

April 25, 1967

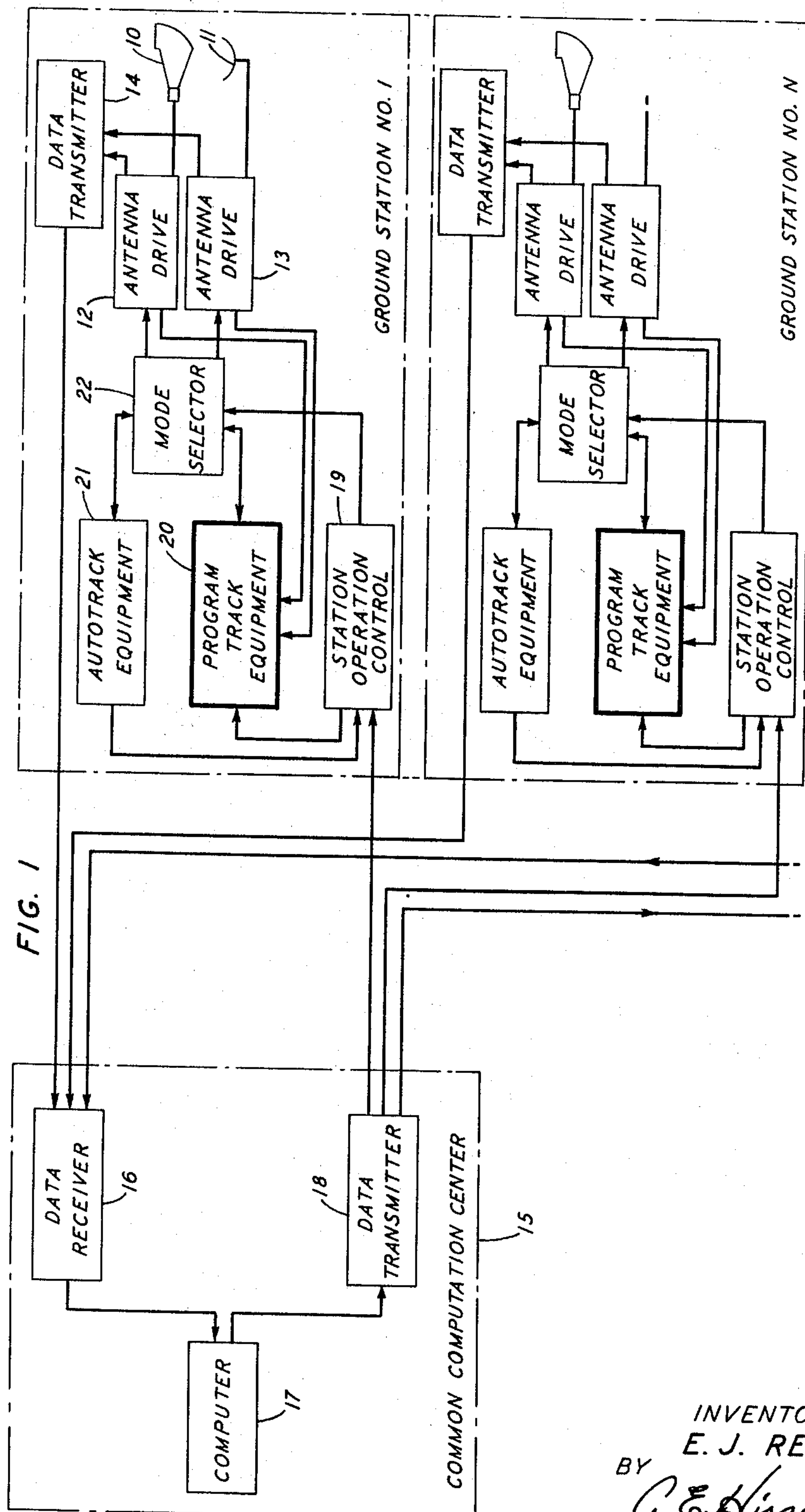
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3,316,552

SATELLITE COMMUNICATION ANTENNA DIRECTION SYSTEM

Filed April 29, 1965

9 Sheets-Sheet 1



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April 25, 1967

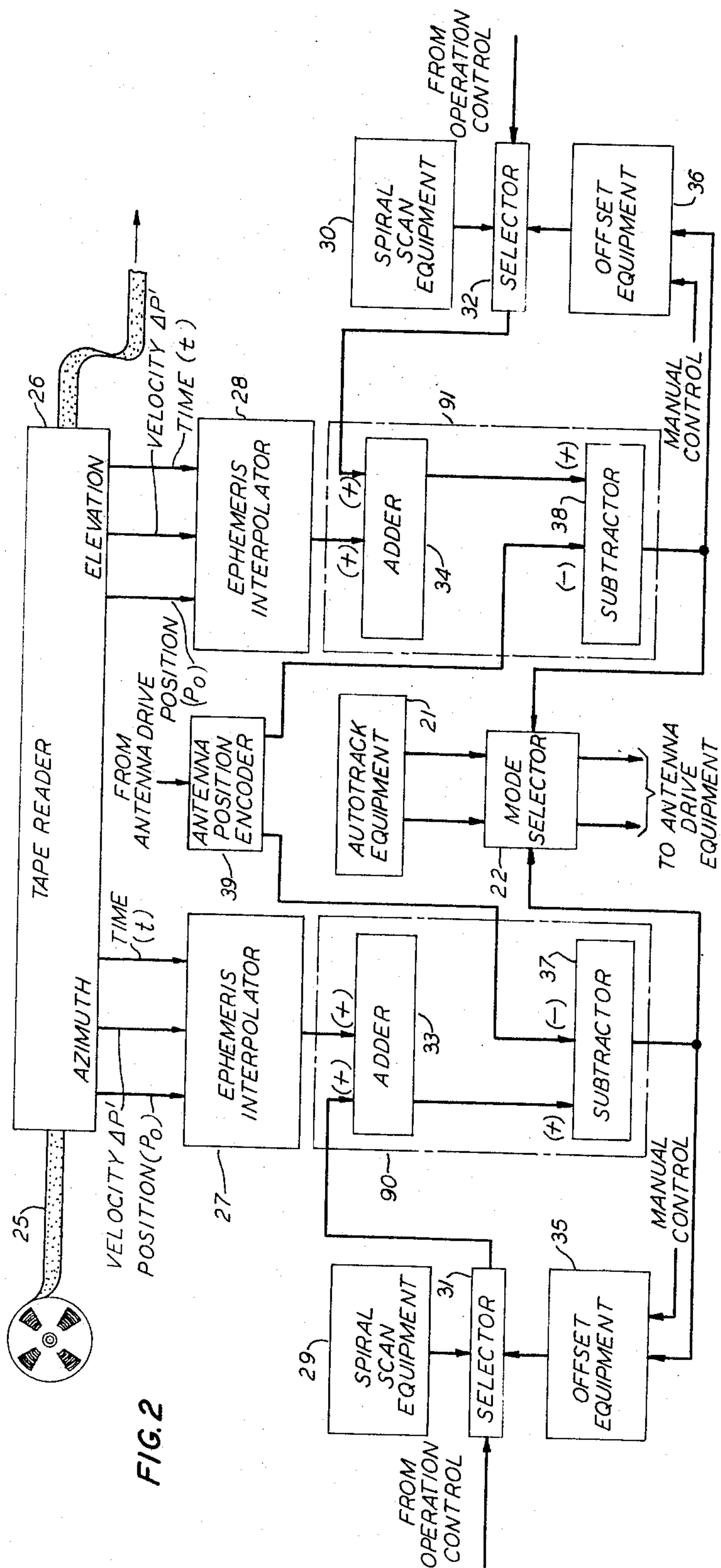
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SATELLITE COMMUNICATION ANTENNA DIRECTION SYSTEM

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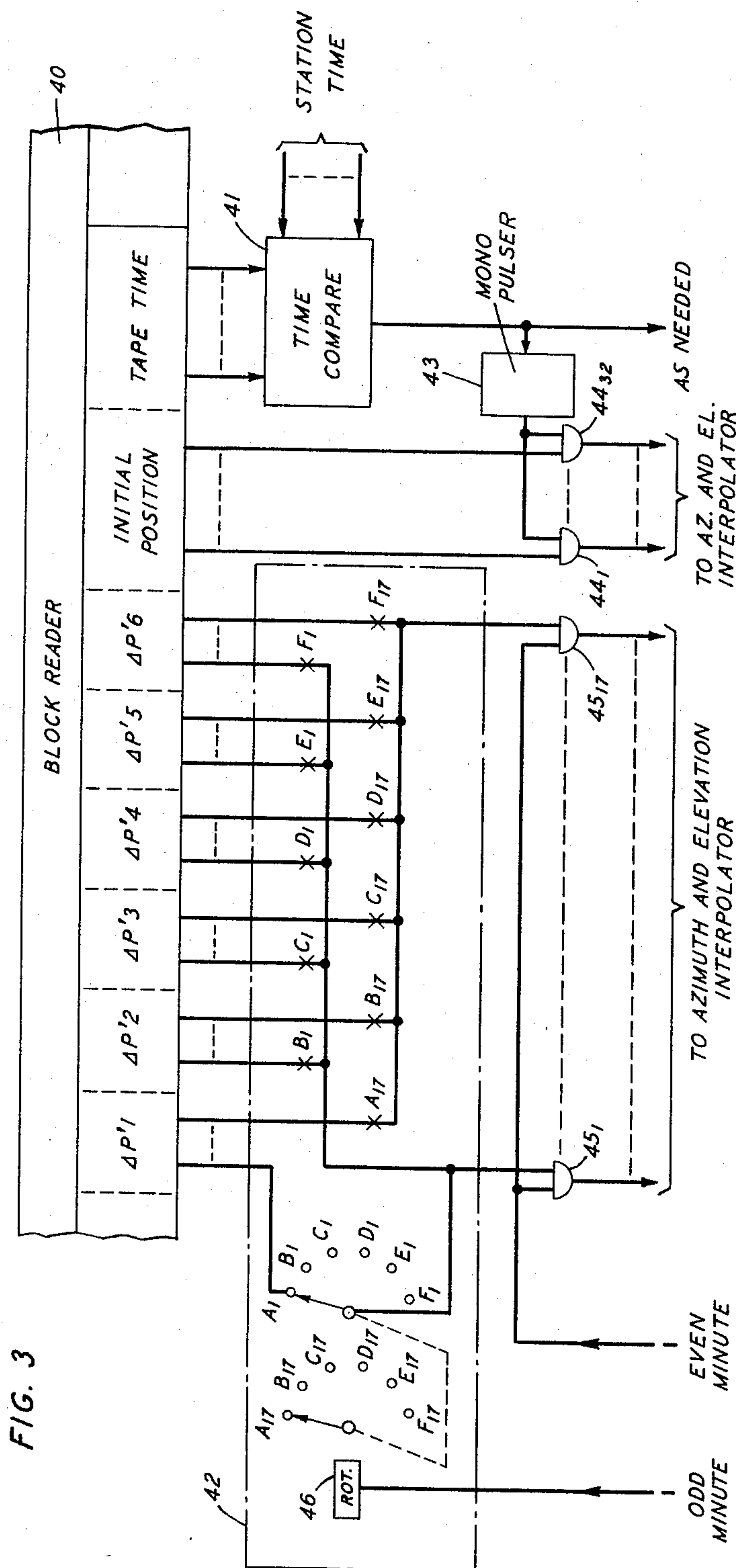
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SATELLITE COMMUNICATION ANTENNA DIRECTION SYSTEM

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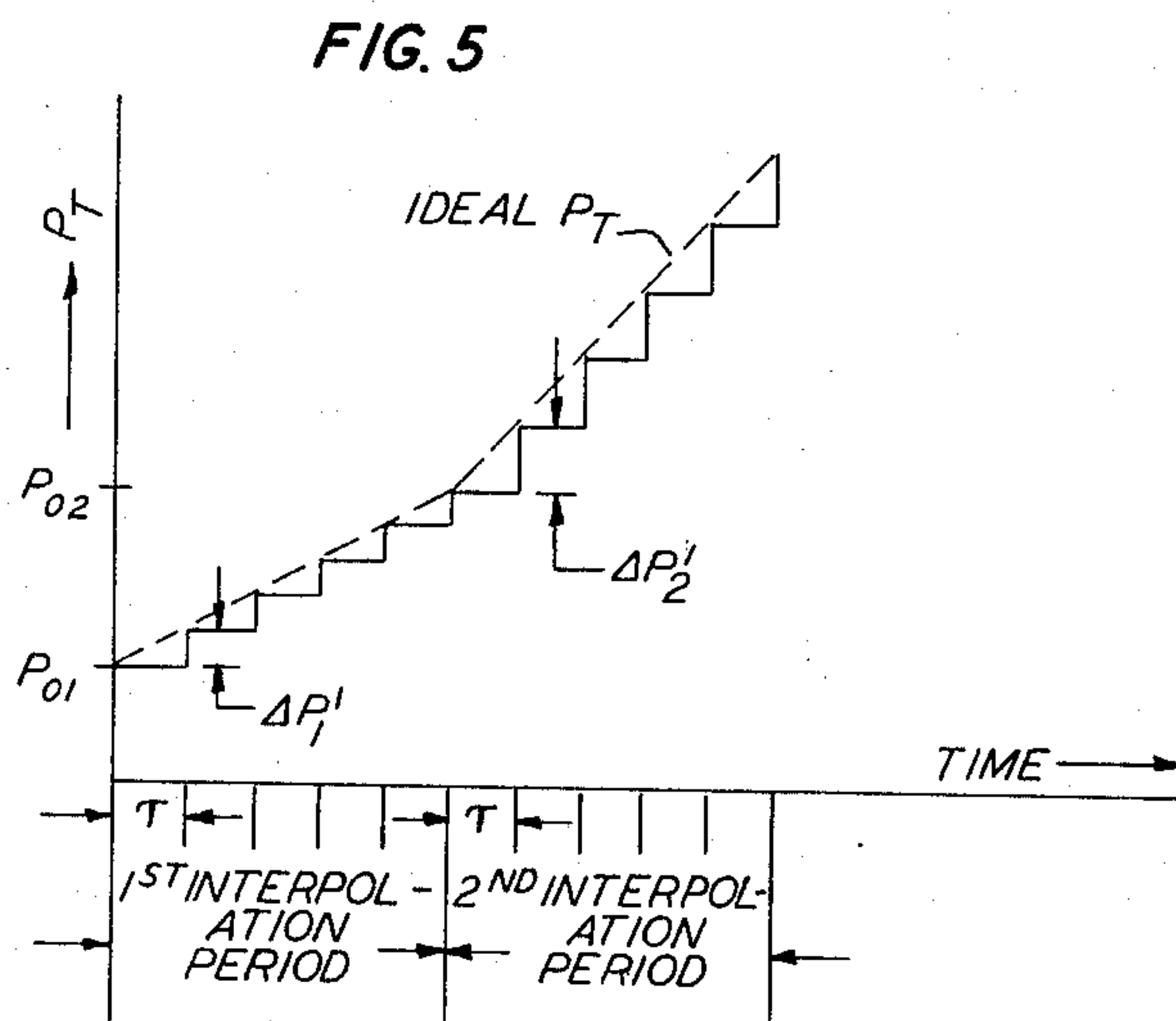
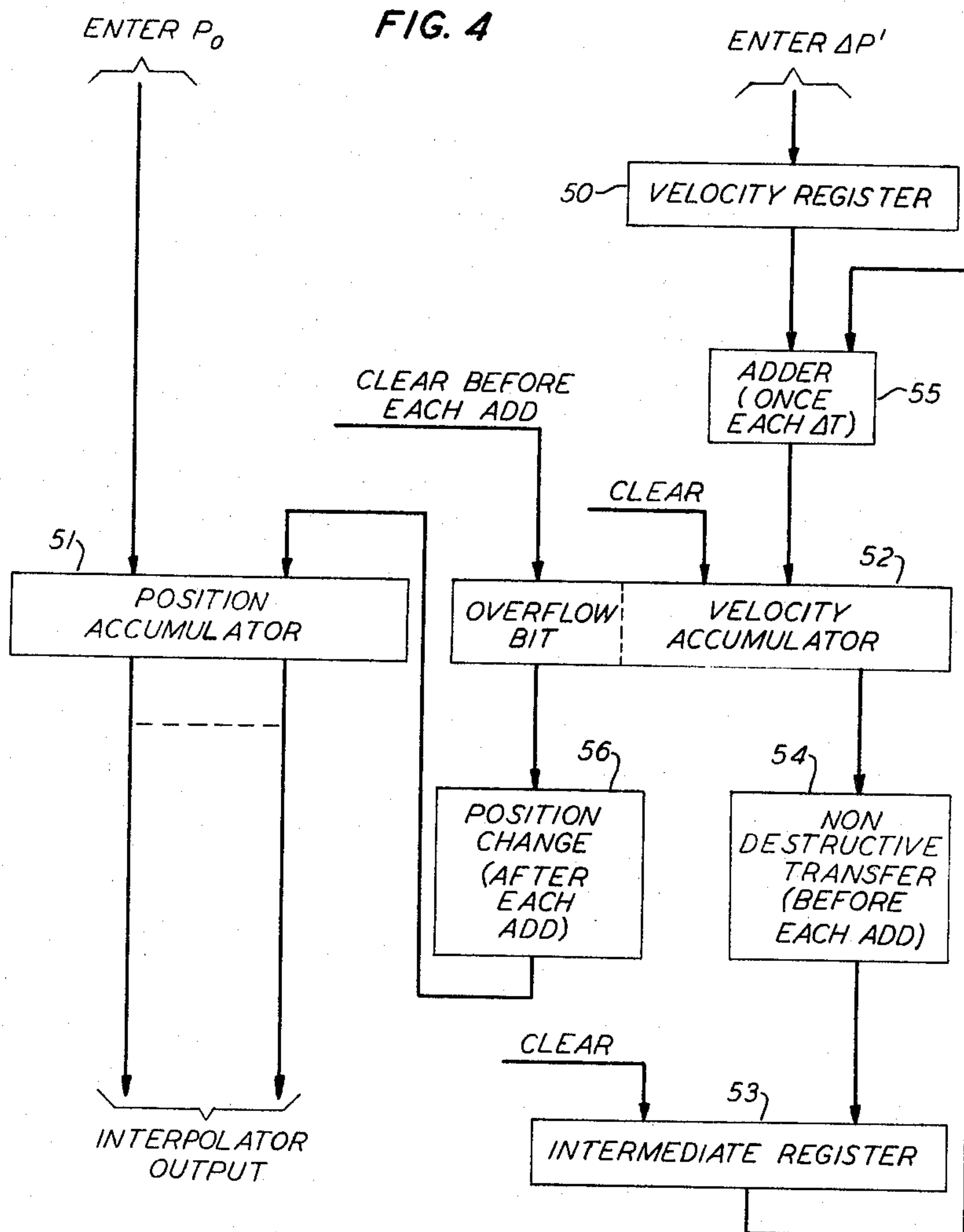
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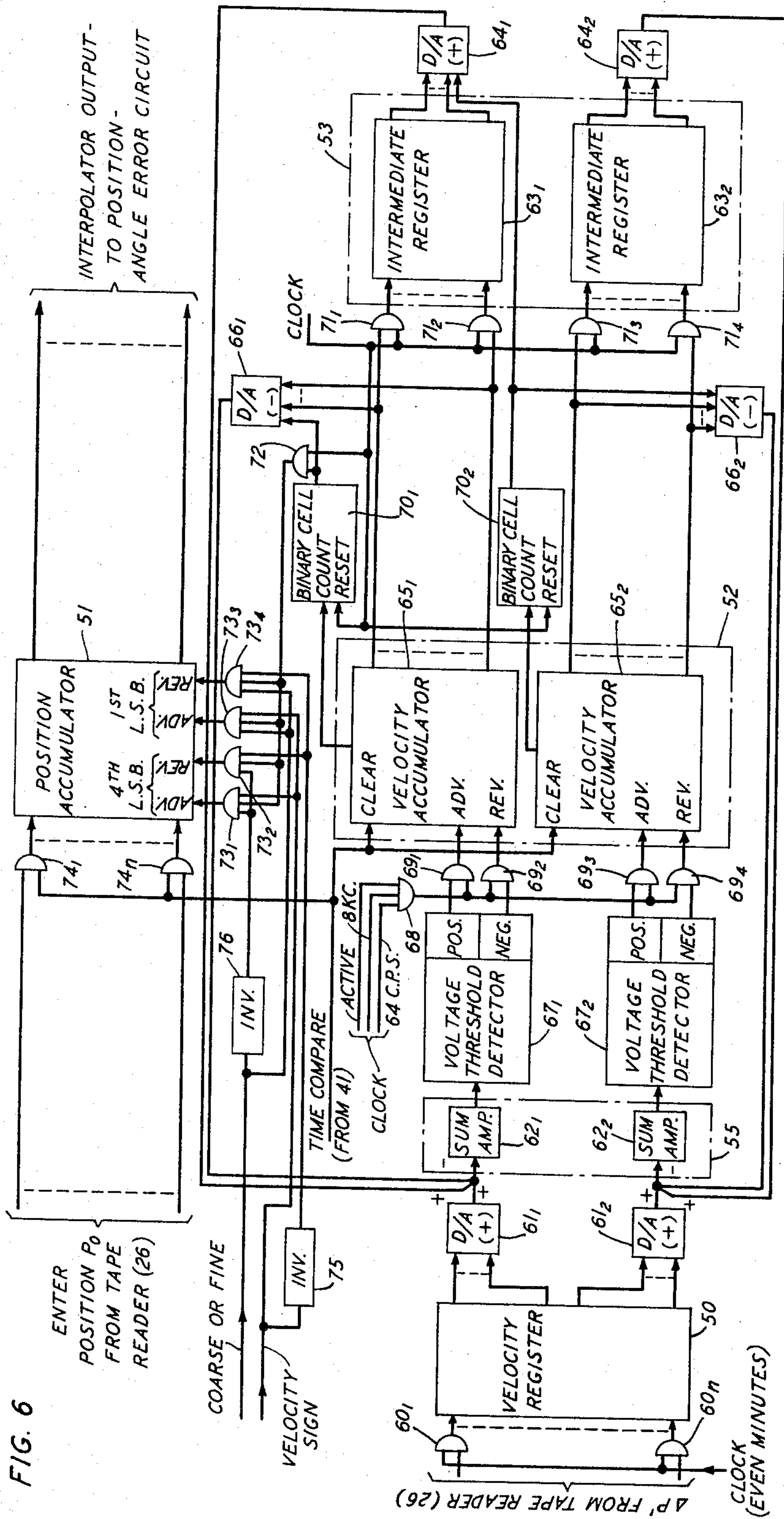


FIG. 6

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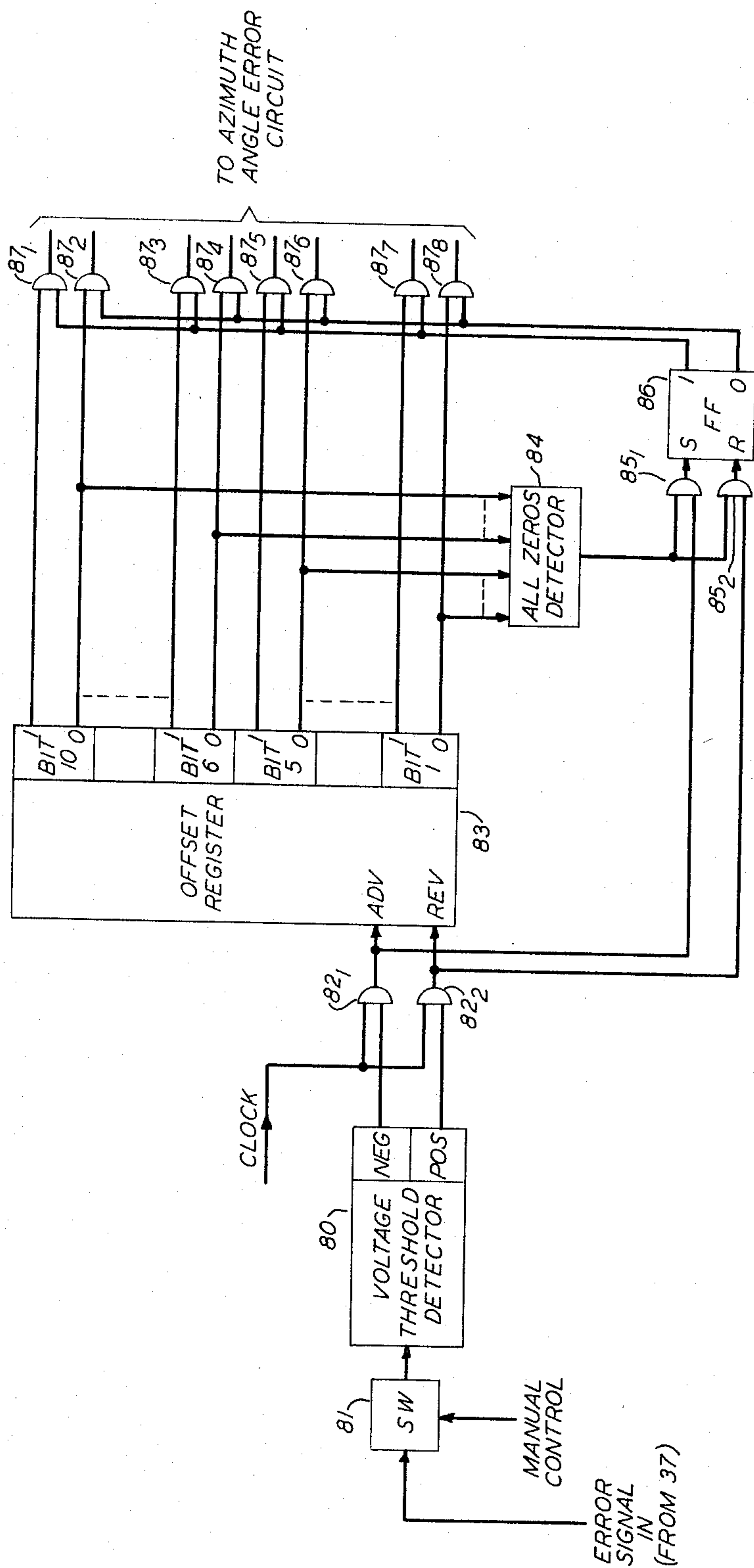
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SATELLITE COMMUNICATION ANTENNA DIRECTION SYSTEM

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FIG. 7



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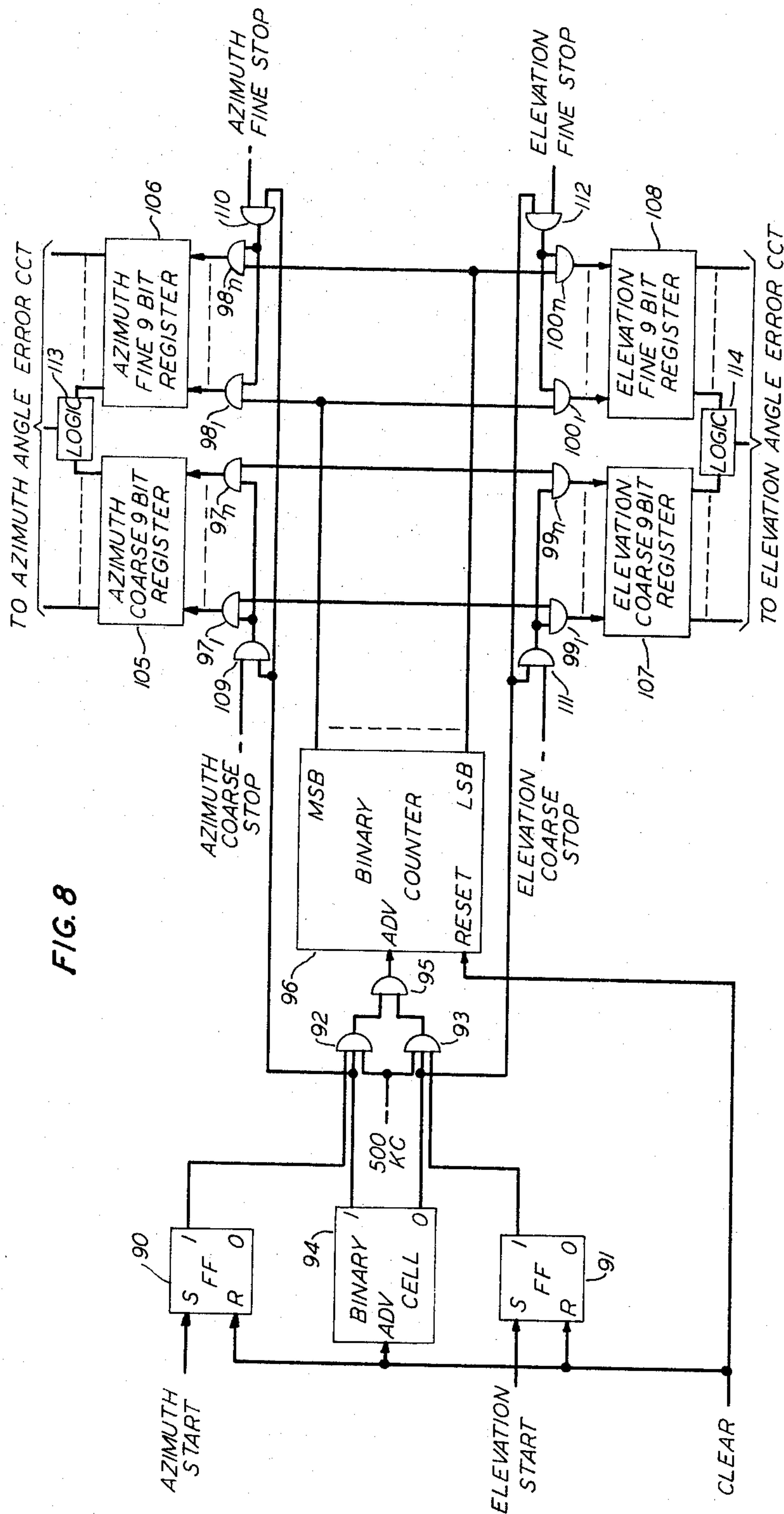
E. J. REID

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SATELLITE COMMUNICATION ANTENNA DIRECTION SYSTEM

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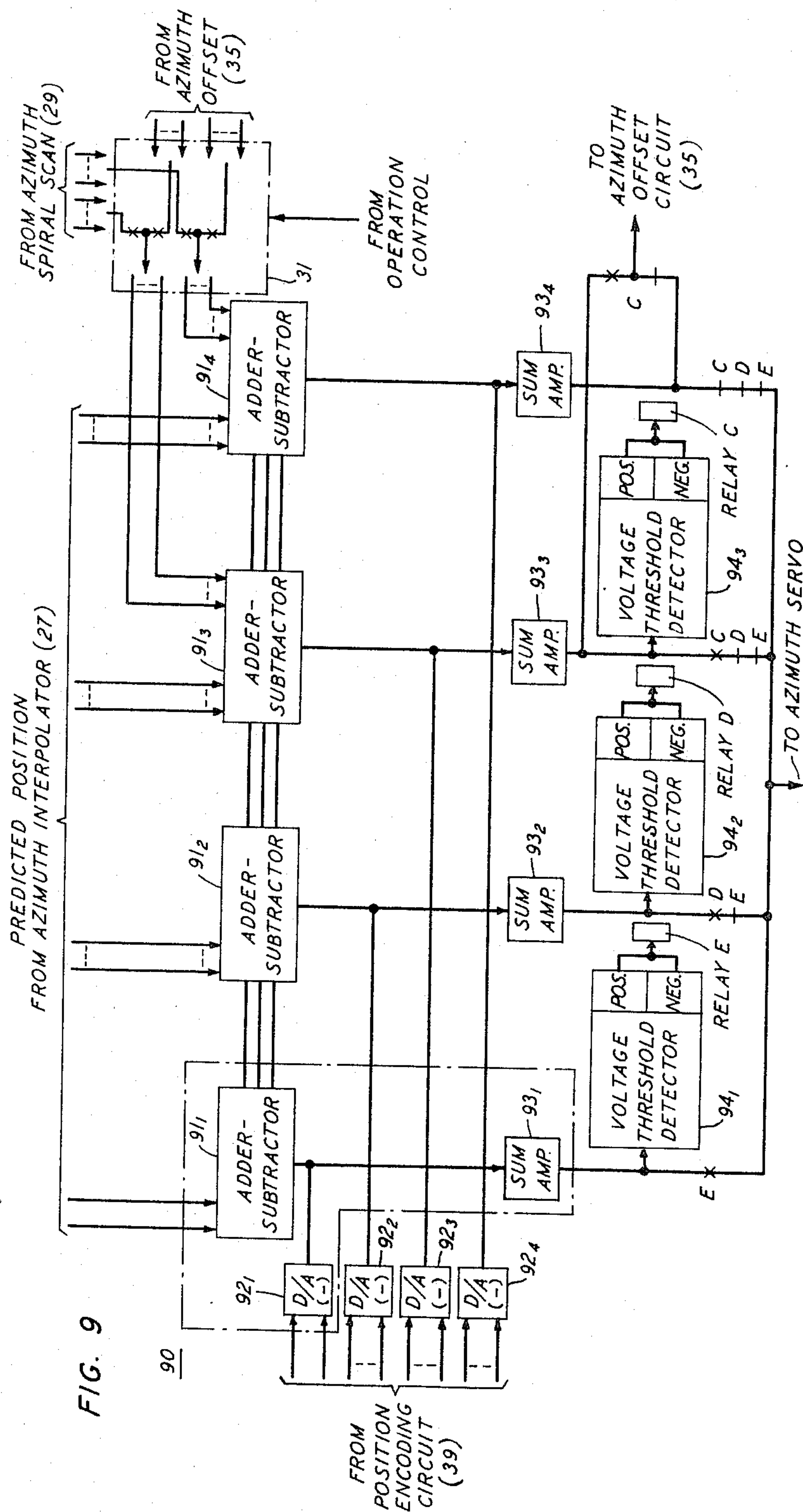
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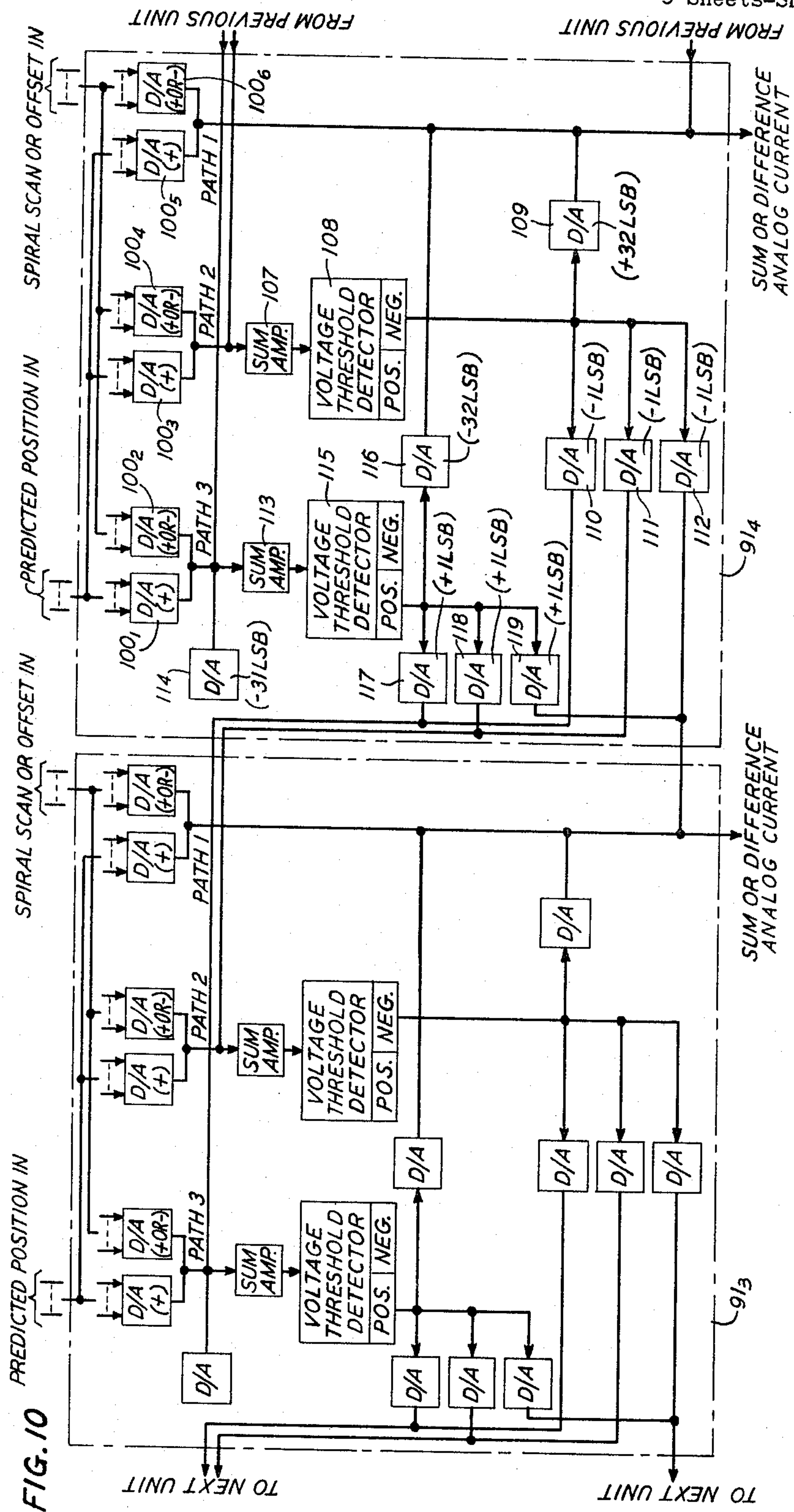
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SATELLITE COMMUNICATION ANTENNA DIRECTION SYSTEM

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Filed Apr. 29, 1965, Ser. No. 451,868

14 Claims. (Cl. 343-117)

This invention relates to antenna pointing systems and, more particularly, to pointing systems employed for directing ground station antennas toward earth satellites in orbital range of the ground station. Its principal objects are a reduction in the complexity of the equipment of such a system and an improvement in the reliability with which antenna pointing is carried out.

The antenna pointing system employed at the ground tracking station of a satellite system, for example, a satellite communications system, performs two primary functions. Initially, it acquires a satellite, i.e., it detects the presence of a satellite in a synchronous or subsynchronous orbit within the range of the station, and points an antenna toward the satellite. It then provides means for determining the satellite orbit so that pointing instructions may be generated to enable the antenna, along with others at the stations, to track the satellite continuously.

These functions may be carried out in a number of ways. For example, a fully programmed control system may be used in which past or predicted ephemerides are initially employed to point the antennas toward the satellite. New data are then collected during tracking for the computation of new ephemerides. Alternatively, the ground station antenna may be made self-tracking. Once a satellite is acquired, by any means, optical sighting, radar, reception of a beacon signal or the like, an antenna station operating in this mode relies on beacon signals transmitted to the ground from the satellite for developing antenna pointing signals. In essence, the nature of propagation of received beacon signal is analyzed to develop error signals indicative of the direction the antenna is pointing with relation to the direction the antenna should be pointing.

Experience has shown that self-tracking, commonly called "autotrack" control, is preferred as the primary tracking mode for an operational ground station antenna. This mode achieves better pointing accuracy and higher reliability at lower cost than a programmed control mode in which the antenna is controlled in advance from a computed ephemeris. However, it has been found that even with autotrack operation, some programmed control capability is desirable since an antenna must be pointed so that the satellite is within the beam width of the antenna before the autotrack system can acquire the satellite. The accuracy of pointing necessary for this acquisition function is considerably less, however, than would be required to track entirely on a programmed basis. A programmed control system can also be used to enhance the reliability of a system in which autotrack is the primary tracking mode. Thus, if for any reason the autotrack system loses it lock on the satellite momentarily, the satellite must be reacquired. A programmed tracking system can provide this reacquisition automatically. Programmed control is also desirable in the administration of programming of a ground station which employs several independent antenna systems. Further, assignment, acquisition, handover, and maintenance may be performed auto-

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matically, thus minimizing the personnel required to operate the station.

In a communications system in which a number of geographically separated ground stations simultaneously track the same satellites, it is evident that pointing data defining the position of each of the satellites, developed for example, at one station, may be used at other stations. Accordingly, a common computation center may be employed which both receives tracking data from the antennas at each of the separated ground stations, and processes all of these data to produce pointing information which defines the future positions of each satellite in the system, preferably with relation to the geographic location of each of the ground stations. These data may then be transmitted to each ground station, and employed as required at each ground station, for developing the actual antenna pointing signals used to track each of the satellites from the ground station. Such a system is described in detail in a copending application of H. P. Kelly and W. A. Klute, Ser. No. 451,869, filed April 29, 1965.

By carrying out most of the computations at a common processing center, it remains only for each ground station to process satellite position data received, generally at discrete selected times only, from the common center in order to develop actual antenna pointing signals. The computation burden is thus divided between the common center and each ground station. A relatively continuous set of points defining the path of each satellite with regard to the ground station location may be developed by interpolating between the spaced points received from the computation center. Preferably, autotrack is used as the primary tracking mode. The interpolated pointing data, referred to conveniently as programmed track data, are used only for initial acquisition, for reacquisition in case of an autotrack loss of phase lock, and for backup in case of an autotrack failure.

The present invention is concerned with the development at such a ground station of programmed tracking information in response to data defining spaced future positions of one or more satellites delivered to the station from a common computation center.

In accordance with the invention, the program track equipment at each ground station produces programmed tracking information based on an interpolation between input data points received from a computation center. This information is produced continuously, but used only as required in conjunction with autotrack information. The input data is normally obtained from the common computation center over a data link, for example, a teletypewriter circuit and is employed to punch or print the coded information on a paper tape or the like. In accordance with the invention, a tape block reader is employed to recover appropriate blocks of information, i.e., those pertaining to specified satellites, and to deliver it to the interpolation apparatus. As a result, no auxiliary memory is needed and the blocks of information may be read continuously and in parallel. Information read from the tape is expanded, in accordance with the invention, by a linear interpolator to define the proper antenna direction for tracking each satellite. The predicted tracking information may, if desired be modified by means, for example, of a spiral scan, by position error offset, or by both. The modified predicted position becomes the commanded antenna position and is subtracted from the actual pointing direction in order to produce an error con-

trol signal for redirecting the antenna to the commanded position.

By continuously interpolating pointing signal information prepared at a distinct station, integrating it with autotrack information generated at the ground station, and employing auxiliary signals for modifying commanded position data to fit the individual needs of the ground station, great flexibility is afforded with a minimum of equipment. Data storage is reduced to a minimum and blocks of data received at any convenient time, for example, in a ten minute transmission period, may be used to develop control signals sufficient to energize all of the antennas at the ground station for as much as twenty-four hours of continuous operation.

The invention may be more fully apprehended by the following detailed discussion of an illustrative embodiment thereof taken in conjunction with the appended drawings, in which:

FIG. 1 is a block schematic diagram of a communications system that includes a common computation center and a number of independent ground stations, which shows the manner in which the program track system of the present invention is advantageously employed in such a system;

FIG. 2 is a block schematic diagram showing the arrangement of elements associated with the program track equipment of the present invention;

FIG. 3 shows the tape reader employed in the system of FIG. 2;

FIG. 4 illustrates, in a simplified block schematic diagram, a typical ephemeris interpolator which may be employed in the practice of the invention;

FIG. 5 illustrates a typical staircase characteristic of the interpolator of FIG. 4;

FIG. 6 is a detailed diagram of an azimuth interpolator in accordance with the invention;

FIG. 7 is a block schematic diagram of an azimuth off-set circuit useful in the practice of the invention;

FIG. 8 illustrates the counter and register portions of a typical position encoder;

FIG. 9 illustrates an angle error circuit employed in the program track equipment of the present invention; and

FIG. 10 illustrates a typical digital adder-subtractor employed in the practice of the invention.

FIG. 1 illustrates, in simplified block diagram form, a typical satellite tracking system which employs a number of geographically separated ground stations for individually tracking one or more satellites, and a common computation center for developing pointing data which may be used by the ground stations. Ground stations Nos. 1 and n only are shown in the figure; the other stations in the system typically include the same configuration of elements.

Each ground station, for example ground station No. 1, may include a number of individual antennas, 10 and 11, for tracking and communicating with an orbiting satellite. Each antenna is continuously pointed toward a specified satellite by antenna drive equipment 12 and 13, which includes the necessary servo drive apparatus or the like. As the antennas are moved, signals indicative of the momentary position of each antenna, are supplied to data transmitter 14, encoded as required, and transmitted via a data communication circuit to common computation center 15. In general, computation center 15 is geographically separated from the ground stations. Data defining the actual pointing direction of each antenna at all of the ground stations are recovered by data receiver 16 at the common center and supplied to a computer 17. As discussed in the aforementioned Kelly-Klute application, computer 17 develops, from the applied data, signals which define the positions of each satellite in the system at specified future instances of time and related, preferably, to the individual geographic locations of the ground stations in the system. This information is assembled in individual blocks which define, for each satellite, one

position at one time, changes in position at selected future times, for one ground station. Each block additionally is addressed in a fashion that specifies the particular satellite and ground station to which it pertains.

Blocks of information are thereupon transmitted by data transmitter 18 to each of the ground stations. Ordinarily, a considerable number of individual blocks are transmitted at one time to each station. For example, data defining future positions of each satellite in the system, at twelve minute intervals, sufficient to define satellite positions for a twenty-four hour period, may be transmitted together in one brief signalling period.

At the ground station, incoming data are received by way of a data receiver associated with station operation control apparatus 19. In practice, the individual blocks of information are employed to develop a punched paper tape or the like which may be stored until needed. The information is thereupon delivered to program track equipment 20, either by way of a tape reader, or manually in order that reading of the tape may take place directly in the program track equipment. In addition, station operation control 19 monitors program track information developed by autotrack apparatus 21. So long as continuous pointing signal information is being developed by the autotrack equipment, the operation control permits this information to be supplied by way of mode selector 22 to the antenna drive system where it controls the antenna pointing operation. For initial acquisition, a loss of track, or the like, however, operation control 19 energizes mode selector 22, which transfers control of the antenna system to program track equipment 20. Thus, the primary mode of operation at each ground station is autotrack with a continuous backup by program track. Since the prediction of future satellite positions is carried on at the common computation center for all ground stations, each ground station is required only to interpolate between the spaced pointing information received from the center, in order to develop continuous pointing information. Each ground station integrates this information with locally generated autotrack information.

The present invention concerns itself primarily with the program track equipment 20 of the system described briefly in connection with FIG. 1. FIG. 2 shows, in simplified diagram block form, program track equipment in accordance with the invention. Information concerning the positions of each of the satellites expected to be in orbital range of the stations at discrete future times is supplied to the program track equipment, for example, on a punched paper tape 25. Ordinarily, the tape contains individual blocks of information. Each block defines one position, for one antenna, at one time and selected future changes in that position by way, for example, of a 160-bit code. The tape is supplied to reader 26, of any desired construction, which reads each block in parallel, and delivers the information to azimuth ephemeris interpolator 27 and elevation ephemeris interpolator 28. Although shown as separate units, interpolators 27 and 28, as well as the other elements shown in duplicate form, may of course be consolidated in one physical structure. The interpolators expand this information and produce signals continuously defining the predicted position required for each antenna to enable it to track a defined satellite.

Acquisition of a satellite, preparatory to handling it over to the autotrack equipment, can be accomplished more quickly if the predicted position error is less than one-half of the antenna bandwidth. This is usually the case. However, the error may occasionally be larger. In that event, acquisition capability of the system is enhanced by modifying the interpolated position, for example, by employing effectively a spiral scan search mode. Signals for directing the antenna in such a mode are developed in spiral scan generators 29 and 30 and individually supplied, under control of selection equipment 31 and 32, to adders 33 and 34. They are combined in the adders with the prediction antenna information issuing

from the interpolators. Similarly, when an antenna is autotrack controlled, a momentary tracking loss results in an immediate switch to full program control for reacquisition. The time necessary for reacquisition depends on the degree to which the commanded position error exceeds one-half the antenna bandwidth. The reacquisition operation may be improved by modifying the commanded antenna position by offsetting it by a value equal and opposite to the predicted position error. The suitable offset value is determined during autotrack control by observing the error signal output of the signal track equipment. Suitable offset signals are, accordingly, generated in offset equipments 35 and 36 and are supplied under control of selector equipments 31 and 32 to adders 33 and 34.

The output of the adders constitutes the (modified) commanded position for a single antenna for tracking a given satellite. This position (treating both azimuth and elevation together for simplicity) is compared with the actual antenna pointing position in order to produce the required error signal for actuating the antenna drive system. Accordingly, signals from adders 33 and 34 are supplied, respectively, to subtractors 37 and 38 together with signals from antenna position encoder 39. The differences, if any, constitute the output signals of the tracking equipment, i.e., tracking error signals. The error signals are supplied to mode selector 22 together with signals from autotrack equipment 21. In accordance with the determination made by station operation control 19 (FIG. 1), one or the other sets of error signals are delivered by the mode selector to the antenna drive equipment. Further, azimuth error signals are delivered to offset equipment 25 and elevation error signals are delivered to offset equipment 26 in order continuously to energize the offset equipment in the manner described above.

For the most part, the individual elements of the program track equipment illustrated in FIG. 2 are well known to those skilled in the art. For example, antenna position encoders, autotrack equipment, and mode selector equipment are described in detail in the July, 1963, issue of the Bell System Technical Journal. Similarly, spiral scan, and offset signal generators have been described in the art, for example, in the same issue of the Journal.

Although block tape readers are well known in the art, one suitable arrangement for selectively recovering information from a number of consecutive blocks entered on a tape is shown schematically in FIG. 3. It consists of a block reader 40, time compare circuit 41, and velocity selector 42. Each block on the tape contains a number of different pieces of information, viz., the initial position, P_0 , of a specific satellite at a particular time, t (initial position being defined in terms of both azimuth and elevation), and a number of incremental values, $\Delta P'$, for specified future times. A typical format for a block of information is illustrated in FIG. 3. No attempt has been made to represent the exact manner in which the information is encoded and punched on the tape. The time established for the initial position data may require, for example, 10-bits of information. The azimuth and elevation of the initial position, P_0 , may require 32-bits (to define both azimuth and elevation), and each of six deviations from the initial position e.g., at two minute intervals, may require as much as 17-bits each. Typically, each 17-bit ΔP specification utilizes 8-bits for denoting a change in azimuth position, 1-bit for denoting the algebraic sign of the change, and 1-bit for denoting whether the change is "coarse" or "fine." Changes in elevation are denoted by 6-bits and the algebraic sign of the change is denoted by 1-bit.

Readout of the entire block is initiated by comparing the time indicated on the tape for the block with local station time as determined, for example, by a clock. When tape and real time are identical, as determined by comparator 41, an energizing signal is produced for use

throughout the system. This signal initiates pulse generator 43 which is effective to enable AND gates 44₁ through 44₃₂, the exact number of gates being dependent upon the number of bits used to encode the initial position, P_0 , of the satellite. The initial position data is thereupon delivered both to the azimuth and elevation interpolators, as required.

Incremental position information, contained in the other six portions of the block, are read out at two minute intervals and delivered to the interpolators. This operation is carried out conveniently by means of velocity selector apparatus 42. For convenience, this apparatus is illustrated schematically as a six-throw, 17-pole, rotary switch 46. Initially, the 17 poles (only two of which appear in the illustration) are positioned to connect the 17 read elements associated with the first incremental position portion of the block, namely $\Delta P'1$, by way of AND gates 45₁ through 45₁₇, to the interpolators. Readout takes place on the even minute. On the odd minute, switch 46 advances all poles by one step so that the second incremental value, $\Delta P'2$, will be transferred at the next even minute to the interpolators. Switch 46 continues in this fashion to supply incremental data at two minute intervals, by way of gates 45, to the interpolators for the entire twelve minute block following the specified block time.

Before turning to a consideration of the operation of the ephemeris interpolators (27 and 28 in FIG. 2), it is believed helpful to consider briefly the mode of linear interpolation preferably employed in the practice of the invention.

Linear interpolation obeys the formula:

$$P_T = P_0 + \int_0^T V_0 dt \quad (1)$$

where:

P_0 —initial position of interpolation period, at time $t=0$.

P_T —interpolated position, at time $t=T$.

V_0 —constant velocity necessary for P_T at end of interpolation period to equal the next periods initial position.

If instead of velocity information, position change and digital integration are used for convenience:

$$P_T = P_0 + \sum_0^{T/\tau} \Delta P' \quad (2)$$

where:

τ —a small fixed time interval, e.g., in seconds.

$\Delta P'$ —change in position in time τ at velocity V_0 .

This digital integration approximation to ideal integration can be in error by at most the maximum $\Delta P'$. Hence, τ is chosen to keep the maximum error tolerable.

FIG. 4, illustrates, by way of a functional block diagram, the way such interpolation may be carried out. A detailed description of a suitable azimuth interpolator will follow with reference to FIG. 6. Considering the system of FIG. 4, values of $\Delta P'$, a position change order, and P_0 , the initial position of the satellite at time T , are entered in velocity register 50 and position accumulator 51, respectively. After each τ seconds, the sum of the signals produced by velocity register 50 and a register consisting of position accumulator 51 and velocity accumulator 52 is placed in the accumulators. The resulting contents of these accumulators is the desired position increment P_T , at time $\tau=T$. Note that the time between steps, τ , is fixed and that the increment or step height, $\Delta P'$, varies with velocity. FIG. 5 shows the way in which successive ΔP values are effective in stepping, during each interpolation period, from position P_0 at the beginning of the period, to a new value of P_0 at the end of the period.

Each incremental change in position, $\Delta P'$, has a maximum value based on the maximum allowable digital in-

dication approximation error. If the n least significant bits in velocity register 50 define the maximum $\Delta P'$, the $n+1$ through m bits of the register will always be 0. Also, if the P_T step height of the maximum $\Delta P'$ is allowed, then smaller P_T step heights are unnecessary. Hence, the interpolator output need only be read from position accumulator 51, and need not include the n least significant bits of accumulator 52. Intermediate register 53 facilitates the summing process.

At the beginning of an interpolation period, the following occurs:

(1) Velocity accumulator 52 is cleared (by a signal, for example, developed at a specified clock time).

(2) Intermediate register 53 is cleared.

(3) The absolute value of $\Delta P'$ is entered in velocity register 50.

(4) The $m-n$ most significant bits of P_0 are entered in position accumulator 51 (only the $m-n$ most significant bits are computed for P_0).

Interpolation then proceeds as follows:

(1) After τ seconds, the sum of the quantities in velocity register 50 and intermediate register 53 is entered in velocity accumulator 52.

(2) If this sum contains a "1" as an overflow bit, position accumulator 51 is increased one least significant bit for $\Delta P'$ positive, or decreased one least significant bit for $\Delta P'$ negative. This follows since the overflow bit and the position accumulator least significant bit have equal absolute values.

(3) The velocity accumulator n least significant bits are nondestructively transferred via transfer gate 54 to intermediate register 53, and the overflow bit is cleared.

(4) Steps 1, 2 and 3 repeat at a $1/\tau$ rate.

The interpolator output step height (FIG. 4) is always the maximum allowed $\Delta P'$, and the time between steps varies with velocity.

The size of position accumulator 51 depends on the specification of the required maximum position and position resolution. Moreover, maximum velocity occurs for a velocity word containing all "1's". For this velocity word, position accumulator 51 will be updated (2^n-1) of 2^n adds. Hence, the minimum velocity occurs for a velocity word containing a "1" only in its least significant bit. For this velocity word, the position accumulator will be updated each 2^n adds. Consequently, the size of velocity register 50 depends on the required maximum velocity and velocity resolution.

A somewhat more detailed representation of suitable interpolation apparatus is shown in FIG. 6. In order to simplify the implementation of the interpolator, it is in accordance with the invention to employ both analog and digital equipment, e.g., digital storage devices and analog arithmetic units. Further, it is in accordance with the invention to restrict the number of analog levels to a conveniently small number, for example, to five levels. Accordingly, the four least significant bits (L.S.B.) and the four most significant bits (M.S.B.) of digital quantities, and their analog counterparts, are separately processed.

Position change orders, $\Delta P'$, i.e., incremental changes in the commanded antenna position, are supplied on even minutes to velocity register 50 of the interpolator of FIG. 6. It is these incremental changes that are to be algebraically added to the initial position, P_0 , defined in each consecutive block of information supplied to the ground station, to produce the new commanded position. Typically an 8-bit azimuth change signal is stored in velocity register 50. A plurality of AND gates 60₁ through 60_n may be used to effect the transfer. The digital position difference data read out of register 50 are converted by digital-to-analog converters 61₁ and 61₂ to corresponding analog voltages, which in turn are supplied respectively to the inputs of summing amplifiers 62₁ and 62₂. For convenience, an analog voltage representing the most significant bits, e.g. 4, are processed in amplifier 62₁; an

analog voltage representing the least significant bits, e.g. 4, are processed in amplifier 62₂. The summing amplifiers together comprise adder 55 in the block diagram of FIG. 4.

The latest position definition developed by the interpolator is stored in digital form in position accumulator 51 and intermediate registers 63₁ and 63₂. The latter registers together form register 53 in FIG. 4. A position definition stored in intermediate register 63 is converted to analog form by digital-to-analog converters 64₁ and 64₂ and is continuously supplied to summing inputs of amplifiers 62. Consequently, the analog currents supplied to the summing amplifiers from velocity register 50, representative of incremental position changes, and analog currents supplied by intermediate registers 63, representative of the latest position, are added together to produce sum currents.

Velocity accumulators 65₁ and 65₂, used to handle, independently, 4-bit signals representative of the most and least significant bits of the position definition, record the summation signal which should define the momentary position signal. Velocity accumulators 65 together are denoted as block 62 in the diagram of FIG. 4. If the accumulators 65 contain the desired sum, the analog currents supplied by them, by way of digital-to-analog converters 66₁ and 66₂, are equal to the sum currents supplied to the accumulators from amplifiers 62. To determine if this is the case, the accumulator and sum currents are subtracted from one another. The required subtraction is achieved by inverting the polarity of the accumulator output signals, e.g., in converters 66, and supplying the resultant analog signals to the inputs of summing amplifiers 62₁ and 62₂. If they are not equal, the inequality is sensed by voltage threshold detectors 67₁ and 67₂. In dependence on the polarity of the inequality, signals produced by velocity threshold detectors 67 actuate velocity accumulators 65 and cause them individually to advance or reverse until the currents are equal. Typically, velocity accumulators 65 may be reversible binary counters with advance and reverse inputs. The adjustments, either advance or reverse, may take place at specified clock times by the action of clock signals supplied by way of AND gate 68 and AND gates 69₁ through 69₄. As soon as the currents supplied to the velocity accumulators are equal, the velocity accumulators 65 together contain the desired sum. Latest position data developed in velocity accumulators 65 are supplied, in digital form, at clock intervals by way of AND gates 71₁ through 71₄ to intermediate registers 63₁ and 63₂ for storage.

Since two 4-bit numbers can add to a 5-bit number, each velocity accumulator 65₁ and 65₂ includes an additional binary cell, 70₁ and 70₂, respectively. Binary cell 70₂ provides a carry function from accumulator 65₂ to accumulator 65₁. It becomes the overflow bit in accumulator 65₁. After each add operation, both binary cells are reset from the clock in preparation for the next add operation.

Digital position information from accumulators 65 is supplied by way of AND gates 72 and a series of AND gates 73₁ and 73₄ to position accumulator 51. Position accumulator 51, accordingly, is advanced or retarded in order to alter the latest position definition P_0 stored, for example, as a 32-bit number in the accumulator. Position P_0 is renewed, for example, at twelve minute intervals. Accordingly, whenever the time indication on a tape block corresponds to local clock time, determined, for example, in time compare apparatus 41 of FIG. 3, AND gates 74₁ through 74_n are enabled and the new position definition is entered in accumulator 51. Thereupon accumulator 51 is made to count in advance or in reverse by the magnitude of the correction count supplied by velocity accumulator 65. In doing so, it develops, at the output of accumulator 51, position signals corrected for times intermediate the selected times, e.g.,

twelve minute intervals, at which predicted values P_0 are available. A 1-bit sign signal derived from the input tape (one bit of the ΔP specification) is effective to cause accumulator 51 to advance or retard. The binary sign bit is supplied to one of the inputs of each of AND gates 73. For example, a positive or "one" signal is applied, when called for, to one input of AND gates 73₁ and 73₃ to control the advance operation of accumulator 51. A negative or "zero" signal, when specified, is supplied by way of inverter 75 to one input of AND gates 73₂ and 73₄ to control the reverse count operation of the accumulator. Whether the adjustment is to be "coarse" or "fine" is similarly determined from the tape specification. A 1-bit signal is supplied to AND gates 73₃ and 73₄; a "one" signal is supplied if the adjustment is to be fine. Hence, the advance or reverse counting takes place on the least significant bit inputs of accumulator 51. Coarse adjustment is made by supplying a "zero" signal, by way of inverter 76, to one input of AND gates 73₁ and 73₂ in order to energize the advance and reverse inputs controlling the fourth least significant bits.

During autotrack control of an antenna, any angle error output is due to prediction and roundoff errors. An offset circuit, for example, of the type shown in FIG. 7, is effective, in accordance with the invention, to remove such an error by inserting an equal and opposite offset. A zero error indicates the proper offset; a non-zero error is sensed by voltage threshold detector 80. The error signal may be supplied directly from the interpolator, e.g., from subtractor 37 (FIG. 2), or may be injected from a manual control. The input selection is conveniently made by way of switch 81. Voltage threshold detector 80 thus senses the presence of a non-zero error, determines its polarity, and at the next clock interval supplies a pulse by way of AND gates 82₁ or 82₂ to offset register 83. Register 83, typically, is a reversible binary counter which, when actuated at its advance or reverse input terminals, counts in advance or reverse until the error is removed. In practice, a typical offset register employs ten bits so that the maximum offset is ± 2.8 degrees. Since the digital-to-analog converters employed in the interpolator apparatus are restricted to five levels, the offset generation is performed conveniently in two groups of five bits each, as indicated in FIG. 9. When the offset is positive, register 83 outputs are used, via gates 87₁, 87₃, 87₅ and 87₇. To reduce the offset, the counter is reversed. If during the operation the output of offset register 83 is reduced to a sequence of all zeros, this fact is detected by all-zeros detector 84 in order that AND gates 85₁ and 85₂ may be enabled to pass the advance or reverse command from gates 82₁ or 82₂ to set or reset flip-flop 86. If, for example, the command from gate 82₂ is for reverse, flip-flop 86 is reset, AND gates 87₁, 87₃, 87₅ and 87₇ are inhibited and AND gates 87₂, 87₄, 87₆ and 87₈ are enabled in order to pass the offset signal in register 83 to the azimuth error angle circuit, i.e., to adder 33 in the system of FIG. 2. If the offset is negative and increased, flip-flop 86 is set upon receipt of the "all-zero" code and gates 87₁, 87₃, 87₅ and 87₇ are energized to pass the information to the azimuth angle error circuit. This technique assures that all offset changes, i.e., step heights, are defined with one least significant bit.

Although position error encoders, e.g., antenna position encoder 89 or FIG. 2, have been described in the art, one typical unit found to be effective in practice is illustrated in FIG. 8. The program track apparatus of the present invention is equipped to encode 9 coarse and 9 fine position bits for 17-bit position information, providing a 1-bit overlap. This is accomplished by counting the time between antenna position start and stop pulses produced by antenna position resolver apparatus commonly associated with tracking antennas. One counter is employed for coarse and fine. Further, the counter is

time-shared between the azimuth and elevation angle error circuits.

In the apparatus of FIG. 8 azimuth start pulses set flip-flop 90 and elevation start pulses set flip-flop 91. In the set position, AND gates 92 and 93, respectively, are energized so that binary information from binary cell 94 is advanced, at a 500 kilocycle count rate, through AND gate 95 to binary counter 96. The output of counter 96 supplies an indication of the elapsed time since the time of the last start pulse supplied to AND gates 97 and 98 in the azimuth circuit, and the last start pulse supplied to AND gates 99 and 100 in the elevation circuit. Accordingly, azimuth coarse register 105 and azimuth fine register 106 are continuously advanced. Elevation coarse and fine registers 107 and 108 are similarly advanced. Stop signals, azimuth coarse and fine, and elevation coarse and fine, are supplied, respectively, by way of gates 109, 110, and 111 and 112 to gates 97, 98, 99 and 100. As soon as the stop signals occur, the information in binary counter 96 is thus read out via the azimuth registers 105 and 106, and via the elevation registers 107 and 108, and supplied to the azimuth error angle circuit and the elevation angle error circuit. Flip-flops 90 and 91 are thereupon reset by a clear pulse, for example from the clock, and counter 96 is reset.

Details of a suitable angle error circuit are shown in FIG. 9. The azimuth circuit only is illustrated in the detail of FIG. 9; the elevation error circuit is substantially identical. The angle error equipment of FIG. 9 performs two functions. First, it adds the predicted position supplied to it from azimuth interpolator 27 (FIG. 2) to either spiral scan signals from spiral scan equipment 29 or to position offset signals from equipment 35. These signals, in analog form, are supplied by way of selector switch 31 which is actuated, typically, from the operational control circuit 19 (FIG. 1). Accordingly, one or the other of the auxiliary signals is supplied to the least significant bit positions of composite adder-subtractor 91₁ through 91₄, namely unit 91₃ and 91₄. Since the digital-to-analog converters of the system are restricted to five levels, the add operation is performed in groups of five bits. This produces both a carry and borrow problem between groups, indicated by the interconnections between the individual adder-subtractor elements 91. Both the spiral scan and position offset data can be either positive or negative. With this construction, the adder-subtractor units 91 can effectively handle the problem. The output of units 91 is the analog commanded position.

The second function of the circuit involves the subtraction of the actual antenna position from the commanded position. Actual antenna position information is supplied in digital form from antenna position encoder 39 (FIG. 2) and converted by way of digital-to-analog converters 92₁ through 92₄ to analog form. Subtraction is carried out conveniently by developing a negative output from the digital-to-analog converters 92 so that an adding operation may be used to sum the necessary difference. Addition takes place in summing amplifiers 93₁ through 93₄. The resulting difference is the output angle error signal for the antenna drive equipment. It will be observed at this point that adder-subtractor 91 and summing amplifier 93, together with the polarity inversion action of digital-to-analog converter 92, carry out the functions of adder 33 and subtractor 37 (block 90) in the block diagram of FIG. 2.

The summing operation does not have a borrow or carry problem since only one group subtraction is used at any one time. The group used is the more significant group having a nonzero angle error output. Accordingly, the summation signal developed, for example by amplifier 93₁, is examined by voltage threshold detector 94₁ and, if an error signal is detected, either in a positive or negative sense, relay E is energized. Contacts on this relay serve to close the circuit between summing amplifier 93₁ and the output of the angle error circuit in order to supply

the error signal to the azimuth servo in the antenna drive equipment. Other contacts on relay E open the output circuits of summing amplifiers 93₂, 93₃ and 93₄. Similarly, if the next more significant group is in error, threshold detector 94 energizes relay D which connects the output of summing amplifier 93₂ to the azimuth servo equipment and opens the circuits from amplifiers 93₃ and 93₄. An error in summing amplifier circuit 93₃ actuates detector 94₃, which in turn energizes relay C, and allows the output of summing amplifier 93₃ to reach the servo and also to reach azimuth offset circuit 35. In the absence of an error at the output of amplifiers 93₁, 93₂ or 93₃, the least significant group signal is passed directly from amplifier 93₄ to the azimuth servo apparatus and also to azimuth offset circuit 35.

Details of a typical adder-subtractor element 91 are shown in FIG. 10. Two units, 91₃ and 91₄, with the necessary interconnections are shown; only one unit will be described in detail. The desired sum current for a single adder-subtractor is generated three times. The first, in path 1, is the desired commanded position. The second, in path 2, is examined to determine if it is positive or negative. If it is negative, a borrow operation is called for. The third sum, in path 3, is tested for being a value greater than could be produced with five bits. If it is, a carry operation is called for.

In the figure, predicted position information, spiral scan, and offset information is supplied from the interpolator and delivered individually to digital-to-analog converters 100₁ through 100₆. Successive 5-bit signals representing predicted positions are thus delivered to converters 100₁, 100₃ and 100₅, and 5-bit signals representative of the offset signals are delivered to converters 100₂, 100₄ and 100₆. In path 1, the outputs of converters 100₅ and 100₆ are added together and delivered as the output analog current which, referring briefly to FIG. 9, to summing amplifier 93.

The position signals supplied by converters 100₃ and 100₄ in path 2 are supplied together to summing amplifier 107 and thence to voltage threshold detector 108. Detector 108 determines whether the supplied analog signal is positive or negative and, if the signal is found to be negative, develops an output signal indicating that a borrow operation must be initiated. The borrow is accomplished by energizing digital-to-analog converter 109, which in turn supplies a 32-bit signal to the output, i.e., adds thirty-two bits to the analog signal in path 1. At the same time, to complete the borrow operation, the next adjacent unit 91₃, must be correspondingly decreased by one least significant bit. This is accomplished by energizing digital-to-analog converters 110, 111 and 112, by means of the signal generated by detector 108, in order that a 1-bit signal is delivered to each of the three paths of the next adjacent unit, viz., unit 91₃.

Analog signals developed by converters 100₁ and 100₂ in path 3 are combined and delivered to input of summing amplifier 113. Summing amplifier 113 is also supplied continuously at its input with a 31-bit signal developed by digital-to-analog converter 114. Accordingly, the difference signal developed by amplifier 113 is positive only if the input signals from converters 100₁ and 100₂, together with any analog borrow information supplied by the next adjacent unit (to the right of 91₄ of FIG. 10) exceeds 31-bits. If this is the case, a carry operation is indicated. As a result, voltage threshold detector 115 generates a signal indicative of the positive summation signal which is used to actuate digital-to-analog converters 116, 117, 118 and 119. Converter 116 thereupon generates a 32-bit signal which is subtracted from the analog output signal in path 1. The carry is completed by supplying a 1-bit positive signal, generated individually by converters 117, 118 and 119, to the next adjacent unit (91₃) where it is added individually to the analog signals in paths 1, 2 and 3 of that unit.

Consequently, each adder-subtractor unit 91 produces an analog signal representative of the predicted position

signal, the spiral scan signal, or offset signal supplied from the interpolator. Moreover, the output signal of each of units 91 is an analog signal that adequately defines the 5-bit digital input information.

All of the individual elements shown in block diagram form in the figures not discussed herein in detail are well-known to those skilled in the art. Each may take any desired form. Further, in dependence on the desired implementation, additional bits of information may be used to define any of the signals. If this is done, changes may be made in the actual implementation to accommodate the greater or lesser digital representations. Further, all of the indicated operations may be carried out entirely on a digital basis or entirely on an analog basis; the digital-analog implementation described hereinbefore is merely representative of the preferred mode of practice of the present invention. It will be evident to those skilled in the art that numerous other modifications and additions may be made without departing from the spirit and scope of the invention.

What is claimed is:

1. In a control system for developing antenna pointing signals, the combination which comprises: means for accumulating data defining the expected position and velocity at specified times of a target, means responsive to said accumulated data for incrementally adjusting said data to define the expected position and velocity of a target at times other than said specified times, means for developing data which defines the momentary position of a tracking antenna, means responsive to all of said data which defines the position and velocity of said target and to said data which defines the position of said antenna for developing antenna position error signals, means for selectively modifying said error signals to correct for incremental adjustment errors and means for employing said modified signals for directing said tracking antenna continuously toward said target.
2. In a control system for developing antenna pointing signals, the combination which comprises: means for accumulating data defining the expected position and velocity at specified times of a target, interpolation means responsive to said data for developing expected position and velocity data for said target at other specified times, means for developing data which defines the momentary position of a tracking antenna, means responsive to said data which defines the position and velocity of said target and to said data which defines the position of said antenna for developing antenna position error signals, means for selectively modifying said error signals to correct for interpolation errors, and means for employing said modified signals for directing said tracking antenna continuously toward said target.
3. In a control system for developing antenna pointing signals, the combination which comprises: means for accumulating data defining the expected positions and velocities at specified times of each of a number of targets, interpolation means responsive to said data for developing expected position and velocity data for each of said targets at other specified times, means for developing data which defines the momentary position of a tracking antenna, means responsive to said data which defines the position and velocity of a selected one of said targets and to said data which defines the position of said antenna for developing antenna position error signals, means for selectively modifying said error signals to correct for interpolation errors, and means for employing said modified signals for directing said tracking antenna continuously toward said selected target.
4. In a control system for developing antenna pointing signals, the combination which comprises: means for accumulating data defining the expected positions and velocities at specified times of each of a number of orbiting satellites, interpolation means responsive to said data for developing position and velocity signals for each of said satellites at other specified times, means for selectively

modifying said interpolation signals to correct for interpolation errors, means for developing signals which define the momentary position of a tracking antenna, means responsive to said modified interpolation signals and to said signals which define the momentary position of said antenna for developing antenna position error signals, and means for employing said error signals for directing said tracking antenna continuously toward said selected satellite.

5. The combination as defined in claim 4 wherein said means for accumulating data defining the expected positions and velocities at specified times of each of a number of orbiting satellites comprises, means for receiving position, velocity and time signals from a common computation center, means for storing said received signals, and means for selectively reading out said stored signals at specified times.

6. The combination as defined in claim 4 wherein said means for selectively modifying said interpolation signals to correct for errors comprises, means for developing position signals which exhibit defined perturbations, and means for selectively combining said perturbed position signals and said position and velocity signals developed by said interpolation means.

7. The combination as defined in claim 4 wherein said means for selectively modifying said interpolation signals comprises, means for developing signals which define a prescribed spiral scan pattern, means for developing signals which define a prescribed offset pattern, and means for selectively combining said spiral scan signals and said offset signals with said interpolation position and velocity signals.

8. In an antenna control system which includes, means responsive to a stored record for developing first signals which define the position and velocity of an orbiting satellite at each of a number of specified times with relation to a tracking antenna, and means responsive to control signals for continuously directing a tracking antenna toward an orbiting satellite; means for developing antenna pointing signals which comprise, in combination: means responsive to said position and velocity defining signals for developing second signals which define the position and velocity of said satellite at each of other times intermediate said specified times, means for generating auxiliary position signals, means for modifying said second signals by the selective addition of said auxiliary position signals, means for developing pointing signals which define the momentary pointing direction of said tracking antenna, means for comparing said modified said second signals and said pointing direction signals to produce difference signals, means responsive to said difference signals for producing antenna control signals, and means for employing said control signals for directing said tracking antenna continuously toward said orbiting satellite.

9. In a control system for developing antenna pointing signals, the combination which comprises: a ground station which includes a tracking antenna, means for directing said tracking antenna toward an orbiting satellite, means responsive to data which defines the expected positions and velocities at discrete selected times only of each of a number of orbiting satellites supplied from a common computation center for developing a first set of signals representative of said data, means responsive to said first set of signals for interpolating between the positions specified for each of said satellites at said specified times thereby to produce a second set of signals which define the positions of each of said satellites at other selected times, means for selectively correcting interpolation errors in said second set of signals in accordance with a prescribed schedule, means for developing a third set of signals which define the momentary position of said tracking antenna, means for comparing said third set of signals and said second set of signals, means responsive to said comparison for producing a fourth set of signals which define the errors between said second and third

sets of signals, and means for utilizing said fourth set of signals for actuating said antenna directing means.

10. Apparatus for developing signals which momentarily define the position of an orbiting satellite with relation to a specified ground location in response to infrequent data defining the momentary position of said satellite which comprises: means for storing signals which define the orbital position of said satellite at specified times, means for storing signals which define predicted changes in said orbital positions at specified times, means for incrementally altering said signals which define said orbital positions of said satellite in accordance with said signals which define said predicted changes, and means for selectively combining said incrementally altered signals with said orbital position signals to develop an output signal.

11. Apparatus for developing signals which momentarily define the positions of each of a plurality of orbiting satellites at discrete selected instants only with relation to a specified ground station location in response to data periodically supplied from a distant computation center, which comprises: means for receiving signals from a distant computation center which define spaced future position and velocity of each of a plurality of satellites; means for storing said received signals; means for continuously and independently reading out said stored signals which are together definitive of the position and velocity of a selected satellite at a specified time; means for linearly interpolating between position signals which define the position of each of said satellites at a first specified time to position signals which define the position of each of said satellites at a second specified time at a rate determined by the magnitudes of corresponding velocity signals at said first and second times, thereby to produce interpolation signals; means for continuously modifying said interpolation signals to correct for interpolation errors; means for selectively combining said received position signals with said interpolation signals to develop output signals; and means for utilizing said output signals to direct an antenna selectively toward one of said satellites.

12. A program track system for developing relatively continuous antenna pointing signals, which comprises, in combination: means for receiving from a distant computation center digital data which defines the expected positions and velocities at discrete selected times only of each of a number of orbiting satellites; means for storing said digital data; means for continuously reading out said digital data to produce sequences of digital pulse signals; linear interpolation means responsive to said digital data for developing position and velocity specifications for each of said satellites at other specified times which comprises, signal processing means including, means for storing digital pulse signals, means for selectively converting said digital signals to analog signals, means for incrementally altering the magnitude of said analog signals linearly in accordance with a scheduled dependent on said velocity specifications, means for converting incrementally altered signals into digital signals, means for continuously altering said sequences of pulse signals representative of said received position specifications in accordance with said altered digital signals to produce interpolated digital signals, means for developing digital signals which define the momentary position of a tracking antenna, means for converting said antenna position signals into analog signals, means for converting said interpolated digital signals into analog signals, means for algebraically combining said analog antenna position signals and said analog interpolated signals to produce error signals, and means for converting said analog error signals into digital error signals.

13. A program track system as defined in claim 12 wherein, said means for receiving digital data comprises: a teletypewriter receiver equipped with means for preparing a record of said received data, and wherein said

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means for continuously reading out said digital data comprises a teletypewriter reader supplied with said record.

14. A program track system as defined in claim 12 wherein, said signal processing means included in said linear interpolation means are characterized by the separate processing, both in digital and in analog form, of those signals representative of the most significant portions of said position and velocity specifications, and of those signals representative of the least significant portions of said position and velocity specifications.

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