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TECHNICAL NOTE

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PROJECT ECHO—
ANTENNA STEERING SYSTEM

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PROJECT ECHO— ANTENNA STEERING SYSTEM

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SUMMARY

The Project Echo communications experiment employed large, steerable, transmitting and receiving antennas at the ground terminals. It was necessary that these highly directional antennas be continuously and accurately pointed at the passing satellite. This paper describes a new type of special purpose data converter for directing narrow-beam communication antennas on the basis of predicted information. The system is capable of converting digital input data into real-time analog voltage commands with a dynamic accuracy of ±0.05 degree, which meets the requirements of the present antennas.

PREFACE

The Project Echo communications experiment was a joint operation by the Goddard Space Flight Center of the National Aeronautics and Space Administration (NASA), the Jet Propulsion Laboratory (JPL), the Naval Research Laboratory (NRL), and the Bell Telephone Laboratories (BTL). The equipment described herein, although designed by BTL as part of its own research and development program, was operated in connection with Project Echo under Contract NASW-110 for NASA. Overall technical management of Project Echo was the responsibility of NASA's Goddard Space Flight Center.

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INTRODUCTION

Although satellite-following communications antennas could be slaved to optical or radar trackers at each antenna site, the use of basic orbital information to generate antenna steering instructions is expected to be more economical when many antennas and sites are served. The latter method was used in the Echo I experiments and employed the following steps:

1. Determine satellite positions by accurate radio observations and, from these, calculate the basic satellite orbital elements
2. Use these elements to calculate future satellite positions
3. From these positions, compute pointing angles for the antennas.

In the Echo I experiment, these functions were performed by the Minitrack satellite tracking network and the computing center at the Goddard Space Flight Center. The predicted angles were transmitted by teletypewriter from the Goddard computer at Washington to the Bell Telephone Laboratories antennas at Holmdel, New Jersey.

SYSTEM CONSIDERATIONS

Several factors affect the design of a data processing system for antenna steering. In addition to these factors, the data processing system adopted must provide:

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*The substance of this paper was published in the Bell System Technical Journal, Vol. XL, No. 4, July 1961. It is republished here, with minor revisions, by permission of Bell Telephone Laboratories.

1. Transmission of predicted pointing data from a computer location to the communication antenna site, and temporary storage there prior to each satellite pass
2. Assembly of the data from storage and synchronization to real time
3. Error checking and rejection of erroneous quantities
4. Conversion of the digital orders into analog command signals to control the antenna drive mechanisms.

The most important factor affecting the transmission facility, storage medium, and data reconstruction equipment is the sampling interval of the discrete pointing information delivered by the computer. We will use the term *data point* to denote one sample of this information, and the term *data-point interval* to denote the interval between successive points. A wide range of intervals is possible with various combinations of data transmission rate, storage requirements, complexity of the conversion equipment, and reliability of performance. There is, at one extreme, the possibility of transmitting large numbers of data points with short data-point intervals. Advantages of this approach arise from two considerations. First, the digital-to-analog conversion process involves straightforward conversion of each point into an equivalent analog command, simplifying the conversion equipment and offering advantages in reliability. Second, the data interval is short, and thus errors occurring in transmission, storage, or assembly from storage cause only momentary effects. Disadvantages result from the large quantity of data required to describe each satellite pass. This places an excessive load on the computer and on the transmission and storage facilities.

At the other extreme lies the possibility of transmitting fewer sets of pointing angles with their derivatives at data-point intervals of many seconds Interpolation between data points using these derivatives provides continuous pointing information. Reduction of data for each pass is obtained at the expense of more extensive calculations by the computer and more complex conversion equipment at the antennas. There is a trade between the data rate of the transmission and capacity of terminal storage facilities on one hand, and the complexity of the data-conversion equipment at the antenna on the other.

When long data intervals are used, reliability considerations become more complicated. Discrete samples of position and higher derivatives become initial conditions in an integration process which extends over each data interval. Errors in transmitted data which are not detected and removed affect the system for the duration of the data interval However, in this case redundancy for automatic error checking can be applied to the encoded quantities without requiring prohibitively large amounts of data.

To summarize, the optimum data interval is a function of several factors including the load imposed on the computer in the generation of error-correcting codes and higher-order derivatives, the cost and availability of transmission links, and the complexity of the data conversion equipment needed at each antenna.

Other design considerations include the method used for conversion of the transmitted digital data into antenna steering commands. There are two methods. The first employs electronic decoding of digital pointing commands to equivalent analog signals; these may then be used to direct a number of antennas at one site. A second method involves encoding of the antenna shaft positions in digital form and a subtraction between the encoded positions and the digital command signals. Here digital error signals are derived, which are more easily converted to analog signals to actuate the antenna servos. The latter method, preferred for precise antenna control, requires separate encoding mechanisms and digital subtractors with each antenna mount.

ANTENNA STEERING FOR ECHO I

System Philosophy

In designing a system to transmit pointing instructions from the Goddard computer to Holmdel and there convert them into antenna steering orders, many of the factors discussed above were considered. Uncertainties regarding expected orbital perturbations of the balloon satellite placed emphasis on an approach that would provide updated pointing instructions after each satellite pass. The experimental nature of the project dictated the use of inexpensive transmission and storage media, and a reasonably simple digital-to-analog converter.

The Echo satellites were to be placed in near-circular orbits at altitudes of 800 to 1000 miles. Maximum angular tracking velocities would be under 1.5 degree per second, and average velocities would be much lower than this. Of primary importance are the dynamic range of the steering signals, the conversion precision needed, and the form of analog signals required by the antenna control systems. To insure that data conversion errors would not affect radio transmission characteristics, design error tolerances were set at ±0.05 degree.

Continuous three-wire ac synchro voltages were required as outputs of the converter, to command each antenna and optical mount control system. While direct conversion from digital form to ac signals is possible, an approach using small intermediate servos to position synchro transmitter units was more attractive. Pulse-time-modulation techniques were used to position these servos. Digital input commands were converted into pulse-position-modulated (PPM) signals. At the same time, the servo output shaft positions were monitored by precision resolver angle transducers and the resolver outputs produced PPM signals of the same form. The two PPM signals were compared on a time basis to create the error signals that positioned the servo units.

Input Data Transmission

A 4-second data-point interval was chosen, permitting the description of a single satellite pass to be transmitted over a 60-word-per-minute teletypewriter channel in approximately the time taken by the pass. The choice of a standard-speed teletypewriter was influenced by two factors: conversion equipment was available at the Goddard computer center to produce punched-paper teletypewriter tape from the computer output; and this tape could be transmitted and reproduced at the antenna site to provide economical data storage. The pointing data furnished are the azimuth and elevation antenna angles computed for the geographic location at Holmdel. These are supplemented by the average rates of azimuth and elevation over the succeeding data interval to permit a linear interpolation between data points.

Digital-to-Analog Converter Organization

The data format, scale factors, and coding were chosen to minimize the digital-to-analog converter equipment. Teletypewriter code combinations were used to denote decimal data in an 8-4-2-1 binary code, with the fifth level of the tape being used as a single redundant parity-check bit; this was possible because a total of only 14 characters was needed. Sequences of tape characters called *words* represent the data-point time, azimuth angle, elevation angle, azimuth rate, and elevation rate. Each word is identified on the tape by a "tag" code following the word. These tags also control the switching of the words to the proper destination within the conversion unit. The use of tags makes the operation less dependent on the sequence of words and makes the system more tolerant of errors introduced by transmission links.

The conversion unit assembles the data from tape, synchronizes it with real time, and switches it to counting decoders, which produce PPM signals proportional to the digital data. The following paragraphs describe logical features of the conversion unit; the operation of the counting decoders and conversion of the PPM signals to analog commands are described later.

In the digital-to-analog conversion unit (Figure 1), a photoelectric tape reader reads the tape characters in sequence and converts the information to electrical signals, which are introduced to a shift register used to assemble the serial information from the tape into parallel words. The output of the word-assembly register feeds the counting decoders and the time-comparison circuit. The other input to the time-comparison circuit is the output of a local time counter which provides the conversion unit with real-time synchronization. Reader outputs are also applied to the tag decoder and the parity-check circuit. These actuate the control unit and determine the action taken by the conversion unit.

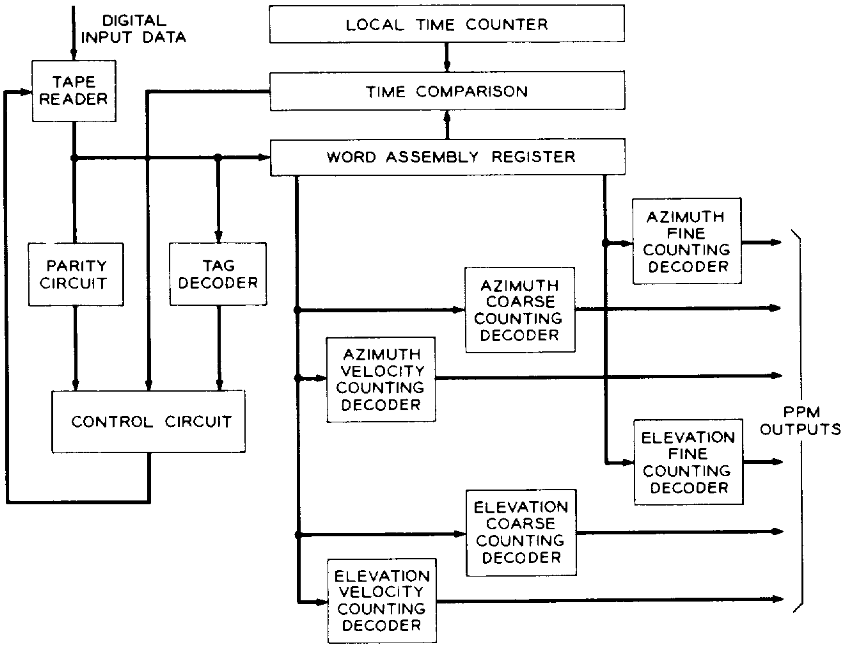


Figure 1 — Data conversion unit for Holmdel, N.J.

A consideration of events occurring when a block of information is read from the tape illustrates the operation of the conversion unit. Assume that the tape is stopped after the reader has read a time tag. This tag identifies the word in position in the word-assembly register as the time word corresponding to the time for the next data point. This time word is compared in the time-comparison circuit with the contents of the local-time counter. An affirmative indication from the time-comparison circuit causes a clock pulse to indicate that the next data point should be decoded and tape reader action is initiated. As the tape moves, each character is examined by the tag decoder. If the tape character being read is not a tag, the contents of the word-assembly register are shifted one digit to the right and the new character is entered on the left.

This process continues until a tag is encountered — in this instance, the azimuth quantity. Detection of the azimuth tag indicates that the azimuth angle is in position in the word-assembly register and is ready for transmission to the azimuth-counting decoders. When a signal from the azimuth decoder indicates that it is ready to receive new data, it is cleared and the new azimuth word is gated from the word-assembly register as reading of the tape continues, each character being introduced to the word-assembly register is examined until the elevation tag is encountered, causing the elevation word to be placed in the elevation decoder. The rate information is handled similarly. After the rate information has been transferred to the rate registers, reading of the tape continues until the next time tag is detected. This indicates that the time word for the next block of information is in the word-assembly register and is being compared with local time, to complete the cycle.

The logic of the time-comparison circuit is so designed that, for data blocks in the proper sequence, the circuit will indicate a comparison as soon as a time tag is detected in the reader. This comparison holds for the 4-second interval. If, when a time tag is read, the contents of the word-assembly register and the local-time counter do not compare, the control circuit causes the tape to advance to the next time tag and make another comparison. If these times compare, it then proceeds as normal; if not, it stops and gives an alarm. If the comparison should become good, it turns off the alarm and proceeds as usual. Thus, in the event of a time-comparison failure, the system makes a quick check to see that it has not somehow got behind, as may happen if an error makes a data character look like a time tag. If the comparison check still fails, the alarm alerts operating personnel. However, if, because of transmission drop-outs or errors, the system has got a few seconds ahead, it will automatically correct itself, probably before any manual maintenance routines can be initiated.

The redundant check bit with each character is checked as the character is read. If a parity error is detected, the control circuit causes the tape to advance to the next time tag. Thus, when an error is detected, the data block is discarded. As will be discussed later, the counting decoders continuously decode azimuth and elevation angles, which are up-dated with the last-received rate information. This gives the system a "coasting" feature, so that erroneous blocks of information may be discarded without seriously affecting the system accuracy.

Counter Decoding

The conversion of digital pointing commands involves an intermediate conversion to PPM signals, which is performed in high-speed sequential counting circuits. The concept is very simple; the number to be converted is placed in a counter which is designed to count toward zero. At the occurrence of a start pulse, this number is reduced by one unit for each elapsed cycle of a stabilized clock pulse source. Zero-detection circuitry arranged on the counter output produces an output pulse when the counter reaches zero. The time interval t_{1d} between the start pulse and the output is related to the clock frequency f_c and the number θ being decoded by the equation

$$t_{1d} = \frac{\theta}{f_c} . \tag{1}$$

This time interval is clearly proportional to θ. Essential portions of the logical connections for a single counting decoder are seen in Figure 2.

By arranging the counter to recycle after it reaches its zero content, successive zero-crossing output pulses are produced at time intervals equal to the product of the

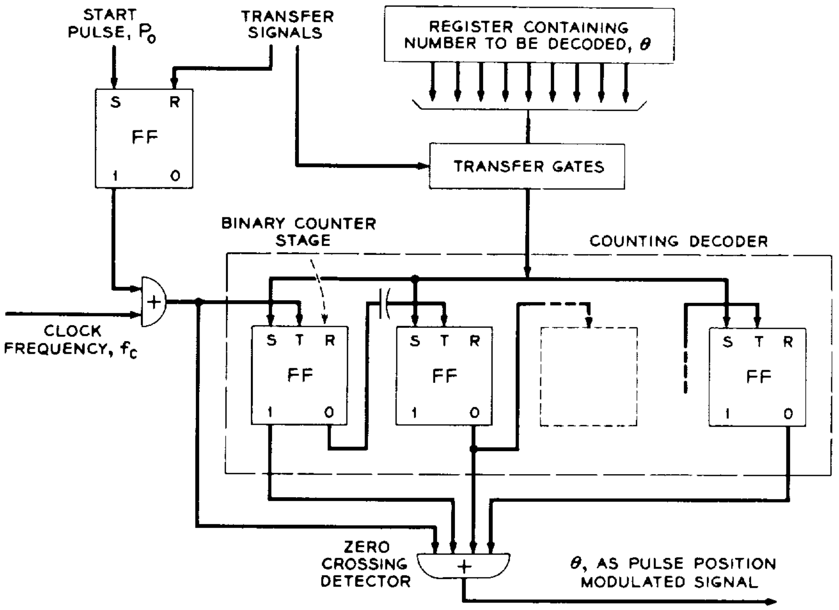


Figure 2 — Counting decoder logic

clock frequency and the total number of states in the counting sequence. Moreover, by arranging the repetition times of the start pulses t_s at

$$t_{ks} = \frac{kC}{f_c} \qquad k = 0,1,2\ldots, \tag{2}$$

where C is the total number of states in the counter, successive zero crossings times t_{kd} are always delayed from the start pulses by the same amount. That is,

$$t_{kd} = \frac{1}{f_c}(\theta + kC). \tag{3}$$

By subtracting Equation 2 from Equation 3, a repeated measure of θ is generated as

$$t_{kd} - t_{ks} = \frac{\theta}{f_c}. \tag{4}$$

Each pulse position is modulated by the digital quantity placed in the counter. The relationships among counter contents, start pulses, and outputs are usually shown as in Figure 3. Although a number placed in the counter is regularly being counted around, storage of that number is provided within the counter as the conversion process proceeds. This results from the unique relation between the counter contents and time for each input.

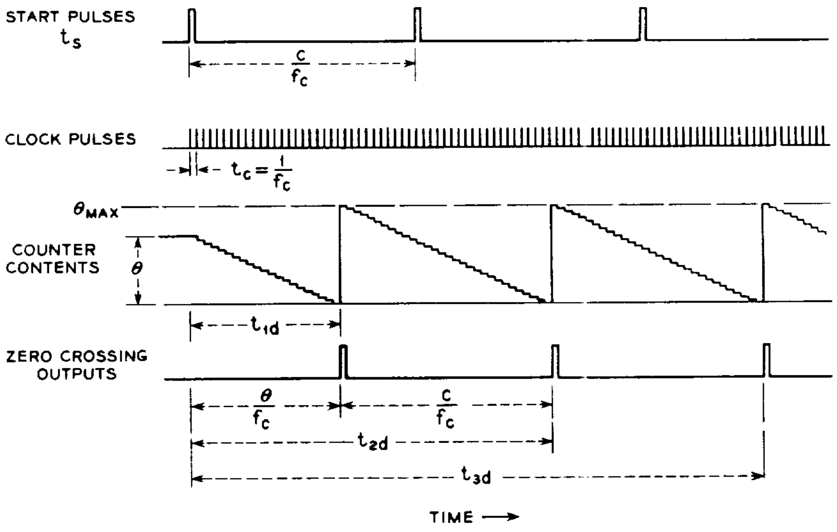


Figure 3 — Counting decoder contents and waveforms

In real-time control system applications, the repetition rate of the decoding process is important. This rate determines the bandwidth of signals that can be decoded. The decoding resolution is, of course, determined by the number of states in the counter. Counter stages operating at 5 Mc allow a sufficient range in resolution and repetition rate.

Interpolation

The counter decoding processes considered thus far have been those in which the counting rate remains constant and uninterrupted; the generated time interval is unchanged. However, by momentarily altering the counting rate, the arithmetic operations of addition and subtraction can be performed on the contents of the counter while the decoding process continues. For example, consider a down-counting sequential counter in which a number of clock input pulses are inhibited. The usual countering process is momentarily halted. The zero crossing occurs later than it ordinarily would have, and a quantity equal to the number of inhibited clock pulses is effectively added to the counter. Similarly, if the clock input is shifted to the next most significant counting stage, the counting sequence is accelerated to twice its usual rate; thus a quantity equal to the number of shifted pulses is effectively subtracted from the counter contents.

The fact that the contents of the counter can be modified is used for interpolating input data over each data interval. Angular position commands are placed in the counters at the beginning of each data-point interval. At the same time, angular velocity commands are placed in similar counters. Time intervals determined by the velocity counter decoders are extracted and used as gating signals to alter the number of clock pulses fed to the position counter decoders. Depending on the polarity of the velocity information, the inputs to the position counters are either inhibited or shifted one stage for the duration of this interval. In this manner, increments of position proportional to average velocity are added to the position command several times during the data interval.

In the digital-to-analog converter, angle position commands are decoded to PPM signals to provide a modulo 360-degree, or coarse, command and a modulo 3.6-degree, or fine, command. Decoding is performed in a three-stage decimal counter, giving a decoding resolution of 0.0036 degree. A counter clock frequency of 500 kc provides outputs at a rate of 500 cps.

Rate information is decoded with a clock frequency of 5 Mc to PPM signals having a 50-kc repetition rate. One of these outputs is extracted 50 times per second, and controls the counting of a decimal stage preceding the fine position decoder. The logical connections for this control are shown in Figure 4. This yields a quasi-linear interpolation in steps of 1/50 second duration, as is shown in Figure 5. The maximum deviation of this output from true linear interpolation is a sawtooth function with a 50-cps repetition rate and a maximum amplitude of 0.036 degree.

THE INSTRUMENT SERVO SYSTEM

The instrument servos convert the PPM signals produced by the counting decoders into analog command signals for the communications antennas. The control systems of these antennas use two-speed synchro control transformers as error detectors. The instrument servos position the two-speed synchro transmitters, which in turn command the antennas. Two instrument servos are required: one to command the azimuth and the other the elevation axes of the antennas. The two units are identical in design and construction and, in the following, θ represents either the azimuth or elevation angle.

System Mechanization

Inputs to the instrument servos are the PPM pulse trains derived from the counting decoders. Corresponding PPM follow-up signals are obtained from two angle-encoding resolvers connected to the 1:1 and 100:1 speed shaft on the servo gear trains. The method of encoding shaft positions with these resolvers will be described later. A block diagram of the instrument servo system (Figure 6), shows the derivation of the position and velocity follow-up signals, as well as the two-speed synchro transmitters which command the antenna control system. A high-speed two-phase servo motor is used to position the instrument servos, and a magnetic amplifier provides the power for the controlled phase of the motor.

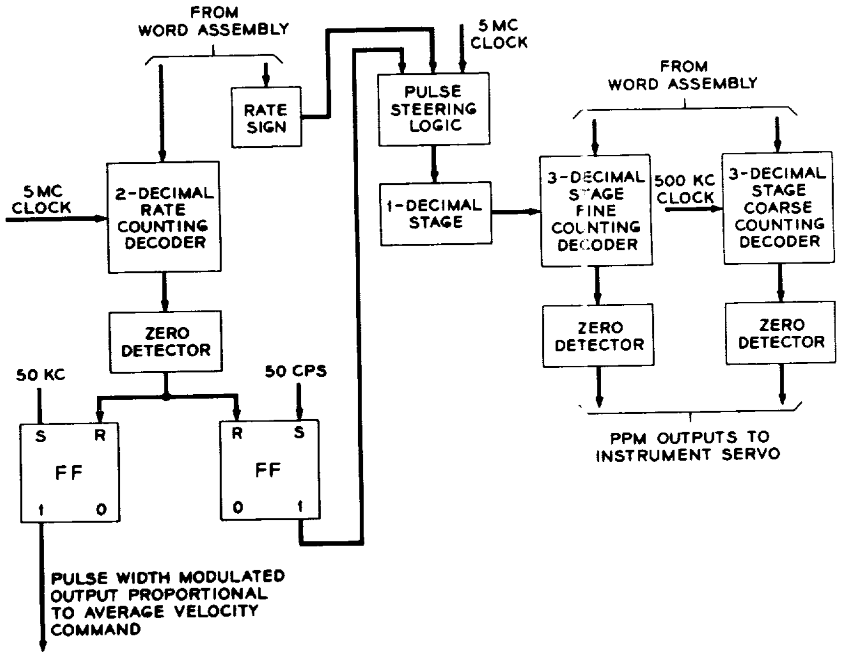


Figure 4 - Interpolation logic

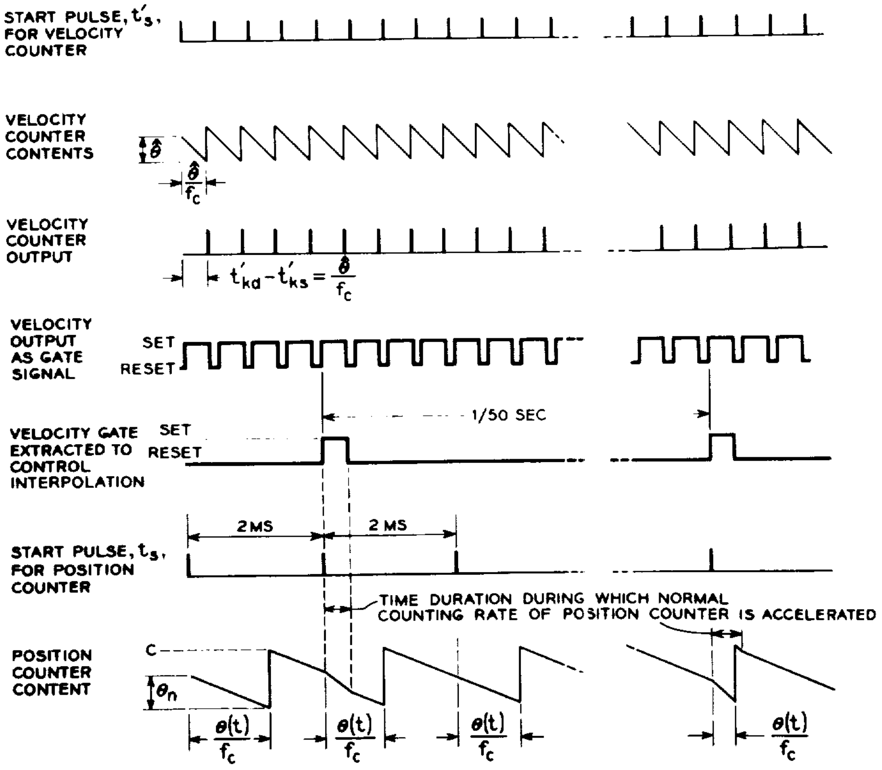


Figure 5 -Quasi-linear interpolation

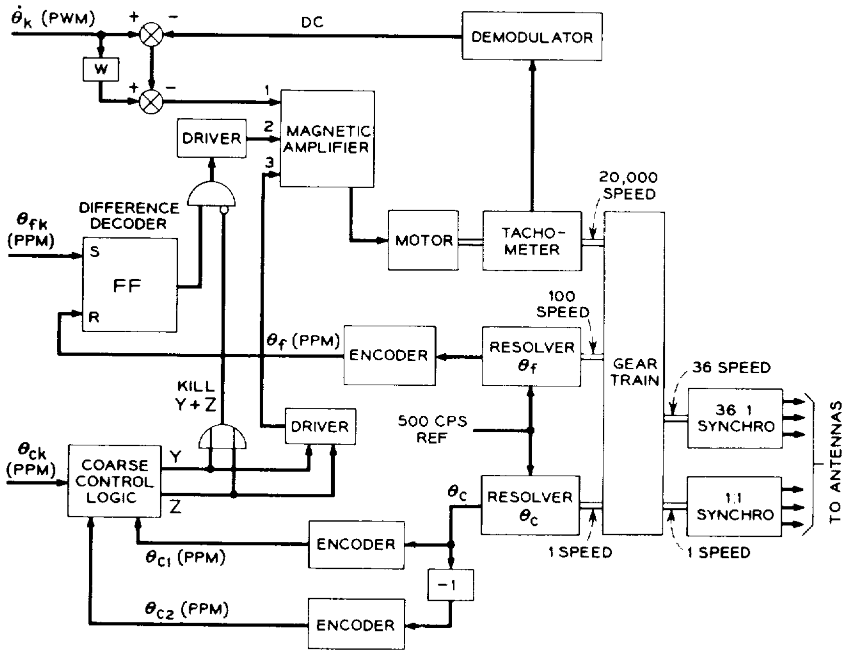


Figure 6 — Block diagram of the instrument servo

Tracking Control System

If the error between the angle θ called for by the counting decoders and the angle encoded from the resolvers is less than 1.8 degrees, a system using θ_{fk} as a command and θ_f as a follow-up signal controls the servo. For errors larger than 1.8 degrees a slewing mode of operation is employed, which will be described presently. The circuitry used in the tracking mode consists of the position feedback loop controlled by the fine position command θ_{fk}, the velocity loop controlled by the velocity command $\dot{\theta}_k$, and the feed-forward compensation represented by the block w in Figure 6.

In the *fine position loop* the follow-up pulse train θ_f is phased with respect to the decoded command pulse train θ_{fk} so that for zero error the pulses of one train occur halfway between the pulses of the other. The difference decoder is a flip-flop, with the θ_{fk} pulse train applied to the "set" input and θ_f to the "reset" input. For zero error the flip-flop spends equal time in the two states. For a nonzero error, the duration of one of the states exceeds the other by an increment linearly proportional to the error. A current proportional to the difference of the dwell times of the two states is used to drive one of the control windings of the magnetic amplifier, which in turn controls the motor. Figure 7 shows the simplified circuit between the output of the difference decoder and the magnetic amplifier. In absence of a "kill" signal, that is, with transistors T_{2A} and T_{2B} non-conducting, the flip-flop drives the magnetic amplifier through alternate switching of

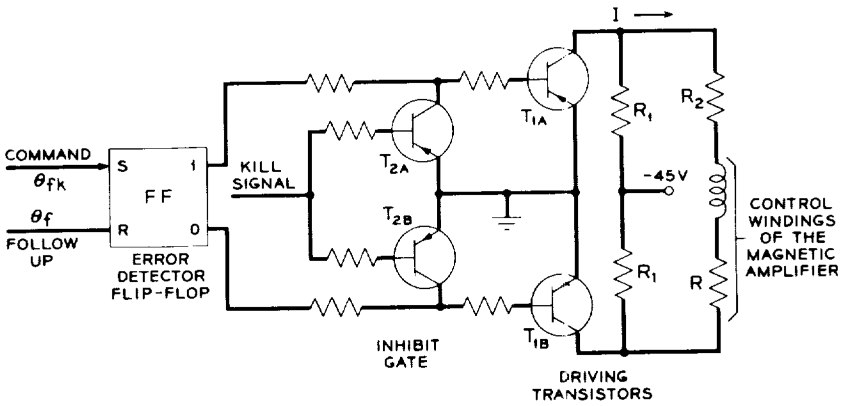


Figure 7 — Simplified θ_f circuit

transistors T_{1A} and T_{1B}. The gain of the fine position loop is set by the voltage applied to R_1 and R_2 and the resistance R of the control winding circuit. To provide the required tracking accuracy the gain is adjusted so that an error of 0.01 degree gives ample drive to overcome sticking friction of the motor and gear train.

The high gain of the fine position loop requires that it be disabled when the error is greater than 1.8 degrees, to prevent it from interfering with the slewing mode of operation. The "kill" signal actuates the inhibiting gate composed of T_{2A} and T_{2B}, which disables the loop. The generation of the "kill" signal is indicated in Figure 6.

The *velocity feedback loop* is necessary to stabilize the system and improve its dynamic response. To prevent tachometric feedback from causing tracking errors proportional to motor velocity, a signal proportional to the difference between the actual and commanded motor speeds is used to drive the magnetic amplifier. The command signal is obtained from the rate-counting decoder. It is a pulse-width-modulated (PWM) signal whose average value is proportional to $\dot{\theta}_k$. The follow-up consists of an ac tachometer followed by a demodulator producing a dc voltage proportional to the motor speed.

Ideally the *feed-forward compensator* (w) should provide a signal which is equal to that required by the motor to follow the commanded input. Tracking a satellite requires operation of the servo at almost constant speeds for periods which are long with respect to the characteristic time constants of the servo. Hence the feed-forward path provides the magnetic amplifier with a signal necessary to obtain the commanded velocity under steady-state operation. Since the relation between the steady-state motor speed and the magnetic amplifier control winding current is almost linear over the range of speeds used in tracking, the required block (w) of Figure 6 is a fixed attenuator. This is mechanized by increasing the voltage gain of the $\dot{\theta}_k$ decoder in the velocity loop, and therefore no additional circuitry is needed.

The instrument servo-tracking control system provides a static accuracy of ±0.01 degree and maximum errors in the tracking mode of ±0.025 degree.

Slewing Control System

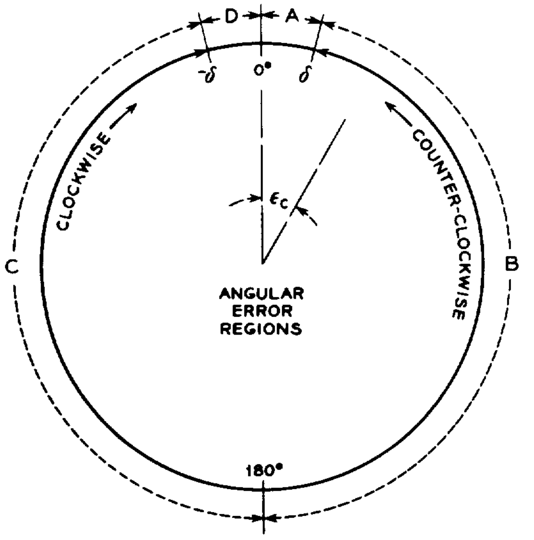
If the magnitude of the position error is greater than 1.8 degrees the θ_f loop cannot bring the error to zero. This is because the θ_f loop operates on the error modulo 3.6 degrees. If the position error ϵ_c, as determined by the comparison of θ_{ck} and θ_c, exceeds an angle of δ degrees (where $\delta \leq 1.8$ degrees) the fine loop is disabled by the "kill" signal. A saturation torque is commanded to decrease the error to a value less than δ degrees in minimum time. The actuating signal produced by the slewing control system assumes one of three values: zero, clockwise saturation torque, and counter-clockwise saturation torque. Figure 8 illustrates the slewing strategy. The follow-up pulse trains θ_{c1} and θ_{c2} shown in Figure 6 are used to obtain gate signals corresponding to the regions A, B, C, and D of Figure 8. Since A, B, C, and D form a mutually exclusive complete set of time intervals over the 1/500-second command repetition time, the command pulse θ_{ck} will then occur during one of these gate pulses and determine the error region. Let the commands of the clockwise and counter-clockwise torque be represented by binary functions Y and Z respectively; for example, the counter-clockwise torque is commanded if and only if Y = 1. From Figure 8,

counter-clockwise: $Y = \theta_{ck} \otimes B,$

clockwise: $Z = \theta_{ck} \otimes C,$

also the kill signal: $K = Y \oplus Z,$

where $\oplus$ = logical OR, $\otimes$ = logical AND.



SLEWING CONTROL LOGIC

ERROR REGION	TORQUE COMMAND
A OR D	NONE
B	COUNTER-CLOCKWISE
C	CLOCKWISE

$\epsilon_c = \theta_{ck} - \theta_{c1}$

Figure 8 — Slewing strategy in θ_c control logic

The timing pulses for the generation of the gate signals are obtained from θ_{c1} and θ_{c2}. The phase of the follow-up pulse train θ_{c1} is adjusted so that for zero error it coincides with θ_{ck}, the coarse command pulse train. The θ_{c2} follow-up signal is 180 electrical degrees behind θ_{c2}. Circuits providing a time delay corresponding to δ degrees are used in the generation of the gate signals. Figure 9 shows the generation of the gates a, b, and c by a set of flip-flops operated by the follow-up signals. By comparing Figures 8 and 9 it is evident that:

$$a = A = \partial D,$$

$$b = B,$$

$$c = \partial C,$$

where ∂ is a delay operator of δ degrees.

The determination of the error regions is done 500 times per second. Flip-flops Y and Z are set by the detection of error region B and C respectively; both are reset by the detection of region A or D. The required output to drive the motor is obtained from one of the two flip-flops. Therefore:

$$\begin{aligned}
Y_s &= \theta_{ck} \otimes B = \theta_{ck} \otimes b, \\
Z_s &= \theta_{ck} \otimes C = \partial\theta_{ck} \otimes \partial C = \partial\theta_{ck} \otimes c, \\
Y_r &= Z_r = (\theta_{ck} \otimes A) \oplus (\theta_{ck} \otimes D) = (\theta_{ck} \otimes A) \oplus (\partial\theta_{ck} \otimes \partial D) \\
&= (\theta_{ck} \otimes a) \oplus (\partial\theta_{ck} \otimes a) = (\theta_{ck} \oplus \partial\theta_{ck}) \otimes a, \\
K &= Y \oplus Z,
\end{aligned}$$

where Y_s and Y_r are the set and reset inputs to the Y flip-flop respectively; and similarly for the Z flip-flop. A circuit diagram for the above logic is shown in Figure 10. The signals Y and Z are applied to a pair of transistors driving the magnetic amplifier control winding No. 3 as shown in Figure 11.

Resolver Encoding

Shaft positions of the instrument servos are encoded to PPM signals by resolver encoding techniques. Two precision resolvers are used with each instrument servo: the first rotates 1:1 with the servo output to give a modulo 360-degree indication of the shaft angle, the second rotates 100:1 with respect to the output, to give the modulo 3.6-degree indication of the shaft angle. These ratios were chosen to match the coarse and fine outputs of the decimal counting decoders.

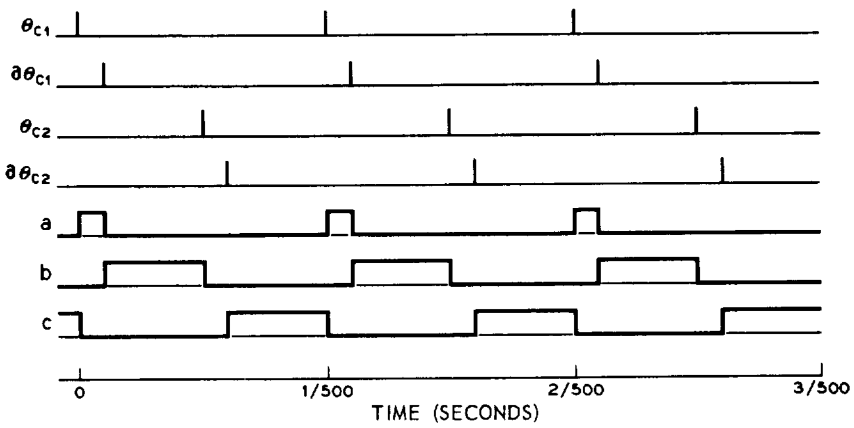


Figure 9 — Generation of gates a, b, and c in θ_c control logic

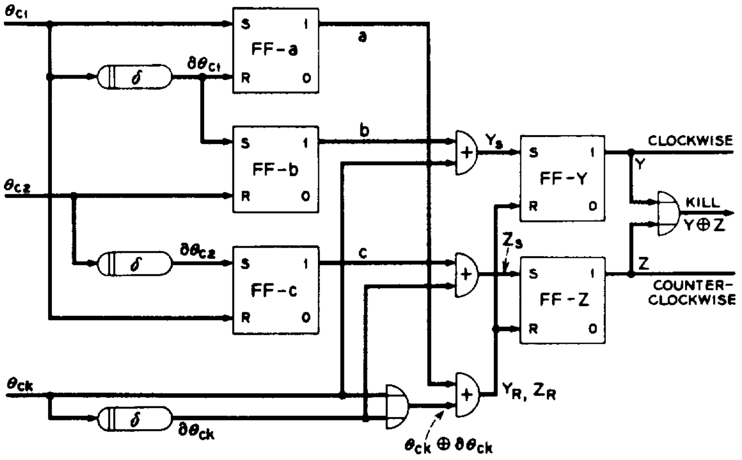


Figure 10 — Circuit diagram for θ_c control logic

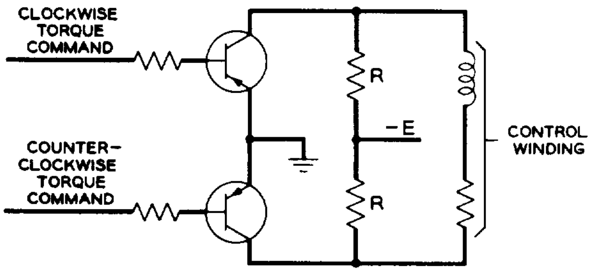


Figure 11 — Coarse control circuit

The method used to convert these resolver outputs to PPM signals has been described in another paper,* but will be reviewed briefly here for completeness. Electrically, each resolver is a mechanically variable transformer with couplings between the primary and secondary windings, both functions of the rotor angle θ_R. When excited by the ac signal

$$E_{in} = E_{max} \sin \omega t,$$

output voltages are the input voltage modulated by the sine and cosine of the rotor shaft angle θ_R. The resolver outputs are combined in phase-shifting networks which advance the phase of the sine voltage by $\pi/2$ degrees and add it to the cosine voltage. Thus a phase-modulated signal results, according to:

$$E_{max} \sin\left(\omega t + \frac{\pi}{2}\right) \sin \theta_R + E_{max} \sin \omega t \cos \theta_R = E_m \sin(\omega t + \theta_R).$$

The positive-going zero crossing of this signal is the desired PPM signal representing the shaft position. Since the excitation voltage is 500 cps, a 0.18 degree movement in the output of the instrument servo causes a change of 1 microsecond in the PPM output of the coarse encoder. Similarly, a movement of 0.0018 degree causes a 1-microsecond change in the PPM output of the fine encoder.

Resolver excitation is derived from the digital-to-analog converter central timing by filtering and amplification of a 500-cps square wave. A zero-crossing detector, similar to the one used for encoding the phase-shifted resolver output, is connected to the resolver excitation. This output is the start pulse and therefore phase-locked to the resolver excitation. It is used in the digital portion of the conversion equipment to time the start of the counter decoder sequence.

CONCLUDING REMARKS

The above is a description of a new type of special purpose data converter for directing narrow beam communication antennas from predicted information. It is capable of converting digital input data into real-time analog voltage commands with a dynamic accuracy ±0.05 degree, which is sufficiently accurate for the present antennas. It employes a moderate quantity of input data, and a reasonably simple digital-to-analog converter.

The single-parity-bit error detection provides moderate resistance to transmission errors. During the Echo I experiments the number of errors in transmissions from Goddard Space Flight Center were logged for 30 passes. Out of a total of 250 errors, the

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*Kronacher, G., "Design, Performance, and Application of the Vernier Resolver," Bell Sys. Tech. J. 36:1487-1500, November 1957 single-parity detection was effective in rejecting over 90 per cent. During these periods the coasting features designed into the converter provided adequate antenna commands.

Using instrument servos as an intermediate step in the conversion process provides convenient generation of two-speed voltages for commanding more than one antenna or optical mount simultaneously. Separate synchro units can be placed on the gear trains for each antenna, and each synchro can be excited by the particular frequency required by that mount. Furthermore, choice of the ratios in the gear train provides outputs in the "two-speed" combination required by each mount.

The use of counter decoders is quite attractive; they provide the storage necessary to give continuous outputs to command the servos. Data interpolation makes possible an input data interval of sufficient duration that ordinary teletypewriter transmission can be used. The interpolation method outlined herein makes additional use of the counter decoders, without the need for a conventional arithmetic unit. The interconnections between counters needed to perform interpolation require simple control logic. Since the decoders and many of the low-speed operations in the converter operate synchronously, the additional pulse rates needed for interpolation are already available from the timing section.

The resolver encoding technique converts instrument servo shaft positions into pulse-position-modulated signals of the same general form as the counter output. These signals are easily combined to form error signals to control the servos. In the same manner that gear ratios can be chosen to provide outputs at a desired "two-speed" ration, the gearing between resolver encoders can be chosen to yield PPM signals in any desired speed ratio. This allows freedom of the number base in which the decoding process is performed.

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