

A METHOD AND A SYSTEM FOR DETERMINING LOCATION PROPERTIES OF AN EMITTER

FIELD OF THE DISCLOSED TECHNIQUE

5 The disclosed technique relates to locating a radiator, in general, and to methods and systems for determining location properties of an emitter according to non-common pulse trains received by receivers, in particular.

BACKGROUND OF THE DISCLOSED TECHNIQUE

10 Known in the art systems for determining the location of a transmitter, such as a radio transmitter, employ the timing properties of received pulses for determining the location of the transmitter that transmitted the pulses. One application for determining the location of a
15 transmitter is, for example, determining the location of an emergency transmitter located on a life raft or a lifeboat. Another exemplary application is the location of stolen cars. A car is fitted with a transmitter. When the car is stolen, the location of the car is determined by locating the transmitter. Yet another exemplary application is determining the location
20 of a wireless transmitting node in a network. This exemplary application includes determining the location of a cellular telephone in a cellular network or determining the location of a node in a wireless ad hoc network (e.g., WLAN). Known in the art methods, used to determine the location of a transmitter are, for example, the Time Of Flight method (i.e., TOF – the
25 propagation time of a signal between the emitter and the receiver), the Time Difference Of Arrival method (i.e., TDOA – the difference between the times of arrival of a pulse at different receivers) and the Angle Of Arrival method (i.e., AOA – the angle from which a signal was received at a receiver relative to a reference line).

30 A transmitter may emit a periodic pulse. Alternatively, a

FIG. 1

transmitter may emit a periodic pulse train. Reference is now made to Figure 1, which is a schematic illustration of two pulse trains, generally reference 50 and 52, which are known in the art. Each of pulse trains 50 and 52 includes three pulses. Pulse train 50 includes pulses 54, 56 and 58. Pulse train 54 includes pulse 60, 62 and 64. Time interval 66 is the duration of pulse train 50 and time interval 68 is the duration of pulse train 52. The duration of a pulse train will be referred to hereinafter as 'Pulse Train Repetition Interval' (PTRI). Time interval 70 is the time interval between pulses 54 and 56 and time interval 72 is the time interval between pulses 56 and 58. It is noted that time intervals 70 and 72 do not necessarily exhibit the same time duration. However, pulse trains 50 and 52 are identical with respect to the number of pulses in each of pulse trains 50 and 52 and the time duration between the pulses in pulse trains 50 and 52. It is noted that a pulse train may include at least one pulse. Thus the PTRI reduces to the Pulse Repetition Interval (PRI).

U.S. Patent 6,933,888, to Schiffmiller et al, entitled "Multi-Ship Coherent Geolocation System", directs to a method for ascertaining the position of an emitter according to TOA measurements of pulses arriving at collecting receivers. The collecting receivers may not see the same pulses. According to the method directed to by Schiffmiller et al, each collecting receivers accumulates an ensemble of TOA's of received pulses. A position of the emitter is postulated and the expected TOA of the pulses, at the locations of the receivers are determined. The differences between the actual TOA's and the postulated TOA's are used to determine a new postulated position of the emitter. Thus, the postulated emitter location that minimizes the differences between the actual TOA's and the postulated TOA's is determined as the emitter location. Each receiver can measure the TOA of a pulse from the emitter on the same timeline as the other receivers.

The publication entitled "Robust Parameter Estimation for Periodic Point Process Signals Using Circular Statistics" to Elton et al,

directs to a method for estimating *TOA phase* and *jitter variance* of a data sample, which may include missing pulses. Given a sequence of pulses, with the TOA's thereof, each event TOA is transformed into a circular observation through a folding operation (i.e., the TOA sequence can be
5 regarded as being wrapped around a circle of a circumference equal to the folding period. The parameters of the TOA sequence will be determined according to the statistical distribution of the TOA about the periodic sequence. Thus, if the distribution of the TOA's of the sequence is a Gaussian distribution, then, the folding operation yields a wrapped normal
10 phase distribution with a mean μ_ϕ and a variance σ_ϕ . Thus, by estimating μ_ϕ and σ_ϕ one can obtain estimates of the TOA phase and jitter variance.

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SUMMARY OF THE PRESENT DISCLOSED TECHNIQUE

It is an object of the disclosed technique to provide a novel method and system for determining location properties of an emitter. In accordance with the disclosed technique, there is thus provided a method for determining location properties of an emitter, emitting repetitive pulse trains received by at least two receivers. The method includes the procedures of receiving the repetitive pulse trains, by each the at least two receivers and recording the Time Of Arrival (TOA) of each pulse in the received repetitive pulse trains and determining the Pulse Train Repetition Interval (PTRI) of the emitter. The method further includes the procedure of determining, for each receiver, the TOA-phase of each received pulse train according to the PTRI and the TOA respective of each pulse train and determining, for each receiver, a respective characteristic TOA-phase curve of the respective repetitive pulse trains received thereby, according to the TOA-phase respective of the received repetitive pulse trains. The method also includes the procedure of, determining, for each pair of receivers, the location properties of the emitter according to the characteristic TOA-phase curves respective of pulse trains received by each receiver.

In accordance with another aspect of the disclosed technique, there is thus provided a system for determining location properties of an emitter. The system includes least two receivers, at least one Time Of Arrival (TOA) recorder, a Pulse Train Repetition Interval (PTRI) determinator, at least one characteristic TOA-phase determinator and a location properties determinator. The at least one Time Of Arrival (TOA) recorder is coupled with the at least two receivers. The PTRI determinator is coupled with the at least one TOA recorder. Each of the at least one TOA-phase determinator is coupled with the PTRI determinator. The location properties determinator is coupled with each of the at least one characteristic TOA-phase determinator. Each of the at least two receivers receives plurality of repetitive pulse trains from an emitter. The at least

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one Time Of Arrival (TOA) recorder records the TOAs of each pulse in the plurality of repetitive pulse trains. The PTRI determinator determines the PTRI of the pulse trains transmitted by the emitter, according to the TOAs of the pulse trains received by one of the at least two receivers. The at least one TOA-phase determinator determines the TOA-phases of the pulse trains received by each of the receivers respectively. The at least one characteristic TOA-phase determinator determines a characteristic TOA-phase curve of the pulse trains respective of each of the receivers, according to the respective TOA-phases respective of the pulse trains received by each receiver. For each pair of the at least two receivers, the location properties determinator determines the difference between the characteristic TOA-phase curves, respective of each receiver in the pair of receivers.

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BRIEF DESCRIPTION OF THE DRAWINGS

The disclosed technique will be understood and appreciated more fully from the following detailed description taken in conjunction with the drawings in which:

5 Figure 1 is a schematic illustration of two pulse trains, which are known in the art;

 Figure 2 is a schematic illustration of a system for determining the location properties of an emitter, constructed and operative in accordance with an embodiment of the disclosed technique;

10 Figures 3A and 3B are an exemplary timing diagram of pulse trains emitted by an emitter and received by receivers, in accordance with an embodiment of the disclosed technique;

 Figures 4A and 4B are schematic illustration of timing diagrams of pulse trains received by receivers in accordance with an embodiment of
15 the disclosed technique;

 Figure 5 is a schematic illustration of a method for determining the location properties of an emitter, in accordance with another embodiment of the disclosed technique;

 Figure 6A and 6B are a schematic illustration of timing diagrams
20 of pulse trains received by the receivers when relative motion exists between the emitter and the receiver in accordance with a further embodiment of the disclosed technique;

 Figures 6C, 6D and 6E are schematic illustrations of curves determined in accordance with a further embodiment of the disclosed
25 technique;

 Figures 7A, 7B and 7C are schematic illustrations of curves determined according to the TOA-phases of pulse trains received by the receivers when clock irregularities occur, in accordance with another embodiment of the disclosed technique; and

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Figure 8 is a schematic illustration of a method for determining the location properties of an emitter, operative in accordance with a further embodiment of the disclosed technique.

DETAILED DESCRIPTION OF THE EMBODIMENTS

The disclosed technique overcomes the disadvantages of the prior art by providing a method and a system for determining the location properties of an electromagnetic waves emitter that emits pulse trains, received by a receiver. The emitter may be a transmitter transmitting the pulse trains. The emitter may also be a reflector that reflects the pulse trains (i.e., that are produced by a transmitter). The location properties are related to the timing characteristics of the received pulse trains. These timing characteristics are either a characteristic TOA-phase or the characteristic TOA-phase curve. Furthermore, the timing characteristics may further be determined according to either TOA-phase, or characteristic TOA-phase curve or both. The TOA-phases and the TOA-phase curves of the received pulse trains are determined according to the TOA and the PTRI of the received pulse trains. The timing characteristics are related to location properties of the emitter.

The term 'location properties' herein relates to the actual location of the emitter or a set of possible locations of the emitter relative to a reference coordinate system. The term 'location properties' may further relate herein the motion properties of the emitter relative the receiver. The term 'motion properties' relates to relative motion between the emitter and each one of the receivers. The term 'motion properties' may further relate to a set of possible trajectories of the emitter in a reference coordinate system.

The system according to the disclosed technique includes at least two receivers, each receives a plurality of repetitive pulses or repetitive pulse trains emitter by an emitter. The system records the TOA of the received pulse trains and determines the PTRI. Thereafter, the system determines the TOA-phase of each pulse train received thereby, according to the TOA of each pulse train and the PTRI. The TOA-phase is determined according to the residue of the division of the TOA of the pulse trains by the number of PTRI's counted from the start of reception of the

pulse trains. In other words, the time axis is wrapped according to the PTRI's and the TOA-phases are determined according to the TOA of the pulse trains on the wrapped time axis. The system determines a characteristic TOA-phase of the pulse trains, according to the TOA-phases of the pulse trains (i.e., the characteristic TOA-phase represents the TOA-phases of the received pulse trains) respective of each receiver. The location properties of the emitter are determined according to the characteristic TOA-phase respective of the receivers. It is noted that the each pulse in the received pulse trains may be modulated or un-modulated repetitive pulse trains.

When relative motion exists between the emitter and a receiver or when clock irregularities occur, the TOA-phases of the received pulse trains may deviate from a substantially constant value (i.e., each received pulse train may exhibit a different TOA-phase). Therefore, instead of determining a single characteristic TOA-phase, the system according to the disclosed technique determines a characteristic TOA-phase curve according to the TOA-phases of the received pulse trains. This characteristic TOA-phase curve is related to the either the relative motion between the emitter and the receiver or to the clock irregularities.

Reference is now made to Figure 2, which is a schematic illustration of a system, generally referenced 100, for determining the location properties of an emitter 102, constructed and operative in accordance with an embodiment of the disclosed technique. System 100 includes two receivers 104, 106 coupled with a controller 108. For example, both receiver 104 and receiver 106 are attempting to locate emitter 102. Each of receivers 104 and 106 includes a TOA recorder, TOA-phase determinator, and a characteristic TOA-phase determinator. Receiver 104 includes TOA recorder 110, TOA-phase determinator 112 and a characteristic TOA-phase determinator 114. Receiver 106 includes TOA recorder 116, TOA-phase determinator 118 and a characteristic

TOA-phase determinator 120. Controller 108 includes a PTRI determinator 122 and location properties determinator 124.

PTRI determinator 122 is coupled with one of TOA recorders 110 or 116. PTRI determinator 122 is further coupled with each of
5 TOA-phase determinators 112 and 118. Characteristic TOA-phase determinator 114 is coupled with TOA-phase determinator 112 and with location properties determinator 124. Characteristic TOA-phase determinator 120 is coupled with TOA-phase determinator 118 and with location properties determinator 124.

10 It is noted that each of PTRI determinator 122 and location properties determinator 124, may be embedded in any one of receivers 104 and 106 (i.e., not necessarily in the same receiver). Furthermore, of TOA-phase determinators 112 and 118 and characteristic TOA-phase determinators 114 and 120 may be embedded in controller 108.
15 Moreover, instead of TOA-phase determinators 112 and 118 and characteristic TOA-phase determinators 114 and 120, controller 108 may include a single TOA-phase determinator (not shown) and a single characteristic TOA-phase determinator (not shown) that determine the TOA-phase and the characteristic TOA-phase for both receivers 104 and
20 106. When system 100 includes a single TOA-phase determinator and a single characteristic TOA-phase determinator, then PTRI determinator 122 is coupled with one of TOA recorders 110 or 116. PTRI determinator 122 is further coupled with the TOA-phase determinator. The Characteristic TOA-phase is coupled with the TOA-phase determinator and with location
25 properties determinator 124. It is further noted that system 100 may include single TOA recorder, embedded in controller 108, coupled with the TOA-phase determinator. Controller 108 simultaneously or alternately processes the received pulse trains (e.g., according to tags associated with each pulse representing the receiver that received that pulse). It is
30 also noted that receiver 104 and receiver 106 share a common time axis.

FIG. 3B

Thus, a time measurement of an event in one receiver is substantially the same as the time measurements of the same event in the other receiver.

Emitter 102 emits a plurality of pulse trains 126. Each of receivers 104 and 106 receives a plurality of pulse trains emitted by emitter 102. Receiver 104 receives plurality of pulse trains 126' and receiver 106 receives plurality of pulse trains 126". Each of receivers 104 and 106 records the TOA of each received pulse thereby. TOA recorder 110 records the TOA of the pulse trains received by receiver 104 and TOA recorder 116 records the TOA of the pulse trains received by receiver 106. It is noted that the pulse trains received by receiver 104 are not necessarily the same pulse trains received by receiver 106. In other words, plurality of pulse trains 126' are not necessarily the same as plurality of pulse trains 126".

PTRI determinator 122 determines the PTRI of the pulse trains emitted by emitter 102 according to the TOAs of the received pulse trains (i.e., the pulse trains received by either receiver 104 or receiver 106). Each of receivers 104 and 106 receives the determined PTRI from PTRI determinator 122. Determining the PTRI is further explained below. Each of receivers 104 and 106 determines the TOA-phase of each pulse train received thereby. TOA-phase determinator 112 determines the TOA-phases of the pulse trains received by receiver 104 and TOA-phase determinator 118 determines the TOA-phases of the pulse trains received by receiver 106. As mentioned above, the TOA-phase is determined according to the residue of the division of the TOA of the pulse by the number of PTRI's counted from the start of reception of the pulse trains. Determining the TOA-phase is further explained herein below in conjunction with Figures 3A and 3B.

Reference is now made to Figures 3A and 3B and referring back to Figure 2. Figure 3A is an exemplary timing diagram of pulse trains emitted by emitter 102 and received by receiver 104 (Figure 2) in accordance with an embodiment of the disclosed technique. Figure 3B is

FIG. 2

an exemplary timing diagram of pulse trains emitted by emitter 102 and received by receiver 106 (Figure 2) in accordance with an embodiment of the disclosed technique. In Figures 3A and 3B, the emitted pulse trains include only one pulse. Receiver 104 received pulses 150, 152, 154 and 156 and receiver 106 received pulses 180, 182, 184 and 186. Receiver 104 records the TOA's, T_{11} , T_{12} , T_{13} and T_{14} , of pulses 150, 152, 154 and 156 respectively. Receiver 106 records the TOA's T_{21} , T_{22} , T_{23} and T_{24} of pulses 180, 182, 184 and 186 respectively. It is noted that, in Figures 3A and 3B, TOA's T_{11} , T_{12} , T_{13} , T_{14} , T_{21} , T_{22} , T_{23} and T_{24} are recorded at the center of the respective pulse thereof. However, TOA's T_{11} , T_{12} , T_{13} , T_{14} , T_{21} , T_{22} , T_{23} and T_{24} may be recorded at the rising or falling edge of the respective pulse, or at any distinct feature of the pulse shape (e.g., zero crossing if such exist). Time-periods 158, 160, 162 and 164 in Figure 3A and time periods 188, 190, 192 and 194 in Figure 3B exhibit the duration of the PTRI. Since receivers 104 and 106 receive a common clock signal, periods 158, 160, 162 and 164 in Figure 3A and period 188, 190, 192 and 194 in Figure 3B exhibit substantially the same time duration (i.e., the duration of the PTRI). Furthermore, the time instants S_1 , S_2 , S_3 and S_4 , of the start of each of PTRI's 158, 160, 162, 164, 158, 160, 162 and 164, are substantially the same.

TOA's T_{11} , T_{12} , T_{13} and T_{14} and time instants S_1 , S_2 , S_3 and S_4 determine the TOA-phases of received pulses 150, 152, 154 and 156 respectively. TOA's T_{21} , T_{22} , T_{23} and T_{24} and time instants S_1 , S_2 , S_3 and S_4 determine the TOA-phases of pulses 180, 182, 184 and 186 respectively. Accordingly, intervals 166, 168, 170 and 172 (Figure 3A) determine the TOA-phases of received pulses 150, 152, 154 and 156 respectively and intervals 196, 198, 200 and 202 (Figure 3B) determine the TOA-phases of received pulses 180, 182, 184 and 186 respectively. In other words, the difference between TOA's T_{11} and S_1 determine TOA-phase 166 of pulse 150, the difference between TOA's T_{12} and S_2 determine TOA-phase 168 of pulse 152 etc. The difference between

TOA's T_{21} and S_1 determines TOA-phase 196 of pulse 180, the difference between TOA's T_{22} , and S_2 determine TOA-phase 198 of pulse 182, etc. In general, the TOA-phase is determined as follows:

$$\text{TOA_PHASE} = \text{rem} \left[\frac{\text{TOA}}{N * \text{PTRI}} \right] \quad (1)$$

5 wherein N is the number of PTRI's counted from the start of reception of the pulse trains from the start and *rem* is the remainder operator. It is noted that the values of a TOA-phase of a pulse train may be in time units or normalized units (i.e., relative to the duration of the PTRI). In other words, a TOA-phase of a pulse is a mapping of the TOA of that pulse to a
10 value relative to the start of the PTRI during which the pulsed was emitted (i.e., a value which is modulo PTRI).

Still referring to Figure 2, once receivers 104 and 106 determined the TOA-phases respective of the pulse trains received thereby, each of receivers 104 and 106 determines the characteristic
15 TOA-phase respective thereof. Characteristic TOA-phase determinator 114 determines the characteristic TOA-phase of the pulse trains received by receiver 104 and characteristic TOA-phase determinator 120 determines the characteristic TOA-phase of the pulse trains received by receiver 106. The characteristic TOA-phase of a receiver is determined
20 according to the TOA-phases of the pulse trains received thereby as further explained in conjunction with Figures 4A and 4B.

Reference is now made to Figures 4A and 4B and with further reference to Figure 2. Figure 4A is a schematic illustration of a timing diagram of pulse trains received by receiver 104 in accordance with an
25 embodiment of the disclosed technique. Figure 4B is a schematic illustration of a timing diagram of pulse trains received by receiver 106 in accordance with an embodiment of the disclosed technique. In Figures 4A and 4B, the emitted pulse trains include only one pulse. The timing diagrams of Figures 4A and 4B are in the form of a "falling raster", in which
30 successive PTRI's, with the received pulse trains during these PTRI's, are

vertically ordered (i.e., the time axis is wrapped). Time duration 228 (Figure 4A) and time duration 248 (Figure 4B) exhibit the duration of the PTRI. Receiver 104 receives pulses 220, 222, 224 and 226. TOA-phase determinator 112 determines TOA-phases 232, 234, 236 and 238 as the
5 respective TOA-phase of pulses 220, 222, 224 and 226 respectively. It is noted that TOA-phases 232, 234, 236 and 238 are not necessarily the same (e.g. due to jitter in the PTRI of the emitted pulse. This jitter is caused due to clock drift of either the receiver clock or transmitter clock (i.e., either the transmitter that produced the pulse trains reflected by a
10 reflector or the transmitter that transmitted the pulse trains directly to the receivers), or both, or due to motion of the emitter or of the receivers. Characteristic TOA-phase determinator 114 determines the time interval 230 as the respective characteristic TOA-phase of pulses 220, 222, 224 and 226 according to TOA-phases 232, 234, 236 and 238 and determines
15 a point P_1 on the wrapped time axis as representing this characteristic TOA-phase.

Similarly, receiver 106 receives pulses 240, 242, 244 and 246. TOA-phase determinator 118 determines TOA-phases 252, 254, 256 and 258 as the respective TOA-phase of pulses 240, 242, 244 and 226
20 respectively. Characteristic TOA-phase determinator 120 determines time interval 250 as the respective the characteristic TOA-phase of pulses 240, 242, 244 and 246 according to TOA-phases 252, 254, 256 and 258 and determines a point P_2 on the wrapped time axis as representing this characteristic TOA-phase.

25 Receivers 104 and 106 determine, for example, the TOA-phase with the largest number of occurrences (e.g., determined according to a histogram of TOA-phases) as the characteristic TOA-phase respective thereof. Alternatively, receivers 104 and 106, determine the characteristic TOA-phase respective thereof by averaging the TOA-phases of the pulse
30 trains received thereby. It is noted that the characteristic TOA-phase may be determined even if one or more of the received pulse trains are

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missing. It is further noted that the difference between two characteristic TOA-phases, respective of two receivers, determines the TDOA between the received pulse trains. It is also noted that the pulse trains received by the receivers, need not be common pulse trains (i.e., the pulse trains
5 received by one receiver are not necessarily the pulse trains received by another receiver). In other words, at least one pulse train received by one receiver is absent from the pulse trains received by the other receiver. Given that the transmission time of the pulse trains is known or determined, location properties determinator 124 determines the TOF of
10 the received pulse trains, and consequently the location of emitter 102. When determining the location of the emitter according to the TDOA method, the TDOA is determined according to the difference between the characteristic TOA-phases (i.e., P_2 in Figure 4B and P_1 in Figure 4A) of receiver 104 and 106.

15 Reference is now made to Figure 5, which is a schematic illustration of a method for determining location properties of an emitter, in accordance with another embodiment of the disclosed technique. In procedure 300, a plurality of repetitive pulse trains, emitted by an emitter, are received by at least two receivers and the TOA of each received pulse
20 is recorded. The emitted pulse trains include at least one pulse. As mentioned above, the receivers share a common time axis. With reference to Figure 2, receiver 104 and 106 receive a plurality of repetitive pulse trains emitted by emitter 102 and record the TOA of each received pulse. TOA recorder 110 records the TOAs received at receiver 104 and
25 TOA recorder 116 records the TOAs received at receiver 106. With reference to Figures 3A, receiver 104 receives pulses 150, 152, 154 and 156 and records TOA's T_{11} , T_{12} , T_{13} and T_{14} respective thereof. With reference to Figures 3B, receiver 106 receives pulses 180, 182, 184 and 186 and records TOA's T_{21} , T_{22} , T_{23} and T_{24} respective thereof.

30 In procedure 302, the PTRI of the emitter is determined. The emitter exhibits a stable PTRI or a modulated PTRI. The PTRI is

determined according to the received pulse trains. Alternatively, the PTRI is heuristically determined (e.g., according to external information such as emitter characteristics). Determining the PTRI is further explained below. With reference to Figure 2, PTRI determinator 122 determines the PTRI of emitter 102. Receivers 104 and 106 receive the determined PTRI from controller 108. With reference to Figures 3A and 3B Time periods 158, 160, 162 and 164 in Figure 3A and time periods 188, 190, 192 and 194 in Figure 3B, exhibit the same time duration substantially equal to the PTRI.

In procedure 304, for each receiver, the TOA-phase respective of each received pulse train is determined according to the PTRI and the TOA respective of each pulse trains. The TOA-phase is determined according to the residue of the division of the TOA of the pulse by the number of PTRI's counted from the start of reception of the pulse trains. As mentioned above, this can be regarded as wrapping the time according to the PTRI's and the TOA-phases are determined according to the TOA of the pulse trains on the wrapped time axis (i.e., the TOA-phase is a value modulo PTRI). With reference to Figure 2, TOA-phase determinator 112 determines the TOA-phases of the pulse trains received by receiver 104 and TOA-phase determinator 118 determines the TOA-phases of the pulse trains received by receivers 106. With reference to Figures 3A and 3B intervals 166, 168, 170 and 172 (Figure 3A) determine the TOA-phases of received pulses 150, 152, 154 and 156 respectively and intervals 196, 198, 200 and 202 (Figure 3B) determine the TOA-phases of received pulses 180, 182, 184 and 186 respectively.

In procedure 306, for each receiver, a respective characteristic TOA-phase of the pulse trains received thereby, is determined according to the TOA-phases respective of the received pulse trains. The characteristic TOA-phase may be determined according the largest number of pulse trains with the same TOA-phase. Alternatively, the characteristic TOA-phase may be determined according to the average of the TOA-phases of the pulse trains. The average may be a simple

average or a weighted average. When employing a weighted average, the weights of the TOA-phases may be determined, for example, according to the amplitude of the received pulse, the width of the received pulse (i.e., the wider the received pulse the less reliable is the TOA of the pulse), the integral of the received pulse or the product of the pulse amplitude and the pulse width. According to other alternatives, the characteristic TOA-phase may be determined according to the median of the TOA-phases or the Root Mean Square (RMS) of the TOA-phases. With reference to Figure 2, characteristic TOA-phase determinator 114 determines the characteristic TOA-phase respective of receiver 104 according to the characteristic TOA-phase respective of the pulse trains received by receiver 104 and characteristic TOA-phase determinator 120 determines the characteristic TOA-phase respective of receiver 106 according to the characteristic TOA-phase respective of the pulse trains received by receiver 106. With reference to Figure 4A, interval 230 is the characteristic TOA-phase of receiver 104. With reference to Figure 4B, interval 250 is the characteristic TOA-phase of receiver 106.

In procedure 308, for each pair of receivers, the location properties of the emitter are determined according to the characteristic TOA-phases, respective of pulse trains received by each receiver. As mentioned above, the location properties of the emitter may be the actual location of the emitter in a reference coordinate system determined according to the TOF, TDOA or AOA methods. The location properties may further be the TOAs the TDOAs or the AOAs of the received pulse trains. For example, for each pair of receivers, the TDOA of the pulse trains at the receivers is determined according to the difference between the determined characteristic TOA-phases respective of the receivers. With reference to Figure 2, location properties determinator 124 determines the location properties of emitter 102 according to the characteristic TOA-phases respective of receivers 104 and 106.

As mentioned above, the TOA-phases, of the received pulse

FIG.

trains, may deviate from a substantially constant value (i.e., each received pulse train exhibits a different TOA-phase) when relative motion exists between the emitter and a receiver or when clock irregularities occur. The term 'clock irregularities' hereinafter to the situation where the PTRI of the pulse trains deviates from substantially a constant value (e.g., due to drift or jitter in the clock of the transmitter). Accordingly, instead of determining a single characteristic TOA-phase, the receiver according to the disclosed technique determines a characteristic TOA-phase curve respective of the receiver, according to the TOA-phases of the received pulse trains. Thus, the above description for determining the characteristic TOA-phase, in conjunction with Figures 2, 3A, 3B, 4A, 4B, is a special case of determining the characteristic TOA-phase curve as further explained below. The term 'curvature of degree zero' as used herein relates to a straight line with a slope relative to the time axis. The term 'curvature of degree greater than zero' as used herein relates to a curve. Thus, the characteristic TOA-phase curves and the difference there between may exhibit curvature of degree zero or curvature of degree greater than zero.

Reference is now made to Figures 6A and 6B, which are schematic illustrations of pulse trains received by the receivers when relative motion exists between the emitter and the receiver and referring back to Figure 2. Figure 6A is a schematic illustration of a timing diagram of pulse trains received by receiver 104, in accordance with a further embodiment of the disclosed technique. Figure 6B is a schematic illustration of a timing diagram of pulse trains received by receiver 106, in accordance with a further embodiment of the disclosed technique. In Figures 6A and 6B, each pulse train includes only one pulse. The timing diagrams of Figure 6A and 6B are in the form of a "falling raster", in which successive PTRI's, with the received pulse trains during these PTRI's, are vertically ordered (i.e. the time axis is wrapped). Time duration 408 (Figure 6A) and time duration 428 (Figure 6B) exhibit the duration of the PTRI. Receiver 104 receives pulse 400, 402, 404 and 406. Receiver 104

determines TOA-phases 410, 412, 414 and 416 as the respective TOA-phase of pulses 400, 402, 404 and 406 respectively thereby defining points P_{11} , P_{12} , P_{13} and P_{14} on the wrapped time axis. TOA-phases 410, 412, 414 and 416 are not necessarily the same due to the relative motion between emitter 102 and receiver 104. Similarly, receiver 106 receives pulses 420, 422, 424 and 426. Receiver 106 determines TOA-phases 430, 432, 434 and 436 as the respective TOA-phase of pulses 420, 422, 424 and 426 respectively thereby defining points P_{21} , P_{22} , P_{23} and P_{24} on the wrapped time axis. TOA-phases 430, 432, 434 and 436 are not necessarily the same due to relative motion between receiver 106 and emitter 102.

Reference is now made to Figures 6C, 6D and 6E, which are schematic illustrations of curves determined according to points P_{11} , P_{12} , P_{13} , P_{14} , P_{21} , P_{22} , P_{23} and P_{24} in accordance with a further embodiment of the disclosed technique and referring back to Figure 2. In Figure 6C, characteristic TOA-phase determinator 114 determines curve 450 as the characteristic TOA-phase curve respective of receiver 104, according to points P_{11} , P_{12} , P_{13} and P_{14} . Characteristic TOA-phase Curve 450 exhibits curvature equal to zero (i.e., a straight line with a slope relative to the time axis). In Figure 6D, Characteristic TOA-phase determinator 120 determines curve 452 as the characteristic TOA-phase curve respective of receiver 106 according to points P_{21} , P_{22} , P_{23} and P_{24} . Characteristic TOA-phase curve 452, exhibits curvature greater than zero (e.g., a polynomial of a desired degree greater than one, fitted to points P_{21} , P_{22} , P_{23} and P_{24}).

Reference is now made to Figure 6E, which is a schematic illustration of a difference curve, generally referenced 454, determined according to the difference between curve 450 (Figure 6C) and curve 452 (Figure 7D) in accordance with a further embodiment of the disclosed technique. Difference curve 454 relates to the location properties of emitter 102 (Figure 2). Specifically, difference curve 454 relates to the

relative motion between emitter 102 and receivers 104 and 106 (Figure 2), or the relative motion between emitter 262. Difference curve 454 exhibits curvature of degree greater than zero. Difference curve 454 may represent the TDOAs between the pulse trains received by receivers 104 and 106 (Figure 2). Thus, the difference curves define a plurality of hyperbolas.

The above description, in conjunction with Figure 6A, 6B, 6C, 6D and 6E, the received pulse trains include only one pulse. When the received pulse trains include more than one pulse, then, the characteristic TOA-phase curve, respective of each receiver, is determined either according to the TOA-phase of the same one pulse in each of the pulse trains. Alternatively, the characteristic TOA-phase curve, respective of the receiver, may be determined either according to the TOA-phase of all the pulses in the received pulse trains. It is noted that the characteristic TOA-phase curve may be determined even if one or more of the received pulse trains are missing.

As mentioned above, the characteristic TOA-phase is a special case of the characteristic TOA-phase curve. For example, when the characteristic TOA-phase curve is represented by a polynomial or a plurality of polynomials (i.e., these plurality of polynomials may be piecewise polynomials), the characteristic TOA-phase is a polynomial of degree zero (i.e., a constant value). It is further noted that when receivers 104 and 106 determine the characteristic TOA-phase curves respective thereof, receivers 104 and 106 need only to transmit the parameters of the curves to controller 108.

Reference is now made to Figures 7A, 7B and 7C, which are schematic illustrations of curves determined according to the TOA-phases of pulse trains received by receivers when clock irregularities occur, in accordance with another embodiment of the disclosed technique and referring back to Figure 2. In Figures 7A, 7B and 7C, the emitter and the receivers do not exhibit relative motion there between. In Figure 7A, curve

460 is the characteristic TOA-phase curve determined according to the TOA-phases of received pulse trains received by a first receiver. In Figure 7B, curve 462 is the characteristic TOA-phase curve determined according to the TOA-phases of the pulse trains received by a second receiver. It is noted that curve 460 and curve 462 exhibit substantially the same shape since the emitter and the receivers exhibit no relative motion there between. Furthermore, characteristic TOA-phase curves 460 and 462 exhibit a relative time shift there between (i.e., a modulo PTRI time shift). In Figures 7A and 7B, characteristic TOA-phase curves 460 and 462 exhibit curvature of degree greater than zero

In Figure 7C, line 464 is the difference between curve 460 and curve 462 curve determined according to the difference between characteristic TAO-phase curve 460 and characteristic TAO-phase curve 462. Line 464 is perpendicular to the time axis and relates to the location properties of emitter 102. Characteristic TOA-phase curves 460 and 462 exhibit a substantially similar shape. However, characteristic TOA-phase curves 460 and 462 exhibit a relative time shift there between (i.e., a modulo PTRI time shift). Thus, the difference between these curves results in a constant time value (i.e., intersection of line 464 with the time axis) at point D_1 . This time value is the TDOA between the pulse trains received by each receiver. It is noted that the situation may arise where the emitter and the receiver exhibit relative motion there between and clock irregularities occur. This situation is similar to the situation where the emitter and the receivers exhibit relative motion there between.

Reference is now made to Figure 8, which is a schematic illustration of a method for determining location properties an emitter, in accordance with a further embodiment of the disclosed technique. In procedure 500, a plurality of repetitive pulse trains, emitted by an emitter, are received by at least two receivers and the TOA of each received pulse is recorded. The emitted pulse trains include at least one pulse. With reference to Figure 2, receiver 104 and 106 receive a plurality of repetitive

pulse trains emitted by emitter 102 and record the TOA of each received pulse. TOA recorder 110 records the TOAs received at receiver 104 and TOA recorder 116 records the TOAs received at receiver 106. With reference to Figures 6A, receiver 104 receives pulses 400, 402, 404 and 406 and records TOA's respective thereof. With reference to Figures 6B, receiver 106 receives pulses 420, 422, 424 and 426 and records TOA's respective thereof.

In procedure 502, the PTRI of the emitter is determined. The emitter exhibits a stable PTRI or a modulated PTRI. The PTRI is determined according to the received pulse trains. Alternatively, the PTRI is heuristically determined. Determining the PTRI is further explained below. With reference to Figure 2, PTRI determinator 122 determines the PTRI of emitter 102. Receivers 104 and 106 receive the determined PTRI from controller 108. With reference to Figures 6A and 6B time-period 408 in Figure 6A and time-period 428 in Figure 7B, exhibit the same time duration substantially equal to the PTRI.

In procedure 504, for each receiver, the respective TOA-phase of each received pulse train is determined according to the PTRI and the TOA respective of each pulse trains. The TOA-phase is determined according to the residue of the division of the TOA of the pulse by the number of PTRI's counted from the start of reception of the pulse trains. As mentioned above, this can be regarded as wrapping the time according to the PTRI's and the TOA-phases are determined according to the TOA of the pulse trains on the wrapped time axis (i.e., the TOA-phase is a value modulo PTRI). With reference to Figure 2, TOA-phase determinator 112 determines the TOA-phases respective of the pulse trains received by receiver 104 and TOA-phase determinator 118 determines the TOA-phases respective of the pulse trains received by receiver 106. With reference to Figures 6A and 6B intervals 410, 412, 416 and 172 (Figure 6A) determine the TOA-phases of received pulses 400, 402, 404 and 406

respectively and intervals 430, 432, 434 and 436 (Figure 6B) determine the TOA-phases of received pulses 420, 422, 424 and 426, respectively.

In procedure 506, for each receiver, a respective characteristic TOA-phase curve of the pulse trains is determined according to the TOA-phases respective of the received pulse trains. The characteristic TOA-phase curve is determined by fitting a curve to TOA-phases (e.g., polynomial, exponential piecewise linear and the like). With reference to Figure 2, characteristic TOA-phase determinator 114 determines the characteristic TOA-phase curve respective of receiver 104 according to the characteristic TOA-phase respective of the pulse trains received by receiver 104 and characteristic TOA-phase determinator 120 determines the characteristic TOA-phase curve respective of receiver 106 according to the characteristic TOA-phase respective of the pulse trains received by receiver 106. With reference to Figure 6C, curve 450 is determined according points P_{11} , P_{12} , P_{13} and P_{14} . Curve 450 is a straight line. With reference to Figure 6D, curve 452 is determined according points P_{21} , P_{22} , P_{23} and P_{24} .

In procedure 508, for each pair of receivers, the location properties of the emitter are determined according to the characteristic TOA-phase curves respective of pulse trains received by each receiver. For example, when the difference between the characteristic TOA-phase curves of at least one pair of receivers, is a curve with a degree equal to or greater than zero, then, the relative motion between the emitter and the receivers can be determined therefrom. As a further example, when the difference between the characteristic TOA-curves of all the pairs of receivers is a constant value, then, the location of the emitter, relative to the receivers can be determined therefrom. With reference to Figure 2, location properties determinator 124 determines the difference between the characteristic TOA-phase curves of receivers 104 and 106. Figure 6E, curve 454 is the difference curve determined according to the difference between curve 450 and curve 452. Curve 454 exhibits a curvature greater

than zero. Figure 7C, line 464 is the difference between characteristic TOA-phase curves 460 and 462. Line 464 is perpendicular to the time axis. Thus, the difference between these curves results in a constant time value (i.e., intersection of line 464 with the time axis) at point D₁. Curves
5 454 and 464 are related to the location properties of the emitter.

It is noted that the system described hereinabove in conjunction with Figures 2, 3A, 3B, 4A, 4B, 5, 6A-6E, 7A-7C and 8 is applicable to any scale. In other words, the relative distance between the receivers and the emitter may be in the order of tens of kilometers or tens of meters.

10 As mentioned above, the system according to the disclosed technique determines the PTRI according to the received pulse trains. One method for determining the PTRI is the difference histogram method. According to the difference histogram method the difference between the TOA of adjacent pulses are arranged in a histogram of TOA differences. If
15 a peak above a threshold is found in the histogram, then, that difference is determined as the PTRI. However, if a peak is not found, then, a new histogram with the difference between the TOA of a pulse and the TOA of the next pulse but one is determined and added to the first histogram. This cumulative histogram is examined for peaks. Once a peak is found,
20 the histogram bin of the peak is determined as the PTRI. When a desired degree of accuracy is required, then, the above procedure may be repeated with only the TOA's of the pulses in the bin, which exhibits the highest peak. Accordingly, these TOA differences are arranged in a new histogram wherein each bin is associated with a TOA difference of
25 increased accuracy and this new histogram is examined for peaks. Thus, a PTRI with increased accuracy is determined.

Alternatively, the system according to the disclosed technique determines the PTRI of the received pulse trains by guessing initial values (i.e., more than one) of the PTRI within an initial range of possible PTRI's.
30 The system determines the TOA-phases of the received pulse trains for each initial guess. For each PTRI guess, the system determines a

histogram of the TOA-phases, determines the maximum value in each histogram and selects the PTRI whereat the maximum of maximums (i.e., of the histogram values) occurred. Thereafter, the system iteratively repeats the process with a new set of guesses of PTRI's, within a range of
5 possible PTRI's, which is smaller the initial range and includes the PTRI whereat the maximum of maximums occurred.

It will be appreciated by persons skilled in the art that the disclosed technique is not limited to what has been particularly shown and described hereinabove. Rather the scope of the disclosed technique is
10 defined only by the claims, which follow.

CLAIMS

1. Method for determining location properties of an emitter, emitting repetitive pulse trains received by at least two receivers, the method comprising the procedures of:

5 receiving said repetitive pulse trains, by each of said at least two receivers and recording the Time Of Arrival (TOA) of each pulse in said received repetitive pulse trains;

 determining the Pulse Train Repetition Interval (PTRI) of said emitter;

10 for each receiver, determining the TOA-phase of each received pulse train according to said PTRI and said TOA respective of each pulse train;

 for each receiver, determining a respective characteristic TOA-phase curve of said repetitive pulse trains received thereby,
15 according to the TOA-phase respective of said received repetitive pulse trains; and

 for each pair of receivers, determining the location properties of said emitter according to the characteristic TOA-phase curves
20 respective of pulse trains received by each receiver.

2. The method according to claim 1, wherein said procedure of determining the location properties of said emitter includes the determining the difference between said characteristic TOA-phase curves.

- 25
3. The method according to claim 2, wherein said procedure of determining location properties includes determining the motion properties of said emitter.

4. The method according to claim 3, wherein said procedure of determining motion properties includes determining the relative motion between said emitter and said at least two receivers.
- 5 5. The method according to claim 3, wherein said procedure of determining motion properties includes determining the trajectory of said emitter in a reference coordinate system.
6. The method according to claim 2, said procedure of determining
10 location properties includes determining the location of said emitter in said reference coordinate system.
7. The method according to claim 2, wherein said location properties are supplemented with additional location information to determine the
15 location of said emitter.
8. The method according to claim 7, wherein said additional location information is a line representing the direction of said emitter relative to a known location in said reference coordinated system.
20
9. The method according to claim 7, wherein said additional location information is a circle representing the distance of said emitter relative to a known location in said reference coordinated system.
- 25 10. The method according to claim 1, wherein at least one of the repetitive pulse trains, used to determined the characteristic TOA-phase of one of said at least two receivers, is absent from the repetitive pulse trains used to determine the characteristic TOA-phase in the other said at least one receiver.

11. The method according to claim 1, wherein said PTRI is heuristically determined.
12. The method according to claim 1, wherein said PTRI is determined
5 according to the difference histogram method.
13. The method according to claim 1, wherein determining said PTRI includes the sub-procedures of:
- guessing at least one initial value of said PTRI within an initial
10 range of possible PTRI's;
- determining the TOA-phases of the received pulse trains according to each one of said at least one initial value;
- for each guessed PTRI value, determining a histogram of the determined TOA-phases;
- 15 determining the maximum value in each histogram and selecting the PTRI whereat the maximum of maximums of said histogram values occurred; and
- repeating from said sub-procedure of guessing initial values, with a new set guessed PTRI values, within a range of possible
20 PTRI's, which is smaller said initial range and including the PTRI whereat the maximum of maximums occurred.
14. System for determining location properties of an emitter, the system comprising:
- 25 at least two receivers, each receiving a plurality of repetitive pulse trains from said emitter;
- at least one Time Of Arrival (TOA) recorder, coupled with said at least two receivers, said at least one TOA recorder recording the TOAs of each pulse in said plurality of repetitive pulse trains;
- 30 a Pulse Train Repetition Interval (PTRI) determinator, coupled with said at least one TOA recorder, determining the PTRI of the

pulse trains emitted by said emitter, according to said TOAs of said pulse trains received by one of said at least two receivers;

at least one TOA-phase determinator, each coupled with said PTRI determinator, determining the TOA-phases of the pulse trains received by each of said receiver respectively;

at least one characteristic TOA-phase determinator, each coupled with a respective one of said at least one TOA-phase determinator, determining a characteristic TOA-phase curve of the pulse trains respective of each of said receivers, according to the TOA-phases respective of said pulse trains received by each receiver; and

a location properties determinator, coupled with each of said at least one characteristic TOA-phase determinator, for each pair of said at least two receivers, said location properties determinator determining the difference between the characteristic TOA-phase curves, respective of each receiver in said pair of receivers.

15. The system according to claim 14, wherein said TDOA and location determinator determines said location properties of said emitter, in a reference coordinate system, relative to said at least two receivers according said difference between said characteristic TOA-phase curves.

16. The system according to claim 15, wherein said location properties include motion properties.

17. The system according to claim 16, wherein said TDOA and location determinator determines the relative motion between said emitter and said at least two receivers according to said motion properties.

18. The system according to claim 16, wherein said TDOA and location determinator determines the trajectory of said emitter in a reference coordinate system according to said motion properties.
- 5 19. The system according to claim 15, wherein said TDOA and location determinator determines the location of said emitter, in said reference coordinate system, according to said location properties.
- 10 20. The system according to claim 19, wherein said TDOA and location determinator determines said location of said emitter according to an intersection one hyperbolas determined according to the difference between the characteristic TOA-phase curve respective of one pair or receivers, and another hyperbola determined according to the difference between the characteristic TOA-phase curve respective of
15 another pair or receivers.
21. The method according to claim 15, wherein said location properties are supplemented with additional location information to determine the location of said emitter.
- 20 22. The method according to claim 21, wherein said additional location information is a line representing the direction of said emitter relative to a known location in said reference coordinated system.
- 25 23. The method according to claim 21, wherein said additional location information is a circle representing the distance of said emitter relative to a known location in said reference coordinated system.
- 30 24. The system according to claim 14, wherein at least one of the repetitive pulse trains, used to determined the characteristic TOA-phase of one of said at least two receivers, is absent from the

repetitive pulse trains used to determine the characteristic TOA-phase in the other said at least two receivers.

25. The system according to claim 14, wherein said PTRI determinator
5 heuristically determines said PTRI.

26. The system according to claim 14, wherein said PTRI determinator determines said PTRI according to the difference histogram method.

10 27. The system according to claim 14, wherein PTRI determinator determines said PTRI according to the following procedures of:

guessing at least one initial value of said PTRI within an initial range of possible PTRI's;

15 determining the TOA-phases of the received pulse trains according to each one of said at least one initial value;

for each guessed PTRI value, determining a histogram of the determined TOA-phases;

20 determining the maximum value in each histogram and selecting the PTRI whereat the maximum of maximums of said histogram values occurred; and

repeating from said sub-procedure of guessing initial values, with a new set guessed PTRI values, within a range of possible PTRI's, which is smaller said initial range and including the PTRI whereat the maximum of maximums occurred.

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28. The system according to claim 14, wherein the number of said at least one TOA-recorder, equals the number of said at least two receivers, and

30 wherein each TOA-recorder is associated with a respective one of said at least two receivers and coupled therewith.

29. The system according to claim 14, wherein the number of said at least one TOA-phase determinator, equals the number of said at least two receivers, each TOA-phase determinator is associated with a respective one of said at least two receivers, each said TOA-phase determinator is coupled with a respective one TOA-recorder, each TOA-phase determinator determines the TOA-phases of the pulse trains received by the respective receiver thereof.
30. The system according to claim 14, wherein the number of said at least one characteristic TOA-phase determinator, equals the number of said at least two receivers, each characteristic TOA-phase determinator is associated with a respective one of said at least two receivers, each said characteristic TOA-phase determinator is coupled with a respective one TOA-phase determinator, each of characteristic TOA-phase determinator determines the characteristic TOA-phase curve of the pulse trains received by the respective receiver thereof.