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THE ORNITHODOLITE: AN INSTRUMENT FOR COLLECTING LARGE SAMPLES OF BIRD SPEED MEASUREMENTS

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CONTENTS

An instrument is described in which a rangefinder is mounted on an alt-azimuth mount, and readings of azimuth, elevation and range are obtained by means of digital photoelectric angular encoders. The readings are passed as eight-bit numbers to a microcomputer, which logs them together with the time. A series of timed position observations (or 'run'), is acquired and then recorded on cassette tape together with details of the species, its behaviour, and the wind. The tape is later read back into the computer, and the data are printed out. The instrument is battery powered, fully portable, and requires only one operator.

1. INTRODUCTION

Several methods have been used to determine flight speeds of birds in the wild. The largest volume of data has come from studies of migration with use of surveillance radar. Alerstam (1978) has reviewed the problems inherent in this, notably the difficulty of identifying the echoes. For tracking radars, which are capable of locking onto an individual bird and automatically following it, the target can sometimes be identified visually. Such radars have been used by several authors, notably Williams *et al.* (1972) and Bruderer & Steidinger (1972). In an effort to devise cheaper, simpler and more portable equipment, Lanyon (1962) developed a Doppler radar for use with birds. This device gives a direct indication of speed when positioned on the line of flight, but otherwise the output is difficult to interpret. The range attainable is much less than with other types of radar. Airspeeds of some large species have been measured by following with an aircraft and measuring the relative speed between aircraft and bird (Pennycuick 1971), while average groundspeeds have been measured simply by following individuals or flocks over substantial distances (Pennycuick 1972; Pennycuick *et al.* 1980). An optical method was devised by Tucker & Schmidt-Koenig (1971), who used two phototheodolites, some distance apart, coordinated by a radio link. This method is capable of high precision and long range, but is complicated and expensive.

The primary measurement made by all the above methods, except for short-period aircraft measurements, is the bird's groundspeed. Before airspeeds can be estimated, the wind has to be measured. For tracking radar and phototheodolite observations, the wind can be determined by tracking a pilot balloon, while with surveillance radar it is usually necessary to rely on doubtfully reliable estimates supplied by local meteorological services.

In the present paper an instrument is described for collecting large samples of flight speed estimates of birds at short ranges, up to 160 m or so. Its primary purpose was to observe albatrosses and petrels in and around South Georgia, both from sites on land and from a ship. The design requirements were that it be cheap, battery powered, portable by back-packing over rough terrain, and capable of operation by a single observer.

The principle adopted was to mount a rangefinder on an alt-azimuth mount and determine the bird's position by measuring its range and angles of elevation and azimuth. A primitive instrument of this kind was used by Pennycuick (1960) to measure speeds of slope-soaring birds. The method then was to transfer the three angular readings via Bowden cables to a chart recorder, and measure the polar coordinates and their derivatives from the chart later, by hand. In the present instrument, azimuth, elevation and range were measured electrically. The readings, together with the time, were temporarily stored in a microcomputer, then recorded on magnetic tape, and later read back and printed out. A record (or 'run') consisted, in effect, of a series of timed, three-dimensional positions in space. Speed estimates were obtained by comparing successive positions. The principle of operation bore some resemblance to that of a recording theodolite, by analogy with which the instrument was named an 'ornithodolite'.

2. DESIGN

The design objectives became practicable with the appearance of cheap microcomputers, in the form of kits suitable for construction by amateurs. The ornithodolite was designed to interface to the Z80-based Nascom 1 microcomputer. At the time the system was designed

(1978), the Nascom 1 had just become available in Britain, and was the only computer offering a television (t.v.) interface, cassette recorder interface and parallel input–output interface (p.i.o.) all on a single board, plus a sufficient amount of memory. More modern microcomputers differ mainly in having greatly increased memory capacity, usually including a BASIC interpreter. This would allow some processing of the data to be done at the stage of reading back the tape and printing out the results. The methods of encoding and recording the data in the first place (described below) would, however, remain appropriate for other computers. The principles will be explained at some length, as they can be adapted to many other purposes.

2.1. *The angular encoders*

The general arrangement of the instrument is shown diagrammatically in figure 1. The rangefinder was mounted on a tilting frame, which could be tilted about the elevation axis EE. This mechanism could itself be rotated about the azimuth axis AA. The rangefinder knob rotated about its own axis RR. These three axes were the measurement axes, and each carried a photoelectric encoder.

Since the Nascom 1 was an eight-bit computer, each of the primary variables was encoded as an eight-bit binary number. This meant that the full scale for each variable could be divided into a maximum of 256 divisions. It was decided to measure azimuth angle on a scale of 128° in steps of 0.5°, and elevation angle over 64° in steps of 0.25°. Photoelectric encoders were used, based on the Texas SDA13 papertape reader module. This consisted of two matched boards, the LEA13 containing a linear array of light emitting diodes (l.e.ds), spaced 0.1 inch (2.54 mm) apart, and the LSA13 containing a similarly spaced array of phototransistors. Each array actually contained nine elements, of which eight were used. The angular information was carried on encoder discs, one of which was mounted on each measurement axis. In each case the disc rotated with the movable part of the instrument, while the sensor array was fixed to the framework.

The azimuth and elevation encoders were drawn on opposite sides of the same disc, which is reproduced in figure 2. The disc pattern was drawn on Bristol board at twice the eventual size, then photographed on Kodalith 2556 35 mm film, and finally printed as a positive transparency on Kodalith 4556 sheet film (thick Estar base). It can be seen from figure 2 that any radius through the disc cuts a unique combination of clear and opaque tracks, which is output by the phototransistors as a corresponding binary number. The device thus does not require calibration, and its accuracy is determined by the accuracy with which the pattern was drawn in the first place. It is also necessary to ensure that the sensors turn on and off cleanly at the transitions, and the phototransistors were masked by rectangular slits to achieve this. Like the encoder discs the mask pattern was first drawn on a large scale, and the actual masks were made by photography on lith film.

It can also be seen from figure 2 that the pattern is not the ordinary sequence of binary numbers, but a different sequence known as Gray code. Ordinary binary code cannot be used in this type of encoder, because errors can arise when more than one digit changes state at the same time. For example, consider the transition from binary 127 (01 111 111) to binary 128 (10 000 000), in which all eight digits change state. In practice it would be impossible to ensure that all eight sensors changed state at exactly the same instant. Depending on the order in which the digits changed, any eight-bit number could be generated momentarily during the changeover. The problem can be avoided by using Gray code, in which the same set of binary

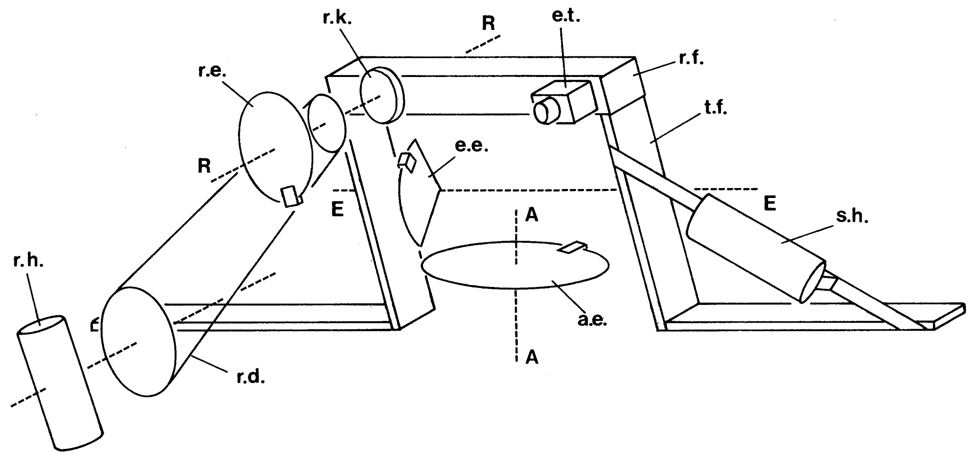

FIGURE 1. Diagram of the ornithodolite. The whole instrument rotates about the azimuth axis AA. The azimuth encoder disc (a.e.) rotates, while the sensing head remains fixed. The rangefinder (r.f.) is carried on the tilting frame (t.f.), which tilts about the elevation axis EE. This movement is sensed by the elevation encoder (e.e.). The rangefinder knob (r.k.) is mounted on a common shaft with the range encoder (r.e.). It is driven by a sprocket-and-chain drive (r.d.) from the ranging handle (r.h.). In use the operator views the bird through the eyepiece telescope (e.t.), and follows it by steering the instrument with the steering handle (s.h.), simultaneously adjusting the rangefinder with the ranging handle. The channel-selector box (not shown) was mounted on the left side of the tilting frame.

numbers occurs in a different order, such that one, and only one digit changes state at each transition. Gray code is easily converted to normal binary. The principles are explained by Kostopoulos (1975). A Z80 machine-code routine for the conversion is given in the Appendix.

2.2. *Range measurement*

The rangefinder was a Rangematic V, a coincident image type with a base length of 25 cm and a × 6 eyepiece telescope. The rangefinder mechanism was operated by a large thumbwheel on the back of the instrument, which was free to rotate through 325°. For normal applications the range scale would extend from 50 m to infinity, but the position of the wheel on the spindle could be adjusted so as to lower both the minimum and maximum ranges. The spindle driving the mechanism was directly accessible via a screw head in the middle of the wheel, and an external actuator shaft coaxial with the spindle was made to mate with this screw head and drive it directly (figure 1). This shaft was in turn driven via a chain-and-sprocket drive from the operating handle, the gear ratio being arranged so that a quarter turn of the wrist on the handle would turn the mechanism through its full travel.

The actuator shaft, driving the rangefinder mechanism, carried an encoder disc similar in principle to the angular encoder discs. However, as the relation of range to the angular position of the shaft was nonlinear, a nonlinear disc was used for this encoder (figure 3). More explicitly, it was found by inspection and experiment that the rangefinder mechanism obeyed the relation

$$r = B/\tan k\phi, \tag{1}$$

where r is the range, B is the base length of the rangefinder, ϕ is the angular position of the ranging knob, and k is determined by the gearing between the ranging knob and the movable mirror in the rangefinder. The constants B and k for the particular rangefinder having been found by experiment, equation (1) was used to construct a nonlinear encoder disc, giving a direct readout of the range.

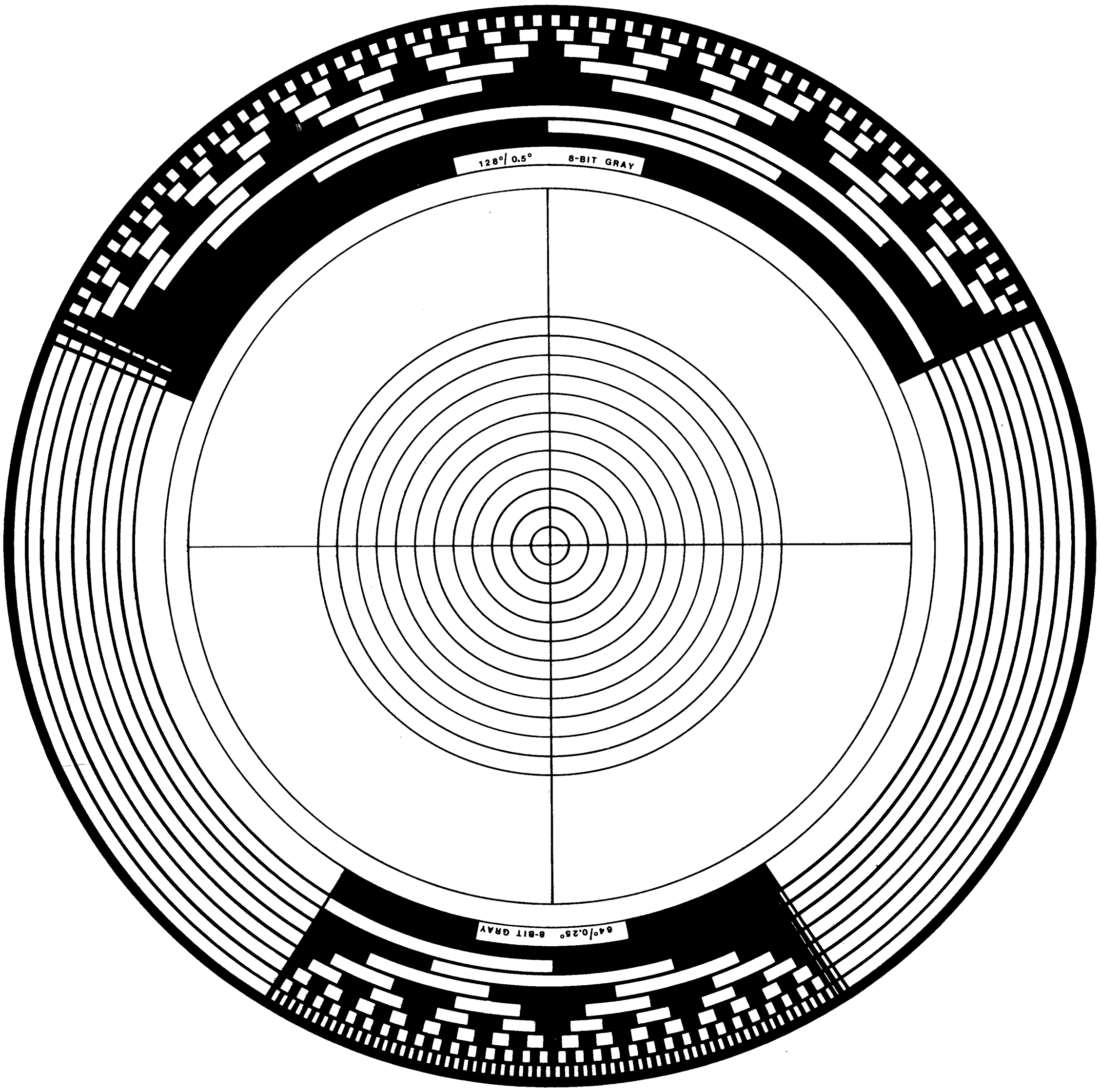

Figure 2. Composite angular encoder disc. The upper encoder, used for azimuth, covers 128° in steps of 0.5°. The lower one, used for elevation, covers 64° in steps of 0.25°. The code is eight-bit Gray code, giving, 256 steps in each scale. The bars at the ends of the encoders are for aligning and adjusting the sensors.

As with the angular discs, the full scale was divided into 256 steps, and a choice had to be made concerning the maximum and minimum ranges, and the precision. The disc shown in figure 3 read from 36 to 163.5 m, in steps of 0.5 m. This disc was used for the studies of petrels and albatrosses, described in the following paper. Another disc was used in a later project, reading from 40 to 295 m, in steps of 1 m. Two further discs were made, having shorter ranges and higher precision, but these have not yet been used.

2.3. *Interface to the computer*

Figure 4 shows the circuit used for each l.e.d.–photodiode pair of each encoder. Of these 24 were required (eight for each encoder). The outputs were fed to the channel selector circuit shown in figure 5. This was made up on Veroboard, and mounted in a plastic box on the tilting

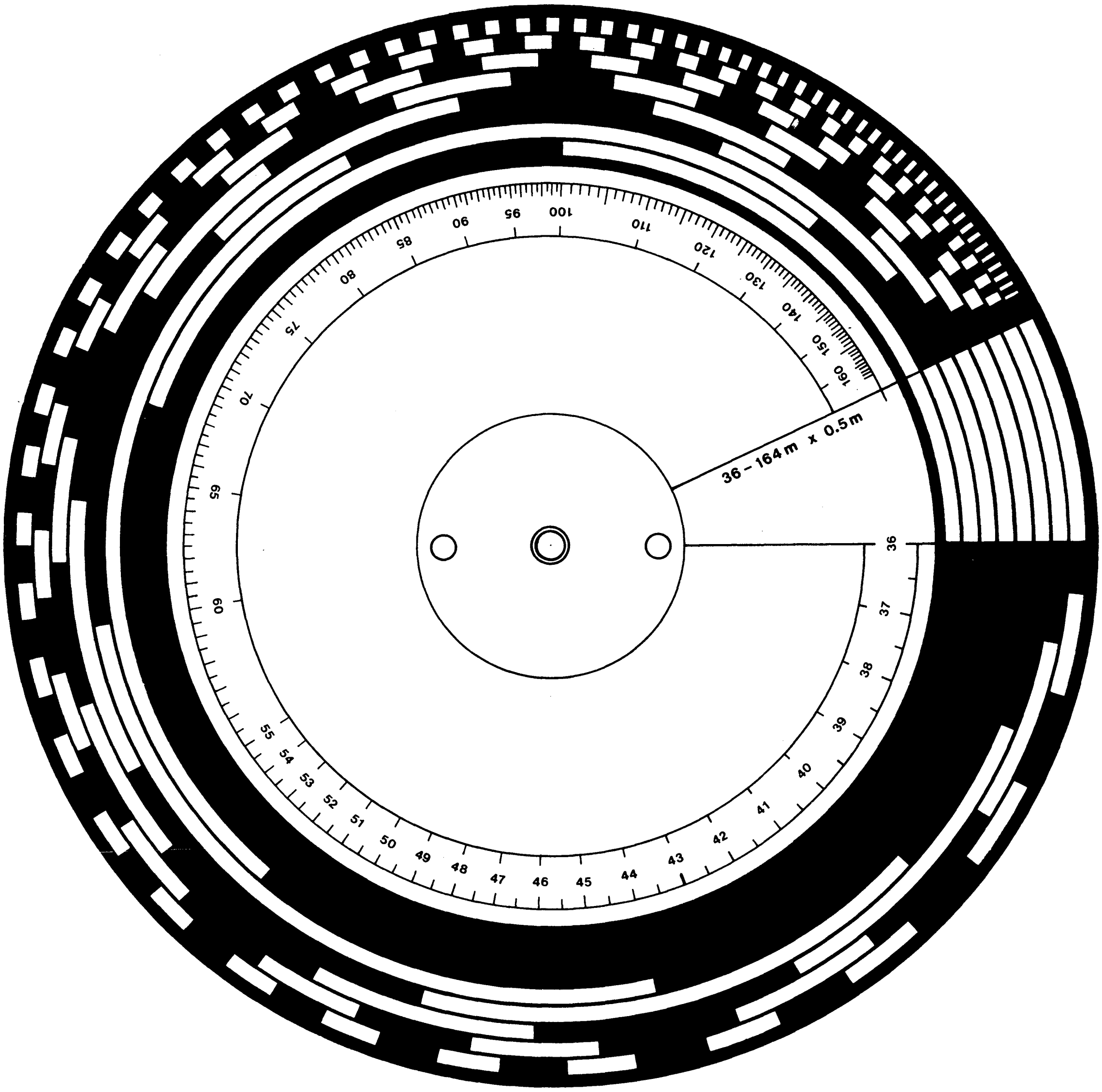

Figure 3. Range encoder disc. The Gray code pattern is nonlinear, to compensate for the nonlinear characteristic of the rangefinder mechanism. The numbered scale is for testing, and was not used for gathering data. An alternative range disc, covering 40–295 m in steps of 1 m, was used for some observations.

frame of the ornithodolite. Its function was to feed the outputs of the three encoders, one at a time, to the computer, under software control. The photodiode outputs were fed to inverting Schmitt triggers (74C14) to give a sharp turn on and turn off. The Schmitt trigger outputs from each encoder were fed to an eight-bit latch, (74198), and thence to an eight-bit tristate buffer (81LS95). The outputs of the three buffers converged to an eight-bit bus, which was connected to the data lines of port B of the Nascom p.i.o.

Both ports of the p.i.o. were used in mode 3, in which each of the eight data lines can be programmed independently as an input or an output, and the handshake lines are not used. All the lines of port B were used as inputs, whereas those of port A were used separately for various control functions, explained below.

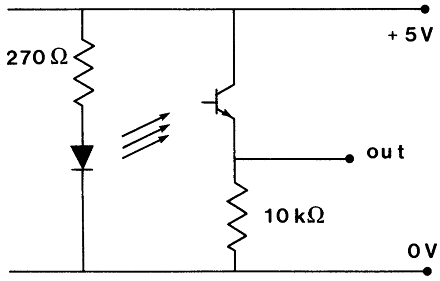

Figure 4. Sensing circuit for each bit of each encoder. The l.e.d. is one element of the Texas LEA13 array, and the phototransistor is one element of the matching LSA13 array.

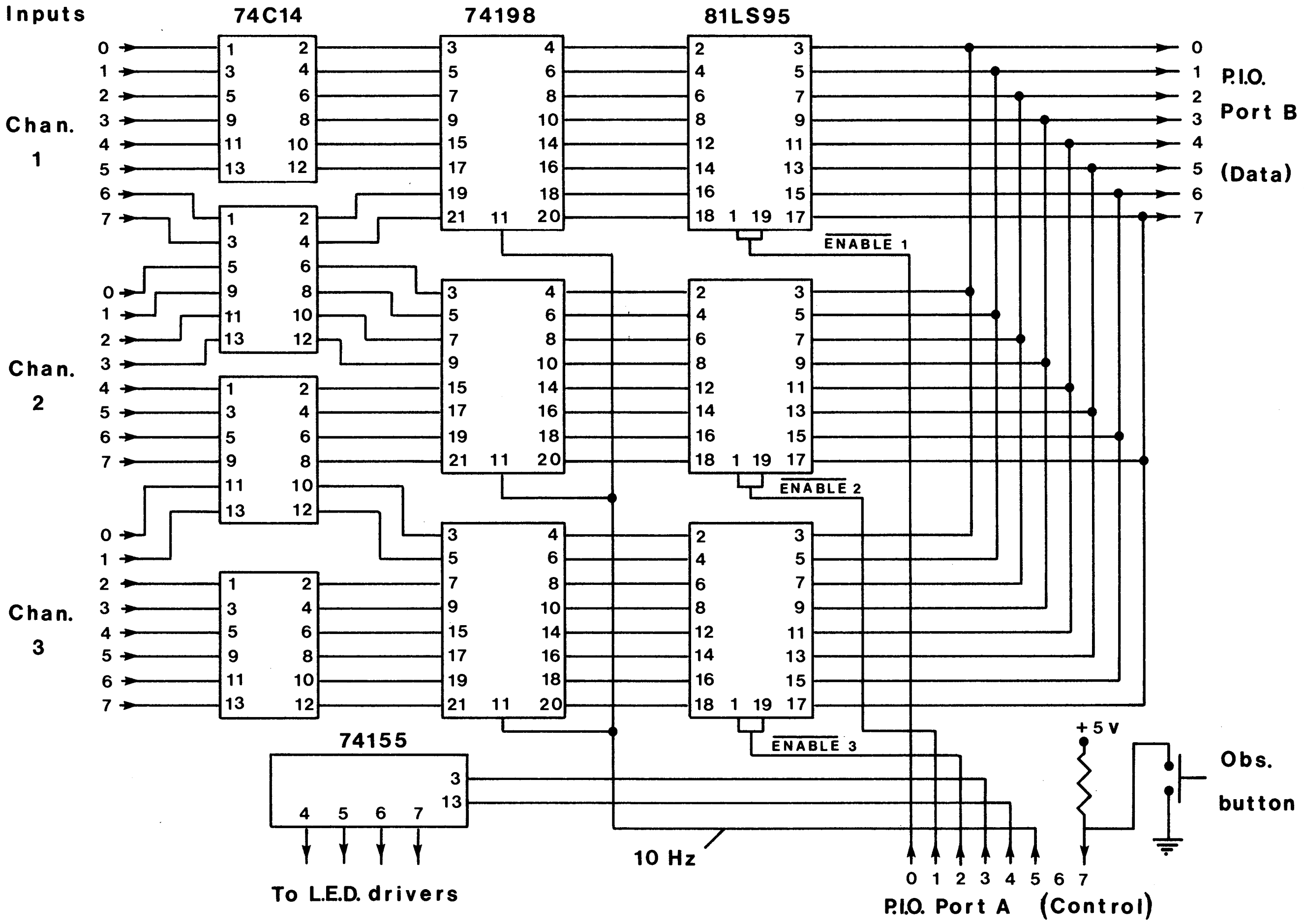

Figure 5. Channel selector circuit (see text).

3. Operation

3.1. *Operating modes*

Two operating modes were used for recording data, three-dimensional for use on land, and two-dimensional for ship-based operation. To each of these corresponded its own print mode, for reading back the data tape and printing out the results. Two further modes provided facilities for setting up and adjusting the encoders, and for checking correct operation in the field.

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All the programs required for the above operations were written in slightly less than 1 K of machine code and recorded in a 2708 EPROM, for which a spare socket was available on the Nascom 1 board. This left the Nascom's somewhat limited RAM free for recording data. The computer had a nominal 1 K of user RAM, some of which was in fact used as scratch pad by the monitor or reserved for the stack, so that around 920 bytes were available in practice.

In all operating modes involving reading data from the ornithodolite, the system was interrupt driven via bit 5 of port A, which was programmed as an input, able to generate interrupts. Interrupts were supplied at intervals of 100 ms from a divider chain of 7490′ s, driven from the 500 kHz signal on pin 14 of IC 1 of the Nascom 1 (ultimately derived from the system clock). The arrival of each interrupt initiated the appropriate interrupt service routine for the operating mode in use (see below). Between interrupts, the computer was in keyboard mode, so that the keyboard could be used at any time to cause a branch to another part of the program.

3.2. *Reading the encoders*

The outputs of the encoders were read into the computer as part of certain interrupt routines. The three encoders were read in turn into port B of the p.i.o., as follows. First, all three outputs were latched by the interrupt signal itself. Then, the three tristate buffers were enabled on to the output bus in turn, being controlled by bits 2, 1, and 0 of port A, which were programmed as outputs for this purpose. Each buffer was read by a READ instruction to port B, so transferring its output to register A of the Z80. This was converted from Gray code to binary, and then stored in RAM.

3.3. *Three-dimensional recording mode*

On entering this mode the register pair HL′ was cleared, and thereafter incremented each 100 ms as the first operation in the interrupt routine. In other words, this register pair acted as a clock, keeping the time from start in units of 0.1 s. As HL′ was a 16-bit register, the maximum time for a run was thereby set at 109 min. This was more than sufficient, although allowance had to be included for time spent waiting for a bird to come within range.

After incrementing the clock count, the next operation in the interrupt routine was to check the status of bit 7 of port A, to see whether the ‘observe’ button was depressed. If not, control was returned to the keyboard, pending the next interrupt. If the button was depressed (*and* if it had not also been depressed on the preceding interrupt), the clock count from HL′ was recorded in two bytes of RAM, and the current values of the encoder outputs in the next three bytes. A pointer to the next available RAM location was maintained in register pair HL, and a count of the number of observations so far in register C. After this, control was returned to the keyboard.

Each observation thus required five bytes of RAM, two for the clock count and one for each of the three encoder outputs. Observations could theoretically be continued up to a maximum of 175, which would have filled the available RAM, although this limit was never approached in practice. On completion of the run, up to 24 characters of text could be entered from the keyboard (used to record species, time of day and wind strength and direction), after which one of three possible branches could be selected from the keyboard. Each of these disabled the interrupts, then took further action as follows.

(*a*) For a successful run, the data were recorded on cassette tape. The record consisted of the run number (incremented each time this branch was used), the number of observations in the run, the text (as entered from the keyboard) and the appropriate number of five-byte groups of observations. The clock count and observation count were then zeroed, and interrupts re-enabled, ready for the next run.

(*b*) If the run was not satisfactory for any reason, it could be aborted, returning to start without incrementing the run number or recording any data.

(*c*) At the end of the session, a dummy run was recorded, with a special 'end of data' symbol replacing the observation count. This was used to terminate the subsequent operation of reading back the tape and printing the data.

3.4. *Two-dimensional recording mode*

Elevation angle could not be measured when observing from a ship, and the elevation encoder was therefore disconnected. Its information channel was, however, used to compensate for the yawing of the ship, which would otherwise have caused errors of azimuth.

This was done with the aid of an old aircraft-type vacuum-driven directional gyro, which was mounted in a box together with the motor-pump unit from an industrial vacuum cleaner, which powered it. The movement of the azimuth ring was transferred to a vertical spindle mounted beside the gyro, by means of a pulley and cord intended for a radio tuning mechanism. The spindle carried an encoder disc similar to that for the angular encoders, except that it was drawn to give a zero reading in the centre rather than at one end. The scale was also expanded to compensate for the effect of the pulley arrangement, resulting in a sensitivity of one division per 0.5° of azimuth, as for the azimuth encoder.

In use, the gyro was set to read zero when the ship was approximately on its mean heading. As the ship yawed, the encoder yielded small positive and negative readings. The interrupt routine read all three encoders as in the land-based mode, then corrected the azimuth reading by adding the output from the gyro-driven encoder, before storing the readings in RAM. Only four bytes of data therefore had to be recorded for each observation, two for the time, one for the range, and one for the corrected azimuth. Apart from this, the two-dimensional mode worked in the same way as described above for the three-dimensional mode.

3.5. *Print modes*

After one or several sessions, the tape was read back and the data were printed. For this purpose a small dot-matrix printer (SWTPC PR-40) was connected to the p.i.o. in place of the ornithodolite. The tape recorder was started and stopped under program control, in such a way as to read one complete run at a time back into the memory locations in which it was originally recorded. The run was then printed out, headed by the run number and text (species etc.) and followed by a list of values of time, range, elevation and azimuth. The program ended when the 'end of data' symbol was found. Two-dimensional and three-dimensional print modes shared most of the same program and differed only in that values for elevation were printed in the three-dimensional mode only.

3.6. *Display mode*

In this mode the three encoders were read at each interrupt, and decimal values were displayed on the t.v. monitor screen. The states of the individual photodiodes were also shown, by displaying the original Gray code outputs, before decoding, in the form of a row of eight zeroes or ones. This mode was used for setting up and adjusting the encoders.

3.7. *Test mode*

Further test procedures were provided for use in the field, to check that the encoders were operating correctly, without recourse to a t.v. monitor. In this mode two spare lines of port A (bits 3 and 4) were used as outputs to drive a two-to-four line demultiplexer chip (74155), and thence four l.e.ds of various colours, which were mounted on the ornithodolite. The encoders were read at each interrupt, and the test worked as follows. One of the three encoders was selected for test, by starting the program at an appropriate point. At each interrupt, the output of the selected encoder was compared with its output at the previous interrupt. If the reading had decreased a red l.e.d. was illuminated, while a green l.e.d. indicated that the reading had increased. Thus, if the instrument were rotated through its full travel in azimuth (say), the green l.e.d. should stay on continuously during rotation from left to right, and the red one when turning the other way. If the green and red l.e.ds went on and off while the instrument was rotated steadily in one direction, this indicated that the numbers were coming up in the wrong sequence. The normal indication could only be obtained if all 256 possible numbers came up in the right order, and was thus a positive confirmation of correct operation.

In addition to this test facility, two further l.e.ds were used for alignment and setting up. A second red l.e.d. came on if the output of the encoder under test was 170 decimal, corresponding to 11 111 111 in Gray code. This could be used as a field check that all eight phototransistors were working. A yellow l.e.d. came on at a reading of 128 decimal (half scale) in azimuth and elevation. This was used to set the reference azimuth on some landmark, whose bearing was then measured with a compass, and to check zero elevation against the horizon. When checking the range encoder, the yellow l.e.d. indicated the maximum reading of 255 decimal, as this was the most convenient reference point for adjusting the encoder.

4. CONSTRUCTION AND POWER SUPPLIES

The ornithodolite head, as shown in figure 1, was mounted when in use on a heavy photographic tripod (Gitzo RA4 with no. 4 head). The channel selector box (figure 5) was mounted on the tilting frame, and its output was fed via a 2 m length of cable to the Nascom 1 computer. The computer consisted of a board measuring 30 cm × 21 cm, which was mounted, together with its power supply circuits, behind a protective aluminium panel in the base section of a small attache case. The keyboard was fitted into the lid. Data were recorded by a Sony TC-44 cassette recorder. During operation the fitted cabin trunk, used for storing and transporting the ornithodolite, was placed beside the tripod, and used as a table for the computer, battery, and tape recorder.

The main power supply requirement was 2.6 A at +5 V. In the interests of portability, this was derived from a 6 V motorcycle battery (Chloride 812, 13 AH) via a series-transistor regulator, which permitted operation down to a battery voltage of 5.6 V. A low-battery warning light was set to come on at 5.8 V, and the observing session was ended when this occurred, usually after operation for 1–2 h. Also tried were 10 AH Varley absorbed-electrolyte batteries (type VPT 6-13/12), but they would only maintain their voltage for a few minutes under load, and were not used in the field. A larger battery of this type would most probably have been satisfactory.

The Nascom 1 also required low-current supplies at +12 and −5 V, to power its EPROMs.

The +12 V supply was derived from the +5 V rail by a small d.c.–d.c. converter module (ASTEC AD1P12A10). A similar convertor was tried for the −5 V rail, but this caused interference which upset the computer. The −5 V supply was eventually derived from a pack of four nickel–cadmium AA cells, monitored by a low-voltage warning which was set to come on at −4.8 V. This proved satisfactory.

5. Wind measurement

When operating on land, and on some occasions at sea, the wind was observed with a Mariner 1 anemometer set. This comprised a sensing unit consisting of a whirling-cup speed sensor and a vane direction sensor (intended for installation on the masthead of a yacht), connected by a 20 m cable to the indicator unit, which was mounted on the ornithodolite. The indicator consisted of a large dial (13 cm diameter) marked in 5° steps, on which wind direction was indicated by a pointer. A two-digit l.e.d. display showed wind speed in knots, to the nearest knot (1 knot = 0.514 m s^{-1}). The speed display showed a steady reading, which was updated at intervals of about 20 s. The instrument required a 12 V supply, which was provided by the ornithodolite's main 6 V battery, in series with a second 6 V battery.

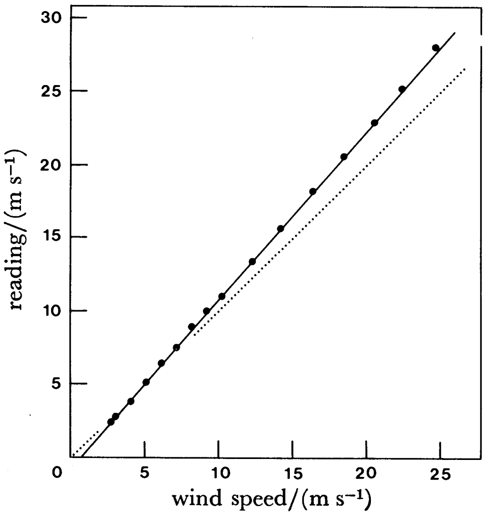
The speed sensor was calibrated against a pitot-static tube and Betz manometer in the 1.1 m wind tunnel at the Department of Aeronautical Engineering, Bristol University. The calibration curve is shown in figure 6. The instrument over-read at wind speeds above 5 ms^{-1}. Readings were converted by multiplying by a composite factor of 0.444, which corrected for the over-reading, and also converted the result to metres per second. The small zero error was neglected.

6. Rangefinder calibration

A test of the rangefinder was carried out at Panama, on a straight section of the causeway road by Perico Island. An observation point at the side of the road having been chosen, five paint marks were made on the trunks of trees on the other side. Their distances from the observation point were measured by repeated use of a 30 m surveyor's tape measure. The range to each point was measured, and recorded on cassette tape, with the ornithodolite as in normal operation. Forty observations were made of each mark, except the nearest, which was measured 20 times. The rangefinder encoder disc in use was the longest-range one, covering 40–295 m, in steps of 1 m. It is assumed that the precision is a function of the range only, and that it would not be affected by the use of shorter-range discs.

The results are plotted in figure 7. The standard deviations are too small to plot as vertical bars, but are shown at the bottom of figure 7, at ten times the scale of the calibration line. The standard deviation of repeated ranging on a static target was found to be about 2.5 m at 100 m range, increasing to about 5 m at 150 m. The bulk of the observations obtained in the South Georgia study were within these limits, being obtained with the range encoder disc shown in figure 3, covering 36.0–163.5 m.

The rangefinder eyepiece was fitted with a ×6 telescope, which had a field of view 7° from edge to edge, both horizontally and vertically. The telescope was not equipped with crosswires, and there was an element of operator skill in keeping the bird centred in the field of view. No means was available to test the precision with which a moving target could be tracked, but it is considered that an angular error of 1° would be typical, and 2° would be extreme. An angular



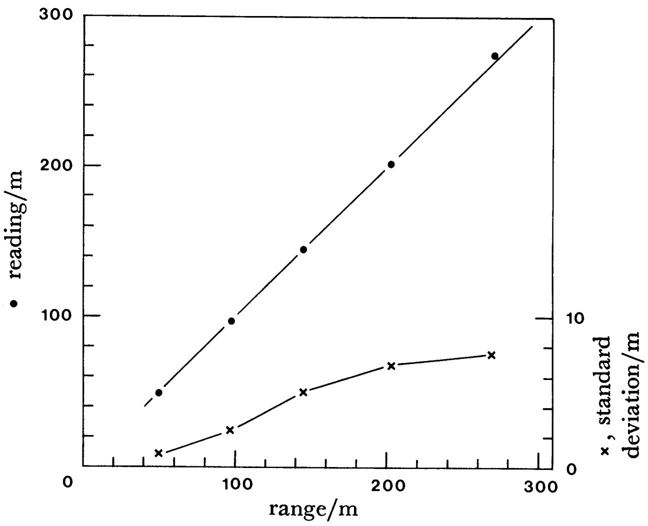


Figure 6. Calibration curve for the Mariner 1 anemometer. The solid line is the regression line, and the dotted line represents 1:1 calibration.

Figure 7. Calibration curve for the rangefinder, made under conditions approximating to those of normal observation (see text). The straight line is the 1:1 calibration line, and ends at the upper and lower limits of the encoder disc used for this test (40–295 m). The lower curve is standard deviation, plotted at ten times the scale of the calibration curve (scale at right).

error of 1.5° would lead to a position error of about 2.6 m at 100 m, which is comparable with the rangefinder error.

While the precision of the instrument was not very high, it is considered to have been well matched to the operational requirement, since it would most probably have been impossible to track a flying bird any more precisely, even if the inherent precision of the instrument were improved.

7. Field experience

The instrument was first used during a six month trip with the British Antarctic Survey (B.A.S.), the results of which are presented in the following paper. Observations were made from the B.A.S. ship R.R.S. *Bransfield*, and on Bird Island, South Georgia, during the southern summer of 1979–1980. The only serious problem was caused by damp on the photoelectric encoder boards. The solder pads connecting to the phototransistors on the backs of the LSA13 boards were very closely spaced, and it was found that the gaps between them could become sufficiently conductive in wet weather to cause interaction between neighbouring phototransistors, so causing encoder errors. The presence of an error was immediately apparent on running the field test routines (§3.7) and it is not likely that any erroneous data were recorded. The trouble was cured by applying silicone water repellent (WD-40) to the backs of the boards. It would probably not have occurred in the first place if the boards had been lacquered after assembly. The Nascom 1 computer gave no trouble whatsoever.

Following the South Georgia trip, the instrument was air-freighted to the Smithsonian Tropical Research Institute, Panama, where it was used in May–June 1980 to observe frigate birds, pelicans and black vultures. It was apparent from damage sustained in transit that the instrument had been very roughly handled, but it was repaired and working correctly within a day of unpacking. One of the 74C14 inverting Schmitt trigger chips failed during use at Panama, for reasons unknown, and had to be replaced, but no other trouble was encountered. The equipment was subsequently air-freighted back to England without further damage.

The above two projects constituted a lengthy and rigorous field trial for an instrument that was previously almost untried. Some 9300 speed observations were collected. The instrument proved robust, reliable, and easy to maintain. It is felt that the principles used in its design can be adapted to a variety of other purposes.

I am deeply indebted to the Royal Society for a Research Investigations Grant, which covered the cost of the equipment described in this paper. I am also grateful to Dr J. W. Flower and Dr R. V. Barrett, of the Department of Aeronautical Engineering, University of Bristol, for their help with calibrating the anemometer. Dr A. E. Copping and Dr L. Burbridge of the Department of Electrical Engineering, University of Bristol, advised me on the design of angular encoders, and kindly allowed me to use their equipment for programming memory chips.

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Appendix

This Z-80 subroutine converts a number in Gray code in register A to its binary equivalent, and leaves the result in register A. The time required is about 350 μs on a Nascom 1 at 2 MHz.

```
00    PUSH BC     C5
01    PUSH DE     D5
02    LD B, 8     06  08
04    LD E, 0     1E  00
06    LD D, A     57
07    BIT 7, D    CB  7A
09    JRZ, 6      28  04
0B    LD A, 1     3E  01
0D    JR, 4       18  02
0F    LD A, 0     3E  00
11    ADD A, E    83
12    LD E, A     5F
13    SRA, A      CB  2F
15    RL, C       CB  11
17    DJNZ, 4     10  02
19    JR, 6       18  04
1B    SLA, D      CB  22
1D    JR, −16H    18  E8
1F    LDA, C      79
20    POP DE      D1
21    POP BC      C1
22    RET         C9
```