An Automated Tracking System for the ARIES Antenna

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A miniprocessor-based tracking system has been developed for the Astronomical Radio Interferometric Earth Surveying (ARIES) antenna. The system is a servo loop in which tracking errors and correction commands are calculated in software.

I. Introduction

An automated tracking system based on a Modcomp II miniprocessor has been developed for the ARIES antenna. The miniprocessor executes a real-time program that calculates antenna position as a function of time and source coordinates entered at a teletype. An error is determined by subtracting the calculated antenna position from the actual position as determined by sensors on the antenna. The error is translated into rate commands, which are sent to the antenna azimuth and elevation motors. An operator may communicate with the program via sense switches and teletype input/output.

II. System Hardware

Figure 1 is a block diagram of the ARIES tracking system. The Universal Time Generator produces 30-bit binary-coded decimal (BCD) Universal Time (UT) and two pulse trains having rates of one and sixty pulses per second. The 1-pulse/s pulses are synchronous with UT, and the 60-pulse/s pulses are synchronous with the 1-pulse/s pulses. These pulses are used as interrupts to drive the real-time tracking program.

The ARIES tracking program is executed by a 16-bit Modcomp II miniprocessor. The Modcomp is configured with 32 k words of memory, a dual digital-to-analog converter (DAC), a teletype, a high-speed paper tape reader, eight Modcomp 1121 digital input ports and five Modcomp 1131 digital output ports.

Modcomp's 1121 input port is a 16-bit parallel transistor-transistor logic (TTL) device. It gates data at its inputs to an internal data bus when the Modcomp executes an input data instruction addressing it. A Modcomp 1131 output port is also a 16-bit parallel TTL device. It will strobe data into an output register when the Modcomp executes a data output instruction addressing it. Data in an 1131 output register will not change until they are over-written by another output data instruction. Neither device is capable of handshaking, and therefore input-output (I-O) synchronization is left to interrupts and software manipulation of I-O ports. In this system, UT input is synchronized by the 1-pulse/s interrupt, and control of the Angle Encoder Interface (AEI), discussed below, requires an 1121 for input and 1131 for control.

A dual DAC develops analog rate signals for the azimuth and elevation motors. Each DAC is a 12-bit device capable of producing voltages in the range ±10 V dc. The DAC pair has a single device address; selection of a particular DAC is via a bit in the data word sent to the pair. In the 16-bit data word sent the pair, bit 0 (the most significant bit) determines the sign of the output voltage, and bit 1 selects the DAC. Bits 5 through 15 contain the digital information to be converted to an analog voltage, and bits 2, 3 and 4 are ignored.

Output voltages developed by the DACs are amplified by operational amplifiers (op amps) and applied to the azimuth and elevation motors. There are no integrators in the system, so it is not necessary for the tracking program to remember the previous commands it sent to the antenna. Antenna motors are geared such that peak output from a DAC will produce a maximum velocity of 0.6 degree/second in either azimuth or elevation.

Antenna position is sensed by four transducers mounted on the antenna. Two of these transducers generate analog voltage equivalents of azimuth and elevation position in fractions of a circle. The remaining transducers produce two switch closures, indicating that the antenna is sensed to be in either the left or right wrap-up region. The switch closures are input directly into an 1121 input port for interrogation by the tracking program.

An NPL Angle Encoder converts the analog position voltages into 18-bit binary azimuth words and 17-bit binary elevation words. Decimal equivalents of binary positions are calculated in the angle encoder and used for display purposes. Analog position data are continuously sampled by the angle encoder, and the binary and equivalent decimal results of analog to digital conversions are stored in four accumulators. Data in an accumulator may be transferred to one of four latching output registers by applying a negative INTERROGATE pulse to the register. INTERROGATE signals are angle encoder inputs; there is one INTERROGATE line for each of the output registers. Data are held constant in an output register until the receipt of the next INTERROGATE pulse.

An angle encoder interface (AEI) was designed to convert 18-bit azimuth words and 17-bit elevation words into a Modcomp 1121 16-bit format. The interface is driven by commands sent via a Modcomp 1131 output port. These commands control the selection of portions of the angle encoder words that are connected to an 1121 input port. Additionally, one bit in the command word is buffered in the interface and connected to the azimuth and elevation INTERROGATE lines. The bit is toggled in software to produce a negative pulse as required by the angle encoder.

Figure 2 illustrates the AEI. The interface is composed of eight 74153 dual four-line to one-line data selectors. The inputs of these gates are connected directly to the binary output registers of the angle encoder. Data selection is determined by two bits in the Modcomp 1131 output port. Note that the AEI separates each angle encoder word into two left-justified 16-bit words with trailing zeros inserted.

III. Software System

The real-time ARIES tracking program was written in Modcomp's Fortran IV using inline assembly code as necessary for driving non-standard interfaces. The paper tape environment of the ARIES Modcomp necessitated developing all software on a disk environment system and transferring the linked object to paper tape. The linked object tape is not stand-alone executable because Fortran calls system services which are expected to be core resident. For this reason an operating system tape must be loaded prior to the ARIES tracking program. The tracking program is loaded and executed via the $EXECUTE command.

The ARIES program is interrupt driven, i.e., most program action is in response to an interrupt. The 1-pulse/s interrupt sets a flag that is tested in the background, and establishes parameters for the 60-pulse/s routine, which is given higher priority than the 1-pulse/s interrupt. In response to a 60-pulse/s interrupt, the program examines current antenna position and sends commands to the antenna. The time when no interrupts are being processed (background) is used for operator communication, diagnostic routines, and calculation of instructed antenna position. The flag set by the 1-pulse/s interrupt routine informs the background that it must calculate a new instructed position.

Calculation of instructed position in the background is necessitated by the non-re-entrancy of Modcomp's Fortran. A decision was made to avoid re-entrancy conflicts and keep the ARIES program a single task rather than to divide the program into several separate tasks.

Although the Modcomp operating system is multi-tasking, the additional core requirements of multiple tasks are prohibitively large for the ARIES configuration. The ARIES Modcomp, being a paper tape system, cannot support real-time program swapping in and out of core; thus the decision to have a single task.

IV. Program Modes

The ARIES program operates in two basic modes. In the tracking mode, the operator inputs the right ascension (RA) and declination (DEC) of a source at the teletype. Program action is to slew the antenna to the azimuth and elevation calculated as a function of time and source coordinates subject to wrap-up and elevation limitations (elevation must be in the range 6.0 deg $\leq$ EL $\leq$ 90 deg). The source is then tracked at the sidereal rate. An on-source message is typed at the teletype when the antenna is positioned within 0.05 degrees of the instructed position. The program endeavors to track with zero error and will inform the operator when the actual antenna position is outside of the 0.05-degree tolerance. Tracking continues until the antenna is stopped or until a new source is entered (see discussion below).

A subset of the tracking mode permits the operator to select a scan procedure. A scan is executed by positioning the antenna a specified offset in azimuth and/or elevation from the source. At a given time, the antenna is swept past the source at a specified rate. Offsets, rates, and start scan times are inputs supplied by the operator.

A local or non-tracking mode is provided in which the operator specifies coordinates in azimuth (AZ) and elevation (EL). In this mode, the antenna is moved to the instructed AZ and EL and stopped. This mode may be used to stow the antenna or position it for maintenance purposes.

An operator may enter new source coordinates, a scan request and scan parameters, position offsets, or request a diagnostic test by a combination of sense switch settings and teletype input-output. Sense switches are used as break points in the program to initiate the input-output routines desired by the operator. Diagnostics are included with the ARIES program that relate to hardware peculiar to the pointing system, e.g., a UT diagnostic, and an angle encoder diagnostic.

Several means have been provided to stop the antenna. Panic stops may be performed via a sense switch. This switch is tested in the 60-pulse/s routine and when set will cause a zero-rate command to be sent to the antenna motors. Antenna motion resumes when this switch is reset. Additionally, each time the operator sets the sense switch signaling the desire to enter new source coordinates, the antenna is stopped. Antenna motion resumes when a new source has been entered. Completion of a scan will also stop the antenna and requires that the operator enter a new source. Finally, should the coordinates of a newly entered source correspond to an elevation below the horizon, the source is checked to determine whether or not it is rising. A rising source will be followed in azimuth and tracked when it appears above the horizon. If the source is determined to be setting, the antenna is stopped and a message typed at the teletype. The operator must then enter a new source.

V. Program Structure

Figure 3 is a simplified flowchart of the ARIES background routine. Several subroutines are called to initialize interrupts and constants, and to check for operator input-output requests. At several points, the background checks a 1-pulse/s flag. This flag is set by the 1-pulse/s interrupt routine to indicate to the background that it must calculate new antenna positions. Variable ISTOP is used as a flag to indicate that a source has been entered. When ISTOP is positive, the 60-pulse/s interrupt routine may move the antenna. Variables ION and ISLEW are used in a software flip-flop to indicate when the antenna is on or off source. When the antenna is off source, ISLEW is set to 1 and ION to 0. The flip-flop is changed when the antenna has moved on source. On and off source is determined by parameters IAZON and IELON, which are set in the 60-pulse/s routine.

Details of the 1-pulse/s routine, ONEPPS, are shown in Figure 4. This routine is entered either by a 1-pulse/s interrupt or by a call from the background routine to calculate new positions. ONEPPS maintains two sets of position parameters. A "current" set describes the antenna position (AZ,EL) and rates (DAZ,DEL) during the current second. A "next" set describes antenna motion and position during the next second (AZN, ELN,DAZN,DELN). "Next" values are calculated when ONEPPS is called from the background routine. When entered by an interrupt, ONEPPS sets the "next values" equal to the "current" values and sets the 1-pulse/s flag.

The 60-pulse/s routine is illustrated in Figure 5. This routine begins by checking ISTOP. If ISTOP is negative, zero rate commands are sent to the antenna. For ISTOP positive, PPS60 reads the actual antenna position and wrap-up conditions. DAZ and DEL are added to AZ and EL to update the instructed position. Commands AZCOM and ELCOM are determined by subtracting the instructed positions from the actual positions. The commands are scaled and AZCOM is adjusted as necessary to compensate for wrap-up conditions. For AZCOM and/or ELCOM less than 0.05 degrees, IAZON and/or IELON are set to 1. Subroutine IFIX is called to change AZCOM and ELCOM to IAZCOM and IELCOM. Although changing floating point numbers to integers is a FORTRAN function, its use would cause a re-entrancy problem. IFIX was written in assembly language and called by a branch and link (BLM) instruction. Finally, IAZCOM and IELCOM are output to the dual DACs.

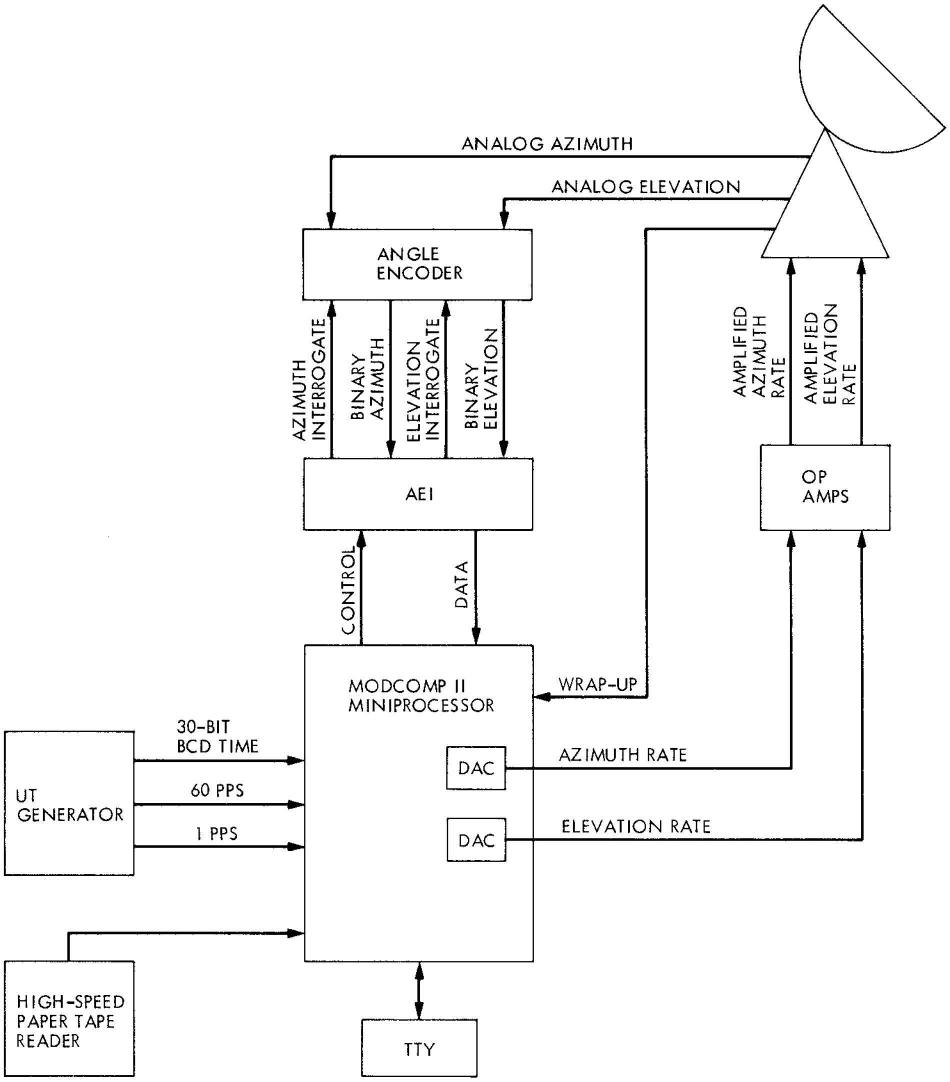
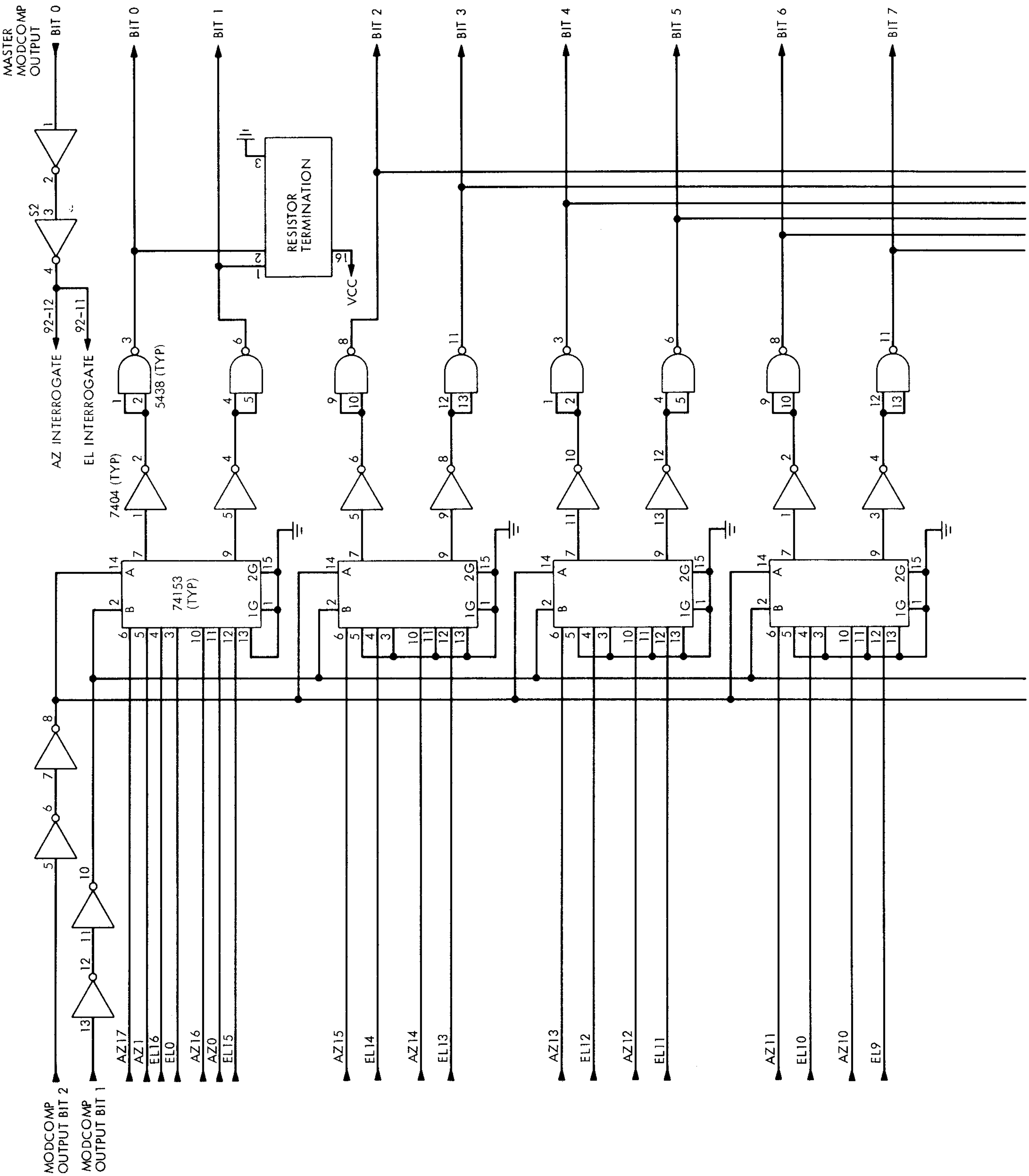


Fig. 1. ARIES automated tracking system


MASTER MODCOMP OUTPUT
BIT 0
BIT 1
BIT 2
BIT 3
BIT 4
BIT 5
BIT 6
BIT 7
S2
RESISTOR TERMINATION
VCC
AZ INTERROGATE
92-12
EL INTERROGATE
92-11
5438 (TYP)
7404 (TYP)
74153 (TYP)
MODCOMP OUTPUT BIT 2
MODCOMP OUTPUT BIT 1
AZ17
AZ1
EL16
EL0
AZ16
AZ0
EL15
AZ15
EL14
AZ14
EL13
AZ13
EL12
AZ12
EL11
AZ11
EL10
AZ10
EL9

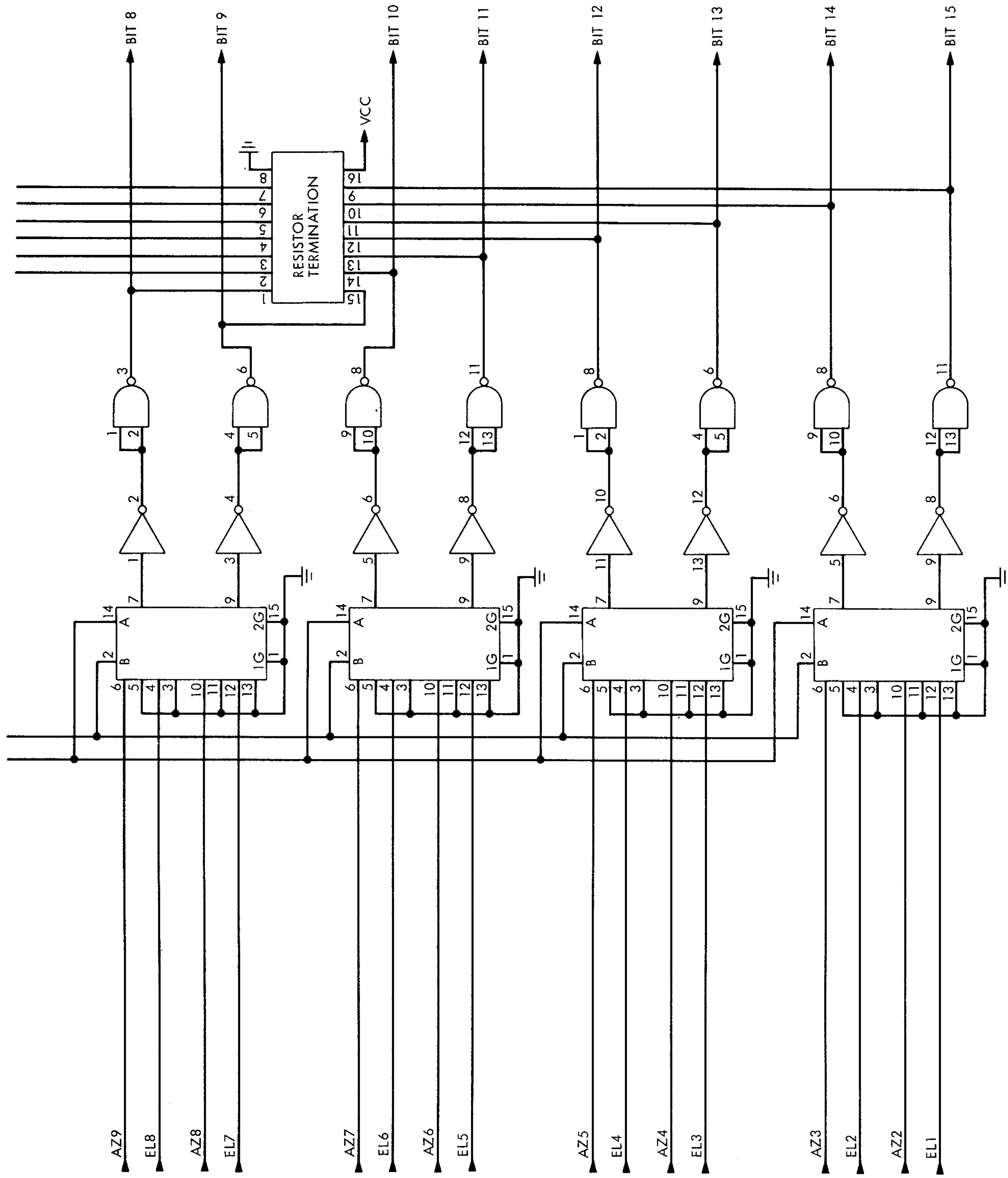


Fig. 2. Angle encoder interface

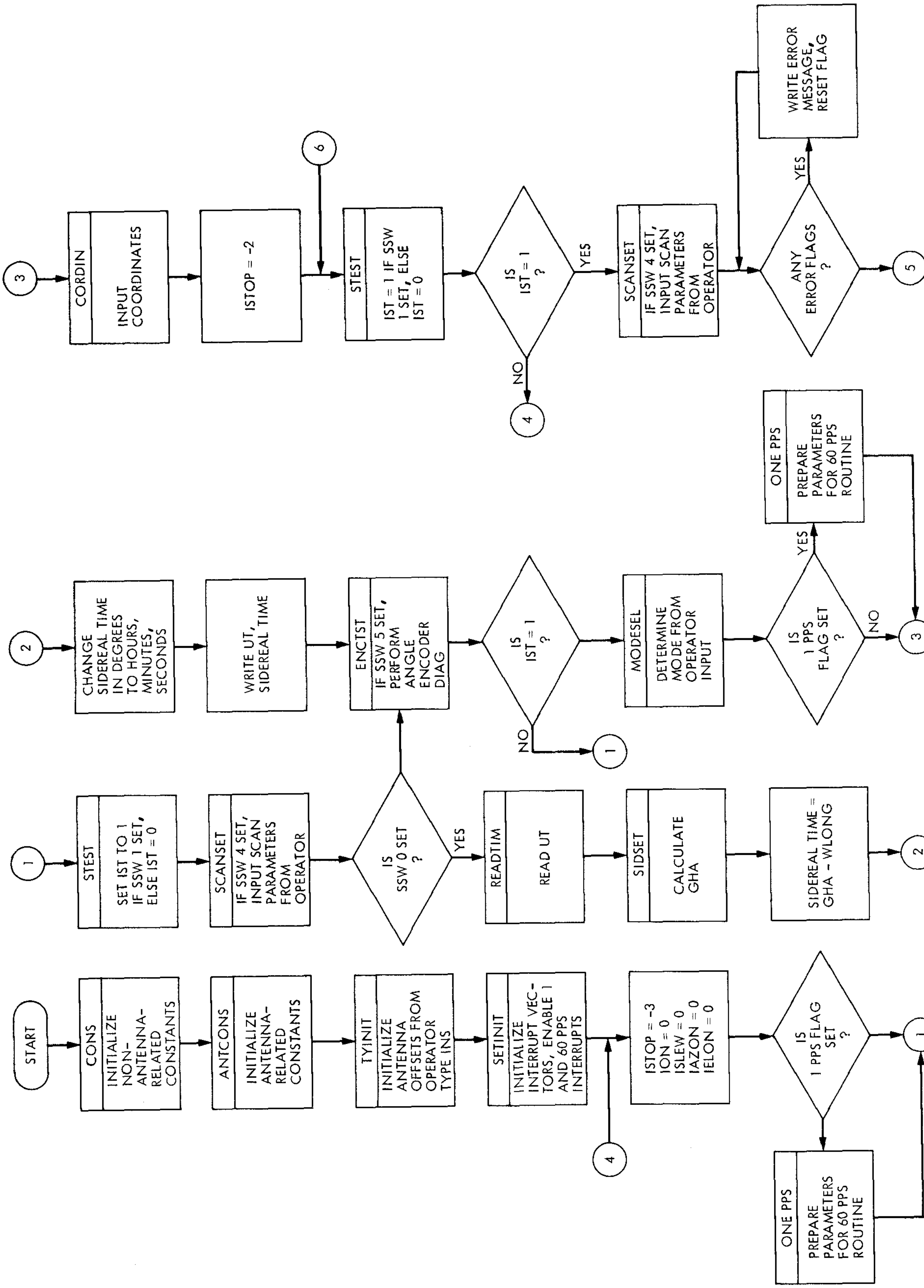


Fig. 3. Background routine

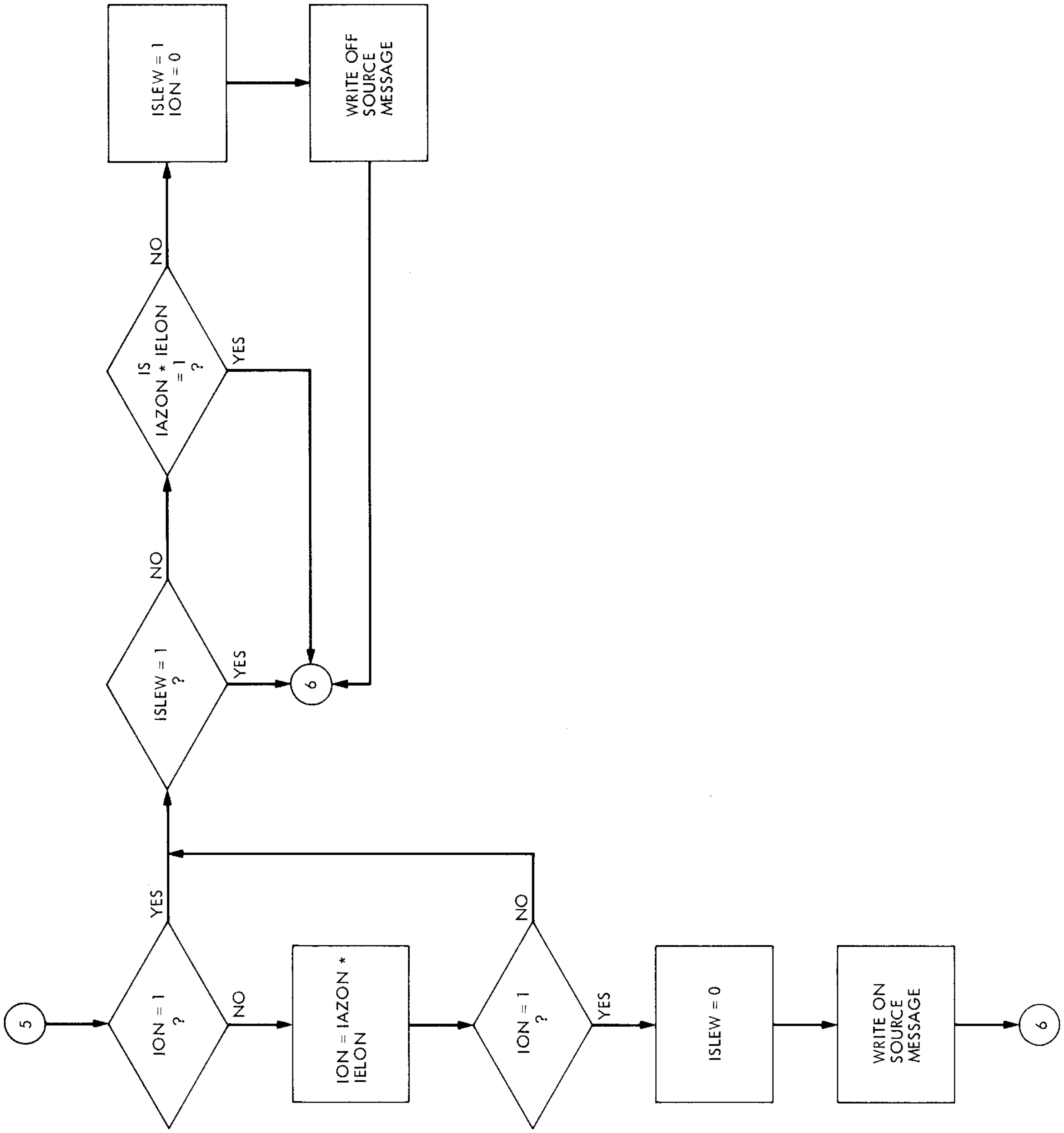

5
ION = 1 ?
YES
NO
ION = IAZON * IELON
ION = 1 ?
NO
YES
ISLEW = 0
WRITE ON SOURCE MESSAGE
6
ISLEW = 1 ?
YES
NO
6
IS IAZON * IELON = 1 ?
YES
NO
ISLEW = 1
ION = 0
WRITE OFF SOURCE MESSAGE

Fig. 3 (contd)

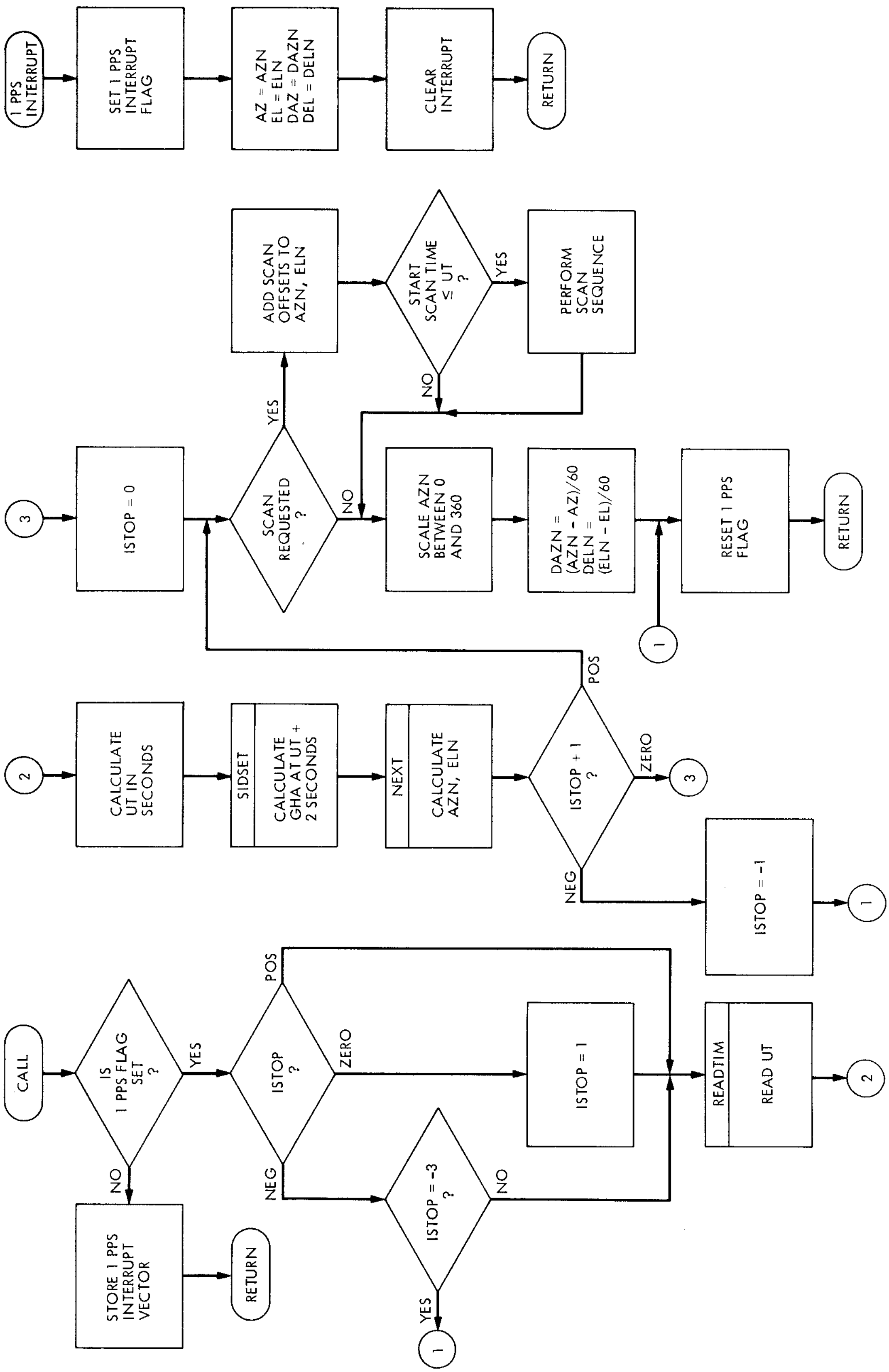


Fig. 4. One-PPS routine

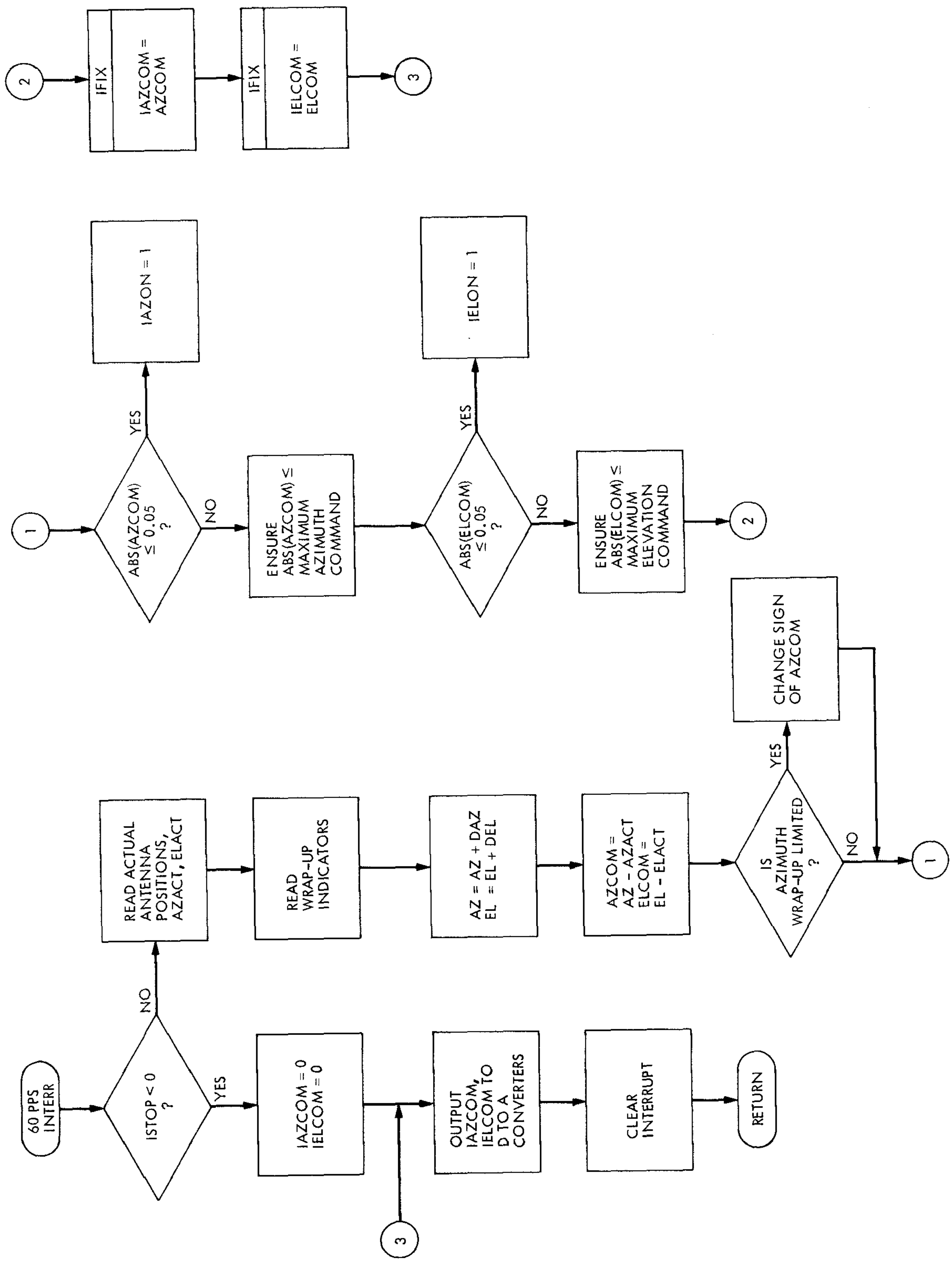


Fig. 5. Sixty-PPS routine

Appendix

Calculation of azimuth and elevation from right ascension and declination requires four subroutines. Subroutine READTIM reads the current UT from the UT generator. The program calculates "next" AZ and EL values for two seconds from the current time. Thus, when the 1-pulse/s interrupt occurs, e.g., at T(0), the values of AZN and ELN which are set equal to AZ and EL were calculated at T(–2), and the values of AZN and ELN calculated at T(0) will be used as the current values at T(2). Subroutine SIDSET, which calculates the Greenwich hour angle (GHA), therefore adds two seconds to the time read by READTIM. The formula used to calculate GHA is GHA = (IDAYS–1) * SOLSID + GHO + TIME* SIDRAT, where TIME is UT in seconds, IDAYS is the day number from January 1, SOLSID is the solar to sidereal constant (= 0.98564540 deg/day), GHO is the Greenwich hour angle on January 1 (= 100.02578 deg for 1975), and SIDRAT is the sidereal rate (= 0.004178074622 deg/sec).

After determining the value of GHA in SIDSET, subroutine NEXT is invoked. NEXT computes the local hour angle (HA) from GHA, RA, and the west longitude (WLONG) of the antenna position; HA = GHA – WLONG – RA. Subroutine CORCON (not shown) is called by subroutine NEXT to perform the coordinate conversions. CORCON uses the following equations:

$$\mathrm{HAR} = \mathrm{HA} * \mathrm{DEGRAD}$$

$$\mathrm{COSH} = \mathrm{COS(HAR)}$$

$$\mathrm{SINH} = \mathrm{SIN(HAR)}$$

$$\mathrm{DECR} = \mathrm{DEC} * \mathrm{DEGRAD}$$

$$\mathrm{COSD} = \mathrm{COS(DECR)}$$

$$\mathrm{SIND} = \mathrm{SIN(DECR)}$$

$$\mathrm{X1} = -\mathrm{COSD} * \mathrm{SINH}$$

$$\mathrm{X2} = \mathrm{SIND} * \mathrm{COSL} - \mathrm{COST} * \mathrm{SINL} * \mathrm{COSH}$$

$$\mathrm{X3} = \mathrm{SIND} * \mathrm{SINL} + \mathrm{COSD} * \mathrm{COSL} * \mathrm{COSH}$$

$$\mathrm{X4} = \mathrm{SQRT(X1 * X1 + X2 * X2)}$$

$$\mathrm{AZN} = \mathrm{ATAN2(X1, X2)} * \mathrm{RADDEG}$$

$$\mathrm{ELN} = \mathrm{ATAN2(X3, X4)} * \mathrm{RADDEG}$$

where

$$\mathrm{DEGA} = \pi/180$$

$$\mathrm{RADDEG} = 180/\pi$$

$$\mathrm{COSL} = \mathrm{COS(ALAT)}$$

$$\mathrm{SINL} = \mathrm{SIN(ALAT)}$$

$$\mathrm{ALAT} = \mathrm{LAT} * \mathrm{DEGRAD}$$

and LAT is the latitude of the antenna position.

CORCON returns AZN, and ELN to NEXT, which then scales AZN to fall in the range $0 \leq \mathrm{AZN} \leq 360$. Subroutine REFR (not shown) is then called to compute the refraction correction to be added to ELN as follows:

$$\mathrm{ZD} = 90.0 - \mathrm{ELN}$$

$$\mathrm{ANUM} = ((\mathrm{P3} * \mathrm{Z1}) + \mathrm{P2}) * \mathrm{ZD} + \mathrm{P1}) * \mathrm{ZD} + \mathrm{P0}$$

$$\mathrm{DEN} = (\mathrm{Q2} * \mathrm{ZD} + \mathrm{Q1}) * \mathrm{ZD} + \mathrm{Q0}$$

$$\mathrm{ELN} = \mathrm{ELN} + \mathrm{RCON} * \mathrm{ANUM}/\mathrm{DEN}$$

where

$$\mathrm{P0} = 0.00010076196$$

$$\mathrm{P1} = 0.00025124078$$

$$\mathrm{P2} = -0.44557132 \times 10^{-5}$$

$$\mathrm{P3} = 0.18838847 \times 10^{-5}$$

$$\mathrm{Q0} = 1.0$$

$$\mathrm{Q1} = -0.022050589$$

$$\mathrm{Q2} = 0.00012174320$$

$$\mathrm{RCON} = \mathrm{P}/760.0$$

$$\mathrm{P} = 657.0$$