1990JBAA..100...24E

A simple automatic photoelectric telescope

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Part II: Hardware

An overview of a simple APT has already been given.[1] This part describes in detail the telescope and mounting, the drive system, photometry equipment, computer equipment and the observatory.

Introduction

The word 'hardware' in the title is intended to be taken broadly: to include all equipment associated with the APT system. (Software is the subject of Part III.) Particular attention has been paid here to the telescope, its mounting, and the mechanics of the drive system. There has been only limited discussion of these in the literature of APTs, surprisingly, since mechanical requirements are very stringent. On the electrical and computer interfacing aspects of hardware, this paper gives little theoretical background, and largely restricts itself to circuit diagrams and parts lists; instead, readers are referred to those with more expertise than the authors.

Optics

A 212-mm diameter f/4.0 Newtonian reflector was decided upon. This size of telescope gathers enough light to be able to work down to magnitude 10 at our site, and there is much work to be done with stars brighter than this limit. We did not attempt a larger telescope, as it was (for us) an experimental project.

The main mirror support is conventional: three screws support the mirror from below, and allow for aligning the mirror axis; four small clips secure the mirror at the top edge; and four screws support the sides, allowing lateral adjustment. The 64-mm minor-axis secondary mirror is slightly smaller than is conventional, and is just large enough to ensure that the pinhole is fully illuminated; off-axis vignetting is unimportant in this work, as one only has to recognise star fields during set-up, and all data gathering is done with the star in an on-axis pinhole. Ray tracing shows that, because of the short focal ratio, the secondary mirror has to be offset both 3 mm towards the main mirror and 3 mm further away from the eyepiece.

Telescope tube

The aluminium alloy telescope tube is 250 mm square and of screwed construction, made from 30-mm by 30-mm by 5-mm angle, covered with 1.5-mm-thick sheet. It is built in two parts. The top part, 345 mm long, holds the spider and the eyepiece tube, and is a rotating head, allowing the eyepiece to be horizontal, whatever the position of the telescope. The eyepiece tube is sited 280 mm down in this head, reducing the entry of stray light, and protecting the secondary mirror from dew. The lower part – the main tube – is 620 mm long. On opposite sides at the top end of the main tube are 250-mm-square by 5-mm-thick reinforcing plates, which carry the declination bearings. There is a hatch in one side of the main tube, allowing access to the mirrors.

Figure 1c shows the arrangement for joining the two portions of the tube. At the top of the main tube there is a 6-mm-thick plate with a 212-mm-diameter hole (plate A), another similar plate (B) forms the bottom of the rotating head. Four clips, attached to plate A at the edge of the large circular hole, are lined with PTFE on two sides, and there are also PTFE pads fixed to plate A, adjacent to each clip. These clips clamp plate B, sandwiching it between lightly compressed layers of PTFE. With this arrangement, the rotating head may be easily moved to, and will then remain in, any desired position, without any additional clamping. The same principle – of joints with sandwiched PTFE – is of wide applicability, and has been used in the construction of the adjustable chart-holder mentioned in Part I.[1]

The declination sector, centred on the declination axis, is rigidly attached to the main tube, at a distance of 20 mm from it, by means of three bolts and spacers; there is also an attachment at the declination bearing – see Figure 1b. This large (368-mm-radius) sector, made from 6-mm aluminium alloy plate, is the final element of the declination drive system, and is also used as a setting circle, marked in degrees from −20° to +90°.

All moving components of the telescope are balanced about their axes of rotation. On the rotating head of the telescope tube, the photometer head is balanced by the finder mounted on the opposite side. The telescope tube as a whole is balanced about the declination axis, using two sets of weights: the declination sector is balanced by weights on the opposite side of the main telescope tube; further weights, beneath the main mirror, complete the balancing.

The weight of the telescope tube assembly – which includes optics, declination sector, counterbalancing, and all other items described in this section – is about 35 kg.

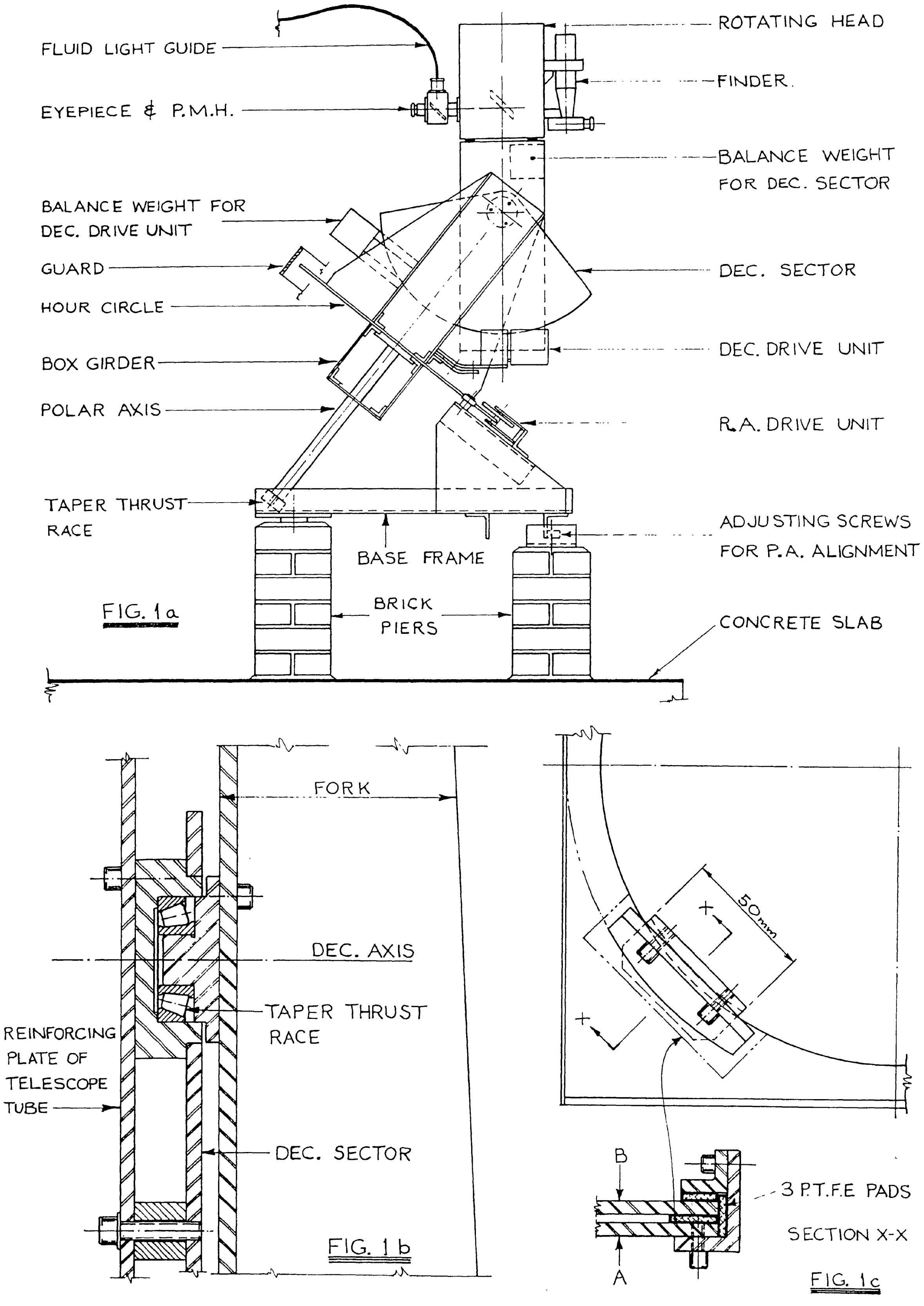


Figure 1. Telescope construction. Figure 1a shows a general view of the telescope and mounting. Figure 1b shows detail of one of the declination axis bearings. Figure 1c shows detail of the clips used to join the rotating head to the main telescope tube.

Mounting

The quality and rigidity of the mounting is crucial to success, as the computer must be able repeatedly to centre a star in a 60-arcsecond diameter pinhole, situated in the focal plane. For our telescope, this pinhole is only 0.25 mm in diameter, so the star image must be placed in the focal plane with a positional accuracy of 0.02 mm, or better. Figure 1a gives a general view of the equatorial fork mounting, as does Figure 2 of Part I of this paper.[1]

The polar axis is a 610-mm-long, 38-mm-diameter solid steel shaft. The lower, southern end fits into a 40-mm-diameter taper-roller thrust-bearing. The top, northern end of the shaft has a 150-mm-diameter by 13-mm-thick steel flange welded to it, and this in turn is securely bolted to a large (760-mm-diameter by 8-mm-thick), aluminium alloy hour circle. Two 38-mm-diameter ball-races, secured to the base-frame of the mounting, and situated 90° apart, support the rim of the hour circle. The polar axis is therefore supported by three bearings in such a way as to give backlash-free polar motion, which operates smoothly and with low torque requirements.

The aluminium alloy fork arms are made from 6-mm plates, joined together using screws and 38-mm by 38-mm by 6-mm angle, and are as large as possible where they are attached to the hour circle. The declination drive assembly, mounted on one fork arm, is balanced by weights mounted diagonally opposite on the other fork arm. Initially the hour circle itself acted as a base for the fork, but this flexed alarmingly. A U-girder was therefore bolted to the underside of the hour circle, in such a way as to form a box-shaped fork base. This U-girder is 200 mm square, made from three 3-mm-thick steel plates, joined with the help of (38-mm by 38-mm by 6-mm) steel angle. Additional bracing bars, of the same steel angle, were bolted to the hour circle at this time. With these additions, the fork is extremely rigid. The entire fork assembly, comprising polar axis, hour circle, fork, and declination drive plus counterbalance, weighs about 55 kg.

The hour circle combines three functions, more usually shared by two disks. These are: as a setting circle, divided into hours, quarter hours, and five minute intervals; as a part of the north end of the polar axis, supporting the telescope; and also as being the final element in the right ascension drive. A 100-mm-wide by 2.5-mm-thick steel guard plate, placed around the hour circle at a distance of about 30 mm, protects the rim against damage.

The declination axis comprises two opposed 40-mm-diameter taper-roller thrust-bearings, each mounted in a housing near the top of a fork arm, as shown in Figure 1b. One half of each housing is secured to the fork, and the other to a reinforcing plate on the main telescope tube. Fine positional adjustment of each bearing is achieved by six opposing screws. These screws are also used to exert a pre-loading of about 4 kg on the bearings ('squeezing the telescope tube between the arms of the fork'), so eliminating backlash in the declination axis.

The base-frame of the mounting is a rigid, screwed and bolted steel framework, of 70-mm by 70-mm by 8-mm angle, together with 6-mm and 8-mm plate. It weighs about 80 kg, and rests on three steel-capped brick piers, which bring the instrument to a convenient height. An arrangement of five 10-mm-diameter steel screws between the base-frame and the piers allows polar axis alignment and positional locking.

Drive system

The gearless reduction boxes, one for each axis, are identical, and are similar in principle to that described by Knight.[2] Each box, as shown in Figure 2, is divided into two parts, A and B, held together by a leaf spring C. Part A houses the stepper motor whose 6-mm-diameter output shaft bears directly onto the 81-mm-diameter aluminium alloy disk D, mounted on a 9.5-mm-diameter stainless steel shaft E. A small spring-loaded Rulon pad presses the motor shaft against disk D. (Initially a PTFE pressure pad was used, but this was found to flake, and so Rulon – PTFE with rouge filler – was substituted.) It is necessary that disk D is

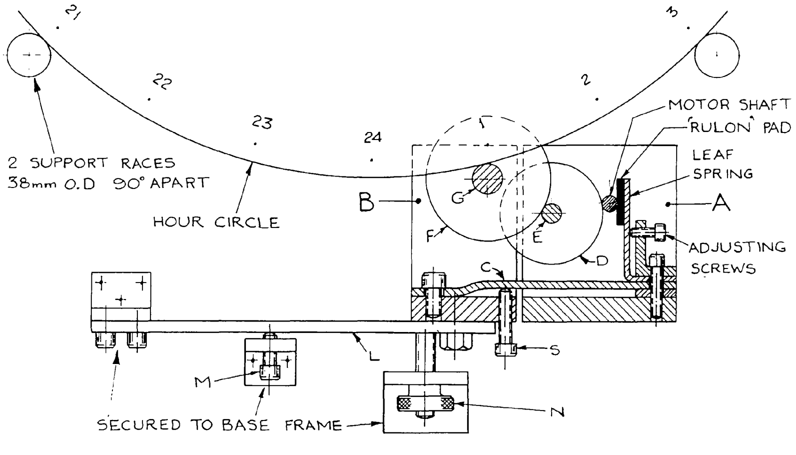


Figure 2. The right ascension gearless-reduction drive. The declination drive box is identical, but mounting slightly differently. The reduction given by each box is 144:1, measured from the stepper motor drive-shaft to roller G.

concentric with its shaft and that the motor shaft bears squarely onto it, otherwise slippage may occur.

The shaft E is pressed onto the 108-mm-diameter aluminium alloy disk F, by the force of spring C which may be adjusted by screws S. Disk F is in part B, and is mounted on a stainless steel 25.4-mm-diameter shaft G. The reduction, from the stepper motor shaft to roller G, is 144 to one. Both shafts, E and G, are mounted in two double-row self-aligning ball races.

The large circle and sector, which the right ascension and declination reduction boxes drive, have radii of 380 mm and 368 mm, giving over-all reductions of 4320 and 4176 to one respectively. Because of this, each (1.8°) step of the right ascension motor moves the polar axis 1.5 arcseconds, whereas each step of the declination motor causes a movement of 1.55 arcseconds. The reduction was chosen so that the sidereal rate corresponds to 10 steps per second.

The right ascension drive box is mounted at one end of a large leaf-spring L, which is fixed at the other end to the base-frame, with a loading of about 30 kg between roller G and the rim of the hour circle. Similarly, the declination drive box is mounted on a large leaf-spring L, fixed near the bottom of one of the fork arms. There is a loading of about 20 kg between roller G and the rim of the declination sector. Both leaf-springs L, may be adjusted, using screws M, and may also be clamped back using clamps N, disengaging the drive assemblies, so allowing the telescope to be moved freely by hand.

Testing the drive system

Many tests, totalling about 200 hours (over an eight week period), were performed on the drive system while the telescope was still indoors, with the aim of determining the accuracy and the factors affecting performance. During this time, we experimented with changing spring loadings between the rollers, and carefully made all axes parallel. Tests began with the stepper motors alone, and built up, one roller at a time, to the full drive system. There was some evidence of a 'running in' period, during which the rollers became polished.

Preliminary full-drive-system tests, slewing to-and-fro by 5000 steps about the polar axis, indicated that the angular distances moved in each direction were constant and repeatable, but differed in size by about one part in 2000. It was quickly realised that this was mainly due to imperfect balancing of the telescope and mounting, and, once this had been improved, the difference was reduced to one part in 5000.

It is sometimes stated that there is no slippage with a gearless drive, but we found that this was not entirely the case. The word 'slippage' conjures up an image of one or more steps being lost, and no slippage of this type occured. On the other hand, small-scale slippage was found, as described in the previous paragraph. What we believe is happening is that a thin film of grease between rollers is subjected to a shear stress, causing a minute relative movement. Such slippage is not noticeable during tracking because, owing to its consistent nature, it may be cancelled by a small adjustment to the tracking rate.

To allay fears that large-scale slippage might occur if oil was to get onto the rolling surfaces, all the contact rollers and disks were generously coated with lubricating oil, and the tests repeated. These tests indicated that the amount moved through in each direction decreased by one part in 2000, but was still sensibly constant, consistent with our shear stress explanation for small-scale slippage.

During this period, we determined that the pull-in rate for the motors (the maximum rate at which they would start under load, without losing steps) was about 800–900 steps per second. In use, we have chosen lower slewing rates – typically 400 steps per second – so as to have surplus torque. With differential photometry, only small distances are moved over, so the slew rate is not critical to efficiency.

By the end of the indoor testing period, we were satisfied that the small-scale slippage remaining was of no consequence, and this proved to be the case. Outdoor testing showed that the telescope performed extremely well: in tracking tests, a star would remain within a few arcseconds of the centre of a graticule for several hours; and in slewing over a distance of 6° to a star, the error on arrival was typically less than 8 arcseconds.

Observatory

The three brick piers of the telescope rest on a 125-mm-thick concrete foundation slab, which is 1145-mm-wide and 3125-mm-long. There is a generous paved area around this slab, to save the operators from having to tread on wet grass. The slab also holds the rails (two 2970-mm lengths of 25-mm by 25-mm by 3-mm steel angle), on which the run-off shed rolls, on four small ball races. The wooden run-off shed, approximately 1070 mm wide, 1300 mm long and 1700 mm high, is supplied with normal mains power. The trolley containing the electronics is shut in this shed while the telescope is in use.

A simple test was performed to check the rigidity of the slab: the observer stood at the eyepiece of the APT, watching a star being tracked on the graticule, and another person, weighing about 70 kg, walked back and forth close by. No movement of the star in the eyepiece was observed during this time.

There is an electrical timer switch in the hut, which can be set to cut off power before daylight arrives, and which also acts as a safety device: in the event of a short night-time power-cut the switch will remain off even when power is restored. This is to protect the expensive photomulitplier tube, which might be damaged if it were exposed to daylight while powered-up. The computer cannot switch off power after such an event, as it would have crashed.

Computer equipment

Controlling the APT is a BBC microcomputer, with twin 80-track disc drives, and a small black-and-white monitor. Programs were written in BBC BASIC, with some low-level routines written in the built-in 6502 assembler.

We chose the BBC microcomputer because we had experience in its use with our manual PEP system,[3] and portions of programs from this system were used for the APT. One disadvantage of the BBC is its limited (32K) memory, and because of this the main program had to be written in several parts, using overlays.

A feature of the BBC microcomputer is its internal timers.[4] There is an Interval Timer which we use to control exposure times for taking readings. Associated with this timer is a BBC BASIC pseudo-variable called TIME, which increments at a nominal 100 Hz, and is used (after calibration) as a clock. The User 6522 VIA chip has two timers, T1 and T2. Timer T1 may be made to generate interrupts at the sidereal rate of about 10 Hz. (T1 works by repeatedly: leading a value X into a register; decrementing this register at a rate of 1MHz; and generating an interrupt when the register reaches zero. Thus, very fine adjustments may be made to the sidereal rate, by small adjustments to the value X.) The second timer, T2, works in a similar way, and is used to generate interrupts at the slewing rate (typically 400–700 Hz).

Stepper motor electrics

Table 1 lists major parts for the stepper motors and the associated driving circuitry. We have included this list as neither of us has any expertise in electronics, and might otherwise omit important information.

Figure 3 shows the power supply for the stepper motors. It is based on RS (RadioSpares) Data Sheet 5128, where the theory of power supply construction is discussed. The power supply delivers 27.5 volts DC, and may take a current of 1 amp.

The 1.8° stepper motors and their drive boards are described in RS Data Sheet 7017, and the circuit shown in Figure 4 is based on a diagram in this sheet. The resistors R3 have metal jackets and become very hot. They are housed in a separate metal box – not shown in the figure – which gives enough heat to protect all the electronic equipment on the trolley from damp, while it is shut in the run-off shed.

Table 1. Major parts list.

This lists the major parts for the stepper motor drive system – leads and connectors are omitted. Codes refer to Figures 3 and 4, Six digit part numbers are RS (RadioSpares); other part numbers are Maplins.

(a) Stepper Motor Power Supply.

Code	*Part no.*	*Description*
S1	YR68Y	Switch
T1	207–318	Transformer (20V 5A)
REC	262–078	Rectifier
REG	304–627	Voltage regulator
	GF51F	Heat sink for above
	WR24B	Mounting kit for above
C1	104–382	Capacitor, 10000 μF, electrolytic
	FF35Q	Mounting clip for above
C2	YY11M	Capacitor, 0.1 μF
C3	WW60Q	Capacitor, 1.0 μF, electrolytic
R1	U15R plus U220R	Resistor, 235 Ω
R2	U330R plus U4K7	Resistor, 5030 Ω

(b) Stepper Motor Drive Circuits.

Code	*Part no.*	*Description*
IC1	309–054	74LS05 chip
DRIVE BOARD	332–098	Stepper motor drive boards (2 off)
	467–453	Sockets for above (2 off)
STEPPER MOTOR	332–082	1.8° stepper motors (2 off)
R3	157–566	Big resistors, 22Ω 25W (4 off)
METAL CASE	XY49D	Housing for drive system

The drive boards cannot be controlled directly from the BBC microcomputer, and IC1, which is a 74LS05 chip (‘Hex inverter, open collector output’), acts as an intermediary. This chip effectively comprises six switches, joining pin 7 to pins 2, 4, 6, 8, 10 and 12. Each pin 1, 3, 5, 9, 11 and 13 controls its respective switch. So pin 1, for example, controls the switch between pins 7 and 2: when pin 1 is high this switch is closed; and when pin 1 is low this switch is open. IC1 is connected to, and is powered from, the printer port of the BBC microcomputer: Figure 5 gives the pinouts. (Our printer is never taken out to the telescope, and is only used later for data reduction.)

The button-box, connected to the User Port of the BBC microcomputer, is used to steer the telescope during set-up: Figure 5 shows the circuit and the pinouts. There are four direction buttons, marked RA+, RA−, DEC+, and DEC−, laid out in a diamond

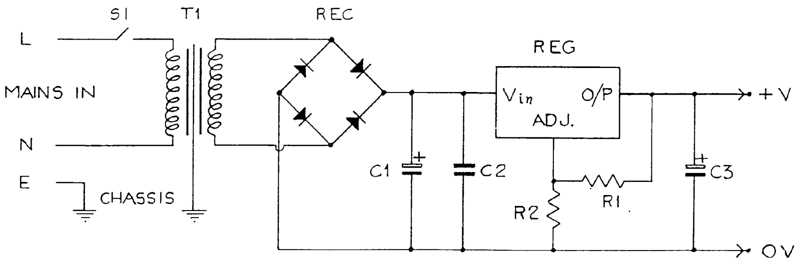
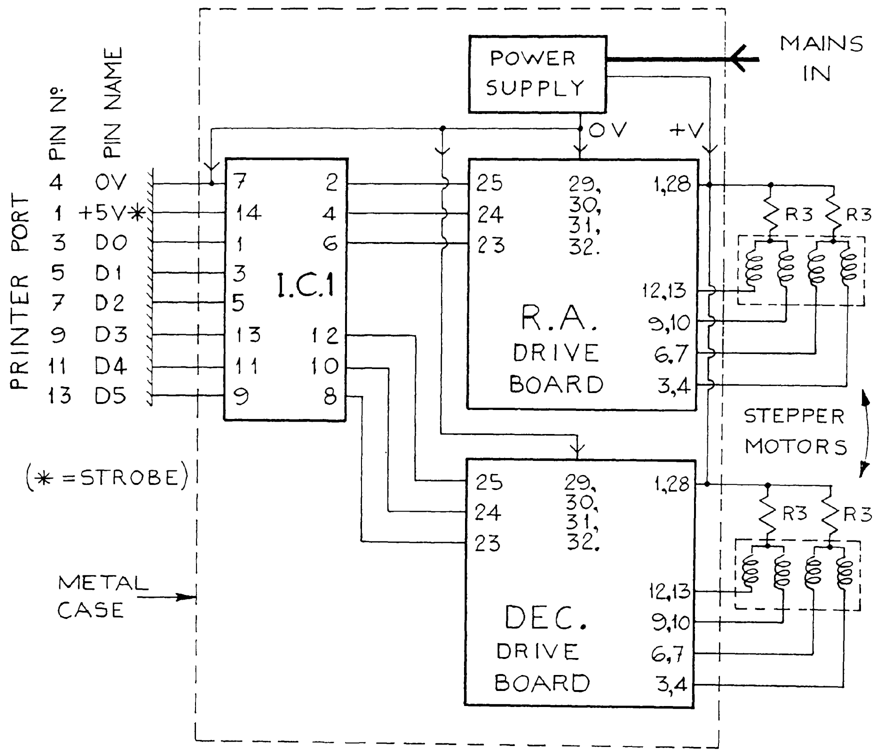


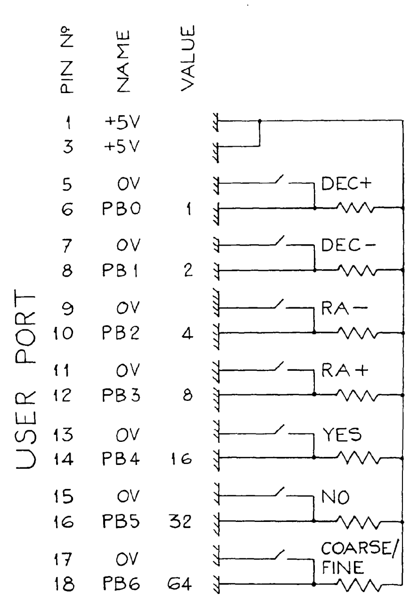
Figure 3. Circuit diagram for the stepper motor power supply. Information about components is given in Table 1.



PIN No	PIN NAME
4	0V
1	+5V✱
3	D0
5	D1
7	D2
9	D3
11	D4
13	D5

LINES	LOW	HIGH
D0	R.A. MOTOR FULL STEP	R.A. MOTOR ½ STEP
D1	PULSES TO R.A. MOTOR	
D2	R.A. MOTOR ANTI-CLOCKWISE	R.A. MOTOR CLOCKWISE
D3	DEC. MOTOR FULL STEP	DEC. MOTOR ½ STEP
D4	PULSES TO DEC. MOTOR	
D5	DEC. MOTOR ANTI-CLOCKWISE	DEC. MOTOR CLOCKWISE

Figure 4. Schematic of stepper motor drive circuits, showing interfacing to the Printer Port of the BBC microcomputer, and including pinout detail. Information about components is given in Table 1.



PIN No	NAME	VALUE
1	+5V	
3	+5V	
5	0V	
6	PB0	1
7	0V	
8	PB1	2
9	0V	
10	PB2	4
11	0V	
12	PB3	8
13	0V	
14	PB4	16
15	0V	
16	PB5	32
17	0V	
18	PB6	64

Figure 5. The button-box circuit, showing pinouts from the User Port of the BBC microcomputer.

pattern. There is also a coarse/fine switch on the button box: if this switch is set to coarse, then the computer will send a batch of 60 steps to the appropriate motor when a direction button is tapped; if the switch is set to fine, then only one pulse will be sent. Holding down a direction button continuously will give either fast or slow slewing, depending on the position of the switch. There are two further buttons on the box, marked YES and NO, the use of which will be described in Part III. The number read by the computer at the User Port is equal to 255 minus the sum of the values associated with each button. (See the column marked VALUE in Figure 5.) Conversely, from the number read, the computer can determine which buttons are being pressed.

Photometer

The photometer head and associated electronics are a pre-production prototype of the JEAP photometer, bought from Norman Walker, who was assisted with the electronics by John Watson and Richard Young. A paper by Walker describing this unusual photometer has previously appeared in the Journal,[5] and an outline of how this photometer works is also given in Part I of this paper.[1]

The APT's prototype JEAP differs from the production version in two particulars. First, the prototype APT JEAP has a parallel interface which is connected to the 1-MHz Bus of the BBC microcomputer, whereas the production version of the JEAP has a serial (RS232) interface, which would be connected to the BBC microcomputer's RS423 port. Second, we do not have the timer board which is now supplied as standard with the JEAP, and instead we make use of the BBC microcomputer's internal timers, as already described.

Walker, who supplies the JEAP, has details about how to interface it to home microcomputers, including the BBC and the IBM PC.

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Received 1989 January 25; accepted in revised form 1989 March 29

Part III: Software

The software, written to control the simple APT,[1,2] is discussed in non machine-specific terms. It is shown how the design requirements of flexibility and the ability to cope with poor weather conditions have been met.

Introduction

Designing software to control an APT is a large undertaking and will continue to occupy us for some time to come. The system is now functioning reliably and producing good results. Future work will build upon that already done, rather than involve substantial changes, so it is appropriate to describe the software in its present state.

Writing such software involves some special difficulties. From about the time when the procedure to centre stars is written, bench testing is no longer possible, and one must test the system *in situ*. This means that program errors have to be diagnosed and corrected under onerous conditions. The software must not only control the telescope and collect data for the observer, but must also display plentiful information on the computer screen for the benefit of the programmer. For instance, should the system not find a star, the programmer would want to know which procedure failed and also where it had failed. Furthermore, setting up the telescope depends on a complex interaction between computer, observer and telescope, and so the best method of doing this cannot be predicted in advance but must be found by experience.

Certain topics below are treated in depth, particularly if they are original (such as the interrupt driven tracking), or contain refinements needed to cope with the uncertain English weather. Other topics are omitted; for instance the data analysis routines, which involve only standard programming techniques, and which are similar to programs written for our previous system.[5] The programs discussed (with the exception of AcornSoft's Database), will be made freely available.

Combining tracking and slewing

With only a single stepper motor on each axis of the telescope, there arose the problem of how to combine tracking and slewing. An unsuccessful technique we initially tried was to have an interrupt service routine,[4] activated ten times per second (the sidereal rate), which sent a tracking pulse to the right ascension stepper motor. Simulation testing, with the telescope indoors, we found that the telescope would track accurately when pointing at a single star but would drift badly in right ascension when slewing between stars. This was because slewing pulses could be sent arbitrarily close to tracking pulses, resulting in pulses being lost by the stepper motor.

Soon we found an excellent software solution, in which tracking is done transparently. By this we mean that, having written the tracking routines, we could thereafter ignore the rotation of the Earth in writing the Main Program. This solution requires three simultaneous processes going on inside the microcomputer, and two variables, which are shared between them.

The two shared variables are called ra–steps, and dec–steps, and represent the pointing error of the telescope in right ascension and declination respectively; the telescope is pointing in the correct direction only when ra–steps and dec–steps are both zero. Because these variables are shared, any process accessing either has to lock the other processes out by temporarily disabling interrupts.

The three processes are:

(1) The Sidereal Process. This is an interrupt service routine, activated at the sidereal rate of 10 Hz, which decrements the ra–steps variable.