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An Auto-Tracking Antenna System

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CONTENTS

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ABSTRACT

A systematic approach has been made to the design of a digital auto-tracking antenna system. When such a system is converted from a manual tracking system, the main design criteria of accuracy, reliability, ease of maintenance, and minimum cost are advanced by designing the new system around one of the present modes of operation. An optimum technique to convert from a manual tracking antenna system to an auto-tracking antenna system is made possible by the commercial availability of low-cost and accurate digital-to-synchro (D/S) converters and the development of a special-purpose system controller, the automatic control unit ACU-1. The auto-tracking system is designed to relieve the system operator of menial tasks while taking maximum advantage of his ability to make decisions.

In the example of this report, an operator prepares a punched-paper tape using an off-line computer. He then verifies the tape to insure accuracy. The azimuth and elevation information for two antennas is stored on the paper tape in binary form. The tape is read by the ACU-1, which reformats and transmits the digital data at specific time intervals to a D/S converter for each antenna. The converter outputs synchro position data through the previously existing manual command unit to the pedestal drive circuitry in a servo control loop, also previously existing. The auto-tracking process is started at a preset time and automatically stops at the completion of the specific task. Audio alarms are used to alert the operator to system malfunctions.

PROBLEM STATUS

This is a final report on one phase of the NRL problem.

AUTHORIZATION

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AN AUTO-TRACKING ANTENNA SYSTEM

INTRODUCTION

Many directional tracking antenna systems presently in operation were designed for manual operation. An operator is required to manually position the antenna through a position synchro or through a servo rate-control system. These systems require constant updating by a skilled operator as data are monitored from a moving signal source. The operator requires a starting azimuth, elevation, and time as well as a constantly radiating beacon on the source which he can monitor. Once the operator has initially acquired the source, he can follow it by trial-and-error positioning of the antennas. The received signal-to-noise ratio (S/N) of the beacon is the figure of merit. This tracking technique has the disadvantage of potentially large variations in S/N as the operator performs his trial-and-error iterations. The operator may even lose track of the source completely, and the source may be very difficult to locate again.

Against signal sources such as satellites which have a predictable or programmable flight pattern, a better approach to tracking is to supply the operator with detailed tracking information. For example the operator could be supplied with a table of azimuth and elevation headings as a function of time. The operator is then required to update the antenna system to a predetermined position at specific time intervals. This of course requires detailed, accurate information about the movement of the source to be monitored.

Many tracking systems typically require the use of both techniques. The first method is used when detailed information about the source is not available. This corresponds to the initial stages of a project or when it is initially determined that a source would be desirable to monitor. The second method is used when detailed information is available about the source.

With the advent of good, reliable, and accurate digital-to-analog converters it has become possible to update manual tracking systems to automatic/manual tracking systems at a minimum cost. This allows an operator to control an antenna system manually when this is the optimum mode of operation, as in the first tracking method discussed. It also allows a system controller unit or similar piece of equipment to control the antennas when such is the optimum mode of operation, as in the second method, when detailed information is available about the source to be tracked.

An antenna system typical of the manual tracking systems mentioned has been in use in the Space Systems Division of the Naval Research Laboratory for several years. This is the Scientific-Atlanta, Inc., model J330 tracking pedestal set. (The appendix gives a detailed discussion of this system.) Figure 1 is a simplified block diagram of this system. This diagram shows signal loops for only one axis of rotation because the electrical systems for both the azimuth and elevation axes are identical and operate independently. Each axis of the antenna pedestal may be operated in the slave (remote input), manual-rate, manual-position, or standby mode (the two axes usually being operated in the same mode). A synchro output is provided for remote position indication or for slaving other equipment to the pedestal.

Primary limit-switches on each pedestal axis determine the rotation sector within a normal adjustment range of ±360 degrees in azimuth and 0 to 180 degrees in elevation.

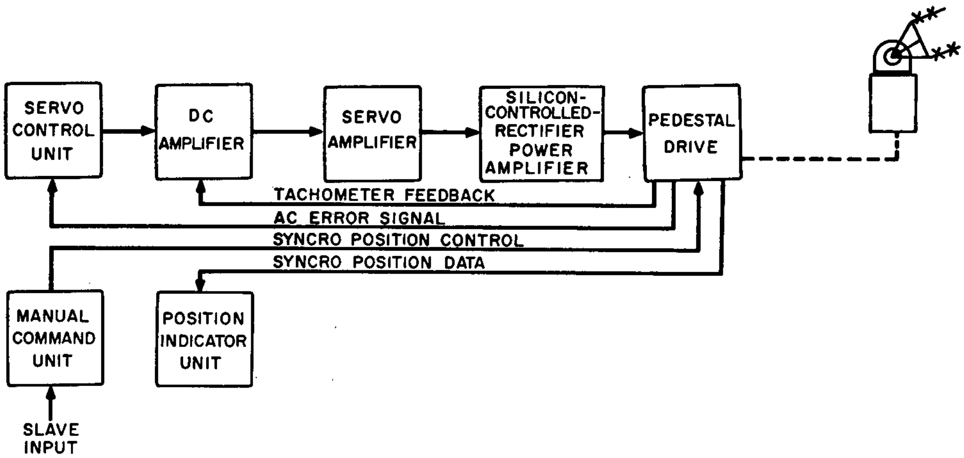

Fig. 1 - Scientific Atlanta, Inc., model J330 tracking antenna system

Rotation of an axis to either limit actuates the proper limit switch, which de-energizes the drive mechanism, applies the brakes, and lights the appropriate limit indicator on the servo control unit panel. An automatic backout circuit permits a pedestal axis in any mode to be rotated in the direction opposite to that in which the limit switch was actuated.

Secondary limit-switches are provided on the azimuth axis to prevent damage to the cable wrapup if a primary limit switch fails; these switches are set to actuate at approximately ±370 degrees. Actuation of either secondary limit switch removes the azimuth drive, applies the brakes, and lights both azimuth limit indicators. Backout from a secondary limit must be accomplished with mechanical hand drives on the pedestal; no electrical backout is provided from the secondary limit.

The four modes of operating the antenna system consist of three primary modes and the standby mode. In all three primary modes a closed loop is formed to control position. However, the type of closed loop is different for the different modes.

In the manual-rate mode of operation the antenna is rotated at a speed set by a front-panel rate control on the servo control unit. The control operates a potentiometer which supplies a dc voltage input to the error amplifier chain. The magnitude and polarity of the dc voltage determines the speed and direction of rotation of the antenna, which will rotate at a constant speed until the rate control is changed manually or a limit switch is reached. A dc tachometer feedback voltage is compared with a dc input voltage to insure a constant rotation rate. This of course requires an operator's judgment and attention to determine the optimum speed and when and in what position the antenna is to be stopped. Figure 2 shows a simplified block diagram of two forms the closed control loop might take. There would be no closed loop if there were no operator in this mode of operation. Therefore, constant operator attention is required. For example, when the pedestal drive is not activated, the antenna may drift from the position it was left in. This drifting becomes particularly severe when the unsymmetrical wind loading on the antenna is high.

Another mode of operation is the manual-position mode. The operator positions the pedestal by rotating a synchro transmitter shaft manually via a front-panel handcrank on the manual command unit (Fig. 3). The synchro position data from this synchro transmitter is compared to actual pedestal position by a synchro control transformer at the pedestal. The ac error signal derived from the synchro control transformer is applied

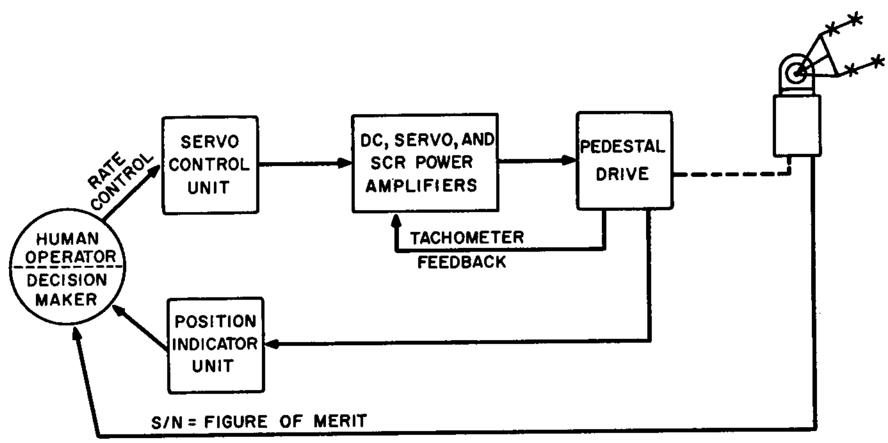

Fig. 2 - Manual-rate mode of operation of the model J330 tracking antenna system

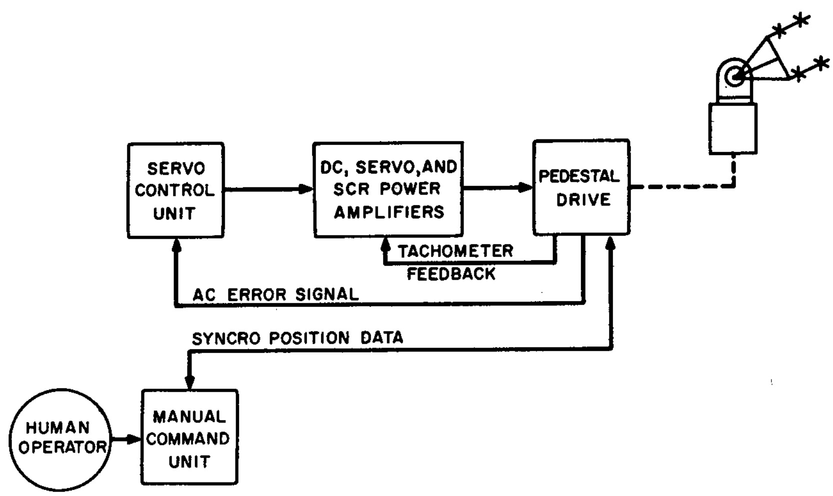

Fig. 3 - Manual-position mode of operation of the model J330 tracking antenna system

to a demodulator circuit in the servo control unit. The ac error signal, which is proportional to the angular error between the shaft of the synchro transmitter and the pedestal drive shaft, is converted to a dc error signal in the demodulator circuit of the servo control unit. The dc error signal is then used to drive the pedestal shaft in a direction to reduce the error to zero and make the position of the control transformer shaft coincide with that of the transmitter shaft. Stable operation of the servo and pedestal in this mode is insured by appropriate tachometer feedback and compensation. The human operator merely sets the desired position into the manual command unit. He is then out of the control loop until the next position update.

The third mode of operation is the slave mode (Fig. 4). This mode of operation is identical to the manual-position mode except that the synchro position data are not generated by the synchro transmitters located in the manual command unit. The synchro position data come from another source, but they must be identical to the output of the

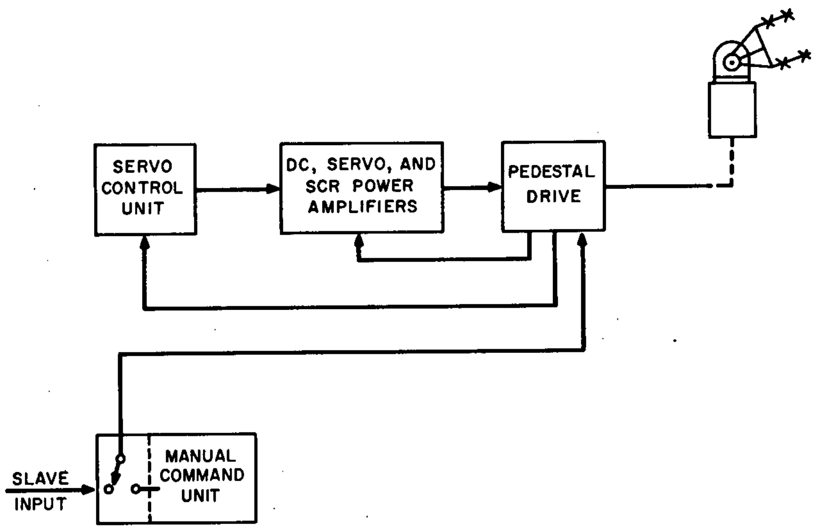

Fig. 4 - Slave mode of operation of the model J330 tracking antenna system

synchro transmitters in the manual command unit. This mode of operation allows sets of antennas to be slaved together for ease of operation.

SYSTEM DESIGN

When converting a manual tracking system into an auto-tracking system, the main design criteria should be accuracy, reliability, ease of maintenance, ease of operation, and minimum cost. All of these design criteria are enhanced when a minimum of new equipment is required to realize the conversion. The obvious way to minimize new equipment is to design the auto-tracking system around one of the present modes of operation. The modes of operation available for use are those represented in Figs. 2, 3, and 4. For this particular application the operation of the slave mode (Fig. 4) can be considered the same as operation of the manual-position mode (Fig. 3). Therefore consideration will be given to designing the auto-tracking system around the manual-rate mode of operation (Fig. 2) and the manual-position mode of operation.

Figure 5 represents a reasonable approach using the manual-rate mode of operation. The antenna-position information is stored digitally on punched-paper tape and compared with the actual antenna position from the synchro-to-digital converter. If the two positions do not compare favorably, an error signal activates the rate control in the servo control unit. The control unit determines the time between updates and insures that the digital comparator receives digital information in the proper format. This approach requires that four additional functions be added to the existing manual system: synchro-to-digital (S/D) converter, digital comparator and error generator, control, and digital storage. The system in Fig. 5 uses the existing rate-control loop and adds a position-control loop. That is, the antennas are held in the proper position only by the continuous comparison of the actual position and the desired position. In implementing this system, care must be taken to eliminate the possibility of oscillations; hence a damping factor must be designed into the comparator and error generator function. This method of converting manual tracking systems to auto-tracking systems has been the standard method until this time.

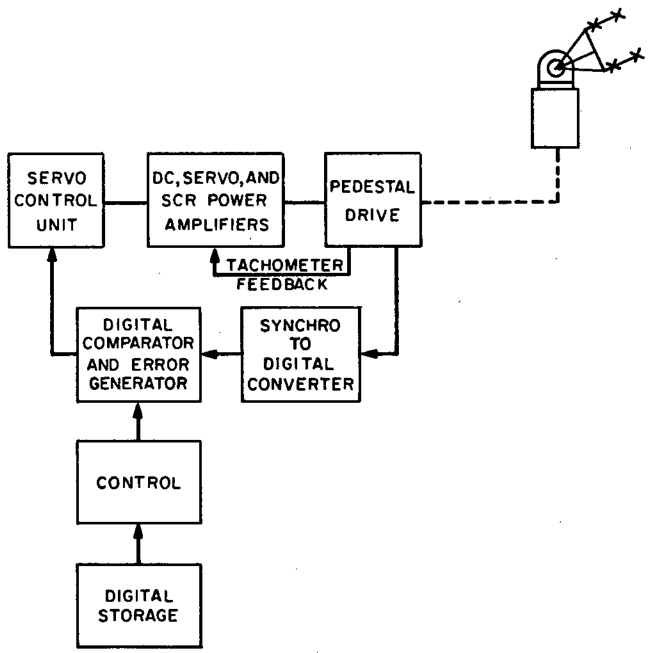

Fig. 5 - Design of an auto-tracking system using the manual-rate mode of operation shown in Fig. 2

When an auto-tracking system is instead designed around the manual-position mode of operation, the system may be somewhat simplified. Figure 6 represents a reasonable approach to the design of an auto-tracking system around the manual-position mode of operation. The antenna-position information is stored digitally and converted to synchro information by the digital-to-synchro (D/S) converter. The control unit determines the time between updates and insures that the D/S converter receives the digital information in the proper format. This approach requires that three additional functions be added to the existing manual system: digital storage, control, and a D/S converter, This system uses two existing control loops: the rate control loop and the position control loop.

To compare the two techniques for updating a manual tracking system to an auto-tracking system, one must apply the design criteria of accuracy, reliability, ease of maintenance, ease of operation, and minimum cost. The accuracies associated with the model J330 tracking pedestal will be given later in Table 1. Both techniques use the same synchros, and the additional components used in updating are significantly more accurate than the synchros. Therefore accuracy is not the major consideration in the comparison. Reliability, ease of maintenance, ease of operation, and minimum cost are optimized when the number of new functions required by the system is minimized. Designing the auto-tracking system around the manual-rate mode of operation requires the addition of four functions: storage, control, a S/D converter, and the digital comparator and error generator. Designing the auto-tracking system around the manual-position mode of operation requires the addition of only three new functions: storage, control, and a D/S converter. Thus a more optimized auto-tracking system will result when it is designed around the manual-position mode of operation.

Several manufacturers produce D/S converters. They may be designed to accept true binary or binary-coded decimal (BCD) data. All accept the digital input in a parallel

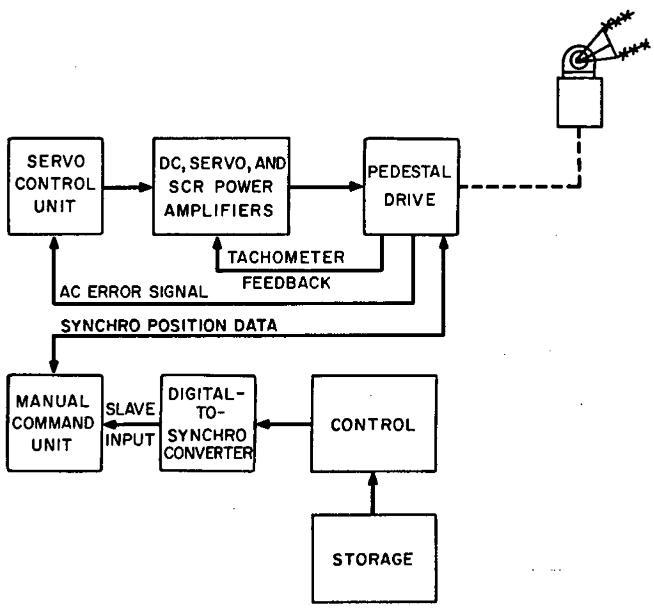

Fig. 6 - Design of an auto-tracking system using the manual-position mode of operation shown in Fig. 3

fashion. The D/S converters that operate on straight binary information allow the amount of information stored to be minimized. This is a result of binary coding being more efficient than BCD coding. The interface between the control and storage portion of the system and the D/S converter is greatly simplified if the D/S converter does not require the digital input to be always present. This can be implemented by a D/S converter that accepts input data that are strobed into it and then stores this information until it is updated by another strobe signal.

The control and storage portion of the digital auto-tracking system may be implemented several ways. A computer can be used to perform this function. The smallest minicomputer is capable of relatively large storage and fast input and output. Using a computer in place of the control and storage portion of the system may be advantageous if the source to be tracked is moving extremely fast, requiring many updates over a short period of time; if many different types of sources are to be tracked, requiring a great amount of versatility; if the source to be tracked follows a very complex trajectory; or if the computer can do other jobs when it is not controlling the antenna system. Generally a computer will not be efficiently used unless the particular application is unusual and complex. If a computer is not used, control and storage must be considered as separate entities.

Three main techniques for storing digital information could apply to this application: magnetic tape, IBM cards, or punched-paper tape. Magnetic tape allows large amounts of digital information to be stored reliably and compactly. The information on magnetic tape may be accessed at a high rate. However, magnetic-tape readers are generally temperamental devices that require special controlled operating environments, and a great deal of maintenance. They also are relatively expensive. An IBM card allows a maximum of 960 bits of data storage. For many applications this is insufficient. The greatest disadvantage of using IBM cards is that incremental card readers are unreliable and relatively expensive; hence this type of storage is not recommended. Punched-paper-tape storage gives a good cost-efficiency tradeoff. A maximum of 80 bits per inch of data can be stored on an eight-level tape, and since the tape can be made any length, the amount of storage is not a problem. Paper-tape readers are relatively inexpensive and reliable. In conclusion, for this application, paper-tape storage is the most cost effective.

Some device must control the auto-tracking process and thus relieve the human operator of the tedious job of operating the routine portion of the auto-tracking process. This device, called the controller, should (a) start the tracking process at a predetermined time, (b) control the information flow from the storage device into the D/S converter, reformatting the data where necessary, and (c) monitor certain critical aspects of the system and sound an alarm if there is a malfunction. Figure 7 shows the D/S converter, the controller, and paper-tape storage for a typical auto-tracking system.

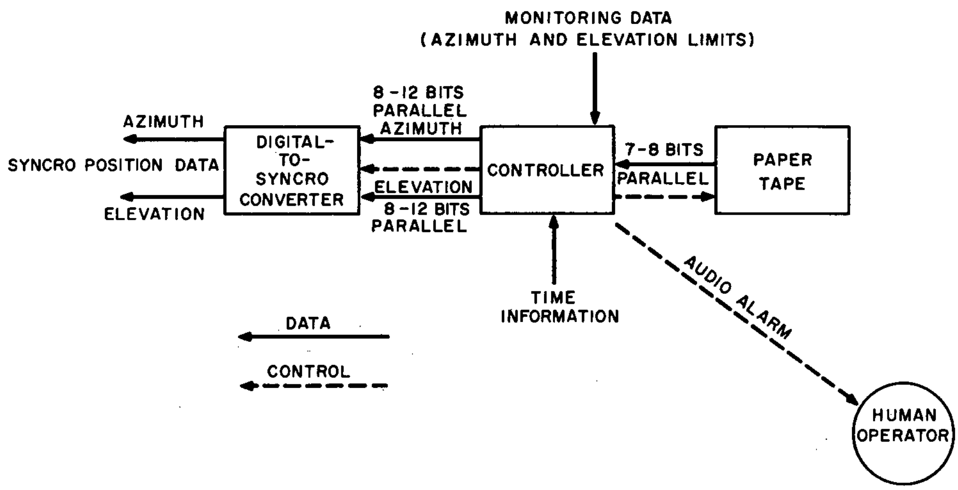

Fig. 7 - Additional equipment required to update a manual tracking system into an auto-tracking system by using the manual-position mode of operation as shown in Fig. 6

The auto-tracking system must be able to position the antennas at least as accurately as the manual tracking system. This means that the absolute positioning error for the auto-tracking system must not exceed that of the manual tracking system. For various loops of the updated system and the original manual system as shown in Fig. 8, Table 1 compares the error contributions. All values are taken from the appropriate specifications of the manufacturers. The loop marked X denotes the rate control loop that is common to both the auto-tracking and manual tracking systems. The positioning error contributed by this loop is denoted by ΔX and is the same for both auto-tracking and manual tracking. The loop marked Y is the manual position-control loop. The errors associated with this loop are ΔY_1, ΔY_2, and ΔY_3. The error components of the auto-tracking system which correspond to the ΔY's are ΔZ_1, ΔZ_2, and ΔZ_3. The position error contributed by the synchro in the pedestal is the same for both cases; therefore, $\Delta Y_3 = \Delta Z_3$. The only errors that the designer has any control over in keeping the auto-tracking system at least as accurate as the manual tracking system are ΔZ_1 and ΔZ_2 in the D/S converter.

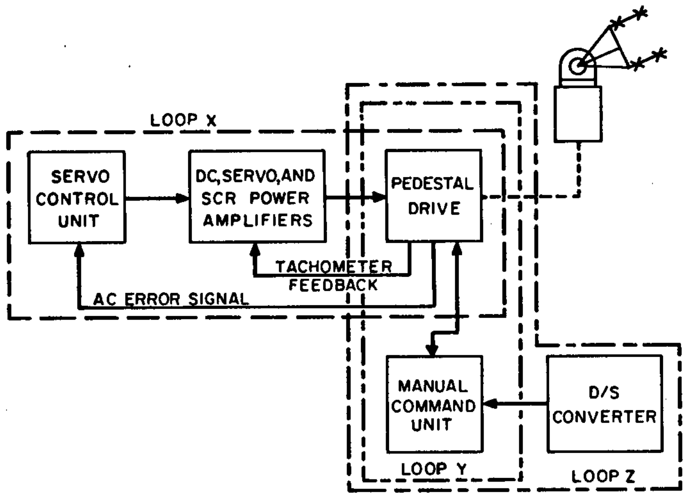

Fig. 8 - Three error-contributing loops of the system shown in Fig. 6

Table 1
Errors Associated with the Loops Indicated in Fig. 8, with Loop X being the Rate Control Loop Common to the Manual System and the Auto-Tracking System, Loop Y the Position-Control Loop of the Manual System, and Loop Z the Position-Control Loop of the Auto-Tracking System

Loop X	
ΔX	= positioning error from the rate control loop = $\pm 0.25°$
Loop Y	
Y_0	= position increment of the manual command unit = $1°$
ΔY_1	= position error of the manual command unit = $\pm 0.5°$
ΔY_2	= synchro error of the manual command unit = $\pm 0.1°$
ΔY_3	= position error of the pedestal drive synchro = $\pm 0.1°$
Loop Z	
Z_0	= minimum position increment of the D/S converter = $0.35°$
ΔZ_1	= minimum position error of the D/S converter = $\pm 0.175°$
ΔZ_2	= output error of the D/S converter synchro = $\pm 0.05°$
ΔZ_3	= position error of the pedestal drive synchro = $\pm 0.1°$

Since the position error in the auto-tracking system must be no greater than the position error in the manual tracking system, then

$$\Delta Z \leq \Delta Y .$$

But

$$\Delta Z_3 = \Delta Y_3 \ .$$

Hence

$$|\Delta Z_1| + |\Delta Z_2| \le |\Delta Y_1| + |\Delta Y_2| \ ,$$

$$\Delta Z_1 + 0.05^\circ \le 0.5^\circ + 0.1^\circ \ ,$$

$$|\Delta Z_1| \le 0.6^\circ - 0.05^\circ = 0.55^\circ \ ,$$

$$\Delta Z_1 \le \pm 0.55^\circ \ .$$

For $\Delta Z_1 \le \pm 0.55^\circ$ the position increments from the D/S converter must be less than or equal to 0.55 + 0.55 or 1.1°. A table of position increments versus bits is given in Table 2 for both azimuth and elevation. The difference between the two is that the antennas must be able to travel between 0° and 360° in azimuth but only 0° to 180° in elevation. From Table 2 it can be seen that to meet the accuracy criterian nine bits are needed for the azimuth D/S converter channel and eight bits are needed for the elevation channel. Off-the-shelf D/S converters are available with ten bits of accuracy, not nine. Therefore a D/S converter with ten bits of accuracy should be used for the azimuth channel. The ten-bit D/S converter should also be chosen for the elevation channel; this allows both azimuth and elevation channels to be identical.

Table 2
Number of Bits Needed for a Given Position Increment

Position Increment	Number of Bits Needed		Position Increment	Number of Bits Needed	
	Azimuth	Elevation		Azimuth	Elevation
180°	1	-	5.625°	6	5
90°	2	1	2.8125°	7	6
45°	3	2	1.40625°	8	7
22.5°	4	3	0.703125°	9	8
11.25°	5	4	0.3515675°	10	9

Auto-tracking systems converted from Model J330 manual tracking systems are to be used by NRL in a particular application. This auto-tracking system will be the subject of the rest of the report. At each location where the auto-tracking system will be used, there are two antenna systems (Fig. 9). One system is called system 1 or the primary (PRIM) system, and the other system is called system 2 or the secondary (SEC) system. If the control and storage functions are not common to both antenna systems, then they must be duplicated. However, as shown in Fig. 9, the control and storage can be shared; in fact, this is the more optimum mode of operation. This means that the paper tape must store the azimuth and elevation updates for both antenna systems. To update both systems one time requires 40 bits of information.

Data are packed on the tape in the most efficient means possible. The position data are put on the tape eight bits per line in a true binary form, with the presence or absence

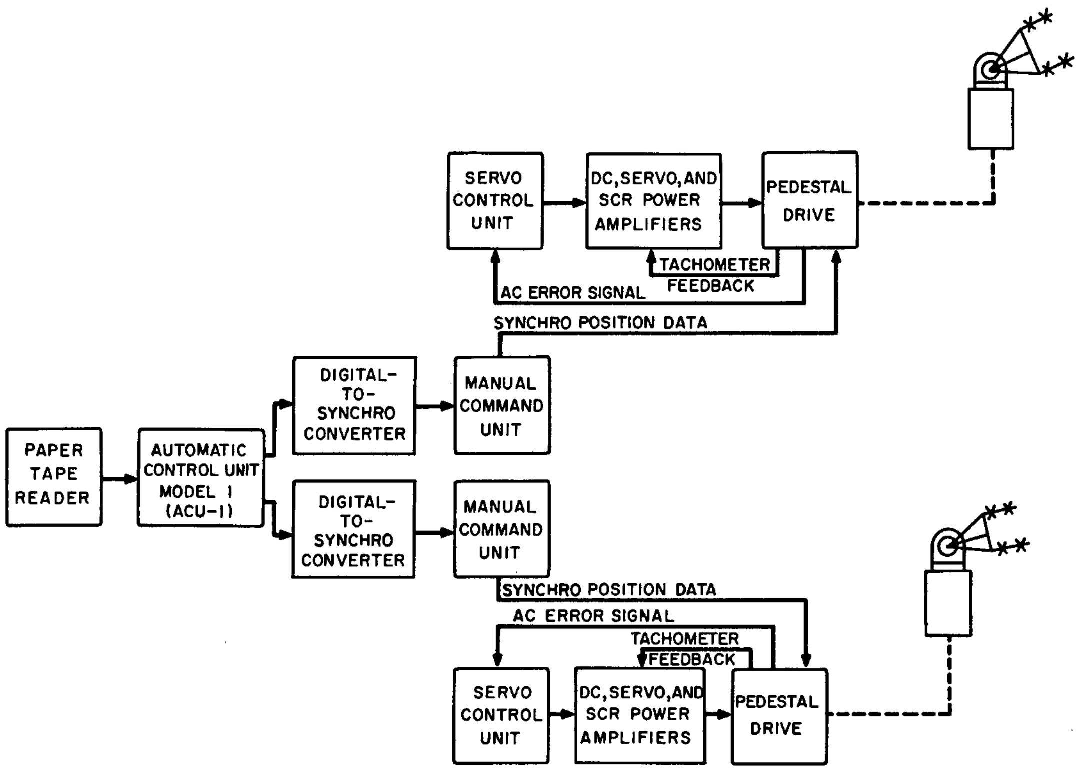

Fig. 9 - Design of the auto-tracking system with two antenna systems that is the subject of this report and is a particular example of the concept shown in Fig. 6

of sprocket holes distinguishing lines of data from blank tape. The position information for two antenna systems is placed on one tape (Fig. 10). The first ten bits read are azimuth information for system 1, the second ten bits are elevation information for system 1, the third ten bits are azimuth information for system 2, and the fourth ten bits are elevation information for system 2.

DESIGN OF THE SYSTEM CONTROLLER: THE AUTOMATIC CONTROL UNIT, MODEL 1 (ACU-1)

The system controller must increment the tape reader as necessary, read five lines of data from the paper tape, reformat the digital position data, transmit the digital position data in parallel to the D/S converter, strobe this information into the D/S converter, and repeat the preceding steps until tracking is terminated. It must also monitor the limit signals from the antenna systems and output an audio alarm if an antenna hits a limit. The system controller should have the capability of manual start, manual stop, automatic start, and automatic stop. A block diagram of the ACU-1 and the functions it interfaces with is shown in Fig. 11. The clock signal is a 1-pulse-per-second (1-pps) TTL-compatible signal that is on for 200 ms and off for 800 ms. The BCD time of day is updated by the time code generator once per second on the trailing edge of the 1-pps clock signal. Registers F1 and F2 are buffer registers located in the D/S converters. Information may be stored in the registers and updated periodically. The D/S converters continuously monitor the contents of F1 and F2.

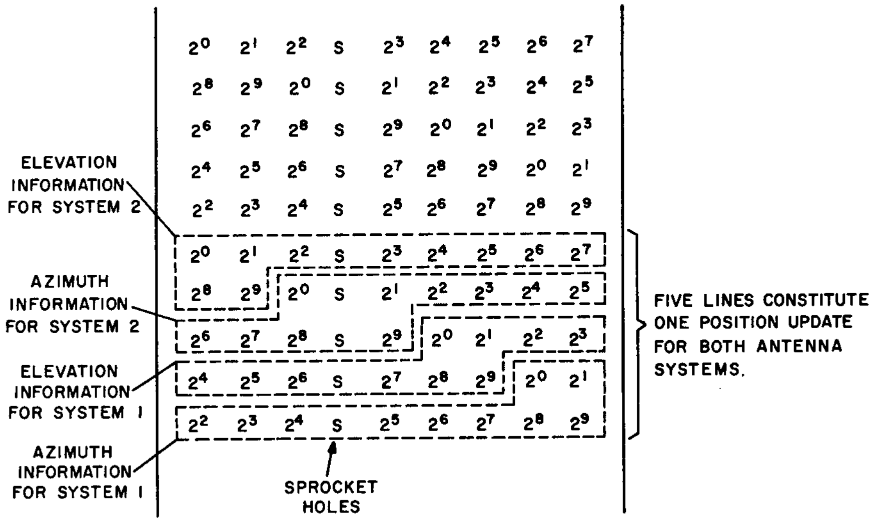

Fig. 10 - Data format on the punched-paper tape for the system of Fig. 9

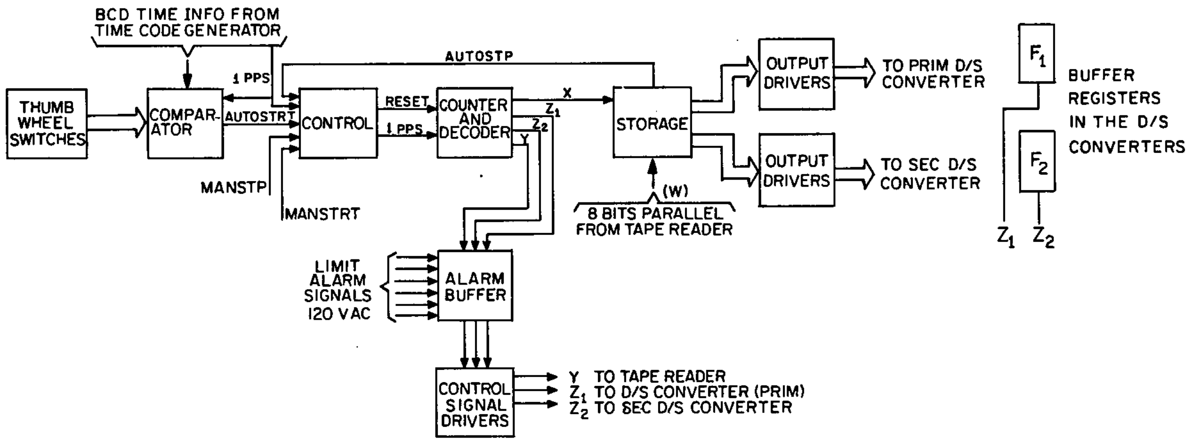

Fig. 11 - The automatic control unit, model 1 (ACU-1), and portions of the system it interfaces with. The two antennas in Fig. 9 are identified here as the primary (PRIM) and secondary (SEC) antenna systems

The most basic function of the ACU-1 is the control of the auto-tracking system; that is, to increment the paper tape, read the data necessary for an antenna position update, and output this data to the appropriate D/S converter. These functions are controlled by a 15-cycle sequence generated by the subinterval counter. This counter is clocked by a 1-pps signal that is generated by the time code generator. The transfer relations* of this counter are

$$
\begin{array}{l|r}
\bar{Q}_s p_0 & P + 1 \rightarrow P \\
\bar{Q}_s p_1 & P + 1 \rightarrow P \\
\bar{Q}_s p_2 & P + 1 \rightarrow P \\
\bar{Q}_s p_3 & P + 1 \rightarrow P \\
\bar{Q}_s p_4 & P + 1 \rightarrow P \\
\bar{Q}_s p_5 & P + 1 \rightarrow P \\
\bar{Q}_s p_6 & P + 1 \rightarrow P \\
\bar{Q}_s p_7 & P + 1 \rightarrow P \\
\bar{Q}_s p_8 & P + 1 \rightarrow P \\
\bar{Q}_s p_9 & P + 1 \rightarrow P \\
\bar{Q}_s p_{10} & P + 1 \rightarrow P \\
\bar{Q}_s p_{11} & P + 1 \rightarrow P \\
\bar{Q}_s p_{12} & P + 1 \rightarrow P \\
\bar{Q}_s p_{13} & P + 1 \rightarrow P \\
\bar{Q}_s p_{14} & 0 \rightarrow P
\end{array}
$$

The design equation for this counter can be derived from the following table which assumes the use of trailing-edge-triggered toggle flip-flops. A ripple counter is considered here, because the speed requirements do not require anything more complex.

*The variables and the transfer relations used in this report are described in detail in "Theory and Design of Digital Machines," by T. C. Bartee, I. L. Lebow, and I. S. Reed (New York: McGraw-Hill, 1962).

Clock	T_4	T_3	T_2	T_1	Q_4	Q_3	Q_2	Q_1
1	–	–	–	TE*	0	0	0	0
1	–	–	TE	TE	0	0	0	1
1	–	–	–	TE	0	0	1	0
1	–	TE	TE	TE	0	0	1	1
1	–	–	–	TE	0	1	0	0
1	–	–	TE	TE	0	1	0	1
1	–	–	–	TE	0	1	1	0
1	TE	TE	TE	TE	0	1	1	1
1	–	–	–	TE	1	0	0	0
1	–	–	TE	TE	1	0	0	1
1	–	–	–	TE	1	0	1	0
1	–	TE	TE	TE	1	0	1	1
1	–	–	–	TE	1	1	0	0
1	–	–	TE	TE	1	1	0	1
1	TE	TE	TE	–	1	1	1	0

*Trailing edge.

The equations by inspection are

$$T_4 = Q_3 \ ,$$

$$T_3 = Q_2 \ ,$$

$$T_2 = Q_1 + \text{clock}\ (Q_4 \cdot Q_3 \cdot Q_2) \ ,$$

$$T_1 = \text{clock}\ (\bar{Q}_4 + \bar{Q}_3 + \bar{Q}_2)$$

$$= \text{clock}\ \overline{(Q_4 \cdot Q_3 \cdot Q_2)} \ .$$

This design allows a medium-scale-integration four-bit binary ripple counter to be used in implementing the subinterval counter. Figure 12a shows the implementation of the counter.

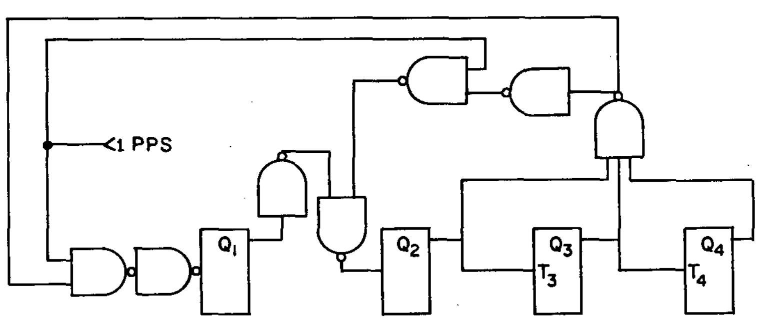

Fig. 12a - Subinterval counter

The transfers that take place during each sequence of the subinterval counter are shown below.

$\bar{Q}_s p_0$	Y = increment the tape reader
$\bar{Q}_s p_1$	X = read word into storage
$\bar{Q}_s p_2$	Y
$\bar{Q}_s p_3$	X
$\bar{Q}_s p_4$	Y
$\bar{Q}_s p_5$	X
$\bar{Q}_s p_6$	Y
$\bar{Q}_s p_7$	X
$\bar{Q}_s p_8$	Y
$\bar{Q}_s p_9$	X
$\bar{Q}_s p_{10}$	Z_1 = strobe data into primary D/S converter
$\bar{Q}_s p_{11}$	Z_2 = strobe data into secondary D/S converter
$\bar{Q}_s p_{12}$	-
$\bar{Q}_s p_{13}$	-
$\bar{Q}_s p_{14}$	-

During $\bar{Q}_s(p_0, p_2, p_4, p_6, p_8)$ a pulse is generated and transmitted to the tape reader. This pulse increments the paper tape to the next word. During $\bar{Q}_s(p_1, p_3, p_5, p_7, p_9)$ the word on the paper tape is read and stored in the storage area of the ACU-1. This storage area consists of five eight-bit shift registers: A_I, B_I, C_I, D_I, and E_I. The data flow into the storage area is controlled by the preceding transfer relations. The design procedure to implement the proceeding transfer relations follows. The circuitry can be minimized if loops can be implemented that are common to more than one of the output functions Y, X, Z_1, and Z_2. By selecting the proper binary count sequence and by assigning the output functions as shown, the Karnaugh map shown in Fig. 12b can be made.

Count Sequence	Count				Output Function
	Q_4	Q_3	Q_2	Q_1	
$\bar{Q}_s p_0$	0	0	0	0	Y
$\bar{Q}_s p_1$	0	0	0	1	X
$\bar{Q}_s p_2$	0	0	1	0	Y
$\bar{Q}_s p_3$	0	0	1	1	X
$\bar{Q}_s p_4$	0	1	0	0	Y
$\bar{Q}_s p_5$	0	1	0	1	X
$\bar{Q}_s p_6$	0	1	1	0	Y
$\bar{Q}_s p_7$	0	1	1	1	X
$\bar{Q}_s p_8$	1	0	0	0	Y
$\bar{Q}_s p_9$	1	0	0	1	X
$\bar{Q}_s p_{10}$	1	0	1	0	Z_1
$\bar{Q}_s p_{11}$	1	0	1	1	Z_2
$\bar{Q}_s p_{12}$	1	1	0	0	-
$\bar{Q}_s p_{13}$	1	1	0	1	-
$\bar{Q}_s p_{14}$	1	1	1	0	-

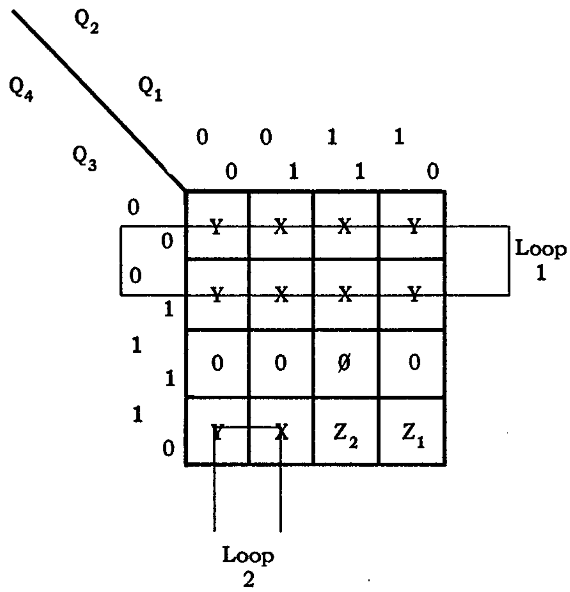

Fig. 12b - Karnaugh map corresponding to the assignment of output functions tabulated

Selecting loops 1 and 2 which are both common to the output functions X and Y, the following equations may be written:

$$\text{Loop } 1 = \bar{Q}_4 ,$$

$$\text{Loop } 2 = \bar{Q}_3 \bar{Q}_2 ,$$

$$X + Y = \bar{Q}_4 + \bar{Q}_3 \bar{Q}_2 .$$

The equations for the output functions can be written as

$$Y = (1\ \text{pps})(\bar{Q}_1)(\bar{Q}_4 + \bar{Q}_3\bar{Q}_2)\ ,$$

$$X = (1\ \text{pps})(Q_1)(\bar{Q}_4 + \bar{Q}_3\bar{Q}_2)$$

and similarly

$$Z_1 = (1\ \text{pps})(\bar{Q}_1)(Q_2 \cdot \bar{Q}_3 \cdot Q_4)\ ,$$

$$Z_2 = (1\ \text{pps})(Q_1)(Q_2 \cdot \bar{Q}_3 \cdot Q_4)\ .$$

Figure 12c shows the logic implementation of the equations for Y, X, Z_1, and Z_2. Figure 13 is the circuitry on the actual printed circuit card that is used to implement this subinterval counter and decoder.

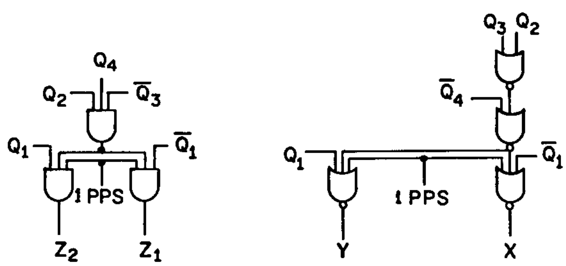

Fig. 12c - Decoder logic

The auto-tracking system should begin operation when it receives either a manually generated asynchronous start signal or when a preset time is reached. Time of day is available continuously in a BCD format from an existing time code generator. When the BCD output of the time code generator coincides with the preset time, a synchronous auto-start signal should be generated. The transfer relation of this is

$$Q_s p_0 \ \Big|\ \overline{(\text{MANSTRT} + \text{AUTOSTRT}) \cdot Q_s} \longrightarrow Q_s\ .$$

The preset time which is compared with the BCD time of day is selected via thumbwheel switches. Twenty signal lines are required to specify the time of day (hours, minutes, seconds) in BCD format. Figure 14 is a block diagram showing the generation of the auto-start signal:

$$\text{AUTOSTRT} = (p_0 + 1)(\overline{T \oplus G})\ .$$

Figure 15 is the actual schematic. The auto-start function is implemented using medium-scale-integration dual four-bit comparators.

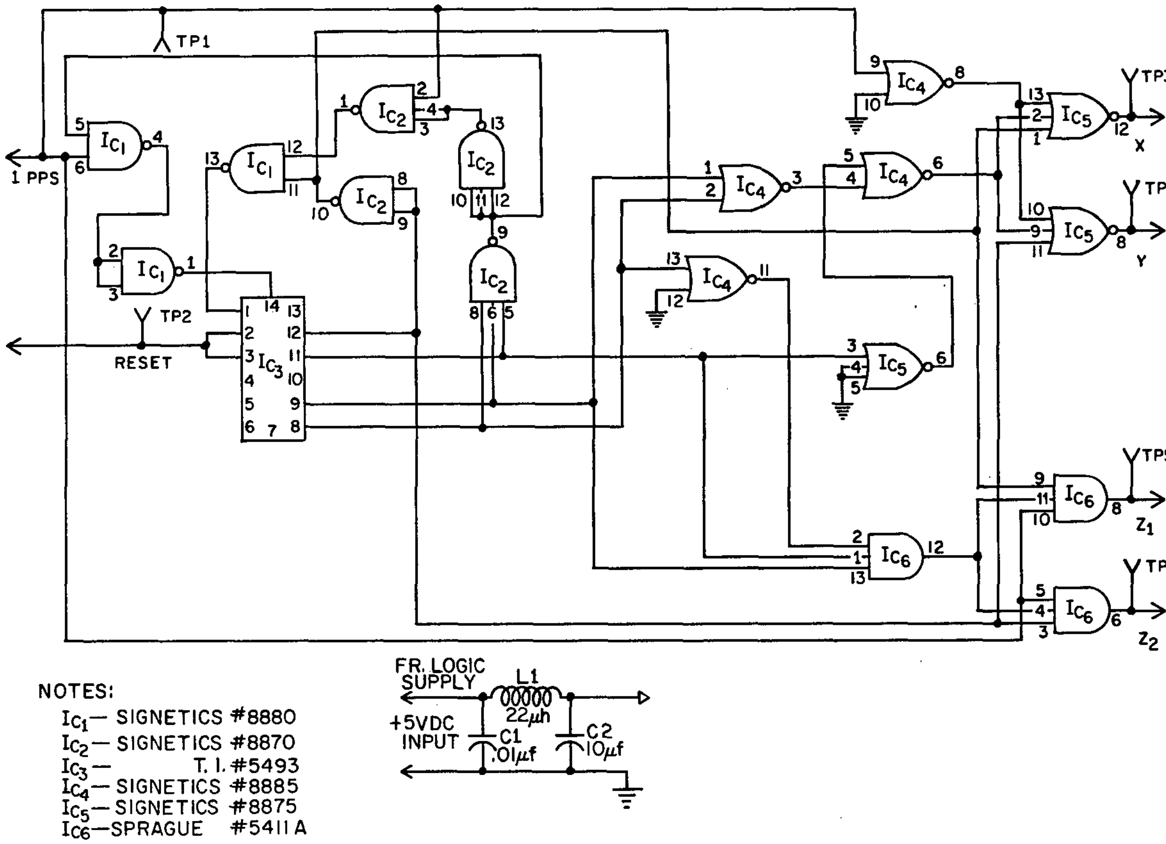

Fig. 13 - Logic diagram for the subinterval counter and decoder

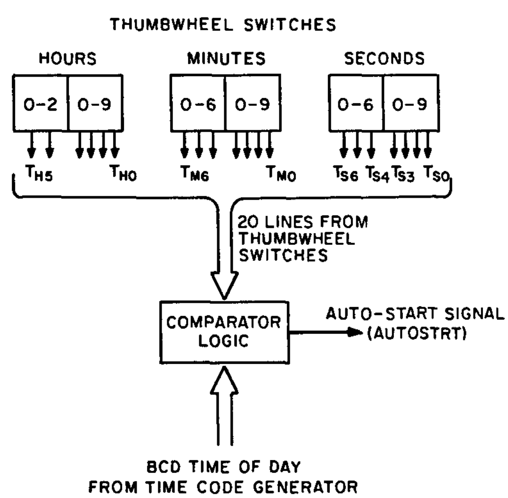

Fig. 14 - Comparator function for the generation of an auto-start signal

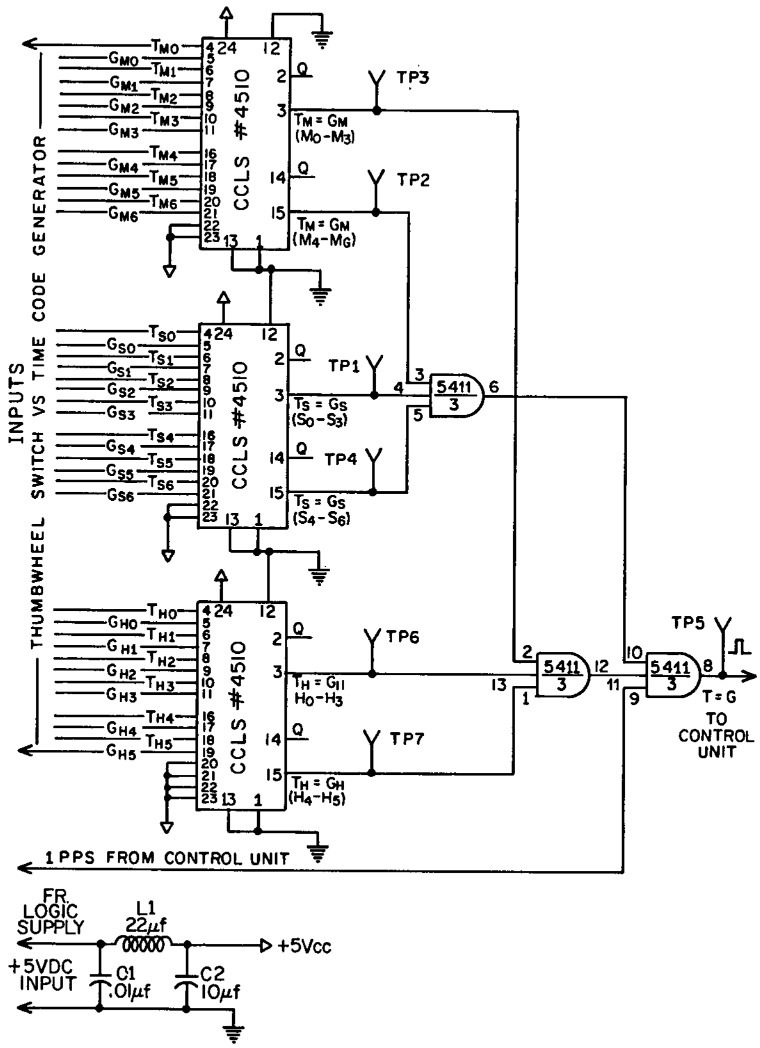

Fig. 15 - Logic diagram for the comparator board used in generating an auto-start signal

There should be a method to terminate the auto-tracking process automatically. Rather than use additional hardware for this termination, it is possible to use one of the 40 bits of data from the paper-tape reader which is not used as position data to the D/S converter. The transfer relation for this follows:

$\bar{Q}_s p_0$	
⋮	
$\bar{Q}_s p_{10}$	
$\bar{Q}_s p_{11}$	$(Z_2 \cdot D_6) \rightarrow \text{AUTOSTP} \rightarrow Q_s$
$Q_s p_0$	
$Q_s p_0$	

In addition to the synchronous method of start/stop, namely AUTOSTRT and AUTOSTP, there is an asynchronous start/stop method via front-panel switches. These are MANSTRT and MANSTP.

The start/stop signals activate a control flip-flop (Q_s) in the ACU-1. This flip-flop allows or inhibits/clears the subinterval counter. The equations which control the operation of the control flip-flop are

$$\text{CLR INPUT} = \overline{\text{AUTOSTRT}} + \overline{\text{MANSTRT}}$$

AUTOSTRT \ MANSTRT	0	1
0	1	0
1	0	0

$$\text{SET INPUT} = \overline{\text{AUTOSTP}} \cdot \overline{\text{MANSTP}} + \overline{Z_2} \cdot \overline{\text{MANSTP}}$$

$$= (\overline{\text{AUTOSTP}} + \overline{Z_2})\overline{\text{MANSTP}}$$

AUTOSTP	Z_2 \ MANSTP	0	1
0	0	1	0
0	1	1	0
1	1	0	0
1	0	1	0

$$1 \text{ pps to COUNTER} = 1 \text{ pps} \cdot \bar{Q}_s$$

$$\text{RESET to COUNTER} = Q_s$$

$$\overline{\text{RESET}} \text{ to BUFFER \& ALARM} = \bar{Q}_s$$

1 pps \ Q_s	0	1
0	0	1
1	1	0

The circuitry used to implement the above equations is shown in Fig. 16.

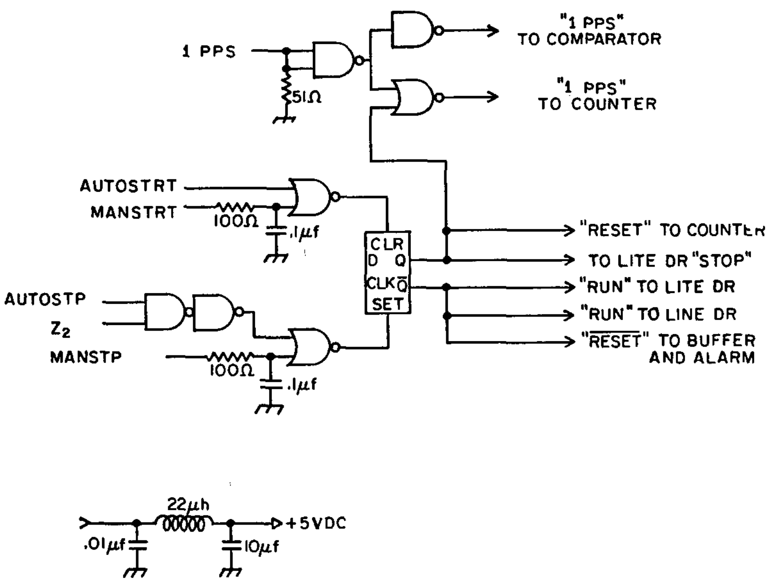

Fig. 16 - Logic diagram for the control unit

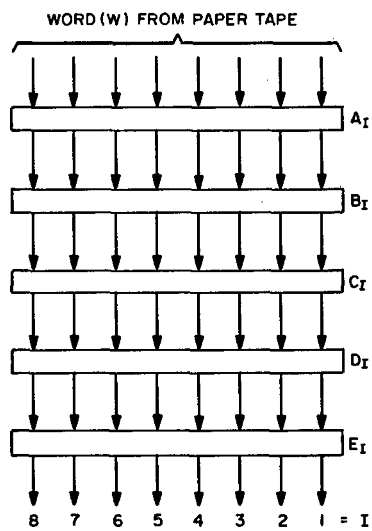

Fig. 17 - Shift registers in the storage area of the ACU-1

The position data is read from the paper tape (eight bits per word) into the storage area of the ACU-1. This storage area consists of five eight-bit shift registers (Fig. 17). The transfer relations of these storage registers are

$\bar{Q}_s p_0$	
$\bar{Q}_s p_1$	$W \rightarrow A_I;\ A_I \rightarrow B_I;\ B_I \rightarrow C_I;\ C_I \rightarrow D_I;\ D_I \rightarrow E_I$
$\bar{Q}_s p_2$	
$\bar{Q}_s p_3$	$W \rightarrow A_I;\ A_I \rightarrow B_I;\ B_I \rightarrow C_I;\ C_I \rightarrow D_I;\ D_I \rightarrow E_I$
$\bar{Q}_s p_4$	
$\bar{Q}_s p_5$	$W \rightarrow A_I;\ A_I \rightarrow B_I;\ B_I \rightarrow C_I;\ C_I \rightarrow D_I;\ D_I \rightarrow E_I$
$\bar{Q}_s p_6$	
$\bar{Q}_s p_7$	$W \rightarrow A_I;\ A_I \rightarrow B_I;\ B_I \rightarrow C_I;\ C_I \rightarrow D_I;\ D_I \rightarrow E_I$
$\bar{Q}_s p_8$	
$\bar{Q}_s p_9$	$W \rightarrow A_I;\ A_I \rightarrow B_I;\ B_I \rightarrow C_I;\ C_I \rightarrow D_I;\ D_I \rightarrow E_I$
$\bar{Q}_s p_{10}$	$A_I,\ B_I,\ C_{1\ldots4} \rightarrow$ primary D/S CONVERTER
$\bar{Q}_s p_{11}$	$C_{5\ldots8},\ D_I,\ E_I \rightarrow$ secondary D/S CONVERTER
$\bar{Q}_s p_{12}$	
$\bar{Q}_s p_{13}$	
$\bar{Q}_s p_{14}$	

where

w = word from the tape reader,

$I = 1, \ldots, 8.$

Figure 18 is the implementation of these transfer relations.

Since this is an auto-tracking antenna system, system malfunctions must alert an operator so that he can manually override the auto-tracking process. The antennas normally have 720° of freedom in azimuth and approximately 180° in elevation. The normal mode of operation of this system is to initially set the antennas at 0° azimuth and 0° elevation. This allows ±360° of movement in azimuth and -0°, +180° in elevation. After each task the antennas are returned to the starting point by the same route that they traveled to get to the endpoint, so that an antenna should never exceed its freedom of movement. (Although the return route is the same, the time of travel is less because time lapses between position updates are eliminated.) If the freedom of movement is exceeded,

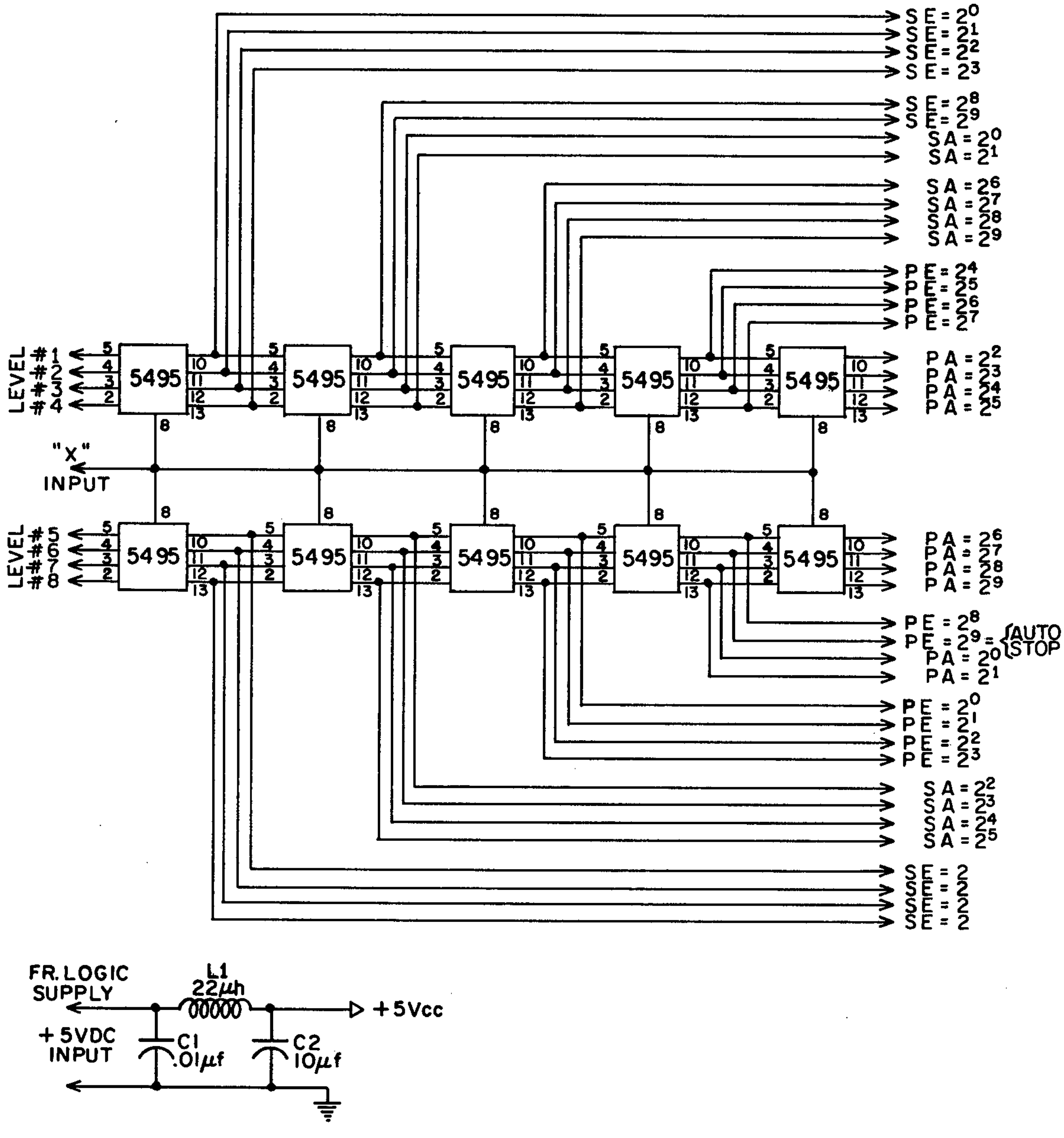

Fig. 18 - Logic diagram for the storage register

however, a limit switch is activated in the antenna pedestal. This limit switch in turn activates a limit light on the servo control unit. In azimuth there are limit lights for the clockwise (CW) limit and the counterclockwise (CCW) limit. The elevation limits are not monitored, because in this application they convey no useful information.

By monitoring the limit relays in the servo control unit, it is possible to determine when a limit switch is activated. The voltage at the limit relays is 120 V ac under normal conditions. However, when the limit is activated, this voltage drops to less than 25 V ac. The voltage at the limit relays is also less than 25 V ac when the servo control unit is not operating. However, it is not desirable to sound an alarm when the unit is not operating. For this reason the line voltage of each servo control unit is also monitored to detect whether the unit is operating. The logic equation for the audio alarm for both the primary and the secondary antenna system is

$$\mathrm{ALARM} = \mathrm{power}\ (\mathrm{CW\ limit} + \mathrm{CCW\ limit})\ .$$

In order to be more explicit, new terminology is defined:

primon = power on to the primary system,

$\mathrm{CW_p}$ = 120 V ac at the CW monitor point of the primary system,

$\mathrm{CCW_p}$ = 120 V ac at the CCW monitor point of the primary system,

secon = power on to the secondary system,

$\mathrm{CW_s}$ = 120 V ac at the CW monitor point of the secondary system,

$\mathrm{CCW_s}$ = 120 V ac at the CCW monitor point of the secondary system,

rst = activation of the front panel reset switch on the ACU-1,

$$\mathrm{ALARM}_{\mathrm{limit}} = \left[\overline{\mathrm{primon}}\ (\overline{\mathrm{CW}}_p + \overline{\mathrm{CCW}}_p) + \mathrm{secon}\ (\overline{\mathrm{CW}}_s + \overline{\mathrm{CCW}}_s)\right] \overline{\mathrm{rst}}\ .$$

It is desirable also to have the alarm sound briefly when the auto-tracking system begins operation so that an operator can check to insure proper operation. The transfer relations for this are

$\bar{Q}_a\bar{Q}_s P_0$	
$\bar{Q}_a\bar{Q}_s P_1$	
⋮	
$\bar{Q}_a\bar{Q}_s P_{10}$	$1 \rightarrow \mathrm{ALARM}$
$\bar{Q}_a\bar{Q}_s P_{11}$	$1 \rightarrow Q_a$
$Q_a\bar{Q}_s P_{12}$	
$Q_a\bar{Q}_s P_{13}$	
$Q_a\bar{Q}_s P_{14}$	

To realize these transfer and logic equations, the 120-V-ac signals from the limit indicators must be converted to logic-compatible levels. Each 120-V-ac signal is converted to a dc signal by a half-wave rectifier with a capacitive filter. The dc component of the limit signal is then divided and level detected by a zener diode and transistor. These circuits are shown in Figs. 19 and 20. Since the A/D converters have a high (+5 V dc) output for a low ac input, the logic equation for the limit alarm must be rewritten:

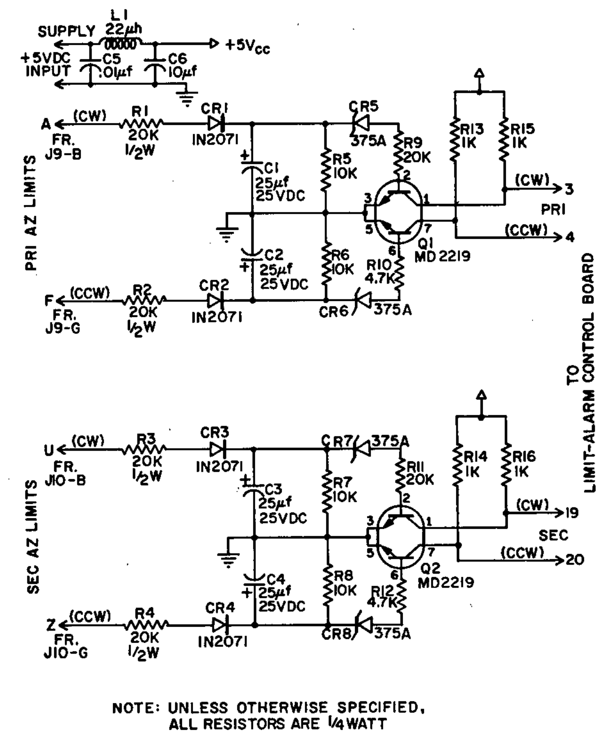

Fig. 19 - Circuits to sense when the azimuth CW or CCW limit switches are activated in the primary (PRI) or secondary (SEC) antenna pedestals

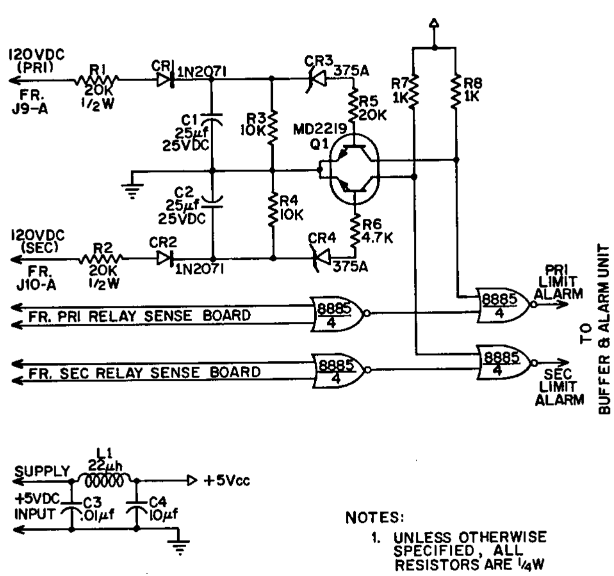

Fig. 20 - Limit-alarm board referred to in Fig. 19

$$\mathrm{ALARM}_{\mathrm{limit}} = \left[(\mathrm{CW_p} + \mathrm{CCW_p})\,\overline{\mathrm{primon}} + (\mathrm{CW_s} + \mathrm{CCW_s})\,\overline{\mathrm{secon}}\right]\overline{\mathrm{rst}}\;.$$

This logic equation then is the equation for the limit-activated alarm. The alarm is also activated for a short duration when the auto-tracking system begins operation as stated in the previous transfer relations. The short-duration pulse to the alarm is generated by a one-shot multivibrator which is activated on the trailing edge of $\bar{Q}_a\bar{Q}_s p_{10}$. Figure 21 is the actual implementation of the alarm signal. The logic equation for the alarm is

$$\mathrm{ALARM} = \left[(\mathrm{CW_p} + \mathrm{CCW_p})\,\overline{\mathrm{primon}} + (\mathrm{CW_s} + \mathrm{CCW_s})\,\overline{\mathrm{secon}}\right]\overline{\mathrm{rst}} + \bar{Q}_a\bar{Q}_s p_{10}\;.$$

Figure 21 also contains, at the top, the one-shot multivibrator which activates the tape reader. To increment the tape reader, it must output a pulse whose duration does not exceed 5 ms. The one-shot multivibrator provides this signal duration.

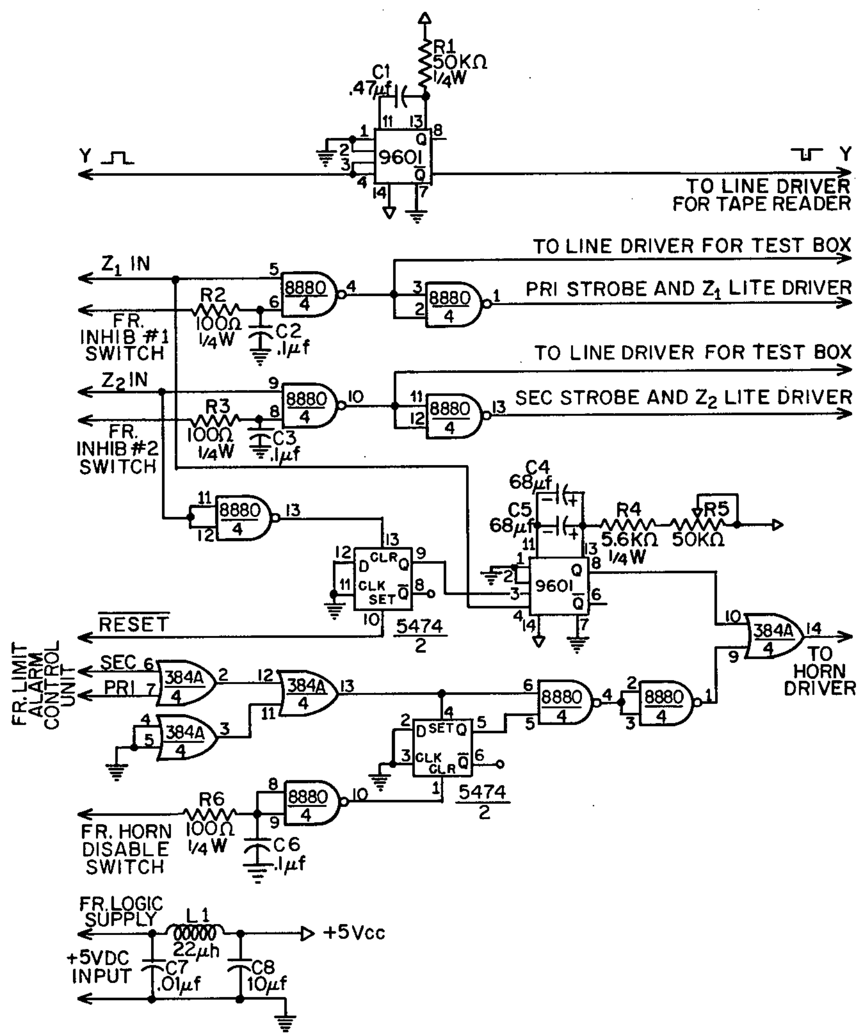

Fig. 21 - Logic diagram for the buffer and alarm unit referred to in Fig. 20

The ACU-1 is interfaced to the time code generator as follows. The 1-pps clock signal is driven at the time-code generator by a 50-Ω discrete-circuit driver of the type used in the ACU-1. The signal is transmitted through 50-Ω coaxial cable and terminated in 50 Ω in the ACU-1. The time of day from the time-code generator is not so stringently treated, because the time changes on the trailing edge of the 1-pps signal and is not monitored by the ACU-1 until the next 1-pps signal, 800 ms later. The time-of-day signals are driven by standard IC line drivers through a multiwire shielded cable.

Data are transferred from the tape reader to the ACU-1 through a multiwire shielded cable containing eight data wires and a ground wire. The data lines are driven at the tape reader by standard IC line drivers. The control signal from the ACU-1 to the tape reader is driven by a discrete-circuit line driver through 50-Ω coaxial cable, and the cable is terminated in 50 Ω at the tape reader.

Data are transferred from the ACU-1 to the D/S converters through multiwire shielded cable containing 20 data lines and one ground line. The data lines are driven by standard IC line drivers, SN7440. The update command is sent to the D/S converters through 50-Ω coaxial cable. This cable is driven at the ACU-1 by discrete-circuit 50-Ω line drivers and is terminated at the D/S converter in 50 Ω. Figure 22 is a schematic of a discrete-circuit line-driver board.

The following is a summary of the transfer relations of the ACU-1:

Operations Relations

$\bar{Q}_s P_0$	Y
$\bar{Q}_s P_1$	X
$\bar{Q}_s P_2$	Y
$\bar{Q}_s P_3$	X
$\bar{Q}_s P_4$	Y
$\bar{Q}_s P_5$	X
$\bar{Q}_s P_6$	Y
$\bar{Q}_s P_7$	X
$\bar{Q}_s P_8$	Y
$\bar{Q}_s P_9$	X
$\bar{Q}_s P_{10}$	Z_1
$\bar{Q}_s P_{11}$	Z_2
$\bar{Q}_s P_{12}$	
$\bar{Q}_s P_{13}$	
$\bar{Q}_s P_{14}$	

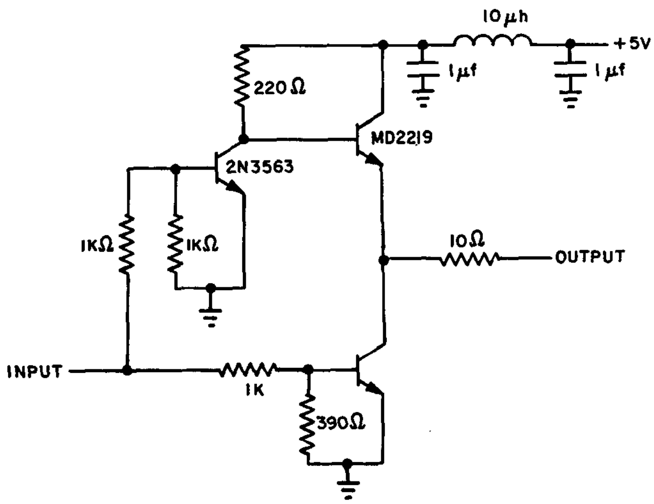

Fig. 22 - Discrete-circuit line driver for the update command from the ACU-1 to the D/S converters

Start Control

	Synchronous	Asynchronous
Q_sP_0	$\overline{AUTOSTRT \cdot Q_s} \rightarrow Q_s$	$\overline{MANSTRT \cdot Q_s} \rightarrow Q_s$
Q_sP_0	$\overline{AUTOSTRT \cdot Q_s} \rightarrow Q_s$	
⋮		

Stop Control

	Synchronous	Asynchronous
$\bar{Q}_sP_0$		$MANSTP \rightarrow Q_s$
$\bar{Q}_sP_1$		
⋮		
$\bar{Q}_sP_{11}$	$AUTOSTP \rightarrow Q_s$	
Q_sP_0		
⋮		

Subinterval Counter

$\bar{Q}_s P_0$	$P + 1 \rightarrow P$
$\bar{Q}_s P_1$	$P + 1 \rightarrow P$
$\bar{Q}_s P_2$	$P + 1 \rightarrow P$
⋮	
$\bar{Q}_s P_{14}$	$0 \rightarrow P$

Alarm

	Synchronous	Asynchronous
$\bar{Q}_A \bar{Q}_s P_0$		$ALARM = \left[(CW_p + CCW_p)\,\overline{primon} + (CW_s + CCW_s)\,\overline{secon}\;\;\overline{rst}\right]$
$\bar{Q}_A \bar{Q}_s P_1$		
⋮		
$\bar{Q}_A \bar{Q}_s P_{10}$	$1 \rightarrow Alarm$	
$\bar{Q}_A \bar{Q}_s P_{11}$	$1 \rightarrow Q_A$	
$Q_A \bar{Q}_s P_{12}$		
$Q_A \bar{Q}_s P_{13}$		
$Q_A \bar{Q}_s P_{14}$		

CONCLUSION

Two Scientific-Atlanta, Inc., J330 tracking antenna systems were updated to the auto-tracking system shown in Fig. 9. The technique used to accomplish this update is superior to previously existing techniques because it minimized the number of new functions which must be added to the system. The auto-tracking system was designed around the manual-position mode of operation. This could be done because of the availability of low-cost and accurate D/S converters and the development of the automatic control unit, ACU-1. The primary system design goals were accuracy, reliability, ease of maintenance, and ease of operation.

When the system is operating in a manual mode, the antenna positioning accuracy is ±0.95 degree. The different components of this error are: positioning error from the rate control loop = ±0.25°, manual command unit position error = ±0.5°, manual command unit synchro error = ±0.1°, and pedestal drive synchro position error = ±0.1°. In the auto-tracking mode of operation the positioning accuracy is reduced to ±0.575 degree.

The different components of this error are: positioning error from the rate control loop = ±0.25°, D/S converter position error = ±0.175°, D/S converter synchro output error = ±0.05°, and pedestal drive synchro position error = ±0.1°. Thus a significant improvement in positioning accuracy was realized as a result of the update.

The design goals of reliability and ease of maintenance are furthered when a minimum of new equipment is required. To update the J330 system to an auto-tracking system required one paper-tape reader, two D/S converters, and the ACU-1. All of this equipment uses reliable, long-life solid-state circuitry. In addition, ease of maintenance is furthered in that no new closed control loops were added to the existing system.

Ease of operation is a most necessary design goal. The system design of the auto-tracking system considered in detail means to relieve the system operator of menial tasks while taking maximum advantage of his ability to make decisions. The operator prepares the paper tape on an off-line computer and then verifies it to insure that it is punched properly. He then loads the paper-tape reader and sets the time that tracking is to commence into the ACU-1. When tracking begins, the operator is notified via an audio alarm from the ACU-1. If the antennas hit a limit or are deactivated during the tracking process, the operator is notified by the audio alarm from the ACU-1. When the tracking process is completed, a unique character is read from the paper tape and the ACU-1 deactivates the system. Furthermore, any time during the tracking process, in particular when there is an equipment malfunction, the operator can take over control of the system by switching back to one of the manual modes of operation.

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Appendix

SCIENTIFIC ATLANTA, INC., MODEL J330 ANTENNA SYSTEM

The functional relationship of the pedestal, the control elements, and the associated telemetry system for all modes of operation is shown in Fig. A1. The blocks show the elements of the system and the signal paths. The dashed lines indicate the physical grouping of the elements into the major electronic chassis. The mode-selector switches are shown in the manual position mode. The signal channels for only one axis of rotation are shown; but the azimuth and elevation channels are identical, and each can be operated independently.

In all modes of operation except standby, dc amplifier 2 in the dc amplifier unit receives an actuating error signal from the summing junction. The amplifier gain-versus-frequency characteristics are determined by servo compensation networks that are switched for each mode. The magnitude and polarity of the output of dc amplifier 2 represent the required amount and direction of pedestal rotation; this output is fed from the dc amplifier unit to the servo controlled amplifier (SCA) in the servo amplifier chassis. The SCA uses this dc error voltage to generate a train of control pulses on either its forward or its reverse output channel. The pulse repetition rate is synchronized with the power-line frequency, and the number and phase of pulses per half-cycle is proportional to the magnitude of the actuating error signal. In the power amplifier at the pedestal, receipt of the control pulses on either the forward or reverse input will supply the ac drive motor with the phase for the required rotation. The magnitude of the drive current and power delivered to the pedestal load depends on the number of control pulses in each train, which establishes the firing angle of the silicon-controlled rectifiers (SCR's) on each half-cycle of the power-line voltage. The reference phase for the two-phase ac drive motor is supplied from an additional SCA in the servo amplifier.

A tachometer, attached to the shaft of the motor on each axis, generates a dc voltage proportional to the pedestal rotation speed. In the dc amplifier unit the tachometer feedback signal is combined with the error signal at the summing junction. The insertion of a feedback voltage proportional to the rotation speed ($d\theta/dt$) allows the control system to reduce or increase the actuating error so as to counteract antenna momentum and stabilize against varying external loads. The tachometer feedback level is switched for each mode.

The motor on each pedestal axis drives the respective turntables through power gear trains. The azimuth axis has a motor, a gearbox, one ring gear, and one turntable. The elevation axis has a motor, a gearbox, and two turntables that are connected by an elevation shaft, on which the main drive gear is mounted.

An electromechanical brake is attached to the shaft of each gear train. For failsafe operation the brakes are applied by spring-loading and released when electrically energized. The brakes are automatically applied when the power is off, the standby mode is selected, or a limit switch is actuated. The brakes on each axis are released when a pedestal stow pin is removed from its storage receptacle. Also, if a stow pin is removed from its storage receptacle, interlock switches de-energize the equipment.

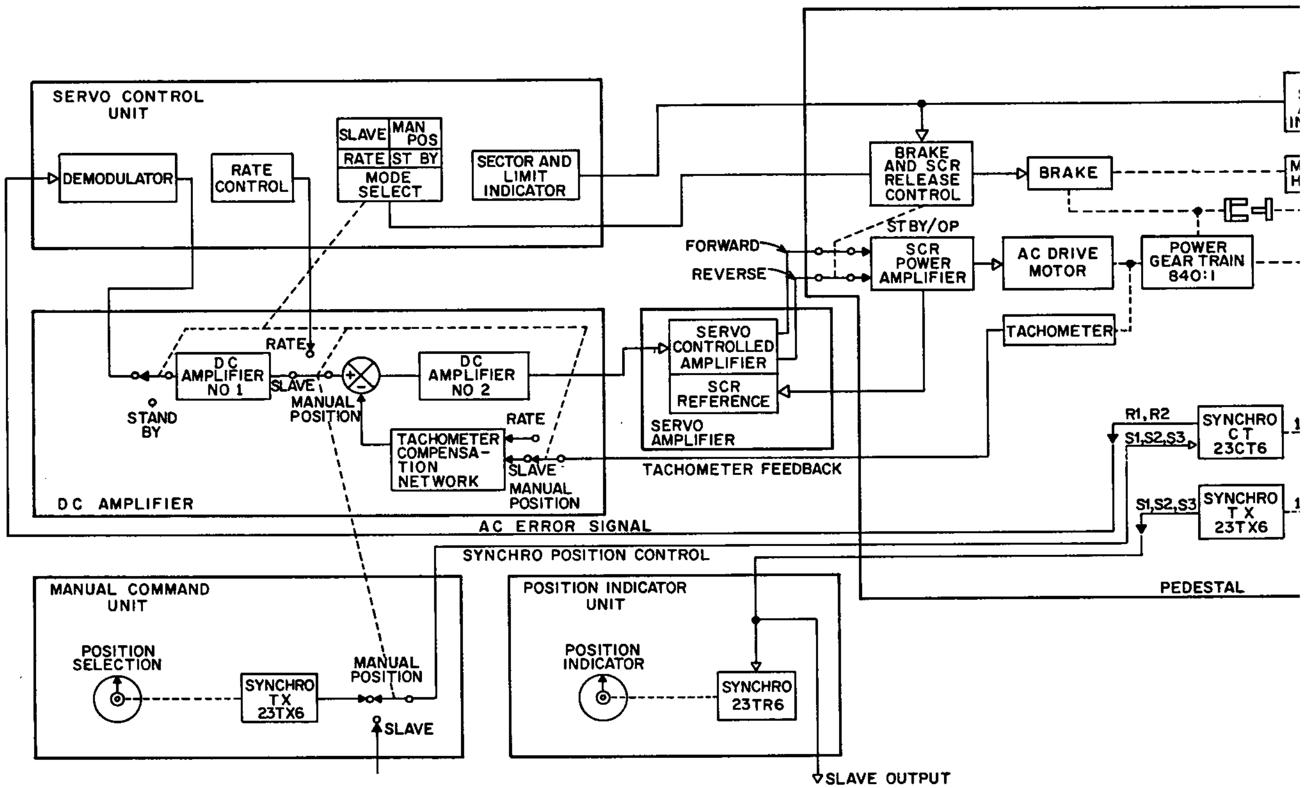

Fig. A1 - Model J330 antenna system

If a pedestal axis is rotated to the end of its sector, a limit switch prevents further rotation in that direction and lights the proper limit indicator. Automatic backout circuits release the brakes and energize the equipment when the controls are operated to drive the pedestal in the direction opposite to the actuated limit switch.

Data takeoff units are connected to the output gear on each axis by means of anti-backlash gears. The data takeoff units contain synchros and other optional data devices.

The stators of the synchro control transformers (CT's) in the takeoff units are energized by the slave input signal, and their rotor outputs are fed to the demodulator in the servo control unit as an ac error signal. The synchro transmitter (TX) rotors are energized by the 120-V-ac reference phase; their stator outputs are connected to the local position indicator, as well as to the pedestal slave output.

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13. ABSTRACT

A systematic approach has been made to the design of a digital auto-tracking antenna system. When such a system is converted from a manual tracking system, the main design criteria of accuracy, reliability, ease of maintenance, and minimum cost are advanced by designing the new system around one of the present modes of operation. An optimum technique to convert from a manual tracking antenna system to an auto-tracking antenna system is made possible by the commercial availability of low-cost and accurate digital-to-synchro (D/S) converters and the development of a special-purpose system controller, the automatic control unit ACU-1. The auto-tracking system is designed to relieve the system operator of menial tasks while taking maximum advantage of his ability to make decisions.

In the example of this report, an operator prepares a punched-paper tape using an off-line computer. He then verifies the tape to insure accuracy. The azimuth and elevation information for two antennas is stored on the paper tape in binary form. The tape is read by the ACU-1, which reformats and transmits the digital data at specific time intervals to a D/S converter for each antenna. The converter outputs synchro position data through the previously existing manual command unit to the pedestal drive circuitry in a servo control loop, also previously existing. The auto-tracking process is started at a preset time and automatically stops at the completion of the specific task. Audio alarms are used to alert the operator to system malfunctions.

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