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Joseph

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[54] **SLOW MODULATION DISTANCE MEASURING APPARATUS**

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[73] Assignee: **The United States of America as represented by the Secretary of the Navy,** Washington, D.C.

[22] Filed: **Jan. 26, 1973**

[21] Appl. No.: **326,922**

[52] **U.S. Cl.**..... **235/181,** 343/100 CL, 343/112 R, 360/7, 360/75

[51] **Int. Cl.**..... **G06g 7/19,** G01s 9/24

[58] **Field of Search**..... 235/181; 340/15.5; 343/100 CL, 112 R; 324/77 G, 77 H; 360/7, 69, 70, 75

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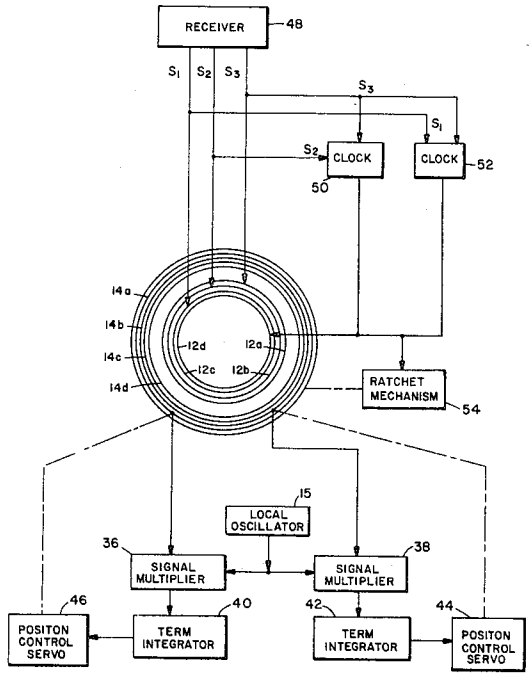
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[57] **ABSTRACT**

Apparatus for locating a source of slow modulation or intermittent, radiant energy. Transmitted signals are received by a pair of separated, remote receiver stations and at a local station. The signals received at the remote stations are relayed to the local station where each signal is recorded on a separate track after each is normalized to the same average amplitude. The recorded signals are played back on apparatus having a movable head which can be positioned relative to a stationary head while at the same time permitting both to follow high-speed paths at the same angular velocity except for the phase angle difference. The movable head plays back the signal from one of the remote stations and the stationary head plays back the signal from the local station. The instantaneous amplitudes of the two signals are superimposed on each other and multiplied together to form an autocorrelation function. The process is repeated with a different position of the movable head until the average product reaches a maximum value. The maximum value is compared with the square of one of the signal amplitudes averaged over the same time interval, and if the maximum and square are substantially equal the unique correlation is reached when the difference in head position measures the time delay. If a satisfactory match is not obtained, a new area of the recorded signal is searched.

3 Claims, 8 Drawing Figures



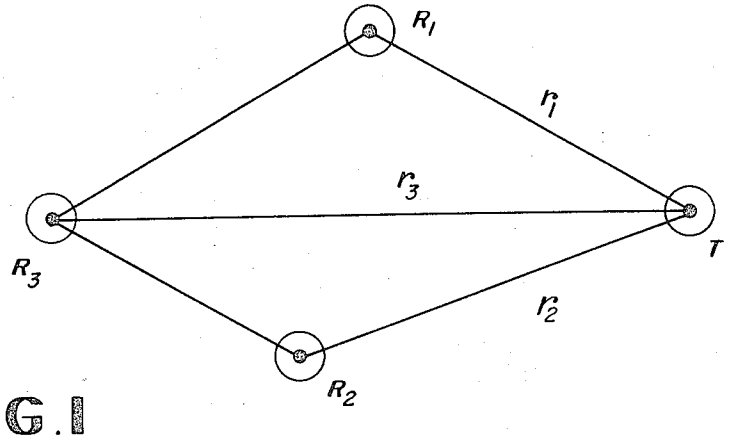

R_1
r_1
r_3
R_3
T
r_2
R_2

FIG. 1

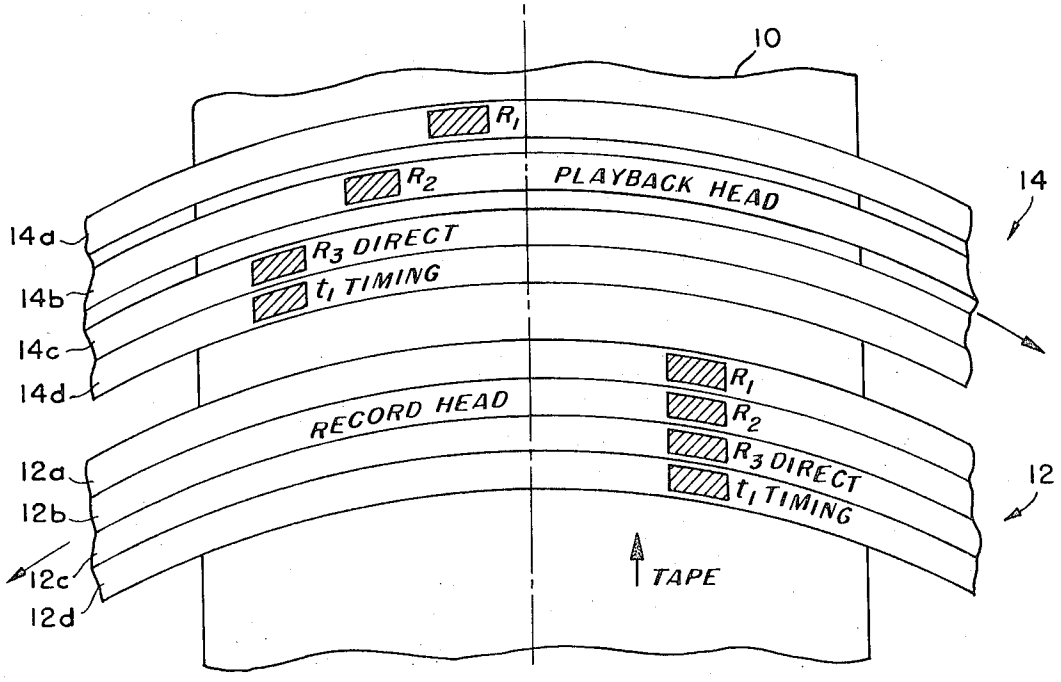

10
R_1
R_2
PLAYBACK HEAD
14
14a
R_3 DIRECT
14b
t_1 TIMING
14c
14d
RECORD HEAD
R_1
R_2
R_3 DIRECT
t_1 TIMING
12
12a
12b
12c
12d
TAPE

FIG. 2

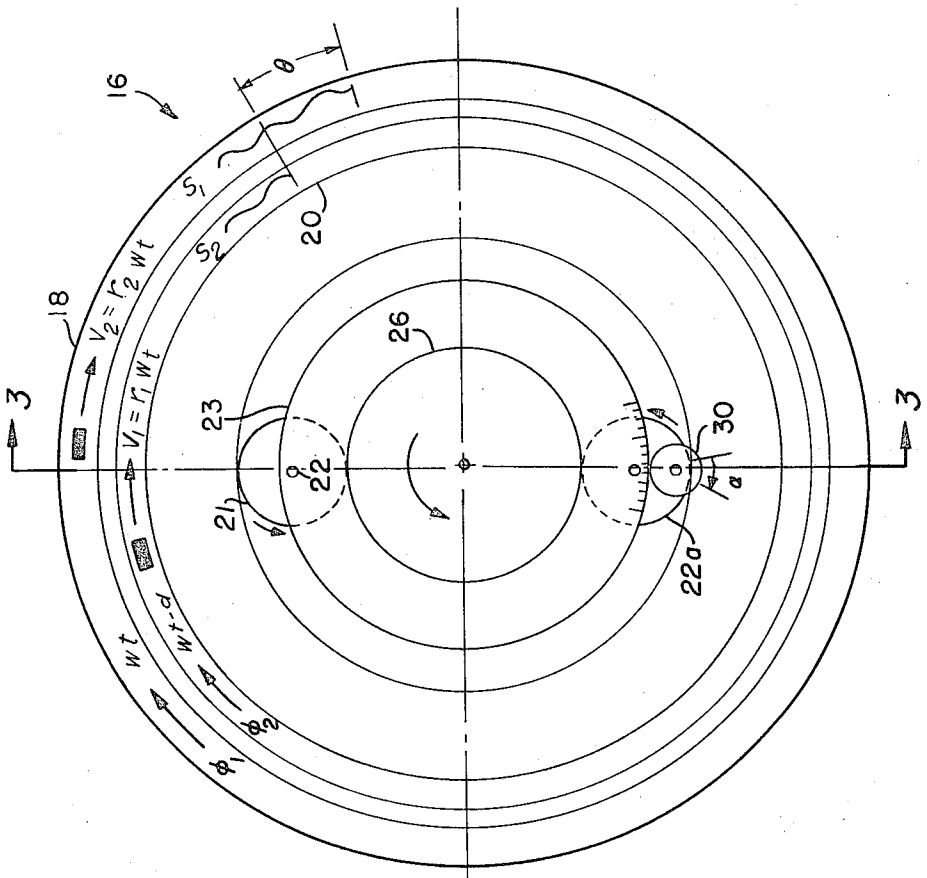

16
θ
S1
S2
20
18
V2 = r2 Wt
V1 = r1 Wt
Wt
Wt-d
θ2
θ1
3
3
23
22
21
26
30
a
22a

FIG 4

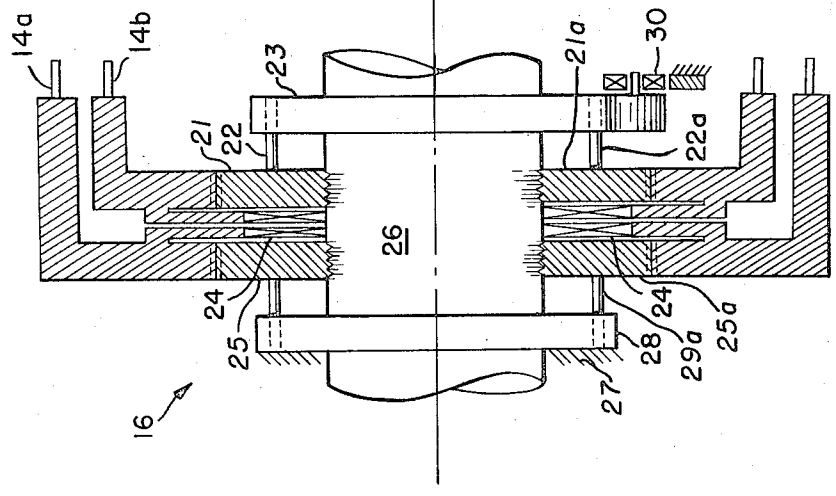

14a
14b
23
21a
30
21
22
22a
26
24
25
24
28
29a
25a
27
16

FIG 3

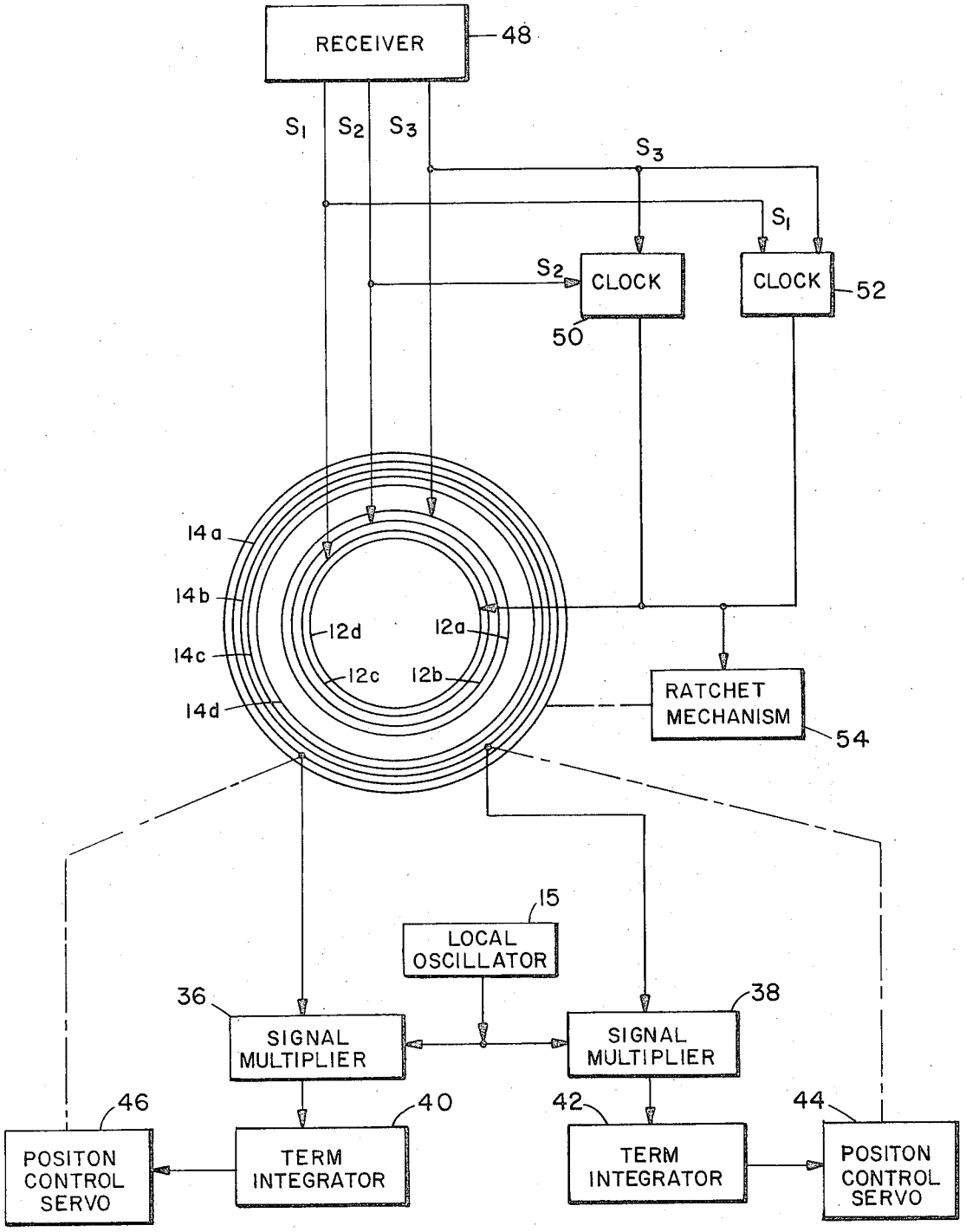

RECEIVER
48
S1
S2
S3
S3
S1
S2
CLOCK
CLOCK
52
50
14a
14b
14c
14d
12d
12a
12c
12b
RATCHET MECHANISM
54
15
LOCAL OSCILLATOR
36
38
SIGNAL MULTIPLIER
SIGNAL MULTIPLIER
46
40
42
44
POSITON CONTROL SERVO
TERM INTEGRATOR
TERM INTEGRATOR
POSITON CONTROL SERVO

FIG. 5

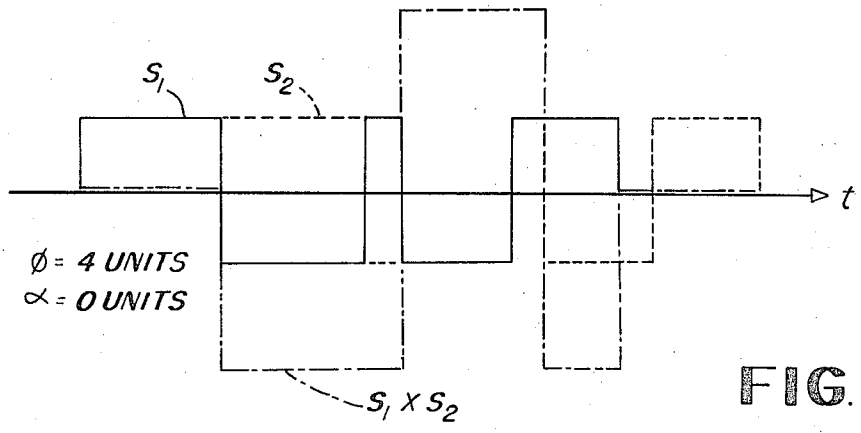


FIG. 6a

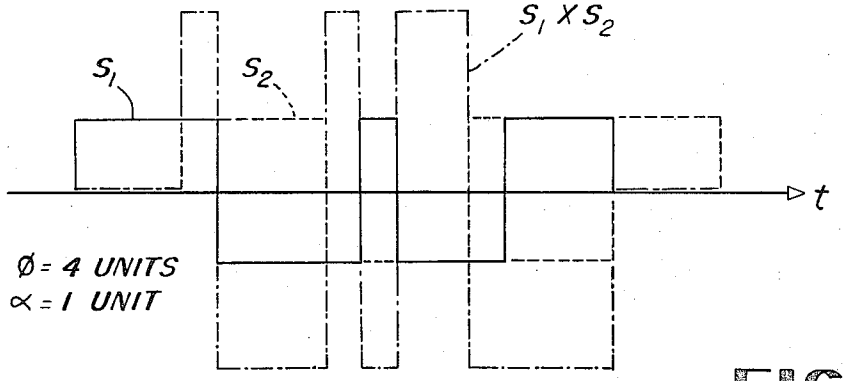


FIG. 6b

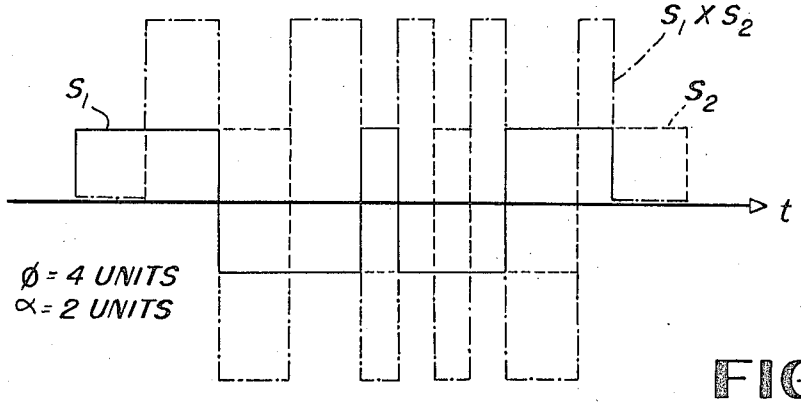


FIG. 6c

SLOW MODULATION DISTANCE MEASURING APPARATUS

BACKGROUND OF THE INVENTION

Prior art transmitter location techniques generally employ triangulation between an unknown radiation source and known receiver stations wherein the signal angle of arrival is measured at a number of known locations simultaneously or sequentially. The angle measurements are based on directionality of receiving sensitivity and unless very large (with respect to wavelength) receiving antennas are used erroneous results will be obtained. Consequently many measurements spaced far apart must be made to improve the accuracy. Alternatively, length in signal time of arrival can be measured by differences of propagation time from transmitter to each of a number of receiver locations whereby accurately measurable frequencies can be used to determine positions with relatively fewer measurements.

Time of arrival is generally determined by counting the number of clock pulses that occur before coincidence with a propagated wave. A close measurement match requires a short, sharp pulse which rises rapidly enough to penetrate noise before coincidence is measured. This characteristic is essential for coincidence, but if signal modulation is slow and unpredictable, such as in voice modulation, the precise time when a signal appears is difficult to measure to within a time interval that is very short compared to the modulation period. In effect, the signal rises slowly through noise; consequently, transmitters have been difficult to locate accurately when their operation is intermittent and time does not permit the taking of many measurements necessary for triangulation.

SUMMARY OF THE INVENTION

Apparatus is disclosed for locating radiation sources which emit slowly modulated, intermittent signals. The apparatus determines differential time of arrival at two remote and one local receiving stations by cross-correlation of received signals. Signals received at the two remote stations are repeated without delay (with known delay) and retransmitted to the local station where all three received signals and locally generated timing signals are each recorded on a video tape loop by one of a quadruple set of recording heads that move across the tape in a circular path. Four independently mounted playback heads move in concentrically located circles but opposite in direction to the recording heads. When the signal received directly at the local station disappears, two counter clocks are started, one of which stops when it receives a signal relayed from one of the remote stations and the other, when it receives a signal from the other remote station. The clock outputs set the position of two corresponding movable, playback heads to the delay corresponding to the clock count. Each of the two signals from the two movable heads are multiplied with the signal received at the local station and the product signals are coupled to servo devices to control the positions of the two movable heads so that the corresponding product signals reach maximum. Time scales in the servo devices will indicate the delay times whereby geometric calculations can be used to determine the bearing of the unknown energy source.

OBJECTS OF THE INVENTION

It is the primary object of the present invention to provide transmitter location apparatus which can be used with transmitters which radiate intermittent, slowly modulated signals;

It is another object of the present invention to provide apparatus for locating unknown transmitters by means of correlation control of playback head position.

Other objects, advantages and novel features of the invention will become apparent from the following detailed description of the invention when considered in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a simplified illustration of the geometry of an unknown transmitter and three known receiver stations which will be used to describe the inventive concept disclosed herein.

FIG. 2 is a sectional simplified illustration of the recording head and playback head mechanism of the present invention.

FIG. 3 is a sectional view of the apparatus of FIG. 4 which comprises novel apparatus for recording and playing back signals in accordance with the inventive concept.

FIG. 5 is a simplified block diagram of the recording apparatus.

DESCRIPTION OF THE PREFERRED EMBODIMENT

Before proceeding to a discussion of the drawings the theory and concept of the present invention will be discussed. The technique essentially comprises a cross-correlation of slowly modulated, intermittent signals received at a plurality of receiver stations, R_1, R_2, and R_3, to determine differential times of arrival from the transmitter, T, wherefore correlation control of movable playback heads can be achieved. The form of the signal, S_n, received at each location from the transmitter will be the same except for the difference in time of arrival as shown below:

$S_1 = S_T(t-\tau_1)$
$S_2 = S_T(t-\tau_2)$
$S_3 = S_T(t-\tau_3)$

where

S_n = the normalized signal at the nth receiver (with a.g.c.)
S_t = the transmitted signal normalized to uniform antenna gain, and
τ_n = time of propagation from transmitter to nth receiver, and where
$n = 1, 2, 3$

The cross-correlation, ρ_{31}, function of S_1 and S_3 can be formed as follows:

$$\rho_{31} = \frac{1}{\tau}\int_0^{+T} S_T(t-\tau_1-\delta_1)\,S_T(t-\tau_3)\,dt$$

where

δ_1 = the delay between receipt of the S_1 and S_3 at R_3, and
T = averaging time

If a received signal is not cyclic within T and has an average value of zero, then ρ_{31} has the unique maximum when the following condition occurs:

$$\delta_1 = \tau_3 - \tau_1$$

and its value is equal to the following:

$$\rho_{31} = \frac{1}{\tau}\int_0^{+T} S_T^2\,(t-\tau_3)\,dt = \rho_{33\,\max.} = \overline{S^2}\,.$$

Likewise,

$$\rho_{32\,\max.} = \overline{S^2}$$

when $\rho_3 - \rho_2 = \delta_2$.

The above values of δ_1 and δ_2 measure time difference between receipt at R_3 of the transmitted signal R_3 and the repeated signals S_1 and S_2 from R_1 and R_2, respectively. The values are, in effect achieved by "sliding" one signal waveform over the other until a maximum correlation occurs. Although only one "best" match occurs at maximum correlation, there are many lesser peaks, especially if there is some degree of repetitiveness. Often matched conditions cannot be found because of the large area searched and the uncertainties introduced by noise and imperfections in the measuring equipment. Consequently, it is necessary to obtain some a priori knowledge of the approximate value and position of the peak.

The above-described technique of maximization of received signals to determine an auto-correlation function comprises the theoretical basis of the inventive concept to be disclosed herein for measuring the position of transmitters emitting slowly, possibly randomly, modulated signals transmitted from a transmitter T as shown in FIG. **1**. The signals are received at the receiving stations R_1, R_2, and R_3. In the discussion R_1 and R_2 will be described as the far stations and R_3 as the local station. Signals received at the far stations, R_1 and R_2, are repeated without delay to the station R_3 but at a different frequency. All three signals are received at R_3 by the receiver **48** as shown in FIG. **5**.

At R_3 all three signals plus a timing signal t_1 which is generated locally by the clocks **50** and **52** are recorded on a video tape loop as shown in FIG. **2** and FIG. **5** by one of a quadruple set of recording heads **12***a*, **12***b*, **12***c*, and **12***d*. As shown by the arrow, the heads move across the tape **10** in a circular motion.

Outside the circle, four independently mounted playback heads **14***a*, **14***b*, **14***c*, and **14***d* move in concentrically located circles, one outside the other, but opposite in direction to the recording heads **12***a*–**12***d*. Two of the heads, **14***a* and **14***b*, which play back signals from R_1 and R_2, can be moved relative to the other two heads by use of the planetary gear mechanism which will be described in more detail with respect to FIGS. **3** and **4**, and for a purpose to be described hereinafter, and for a purpose to be described hereinafter.

Eventually, the signal S_3 received directly at the station R_3, and which either arrives first or simultaneously with a repeated signal from R_1 or R_2, either ends its amplitude or diminishes below a predetermined level. When this occurs, the two counter-clocks **50** and **52** are started. One of the two clocks stops when one of the signals which is relayed from R_1 or R_2 ceases. Likewise, cessation of the other relayed signal stops the second clock. The timing signal outputs from the clocks are recorded by the record head **12***d* for time reference purposes. The clock which stops last inhibits tape motion by means of the ratchet mechanism **54** of FIG. **5** whereby all three tracks are stopped under the corresponding counter-rotating recorder heads in a manner to be described hereinafter.

Each of the two resultant clock counts is used to position a corresponding one of the two independent playback heads by means of a planetary gear as shown in FIG. **3**. Each head is positioned to approximately the delayed position corresponding to the count, thereby furnishing a center for the area of "fine" search. The position of the planetary gear with respect to the scale on the ring **23** of FIG. **4** will measure the delay.

The mechanism of FIGS. **3** and **4** embodies the phase-angle, time variation concept of the present invention. FIG. **3** is a sectional view of FIG. **4** along the center line *a*—*a* below the movable ring **23** and excluding the drive shaft **26.**

The apparatus essentially comprises the aforementioned drive shaft **26** which is driven by an external motor force (not shown). The shaft is mechanically connected at one end to the fixed ring **28** which is rigidly attached to a frame member **27.** At the other end it is connected to the movable ring **23.**

The four pinion gears **21** and **21***a* and **25** and **25***a* are also rotatably mounted about the circumference of the shaft **26** as shown in the figures. The outer surface teeth of the pinion gears **21** and **21***a* and **25** and **25***a* are connected to the playback heads **14***b* and **14***a*, respectively, as shown.

The pinion shafts **22** and **22***a* are connected between the movable ring **23** and the pinion gear **21,** and the shafts **29** and **29***a* are connected between the fixed ring **28** and the pinion gear **25.** Conventional bearings **24** are located between the pinion gears **21** and **25.** Thus as the drive shaft rotates, it rotates, in the same direction, the movable ring **23** and the pinion gears **21** and **21***a*, and **25** and **25***a*.

Connected to the lower, outside surface of the movable ring **23** is an angle drive device **30** which is attached to the frame **31** and which includes the bearings **30***a*.

The apparatus of FIG. **3** operates as follows. A motor rotates the drive shaft **26** at a selectively predetermined constant speed. Gear teeth on the shaft which are in contact with teeth on the pinion gears **21, 21***a*, **25,** and **25***a*, cause the pinion gears to rotate on the pinion shafts **22, 22***a*, **29,** and **29***a*, respectively, in the same direction as the shaft.

As a result, the pinion gears rotate the fixed heads **14***c* and **14***d* at a constant speed. As can be seen, if the position of the angle drive **30** is fixed and if the scale on ring **23** is stationary, the movable ring **23** and the pinion shaft openings are held in position and the movable heads **14***a* and **14***b* will move about the center of the shaft in the same direction and at the same angular rate as the fixed heads **14***c* and **14***d* (not shown).

If the position of the scale is changed, the relative position of the two rings (**23** and **28**), and the positions of the pinion shafts **22***a* and **29***a* will also be changed, as will the relative position of the movable head **14***b*. Thus signal recording and playback processes will be alike for the two sets of heads except for the change in angular origin.

For the purpose of trilateration, the waveform of the signal in each channel is assumed to be identical to the others. However, because they are received at different locations, they differ in time origin.

Thus, in operation, received signals are recorded with the scale set to zero. The played back signals are

then correlated over a reasonable time or over their duration, whichever is shorter.

The separation, α, is increased by stepping the angle drive **30**, and the new result is compared to the prior one. If the new result is larger, a new composition is made often again increasing the, α, by stepping the angle drive. The process is continued until a smaller correlation product is obtained.

Since, as mentioned earlier, the signals have been normalized, the magnitude of the correlation is known. Thus a comparison is made between the correlation value and the local maximum to see if the "best" maximum (correlation) has been obtained.

FIG. **6** graphically illustrates exemplary waveforms for purposes of amplifying the above description. Square waves are shown solely to simplify the discussion; it can be appreciated that the same correlation conclusions would result with other waveforms.

It can be readily seen from FIGS. **6***a*–**6***c*, that assuming a signal delay, ϕ, equal to four arbitrary units, the algebraic sum of the signal products, S_1 and S_2, reaches a maximum when the readout delay, α, is selectively set to the same value as ϕ by using the scale to vary θ in FIG. **4**. The direction of α is known as described herein; however, in general, it can be found by investigating the opposite direction.

Obviously a third channel is required for the third signal to complete the trilateration process. It can be appreciated that the above procedure would be repeated with the third channel signal.

As shown in FIG. **5**, signals from each of the two movable playback heads **14***a* and **14***b* are fed to a corresponding signal multiplier **36** or **38**. Each of the two multipliers is also fed a signal from the local oscillator **15**.

The output of the multipliers **36** and **38** is coupled to the term integrators **40** and **42**, respectively. The outputs from **40** and **42** are coupled as control signals to the position control servos **46** and **48**, respectively.

The servos, in turn, control the movable head positions by means of a small motor, or the like, which moves the corresponding appropriate planetary gear stator. The stator is moved to a position where the corresponding output product reaches maximum value after it is averaged over a selectively predetermined portion of the typical, longest modulation cycle period. The term integrators **40** and **42** can comprise conventional RC integrator circuits.

The position of the planetary gear scale **23** will show the delay on the stationary mechanical scale as a check upon timing. A similar movement of the gear mechanism will position the other movable head. The resultant playback head positions will determine the delay times δ_1 and δ_2, whereby permit calculations as described previously can be performed.

The above discussion assumed that only one "pure" signal traveled directly from the transmitter to each receiver. In practice, both the uniqueness and purity may not exist and there can be several signals received despite other artifices of narrow tuning frequency range and antenna directivity.

Each signal will furnish its own interruption and corresponding set of delays. However, unless the transmitters are nearly contiguous, their times of arrival will be grossly different, and only the signal which causes a "stop" will be available in the search range. Because each signal is normalized as previously described, the largest maximum is thus determined by determining the signal which produced a stop and hence this level can be used to indicate the level for good monitoring of other signals.

Signal contamination created by multipath propagation will create nearby, later, peaks if interfering propagation times are within a significant fraction of the modulation period. If propagation times are less, contamination will produce errors, which are ameliorated since such reflections are often weaker than the direct signal and since small deviation from a straight path creates relatively small changes in path length.

Since the amplitude of the auto-correlation function is known from individual signal strength, the possibility that false correlations will occur is remote. False correlations will occur, however, if transmissions identical to modulation form are received from different transmitters. Accordingly, maxima corresponding to each location will have to be suported utilizing other information such as rough measures of signal strength or direction-finding bearing.

Ratcheting of the magnetic tape as described previously is used so that the tracks correspond to the channels represented by each different head and is accomplished by moving the tape so that the playback of the timing signal from the corresponding tape track is held to maximum amplitude output. If head speed is maintained substantially constant all the heads will maintain registry. The timing signals which are played back can also be used to correct the timing reference positions to minimize the effects of tape stretch and residual recording speed variations.

If signal characteristics are repetitive enough to provide more than one apparent position of maximum integrated product, it may be necessary to find the maximum which equals the normalized RMS value, i.e., the largest maximum. Although unique in theory, circuit error and noise may preclude determination of greatest peak, especially if the modulation is a constant PRF, pulse type, or a repetitive wave. If there is no irregularity sufficient to resolve the ambiguity, it will be necessary to utilize all possible results, calculate all positions, and resolve the situation with the aid of outside information.

The device can thus be used to locate transmitters that emit signals with low frequency modulation for short periods, and which utilized information content of transmitted signals regardless of modulation type. The device includes counter rotating heads which allows attainment of highest, doubled, playback speed and, hence, corresponding resolution without increasing stresses beyond those of recording speed.

For example, counter-rotating heads need not be used if increased record surface/head speed available in disc or drum records is not needed. If disc or drum recorders are used, the tracks should have a spiral form or disc or a helical form on cylinder. Also, the movable playback heads can each be driven by a synchronous motor excited by a differently phased voltage to change relative head position, whereby phase will measure delay.

Recording heads can be used as playback heads by switching to appropriate input circuitry for their output and either reversing the drum, disc, or tape, or waiting until the loop repeats. Delay will be determined by measuring the time between signal stoppages on each track. Fine grain determination can then be made by

changing the relative position of the heads by either the methods applicable to movable heads, or, if stationary, by moving the appropriate one as necessary to achieve maximum (auto) correlation.

Signal relaying has been assumed to occur without delay as passive reflectors do, but their use entails disadvantages arising from the necessity for orienting these reflectors and from the difficulties incurred by the identity between the reflected signal and the directly received signal, which differ only in delay and direction. Multipath delays are indistinguishable from reflected path types and direction is often difficult to determine. Consequently, active repeaters that repeat strongly at another carrier frequency, possibly laser-optical, which are designed to have delays that are constant over the signal bandwidth often appear to be better solutions to problems of distinguishing deliberately reflected signals from multipath effects.

However, poor propagation conditions over paths between receiving stations can add uncertainties which may be avoided by utilizing signal derived from a stable local oscillator that is synchronized to one at, say No. 3, quite often, for instance every 3 seconds. The records can be brought to one location and played back using the timing signals to check speed and measured auto correlation time as described above. Or each may be played back from its location to the common location when transmission conditions are good, possibly at a slow rate to conserve bandwidth and reduce interfering noise.

Obviously many modifications and variations of the present invention are possible in the light of the above teachings. It is therefore to be understood that within the scope of the appended claims the invention may be practiced otherwise than as specifically described.

What is claimed is:

1. A transmitter location system comprising:

receiver apparatus for receiving signals S_1, S_2, and S_3, transmitted by an unknown transmitter, and wherein S_1 and S_2 are relayed from known transmitters to the said receiver apparatus and wherein S_3 is transmitted directly to said receiver apparatus from said unknown transmitter;

first and second clock counter means connected to the output of said receiver means for measuring the relative elapsed times between receipt of S_3 and S_1, and S_3 and S_2, and for producing clock counts, t_1 and t_2, corresponding to said elapsed times, respectively;

video recorder apparaus connected to the output of said receiver and said clock means and comprising four circular recorder heads mounted in a fixed, concentric manner with respect to each other for recording said received signals S_1, S_2, and S_3, upon magnetic tape,

tape movement means adapted to move said tape under said tape under said recorder heads,

said recorder head being adapted to move over said tape in a circular and counterclockwise manner,

four circular playback heads mounted on the same plane as said recorder heads and in a concentric manner with respect to each other and without said recorder heads, and further adapted to move over said tape in a circular and clockwise manner,

two of said playback heads being independently rotatable with respect to the other two of said playback heads and being adapted to play back S_1 and S_2, respectively,

ratchet mechanism means coupled to said tape movement means and connected to the output of said clock means to inhibit motion of said tape in response to said clock counts t_1 and t_2 signals produced by said clock means indicating that S_1, S_2, and S_3, have been received;

servo means connected to the outputs of said two movable playback heads and including means for multiplying each of the signals S_1 and S_2 recorded thereon with a reference signal to produce first and second control signals proportional to the corresponding maximum values of said multiplication, and,

planetary gear means coupled to said two movable playback heads and being connected to the output of said servo means and being responsive to said first and second control signals to rotate said movable heads with respect to the other two playback heads an angular distance corresponding to said clock counts t_1 and t_2.

2. The system of claim **1** wherein said servo means further includes integrator means connected to the output of said multiplier means.

3. The system of claim **1** wherein said recorder apparatus further includes means for measuring said angular rotation of said rotatable heads.

* * * * *