

METHOD AND APPARATUS FOR LOCATING THE SOURCE OF AN UNKNOWN SIGNAL

This invention relates to a method and apparatus for locating the source of an unknown signal received by a plurality of signal relays.

In IEEE Trans. on Aerospace and Electronic Systems, Vol. AES-18, No. 2, March 1982, P C Chestnut describes the basic technique of locating the source of an unknown signal such as a ground-based communications antenna; it involves determining the time difference of arrival (TDOA) and/or frequency difference of arrival (FDOA) of two signals from the source relayed to receivers by respective intercept platforms in the form of relay satellites in geostationary or geosynchronous orbits. The signals are relayed by the satellites along two independent signal paths to a receiving station, ie ground – satellite – ground paths. One satellite lies in the main beam or lobe of the source antenna radiation pattern and the other in a sidelobe. Each satellite accepts a signal (uplink) from the source, frequency shifts it using a turnaround oscillator and returns its frequency-shifted equivalent (downlink) to a ground receiver. The two signal path lengths are normally unequal, and this gives two signal arrival times at the receiver differing by the TDOA value. FDOA is due to relay satellite motion relative to the Earth and to one another, which Doppler shifts both downlink signal frequencies. The positions of the two satellites and the receiving station are known, and the locus of points of constant TDOA or FDOA is in each case a surface which intercepts the Earth's surface to define a curve referred to as a line of position (LOP). Two measurements of TDOA or FDOA at different times, or one of each at one or more times, provides two LOPs which intersect at the position of the source to be located.

TDOA is also referred to as differential time offset (DTO) and FDOA as differential frequency offset (DFO) or differential Doppler shift.

The technique of determining TDOA and FDOA from two received signals is described in IEEE Trans. on Acoustics Speech and Signal Processing, Vol. ASSP-29, No. 3, June 1981 by S Stein in a paper entitled "Algorithms for Correlation Function Processing". It is also

described in US Patent No 5,008,679 relating to a transmitter location system incorporating two relay satellites and using both TDOA and FDOA measurements. The technique involves deriving the degree of correlation between the signals by multiplying them together and integrating their product. Trial relative time shifts and frequency offsets are introduced in sequence between the signals and their correlation is determined for each. The time shift and frequency offset which maximise the correlation are taken to be the required TDOA and FDOA, subject to correction for signal propagation delays in satellite transponders and frequency shifts in satellites and in processing.

The degree of correlation is determined from what is referred to by Stein as the cross ambiguity function or CAF $A(\tau, \nu)$ defined by:

$$A(\tau, \nu) = \int_0^{\tau} z_1^*(t) z_2(t + \tau) e^{-2\pi i \nu t} dt \quad (1)$$

$A(\tau, \nu)$ is the integral of the product of two signals $z_1(t)$ and $z_2(t)$ [complex or analytic versions of real signals $s_1(t)$ and $s_2(t)$] after a trial time shift τ and a trial frequency shift ν have been introduced between them in processing after reception at the receiving station. The asterisk in $z_1^*(t)$ indicates a complex conjugate. When a maximum value of the modulus of $A(\tau, \nu)$, ie $|A(\tau, \nu)|$, is obtained, this being a correlation peak in the surface $|A(\tau, \nu)|$ as a function of the two variables τ and ν , the values of τ and ν for the peak are the required TDOA and FDOA.

The system of US 5,008,679 requires satellite positions and velocities to be known accurately, and needs highly stable phase in ground station and satellite oscillators. It has bandwidth limitations for satellite orbits inclined to the Earth's equatorial plane, and needs two receivers which are on the same site and have common time and frequency references.

International Patent Application No PCT/GB95/02211 under the Patent Co-operation Treaty, published as WO 97/11383, relates to a transmitter location system employing a reference signal passing via the same satellite relays as the unknown signal and processed in phase coherence with it. The reference signal is used to remove a number of sources of error and limitations to which earlier techniques are subject, giving improved accuracy and capability

7 JANUARY 2004

3

for use under a wider range of conditions. Despite this improvement it has been found surprisingly that from time to time it can be impossible to discern a correlation peak in the CAF surface $|A(\tau, \nu)|$ - all that can be seen is noise.

A related but different technique for counteracting sources of error using a broad band approach is disclosed in US Pat No 5,594,452 to Webber *et al.*

It is an object of this invention to provide an alternative method and apparatus for transmitter location.

The present invention provides a method of locating the source of an unknown signal received by a plurality of signal relays, the method including the steps of:-

- (a) arranging for a plurality of receivers to receive replicas of the unknown signal via respective signal relays; and
- (b) subjecting the replicas to correlation processing;

characterised in that correlation processing in step (b) is performed with data sets adapted in phase and subject to sample adjustments to counteract time dilation arising from relay motion relative to the source and receivers.

The data sets may be subject to data replication or removal.

In a preferred embodiment of the invention, correlation processing in step (b) is also performed with a complex correlation function (CCF) at least partly compensated for change in the replicas' Differential Frequency Offset (DFO) with time due to relay motion relative to the source and receivers.

As indicated above it has been found that the reason for failure to obtain a correlation peak using a prior art ambiguity function is due to relay motion relative to the source and receivers. This is very surprising for geostationary satellite relays in particular, because their motion has hitherto been treated as constant over a measurement interval, which in turn implies that it affects all measurements at a site equally. Satellite motion alone would not have been expected to make a correlation peak obtainable on some occasions but not others. Despite this,

Empfangszeit 13. Aug. 11:15

AMENDED SHEET

7 JANUARY 2004

4

in accordance with the invention it has been discovered that signal correlation is affected by velocity and acceleration components of the relay satellite along the lines joining

it to the source and receiver, which results in the replicas' DFO and Differential Time Offset (DTO) being time dependent. DTO variation can be compensated by adapting data samples and DFO variation can be compensated as indicated above by adapting the correlation function.

Correlation processing in step (b) may include introducing a trial time offset between the replicas and evaluating their correlation and iterating this to obtain a correlation maximum and derive at least one of the replicas' DTO and DFO; it may be carried out with a CCF containing an exponent of a function of time having a first term which is a constant DFO value and a second term which is a product of time and a constant value for rate of change of DFO with time, ie a constant differential frequency rate offset (DFRO) value, and wherein step (b) also includes introducing a trial value corresponding to DFRO prior to evaluating correlation and iterating one type of trial value for each of the other type, repeating for more values of the other type and determining a DFRO value appropriate to compensate at least partly for change in DFO with time.

The CCF may be expressed as $A(\tau_0, b_1, b_2)$ given by:

$$A(\tau_0, b_1, b_2) = \int_0^T z_1^*(t) z_2(t + \tau_0) e^{-2\pi i (b_1 + 2b_2 t) t} dt \quad (2)$$

where z_1 and z_2 are data sets representing two signals being correlated after traversing different paths, the asterisk denoting the complex conjugate of z_1 , T is a time over which data sets are taken, τ_0 is the signals' DTO, and b_1 and b_2 are constants in a linear approximation to the variation of their DFO with time t as follows:-

$$DFO = \nu = b_1 + 2b_2 t \quad (3)$$

where b_1 is an initial constant DFO value at initiation of data recordal and $2b_2$ is DFRO as defined above.

The constant DFO value b_1 may be determined by Fourier transformation of the Equation (2) product of $z_1^*(t) z_2(t + \tau_0) \exp(-2\pi i b_2 t^2)$ to the frequency domain (ie ignoring the b_1 term) after each iteration of Step (b), b_1 being subsequently determined as the frequency at which the

7 JANUARY 2004

5

CCF maximum occurs. This reduces the computation required because it avoids stepping through trial values of b_1 and re-evaluating the CCF for each. For a data set of N samples it reduces the number of computations from of order N^2 to $N \log_e N$, a substantial reduction for large $N \sim 10^6$.

Correlation may be performed with a sample data set adapted in phase and number of samples, samples being replicated in or removed from the set according which data set is selected for adaptation (z_1 or z_2) and also to the sign of the rate of change with time of DTO associated with the data set. Data samples in one of two data sets to be correlated may adapted in phase by samples following a removed sample being multiplied by a phase factor or by samples including and following a replicated sample being multiplied by such a factor, the phase factor being either $e^{2\pi i f \Delta t}$ or $e^{-2\pi i f \Delta t}$ according to which of the two data sets is adapted and to the sign of DTO change with time, and wherein f is a signal band centre frequency of the samples after downconversion for sampling and Δt is the interval between samples.

Samples may alternatively be selected for removal and replication on the basis of the following equation:

$$\tau_m = -\frac{\lambda}{c} b'_1 t_m - \frac{\lambda}{c} b_2 t_m^2 = m \Delta t \quad (4)$$

where t_m is the time from initiation of sampling to the m th sample selected for alteration, m is the selection number, Δt is the sampling interval, τ_m is the time dilation (expressed as a number of sampling intervals) and λ is the wavelength at the centre frequency of the signal sampling band before any frequency downconversion at a receiving site. The parameter b'_1 is an estimate of DFO (b_1) with any systematic error (eg frequency shift at a satellite relay) counteracted by deriving an estimated correction using a reference signal. The parameter b'_1 may alternatively be derived by using trial values of it and calculating the modulus of the CCF until a CCF maximum is obtained. It also is possible to exploit b_2 in the above expression as an independent parameter, thereby dissociating time dilation and time variation of DFO. Equation (4) is solved for t_m to determine times at which time dilation results in data sets z_1 and z_2 being out of step by successive increments of Δt . If the effects of time dilation are not too severe, a linear approximation may be employed by deleting the t_m^2 term in Equation (4).

Empfangszeit 13. Aug. 11:15

AMENDED SHEET

7 JANUARY 2004

6

In an alternative aspect, the present invention provides a location device for locating the source of an unknown signal received by a plurality of signal relays, and including:-

(a) a plurality of receivers for receiving replicas of the unknown signal via respective signal relays;

(b) a correlation processor for correlating the replicas and obtaining a correlation maximum indicating at least one of their DTO and DFO;

characterised in that the correlation processor is arranged to perform correlation with data sets adapted in phase and subject to sample adjustments to counteract time dilation arising from relay motion relative to the source and receivers.

The correlation processor may be arranged to perform correlation with data sets subject to data replication or removal.

In a preferred embodiment of the invention, the correlation processor is also arranged to perform correlation with a complex correlation function (CCF) at least partly compensated for change in DFO with time due to relay motion relative to the source and receivers.

The correlation processor may be arranged to employ a CCF containing an exponent of a function of time having a first term which is a constant DFO value and a second term which is a product of time and a constant value for rate of change of DFO with time, ie a constant differential frequency rate offset (DFRO) value, and wherein the correlation processor is also arranged to introduce trial values of DFRO and to evaluate correlation for pairs of trial values of DTO and DFRO iteratively to obtain a correlation maximum.

The correlation processor may be arranged to introduce a trial time offset between the replicas, evaluate their correlation and iterate this procedure to obtain a correlation maximum. It may employ a sample data set adapted in phase and number of samples, samples being replicated in or removed from the set according which data set is selected for adaptation (z_1 or z_2) and also to the sign of the rate of change with time of DTO associated with the data set. It may be arranged to adapt samples in one of two data sets to be correlated in phase by multiplying samples following a removed sample by a phase factor or by

with the data set. It may be arranged to adapt samples in one of two data sets to be correlated in phase by multiplying samples following a removed sample by a phase factor or by multiplying samples including and following a replicated sample by such a factor, the phase factor being either $e^{2\pi f\Delta t}$ or $e^{-2\pi f\Delta t}$ according to which of the two data sets is adapted and to the sign of DTO change with time, and wherein f is a signal band centre frequency of the samples after downconversion for sampling and Δt is the interval between samples.

The correlation processor may select samples for removal and replication on the basis of the correlation function's time dimension spread over an interval in which the samples were obtained. If a CCF peak is obtainable from data without time dilation compensation, the time over which correlation extends may be estimated. A selected data set may be contracted or expanded by the removal or insertion of samples according to whether data set z_1 or z_2 is adjusted and also according to whether time dilation is positive or negative. Alternatively, the correlation processor may select samples for removal and replication on the basis of Equation (4) above or a linear approximation thereto

In order that the invention might be more fully understood, an embodiment thereof will now be described, by way of example only, with reference to the accompanying drawings, in which:-

Figure 1 illustrates signal propagation between an Earth-based transmitter, satellite relays and Earth-based receivers;

Figure 2 indicates effects to be compensated by a location system of the invention;

Figure 3 shows schematically processing circuitry of a location system of the invention;

Figure 4 is a two dimensional plot of the modulus of the prior art cross ambiguity function $|A(\tau, \nu)|$ as a function of the two variables τ and ν obtained using data affected by satellite motion relative to source and receivers;

Figure 5 is equivalent to Figure 4 in all respects except that in accordance with the invention the complex correlation function $|A(\tau, b_1, b_2)|$ is plotted.

Figures 6 and 7 are graphs of complex correlation function signal power against frequency for equivalent situations except that in the former case there is no relay motion compensation whereas in the latter case there is.

Figures 8 to 11 are graphs of simulated noise-free results for DTO and DFO plotted against one another and showing time and frequency distortion, frequency compensation, time compensation and time and frequency compensation respectively.

Figures 12 to 14 are equivalent to Figures 8, 9/10 and 11 respectively with addition of the effects of noise.

Referring to Figure 1, an unknown transmitter 10 located in the United States of America 11 generates a signal which causes interference with satellite communications. The transmitter 10 has a radiation intensity pattern 12 with a sidelobe 12A directed to a first satellite 14 in a geostationary orbit, to which its signal propagates along a first uplink path ℓ_1^u (dotted line). It also has a radiation pattern main lobe 12B directed to a second satellite 16 in such an orbit; its signal propagates along a second uplink path ℓ_2^u to the satellite 16 and produces interference with communications signals using the latter. The unknown signal frequency is determined by spectrum analysis equipment which routinely monitors satellite channels. A typical communications satellite operating at Ku band (11 - 14 GHz) has 16 channels each 36 MHz wide and each capable of carrying 100 communications signals. The superscript "u" to path references ℓ_1^u and ℓ_2^u denotes uplink from the unknown transmitter 10.

The satellites 14 and 16 are monitored by respective receivers in the form of ground station antennas 18A and 18B located in England and referred to collectively as receivers 18. They receive the signal from the unknown transmitter 10 and retransmit it along first and second downlink paths ℓ_1^d and ℓ_2^d to respective receivers 18. Here the superscript "d" denotes a downlink path to a monitoring receiver. The receivers 18 receive respective replicas of the unknown signal which include path delays and Doppler frequency shifts from satellite

motion. The receivers 18 also transmit reference signals to the satellites 14 and 16 respectively, these signals being replicas of one another which are phase-locked together when transmitted initially. The satellites 14 and 16 return frequency shifted equivalents of the reference signals to respective receivers 18.

Referring now also to Figure 2, in which elements previously described are like-referenced, effects to be counteracted by the invention are indicated upon a schematic drawing of source/satellite/receiver geometry. These effects were discovered in experiments to investigate the feasibility of processing large sets of data obtained using satellites in geosynchronous orbits. It was found that failures to obtain correlation peaks with acceptable signal to noise ratio were due to specific aspects of satellite motion. This is very surprising, because geostationary or geosynchronous satellite motion relative to a source or receiver has hitherto been treated as being substantially constant over the relatively short sampling periods required for geolocation of a source, which implies that it would have an equal effect on all measurements in that interval at an individual site. One would not therefore expect satellite motion alone to be responsible for making a correlation peak obtainable on some occasions but not others. Despite this, in accordance with the invention it has been discovered that signal correlation is affected by satellite velocity and acceleration components along the lines joining the satellite to the source and receiver. As will be described later in more detail, it has been found that during a geolocation measurement these components can be sufficiently different at different times to make correlation obtainable on some occasions but not others.

Figure 2 is marked with arrows 20 to indicate parameters comprising components of satellite velocity and acceleration (eg v_{1u} , a_{1u}) in the directions of the source 10 and receivers 18, together with signal time delay and associated signal paths as defined in the table below. The present invention involves processing which counteracts time varying DFO and preferably also time varying time dilation; the latter is depicted in Figure 2 by a linear source time axis 22 and a non-linear receiver time axis 24. The axes 22 and 24 indicate that there is a time varying time separation or dilation between successive signals arriving at a receiver 18 because of satellite motion.

Time Delay τ_{xy} , Velocity Component v_{xy} or Acceleration Component a_{xy}	Path (τ_{xy}) or Direction (v_{xy} or a_{xy}) and Satellite or Receiver
τ_{1u}	Delay on Uplink path l_1^u to Satellite 14
τ_{1d}	Delay on Downlink path l_1^d to Receiver 18A.
τ_{2u}	Delay on Uplink path l_2^u to Satellite 16.
τ_{2d}	Delay on Downlink path l_2^d to Receiver 18B.
v_{1u}	Satellite 14 velocity component along uplink path l_1^u to Source 10.
v_{1d}	Satellite 14 velocity component along downlink path l_1^d to Receiver 18A.
v_{2u}	Satellite 16 velocity component along uplink path l_2^u to Source 10.
v_{2d}	Satellite 16 velocity component along downlink path l_2^d to Receiver 18B
a_{1u}	Satellite 14 acceleration component along uplink path l_1^u to Source 10.
a_{1d}	Satellite 14 acceleration component along downlink path l_1^d to Receiver 18A.
a_{2u}	Satellite 16 acceleration component along uplink path l_2^u to Source 10.
a_{2d}	Satellite 16 acceleration component along

	downlink path l_2^d to Receiver 18B.
--	--

Figure 2 shows what would happen to points originally regularly spaced on a waveform which passes over a path in space and is subjected to time varying Doppler effect. An analogue to digital converter (ADC) is used to sample a received signal and gives a regular set of samples to a signal which has undergone Doppler effect; these samples require timing adjustment, in one of the data sets z_1 or z_2 in Equation (2), in order to correspond to samples in the other data set which have undergone a different degree of Doppler effect. Figure 2 does not portray this – but instead what is shown is the result of differential Doppler effect on an array of points on a waveform which were originally regularly spaced. The dilation differs across four receiver channels to be described later, and is shown schematically at 22 for a single channel.

Referring now also to Figure 3, a signal processing system for a transmitter location system (TLS) of the invention is shown schematically and indicated generally by 30. It is emphasised that this drawing is schematic and does not show all system features in detail. It will be described in outline only, because transmitter location is described in great detail in the prior art of US Pat No 5,008,679 and published PCT Appln No WO 97/11383. Readers of this specification are referred to PCT Appln No WO 97/11383 for a detailed description of how transmitter location may be put into practice, except as regards measurement of additional parameters and complex correlation function processing to achieve satellite motion compensation in accordance with this invention.

To simplify description, the processing system 30 is illustrated functionally rather than in terms of actual items of apparatus; some items subsume multiple functions and others shown separately may be implemented together as a single device. The processing system 30 has four channels 32AR, 32AU, 32BR and 32BU; suffixes A and B indicate association with receivers 18A and 18B respectively and suffixes R and U indicate association with reference and unknown signals respectively. Components have like numerical references with differing suffixes distinguishing channels. The channels and their components will be referred to without suffixes to indicate any or all without differentiation, and with suffixes if

necessary to be specific. Receiver 18A is connected to channels 32AU and 32AR, and receiver 18B is connected to channels 32BU and 32BR.

Each channel 32 contains a series-connected arrangement of a mixer stage 34 for frequency down conversion and analogue filtering, an analogue to digital converter (ADC) 36 and an exponentiation stage 38 (H) for conversion of real signals to complex equivalents with in-phase and quadrature components. The mixers 34 are connected to a common local oscillator signal feed LO. Outputs from exponentiation stages 38AU and 38BU pass to a first correlation processing stage 40U, and that from the exponentiation stages 38AR and 38BR to a second correlation processing stage 40R. The processing stages 40U and 40R carry out parameter determination and correlation function processing as will be described later in more detail. Geometrical calculation and mapping to locate the unknown transmitter 10 is done in a mapping stage 42. The exponentiation, correlation processing and mapping stages 38, 40 and 42 may be implemented in a single computer.

The processing system 30 operates as follows. Signals from the receivers 18 are amplified and fed to the mixer stages 34 where they are filtered and downconverted to a centre frequency suitable for analogue to digital (A/D) conversion. Downconversion takes place in several stages, with filtering to define the relevant signal frequency band in each case and to prevent aliasing at the A/D stage. Mixer stages 34AU and 34BU are tuned to extract the unknown signal, and mixer stages 34AR and 34BR are tuned to extract the reference signal.

The ADCs 36 sample signals from the respective mixer stages 34 using automatic level control (ALC) to minimise the effect of quantisation noise. The signal samples so formed are real, and the exponentiation stages 38 convert them to analytic or complex form using the Hilbert Transform. In particular, a set $s_1(t)$ of signal samples from channel 32AU is converted to an analytic sample set $z_1(t)$ which is then conjugated to form a set $z_1^*(t)$. A similar procedure but without conjugation is followed for channel 32BU to produce a sample set $z_2(t)$. These two analytic sample sets for the unknown signal are then correlated together at 40U as will be described later to determine their DFO and DTO. Like sample sets are produced at 38AR and 38BR for the reference signal and are correlated at 40R.

The real and imaginary parts of the complex sample are denoted as follows: channel 32AU: $(x_1(t_i), y_1(t_i))$ or z_1 ; channel 32BU $(x_2(t_i), y_2(t_i))$ or z_2 ; channel 32AR $(r_1(t_i), s_1(t_i))$ or p_1 ; channel 32BR $(r_2(t_i), s_2(t_i))$ or p_2 .

Each correlation processing stage 40 correlates two sets of signal samples obtained respectively from distorted versions of the same original signal, the distortion arising from propagation via satellite relays; ie the two versions of the unknown signal in channels 32AU and 32BU are correlated with one another, as are the two versions of the reference signal in channels 32AR and 32BR. Each of the sample sets also has a noise component which is statistically independent of the noise component of sample sets from other channels.

As in the prior art, the procedure is to equalise the sample sets used in correlation, by introducing adjustable parameters into a correlation operation until the correlation function is a maximum; the parameters are related to the source/satellite/receiver geometry. The reference signal is used as in the prior art to remove noise which is correlated with that in the unknown signal, and the reference signal source provides a reference point with respect to which the unknown source location is determined. However, in the prior art each correlation operation involved only fixed values of differential frequency offset (DFO or ν) and differential time offset (DTO or τ). In the present invention, an expression for time varying DFO is used to compensate for satellite motion and if necessary time varying DTO is counteracted. If satellite motion is not too severe it is possible to obtain adequate results by compensating for time varying DFO only. The correlation operation is changed to implement this using a new correlation function different to that of Equation (1). The new function is referred to as the complex correlation function or CCF to distinguish it from the earlier expression; it is suitable for counteracting time varying DFO using geosynchronous satellites in orbits inclined to the ecliptic. It does not counteract time varying DTO, which is a different procedure to be described later. The CCF is expressed as $A(\tau_0, b_1, b_2)$ given by Equation (2) above and repeated below for convenience:

$$A(\tau_0, b_1, b_2) = \int_0^{\tau} z_1^*(t) z(t + \tau_0) e^{-2\pi i(b_1 + 2b_2 t)t} dt \quad (2)$$

where z_1 and z_2 are sets of data samples representing two signals being correlated, the asterisk denotes the complex conjugate of z_1 , T is the time over which samples are taken, τ_0 is a time invariant component of the differential time offset (DTO) between the signals because of their different paths, and b_1 and b_2 are constants in the Equation (3) expression for DFO:-

$$DFO \equiv \nu = b_1 + 2b_2t \quad (3)$$

The constant b_1 is an initial value of DFO at the beginning of data recordal in a measurement; $2b_2$ is the rate of change of DFO with time, referred to as the differential frequency rate offset or DFRO.

Equation (3) expresses the discovery in accordance with the invention that in the case of geosynchronous satellites the variation of DFO over a measurement can often be assumed to be linear with time to a good approximation. If the variation of DFO with time is sufficiently non-linear, higher powers of time t - ie b_3t^2 , b_4t^3 etc - may be included in the expression for DFO in Equation (3), but these can be omitted under most circumstances. They would be included if the motion of the satellite intercept platform were to require it, but at the expense of additional processing. The parameters τ_0 and b_2 are determined by inserting trial values of each into Equation (2), evaluating the CCF and iterating this procedure to find the maximum value of the correlation surface $|A(\tau_0, b_1, b_2)|$, ie the modulus of the CCF as a function of τ_0 , b_1 , b_2 . It is not necessary to iterate b_1 , because this is determined by inspection from the position of the CCF peak in the frequency domain as will be described later in more detail.

The correlation function $A(\tau_0, b_1, b_2)$ is applicable to situations where the satellite relays or intercept platforms are geostationary (GEO) and large data sets are required, leading to long data collection times and changing DFO. It is also applicable in situations where other types of intercept platforms are used, eg aircraft, GEO - LEO (low Earth orbit) MEO - MEO (medium Earth orbit) and LEO - LEO satellite combinations, but the additional technique of time dilation compensation is then relevant as will be described later.

In more detail, the correlation procedure using Equation (2) is as follows. Values for the delay and DFRO parameters τ_0 and b_2 are chosen. Initially, these parameters are set to zero,

and each is subsequently incremented through a predetermined range in discrete steps: each step is a multiple of a basic increment determined by the time Δt between successive signal samples (that is, a multiple of the inverse of the sampling rate). The sampling rate is numerically equal to twice the sampling bandwidth set by low pass filters incorporated in the mixers 34.

The basic increments in τ_0 and b_2 are denoted Δt and Δb_2 respectively; $\Delta t = 1/2B_s$ and $\Delta b_2 = 1/2T^2$, where B_s and T are respectively the sampling bandwidth and sampling period of the ADCs 36.

For each selected value of DTO τ_0 , and DFRO b_2 , a fast Fourier transform (FFT) of the inner product of $z_1^*(t) z_2(t+\tau_0)$ multiplied by $\exp(-2\pi i b_2 t^2)$ is taken in order to convert it to the frequency domain. This enables the DFO b_1 to be determined automatically as that frequency offset at which the CCF function maximum occurs. All values of DFO are accounted for in a single FFT operation, so it is unnecessary to increment in steps Δb_1 and evaluate the CCF after each step. The FFT is repeated for each set of values of (τ_0, b_2) ; ie first values of τ_0 and b_2 are selected and an FFT of $z_1^*(t) z_2(t+\tau) \exp(-2\pi i b_2 t^2)$ is evaluated. This is repeated for a range of values of τ_0 in incremental steps of $\Delta t = 1/2B_s$; b_2 is then incremented by one 0.001 Hz/second increment (this is a nominally convenient value) and the range of values of τ_0 and associated FFT evaluations is repeated. The procedure is repeated until all values of τ and b_2 in their respective ranges have been used. For operation in the SHF frequency band, from 7.9 GHz to 8.4 GHz, with GEOSat intercept platforms, a typical value of b_2 was found to be 0.05 Hz/second. The modulus of the complex correlation function (CCF) has a maximum in the frequency domain, and the values of τ_0 and b_1 at this maximum provide the required DTO and DFO. This provides a computationally efficient method of evaluating the CCF for a range of values of (τ_0, b_1, b_2) .

The foregoing procedure locates the CCF maximum approximately. The location accuracy can be improved by interpolation as described in detail in International Patent Application No WO 97/11383 referred to above in relation to the complex ambiguity function (CAF). A range of values of the modulus (or modulus squared) of the CCF about its maximum value is

taken, and interpolation is used to obtain a better estimate of the DTO, DFO and DFRO values.

This procedure results in values for τ_0 , b_1 and b_2 for the signal from the source to be located. It is repeated for the reference signal to obtain corresponding values $\tau_{0,ref}$, $b_{1,ref}$ and $b_{2,ref}$. The procedure gives DFO corrected to the instantaneous value it had at the beginning of data gathering when $t = 0$; Equation (3) refers.

The values of τ_0 and $\tau_{0,ref}$ are used to determine the uplink time difference of arrival TDOA_u, ie the difference between the times of arrival of the two signals or signal replicas from the unknown source 10 at respective satellites 14 and 16. The values of b_1 , $b_{1,ref}$, b_2 and $b_{2,ref}$ are used to determine the DFO values for the unknown signals and the reference signals. A theoretical treatment of this will now be given.

Referring firstly to use of τ_0 and $\tau_{0,ref}$ DTO is the difference in the time for two distorted versions of an original unknown or reference signal to traverse a two different paths to a receiver, ie either from the source 10 to a receiver 18 or from and to a receiver 18 via satellite 14 or 16. It can be represented as a function of time t over the duration of the sample, in terms of independent, time-constant parameters (τ_0 , b_1 , b_2 , .. etc) related to the kinematics of the source/satellite/receiver system:

$$DTO \equiv \tau = \tau_0 + a_1 t + a_2 t^2 + a_3 t^3 + \dots \quad (4)$$

The DTO τ is formed from the difference of two terms, τ_1 and τ_2 , which represent signal propagation delays arising from traversal of different paths by replicas of an single original signal. It may be expressed as the sum of uplink and downlink delays plus any additional delay experienced in traversing electronic signal channels (e.g. a satellite transponder system) as follows:

$$\tau = \tau_1 - \tau_2 = (\tau_{1u} + \tau_{1d}) - (\tau_{2u} + \tau_{2d}) = (\tau_{1u} - \tau_{2u}) + (\tau_{1d} - \tau_{2d}) \quad (5)$$

where terms are defined in Table 1. Equation (5) represents the DTO in terms of the sum of the difference of uplink delays and difference of downlink delays, and subsumes within these any difference between electronic delays.

Sampling periods required for geolocation are usually relatively short (milliseconds to tens of seconds), and despite satellite motion it has been found that uplink and downlink delays can be represented as truncated power series in time t as follows:

$$\tau_{lu} = \tau_{0,lu} + a_{1,lu}t + a_{2,lu}t^2 + \dots \quad (6)$$

with similar expressions for other delays given in the table earlier, ie τ_{ld} , τ_{ud} and τ_{dd} , with appropriate changes in coefficient indices to $a_{1,ld}$ etc. The coefficients $a_{1,lu}$ etc are not the same as the accelerations defined in the earlier table, but can be related to satellite velocities and accelerations. The full expression for the DTO becomes:

$$\begin{aligned} \tau = & ((\tau_{0,lu} - \tau_{0,2u}) + (\tau_{0,ld} - \tau_{0,2d})) + ((a_{1,lu} - a_{1,2u}) + (a_{1,ld} - a_{1,2d}))t \\ & + ((a_{2,lu} - a_{2,2u}) + (a_{2,ld} - a_{2,2d}))t^2 + \dots \end{aligned} \quad (7)$$

The parameters τ_0 , a_1 , and a_2 etc can be found by inspection, ie by equating coefficients of powers of time t in Equations (4) and (7).

Equation (7) for the DTO τ contains an uplink contribution which relates directly to the unknown source position to be determined, and a downlink contribution which is known from the satellite/receiver system geometry. The uplink contribution is referred to as the $TDOA_u$. In order to remove biases from the estimate of $TDOA_u$, an equivalent expression for the DTO of the reference signal is subtracted from the DTO of the unknown source signal. The known geometry of the source/satellite/receiver system allows the DTO of the reference signal to be calculated, apart from biases (e.g. satellite processing delays) affecting it in the same way as they affect the source signal DTO. This is why the reference signal DTO is also measured. The $TDOA_u$ is related to the measured DTO values through the relation:

$$TDOA_u = \tau - \tau_{ref} + \frac{(l_1^u - l_2^u)_{ref}}{c} = \tau - \tau_{ref} + \frac{(l_1^d - l_2^d)_{ref}}{c} \quad (8)$$

where c is the velocity of light and the subscript 'ref' in (8) indicates the paths are between the satellites and the receiving ground terminals over which the reference signal passes. DFO ν is the difference in frequency between two received signals. It can be expressed in terms of the kinematics of the source/satellite/receiver system using the general relationship between Doppler, velocity and rate of change of time delay with time, exemplified for the satellite uplinks, as follows:

$$\Delta \nu_{1u} = \frac{d}{dt} \phi_{1u} = -\frac{d}{dt} \left(\frac{l_1^u}{\lambda_u} \right) = \frac{\nu_{1u}}{\lambda_u} = -\frac{c}{\lambda_u} \frac{d}{dt} \tau_{1u} \quad (9)$$

where $\Delta \nu_{1u}$ is the Doppler shift in frequency occurring on the uplink path l_1^u to satellite 14, τ_{1u} is the phase and λ_u the wavelength of a signal (at its centre frequency) as received at the satellite 14 or 16 on uplink. Similar expressions for other system uplinks and downlinks are obtainable by change of indices.

The unknown signal DFO is given by:

$$DFO \equiv \nu = -\frac{c}{\lambda_u} \left[\frac{d}{dt} \tau_{1u} - \frac{d}{dt} \tau_{2u} \right] - \frac{c}{\lambda_d} \left[\frac{d}{dt} \tau_{1d} - \frac{d}{dt} \tau_{2d} \right] + bias \quad (10)$$

where λ_u and λ_d are the free space wavelengths of the uplink and downlink signals respectively at their centre frequencies, and bias arises from satellite turnaround frequency shift and from satellite positional error.

The reference signal DFO is similarly given by:

$$DFO_{ref} \equiv \nu_{ref} = -\frac{c}{\lambda_{u,ref}} \left[\frac{d}{dt} \tau_{1u} - \frac{d}{dt} \tau_{2u} \right]_{ref} - \frac{c}{\lambda_{d,ref}} \left[\frac{d}{dt} \tau_{1d} - \frac{d}{dt} \tau_{2d} \right]_{ref} + bias \quad (11)$$

Subtracting (11) from (10) cancels out bias which is the same in both equations and gives an expression for the uplink frequency difference of arrival $FDOA_u$:

$$FDOA_u = \nu - \nu_{ref} + \frac{c}{\lambda_d} \left[\frac{d}{dt} \tau_{1d} - \frac{d}{dt} \tau_{2d} \right] - \frac{c}{\lambda_{u,ref}} \left[\frac{d}{dt} \tau_{1u} - \frac{d}{dt} \tau_{2u} \right]_{ref} - \frac{c}{\lambda_{d,ref}} \left[\frac{d}{dt} \tau_{1d} - \frac{d}{dt} \tau_{2d} \right]_{ref} \quad (12)$$

where the last three terms are known from the system geometry, and the first two terms are the unknown and reference DFOs measured by determining the CCF maximum as described earlier. A further measurable is also determined, the differential frequency rate offset ($DFRO = 2b_2$), this being the difference between Doppler rates (DFO rates of change) of signals measured along respective paths from the source 10, through the satellite intercept platforms 14 and 16, to the terrestrial intercept stations 18 as shown in Figure 2. It may be used to form a parameter known as the uplink differential Doppler rate of arrival ($DDROA_u$) which exploits the acceleration effects of the source/satellite/receiver system. The $DDROA_u$ is the difference in Doppler-rates measured along the paths from the unknown source 10 to the satellite intercept platform 14 and 16. It is useful for the location of moving sources. The $DDROA$ can be expressed in terms of the $DFRO$ by direct differentiation of (12) as follows:

$$DDROA_u = DFRO - DFRO_{ref} + \frac{c}{\lambda_d} \left[\frac{d^2}{dt^2} \tau_{1d} - \frac{d^2}{dt^2} \tau_{2d} \right] - \frac{c}{\lambda_{u,ref}} \left[\frac{d^2}{dt^2} \tau_{1u} - \frac{d^2}{dt^2} \tau_{2u} \right]_{ref} - \frac{c}{\lambda_{d,ref}} \left[\frac{d^2}{dt^2} \tau_{1d} - \frac{d^2}{dt^2} \tau_{2d} \right]_{ref} \quad (13)$$

The uplink TDOA ($TDOA_u$ as in (8)) and the uplink FDOA ($FDOA_u$ as in (12)) are used in the process of emitter position location of stationary RF sources (on the Earth's surface), as in the prior art of published International Application No WO 97/11383. In this particular case the $DDROA_u$ is not used explicitly. However, even when this is the case, the effect of satellite acceleration, which gives rise to the $DDROA_u$, is counteracted in the CCF as

previously described using trial values of the parameter b_2 as described earlier. This parameter must be utilised in evaluating the CCF even when it is not needed further in locating the source 10. This is because the RF emitter location problem has two parts. The first is detection of the peak of the CCF and the second is relating the peak of the CCF to a position on the Earth's surface. The first phase is sensitive to the effects of satellite motion; requiring b_2 as a compensation parameter in addition to those used in prior art (τ_0 and b_1).

The source 10 is located by using the determined TDOA_u and FDOA_u values to the Earth's surface by prior art geometrical methods. Firstly, the parameters τ_0 , b_1 and b_2 are obtained for the unknown and reference signals by maximising the CCF in Equation (2) as described earlier. The values of b_1 , $b_{1,\text{ref}}$, b_2 and $b_{2,\text{ref}}$ are used to determine the signal and reference DFO values by insertion in Equation (3) with time t set to zero. This sets DFO as its instantaneous value at the beginning of data gathering – it is convenient to correct DFO to the value at this time but not essential.

The values of v and v_{ref} are substituted into Equation (12) to determine FDOA_u . Here again time t is set to zero; a consequence of this is that the location of the source 10 is determined using satellite ephemeris data (instantaneous positions in space) associated with the time at the start of sampling.

TDOA_u is multiplied by c the velocity of light to give differential slant range (DSR), this being the difference between the two signal path lengths to the signal relay satellites 14 and 16 from a transmitting station, ie either the reference transmitter location 18A/18B or the unknown source 10. FDOA_u is multiplied by λ_u the signal wavelength in the uplink path to give the differential slant range rate (DSRR) or time rate of change of DSR. International Patent Application No PCT/GB95/02211 under the Patent Co-operation Treaty, published as WO 97/11383, describes in detail how to locate the source 10 on the Earth's surface from DSR and DSRR values using a Taylor expansion approach, and will not be described here.

Counteracting only time varying DFO is sufficient for use with two geostationary satellite (GEOsat) relays when large sample sets are required. It focuses the CCF in the frequency

dimension. Its effects can be seen from Figures 4 and 5; Figure 4 shows results obtained using the prior art ambiguity function of Equation (1) and Figure 5 shows results obtained using the complex correlation function or CCF of Equation (2) in accordance with the invention. The same data sets were used in both cases, obtained using two geostationary satellites. To meet patent requirements, these drawings were produced by tracing from colour prints in which colour indicated magnitude, and because of this they are not highly accurate. They do however provide a reliable indication of the benefits to be obtained by use of the invention.

Figure 4 is a pseudo-three-dimensional view of the prior art complex ambiguity function of Equation (1) plotted against DTO and DFO. All that can be seen is noise. Figure 5 is a similar plot of the complex correlation function of Equation (2) in accordance with the invention. In Figure 5 a sharp correlation maximum 50 is fully resolved and stands well above the noise at 52.

Referring now to Figure 6, the effect of satellite motion is shown once more in a plot of CCF modulus squared or power against frequency. There should be a single CCF peak at the DFO of -820.38 , but instead there is a plateau 60 spread out over more than 16 Hz. This is contrasted with Figure 7, in which DFO variation has been compensated giving a well resolved peak 70.

It may be necessary to use fast moving relay platforms for geolocation, eg aircraft, medium Earth orbit satellites (MEOSat), low Earth orbit satellites (LEOSat), or combinations of these with geostationary satellites (GEOSat). If so the CCF must also be focused in the time dimension to compensate for time dilation. This is necessary to compensate for a time delay τ_0 that varies appreciably in the course of data collection for a measurement.

The CCF of Equation (2) only compensates for DFO variation in the sampling interval T . It does not compensate for time dilation, ie DTO variation in this interval. DTO variation is counteracted by periodic replication or excision of samples to compensate for samples in one data set (z_1 or p_1) being out of step with those in the associated data set (z_2 or p_2). For a

measurement using two satellites, one geostationary and the other low earth orbit, it might involve inserting or removing one sample in every few hundred in a data set having in the order of a million samples. A phase correction is also required, and is applied to all samples in a data set following an insertion or excision, together with the inserted sample if this occurs. Successive phase corrections accumulate, each one being applied from the point of insertion or excision through the subsequent samples in the data set.

The timing of the sample adjustments, insertions/excisions is determined from the time taken for a sample slip to occur. A slip occurs when the value of time dilation changes by an amount equal to the sampling interval at the ADC. The time to the m th slip (total time dilation of m sampling intervals) is estimated by one of two approaches: either (a) from the spread of the ambiguity surface, in the time direction, across the sampling interval, or (b) from use of the τ_0 , b_1 , b_2 parameters obtained from maximising the CCF as described earlier.

In approach (a), the correlation processor selects samples for removal from or replication in a set of data samples on the basis of the complex correlation function's time dimension spread over an interval in which the data set was obtained. If a CCF peak can be obtained from data without time dilation compensation, the number of time intervals Δt over which the correlation is spread is estimated. For a spread of K time intervals, the number of samples between positions of adjustment (successive sample slips) of the data set is N/K where N is the number of samples in the data set. The data set z_1 or z_2 (see Equation (2)) selected for adjustment is a matter of implementation convenience and therefore arbitrary in principle; eg if z_1 corresponds to a signal expanded by time dilation, it can be contracted by sample removal to correct it, or alternatively z_2 may be expanded to match it. The selected data set is contracted or expanded by the removal or insertion of samples according to which of the two data sets is selected for adjustment and also according to whether the time dilation determined is positive or negative; if z_1 is selected, it is expanded if the time dilation is negative, which corresponds to rate of change of DTO being negative.

In the alternative approach (b), the correlation processor 30 selects samples for removal and replication on the basis of the following equation, which is an approximation derived from satellite motion and is quadratic in time:

$$\tau_m = -\frac{\lambda}{c} b'_1 t_m - \frac{\lambda}{c} b_2 t_m^2 = m \Delta t \quad (14)$$

t_m is the time from initiation of sampling to the m th replicated or removed sample, τ_m is the total time dilation experienced up to t_m , m is the number of sampling intervals removed or inserted to counteract time dilation, Δt is the sampling interval (time between successive ADC samples) and λ is the wavelength at the centre frequency of the signal sampling band before any frequency downconversion at a receiver 18. The parameter b'_1 is an estimate of the time invariant component of DFO b_1 with any systematic error (due to satellite turnaround frequency change) corrected using an estimate derived from the reference signal. Alternatively b'_1 may be another parameter which is varied in steps in maximising the modulus of the CCF. It is also possible to exploit b_2 in the above expression as an independent parameter varied in steps, thereby dissociating time dilation and time variation of DFO.

If the effects of satellite motion are not too severe, it is possible to omit the quadratic second term in Equation (14) in t_m^2 , and apply the resulting linear correction.

Samples preceded by an omitted or inserted sample are multiplied by a phase correction factor P given by one of the following:

$$P = e^{2\pi j f \Delta t}, \text{ or } P = e^{-2\pi j f \Delta t} \quad (15)$$

The exponent in the expression for P is positive or negative according to whether the preceding sample is omitted or inserted; f is the centre frequency of the samples' signal after downconversion for input to an analogue to digital converter, and Δt is the interval between successive ADC samples. The samples' signal band is set by an anti-aliasing low-pass filter.

Before time dilation compensation is undertaken, the modulus of the CCF is maximised to obtain approximate values of DFO and the parameters τ_0 , b_1 and b_2 as previously discussed. Time dilation compensation is then implemented by inserting or excising samples as appropriate and adjusting phase in each of the four data sets z_1 , z_2 , p_1 , p_2 to produce compensated equivalents. The CCF is then maximised again using the compensated data sets so formed to provide better values of DTO, DFO and if required DFRO and DDROA.

The process of compensation for change in both DFO motion and time dilation is summarised as follows:-

- (a) obtaining initial values of DFO and DTO using compensation for varying DFO only; (b) time dilation compensation of one data set by delaying/advancing (translating) parts of it relative to an associated data set and applying phase corrections; this involves replicating/deleting samples as appropriate; and
- (c) multiplying the sample sets (in the sense of an inner product) to obtain a measure of the signal energy and to vary parameter values to maximise the modulus of the CCF given in general terms by:-

$$CCF = [z_1^*]T^{-1}D^{-1}[z_2] \quad (16)$$

It is the CCF modulus which is maximised because noise from receiving equipment is included, which makes signal energy a complex quantity (in the mathematical sense). The T^{-1} and D^{-1} notation is used to indicate translation compensation and frequency distortion compensation respectively, the superscripts denoting reversal of effects introduced by system geometry and kinematics. The brackets $[]$ indicate a vector comprising the signal samples. Translation of a relay satellite leads to time dilation because it alters the signal path and therefore also the associated time of flight.

In developing more general expressions for the DTO and DFO it must be borne in mind that the optimisation of the resulting CCF becomes more processor intensive. The approximation described herein using τ_0 , b_1 and b_2 is well within the capabilities of current parallel processors.

It is expedient to represent the distortion compensation in terms of a DFO compensation and a separate DTO compensation because a rapid change of phase is removed by this approach, leaving the DTO dilation compensation acting on one data stream without the need for interpolation between signal samples.

Referring now to Figures 8 to 11, the effects of counteracting DFO variation and time dilation in accordance with the invention are illustrated graphically. These drawings are plots of DTO against DFO derived using simulated data without significant noise. In Figure 8, DFO varies with DTO over a region 80 which includes error limits. Figure 9 illustrates the effect of frequency compensation alone, ie counteracting change in DFO. A region 90 is produced which is parallel to the DFO axis indicating DFO is now constant. Figure 10 is the equivalent of Figure 9 for time or DTO compensation alone, and shows a region 100 of constant DTO. The combination of both these procedures is shown in Figure 11, which shows a single peak of constant DFO and DTO. Compensation for DTO variation was carried out using the linear term in Equation (14) only.

Figures 12 to 14 illustrate graphically the effect of introducing noise. Except as regards noise they were produced using the same data as Figures 8 to 11, and they would show precisely the same features absent the noise. It can be seen that DTO and DFO are not visible in Figures 12 and 13, either without compensation (Figure 12) or with compensation for only one of frequency distortion and time distortion (Figure 13), which give like results. Figure 14 has a single peak 140 easily discernable above surrounding noise such as 142; it demonstrates that compensation for both frequency and time distortion in accordance with this invention leads to DTO and DFO values being obtainable despite the presence of noise.

7 JANUARY 2004

26

CLAIMS

1. A method of locating the source of an unknown signal received by a plurality of signal relays, the method including the steps of:-

(a) arranging for a plurality of receivers (18) to receive replicas of the unknown signal via respective signal relays (14, 16); and

(b) subjecting the replicas to correlation processing;

characterised in that correlation processing in step (b) is performed with data sets adapted in phase and subject to sample adjustments to counteract time dilation.

2. A method according to Claim 1 characterised in that correlation processing in step (b) is performed with data sets subject to data replication or removal to counteract time dilation.

3. A method according to Claim 2 characterised in that samples in one of two data sets to be correlated are adapted in phase by samples following a removed sample being multiplied by a phase factor or by samples including and following a replicated sample being multiplied by such a factor, the phase factor being either $e^{2\pi if\Delta t}$ or $e^{-2\pi if\Delta t}$ according to which of the two data sets is adapted and to the sign of DTO change with time, and wherein f is a signal band centre frequency of the samples after downconversion for sampling and Δt is an interval between successive samples.

4. A method according to Claim 2 or 3 characterised in that samples are selected for removal or replication as the case may be on the basis of the correlation function's time dimension spread over an interval in which the samples were obtained.

5. A method according to Claim 2 characterised in that samples are selected for removal or replication as the case may be on the basis of at least a linear approximation to the following quadratic equation for t_m :

$$\tau_m = -\frac{\lambda}{c} b_1' t_m - \frac{\lambda}{c} b_2' t_m^2 = m\Delta t$$

where t_m is the time to the m th replicated or removed sample, m is the number of replicated or removed samples up to time t_m , τ_m is the total time dilation up to time t_m , Δt is the time

Empfangszeit 13.AUG. 11:15

AMENDED SHEET

7 JANUARY 2004

'27

interval between successive samples and λ is the free space wavelength at the centre frequency of the sampling band, b_1' is an estimate of DFO at initiation of sampling corrected for any systematic error in frequency, and b_2 is half of the rate of change of DFO with time.

6. A method according to Claim 1 characterised in that correlation processing in step (b) is performed with a complex correlation function (CCF) at least partly compensated for change in the replicas' Differential Frequency Offset (DFO) with time due to relay motion relative to the source and receivers.

7. A method according to Claim 6 characterised in that the correlation function is a complex correlation function referred to as a CCF given by:

$$CCF = A(\tau_0, b_1, b_2) = \int_0^T z_1^*(t) z_2(t + \tau_0) e^{-2\pi i(b_1 + 2b_2 t)t} dt$$

where z_1 and z_2 are data sets representing two signals being correlated, the asterisk denotes the complex conjugate of z_1 , T is the time over which samples are taken, τ_0 is a time invariant component of Differential Time Offset (DTO), and b_1 and b_2 are constants in an expression for change in DFO with time t as follows:- $DFO = \nu = b_1 + 2b_2 t$, and wherein the CCF is maximised *inter alia* by inserting therein trial values of b_2 and versions of z_1 and z_2 adapted to contain added or removed sample values to counteract time dilation.

8. A method according to Claim 7 characterised in that after each iteration of step (b) the product of $z_1^*(t) z_2(t + \tau_0) \exp(-2\pi i b_2 t^2)$ is Fourier transformed to the frequency domain, in order to provide for DFO b_1 to be obtainable as the frequency offset at which the CCF maximum occurs.

9. A location device for locating the source (10) of an unknown signal received by a plurality of signal relays (14, 16), and including:-

- (a) a plurality of receivers (18) for receiving replicas of the unknown signal via respective signal relays (14, 16);
- (b) a correlation processor (30) for correlating the replicas and obtaining a correlation maximum indicating at least one of their DTO and DFO;

Empfangszeit 13. Aug. 11:15

AMENDED SHEET

7 JANUARY 2004

28

characterised in that the correlation processor (30) is arranged to perform correlation with data sets adapted in phase and subject to sample adjustments to counteract time dilation.

10. A location device according to Claim 9 characterised in that correlation processing in step (b) is performed with data sets subject to data replication or removal to counteract time dilation.

11. A location device according to Claim 10 characterised in that the correlation processor (30) is arranged to adapt in phase one of two sets of data samples to be correlated by multiplying samples following a removed sample by a phase factor or multiplying a replicated sample and samples following it by a such a factor, the phase factor being either $e^{2\pi if\Delta t}$ or $e^{-2\pi if\Delta t}$ according to which of the two data sets is adapted and to the sign of DTO change with time, and wherein f is a signal band centre frequency of the samples after downconversion for sampling and Δt is an interval between successive samples.

12. A location device according to Claim 10 or 11 characterised in that the correlation processor (30) is arranged to select samples for removal and replication on the basis of the correlation function's time dimension spread over an interval in which the samples were obtained.

13. A location device according to Claim 10 characterised in that the correlation processor (30) is arranged to select samples for removal and replication on the basis of at least the linear term of the following quadratic equation in t_m^2 :

$$\tau_m = -\frac{\lambda}{c} b_1' t_m - \frac{\lambda}{c} b_2 t_m^2 = m\Delta t$$

where t_m is the time from initiation of sampling to the m th replicated or removed sample, m is the number of replicated or removed samples up to time t_m , τ_m is the total time dilation up to time t_m , Δt is the time interval between successive samples, λ is the free space wavelength at the centre frequency of the sampling band, b_1' is an estimate of DFO at initiation of sampling corrected for any systematic error in frequency, and b_2 is half of the rate of change of DFO with time.

7 JANUARY 2004

29

14. A device according to Claim 9 characterised in that the correlation processor (30) is arranged to perform correlation with a complex correlation function (CCF) at least partly compensated for change in DFO with time due to relay motion relative to the source and receivers.

15. A device according to Claim 14 characterised in that the correlation processor (30) is arranged to employ a CCF which contains an exponent of a function of time having a first term which is a constant DFO value and a second term which is a product of time and a constant value for rate of change of DFO with time, ie a constant differential frequency rate offset (DFRO) value, and wherein the correlation processor (30) is also arranged to introduce trial values of DFRO and to iteratively evaluate correlation for pairs of trial values of DTO and DFRO to determine a DFRO value enabling a correlation maximum to be obtained.

16. A device according to Claim 13 characterised in that the CCF is given by:

$$CCF = A(\tau_0, b_1, b_2) = \int_0^T z_1^*(t) z_2(t + \tau_0) e^{-2\pi i(b_1 + 2b_2 t)t} dt$$

where z_1 and z_2 are data sets representing two signals being correlated, the asterisk denotes the complex conjugate of z_1 , T is the time over which samples are taken, τ_0 is a time invariant component of DTO, and b_1 and b_2 are constants in an expression for DFO for change in DFO with time t as follows:- $DFO = \nu = b_1 + 2b_2 t$, and wherein the correlation processor (30) is arranged to maximise the CCF by evaluating it with trial values of b_2 in addition to those of τ_0 , together with versions of z_1 and z_2 adapted to contain replicated or removed sample values to counteract time dilation.

17. A device according to Claim 14 characterised in that the correlation processor (30) is arranged to Fourier transform successive products $z_1^*(t) z_2(t + \tau_0) \exp(-2\pi i b_2 t^2)$ to the frequency domain in order to obtain DFO b_1 as a frequency offset at which a CCF maximum occurs.

17. A device according to Claim 10 characterised in that the CCF is given by:

$$CCF \equiv A(\tau_0, b_1, b_2) = \int_0^T z_1^*(t) z(t + \tau_0) e^{-2\pi i(b_1 + 2b_2 t)t} dt$$

where z_1 and z_2 are data sets representing two signals being correlated, the asterisk denotes the complex conjugate of z_1 , T is the time over which samples are taken, τ_0 is a time invariant component of DTO, and b_1 and b_2 are constants in an expression for DFO for change in DFO with time t as follows:- $DFO \equiv \nu = b_1 + 2b_2 t$,

and wherein the correlation processor (30) is arranged to maximise the CCF by evaluating it with trial values of b_2 in addition to those of τ_0 , together with versions of z_1 and z_2 adapted to contain replicated or removed sample values to counteract time dilation.

18. A device according to Claim 17 characterised in that the correlation processor (30) is arranged to Fourier transform successive products $z_1^*(t) z_2(t + \tau_0) \exp(-2\pi i b_2 t^2)$ to the frequency domain in order to obtain DFO b_1 as a frequency offset at which a CCF maximum occurs.