begins to pay off, so that in general it is only worthwhile for large observational projects. Of course, in many cases several observational programmes are so similar that they can be combined and a single reduction scheme used for all of them up to a certain point in the reduction, or certain building blocks may be applicable in many different computer programmes. We have aimed at providing programmes which are suitable for all the work with the five-colour photometer and can also be adapted to other layouts and photometers without being completely rewritten.

There are two main tasks for the computer in data reduction. One is to detect malfunctions of the digital system and correct them where possible, and to edit the data into a form suitable for further computation; this type of work is largely logical and organizational and generally requires most computer time. The other is the reduction proper, which is to a large extent an arithmetic task. The programmes for both these tasks were written in PL/I, which was chosen because it allows convenient handling of character strings. The point in the reduction where the requirements of photometrists tend to diverge is in the details of correcting for the effects of extinction. We have not attempted to programme this, but do deliver the data in a suitable form for inspection followed by either hand or machine reduction. Where we stop, most of the drudgery of the computations and general checking for errors has been done. Leiden Observatory has a remote-access console connected to the University's central computer; the console can be operated in a language similar to JOSS and should prove valuable for the remaining part of the reductions.

At present we have the following programmes in use:

a) A programme to read the paper tape, to detect parity errors, to detect numbers consisting of too many or too few figures, to separate data from comment, to insert the date and to put all the information on a magnetic tape in an easily handled standard format. This programme also gives a daily summary of the performance of the digital equipment at the telescope and warnings of some error conditions whenever they have occurred.

b) A programme to print the contents of a magnetic tape.

c) A programme to correct, add or delete any piece of data on a magnetic tape; the programme yields a new tape.

d) A programme to analyse the performance of the digital voltmeter.

e) A programme to do the reduction proper. This includes selection and subtraction of the relevant sky measurement, correction for all instrumental parameters, computation of one magnitude, four colours and the air mass, generation of an inspection list and delivery of two tapes for further computation and for generation of various lists and plots for convenient inspection.

f) A programme to select certain specified observations, to sort them into some specified order, and to list them, plot selected data from them, or write them on a magnetic tape.

All our magnetic tapes have one format, so that programmes b, c and f can be applied at any stage in the reduction. Several alternate applications of b and c are usually necessary after programme a.

A cardinal point in the design of the programmes has been not to reject any data that can be saved. For instance, if the output of one photometer channel is irretrievably lost, only those colours affected by it are omitted; or, if a normal channel is lost, but the corresponding attenuated channel is available, the latter is used instead. A piece of information is not considered irretrievably lost if either the punched or the typed record can be interpreted. If a single symbol is lost, or if a number contains one symbol too many, that number is rejected, but the rest of the measurement is saved; this feature makes for a minimum of correction by hand-punched cards. The general reduction method is to run programmes a and b, then correct in programme c all errors found by inspection, again run programme b, then run programme e and b with preliminary data for the digital voltmeter. After inspection of the rough reduction we can correct any further errors found and complete the standard machine reduction with the sequence d, e, (b,f). It is anticipated that further reduction will be largely by desk calculator or by the remote-access console.

One of the greatest dangers of machine reduction, especially if the users of a programme have no programming experience themselves, is that incorrect results (whether through improper functioning of equipment, bad observational technique, or unfavourable circumstances) will not be recognized as such; long printed lists tend to mesmerize even the most critical workers. For this reason we have thought it advisable to keep all comment attached to the observation it refers to, throughout the reduction. Though comment can be altered in programme c, it cannot, by an ordinary user of the programme, be destroyed without trace. The printing programme allows suppression of comment whenever a "clean" list is needed. Since in our system comment is of arbitrary length, the above procedure has caused a considerable amount of extra programming work; it is, of course, a matter of taste whether the time and irritation saved are thought to be worth this extra effort.

The most serious problem remaining is to recognize when incorrect or clumsy programming leads to wrong results. The many lists and plots that are or can be produced are intended to help in this.

More detailed remarks now follow about some of the programmes. The PL/I texts (or possibly card copies) could be made available to those seriously interested.

Programme a: There is one element of this programme which contributes most to its adaptability to other layouts. This is a subroutine that forms a number out of the next few symbols on the paper tape if and only if the symbol immediately following the presumed number is the expected layout symbol (usually a blank or decimal point), or a code derived from it by a single (parity-destroying) punching error. If this condition is not met, but the expected layout symbol is one position early or late, the number to be formed is considered lost and the scan is resumed at a corrected position. If the expected symbol is more than one position from where it should be, the error is taken as irrecoverable and the rest of the measurement is placed in the comment field. Each measurement consists of a numeric field and, optionally, a comment field. The comment field is entered by completion of the numeric field, by an irrecoverable paper-tape error, or by encountering a letter where only figures or layout symbols are expected. The end of the comment is defined by the next apostrophe on the paper tape. Before a measurement is delivered to the output tape, the programme checks that all quantities are within their prescribed limits. In practical operation, the programme takes all paper-tape imperfections in its stride; the worst it does is occasionally put a measurement into the comment field (which can be put right in programme c).

Programme c: Since a tape punch is never completely reliable, and since observations are sometimes influenced by external factors, the output tape from programme a is far from perfect. An easy-to-use correction programme is therefore essential. Our programme allows us to change any part of a measurement, to delete or add a measurement, to delete part or all of the comment (putting something in its place to show that it has been deleted), and to add comment. Identification of a measurement is by sequence number; corrections are punched on cards. Correction of numerical data is either by punching the data in specified columns of the card or by referring to the quantity by name. It is also possible to specify the sequence numbers of the first and the last of a series of measurements which must be deleted or to which a constant correction has to be applied. The card-images containing the corrections are sorted inside the computer into ascending order of sequence numbers before the tape is scanned; this makes the programme immune to sequence errors in the card deck offered to it.

Programme d: This programme uses the attenuated signals, together with their respective unattenuated signals, to detect systematic deviations in the digital voltmeter characteristic from its ideal "straight line through the origin" state. The programme is designed to test models consisting of any combination of zero-point errors, non-linearity, and errors in the input attenuator factors for higher ranges; the criterion used to decide whether the model used was suitable is that the computed value of the attenuation factor, using all the derived or assumed calibrations, should be independent of the voltage measured. The analysis can be carried out per day, for part of a day, or for any group of days. After two or three runs of this programme one can usually guarantee that, provided the calibration constants derived are also used in the reduction, the voltmeter has not significantly affected the system accuracy.

Programme e: Although this programme is for the reduction proper, even here there is some organizational work, and it is this that takes most of the programming time. The programme searches for amplifier zero-points (phase 1); it interpolates and subtracts these, correcting for any digital voltmeter deviations present, and scales the voltages to one capacitor value (phase 2); finally it searches for the specified sky measurement, subtracts this, computes logarithms, colours, air mass, and scales for the effect of the optical attenuator if necessary (phase 3; it is a consequence of observational procedure that scaling for the optical attenuator is carried out here rather than in phase 2). The division into phases has been done to reduce the organizational intricacy involved in searching forward for the next zero point and sky measurement as one scans the magnetic tape; between the phases the data reside on magnetic disk. The various instrumental constants are fed in on cards, the specification including the first and last day for which the constants are valid; after this date has been processed, the programme demands a new batch of cards. The programme has a number of error messages and warnings of abnormal circumstances built in; in all cases the reduction is continued, rightly or wrongly, with the data available.

Three methods are open to the observer to specify which sky measurements are to be used for reducing a star measurement; they have been described in section 4. This feature complicates the programme considerably, but it does ensure a certain flexibility at one of the most essential points and satisfies the requirements of most observers under most circumstances. A list is printed, containing each star measurement (in linear scale), together with the sky measurement selected; this allows one to keep track of the computer's activities at this stage. For inspection purposes, logarithmic measures of the star intensities are also listed, reduced to the zenith with standard extinction coefficients (the values of which can be specified along with the instrumental constants). The measurements in linear scale, as printed in the inspection list, are also written on magnetic tape in the standard format and are in a suitable form for further work (e.g. plotting sky measurements). One point should be mentioned in connection with the accuracy of computation. The desired system accuracy of 0.1 per cent (about 0.001 mag or 0.0004 in units of $\log_{10}$), together with the maximum observed value of the W extinction coefficient (0.5 in units of $\log_{10}$) leads to a desired accuracy of 0.001 in the air mass for the most accurate all-sky work [errors due to varying temperature can in general be kept to 0.001 in the air mass by observing enough standard stars; errors due to varying pressure affect mainly the extinction coefficients (SCHOENBERG, 1929, p. 273)]. The formula used is that given by SCHULTE and CRAWFORD (1961, section II A), with the necessary correction to the decimal point of one of the constants.

Programme f: The selection of measurements is first of all by measurement sequence number, next by type of measurement, and lastly, if desired, by star number. Sorting is done by an IBM-supplied SORT/MERGE utility programme (programme no. 360S–SM–023), which allows sorting into almost any order that could conceivably be useful. A standard application of programme f is the isolation of standard star observations for calculating the atmospheric extinction.

The programmes described above work satisfactorily for the five-colour photometer; their adaptability to another photometer and layout will be put to the test in the near future. For the five-colour photometer we use 30 to 50 hours of time on the IBM 360/50 for handling one year's data; a sizeable part of this time the computer is waiting for input and output operations to be completed.

Our experience suggests that computer reduction is certainly faster than hand reduction, but that the financial advantages have at most been marginal in our project (5 channels, 200 full observing nights). For a larger number of channels, or more observing nights with approximately unchanged equipment, computer reduction is both faster and cheaper. For a smaller project, less flexible (and therefore simpler) programmes could still yield a gain for all those observations that fit the more stringent requirements one would have to impose in that case.

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Note added in proof: During one year's use, none of the condensor ratios have changed by more than 0.1 per cent (data on four integrators).