A system has recently been developed at APL in which an artificial satellite provides determination of the azimuth of a line from north. A single-axis interferometer system is used in conjunction with a specially designed receiver that employs some unusual techniques to make the required radio-frequency measurements. This receiver in particular is described.

A DYNAMIC PHASE-DIFFERENCE MEASUREMENT SYSTEM

E. E. Westerfield

The use of satellite signals for the determination of azimuth has been investigated at APL, the interferometer method used being based on a suggestion by A. M. Stone of this Laboratory. This study required development of specialized instrumentation that could measure very precisely the relative phase of a pair of rather rapidly varying UHF signals. The instrumentation circuitry in the phase-difference measurement system thus developed is the subject of this paper. A generalized functional diagram of such a system is shown in Fig. 1.

The satellite signals whose phases are to be compared arrive at two antennas located horizontally a number of wave lengths apart. A two-dimensional view of this arrangement is shown as Fig. 2. The satellite is effectively at an infinite distance from the two antennas. The difference in length of the two propagation paths can be seen from the sketch to be equal to $D \cos\theta$, where θ is the angle formed by the line connecting the two antennas and the line of sight to the satellite. The signal V_a at antenna A can be written as

$$V_a = V_r \sin 2\pi F_r t, \qquad (1)$$

where V_r is the amplitude of the received signal, F_r is its frequency, and t is time; F_r is a function, not only of the frequency of the transmitted signal, but of the rate at which the range changes between the antenna and the satellite, i.e. as it is affected by the doppler phenomenon.

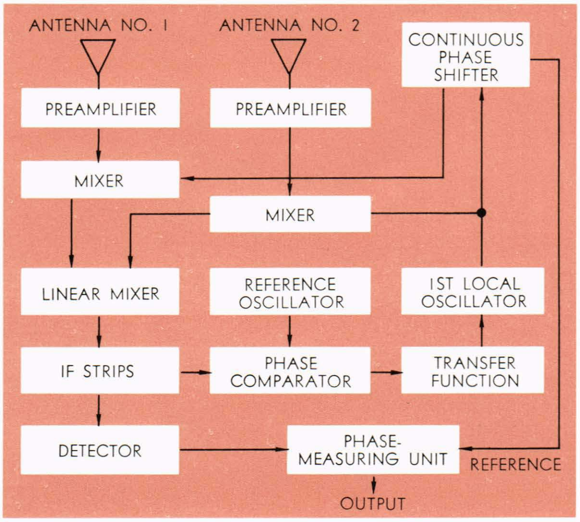

Fig. 1—Functional diagram of a phase-measuring interferometer system.

The signal V_b received by the B antenna is

$$V_b = V_r \sin\left(2\pi F_r t + \frac{2\pi D}{\lambda}\cos\theta\right). \qquad (2)$$

The term $\frac{2\pi D}{\lambda}\cos\theta$ is the phase difference of the two signals.

The way in which the phase of the signals varies during a particular satellite pass is affected by the path of the satellite with respect to the two antennas. As shown previously the RF phase difference ϕ of the two antennas is

$$\phi = \frac{2\pi D}{\lambda}\cos\theta \quad \text{(radians)}. \qquad (3)$$

The phase varies over many rotations of the angle ϕ because the antenna separation is much greater than one wavelength. The current measuring system is capable of measuring phase variations of as much as 200π radians. The curves for several types of satellite passes, with respect to the two antennas, are shown in Fig. 3. Curve A is for the condition where the satellite passes directly overhead and the antennas are located in the plane of the orbit. Maximum phase shift occurs with this situation. In the case of $\lambda \cong 2$ ft and $D \cong 100$ ft, the total phase will vary from -50 to $+50$ complete rotations, or to approximately 18,000° in each direction. Curve B is for the condition where the satellite passes directly overhead and the line joining the antennas is perpendicular to the orbital plane. There is no phase shift during the complete pass under these conditions. The remaining curves of Fig. 3 are for the conditions where the satellite does not pass directly over the receiver. For these the inclination of the orbit B_o with respect to the receiving station is $+25°$. For circular orbits the inclination is here defined to be the angle subtended at the center of the earth by the tracking station and the nearest point of approach of the satellite. Curve C is for the condition where the line connecting the two antennas is perpendicular to the line generated by the plane of the orbit and the earth's surface. It can be seen also that the period over which phase information is obtained is less since the satellite is above the horizon for a shorter period of time. Curve D is essentially the same as Curve C except for a $-25°$ angle of inclination with respect to the receiving station. Curves E and F are for the case where the line connecting the two antennas is parallel to the plane of the orbit.

Design of the Phase-Measuring Receiver System

The block diagram of the receiver is shown as Fig. 4. The design was influenced somewhat by using certain available parts and major assemblies, which in turn made it possible to save a great deal of engineering effort.

Included in the block diagram are the blocks within the receiver itself, as well as such external equipment as portions of the digital readout system. The receiver is designed to operate at the nominal 324-mc signal radiated by the ANNA satellite. The higher of the two RF frequencies radiated by the satellite was selected to reduce adverse effects on the system caused by ionospheric refraction. At the lower left-hand corner of the diagram are the two antennas and two preamplifiers that are mounted directly at the antennas. These preamplifiers have a noise figure of approximately 6 db in the region of interest. They are utilized to provide a low noise figure for the overall operation of the system.

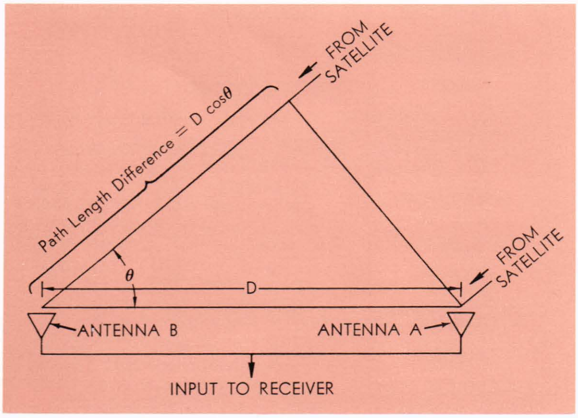

Fig. 2—Antenna geometry of an interferometer system.

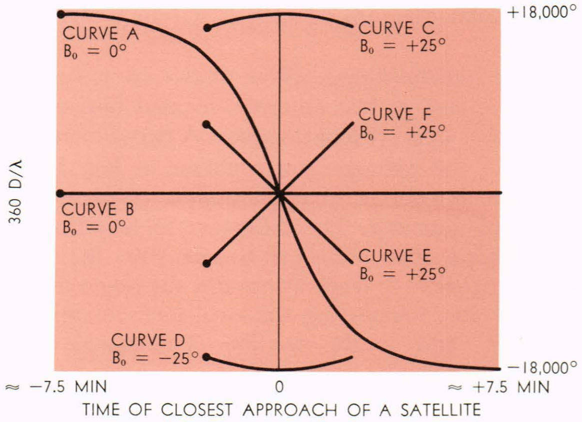

Fig. 3—Phase angle versus time, inclination, and bearing.

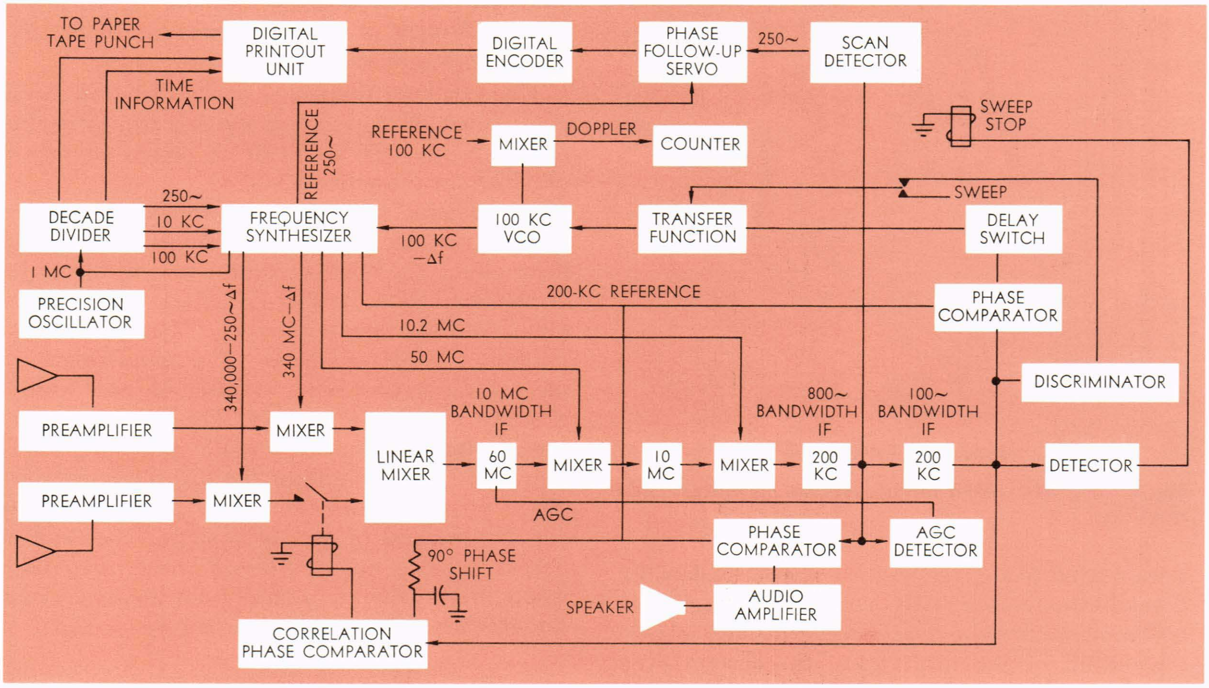

Fig. 4—Block diagram of the phase-measuring interferometer system designed and built at the Applied Physics Laboratory.

The output of the preamplifiers is fed into two independent RF amplifiers and mixer assemblies that are located in the receiver proper. The two local-oscillator (LO) signals are obtained from a frequency synthesizer. One of these signals, when the receiver is tracking a satellite, is at a frequency of 60 mc below the RF frequency of the satellite. In the block diagram the doppler term plus the amount the satellite is below exactly 324 mc is indicated by Δ*f*. As will be shown later, Δ*f* is equal to the amount below 100 kc of the frequency of the Voltage-Controlled Oscillator (VCO), which is a part of the frequency synthesizer. The other LO signal is at a frequency of 60 mc below the received frequency of the satellite, plus 250 cycles. The result is that the signals out of the mixers, for a given signal received by the two antennas, differ by a frequency of 250 cycles. The difference with respect to a reference generated by the frequency synthesizer in the receiver is a function of the phase difference of the signal received by the two antennas. The two signals are mixed in a linear mixer and then fed into a 60-mc IF. Figure 5 is a sketch showing the envelope of the IF bandpass. The two RF signals are present within the bandpass, separated by an amount equal to the 250-cycle difference in the local oscillators. The phase difference between these two signals is also a function of the difference in phase between the two signals received by the two antennas. The first IF strip has a bandwidth of 10 mc and a gain of about 90 db. Ideally, a somewhat lower first IF frequency would be utilized, rather than the one that was chosen because of the availability of the mixer assemblies.

The output of the first IF strip is mixed with a 50-mc signal from the frequency synthesizer to generate a 10-mc signal that is fed into the second IF strip. The function of the latter strip is to prevent the 200-kc IF from seeing an image frequency within the bandwidth of the 60-mc IF strip. It utilizes a crystal filter with a 1-kc bandwidth to provide the necessary rejection. Its output is then mixed with a 10.2-mc signal obtained from the frequency synthesizer. The result is a 200-kc signal that is fed into an IF strip containing a crystal filter with an 800-cycle bandwidth. All LO signals utilized in this down-conversion are obtained from the frequency synthesizer and are fixed multiples of the precision 1-mc oscillator. Within the final 800-cycle IF strip, the two distinct signals shown in Fig. 5 are still present but separated by the 250 cycles. From the signal tracking action of the receiver, one signal will be in the exact center of the IF bandpass while the other will be near the edge. These signals will be maintained precisely in these locations by a phase-lock tracking loop.

The output of the third IF feeds four different units: a 200-kc narrow-band IF strip of 100-cycle bandwidth; an AGC detector; a scan detector; and

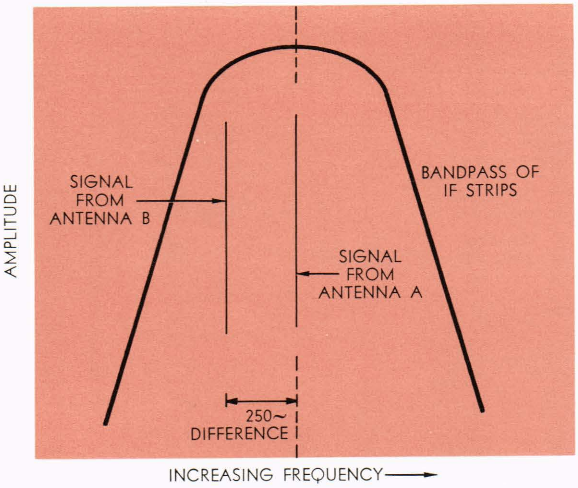

Fig. 5—Signals within an IF receiver amplifier while tracking.

a wide-band phase comparator. The AGC detector develops the required AGC voltage that is fed back to the 60-mc IF strip. This loop is adjusted to keep the output of the first 200-kc IF constant even though the input to the receiver is varied over a wide power range. The phase comparator provides an audio-beat signal that greatly aids in acquiring initial phase lock on the signal from the satellite. The scan-detector output is the 250-cycle beat frequency between the two separate signals mentioned above. Its phase with respect to the reference signal from the frequency synthesizer is indicative of the phase difference of the RF signals received by the two antennas. This signal is fed to a phase-follow-up servo to be described later. The second 200-kc IF has a bandwidth of 100 cycles and filters the signal in such a way that only the signal from one antenna is present at its output. The latter is fed into a phase comparator where the signal is compared to a 200-kc reference signal also obtained from the frequency synthesizer. The output of the phase comparator is an error signal that is a function of the error in phase and, therefore, of the frequency of the first LO. This error signal is applied to the VCO located within the frequency synthesizer, thereby correcting the first LO frequency and accomplishing phase lock.

The frequency synthesizer will not be discussed in detail in this paper other than to say that the frequency of the first LO is controlled directly on a cycle-per-cycle basis by the frequency of the VCO; thus, if the frequency to the VCO decreases by 10 cycles, the frequency of the first LO will also decrease by 10 cycles. This is accomplished by heterodyning the 100-kc VCO frequency up to 264 mc for one of the first LO signals and to a frequency exactly 250 cycles lower for the other. The transfer function used within the frequency tracking loop is of a second order and is variable in bandwidth in steps from 5 to 50 cycles.

The exact RF frequency of the received signal can readily be determined by measuring the frequency of the 100-kc VCO. A period counter is provided for this purpose.

The relative phase of the two signals received at the antenna can be determined directly by determining the relative phase between the output of the scan detector and the 250-cycle reference obtained from the synthesizer. This phase comparison is made by means of a phase-follow-up mechanical servo system, an assembly that utilizes a motor to drive a resolver. The resolver is connected electrically in the servo loop in such a way that it shifts the phase of the 250-cycle reference signal by an amount directly proportional to the angular position of the drive shaft. The resolver output signal is then fed into a phase comparator where it is compared in phase with the signal from the receiver. The comparator output is equal to

$$V_{pc} = V_c \cos(\phi_m - \phi_s), \tag{4}$$

where ϕ_m is the phase of the scan signal with respect to the reference, ϕ_s is the shaft angle measured from a reference position, and V_c is a constant that depends on the amplitude of the two signals. The error signal V_{pc} controls the servo drive motor. The connections are such that the servo tends to drive until ϕ_m equals ϕ_s. A digital encoder is so mounted on the drive shaft that the precise position of the shaft may be measured. The encoder chosen can indicate the shaft position to 0.001 revolution and can count rotations up to 100. The rotation counting feature is needed to keep track of the number of complete rotations of the phase as it varies during the pass.

The output of the receiver system is in two forms. The first is a punched paper tape that provides a data point for every other second during the satellite pass. Each data point includes the time of the point, the signal frequency received, and the phase information. The second output is an analog recording, by means of a galvanometer oscillograph, of AGC voltages, correlation voltages, and other critical receiver parameters.

Due to causes not yet completely resolved, the measurements of angle-of-arrival did not correlate with the computed satellite position to the degree of precision required of the azimuth measurement system. Nevertheless, the equipment performed well and has demonstrated the capability of measuring the phase difference of the signals received by the two antennas to within half a degree, and azimuth to within 6 minutes of arc.