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The PN Technique of Ranging as Applied in the Ranging Subsystem Mark I

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CONTENTS

FIGURES

ABSTRACT

Starting with the basic principles of radar, the concepts of a technique of range determination with pseudo-random codes are developed. Increasingly complex requirements are considered and satisfied in turn by the use of the Gedanken-Experimente approach. The need for ranging codes, their requirements, synthesis, and detection are discussed. A brief functional description of the Ranging Subsystem Mark I is combined with its performance parameters, including the maximum unambiguous range determinable and the resolution and accuracy of the measurement.

I. INTRODUCTION

The determination of range to a distant object is typically accomplished by one of two means. One is the method of triangulation; this involves measurement of the angles between the two ends of a base line of known length and the lines from these ends to the distant object. The other is the method of radar; this involves transmission of a packet of RF energy from the point of observation, reception of the same signal reflected from the distant object, and measurement of the time interval between these two events.

For precise range determination on a distant spacecraft, neither of these means is adequate. The precision of triangulation depends on the length of the base line and the precision to which it is measurable. The maximum unambiguous radar-range determination is limited by the radar-signal periodicity which, in turn, is governed by signal-strength availability for reliable detection.

At the Jet Propulsion Laboratory (JPL), the work of Mahlon Easterling[1] and others resulted in the development of a technique of ranging which overcomes the shortcomings of the above two methods. This technique makes use of pseudo-random binary codes to phase-modulate a carrier and to detect the returned signal. It is characterized by the interplay of three distinct disciplines; namely, information theory, RF engineering, and digital computer technology.

This technique of ranging, implemented in several different mechanizations during the past 5 yr, has been successfully employed in range determinations on the *Echo* balloon, the *Courier* satellite, the planet Venus, and transponder-equipped helicopters at the JPL Goldstone Space Communications Station, as part of a continuing research and development effort.

The Ranging Subsystem Mark I, a special-purpose digital device for use in conjunction with S-band receivers, transmitters, and transponders, was designed and built to satisfy the needs of the JPL Deep Space Net for an operational precision ranging system to be used on spacecraft within an 800,000-km range. The Mark I was subsequently adopted also as part of the Unified S-Band System of the NASA Manned Space Flight Net.

[1]Easterling, Mahlon, *A Long-Range Precision Ranging System*, Technical Report No. 32-80, Jet Propulsion Laboratory, Pasadena, California, July 10, 1961.

II. THE PN TECHNIQUE OF RANGING

The pseudo-noise (PN) technique of ranging is so called because of the PN characteristics of the binary waveforms used in its implementation. The technique measures the round-trip propagation time of a signal from a ground transmitter to a spacecraft transponder and back to a ground receiver. The accuracy and resolution are independent of any motion of the spacecraft. The measurement is made continuously and can be sampled on demand. The unit of measurement is called the "Range Unit" (RU), which has the dimension of time. The RU is defined and determined by the frequency of the transmitter S-band carrier and is otherwise invariant. Specifically, the RU is independent of any doppler shift on the signal received from the spacecraft.

A system based on the PN technique of ranging transmits an S-band carrier, phase modulated by a particular type of pseudo-random binary code (called a ranging code), to a transponder in a spacecraft. The code modulation is detected in the transponder and used to remodulate a down-link S-band carrier (shifted in frequency), which is then received by a ground receiver using the same antenna as is used for transmitting. The ground receiver is a type of phase-locked receiver that tracks both the S-band carrier and the ranging code.

Probably the best way to explain the basic nature of pseudo-random-code ranging is by starting with a basic, though inadequate, concept and, as shortcomings become apparent, increasing its complexity. To this end, a series of "thought experiments" will be presented, or what in German are called "Gedanken-Experimente."

Assume then a reflecting target rather than a transponder and, further, that it be stationary. A scheme for determining its range from ground is shown in Fig. 1.

There is a source of standard frequency that serves to modulate an S-band carrier with periodic single pulses. The reflected modulation signal is detected in a ground receiver and, by means of a phase meter of some sort, the phase difference between transmission and reception of the modulation signal is determined. It will be found that the period of the pulse modulation, i.e., the interval between single-pulse transmissions, must be greater than the round-trip transit time. Otherwise, there will be ambiguities of integral pulse periods. This, of course, is the way conventional pulse radar works.

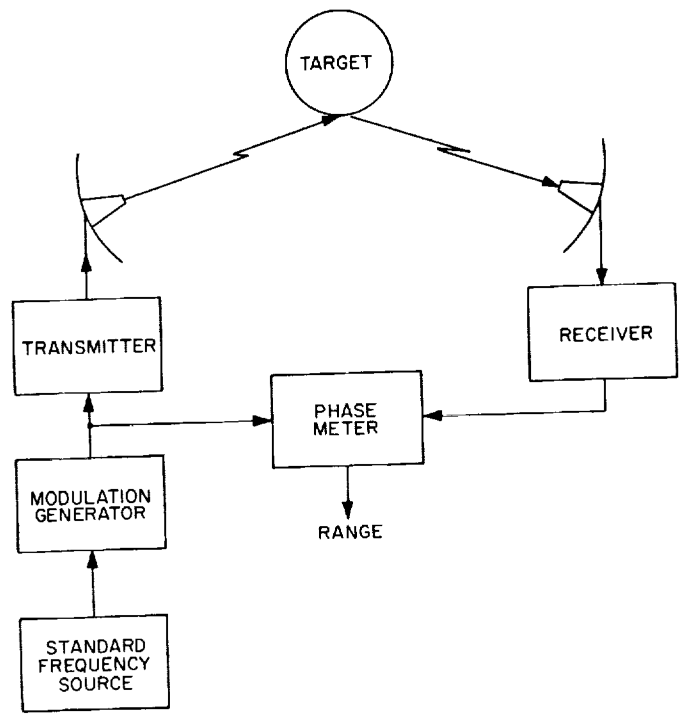

Fig. 1. CW radar ranging system

Next, permit the reflecting target to move, and attempt to detect the resultant changes in range. As the target moves, the phase meter reading changes. Increases in range will increase the meter reading; decreases will decrease the reading.

The resolution of the range-increment detection, and indeed the initial range determination, depends on the precision of the phase meter. If the phase meter were to be a digital device, almost any desired resolution could be attained, which would then be invariant. Figure 2 shows such a higher-resolution implementation.

Here the transmitter is modulated at a much higher frequency than in the previous example. The transmitted and received frequencies are continuously compared in a doppler detector consisting of a mixing device and a counting device. The shorter the period of the modulating pulses, the finer the resolution of measurement.

In general, then, ranging consists of filling the up-link and down-link path with uniformly transmitted cycles of known period, determining the number of cycles in space

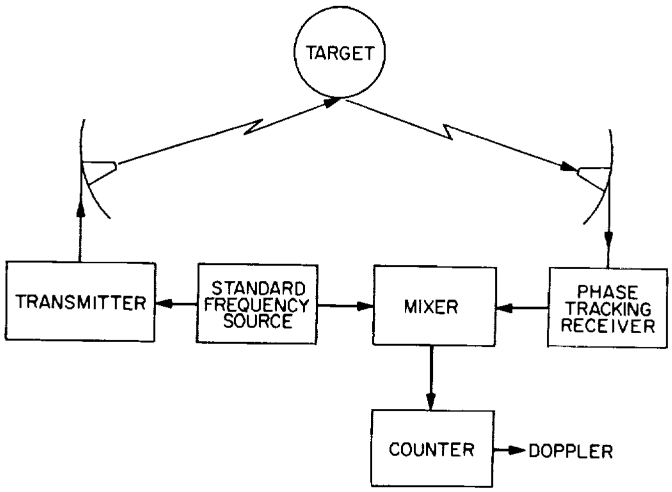

Fig. 2. Doppler measurement by coherent CW radar

at the start of ranging acquisition, and adding (or subtracting) cycles, subsequently, in accordance with motion of the target.

Once again, consider the target anchored in space. A transmitter clock signal is derived by subdividing the transmitter oscillator frequency. This serves as one input to a clock-doppler detector. It also drives a transmitter coder that generates a continuous code (101010 . . .) two bits in length, referred to as transmitter "clock" code. This, then, bi-phase modulates the S-band carrier. (See Fig. 3.)

A receiver clock signal is derived from the received modulation and is fed to the other input of the clock-doppler detector. Then, in the absence of doppler (since the target is stationary), the receiver clock code will be delayed with respect to the transmitted clock code by some unknown integral number n of clock code periods τ, plus a delay d equal to some unknown fraction of τ. That is to say, total round-trip delay $= n\tau + d$.

Determination of the number n will be considered later. A clock transfer loop is provided at this point to help determine the value of d. A range tally, in the form of a digital accumulating register, is also provided. In it range numbers (in range units) are tallied in accordance with outputs from the clock-doppler detector.

At the start of range acquisition, the input to the transfer loop is connected to the transmitter by means of a coaxial switch. The inputs to the clock-doppler detector are then identical and there is no output. The range tally is set to zero range units at this time.

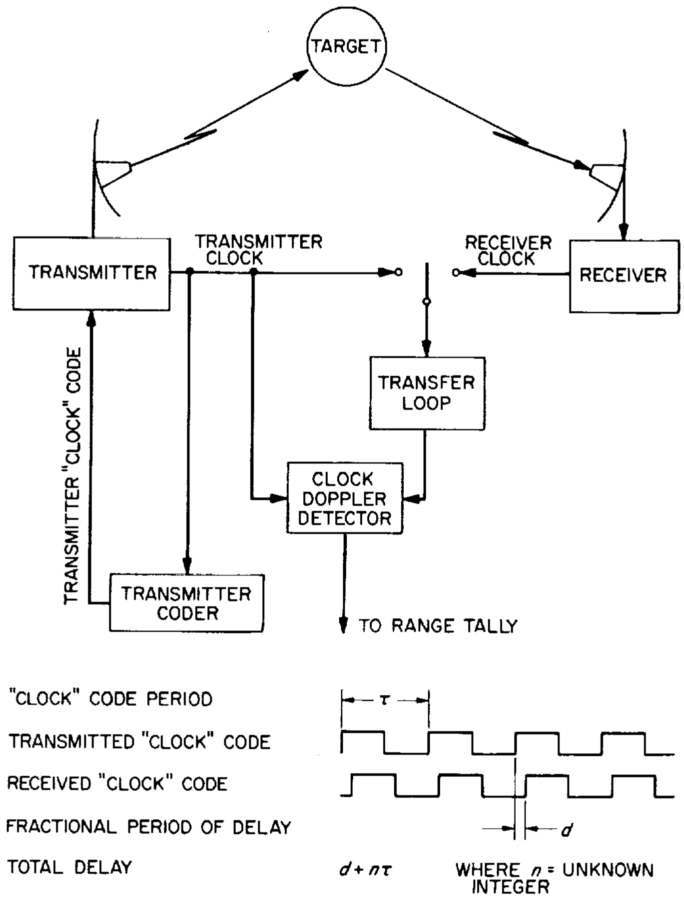

Fig. 3. Use of clock code in range determination

The transfer loop is next switched to the receiver. As the transfer loop tracks into the new phase without loss of lock, the doppler detector keeps track and causes tallying of range numbers in accordance with what appears to be a slight spacecraft motion. This corrects what would otherwise have been an error in range that corresponds to the fractional clock-cycle delay d.

Let the target now begin to move. The resultant increments in range will be detected, clock cycle by clock cycle, in the clock-doppler detector and will be continually tallied in the range tally.

The determination of total range at time t is based on the relation

$$R_t = R_0 + \int_0^t \dot{R}\, dt$$

where R_0 is the range at some reference time zero, and the integral is the sum of range increments since that time. The mechanization of the ranging system is quite analogous to solving this integral equation.

First, the integration

$$\int_0^t \dot{R}\,dt$$

is performed. That is, the incremental range is determined throughout the time required for acquisition and the subsequent time of tracking. This is accomplished by continual tallying of range units corresponding to doppler cycles that, in turn, are derived from comparison of received carrier submultiple with transmitted carrier submultiple. Thus,

$$\int_0^t \dot{R}\,dt = n_{t\tau} - n_{0\tau}$$

Second, the constant of integration R_0 is evaluated. That is, the fixed range at the start of ranging acquisition is determined. This is accomplished by tallying range units that correspond to the time offset (or delay) between transmission and reception of a given point in the ranging code at the start of ranging acquisition, or $R_0 = d + n_{0\tau}$. This, in turn, comprises the determination of the fractional clock-cycle delay d (which has been accomplished) and the determination of the integral number of clock-cycles n (which is done next). The operations required to determine R_0 are referred to as range acquisition and are the *only* operations requiring the use of the pseudo-random codes.

III. RANGING CODES

For the purpose of precisely determining the number of clock cycles n, a modulation pattern having the following four characteristics is desirable:

1. A detectable overall periodicity greater than the maximum anticipated round-trip time. This is required to prevent ambiguous results, and means, in effect, that the measuring tape should be longer than the distance to be measured.

2. A detectable, fixed, high-frequency periodicity within the overall modulation pattern. This is required for the sake of high resolution or precision of measurement. If the bit-repetition rate is chosen sufficiently high, the clock code period of two bits suggested before will serve this requirement. In the Mark I, specifically, the bit repetition rate is about 1 Mc, for a clock-code period of approximately 2 μsec.

3. The characteristic of two-level autocorrelation. This means that the overall pattern must be such that, if the pattern is compared with the same pattern displaced by integral numbers of bits, the two patterns will match exactly in one relative position, and they will fail to match to the same degree in all other relative positions. In this, the criteria for matching are that the patterns be compared bit by bit over a full period, and that the degree of matching (or "normalized correlation") be given by

$$C_n = \frac{A - D}{A + D},$$

where A = number of agreements between patterns (0 & 0 or 1 & 1), and D = number of disagreements (0 & 1 or 1 & 0). Of these two requirements, the basic one is that there be only one relative position that yields maximum correlation. If it is possible to have all other relative positions yield uniformly low correlation, the correlation detection is, of course, greatly simplified because it becomes a binary (or true-false) problem, rather than one of precise measurement.

4. The characteristic of being essentially balanced, i.e., of having as many 1's as 0's in it. While this is not an absolute requirement, balanced use of power in the carrier sidebands increases efficiency and improves system design.

The problem is solved by the use of a pseudo-random binary sequence continually generated in the form of 1's and 0's in digital equipment.

Figure 4 shows two cycles of such a sequence having fifteen binary digits per cycle. Below it is the rectangular

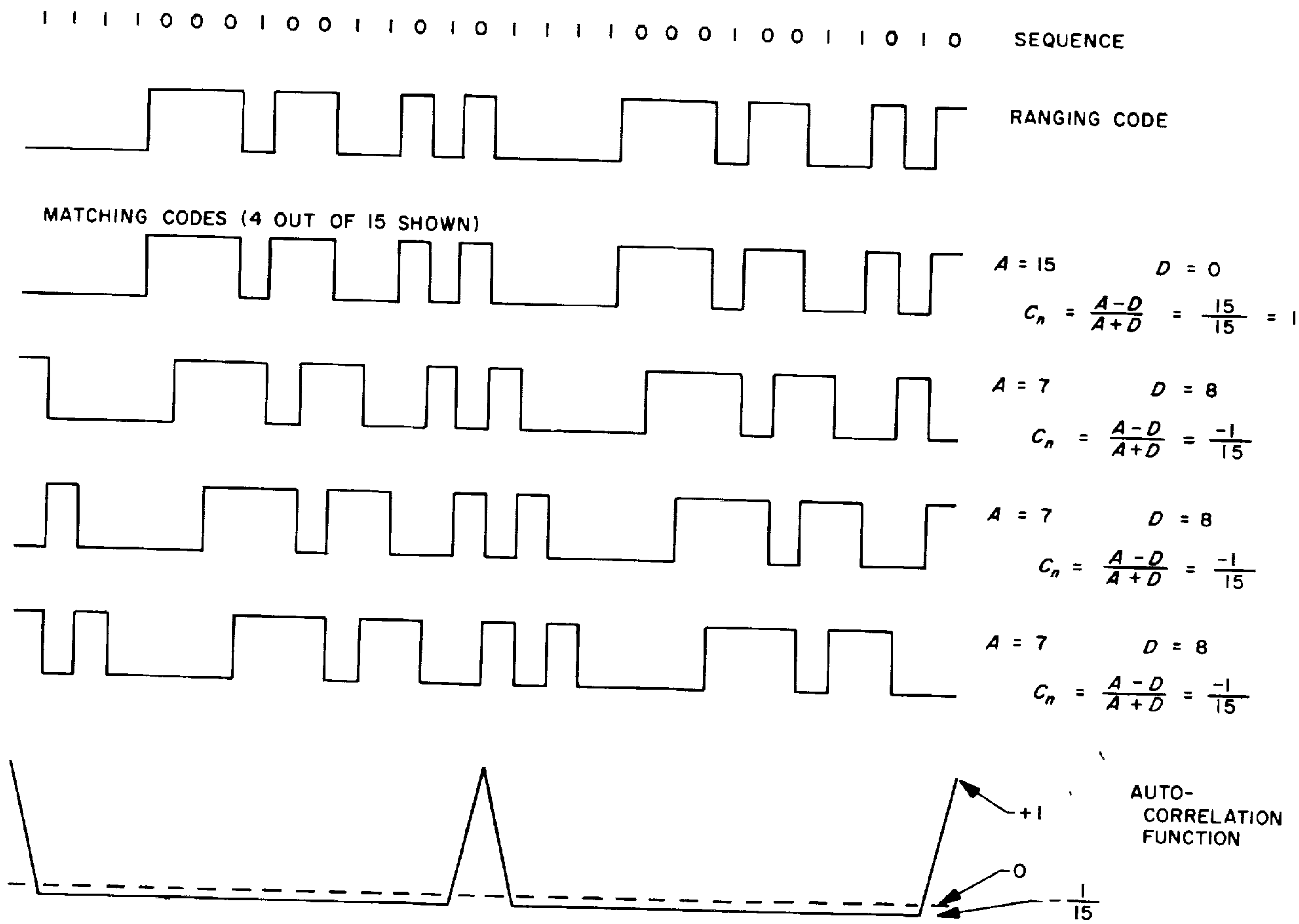

Fig. 4. Matching or correlation of ranging codes

waveform of a ranging code derived from the sequence, where "1" is represented by a low level and "0" by a high level.

To see whether and how this code satisfies this requirement for two-level autocorrelation, a second code, identical to the first, is also shown in Fig. 4. The second code is shown in phase with the first, as well as displaced by one or more bits. The normalized correlation is given in each case and is finally plotted as a function of relative displacement of the two codes. The measure of correlation of digit-by-digit matching is found to be uniformly low when the two codes are out of phase. It is high, of course, when the two codes are in phase, which occurs every fifteen displacements in this example.

The resolution obtainable from a code as such is proportional to the digit period. The total length of the code (here, 15 digit periods) determines the maximum round-trip time that can be determined without ambiguity, and hence the maximum unambiguous range.

IV. RANGE ACQUISITION

In Fig. 5, the transmitter coder has been complicated to generate the repetitive pseudo-random ranging code, now used to biphase modulate the transmitted S-band carrier.

A receiver coder has been provided to generate the same code as the transmitter coder. Additional features in this new unit permit matching this code to the received code in the receiver. It must therefore be time-movable by bits with respect to the received code or, in a way, with respect to the transmitted code. A reference must, of course, be provided for this receiver-code shifting, and it must be provided when the range tally is reset to zero at the start of acquisition. Thus, when the transfer loop is still connected to the transmitter, both coders being in clock-synchronism, the receiver coder is code-synchronized to the transmitter coder, as shown schematically by a switch.

The next concern must be with the overall code to be used. We have stipulated a bit period of approximately 1 μsec. This corresponds roughly to 300 m of round-trip distance or to 150 m of one-way range. The Ranging Subsystem Mark I was intended to reach to 800,000,000 m, requiring then a code of no less than 800/150 or 5⅓ million bits. Such a code can be generated directly, but its acquisition would require 5⅓ million correlation readings to determine the proper match.

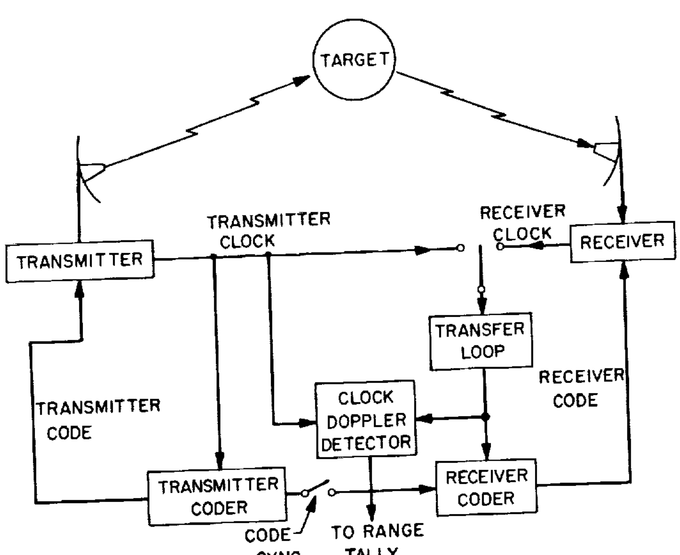

Fig. 5. Range determination with a long pseudo-random code

It is possible, on the other hand, to generate such a long code by combining, bit by bit, several repetitive shorter subcodes or code components, suitably chosen. Each component must meet the requirement for two-level autocorrelation, the same as the total code. Five code components were chosen for the Mark I. Their designations and lengths in bits are as follows:

cl	code component of length 2 bits
x	code component of length 11 bits
a	code component of length 31 bits
b	code component of length 63 bits
c	code component of length 127 bits

Provided their lengths in bits have no common factors, the length in bits of the total code is the product of the lengths in bits of the individual components. Hence, the total combined code length is

$$2 \times 11 \times 31 \times 63 \times 127 = 5{,}456{,}682 \text{ bits.}$$

Further, it is possible to acquire the total code by acquiring the components individually in turn. This reduces the number of correlation readings required from the previously suggested 5⅓ million to

$$11 + 31 + 63 + 127 = 232.$$

It must be noted that the 2-bit cl component is not acquired by digital means in the Mark I, but rather by the process of locking up the clock loop in the ranging receiver.

The transmitter code components are designated by lower-case letters, the corresponding receiver code components by upper-case letters. The transmitter code then contains the five components cl, x, a, b and c, combined bit by bit in accordance with the Boolean logical relationship

$$x\,cl + \bar{x}\,[(ab + bc + ac) \oplus cl].$$

The receiver code as generated by the Mark I itself contains only the components X, A, B, and C; their combination is a function of the program state in which the Mark I is operating, being

$$\bar{X}(AB + BC + AC)$$

in the final, or tracking, state.

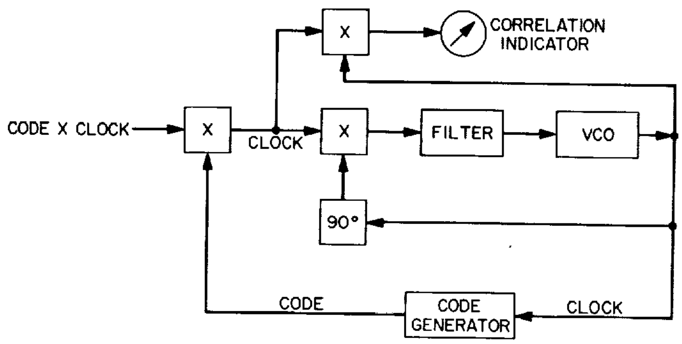

Fig. 6. Double loop code tracking system

Figure 6 shows a schematic diagram of a part of the ranging receiver. The *CL* or *cl* component is designated here as "clock," the components *x*, *a*, *b* and *c*, or *X*, *A*, *B* and *C* in combination as "code," and the combination of all five components as "code × clock." The code generator shown is the receiver coder of the Mark I. Its "code" output, matched against the received "code × clock" in a balanced detector, provides a "clock" output whose average amplitude is a measure of the degree of correlation between the received "code" and the receiver "code."

The inner phase-locked loop, or clock loop, is initially locked up to the incoming "clock" component, which it subsequently tracks, whether or not there is any "code" present.

The outer, or "code," loop is held in gear, as it were, by the locked state of the clock loop. It serves no other purpose than to match the received "code" to the receiver "code."

This matching is accomplished by digitally shifting the components of the receiver code and measuring the correlation indication at each relative shift position until a maximum is obtained. The Mark I performs these functions automatically as part of its range acquisition process.

The total ultimate shift of the receiver code from its initial phase is, of course, a measure of the initial range at the start of acquisition or, more correctly, a measure of $R_0 - d$ (both R_0 and d being in units of time).

For each shift of each component in the process of acquisition the appropriate number of range units is added into the range tally whenever such a shift is made. This in no way interferes with the adding (or subtracting) of the previously mentioned clock-doppler tallies, as required by target motion, which can occur simultaneously.

V. RESOLUTION OF RANGE MEASUREMENT

The resolution of measurement was indicated earlier as being 1 clock-doppler cycle, for the sake of initial clarity. Since this represents two bit periods of about 1 μsec each, it corresponds roughly to 2 μsec, or 600 m of round-trip distance, or 300 m of range. Actually clock-doppler tallies are made every quarter cycle, for a resolution of about 0.5 μsec, or 75 m of range.

Once acquisition has been accomplished, furthermore, the Mark I automatically switches from tallying every ¼ clock-doppler cycle to tallying every 16th S-band doppler cycle. This improves the resolution by a factor of 72, to 1 Range Unit (RU) or approximately 1 m.

At the same time, or any time thereafter, one can disable the full code modulation and instead modulate the carrier with the 2-bit clock component only. There is, as previously indicated, no further need for the code, the clock component alone being responsible for keeping the clock loop in lock.

The advantage of changing from full code to clock code lies in the fact that this not only cuts down on the required sideband power, but also limits the spectral distribution of ranging frequencies to two single spectral lines, approximately 0.5 Mc above and below the carrier frequency.

VI. THE RANGING SUBSYSTEM MARK I

The Ranging Subsystem Mark I (Fig. 7) is a special-purpose binary digital computer having particularly special input and output interface devices. As part of the Receiver-Exciter Ranging System, it makes on-demand range determinations without prior knowledge of approximate range. Details of its operation and implementation may be found in the pertinent JPL functional and detail specifications.

Its construction is almost completely modular (see Fig. 8). Power supplies, monitor and display equipment, and controls are located in the upper half of the single cabinet. Some 300 patch-wired, solid-state, digital logic modules are mounted in the lower half on movable frames.

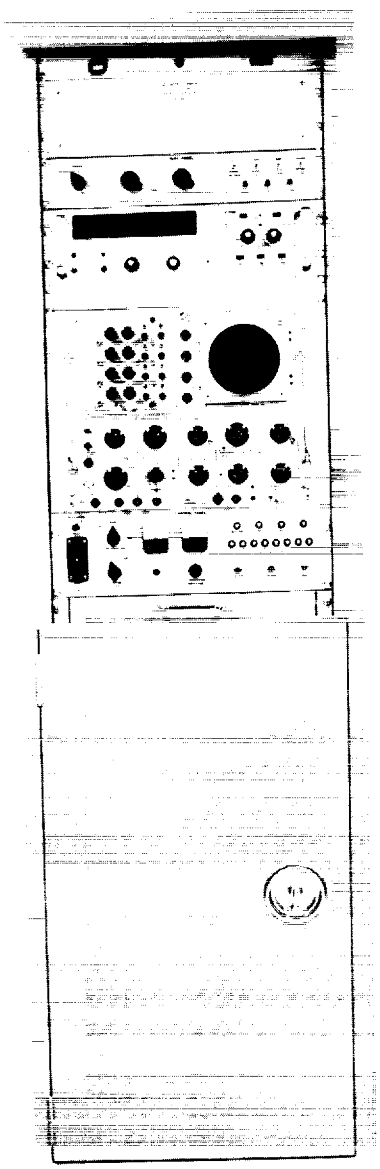

Fig. 7. The ranging subsystem Mark I, front view

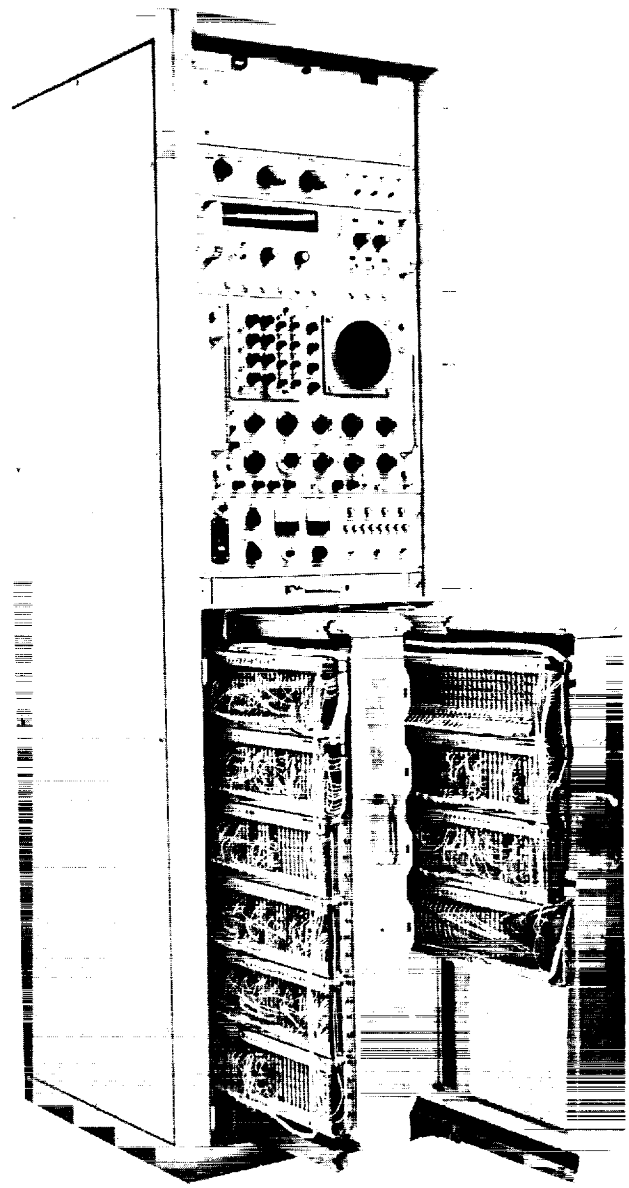

Fig. 8. The ranging subsystem Mark I, showing modular subassemblies

The performance parameters of the Mark I may be summarized as follows:

1. Its maximum unambiguous range is 800,000 km, or twice the distance to the Moon.
2. Its resolution is 1 range unit (RU), which is defined as

$$\frac{221 \text{ light-sec}}{30 \times \text{transmitted frequency}}$$

   and is of the order of 1 m.

3. Overall system inaccuracies of no more than ±15 m are attributable to drifts and instabilities in ground and spacecraft loops.
4. Minimum range acquisition time is 1.6 sec at strong signal levels and may go as high as 30 sec for typical lunar missions.
5. Range data output is in binary range units, and can be effected once per second.

The Ranging Subsystem Mark I is not, in itself, a complete system capable of range determination. Its design concepts and implementation, however, are such that, as a part of the Unified S-Band System, it enhances the features and capabilities of that system to include the precise determination of range in real time, either discontinuously or continuously.

The aim in this report has been a rather general exposé of the basic technique of range determination using pseudo-random ranging codes, with specific application to the Ranging Subsystem Mark I as part of the Unified S-Band System. It was not considered to be within the province of so short a presentation to go into the finer details of the PN technique of ranging and particularly into the complexities of the implementation and operation of the Ranging Subsystem Mark I.