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(54) **Transmitter independent techniques to extend the performance of passive coherent location**

(57) Methods to improve the performance of passive coherent location by non-reliance on a direct view of the signal source (10, 20, 30) are described. Passive Coherent Location, or PCL, has become a promising technology as more computer-processing power has become generally available. Basically, most PCL techniques rely on comparing signal sources with their reflections from an object (100) in order to determine the location of the object (100). However, this requires line of sight access from the receiver system (150) to the signal source (10, 20, 30) which may not always be practical and may limit the performance of the system overall. The techniques described herein do not require line of sight to the transmitter sources (10, 20, 30).

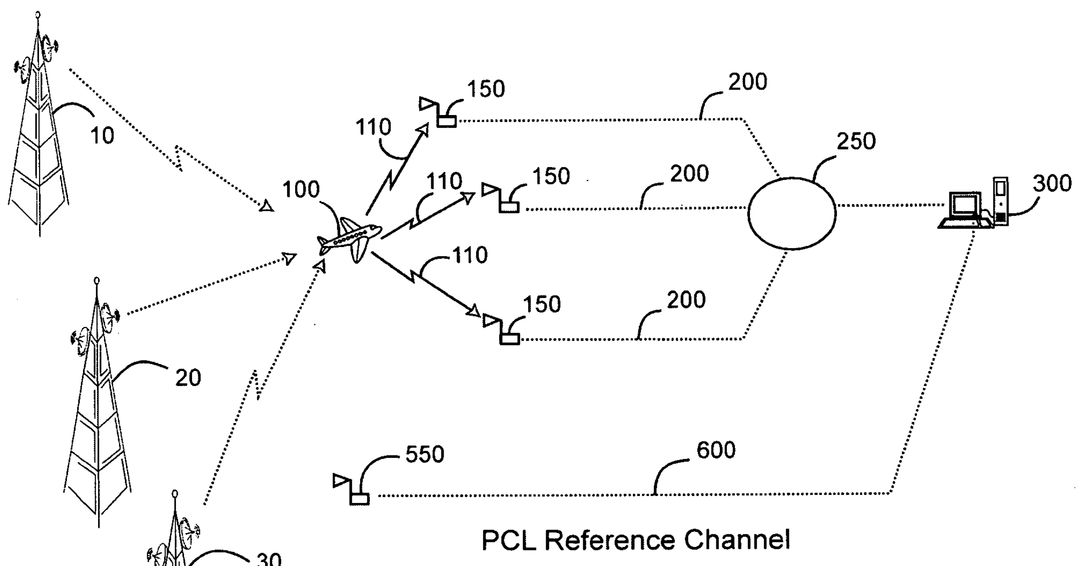

FIG. 1

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Description

FIELD OF THE INVENTION

[0001] The present invention relates to aircraft tracking. In particular, the present invention is directed toward transmitter independent techniques to extend the performance of passive coherent location.

BACKGROUND OF THE INVENTION

[0002] With a conventional radar system, a pulsed signal is transmitted and the time taken for the pulse to travel to the object and back allows the range of the object to be determined. In a passive radar system, there is no dedicated transmitter. Instead, the receiver uses third-party transmitters and measures the time difference of arrival (TDOA) between the signal arriving directly from the transmitter and the signal arriving via reflection from the object, allowing the bi-static range of the object to be determined. In addition to bi-static range, passive radar can also measure the bi-static Doppler shift of the echo and also its direction of arrival allowing the location, heading and speed of the object to be calculated. In some cases, multiple transmitters and receivers are used to make several independent measurements of bi-static range, Doppler and bearing and hence significantly improve the final track accuracy.

[0003] The Passive Coherent Location (PCL) system is bi-static radar, which measures the elliptical distance and the Doppler frequency shift. It works with continuous wave (CW) transmitters of opportunity, meaning that it uses electromagnetic radiation, primarily assigned for another purpose, for example, radio or television terrestrial broadcasts. It is necessary to detect at least two (in an ideal case three or more) direct signals from transmitters for a proper determination of a target position.

[0004] As of December 2006, there are several PCL systems in various stages of development or deployment, including:

- Silent Sentry is a Lockheed Martin (USA) PCL system that uses FM radio transmissions. Two different antenna variants are believed to be available providing an antenna that provides 360° azimuth coverage from 4 different beams (an Adcock array), and a variant that provides 100° azimuth coverage from six different beams (linear array). It has a range of up to around 100 nautical miles (about 185.2 km) depending on the variant employed and a number of receive nodes at different locations can be combined to provide increased coverage. See, http://www.dtic.mil/ndia/jaws/sentry.pdf.
- Celldar is a British system developed jointly by Roke Manor and BAE Systems. The system is a PCL sensor that can exploit GSM signals, currently in the 900MHz band, but may also be able to use the 900MHz and 1800MHz bands simultaneously in the future. It is believed that Celldar is a low level/surface surveillance system designed to achieve good coverage below 10,000ft (about 3048 meters) and can track targets in 2D over a 100° sector at ranges of up to around 60km. See, http://www.roke.co.uk/skills/radar/.
- CORA is a German PCL sensor, developed by FGAN (Die Forschungsgesellschaft für Angewandte Naturwissenschaften e.V.), that exploits Digital Video Broadcast - Terrestrial (DVB-T) and Digital Audio Broadcast (DAB) transmissions.
- Cristal is a PCL sensor developed by Thales that exploits FM radio transmissions to track targets. In addition to Cristal, it is believed that Thales has a prototype PCL system that uses analog TV or DAB transmissions.
- One of the PCL systems developed by ERA, formerly Rannoch Corporation, (www.rannoch.com) uses FM radio transmissions.

[0005] Each of these systems rely on continuous wave (CW) communications whether or not the CW signal is modulated to provide analog or digital information, as the techniques basically rely on the comparison of delayed versions of the source (i.e., the reflections) with the original CW signal. For example, analog signals include conventional FM radio or television, while digitally encoded signals include new television formats for audio, video, and telecommunications (e.g., DAB, DVB, and GSM).

[0006] U.S. Patent 7,155,240, entitled "Method of Determining the Position of a Target Using Transmitters of Opportunity," (Atkinson et al.), describes a technique for non-reliance on line of sight with a digital source signal such as GSM. That technique claims a method of determining the position of a target using components in a wireless communication system in which pre-stored codes are included in transmissions of communications signals as part of a communication protocol, comprising the steps of: a) providing a transmitter which transmits a communications signal; b) providing a plurality of receivers, in communication with each other, which receive communications signals reflected from the target, the receivers being disposed at locations which are separate from the transmitter and separate from each other, and being time or phase synchronized; c) determining a time of arrival information of the received communications signal at each receiver by continuously correlating the code in the received communications signal with the pre-stored codes in the receiver; and d) using information pertaining to the location of each receiver, together with the information obtained from step c), to determine the target position.

[0007] In essence, the technique described by Atkinson et al uses a priori information relating to digital encoded signals where the receiver essentially identifies embedded data formats such as headers, lead-ins, or other recognizable formats. The technique appears to have been developed with digital communications in mind, and is not described for older analog transmission such as conventional television, FM radio, or other analog signals. Essentially, Atkinson's patent relies on unique or known characteristics contained within the raw digital data encoding of the transmitted signal for time or phase referencing.

[0008] However, it is possible to use unique or identifiable reference information from any type of signal, whether digital or analog, which may be identifiable from the raw signal or from data reduction and analysis of the signal.

[0009] One of the issues with continuous wave tracking techniques is the sheer volume of data and processing power required to characterize and analyze signals. Therefore, it is necessary to consider various methods to reduce the data into salient characteristics for the purpose of comparison and characterization. For example, FM radio characteristics of interest over the typical FM frequency range of 88 MHz to 108 MHz include modulation depth, modulation frequency deviation, and other characteristics such as peak and semi-peak values.

[0010] In addition to using reference characteristics of waveforms for time referencing it is also possible to compare only signal reflections from a common source, even with the coherent source to perform positioning using time difference of arrival techniques.

[0011] Two separate methods are 1) use of unique signal characteristics to use as a time or phase reference or 2) comparison of reflected versions of the same source.

[0012] Therefore, in either of the two cases, it is possible to use the original CW information, or to use a characterization of the signal, such as a Fast Fourier Transform (FFT) or other characterization of the signal as described in the following publications: Slezák, L., Kvasnič ka, M., Pelant, M., Vávra, J., Pl š ek, R.: Simulation and Evaluation of the Passive Coherent Location system. In Proc. International Radar Symposium 2005, Berlin 200; and Kvasnič ka, M., Heř mánek, A., Pelant, M., Pl š ek, R.: Passive Coherent Location FPGA implementation of the Cross Ambiguity Function. In Proc. Signal Processing Symposium 2005, Wilga 2005.

[0013] A significant part of PCL processing is cross ambiguity function (CAF) computation and its decomposition into clutter and target components. The target CAF component is analyzed via a sequential target elimination process. As a result, the parameters defined for each detected target are: instantaneous bi-static radar cross section (RCS), ground clutter estimation, elliptical range and velocity, elliptical acceleration and RCS change during the integration period.

[0014] A sufficiently fast and reliable computation of the cross ambiguity function (CAF) is one of the most important tasks and also a computationally time consuming part of PCL processing. Figure 4 illustrates CAF for Direct and Scattered FM Signals (time delay τ transformed to range in km). Pl š ek et al define the Cross Ambiguity Function (CAF) mathematically as:

$$CAF(\tau, f) = \int_0^T s_1(t) s_2^*(t+\tau) e^{-j2\pi ft} dt \qquad (1)$$

where s_1 and s_2 are continuous-time signals in the analytic signal complex format, T is the integration period (or interval) in seconds, τ is the time delay in seconds, and f is the Doppler frequency offset in Hertz.

[0015] In order to shift equation (1) into the discrete or sampled time domain, let $t = nT_S$ and $f = \frac{kf_S}{N}$, where T_s is the sample period, $f_S = \frac{1}{T_S}$ is the sampling frequency, n represents individual sample numbers, and N is the total number of samples. Inserting these values into eq. (1) and simplifying yields the discrete form of the CAF:

$$CAF(\tau, k) = \sum_{n=0}^{N-1} s_1(n) s_2^*(n+\tau) e^{-j2\pi\frac{kn}{N}} \qquad (2)$$

where s_1 and s_2 are the discrete-time (sampled) signals in the analytic signal complex format, N is the total number of samples in s_1 and s_2, τ is the time delay in samples, and $\frac{k}{N}$ is the frequency difference in digital frequency, or a fraction of the sampling frequency. The magnitude of the $CAF(\tau, k)$, or $|CAF(\tau,k)|$, will peak when τ and $\frac{k}{N}$ are equal to the embedded TDOA (Time Difference of Arrival) and FDOA (Frequency Difference of Arrival), respectively, between the signals s_1 and s_2. Note that $CAF(\tau,k)$ is also capable of a signal detection due to the fact that the presence of peaks in the $CAF(\tau,k)$ may be used as a robust signal detector, even for signals with extremely low signal-to-noise ratio (SNR).

[0016] Computational efficiency becomes a large factor because of the potentially wide range of TDOAs and FDOAs that must be searched. Equation (2) can uncover TDOAs in the range:

$$-N \le \tau \le N \text{ and FDOAs for } k \text{ in the range } -\frac{N}{2}+1 \le k \le \frac{N}{2}.$$

[0017] To search the entire range of possible TDOAs and FDOAs would require $2N^2$ calculations of the CAF, which is an ominous task for large N or equivalently for long integration interval T.

[0018] The optimal algorithm for effective CAF computation is a direct application of the Fast Fourier Transform (FFT) into the signal product of the signals s_1 and s_2,

$$CAF(\tau,k) = FFT\left(s_1(n)\, s_2^*(n+\tau)\right) \tag{3}$$

[0019] Using eq. (3) to calculate CAF for all values of τ and k, an individual FFT computation is required for each value of τ.

[0020] A promising method for a fast and robust CAF calculation is a hardware implementation of the direct FFT method. Another way to perform these tasks is to deploy a cluster of computers with high-speed network interconnections and an appropriate number of computing nodes.

[0021] The basic requirements for CAF calculation in PCL signal processing are as follows:

- Sampling frequency: 100-200 kHz
- Effective bit resolution (dynamic range) for input signals: 18-24 bits (~100dB)
- Total number of samples or integration interval: 2^{17}=131 072 samples or about 1 sec
- Frequency resolution: < 1 Hz
- Accuracy of CAF calculation: absolute error about $10^{-9} \div 10^{-12}$ with comparison to IEEE 64-bit floating-point arithmetic
- Maximum number of time delays: < 1024
- Maximum frequency range: ⟨-300,+300⟩ Hz (about 600 spectral coefficients)
- Total time of computation: < 1 sec (final requirements is about 10ms for real time PCL system)

[0022] This computational task is extremely challenging due to the sheer volume of input data and the need for high accuracy of the CAF computation.

[0023] The basic part of the CAF computation algorithm is a radix-2 implementation of the general FFT algorithm. The theoretical computational complexity of this algorithm is $O(N \log_2 N)$ operations (compare with $O(N^2)$ for a standard DFT). Figure 5 shows the basic computational Eight Point FFT-radix-2 structure in terms of elementary "butterfly" operations.

[0024] More effective implementations of the FFT exist, such as radix-4 and split-radix but they are significantly more complicated to implement, and this example is restricted to radix-2 for the purposes of discussion and presentation.

[0025] A practical approach to FFT/CAF implementation is significantly influenced by the arithmetic representation (fixed or floating-point) and numerical accuracy. As an optimal arithmetic representation, a fixed-point numerical representation with 42-46 bit accuracy may be employed as illustrated in Figure 6. Figure 6 illustrates an FFT-radix2 Error for $N=2^{17}$ Samples for Different Arithmetic Representations.

[0026] For limited frequency ranges, e.g., ⟨-300,+300⟩ Hz, which represents only about a 1% fraction of the frequency range up to the Nyquist frequency, the number of operations may be reduced significantly. Figure 7 illustrates an example of a "butterfly" reduction, which is not necessary for FFT calculation for limited frequency ranges. It is possible to obtain a modified FFT-radix2 algorithm with about 62% reduction of the required "butterfly" operations.

SUMMARY OF THE INVENTION

[0027] The present invention is defined in claim 1 and 8, respectively. Particular embodiments are set out in the dependent claims.

[0028] The present invention is directed toward methods to improve the performance of passive coherent location by non-reliance on a direct view of the signal source. Passive Coherent Location, or PCL, has become a promising technology as more computer processing power has become generally available. Basically, most PCL techniques rely on comparing signal sources with their reflections from an object in order to determine the location of the object. However, this requires line of sight access from the receiver system to the signal source which may not always be practical and may limit the performance of the system overall. The techniques described herein do not require line of sight to the transmitter sources.

BRIEF DESCRIPTION OF THE DRAWINGS

[0029]

Figure 1 is a block diagram of a first embodiment of the present invention, lustrating establishing References from a Source Signal's Characteristics.

Figure 2 is a block diagram of a second embodiment of the present invention, illustrating the relative Comparison of Reflected Signals.

Figure 3 is a block diagram of a third embodiment of the present invention, illustrating the use of Mobile Transmission Sources.

Figure 4 is a diagram illustrating CAF for Direct and Scattered FM Signals (time delay τ transformed to range in km).

Figure 5 is a diagram illustrating an Eight-Point FFT-Radix2 and Elementary Butterfly Operation.

Figure 6 illustrates an FFT-radix2 Error for $N=2^{17}$ Samples for Different Arithmetic Representations.

Figure 7 is a diagram illustrating an FFT-radix2 Butterfly Reduction for $N=2^5$ Samples using 4 Spectral Coefficients.

DETAILED DESCRIPTION OF THE INVENTION

[0030] Figure 1 is a block diagram of a first embodiment of the present invention, illustrating establishing References from a Source Signal's Characteristics. Referring to Figure 1, this embodiment shows several FM transmitters 10, 20, 30 where the signals are reflected from an aircraft 100 and are received at multiple PCL receiver locations 110, 150.

[0031] Unlike conventional PCL, there is no direct line of sight from a reference channel 550, 600 to the transmitters 10, 20, 30. Instead, at receiver locations 150, time references for each of the signals are established through analysis of the reflected signals, such as analog television information patterns, FM modulation characteristics, or through signal characterization and processing, including spectral analysis, of the signals in real time, or near real time with quantifiable known delays such as those associated with gate array technology.

[0032] The time-stamped signals are then forwarded 200 to a central server 250 for PCL processing including detection, correlation, feature extraction, and line tracking, and then sent for display 300 or forwarding for integration with other surveillance systems.

[0033] This embodiment is essentially a distributed timing system, where timing references are established at the receivers 150.

[0034] Figure 2 is a block diagram of a second embodiment of the present invention, illustrating the relative Comparison of Reflected Signals. Referring to Figure 2, this embodiment shows several FM transmitters 10, 20, 30 where the signals are reflected from an aircraft 100 and are received at multiple PCL receiver locations 110, 150.

[0035] Again, unlike conventional PCL, there is no direct line of sight from a reference channel 550, 600 to the transmitters 10, 20, 30.

[0036] Instead at receiver locations 150, signals are down-converted, as in conventional multilateration, into video equivalent signals, which are passed along media 200 sufficient to provide the necessary bandwidth. For example, appropriate media includes fiber or radio link.

[0037] This embodiment shows a high-level two-step process at the central server. Firstly the incoming signals are matched to determine which reflected signals apply to each target, taking into account Doppler effects, and secondly for timing, detection, correlation, feature extraction, and line tracking, and then sent for display 400 or forwarding for integration with other surveillance systems.

[0038] This embodiment is essentially a centralized timing system where the timing is established through relative signal comparison at the central server 300.

[0039] Figure 3 is a block diagram of a third embodiment of the present invention, illustrating the use of Mobile Transmission Sources. Referring to Figure 3, this embodiment shows several aircraft-based transmitters 10, 20, 30 where the signals are reflected from an aircraft 100 and are received at multiple PCL receiver locations 110, 150. In this case there is line of sight to some or all of the aircraft based transmitters and the reference channel 50, 550, 600 to the transmitters 10, 20, 30.

[0040] Typical aircraft transmitters 10, 20, 30 may include CW or pulse systems, such as collision avoidance system, Mode S, or ADS-B transponders, which constantly transmit in typical airspace. Other than the mobile aspect of the transmitters, the PCL can operate in a conventional fashion with line of sight to the transmitters or decoding can be accomplished as in embodiments 1 and 2 above.

[0041] While the preferred embodiment and various alternative embodiments of the invention have been disclosed and described in detail herein, it may be apparent to those skilled in the art that various changes in form and detail may be made therein without departing from the scope thereof.

Claims

1. A method for tracking a target (100) using passive coherent location, comprising the steps of:

receiving, at a plurality of receivers (150), reflections of radio signals from the target (100), the radio signals being generated by one or more of uncontrolled or controlled transmitter sources (10, 20, 30), at least one or more of the plurality of receivers not in a line-of-sight to the transmitter sources (150),
identifying reflection of a radio signals as a reflection from the target (100);
measuring a time difference of arrival of the reflections of the radio signals at the plurality of receivers (150), and determining target position from the time difference of arrival of the reflections of the radio signals.

2. The method of claim 1, wherein the radio signals comprise digitally and/or analog encoded radio signals.

3. The method of claim 1 or 2, wherein the radio signals comprise analog television and/or digital television.

4. The method of any preceding claim, wherein the radio signals comprise one or more of FM radio, analog television, Digital Video Broadcast Terrestrial (DVB-T), Digital Audio Broadcast (DAB), and the Global System for Mobile Communications (GSM).

5. The method of any preceding claim, wherein the step of identifying reflections of radio signals as a reflection from the target (100) comprises the step of applying pattern recognition to the reflections of the radio signals to the reflection of the radio signal to create a distributed timing information system at the plurality of receivers (150).

6. The method of any preceding claim, wherein the step of identifying reflections of radio signals as a reflection from the target (100) comprises the step of comparing techniques of reflection of the radio signaled signals to create centralized timing information system, at the central server (250).

7. The method of any preceding claim, wherein the radio signals are transmitted from one or more of fixed or mobile radar, transponders, navigation equipment, weather system, or communications systems.

8. A system for tracking a target (100) reflecting radio signals, the system comprising:

a plurality of receivers (150), at least one of which is not in line-of-sight with the target (100), adapted to receive reflections of radio signals from target (100), the radio signals being generated by one or more of uncontrolled or controlled transmitter sources (10, 20, 30),
a detector adapted to identify reflections of radio signals reflected from the target, and measuring a time difference of arrival of the reflections of the radio signals at the plurality of receivers (150), and

a calculator adapted to determine target position from the time difference of arrival of the reflections of the radio signals,

wherein the system minimizes effects of co-channel interference by non-reliance on transmitters that are in line of sight, and therefore improving detection, tracking, and overall system performance.

9. The system of claim 8, wherein the detector identifies reflected radio signals from the target (100) using pattern recognition in the reflected signals or analyzed reflected signals to create a distributed timing information system, created at the receivers (150).

10. The system of claim 8 or 9, wherein the detector identifies reflected radio signals from the target (100) using comparison techniques of reflected signals to create centralized timing information system, at the central server (250).

11. The system of any of claims 8-10, wherein the radio signals comprise one or more of FM radio, analog television, Digital Video Broadcast Terrestrial (DVB-T), Digital Audio Broadcast (DAB), and the Global System for Mobile Communications (GSM).

12. The system of any of claims 8-11, wherein the radio signals are transmitted from one or more of fixed or mobile radar, transponders, navigation equipment, weather system, or communications systems.

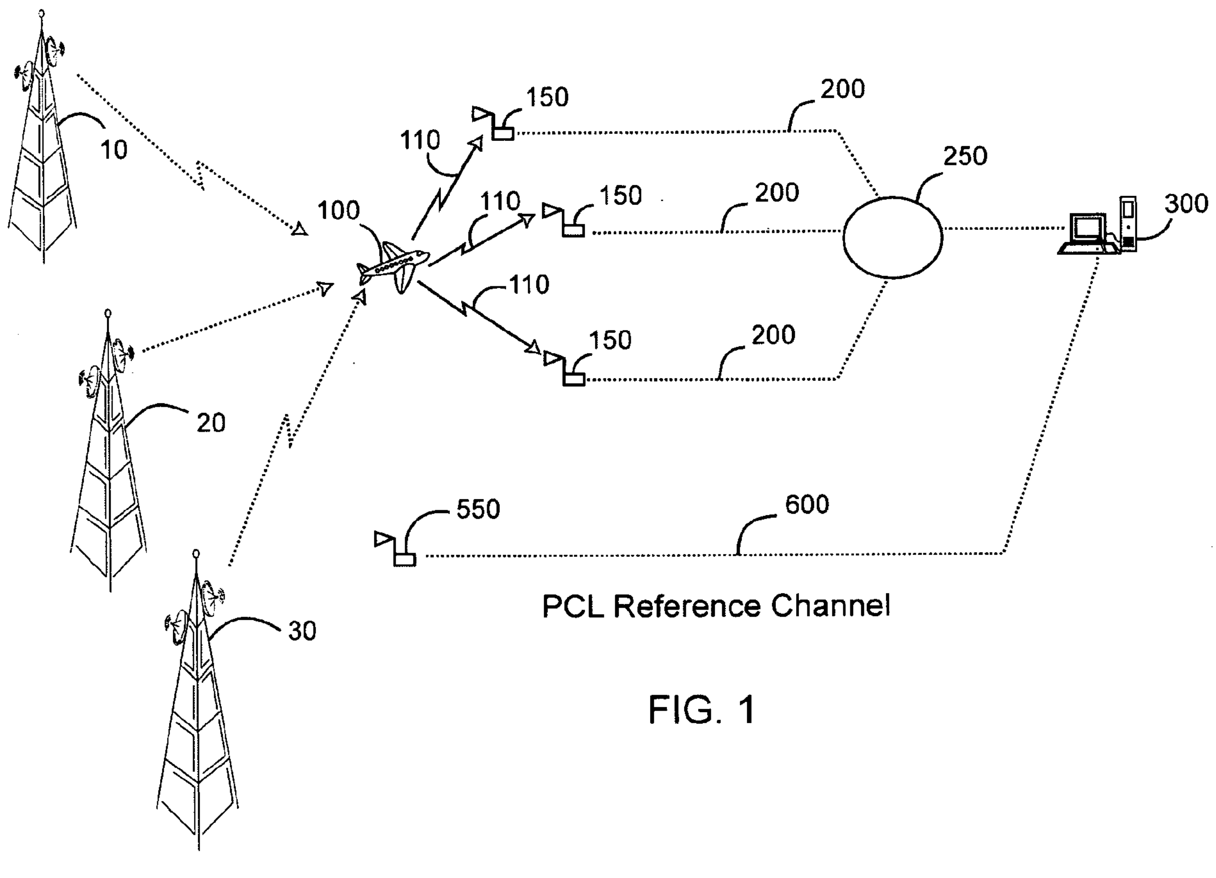
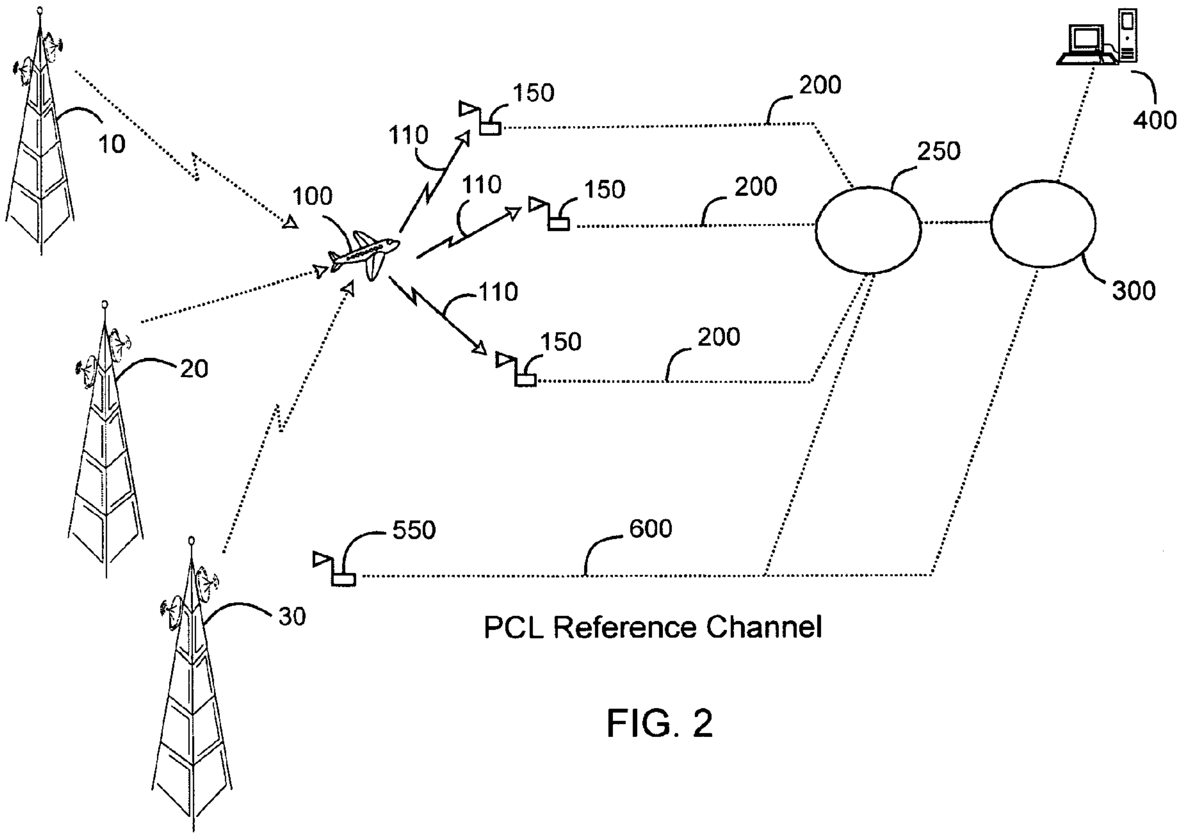

10
20
30
100
110
110
110
150
150
150
200
200
200
250
300
550
600
PCL Reference Channel

FIG. 1


10
20
30
100
110
110
110
150
150
150
200
200
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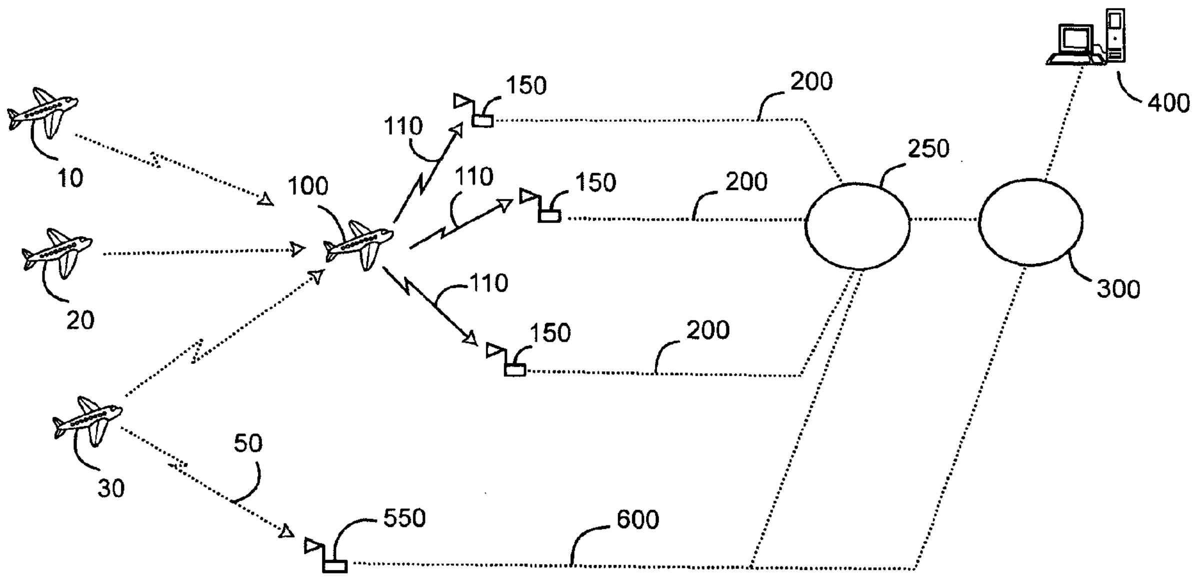
250
300
400
550
600
PCL Reference Channel

FIG. 2



PCL Reference Channel

FIG. 3

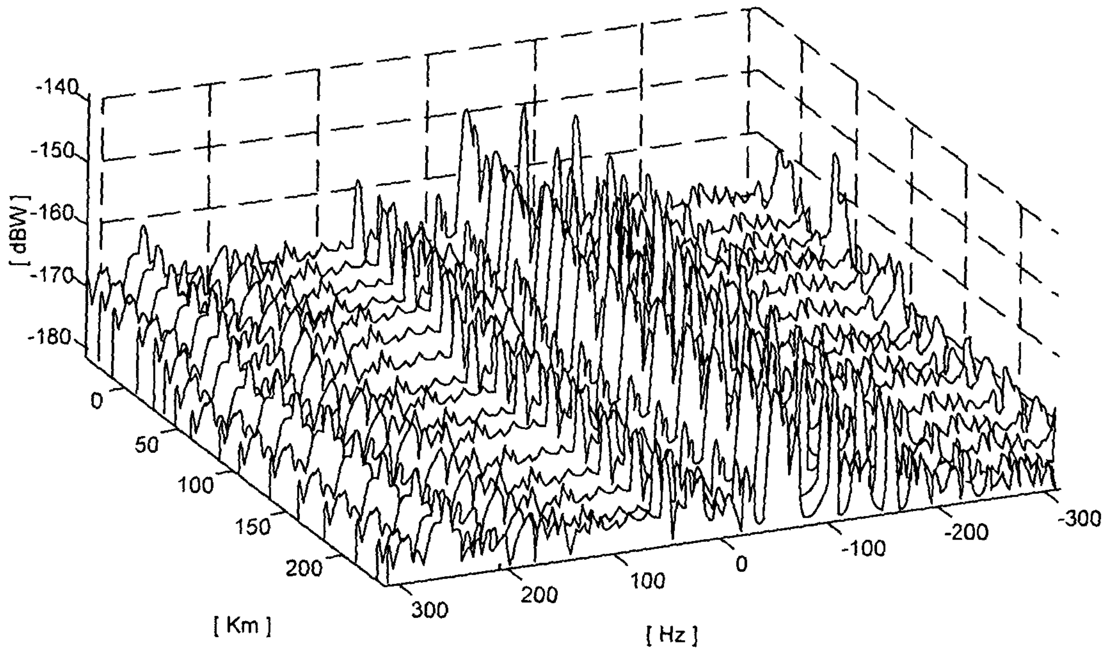

-140
-150
-160
-170
-180
[dBW]
0
50
100
150
200
[Km]
300
200
100
0
-100
-200
-300
[Hz]

Fig 4

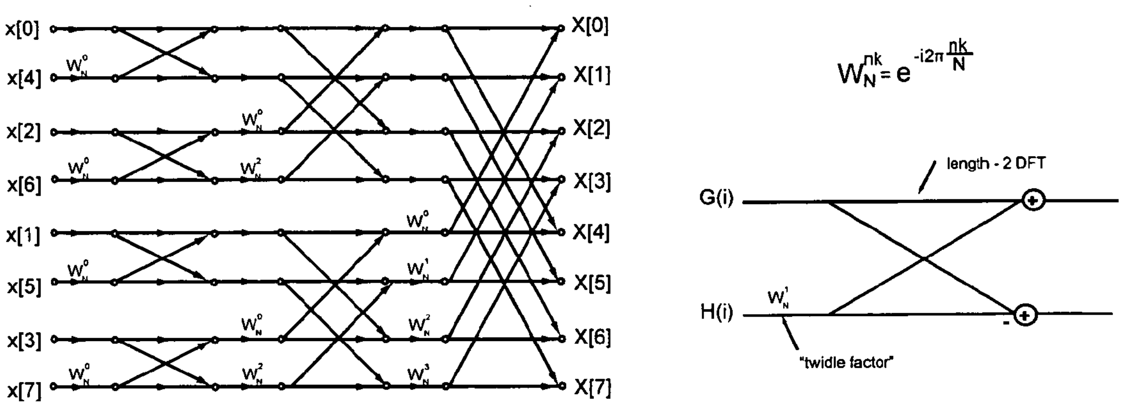
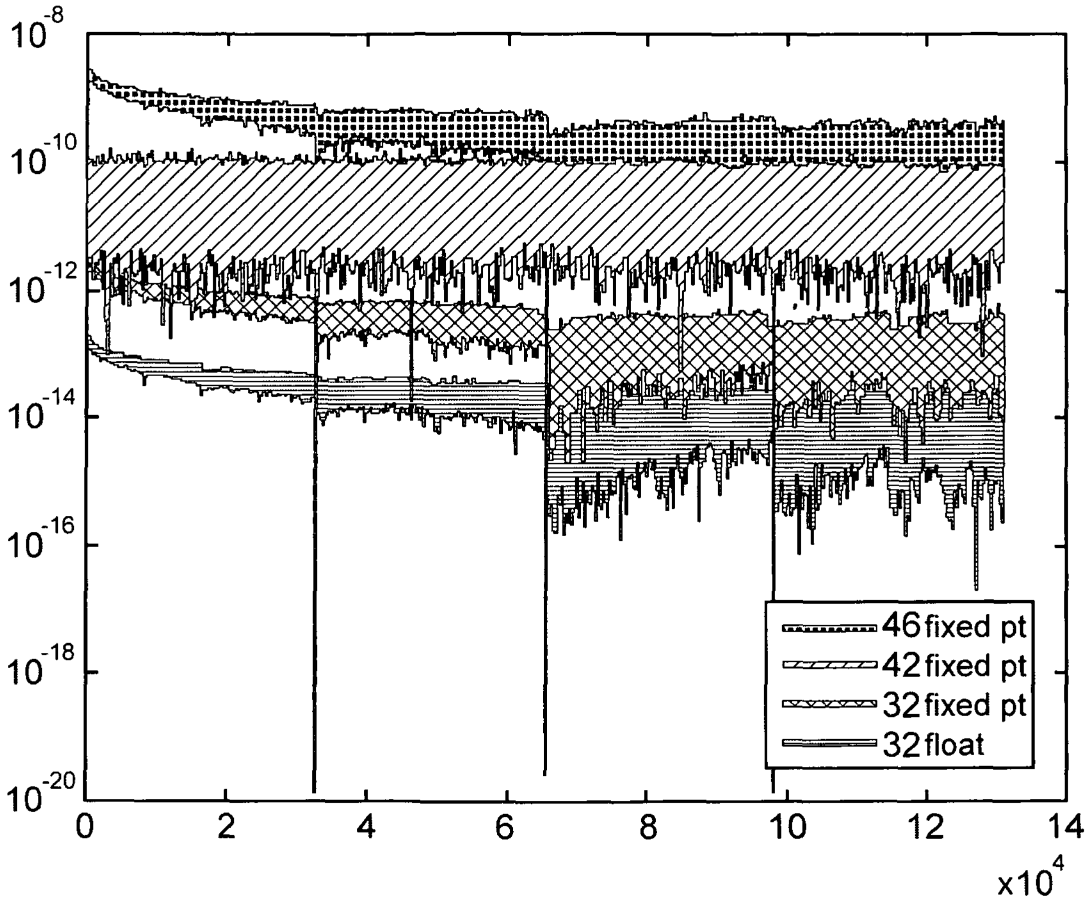

x[0]
x[4]
x[2]
x[6]
x[1]
x[5]
x[3]
x[7]
X[0]
X[1]
X[2]
X[3]
X[4]
X[5]
X[6]
X[7]
$W_N^{nk} = e^{-i2\pi \frac{nk}{N}}$
length - 2 DFT
G(i)
H(i)
"twidle factor"

FIG. 5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10^-12
10^-14
10^-16
10^-18
10^-20
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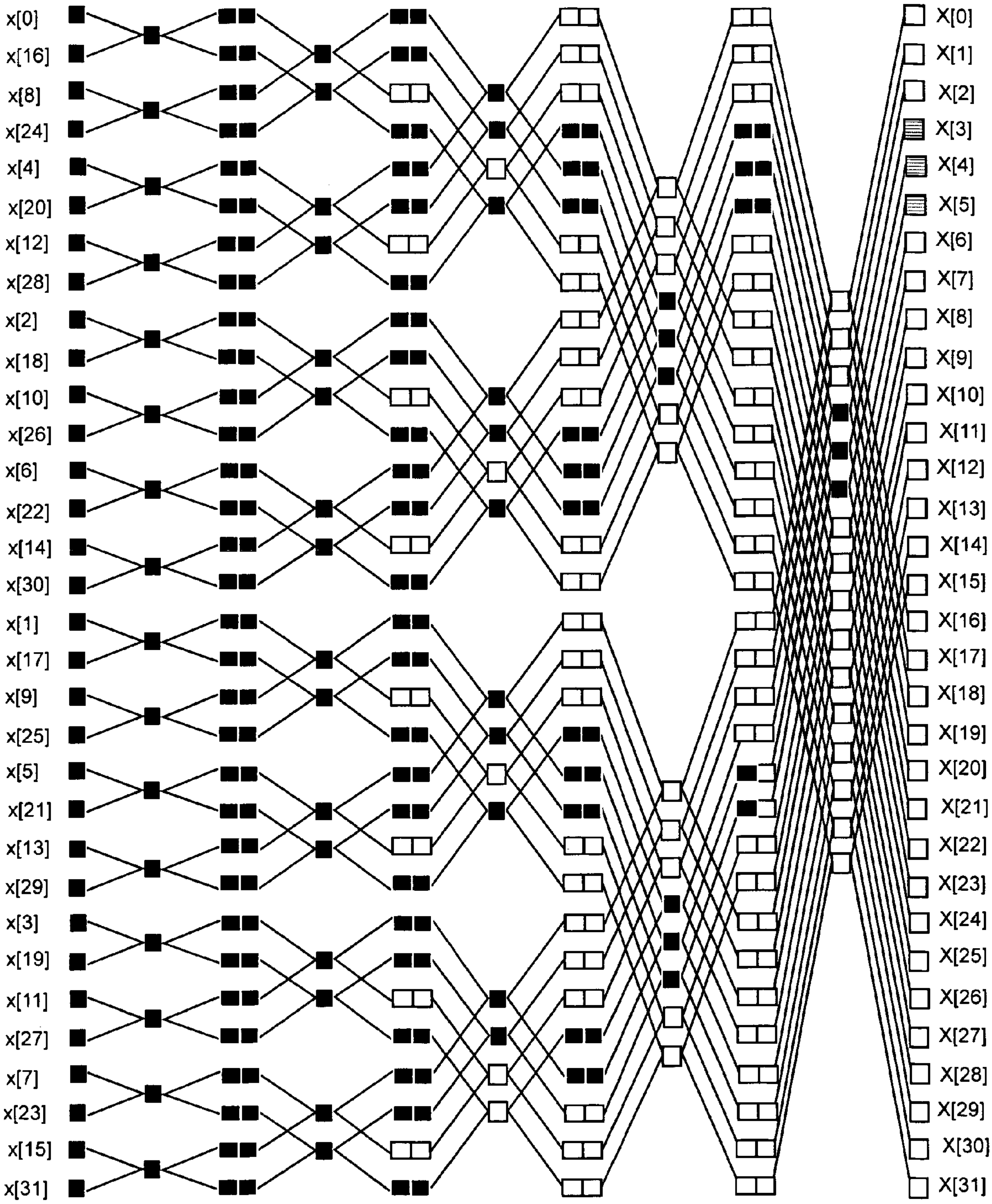
2
4
6
8
10
12
14
x10^4
46 fixed pt
42 fixed pt
32 fixed pt
32 float

FIG. 6


x[0]
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x[4]
x[20]
x[12]
x[28]
x[2]
x[18]
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X[30]
X[31]

FIG. 7

REFERENCES CITED IN THE DESCRIPTION

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Patent documents cited in the description

- US 7155240 B **[0006]**

Non-patent literature cited in the description

- Simulation and Evaluation of the Passive Coherent Location system. *In Proc. International Radar Symposium,* 2005 **[0012]**
- Passive Coherent Location FPGA implementation of the Cross Ambiguity Function. *In Proc. Signal Processing Symposium,* 2005 **[0012]**