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Digital Techniques Used in the Steering Apparatus of the GPO Steerable Aerial at Goonhilly Downs*

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A description of the logic design for the digital control equipment is followed by further descriptions of items of particular interest. The means of applying off-sets to the demanded aerial position for overcoming possible inaccuracy of the predicted orbit; and to demand accurately determined velocities manually; means of conversion from pure binary form to provide displays in terms of angles, and the derivation of analogue voltages for the servo-amplifiers are discussed in detail.

A critical analysis of the equipment in the light of operational experience concludes the paper.

AUTHOR

The prime function of the digital control apparatus was to position the steerable aerial in both azimuth and elevation axes in response to information on a punched tape. Due to the need for efficient use of the tape a system of linear interpolation over 200 millisecond intervals was used. The digital equipment performed the interpolation process and calculated the angular position error signal fifty times per second. Actual positions were determined by an optical Gray Code shaft encoder, suitably decoded, and applied to the error arithmetic unit.

Displays were provided showing aerial position, the angle demanded by the tape, control clock time, and the angular corrections which might prove necessary to cancel out inaccuracies of the predicted trajectory. The other requirements of the digital apparatus were to provide accurate velocity signals, set manually, and to produce punched paper tape records of aerial performance. Further signals, concerned

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with the GPO communication equipment, were recorded on the same tape via a digital data logger.

SYSTEM DESIGN

Design Parameters

The following parameters were given:

1. A sample rate of fifty times per second.
2. Accuracy of digital equipment from tape reader to error better than two minutes of arc.
3. A ten volt range in analogue voltages corresponding to ± 42 minutes of arc error.
4. A standard frequency source of 2 kilocycles per second.
5. Tape information.

Items 1, 2, and 3 were determined by the servo design. Item 4 was a GPO standard. Item 5 will now be discussed in greater detail.

Control Tape Information

The tape information is given in cycles of a second duration. The demanded azimuth and elevation angles are stated in full form once per second.

Increments to be used for linear interpolation are stated in the following form: each increment corresponds to one tenth of the change in position over 200 milliseconds. There are five such increments for each axis. Each increment is used ten times, making—in all—fifty calculations per second of demanded angle, for each axis.

As the information is renewed once per second any errors occurring in the arithmetic can not endure longer than part of a second. A code identifying the tape is stated once per second. Information corresponding to the aerial gain appropriate to the range of the satellite is given once per second.

Standard resistor-transitor printed circuit logic elements are used througohut. This paper is concerned with the use of logic elements—the electronic design of each element used principles treated in detail in the literature.

Waveform Generation

It is convenient to use the standard 2 kilocycle signal to define the digit periods directly. The waveforms are derived by division of the 2 waveform, and subsequent groupings using AND gates (Fig. 1).

Each digit period is divided into four non-contiguous phases. The

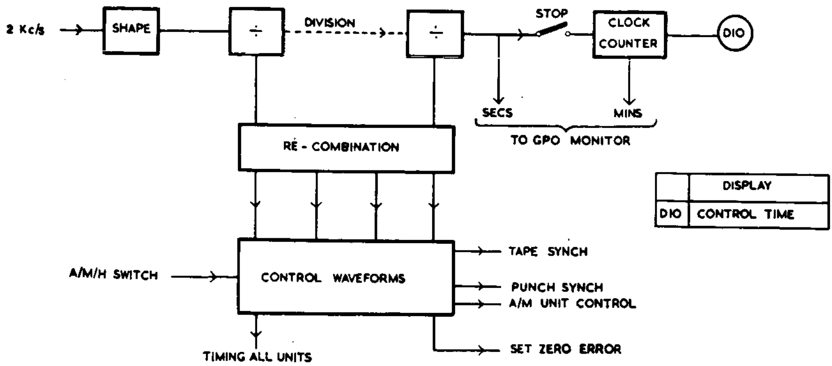

Fig. 1 — Control diagram.

phase waveforms are used as strobes to avoid spurious spikes caused by the AND operation on adjacent edges — this is an established technique.

Operational Mode

In order to obtain the greatest reliability pure binary serial arithmetic is used for the interpolation and error calculation. The use of serial arithmetic requires serial to parallel conversion for error and tape punching. This is accomplished by the use of shift-registers. The only parallel conversion occurs in the Gray to Binary Conversion of the actual position transducers. Simple serial decoding would result in the most significant digit being produced first in time which is inconvenient for the subsequent arithmetic operations.

Peripheral Equipment

Logic design for tape reading and tape punching are well established, and will not be treated here in detail. The decoding techniques for the mechanical encoders used for correction and velocity increments is described in detail later.

Accuracy

The accuracy of two minutes of arc of the digital system is made up of several parts.

1. The accuracy of the shaft encoder.
2. Rounding errors in the arithmetic.
3. Drift in the digital to analogue converter.

The order of 1 and 2 are approximately the quantum step chosen and 3 can be improved by technique. The choice of a 16 bit system; i.e., 216 quanta equivalent to 360° of arc gives a quantum size of 19.77 seconds of arc. This value enables the design figure of 2 minutes to be improved upon under normal circumstances, and leaves error in hand, so to speak, for the rest of the control design.

For accurate interpolation it was necessary to specify the incremental information on the control tape to $2^{-20} \times 360°$, the difference in accuracy of the resultant demanded angle and the 16 bit accuracy of actual position is referred to above as rounding error.

SYSTEM DIAGRAM

The final realisation of the requirements is shown in Fig. 2. The functions of each black box will be described briefly and the more interesting aspects will be treated in detail.

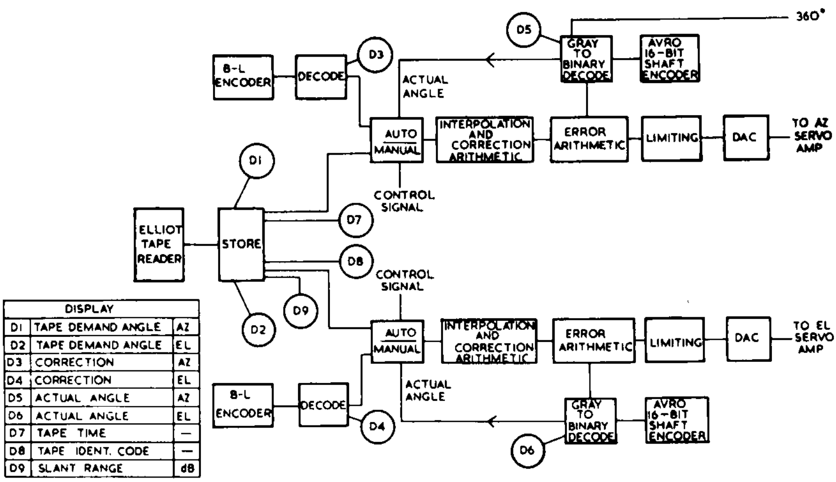

Fig. 2 — System diagram.

Tape Reading

The control tape advances one cycle once per second in response to a control signal. This control signal occurs only when the following conditions apply.

When there is coincidence between the control clock and the last time read from the control tape.

When switching from manual to automatic operation so that the store can be "primed" with sensible information.

After the absence of one time coincidence to prevent the reader stopping in the event of a single misread or mispunch. (This is extremely rare of course).

Tape Store

The data from the tape-reader occurs in sets of four parallel digits, the other track of the five track tape being used for synchronisation. Each set of digits is routed, using gating logic derived from counting rows, into an appropriate store.

Correction Logic

A mechanical encoder with a control knob on its input shaft at the control desk is used to derive parallel signals to be used for correction when on AUTOMATIC control. The same parallel signals are used as increments of position for MANUAL control. The mechanical shaft encoder outputs are in coded form to minimise ambiguity of readout. A decode unit converts to parallel signals representing signal and magnitude.

Auto/Manual Unit

The auto/manual unit selects inputs to the arithmetic unit appropriate to the control mode.

On automatic mode the following operations are performed:

From the store are transferred demanded angle at 1 second intervals and increments at appropriate times to the arithmetic units.

From the correction logic the parallel signals are transferred fifty times per second in serial form to the correction arithmetic.

On manual mode the sequence is:

On first switching use actual angle as initial demanded angle.

Use the correction signal as an increment to be added fifty times per second—this will give rise to a uniform velocity; in order to maintain smooth minimum velocity the significance of the parallel digits is reduced by a factor of 2^{-7}.

Interpolation and Correction Arithmetic

The interpolation arithmetic performs the function of adding each tape demanded increment ten times to the accumulated angle. The value of the increment is renewed five times per second. On manual control the increment remains at a constant value until the encoder shaft at the desk is turned. To avoid ambiguity due to sampling the parallel output while rotating the shaft, a 50 microsecond sampling interval is used.

While the correction signals are used for manual velocity setting their use as corrections as used on "auto" are inhibited.

Error Arithmetic

The difference between the actual and corrected accumulated angles is calculated in the error arithmetic. Negative errors are prefixed by a bar digit.

Limiting

As the range of errors is small compared with a full revolution the digital input to the DAC (Digital to Analogue Conversion) is limited. In the event of a large error the appropriate end limit of the DAC is demanded. This enables the DAC to have a sensible dynamic range.

Digital to Analogue Conversion

The limited parallel digit signal is transferred 50 times per second into the DAC and a signal of ± 5 volts about a $+5.0$ volts level is produced. This is appropriate to an error range of ± 42 minutes or approximately (± 128 quanta).

Shaft Encoders

Avro Sixteen-bit gray-code shaft coders are connected to each axis. These encoders have their own amplifiers which apply signals to the coaxial lines from the aerial site to the steering apparatus room. As the azimuth motion exceeds 360° a signal indicating positive rotation beyond due south is derived from a trip switch. This signal is combined logically with the 180° encoder track signal to produce the digit of significance $360° \times 2°$ when a full rotation has taken place. This digit is referred to as the 17th bit.

Gray to Binary Decoder

The gray to binary decoder converts the sixteen parallel digits from the encoder to pure binary form and adds on the 17th bit where appropriate.

On elevation of course the 180° track would not normally be used as the maximum rotation is only 100° of arc, but for reasons of compatibility the full information is used. The azimuth and elevation channels are made as identical as possible to make testing and fault finding straight forward.

Displays

The displays shown on the diagram are situated on the control desk with the exception of the slant-range db display which is on the beam swingers console. The derivation of all desk displays is considered in detail later. The slant range display is derived from an accurate dc voltage produced by a digital to analogue converter.

CONTROL TAPE READING SCHEME

The control techniques for operating the Elliott high speed tape reader have been described elsewhere. A buffer tape reader was used in order to maintain a loop at the input to the high speed reader. This prevents snatching of the tape by the high speed reader which would give rise to reading errors.

RECORD TAPE PUNCHING

The information to be punched once per second is as follows:

1. Time in hours, minutes, and seconds;
2. Demanded angles at start of second;
3. Error in full form at start of second;
4. Tape identity code;
5. Applied correction; and
6. Data derived from the data logger.

Items 1 and 2 endure for a second and need not be stored again. Items 3, 4 and 5 occur for less than one fiftieth of a second and are stored. The data logger information is held in a store until punching has occurred.

The punch drive scheme was the one recommended by the manufacturer.

The record punch was used on manual operation; also this enabled a check of the equipment to be made conveniently.

LOGIC TECHNIQUES

Much of the logic design uses well established techniques. While no novelty is claimed for the items which are now described, it was considered that they are sufficiently interesting to be described in further detail.

Design of Interpolation and Error Arithmetic

With reference to Fig. 3 it will be seen that the demanded angle accumulator is a 24-bit shift register. The most significant digit is the one referred to as the 17th bit, the next 16 in significance are the digits appropriate to the 16 working bits, and the remaining digits are necessary to prevent coarseness of demanded angle after the addition of several increments.

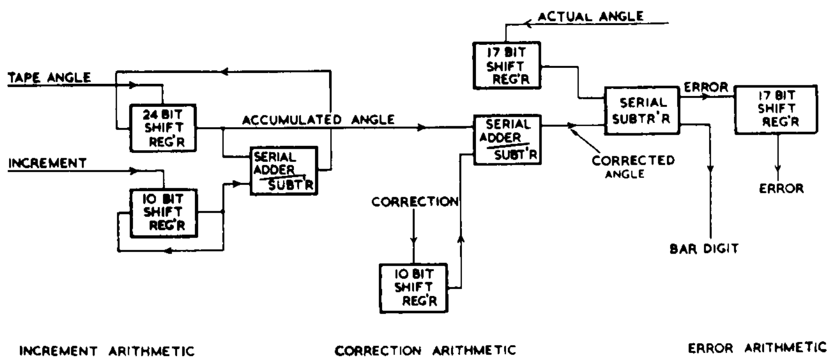

Fig. 3 — Arithmetic scheme.

The 10-bit shift register recirculates to preserve the increment value for succeeding additions. The result of adding or substracting increments to the demanded angle via the add-subtract unit is recirculated into the 24-bit accumulator. The serial accumulated angle has added to it the correction which has been converted to serial form in the shift register shown. The resultant angle is the complete demanded angle.

The actual angle serialised after the Gray to Binary conversion is subtracted from the demanded angle in a subtractor and the result stored in a 17-bit shift register and used in parallel for the digital to analogue conversion.

Logic (not shown in the diagram) inspects the magnitude of the 17-bit number stored in the shift register. If it is less than ± 128 quanta digital-to-analogue conversion takes place and produces an error analogue for normal control of the aerial. If the value exceeds ± 128 quanta but is less than ± 256 quanta limiting occurs in the

DAC as described above. If the value exceeds ±256 quanta protective logic causes the aerial to ignore this gross error condition and to coast for one or two seconds after which emergency stopping action is initiated if the gross error still persists.

Techniques for Generating a Parallel ten-bit Bi-polor Number

As it is impossible to predict the trajectory of a satellite, during the initial orbits, to great accuracy it was necessary to enable corrections to be made to the predicted angles on the control tape.

Any errors in the predicted time of arrival can be corrected in advance the actual launch time then being known, by advancing or retarding the control lock by means of switches on the control desk as shown in the control logic diagram Fig. 1.

The correction signal is generated digitally in terms of sign and magnitude for the following reasons: convenience of calculation in the arithmetic, and convenience of display generation.

The two shaft encoders for each motion consisted of an 8 bit gray fine-encoder and a binary encoder which had lagging and leading contacts to overcome ambiguity of read-out due to the gear-box between the encoders. The fine encoders were driven by hand control knobs, one for each motion, on the control desk (Fig. 4).

The encoders were capable of generating a 12-bit parallel number. The 10 least significant tracks were used for the ten digit number and th most significant track for sign. The other track was not used, but was an alternative sign track should it be needed.

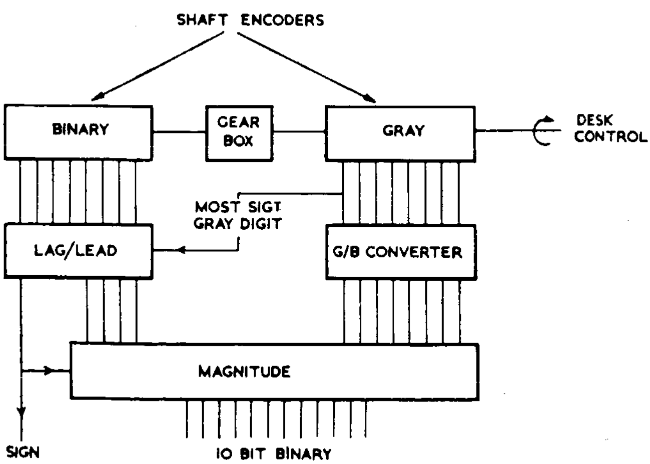

Fig. 4 — Binary code converter.

In this form, of course, negative numbers will not be correctly represented, but by inverting the ten least significant digits when the first track indicates a negative sign (0 for negative, 1 for positive, say) it is possible to approximate to negative numbers, the inaccuracy being one quantum. However, there is an advantage in retaining the accuracy of negative magnitudes in this form as the representation of zero is now two quanta wide. This is convenient as it allows the zero correction to be set more readily. This is also important on manual control where the 10-bit number is used, with the significance of the digits reduced, to produce a velocity signal by accumalition of equal increments. It enables zero velocity to be obtained and held with greater reliability.

As the display of correction was to the nearest minute it was necessary to provide an additional indication of true zero. This was achieved by surrounding the display "zero" with a "green-field".

Means of Obtaining Displays

Elevation and Azimuth Applied Correction Display

The display logic converts two 10-digit binary numbers into degrees and minutes. Angles up to a maximum of 5 degrees are converted and displayed at intervals of 0.5 second. A simplified diagram of the system is shown in Fig. 5.

System Outline

A negative pulse sets the binary counter B and the degree and minute counter D to zero and at the same time a positive pulse puts the input binary number into stores S1. A start pulse sets the binary output F to "1" allowing 4 Kc/s pulses to pass through the gate G into the binary counter B and through M into the degree and minute counter D.

When a binary number counted in B and the input binary number stored in S1 are identical, the output from the coincidence logic C becomes "0" resetting the binary output F to "0". This inhibits the input gate G preventing any further count. A positive pulse transfers the completed count in the degree and minute counter D to the stores S2 leaving the system free to make the next conversion. During the next conversion the angle stored in 4, 2, 2, 1 code in S2 is decoded by amplifiers A and displayed as illuminated figures.

The binary to minute conversion is obtained by running counter D slightly less than three times slower than counter B. The minute converter M gives an output minute pulse for every three input pulses except for the 10th minute pulse and every subsequent 29th minute pulse which require four input pulses each.

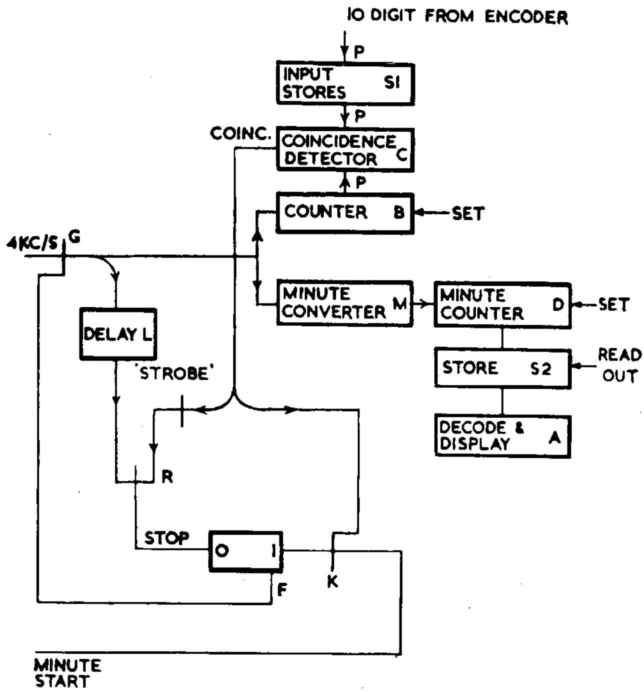

Fig. 5 — Display logic for azimuth and elevation correction.

In the special case of zero binary input the coincidence logic output would be "0" as soon as B had been set to zero. This would not prevent F from going to "12" and a maximum count being obtained. To avoid this the "0" on the coincidence logic is used to prevent the starting pulse from passing through gate K. The edges of the square waves applied to the coincidence logic C from the binary counter B have finite rise and fall times. Because of this there is the possibility that spurious coincidences could occur at the edges of these waveforms. These momentary coincidences would result in negative spikes from the coincidence logic C.

The spikes are prevented from passing through the gate R by strobe pulses which are obtained by delaying the 4 Kc/s pulses at L. The delay time is cut such that strobe pulses are at "0" whenever a spike is present.

When the display reads 0° 0′ the correction signal may be one or two binary digits causing a slow drift on manual control. The outputs of the three zero amplifiers and the zero outputs of the stores for the two least significant input digits are connected to a 3 gate. When all the inputs to the gate are 1, the output is a 0; this inhibits the sign amplifiers and gives a 1 on the input to an amplifier whose output is connected to the display. This gives a green field in place of the + or − sign on the display indicating that the manual correction is at true zero.

Elevation Readout

The elevation logic converts a 15 digit binary number into degrees and minutes up to a maximum of 100 degrees. The conversion is repeated at one second intervals.

The conversion is done in two stages:

1. The four most significant binary digits are counted; each unit representing an angle of 11 degrees 15 minutes.
2. The remaining 11 binary digits are converted using the method described under Applied Correction Readout. A simplified diagram of the system is shown in Fig. 6.

System Outline

A positive pulse puts the binary input number into stores S1, S2 and at the same time a negative pulse sets the counters B1, B2, M and D to zero. A positive pulse starts the degree counter which for each single pulse into B2, counts 11 pulses into D via "or" gate B, and 15 pulses into M via "or" gate A.

When 60 minute pulses have been counted in M the degree pulse carried over to D is delayed at L1 to prevent it reaching the "or" gate B at the same time as one of the degree pulses from the degree counter. When the binary number counted in B2 is identical to the number stored in S2 the output from the coincidence logic C2 becomes a "0" stopping the degree counter.

Sufficient time is allowed for a full count of 15 in B2 if necessary. A negative pulse starts the minute converter which counts out the remaining 11 binary digits. The minute pulses pass the "or" gate A into minute counter M. After sufficient time has been allowed to complete the conversion a positive pulse stores the count in S3 and S4. The angles stored in 4, 2, 2, 1 code in S3 and S4 are decoded by amplifiers A and displayed by digilites.

The degree output from S4 is taken in 4, 2, 2, 1 code to a digital-analogue converter which drives a meter display.

When M is set to zero a delayed pulse is set up in L. This set is prevented from passing into D by inhibiting the gate G with the set pulse. The set pulse is of longer duration than the delayed pulse.

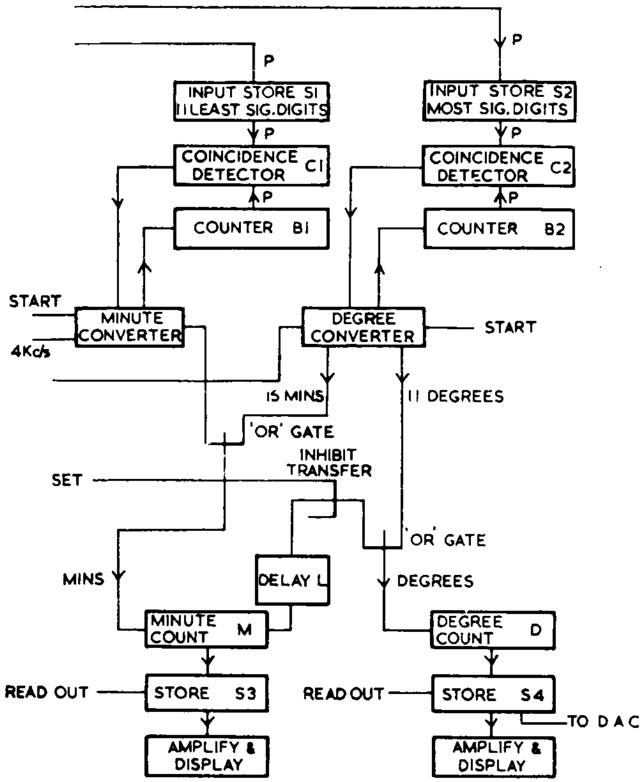

Fig. 6 — Display logic for demanded and actual elevation.

When coincidence occurs this prevents any further count. The degree and minute counters M and D will then contain a multiple of the angle 11 degrees 15 minutes. The minute converter is described under Applied Correction Readout.

Azimuth Readout Tape Demanded and Actual

The azimuth readout converts a 17 digit binary number into degrees and minutes. The angle is displayed in the range ±250 degrees at one second intervals.

The conversion is done in three stages:

1. The binary number 01011000111000111 (250 degrees) is subtracted from the input binary number.
2. The first most significant binary digits are counted, each unit representing 11 degrees 15 minutes, as described under Elevation Readout.

3. The remaining 11 binary digits are converted using the method described under applied Correction Readout.

The last two stages in the conversion are identical to the elevation readout except for the added digit, the subtractor unit and the replacement of the input stores by a shift-register. A simplified diagram of the system is shown in Fig. 7.

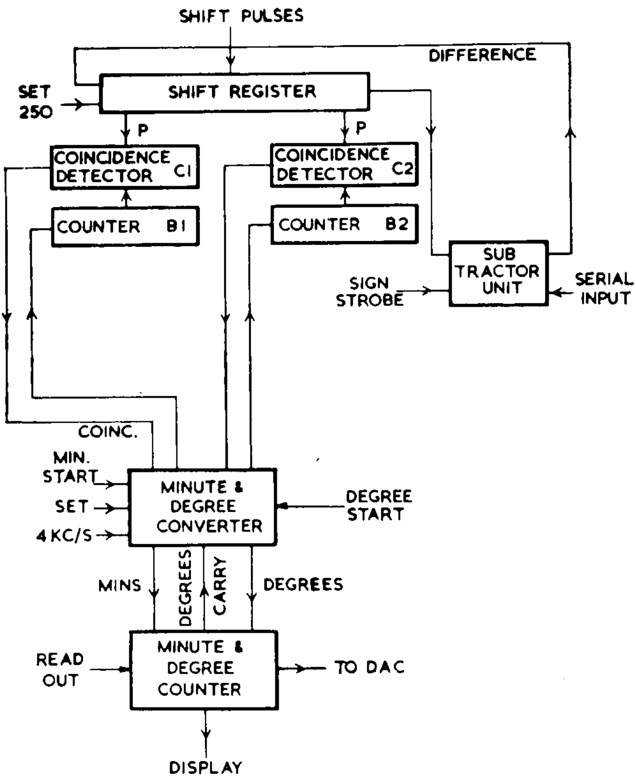

Fig. 7 — Display logic for demanded and actual azimuth.

System Outline

The binary number to be subtracted (250 degrees) is set in the shift register H. This number and serial input are then shifted into the subtractor unit, and the differences replaced in H as it becomes vacated.

When the serial input is greater than 250 the difference (0–250) is positive and is stored in H. The sign from the subtractor is positive.

When the serial input 0 is less than 250 the difference (0–250) is negative. This is recirculated into the subtractor unit and subtracted from the input which is held at zero. The new difference (250–0) is positive and stored in H for the rest of the second.

The binary number in H is converted into degrees and minutes as described under Elevation Readout.

Digital to Analogue Conversion Techniques

The error voltage to be applied to the input of the servoamplifier is in the range 0 to 10 volts, 5 volts representing zero error. This voltage is derived from the output of a summing amplifier of better than 0.1% linearity and drift, which is enclosed in a small constant temperature enclosure—a modular. The input currents to the summing amplifier are derived from a precision voltage source, and precision resistors, also enclosed in the temperature controlled oven. Parallel Transistor switches, with saturated collector-emitter voltages of the digits matches, are driven from stores into which have been transferred the parallel representation of the error. The representation of the error is in bar notation; i.e. the sign digit has significance similar to bar 1, etc. of the familiar logarithm table notation. The error has been generated in this form as it simplifies unipolor switching. In the absence of a bar-digit an input current appropriate to half-scale deflection is applied. In the absence of the least significant digits this is equivalent to zero error.

Full scale positive is produced by energising all switches, full scale negative by all switches being open.

OPERATIONAL EXPERIENCE

A critical analysis of the design of the digital equipment in the light of operational experience would perhaps best be made by others but the following points are worth making.

Re-organisation of tape-format and the need for linear interpolation over 200 millisecond periods could well be investigated further when a full analysis of all likely orbits is made. This would enable longer periods of tape operation and would reduce storage and simplify the logic.

Control under manual operation could be improved by resetting the demanded accumulator angle to the actual angle once per second. This would prevent an occasional gross error from being perpetuated on manual control.

There is insufficient data yet for prediction of future reliability of the digital equipment but the incidence of reading errors and inaccuracies from other sources is extremely low and augurs well for the future.

It is extremely difficult to design digital compensation networks unless the servo parameters are accurately known. Now that the mechanical parameters are well defined it is thought that digital compensation techniques are worthy of further consideration.

CONCLUSIONS

The digital steering apparatus installed at the G.P.O. Radio Station has been described and discussed in detail where it was thought appropriate. This was an example of a digital and analogue servo mechanism of the type where the sample rate was high compared to the bandwidth of the control system. The design of the apparatus was extremely interesting not only for its obvious technical and national interest but for the stimulation it gave to further investigation into the digital control field.

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