(12) **UK Patent Application** (19) **GB** (11)   **2 059 214 A**

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(54) **Range and angle determining
Doppler radar**

(57)   A range, angle, and Doppler
(velocity) measuring radar in which a
CW, PRC radar floodlights a volume of
interest. A receiving antenna in the
form of a linear array generally broad-
side with respect to the bisector of the
volume of interest is commutated (sam-
pled) element-by-element to provide a
phase modulated received signal from
which angle information may be de-
rived. Autocorrelation of the PRC signal
received against the transmitted code
provides for range determination and a
Doppler filter bank is provided corres-
ponding to each discrete receiving
angle, the outputs indicating range and
velocity of a target at each discrete
angle of reception.

Fig.9

GB 2 059 214 A
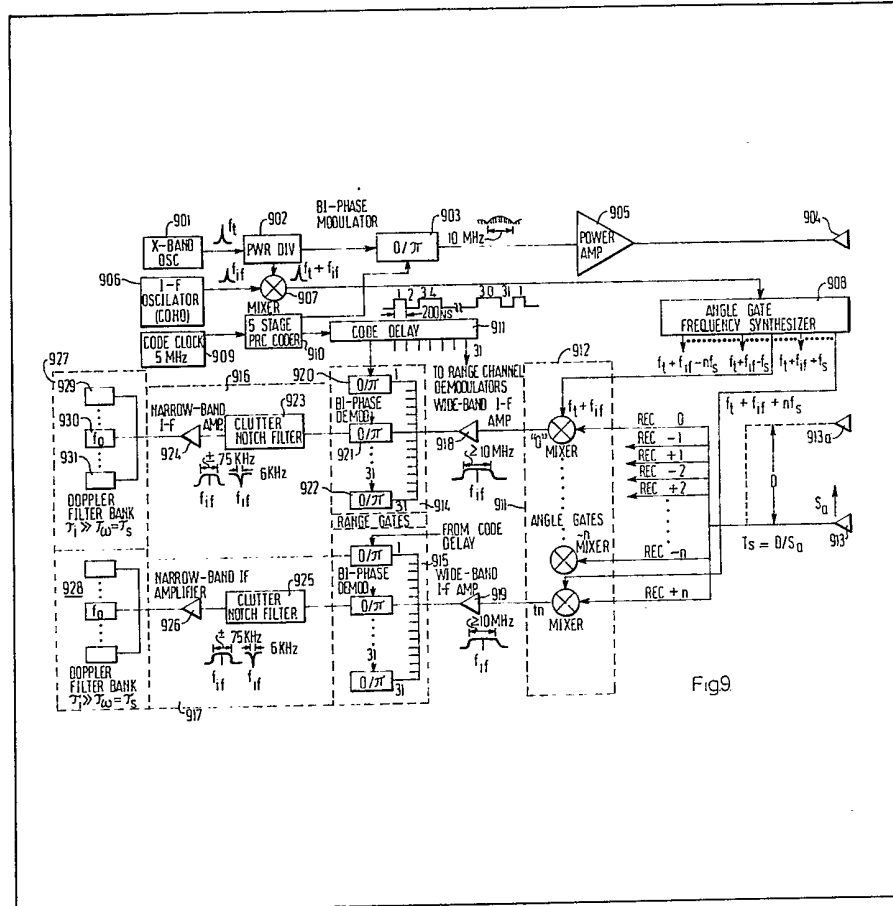
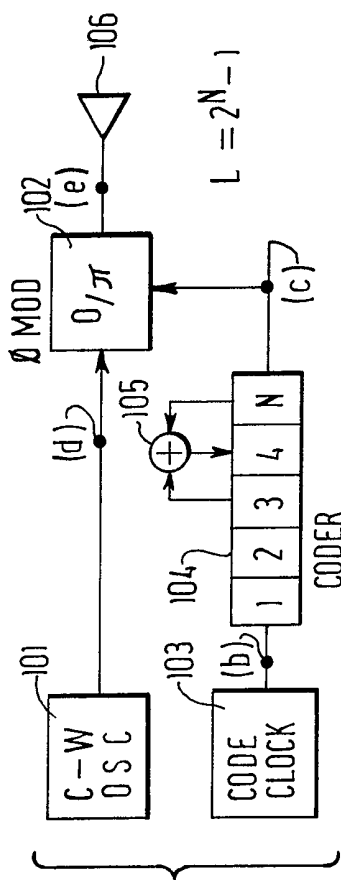Fig.1a.
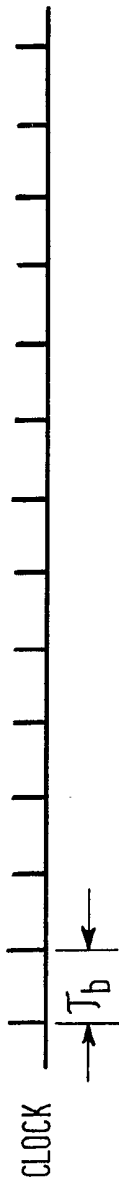
Fig.1b.
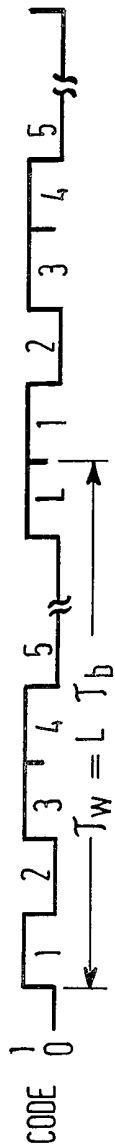
Fig.1c.

Fig.1d.

Fig.1e.

PRC SIGNAL GENERATION PRIOR ART
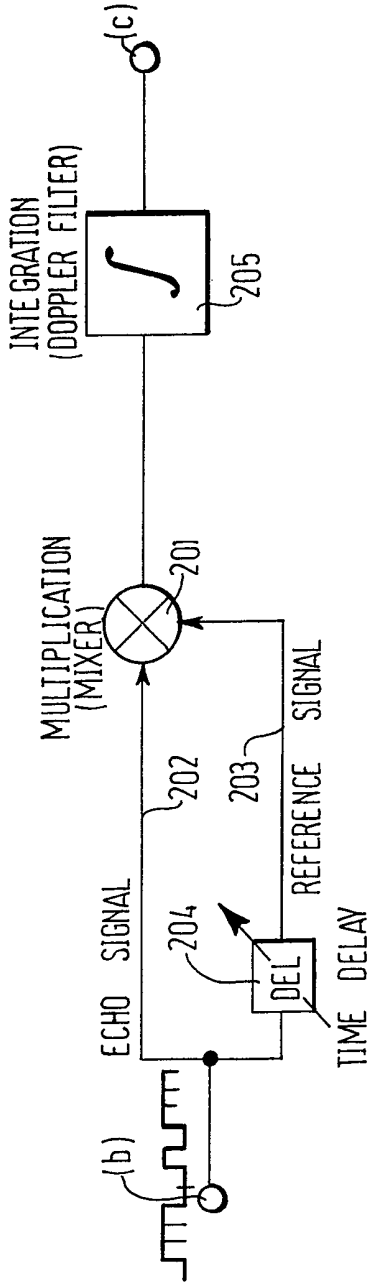
Fig.2a.

MULTIPLICATION (MIXER)

INTEGRATION (DOPPLER FILTER)

ECHO SIGNAL

REFERENCE SIGNAL

TIME DELAY

DEL

201

202

203

204

205

(b)

(c)

Fig.2b.

PRC CODE

$T_b L$

T_b

1 2 3 4 5   L   1 2 3 4 5   L

1
0

Fig.2c.

$+L$

-1

$T_b L$

T_b

0
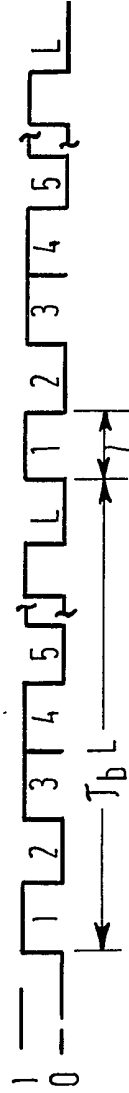
AUTOCORRELATION FUNCTION
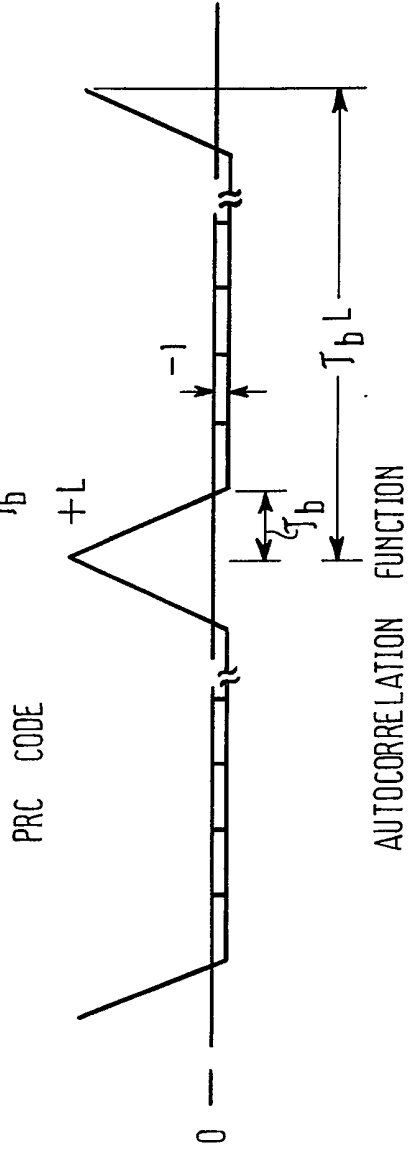
BASIC PRC AUTOCORRELATION   PRIOR ART

f_d (DOPPLER)

T

$\frac{1}{L}$

$1/T_\omega$

$\frac{1}{T_i}$

T_ω

$\frac{1}{T_\omega}$

$+fd$ (MAX)

$-fd$ (MAX)

$L\frac{1}{2}$

T (RANGE)

T_b
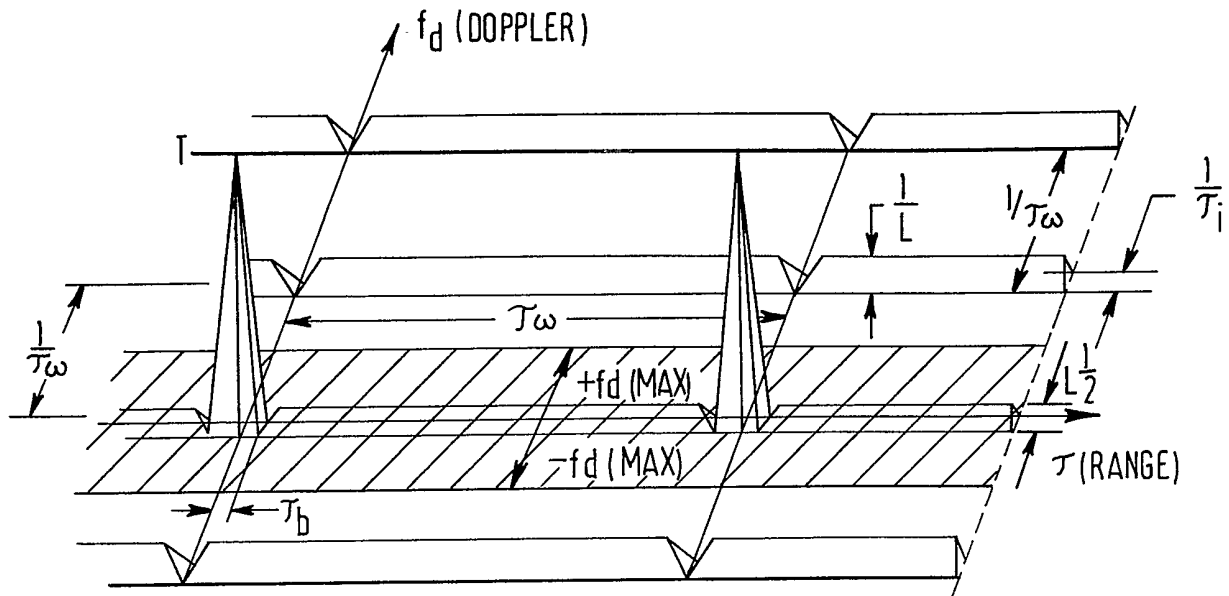
TO ELIMINATE DOPPLER AMBIGUITIES:

$\frac{1}{T_\omega} = $ PRC CODE REPETITION FREQUENCY $\geqslant 2fd$ (MAX)

PRC RADAR AMBIGUITY DIAGRAM

Fig.3.

TARGET

α

α

D

S_a

$D \sin \alpha$

402

404

403

401

f_t

$f_t = \frac{c}{\lambda}$

405

410

408

f_o

ANTENNA MOTION

D

T_s

406

409

$f_t + f_o$

fs

IF AMP.

RESULTANT PHASE MODULATION

$\triangle \phi(\alpha) = \frac{2\pi L}{\lambda} \sin \alpha$

T_s

$f_s = \frac{1}{T_s}$

407

f_L • • • f_o • • • f_h

FILTER BANDWIDTH
$Bf \ll fs$

DOPPLER FILTERS

Fig.4.

BASIC ANGLE MEASURING TECHNIQUES

$\alpha = 0$
$\triangle \phi = 0$

Fig.5a.

$0 < \triangle \phi < 2\pi$

f_s

Fig.5b.

f_t

$\triangle \phi = 2\pi$

f_t $f_t + f_s$

Fig.5c.

$f_0 - \dfrac{f_s}{2}$ f_0 $f_0 + \dfrac{f_s}{2}$

f_0

f_0
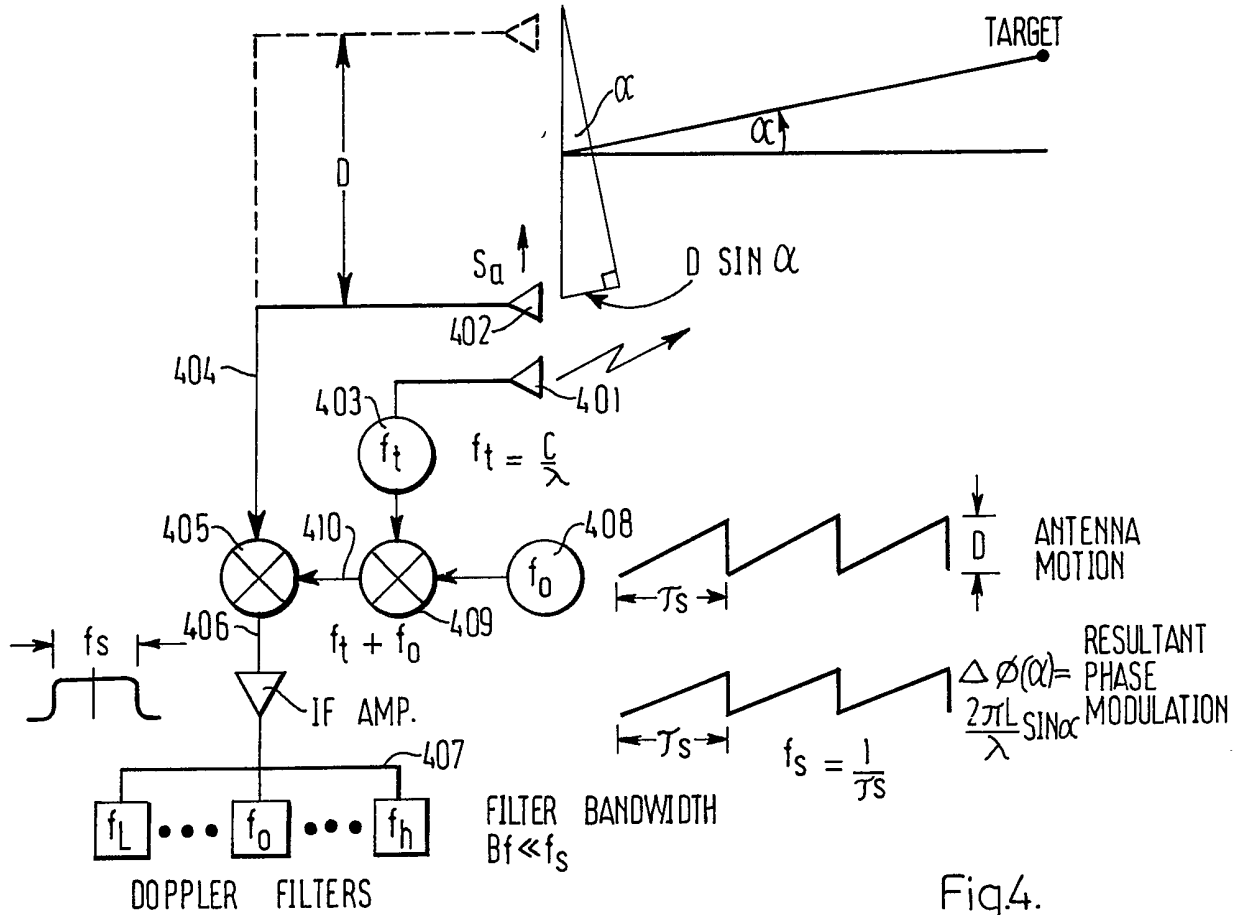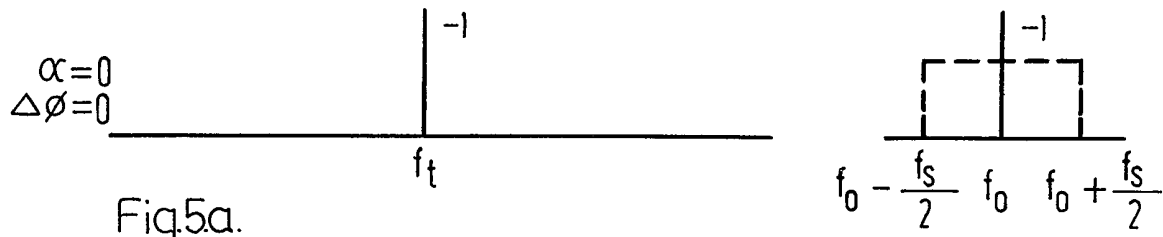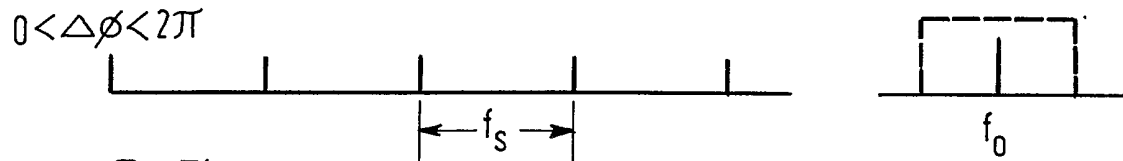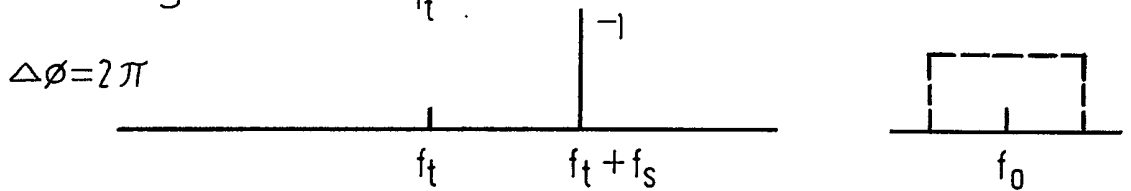
ANTENNA   OUTPUT   OUTPUT   TO   DOPPLER   FILTERS

ANGLE   MEASURING   RADAR   RECEIVER
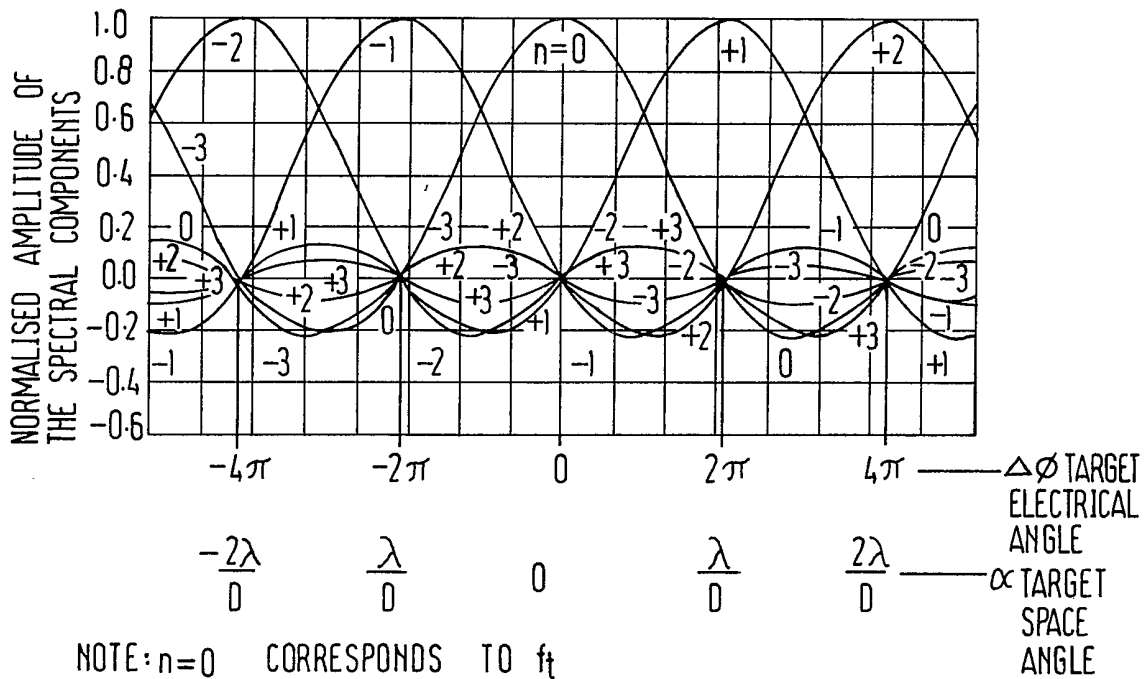
SPECTRA

NOTE: n = 0   CORRESPONDS   TO f_t

n = +1   CORRESPONDS   TO $f_t + f_s$

n = +2   CORRESPONDS   TO $f_t + 2f_s$

ETC.

Fig.6.   ANGLE   MEASURING   RADAR   ANTENNA   OUTPUT   SPECTRAL   COMPONENTS
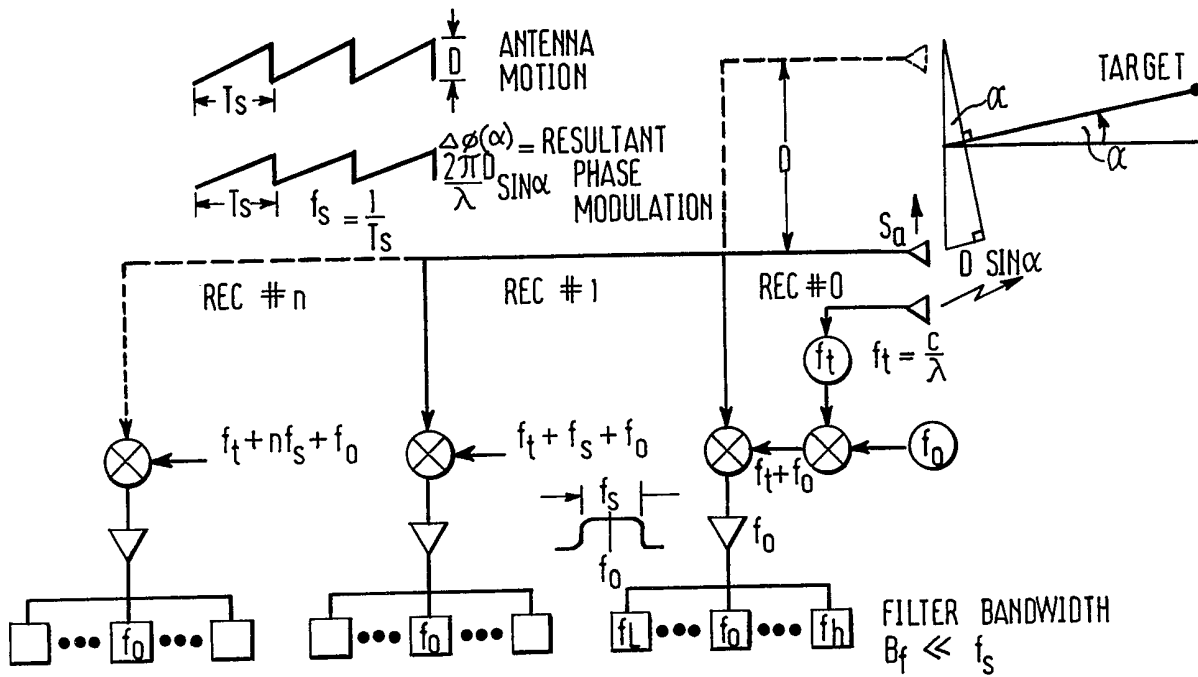
Fig.7.   BASIC ANGLE GATED RADAR
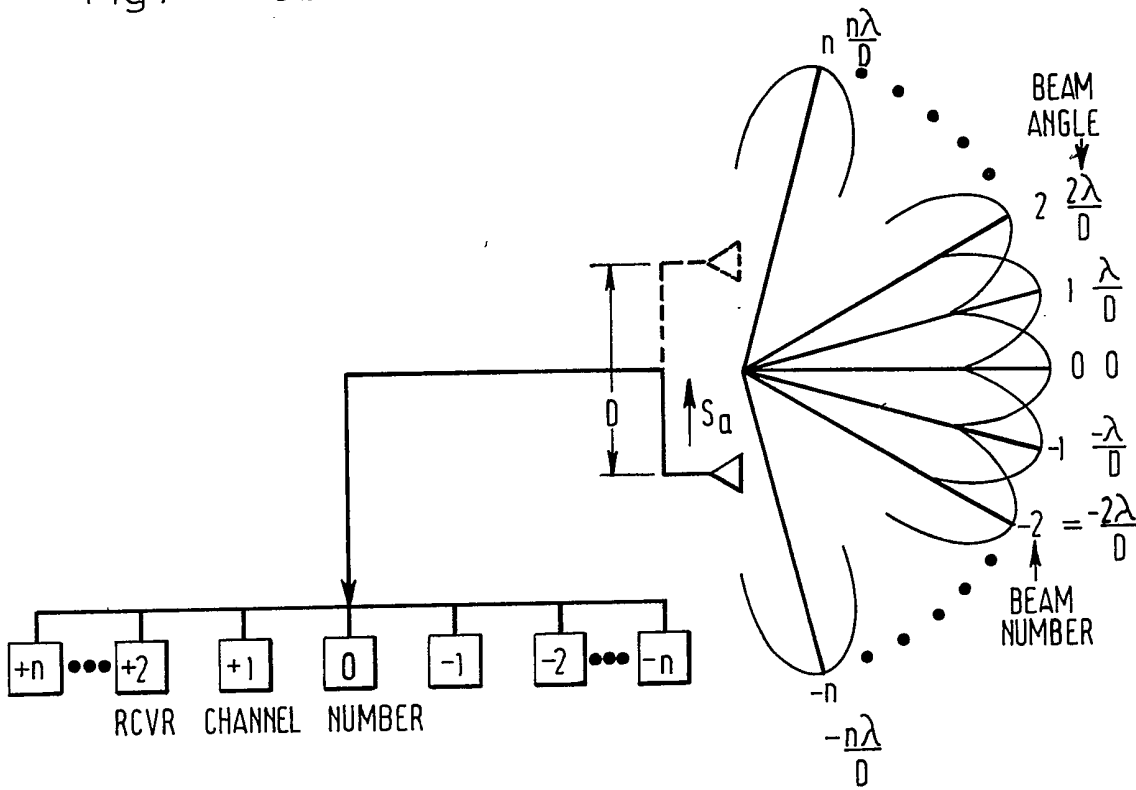
Fig.8.   BASIC ANGLE GATED RADAR
ANGLE COVERAGE

2059214
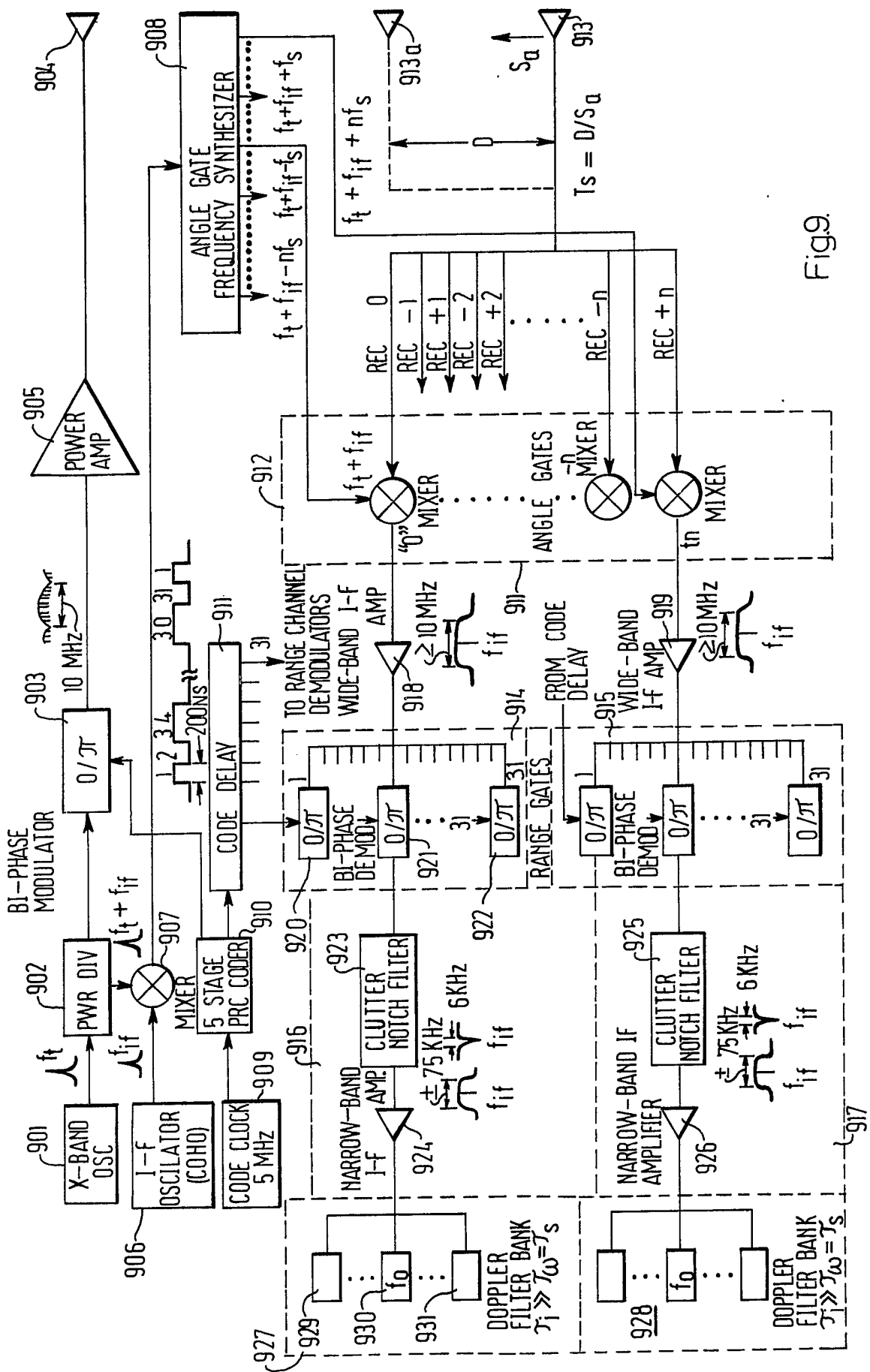
Fig.9.

ADVANCED RANGE ANGLE-DOPPLER RADAR

$$T_S = \frac{1}{f_S}$$

$$T_\omega = \frac{1}{f_\omega}$$

$$T_S = T_\omega = 6.2 \text{ USEC}$$
$$f_S = f_\omega = 161 \text{ KHz}$$
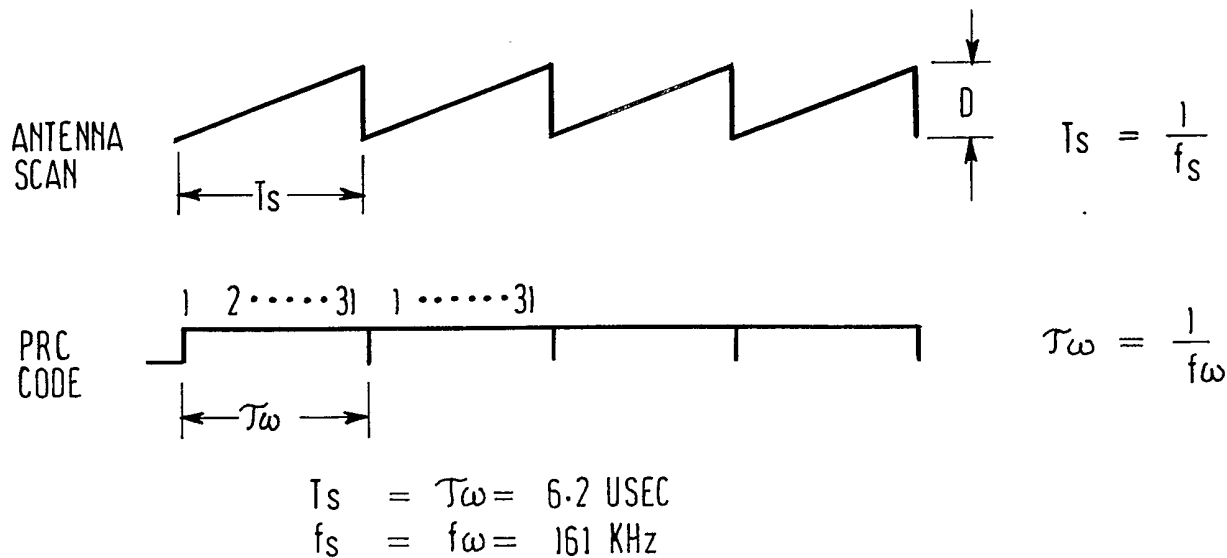
Fig.10.   ADVACED RANGE-ANGLE-DOPPLER RADAR TIMING

$$f_d = KS_a \sin\alpha$$
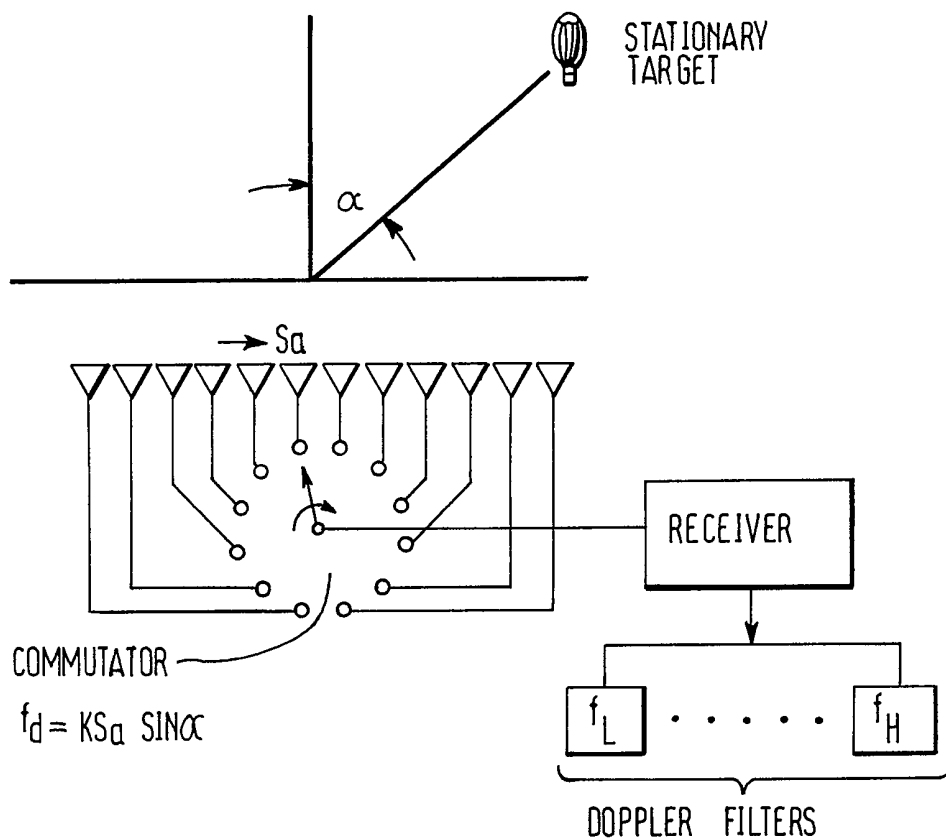
Fig.11.   SIMULATING ANTENNA MOTION BY SWITCHING

8/8

SURVEILANCE
VOLUME

$T_1 (R_1, S_1, \alpha_1)$
$T_2 (R_2, S_2, \alpha_2)$
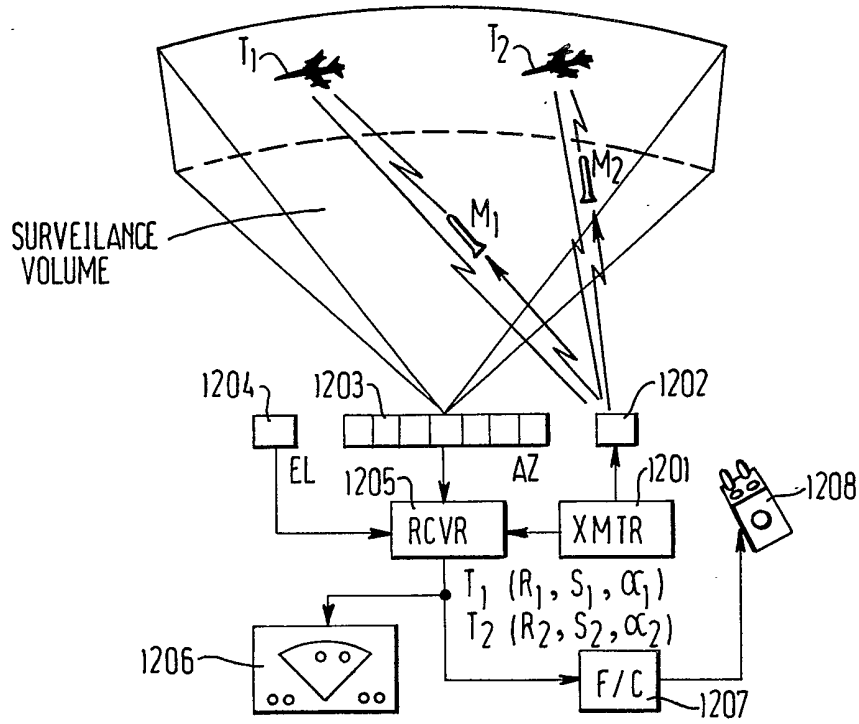
Fig.12.   POTENTIAL FIRE CONTROL APPLICATION
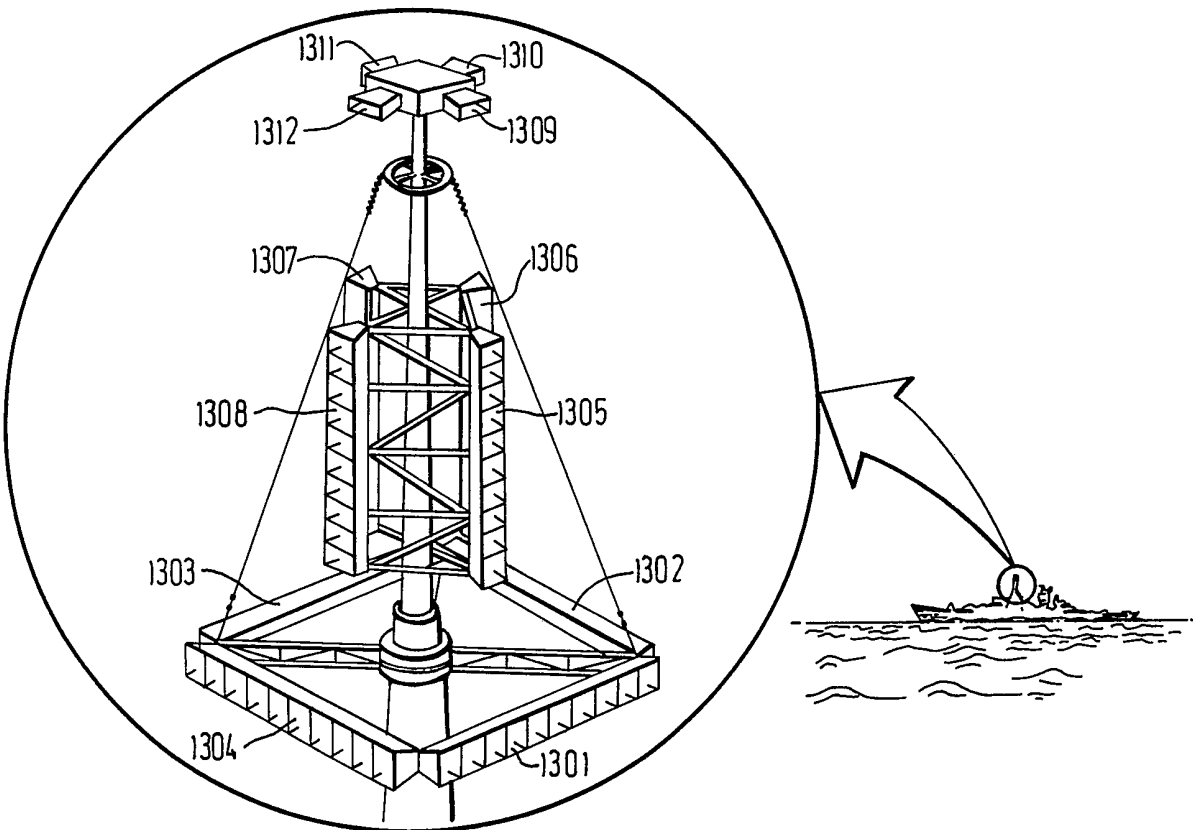
Fig.13.   TYPICAL ANTENNA ASSEMBLY

SPECIFICATION

Range and angle determining doppler radar

5 The invention relates to radar systems, and especially to such systems in which pseudo-random binary   5
coded continuous-wave signals are transmitted, and which have electronic means for angle determination
associated therewith.
     The so-called pseudo-random-coded radar concept is, of itself, well known. Thus see "Modern
Radar"-Analysis, Evaluation and System Design, by Raymond S. Berkowitz, published by John Wiley and
10 Sons, Inc., New York, London and Sydney, (3rd Printing, August 1967), describes this technique, known as   10
PRC radar. Chapter 4 of this text, entitled "Pseudo-random Binary Coded Waveforms", is particularly
pertinent as an elementary reference to PRC radar systems and concepts. The advantages in respect of high
average power-on-target, favourable signal-to-noise ratio, and accuracy of range determination, as well as
adaptability to Doppler velocity determination have long been well known.
15   The synergistic combination of the present invention also borrows from the so-called Doppler scanning 15
radar technique, also known per se, in certain prior art forms. The structural aspects of such simulated
Doppler systems are of interest as background, although the present invention is a new arrangement of the
commutated array technique combined with pseudo-random coding of the Carrier.
     Doppler scanning guidance systems have been much described in the patent and other literature, e.g. see
20 U.S. Patents, 3,626,419; 3,670,337; 3,728,729; and 3,754,261 which are typical of the patent literature on such 20
"simulated" Doppler technology. Also, "Electrical Communication", published quarterly by International
Telephone and Telegraph Corporation, contains a basic and quite complete description of that prior art as
applied to Doppler navigation beacons in Volume 46, No. 4 (1971) beginning at Page 253.
     Also U.S. Patent No. 4042925, entitled "Pseudo-Random Code" (PRC) Surveillance Radar, describes an
25 advanced PRC radar system in which the inherent range and Doppler determination ambiguities in PRC   25
radar systems are dealt with to produce an optimum system in which the first range ambiguity was extended
well beyond the useful range of the system, and in which Doppler ambiguities (i.e., target velocity multiples
providing essentially the same Doppler response) are also placed beyond the velocity range of interest. That
technology is directly applicable to the present invention. The theory described in the above-mentioned U.S.
30 Patent Serial No. 4042925, is also helpful in appreciating the advantages to be obtained from the particular 30
combination of the present invention.
     An object of this invention is to provide a radar system allowing nearly instantaneous measurement of
range, angle, and Doppler, for multiple targets lying within a volume "floodlit" by a radar transmitter.
     According to the present invention there is provided a range and angle determining Doppler radar,
35 including: 35
     (a)   first means for generating a CW RF carrier and a pseudo-random code for modulating said CW RF
carrier with said code and for radiating the resulting signal;
     (b)   second means including a multi-element antenna array for receiving echo signals corresponding to
objects illuminated by said first means;
40   (c)   third means for commutating the elements of said array at a predetermined rate, said third means   40
having a common antenna port, such that each element of said array is connected in succession to said port;
     (d)   fourth means responsive to signals at said port including a plurality of receiver channels and
frequency synthesizer means connected thereto to provide a discrete local oscillator signal to a
corresponding mixer in each of said receiver channels, said receiver channels each being discretely tuned to
45 a frequency component representative of an angle in space with respect to said array; and   45
     (e)   correlation detection means responsive to each of said receiver channels and to said pseudo-random
sequence generated in said first means to provide range determination at each of said angles in space.
     Thus, this invention involves a unique marriage of pseudo-random code (PRC) range measuring
technology and the so-called simulated Doppler angle measuring concepts as referred to hereabove under
50 the prior art discussion specifically. The commonality between these two technologies that both use   50
continuous waveform (CW) and both are inherently capable of providing target Doppler (velocity)
measurements. The resulting combination gives a low probability of intercept, good clutter performance,
anti-jam and anti-ARM performance. The system has simultaneous coverage at all angles of interest and a
capability for either surveillance or weapon fire control functions.
55   Pseudo-random coding is by a maximum length sequence, i.e., one which repeats immediately after the   55
end of each predetermined code word without hiatus. It is important to distinguish at the outset of this
description between the simulated Doppler implied in the so-called Doppler navigation beacon art referred
to above, and target Doppler components due to actual target movement with respect to the radar site at a
predetermined ground location. In the so-called Doppler navigation beacon, a signal is transmitted
60 successively from the elements of the linear array by commutation, and at the airborne station the effect is 60
much the same as if the antenna were physically moving, producing a "simulated" Doppler effect from
which the airborne station can derive navigation angle information. In the combination of the present
invention, however, the commutated antenna receives only the targets separately illuminated from a
separate transmitting antenna covering at least the space sector of interest. This transmitting antenna
65 radiates the CW signal, bi-phase modulated by the pseudo-random maximal length sequence, so, the   65

commutated receiving array effectively phase modulates the received signals, and it will be seen later that an individual spectrum line corresponds to each of the discrete angles in space selected according to criteria which will be better understood later. The receiver circuitry connected to the commutated receiving antenna comprises a corresponding plurality of receiver channels each supplied with a different local oscillator signal

5   and each having the same predetermined IF bandwidth. Thus, each such channel responds only to received   5
signals corresponding to a particular angle in space. This concept forms the basis for effectively angle-gating received signals, the range determination being subsequently accomplished by autocorrelation of the received pseudo-random sequence against the transmitted code of the same form. Doppler determinations are made typically by Doppler filter banks responsive to each of these receiver channels.

10   An embodiment of the invention will now be described with reference to the drawings, in which: 10
Figures 1(a) to *1(e)* show PRC sequence generation with waveforms.
Figures 2(a) to *2(c)* show the autocorrelation concept with waveforms.
Figure 3 is a classical PRC radar ambiguity diagram illustrating the development of ambiguous range and Doppler responses.

15   *Figure 4* shows the basic angle-measuring concept which forms part of the invention.   15
Figure 5 illustrates the development of discrete receivers' spectra corresponding to predetermined space angles.
Figure 6 illustrates, graphically, the amplitudes of spectral components relating to Figures 4 and 5.
Figure 7 illustrates the extension of the concept of Figure 4 to produce angle gating of receive signals.

20   *Figure 8* illustrates the relationship between various angles (beams) in space as related to Figures 4 and 7.   20
Figure 9 is a typical system block diagram of an overall device embodying the invention.
Figure 10 is a timing diagram relating the PRC code word and antenna scan timing.
Figure 11 illustrates the simulation of antenna motion by switching (commutation).
Figure 12 illustrates the application of the system embodying the invention to a fire control application.

25   *Figure 13* is a typical antenna assembly for azimuth, elevation, and target illumination in each of four   25
quadrants.
Before we describe a system embodying the present invention, it is considered useful to review the techniques of pseudo-random coding, and to begin that discussion, reference is made to Figure 1.
In Figure 1(a) a CW oscillator-transmitter 101 feeds a bi-phase modulator 102 which codes, or modulates,

30   the carrier on lead (d) according to pseudo-random sequence and feeds this to an antenna 106. The actual   30
coder 104 may be of the well known shift register type with feedback connection 105, arranged to produce the code on lead (c). The code clock 103 produces master timing pulses as shown in Figure 1(b). These are spaced τ_b which is the bit duration of the code and Figure 1(c) is the code itself. The output of 101 is a steady CW signal, see Figure 1(d), and after being modulated in 102 according to the code of Figure 1(c), the

35   waveform of Figure 1(e) is produced and applied to the antenna 106. Ordinarily in a PRC system, the antenna   35
106 (and this is the case in the present system) may be a relatively simple antenna for producing a relatively broad beam of energy over a sector of space of interest.
In the code the total time of the maximal length sequence before it repeats is the word "duration" τ_w which equals the product of L and τ_b. L equals 2^N-1, which is the length of the code word as a function of the

40   number of states N of the shift register 104. In the present case, N = 5 and L is therefore 31. Note that the   40
invention is not limited to this or any of the specific parameters recited. The reasons for the choices made will be apparent as this description proceeds.
Referring now to Figure 2, the PRC autocorrelation function is seen at Figure 2(c). Classically, the code according to Figure 2(b), which is that of Figure 1(c), is multiplied by itself in a mixer 201. The echo signal as

45   present on lead 202, may be thought of as the received signal and on lead 203 the code is delayed by an   45
amount D in 204. This signal on 203 is the local or reference code signal. Depending upon the alignment of these two code signals as they are applied to 201, an autocorrelation function in accordance with Figure 2(c) is produced. As these codes "slip" by each other, due to the changing range of a moving target echo signal, peaks at a value of +L are produced with spacing of τ_bL spacing as seen. For a time τ_b on either side of a

50   correlation peak, the amplitude of the correlation peak, the amplitude of the correlation function decreases   50
until it reaches a value of −1 between the correlation peaks. The signals shown at Figure 2(b) as present on 202 and 203 may be thought of as video domain signals having instantaneous amplitudes of either 1 or 0 and which appear to occur randomly, hence the name pseudo-random code.
Figure 2(a) includes a Doppler filter 205 through which a discrete value of target Doppler may be isolated,

55   thus for a particular value of the delay 204 and for a particular frequency response of 205, a discrete target   55
range and velocity is detected.   .
For maximal length pseudo-random codes (sequences) as used in the present embodiment, the resultant autocorrelation function, Figure 2(c), always has the same shape. The peak of this function may otherwise be thought of as occurring when the codes are aligned bit-for-bit, giving an amplitude of L, i.e., an amplitude

60   value of 31 in this instance. The range discrimination or resolution time provided is equivalent to a   60
conventional pulse system with a pulse width equal to 7_b. The transmitted signal as PRC modulated is wideband (approximately twice the code clock rate), so when received it must be handled by wideband circuits until after the correlation detection function has been completed. This will be more fully evident at a later point in this description.

65   Figure 3 is a more or less self-explanatory ambiguity diagram of a classical type. The term f_d is target   65

Doppler frequency while τ is representative of range.

It is clear that, for the correlation described in connection with Figure 2, the same response is obtained every τ_w (relative slip) between the received and local codes. That is, the response is ambiguous to the extent that it might be indicative of a range τ_w or a multiple thereof. Although not specifically a part of the present
5 invention, the reader will recall the reference to U.S. Patent No. 4042925, which describes a fully applicable 5 technique for dealing with this range ambiguity problem. For the sake of relative simplicity, however, that additional disclosure has been omitted from this specification, since, although it is a useful addition, it is not germaine to the concepts and specifics of this invention.

As is more or less standard, a relatively short code word τ_w, such as the 31 bit word assumed in this
10 embodiment, is required for the reciprocal of τ_w, which is the PRC code repetition frequency, to be equal to or 10 greater than twice f_d (max). The value f_d (max) is, of course, the maximum expected Doppler velocity. The description in the aforementioned U.S. Patent makes the same choice for the elimination of Doppler velocity ambiguities, but uses a multiple clock frequency with associated logic circuits to recognise and eliminate false range responses out to a range much extended beyond the prima face repundant range of τ_w.
15 In Figure 3, the "0" Doppler lobes are seen to be down by $1/L^2$ from the main response and the Doppler 15 ambiguity sidelobes, although nonexistent for in-range (or zero range) are $1/L$ times the power in the main lobe for out-of-range conditions. The width of the Doppler sidelobes, as well as the main response lobes, is approximately $1/T_i$ where T_i is the available integration time, or the time the transmitter dwells on the target.

Proceeding to Figure 4, the basic angle measuring technique is described in elementary form. Assume a
20 substantially omni-directional antenna 401 excited by transmitter 403 at frequency f_t, and a receiving 20 antenna 402 which moves laterally a distance D in time T_s, then back in zero time (sawtooth motion) as shown. The antenna 401 radiates a CW signal and 402 receives reflected energy from the target illuminated by 401. Further assume that the target is stationary and the discussion is confined to the plane of the paper. If a stationary target is at an angle α, then the motion of the antenna 402 phase-modulates the return signal or
25 lead 404 at f_t linearly with time as shown on Figure 4. Note that the maximum phase angle at a given space 25 angle α measured from a line normal to the antenna motion is

$$\triangle\phi\,(\,\alpha\,) = \frac{2\,\pi\,D\,\sin\,\alpha}{\lambda}$$

30 30
It is well known from phase modulation theory that the resultant frequency spectrum at the antenna output 404 consists of discrete lines (assuming infinite integration) around f_t spaced $f_s = 1/T_s$, where f_s is the frequency of this antenna motion and T_s is its period. The amplitude of the lines depends on $\triangle\phi\,(\alpha)$ the peak modulation on the return from a target at angle α.
35 Before looking at the general case, it will be instructive to look at the easily predicted results. Start with the 35 case of $\alpha = 0$ (i.e., target on the antenna (normal) boresight). In this case $\triangle\phi(0) = 0$, and the antenna output is a single line spectrum at f_t. After mixing in mixer 405, this results in a frequency at f_o on lead 406 and the central filter in the filter bank 407 is excited. A local oscillator 408 at frequency f_o, and mixer 409 operate to provide a mixer reference on lead 410 at $f_t + f_o$. Figure 5(a) depicts this condition, i.e., f_o on lead 406.
40 Now let α increase in an arbitrarily positive direction. If we let α take on a value such that $\triangle\phi = 2\pi$, then 40 again a single line exists at the antenna output at $f_t + f_s$. This result is easily seen since the return signal f_t is being phase-shifted exactly 2π degrees on each scan which is equivalent to being modulated continuously in phase with a phase-time slope $2\pi/T_s = 2\pi F_s$. As is well known, the result of a linear phase modulation on a carrier frequency f_t is a single frequency at $f_t + f_s$. This principal is well known in single-sideband modulation,
45 especially in respect to the so-called serradyne modulator to produce a single spectral line offset from a 45 carrier frequency.

If the i-f amplifier 411 at f_o following the mixer 405 in Figure 4 has a bandwidth of $f_o \pm f_s/2$, then the resulting line at $f_t + f_s$ does not get through and the filter bank is not excited, see Figure 5(c). If α takes an intermediate value such that $0 < \triangle\phi(\alpha) < 2\pi$, then in general, energy appears at f_t and $f_t \pm nf_s$ where n is an
50 integer. In this general case, see Figure 5(b), only the energy at line f_t gets through and excites the filter at f_o. 50
Thus, in general, as α moves from $\alpha = 0\,\therefore(\,\triangle\phi = 0)$ in a positive direction, the output at f_o will start at a maximum and drop to zero at an angle α corresponding to $\triangle\phi(\alpha) = 2\pi$.

Let the angle α at which $\triangle\phi = 2\pi$ be determined. Since

55 $$\triangle\phi\,(\alpha) = \frac{2\pi D}{\lambda}\;\sin\,\alpha = 2\pi$$ 55

$$\sin\,\alpha = \frac{\lambda}{D}$$

60 60
$$\text{for}\,\frac{\lambda}{D} \ll 1\;\text{(i.e. small }\alpha\text{)}$$

$$\alpha \approx \frac{\lambda}{D}$$

65 Note that this is just the beamwidth of a rectangular antenna of length D operating at a wavelength of λ, or 65

the first null on its

$$\frac{\sin X}{X}$$

5

beam pattern.

If the angle α is extended beyond λ/D, the resultant spectrum out of the antenna is a single line at $f_t \pm nf_s$ for angles of α which result in $\triangle\phi = \pm n2\pi$. These angles of α must correspond to $\alpha = \pm n \lambda/D$ or at integral antenna beamwidth angle. (For simplicity, the approximation $\alpha = \pm n \lambda/D$ is used although it must be corrected for large angles).

The general case showing the sideband amplitudes of the phasemodulated spectrum was worked out by R.C. Cummings, see the Proceedings of the IRE, February 1957, PP 175–186, and the result is shown in the self-explanatory Figure 6, interpreted for our example.

This shows that the output of our receiver of Figure 4 (which can only respond to the f_t (n=0) line because of the filtering) traces out a sin X/X response as the space angle α is varied. This again is what would be expected from an ideal rectangular antenna looking broadside. In effect, then, the receiver has provided an angle gate around $\alpha = 0$.

If we now place in parallel with the receiver of Figure 4 another receiver (Figure 7) with its local oscillator offset from the first receiver by f_s, then we have an angle gate (sin X/X antenna response) around the angle+ λ/D. This can be seen by looking at the n= 1($f_t + f_s$) component in Figure 6, which has its maximum at $\alpha = \lambda/D$. Similarly, by placing parallel receivers with their local oscillators at $f_t \pm nf_s + f_o$, we generate a set of angle gates or simultaneous antenna beams in space. Note that the receiver channels are all identical, and the components of Figure 7 are readily recognized from Figure 4. Figure 8 shows still more graphically the situation hereabove developed.

There is understood to be a receiver channel associated with each antenna beam in space, and each receiver responds (except for the sin X/X sidelobe response) only to targets in the corresponding beam.

Note again from Figure 6, that when a target is exactly at $\alpha = n \lambda/D$ (center of n-th beam in Figure 8) only receiver n responds. However, when the target moves off the beam center, there will be coupling between receiver channels per the sin X/X response. For example, when a target lies at the point where two beams intersect ($\lambda/2D$; $3\lambda/2D$__), there is equal response in the two receiver channels associated with the two intersecting beams, as well as smaller responses in the other receivers.

It will be realized by those skilled in this art that the equivalent of a scanning beam can alternatively be achieved by using one receiver whose local oscillator is sequentially switched to the proper offset frequency.

To examine the effect of a moving target, take the simple case where the target is moving directly (radially) toward the antenna at $\alpha = 0$. As stated earlier, if the target is stationary at $\alpha = 0$, only a single line at f_t appears at the antenna output. This is translated down to f_o and rings filter f_o. If the target at $\alpha = 0$ has a radial velocity which causes a Doppler shift f_d, then a single line again appears at the antenna output at $f_t + f_d$. After translation, it appears at $f_o + f_d$ and rings one of the filters in the Doppler filter bank. As long as the maximum Doppler

f_d max $\leqslant f_s/2$ where f_s = antenna scan frequency, the Doppler shift does not cause an ambiguity in the angle measurement. For example, if the Doppler shift were equal to $f_d = f_s$, then the target would appear to be in the next angle "bin". The significant point, then, is that if

$$f_d \text{ max} \leqslant f_s/2$$

45

there is no coupling between the angle and Doppler measurement.

It is obvious then that targets at $\alpha = n\lambda/D$ (the center of the n-th antenna beam) moving radially toward the antenna will produce a Doppler component in the n-th receiver as described for the $\alpha = 0$ case above.

In the general case where the target is off the beam centers, all the resulting spectral lines out of the receiving antenna are shifted by f_d, the target Doppler. This causes the filters at $f_o + f_d$ for each receiver channel to be energised. The levels into each filter are determined by sin X/X response of Figure 6. Remember that for the general stationary target, the filters at f_o in each receiver channel were energised.

Therefore, except for the sin X/X coupling between receivers due to the angle measurement, the n-th receiver measures the Doppler of the target associated with the n-th antenna beam. In effect, discrete angle gates are formed by the first mixer of each receiver channel.

Referring now to Figure 9, the overall system block diagram of a typical arrangement embodying the invention is shown. Note that the transmitter section comprising an X-band oscillator 901, bi-phase modulator 903 and antenna 904, is equivalent to the same components in Figure 1 (a). Also, in the general case shown, a complete PRC receiver channel (as previously identified) would be associated with each angle gate (or beamwidth). This angle gate is formed by the first mixer in each receiver which is fed by a local oscillator signal at $f_t + f_{if} + nf_s$, where n is equal to the corresponding antenna beam at n λ/D. These local oscillator signals are generated coherently in synthesizer 908 which is a multi-frequency generator in effect. As shown in Figure 10, the antenna scan period T_s is made equal to the PRC word period, τ_w. In this manner, both the criteria for proper PRC ranging without encountering Doppler ambiguities,

$$f_w \geqslant 2f_d \text{ (max)}$$

and the criteria for angle gating

5          $f_s \geqslant 2f_d \text{ (max)}$ 5

are met.

In addition, if $f_w = f_s$, it is less likely that unwanted beat frequencies will be created.

Assume first that a target is exactly at $\alpha = n\lambda/D$, a compensating angle point with a Doppler f_d. In the n-th

10   receiver channel (or angle gate), the receiver response is that of a conventional prior art PRC radar since the   10
antenna scanning modulation is compensated for as previously described. The filter at f_d is excited in the
range gate (receiver) channel corresponding to the target range. The other range gates do not correlate
properly, and the corresponding f_d filter response is down by the PRC correlation function $1/L^2$ as predicted
by PRC radar ambiguity diagram of Figure 3.

15   If we place the target at $\alpha = n\lambda/D$ and look at the adjacent angle receivers (or angle gates), the local   15
oscillator compensation moves the entire PRC spectrum by $f_s = f_w$. Here f_s is the scan frequency
(commutation rate) and f_w is $1/\tau_w$, i.e., f_w is the code word repetition frequency. This is equivalent to a PRC
spectrum with a Doppler of $f_d + f_w$. After PRC correlation in the range gate in which the target lies, a single line
at $f_d + f_w$ results. Since the narrow band i-f cuts off at $f_w/2$, the signal is not detected.

20   If we look at the other range gates in the adjacent angle receiver channels, the response is that of a PRC   20
radar which is out of range but at the first Doppler ambiguity response of the PRC ambiguity diagram. Thus
the response is down only $1/L$ again as predicted by the PRC ambiguity diagram. The same reasoning can be
applied to other than the adjacent receiver channels.

When the target is between the $\alpha = n\lambda/D$ points, the situation is more complex as the scan modulation

25   causes additional lines to be generated at multiples of f_s (see Figure 6). The worse case appears to be when a   25
target is exactly between two compensation angle points, for example at $\lambda/2D$; $3\lambda/2D$, etc.

As discussed above in the angle measurement sections, the corresponding two adjacent receivers have
equal responses and are down 3dB from maximum response at $n\lambda/D$. The out-of-range gate response in
these corresponding two adjacent receivers is down by $1/L^2$ from the response in the in-range gate response

30   (which is down 3 dB). Other angle-gated receiver channels are affected by the sin x/x response of the scan   30
modulation as well as the PRC ambiguity diagram response. The unwanted responses, however, may be
expected to be of the order of 10 dB predicted by the sin x/x response of Figure 6 since the PRC unwanted
response is on the order of 15 dB.

On Figure 9 it will be noted that the oscillator 901 is identified as an X-band device, this being a typical

35   radar frequency. The power divider 902 connected to 901 passes most of the relatively low band power of   35
901 to the bi-phase modulator 903. However, a small amount is diverted to mixer 907 where it is mixed with
the output of a stable IF oscillator (coho) 906. The frequency of 901 is identified as f_t and that of the coho 906
as f_{if}, accordingly the output of mixer 907 is $f_t + f_{if}$. The output of 907 drives the angle gate frequency
synthesizer 908 directly, this synthesizer being no more than a multiple frequency generator synchronous

40   with the output of mixer 907. Thus, the multiple local oscillator signals generated by 908 provide phase   40
coherence throughout the signal processing functions following the mixer group 912.

The power amplifier 905 picks up the bi-phase modulated output of 903 and provides wideband
amplification thereof, at least sufficient to accommodate the approximately 10 MHz bandspread at the
output of 903. Subsequently the antenna 904 radiates this energy. The antenna 904 is much the same as a

45   standard PRC sector illuminating radiator and need be no more than a relatively straightforward and simple   45
horn radiator. Later, in connection with Figure 13 the overall antenna arrangement which would be typical of
the combination of the invention will be discussed in more detail.

As is well known in PRC generation, a code clock 909, in this example running at 5 MHz, drives the 5 stage
PRC coder 910, this arrangement being substantially the same as that of Figure 1(a). The output of coder 910

50   not only supplies the maximal length sequence to modulator 903 but also drives the 5 stage binary code   50
delay device 911. This is ordinarily no more than a standard device of one code word total delay wth 31 taps,
whereby the 31 bits of the code word (the bit duration being typically 200 nanoseconds in this example) are
presented at the taps before the word repeats itself. The total word duration τ_w being 6200 NS in this
example, the first redundant range is therefore approximately 930 meters, however, as hereinbefore

55   indicated, the separate technique described in U.S. Patent No. 4042925 can readily be added to the total   55
structure to increase this first redundant range greatly.

The antenna 913 is assumed (for simplicity at this point) to move laterally and linearly with a velocity S_a
(see also Figure 10) and occupies extreme positions 913 and 913a. It is assumed to return from 913a to the
913 position in zero time for the sake of explanation. The output of this antenna which receives the reflected

60   signals from targets illuminated by 904, branches into each of the 2n+1 receiver channels within block 912.   60
Reference back to Figure 8 explains this 2n+1 figure. From the output of block 912, each of the mixers therein
comprising the illustrated zero mixer, the minus n mixer and the plus n mixer, as well as all the remaining
ones of the 2n+1 mixers, has a wideband IF amplifier typically 918 or 919 following it. These wideband IF
amplifiers have a bandwidth of at least 10 MHz centered about f_{if} to accommodate the PRC modulation still

65   present at this point.   65

The mixers within 912 and these wideband IF amplifiers of which 918 and 919 are typical, comprise the receiver channels variously referred to herein. Each of the mixers within 912, having its discrete local oscillator frequency provided by 908 corresponds to a beam (angle gate or angular bin) depicted in Figure 8. Although beams corresponding to these discrete angle "bins" are not actually formed in space, the
5 performance of the overall equipment has very much the equivalent effect and the term "beam" is very often used in this connection and in synthetic aperture radar situations in general.

Two decoder blocks, 914 and 915, are shown, but it is to be understood that there is one such decoder block for each of the 2n+1 receiver channels aforementioned, and within each of these decoder blocks, for example 914, the phase coincidence detectors shown, typically 920, 921, and 922, are only three of the 31
10 such circuits present in 914 and the other such decoder circuits. These blocks may be also characterized as range channel demodulators, the correlation process being carried out therein. In addition, the received signal corresponding to that angle gate (beam), e.g. as received from 918, is fed in parallel to all 31 coincidence circuits of 914. The other input of each of these 31 coincidence circuits of 914 comes from a discrete corresponding one of the 31 outputs of the delay device 911. Concerning that delay device 911, it will
15 be obvious to those skilled in this art that suitable implementations can be obtained from the technologies of delay lines, shift registers or the like.

The blocks 914 and 915 and their companions are followed by blocks typically 916 and 917, the latter containing a clutter notch filter, typically 923 or 925 followed by narrowband IF amplifiers 924 and 926, respectively. The clutter notch filters 923 and 925 merely eliminate frequency components corresponding to
20 non-moving signals, i.e., those whose spectral content does not contain target Doppler (velocity) modulation components. At this point, the PRC coding is no longer present, the inputs to blocks such as 916 and 917 being passable through a bandpass filter having a bandwidth of the order of 75 KHz centered around f_{if}. These blocks 916 and 917, come directly from PRC technology and it will be realised that one clutter notch filter and narrowband IF amplifier follows for each of the 31 coincidence circuits for each of the 2n+1
25 correlators of which 914 and 915 are only typical. Thus, the output of each narrowband amplifier, such as 924 for example, represents a discrete range within a discrete beam or angular "bin". Each of these narrowband IF amplifiers can then indicate at its output in respect to presence or absence of a signal within that range bin and angle bin. Doppler filter banks, typically 927 and 928, following each of those narrowband IF amplifiers, as illustrated at 927 comprise filters 929, 930 and 931 typically. The number of filters in 927 or 928 or any of
30 the other filter banks provided is determined by the velocity resolution desired essentially without regard to other system parameters.

At this point, the significance of Figure 10 having been already appreciated (namely that it places $T_s = \tau_w$, reference is made to Figure 11. In a practical system, the antenna 913 which is assumed to move physically over the distance D in Figure 9 or in Figures 4 and 7 would normally be replaced by a linear array of radiators
35 separately fed through a commutating arrangement in accordance with Figure 11. Figure 11 is otherwise self-explanatory.

At this point it will be realised by those skilled in this art that a simpler system can be configured if one were willing to search with a single angle gate and/or a single range gate per angle channel. Such a modification can be instrumented once the principles of the present invention are clearly understood. In that
40 event, the block 912 of Figure 9 would contain only one mixer and the angle gate frequency synthesizer 908 would issue a programmed local oscillator frequency. Moreover, in such a variation, the correlation process could be carried out by a searching range gate against the output of a single wideband IF amplifier following a single mixer of the block 912.

Figure 12 illustrates a potential fire-control application in which a transmitter 1201 and surveillance
45 volume illuminating antenna 1202 transmit the CW PRC modulated signals as already described.

In Figure 12 the commutated receiving antenna 1203 is as already described, and an additional receiving antenna 1204 is vertically oriented to provide the same angle gating function in elevation as is provided in . azimuth. The receiver 1205 then provides multiple channels for each of the 1203 and 1204 antennas from which target, range, velocity and angle information issues, to an indicator 1206 and also to a control unit
50 1207 relating to missile launcher 1208.

From this complete range, angle (in two dimensions) and Doppler information missiles M, and M_2 can be programmed toward the targets. That is, the seeker-receiver in the missile can be "locked-up" in range, angle and velocity. The semi-active missiles can then use reflected energy from targets resulting from the illumination by 1202 to home on target.
55 The unique advantage in ground-to-air missile (defense) system in employing the present invention is the increased fire power provided by the capability for parallel missile firing. This follows from the contemporaneous range, angle and velocity data for multiple targets which the system of the invention provides.

Referring now to Figure 13, a configuration of antennas is illustrated from which the entire 360° about any
60 given location can (through switching selection) be subjected to the surveillance and control capabilities of the present invention. In azimuth, four multi-element commutatable arrays 1301, 1302, 1303, and 1304 are shown which are selectively employed contemporaneously with one of the elevation arrays 1305, 1306, 1307, or 1308, respectively. A four quadrant transmitting (illuminator) antenna arrangement comprising horns 1309, 1310, 1311, and 1312, is shown, it being understood that the appropriate one of these is also
65 selected for the space quadrant of interest.

The employment of elevation angle determination in accordance with this invention of course requires duplication of the angle gating functions of Figure 9, but the pseudo-random range and Doppler velocity determining functions need not be duplicated. The manner of integrating the elevation operation into the arrangement of Figure 9 will also be evident to those skilled in this art once the principles of the present
5 invention are well understood.
Other modifications and variations and details of arrangements of the system described may present themselves to those skilled in this art, and accordingly, it is not intended that the scope of the present invention should be regarded as limited to the embodiment depicted in the drawings or this description, these being typical or illustrative only.
10

CLAIMS

1. A range and angle determining Doppler radar, including:
   (a) first means for generating a CW RF carrier and a pseudo-random code for modulating said CW RF
15 carrier with said code and for radiating the resulting signal;
   (b) second means including a multi-element antenna array for receiving echo signals corresponding to objects illuminated by said first means;
   (c) third means for commutating the elements of said array at a predetermined rate, said third means having a common antenna port, such that each element of said array is connected in succession to said port;
20 (d) fourth means responsive to signals at said port including a plurality of receiver channels and frequency synthesizer means connected thereto to provide a discrete local oscillator signal to a corresponding mixer in each of said receiver channels, said receiver channels each being discretely tuned to a frequency component representative of an angle in space with respect to said array; and
   (e) correlation detection means responsive to each of said receiver channels and to said pseudo-random
25 sequence generated in said first means to provide range determination at each of said angles in space.
2. A radar according to Claim 1, including a plurality of banks of Doppler filters, one of said banks responsive to the output of each of said correlation detection means to provide an output representing the discrete target velocity for each of said angles.
3. A radar according to Claim 1 or 2, in which said pseudo-random code generating means within said
30 first means comprises digital logic circuits for repetitively generating a maximum length sequence and said means for modulating said RF carrier comprises a bi-phase modulator.
4. A radar according to Claim 1, 2, or 3, in which said array of said second means comprises a linear array of substantially equally-spaced radiators and said radiating means of said first means comprises an antenna having a radiation pattern covering at least a predetermined angular region extending on both sides of a line
35 normal to said linear array.
5. A radar according to Claim 4, in which the line of said linear array is defined as lying substantially in a horizontal plane and said angular region on both sides of said array normal is an azimuth angle, said antenna of said first means having a radiation pattern at least covering a solid angle therefrom bounded by said predetermined angle on both sides of said array, normal in azimuth and a predetermined elevation angle.
40 6. A radar according to Claim 3, in which said array of said second means comprises a linear array of substantially equally spaced radiators and said radiating means of said first means comprises an antenna having a radiation pattern covering at least a predetermined angular region extending on both sides of a line normal to said linear array.
7. A radar according to Claim 1, in which said code generating means of said first means comprises
45 means to generate a binary coded maximal sequence having a word duration τ_w and n bits each of duration τ_b, said modulating means comprises a bi-phase modulator responsive to said code generating means, and in which each of said receiver channels of said fourth means comprises a first IF amplifier following each corresponding mixer and preceding said correlation detection means, said first IF amplifier having a bandwidth sufficiently broad to pass the IF spectrum resulting from reception of pseudo-random coded
50 signals through said array of said second means, said first IF amplifier bandwidth being sufficiently narrow to substantially reject signals having frequency components substantially outside the IF frequency spectrum corresponding to said coded signals for the corresponding angle in space.
8. A radar according to Claim 7, in which said correlation detection means comprises a discrete binary coincidence detector of n stages each having first and second inputs, and including a delay device
55 responsive to said binary code maximal sequence generating means, said delay device having a total delay of τ_w and having n equally spaced taps to provide a delayed local code, each of said taps being connected to a second input of one of said coincidence detector stages, said coincidence detector having an output providing the autocorrelation function of said delayed local code and received signals from said first IF amplifier.
60 9. A radar according to Claim 8, including means for synchronizing said frequency synthesizer from said CW RF carrier generator of said first means.
10. A radar according to Claim 8, including an IF coho oscillator at frequency f_{if} and a synthesizer drive mixer, said mixer being connected to said coho oscillator and the f_t signal generated by said RF CW carrier generator to develop a signal f_t+f_{if}, said frequency synthesizer being synchronized therefrom to provide
65 coherent signal processing of received signals through said receiver channels and said correlation detection

process.

11. A radar system for comtemporaneous angle and range measurement for plural targets within a predetermined solid sector of space, including:

(a) first means for transmitting a CW RF signal modulated by a repetitive, digital. pseudo-random
5 maximal sequence covering at least said solid section of space;

(b) second means including a receiving antenna and scan means whereby the effective instantaneous point of reception provided by said receiving antenna is varied cyclically over a predetermined distance to impose a phase modulation on received echo signals resulting from illumination of targets by said first means such that a frequency spectrum centered about a different discrete frequency corresponds to each
10 discrete angle within said space sector;

(c) and third means responsive to said second means for separating received signals into channels by said discrete frequencies and therefore in accordance with target angle with respect to said receiving antenna, said third means also including means operative within each of said channels for determining target range by autocorrelation of said transmitted maximal sequence against the same code on the
15 corresponding received echo signal.

12. A range and angle measuring radar system comprising:

(a) first means for illuminating a predetermined solid sector of space with a CW transmitted signal modulated by a maximal length pseudo-random sequence;

(b) second means including an antenna array having a plurality of elements each arranged to receive
20 echo signals from targets illuminated by said first means along a different path in space;

(c) scan means for sampling said array elements sequentially at a predetermined rate, thereby generating a scan modulated received signal in which a discrete frequency represents each angle of incidence of a corresponding echo signal at said array; and

(d) third means including a correlation detector for separately processing said discrete frequencies to
25 determine range in a corresponding channel representative of echo signal angle of arrival.

13. A radar according to Claim 11, in which said second means includes Doppler measuring means for measuring target velocity in each of said channels, said Doppler measuring means thereby providing velocity information corresponding to each target range within a discrete angle bin.

14. A radar substantially as described with reference to the accompanying drawings.