Technical Report No. 32-80

A Long-Range Precision Ranging System

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ABSTRACT

A technique is presented that may be used for precision real-time continuous range measuring at long ranges. The technique uses a carrier that is phase modulated by a pseudo-random binary sequence. The characteristics of the sequence that make it acquirable are discussed. The general form of a receiver capable of tracking the carrier is given and is shown to be a kind of phase-locked loop. A two-loop system capable of tracking a pseudo-random sequence and its clock is given. The combination of the receiver and the sequence tracking system form a ranging receiver. The power division necessary between the carrier and the sidebands is shown to be determined by the noise bandwidths of the two tracking systems. The bandwidths necessary for tracking space probes and Earth satellites are given and some experiments in radar-tracking Earth satellites are described. Based on these experiments, estimates are made of the useful range of such a system in tracking space probes.

I. INTRODUCTION[1]

As spacecraft penetrate deeper into space, the problem of tracking; that is, of keeping an accurate log of the location of the spacecraft in space, becomes ever more difficult. The methods most used currently, which rely on angle and doppler measurements, become increasingly inaccurate as the distances involved become large compared with any base line on Earth which might be used for triangulation. As spacecraft enter the regions beyond the Moon, a direct measurement of range becomes a practical necessity in any method for accurate determination of location in space. This Report describes a system which may be used for measuring, precisely and continuously, very long ranges in real time.

[1]Presented on May 4, 1961, joint meeting of International Scientific Radio Union, U.S.A. National Committee and Institute of Radio Engineers, Washington, D.C.

II. THE BASIC SYSTEM

In the basic ranging system, shown in Fig. 1, the transmitter is phase modulated by the transmitter code, which is a long pseudo-random binary waveform. The modulated signal propagates to the spacecraft and is transponded back to Earth. The returned signal is received by the ranging receiver which is a type of correlation receiver for which the receiver coder forms the local model of the received code. When the received code has been acquired; that is, when the local model is in phase with the received code, the phase difference between the transmitter and the receiver codes is a measure of the propagation time to the spacecraft and back and, therefore, a measure of the range. The ranging receiver is made to track the returned signal and the phase-measuring device operates continuously, providing a continuous real-time measurement of range.

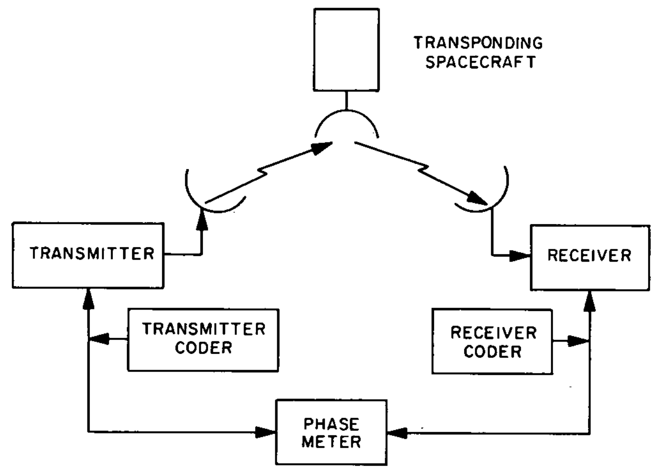

Fig. 1. Basic ranging system

III. THE RANGING CODE

The ranging code is a periodic binary waveform, formed from a continuously repeating, long pseudo-random binary sequence by assigning a period of time, called a digit period, to each digit in the sequence, and causing the waveform to be plus one (+1) when the corresponding digit is zero and minus one (−1) when the corresponding digit is one. Figure 2 shows a pseudo-random sequence of length 7 and the corresponding binary waveform.

If it is to be useful for ranging, a code must have three characteristics:

1. The period of the code must be longer than the propagation time to the spacecraft and back for the longest range to be measured. This assures no ambiguity in the range.
2. The phase of the code must be measurable to the desired degree of precision. For the type of code used, this is equivalent to having a sufficiently short digit period.
3. The code must be acquirable; that is, it must be possible to match the local model to the received code within a reasonable length of time.

The ranging code is derived from a certain type of pseudo-random sequence which has the property that the value of the autocorrelation function is uniformly low if τ differs from zero or a multiple of a period by at least one digit period. Such a binary waveform fulfills the first two requirements for an effective ranging code. Sequences are known that have periods of hours at 1 million digits per sec. The phase of one waveform with

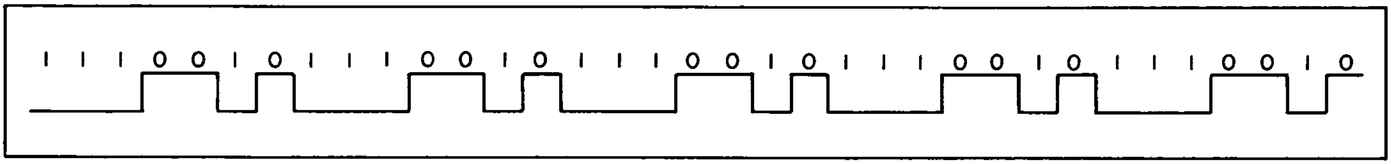

Fig. 2. Binary sequence and waveform

respect to the other can be determined to within one digit period by counting the number of digits by which one is displaced with respect to the other. If a digit period is 1 μsec, this corresponds to measuring the propagation time to within 300 meters or the range to within 150 meters.

In order to meet the third requirement for a ranging code; that is, acquirability, a combination of several pseudo-random sequences is used. If several sequences with relatively prime periods are combined digit by digit, the period of the resulting sequence is equal to the product of the periods of the several sequences. If the appropriate combining function is used; for example, a majority function, the cross-correlation function of the combined sequence with each of the component sequences is high for τ equal to any multiple of the period of the component, but it is uniformly low otherwise. This allows the phase of a component of a combined code to be determined by, at most, p trial correlations, where p is the period of the component. More generally, if there are n components in the code, the period of the combined code would be $p_1 \cdot p_2 \cdot \cdots p_n$, whereas, the maximum number of trial correlations that would be required to determine uniquely the phase of all of the components, and hence of the combined code, would be $p_1 + p_2 + \cdots + p_n$. Figure 3 gives an example of some numbers which might be used in a code with five components. Experience has shown that the time necessary to make a trial correlation is less than 1 sec: the acquisition time, therefore, for such a code is less than 5.5 min.

$p_1 = 23$

$p_2 = 31$

$p_3 = 47$

$p_4 = 103$

$p_5 = 127$

$p_1 + p_2 + p_3 + p_4 + p_5 = 331$

$p_1 \times p_2 \times p_3 \times p_4 \times p_5 = 438,357,391$

MAXIMUM RANGE $\approx 65 \times 10^6$ km

ACQUISITION TIME < 5.5 min

Fig. 3. Example of ranging code

IV. THE CARRIER TRACKING RECEIVER

A receiver which is capable of tracking a carrier at low signal levels is shown schematically in Fig. 4. The two coherent references are derived from the same oscillator which provides the transmitter radio-frequency carrier. The receiver is a closed-loop system. When locked to the incoming signal, the loop is in such a condition that there is essentially no error signal. If the phase of the received signal changes, the phase of the two intermediate-frequency signals tends to change by the same amount, causing an output from the phase detector. This error signal after filtering causes the phase of the voltage-controlled oscillator to shift in such a way that the local-oscillator-signal phase stays in phase with the received signal. The output phase is then a scaled replica of the input phase, and the receiver is a type of phase-locked loop. The additive noise on the input signal causes the phase of the output to be noisy. The filter which precedes the voltage-controlled oscillator is very narrow-band and centered on dc. This filter controls the over-all noise bandwidth and tracking rate of the receiver.

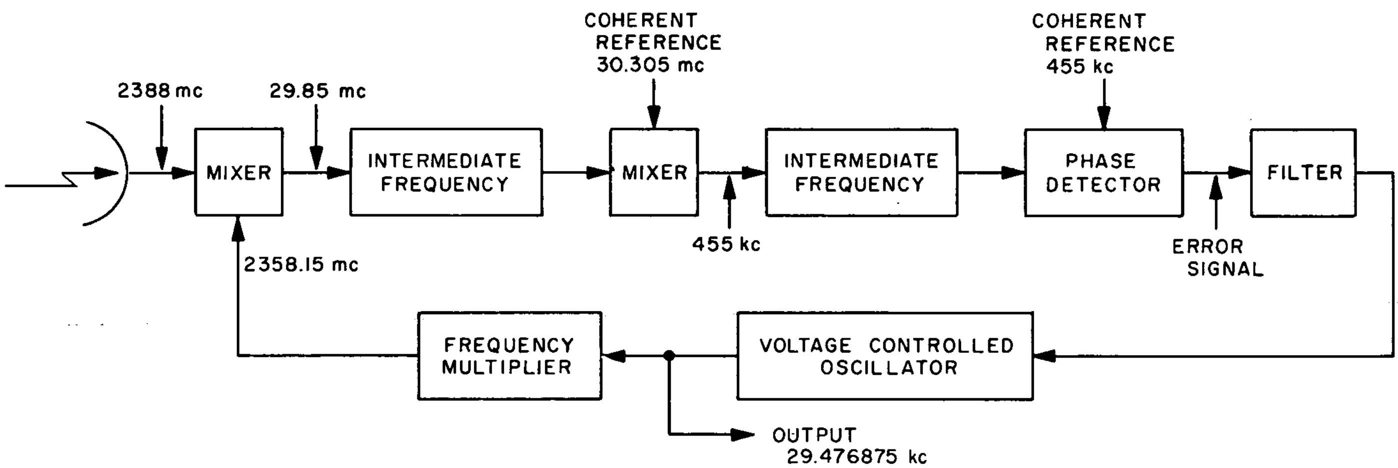

Fig. 4. Carrier tracking receiver

V. CODE TRACKING DOUBLE LOOP

In order to track the ranging code, a double-loop tracking system is added to the carrier tracking receiver, and the ranging code is multiplied by its clock prior to transmission. The clock is a binary waveform with the same digit period as the code and successive digit periods of opposite sign. The basic form of the double loop is shown in Fig. 5. The inner loop is a phase-locked loop to track the clock. The outer loop provides the code to demodulate the clock which has been modulated by (i.e., multiplied by) the code at the transmitter. Since the phase-locked loop tracks the clock and the output of the phase-locked loop drives the coder, the receiver-coder output tracks the received code. The other detector has an output proportional to the clock signal being tracked by the phase-locked loop. As each component of the receiver code is matched with the code being received, the clock is more nearly completely demodulated. When all of the components are matched, the clock is fully demodulated. The indicator, therefore, serves as a correlation indicator which tells when each component has been acquired. The filter in the clock phase-locked-loop controls the noise bandwidth and tracking rate of the loop.

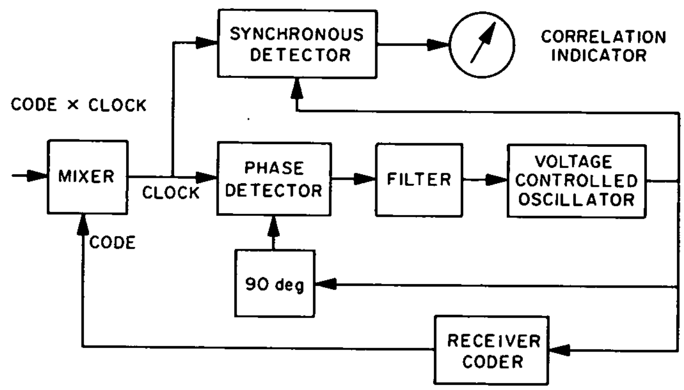

Fig. 5. Double-loop code-tracking system

VI. THE RANGING RECEIVER

The carrier tracking receiver and the two-loop code-tracking system may be combined, as shown in Fig. 6. The additional modulator in the code-tracking portion is necessary because the code-times-clock being tracked enters that portion as a phase modulation on an intermediate-frequency signal. A double demodulation takes place; both the intermediate-frequency signal and the clock are demodulated.

The important factors in the receiver which determine its threshold are the noise figure of the radio-frequency amplifier and the noise bandwidths of the two phase-locked loops. The noise figure of the radio-frequency amplifier is, of course, made as low as possible. The bandwidths of the two phase-locked loops are determined by the doppler rate which each must track. A detailed analysis of the receiver shows that the doppler rate tracked

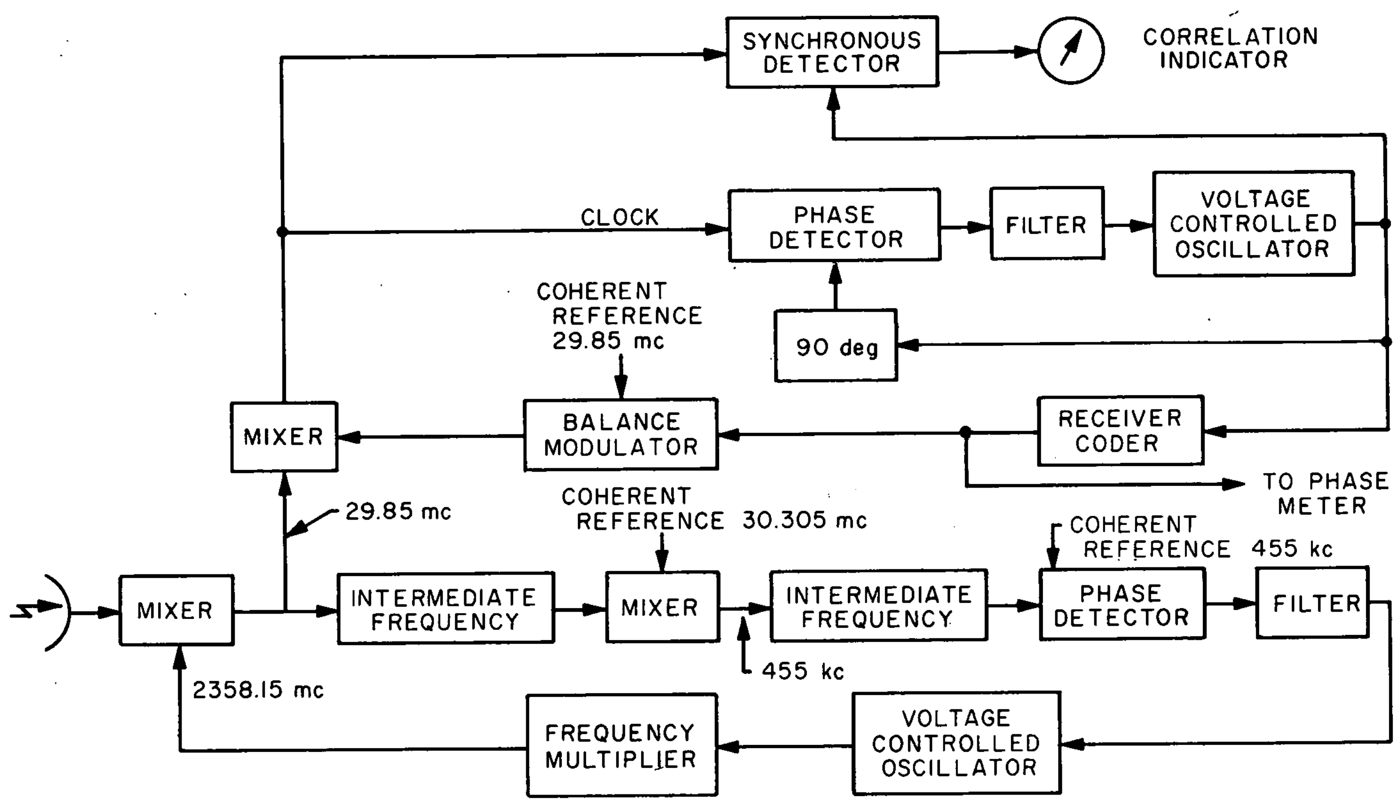

Fig. 6. Ranging receiver

by the radio-frequency loop is 4800 times that tracked by the clock loop. This implies that, to track a given spacecraft acceleration, the minimum bandwidth of the radio-frequency loop must be 4800 times that of the clock loop. It is interesting to note what accelerations may be encountered and what bandwidths are required. An Earth satellite passing overhead at an altitude of 1000 mi in a circular orbit has a radial acceleration of about $^{16}\!/_{25}$ gravity. This causes a doppler rate of 48 cycles per sec per sec for the radio-frequency loop and 0.01 cycle per sec per sec for the clock loop. For a spacecraft between the planets, the acceleration is less by at least one order of magnitude, except possibly during maneuvers.

In a phase-locked loop, the threshold is proportional to the noise bandwidth times the noise spectral density. Thus, for an ideal design, the threshold of the code-tracking double loop would be 4800 times lower than that of the radio-frequency tracking loop for equal powers in the carrier and in the ranging signal. That is, the power in the sidebands need be only $^{1}\!/_{4800}$ times the power in the carrier for both loops to have the same signal-to-noise ratio at their outputs.

VII. EXPECTED PERFORMANCE OF RANGING SYSTEM

For many practical reasons, an ideal receiver design cannot yet be attained. However, a ranging receiver has been built and used to radar-track Earth satellites at very low received-signal levels. During November and December of 1960, in a series of ranging experiments made on the *Echo* balloon satellite, the receiver tracked well at received-signal levels below −130 dbm. After some refinements were made in the receiver, in a second series of experiments made in January 1961 on the *Courier* satellite, the receiver tracked well at signal levels below −145 dbm. In both of these groups of experiments, the satellites were used only as reflectors—the electronics aboard did not contribute to the returned-signal strength.

In the case of a spacecraft in deep space, a transponder would be used to receive and retransmit the carrier and ranging code. In such a system, the spacecraft-to-Earth link is usually the weaker. If one assumes a spacecraft antenna which is 4 ft in diameter and with 100 watts of radiated power, then the ranging receiver used for the satellite-tracking experiments could track the spacecraft to distances greater than 725 million km. This is adequate for the inner portion of the solar system.