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(54) Title: CRYSTAL OSCILLATOR CALIBRATION

(57) Abstract: Systems and methods for temperature-calibration of an uncompensated XO in a mobile device during mobile device operation. The XO is temperature-calibrated based on assistance from wireless signals, such as from satellite source, and optionally from terrestrial sources such as WWAN, CDMA, etc. Based on one or more received wireless signals received at a receiver, corresponding frequency estimates of the XO are obtained and correlated with corresponding operating temperatures in a processor. Based on one or more samples of frequency estimates and associated temperatures, the XO is temperature-calibrated in the processor wherein a frequency-temperature (FT) model is formulated for the XO. The frequency of the temperature-calibrated XO can be determined from the FT model at any given temperature.

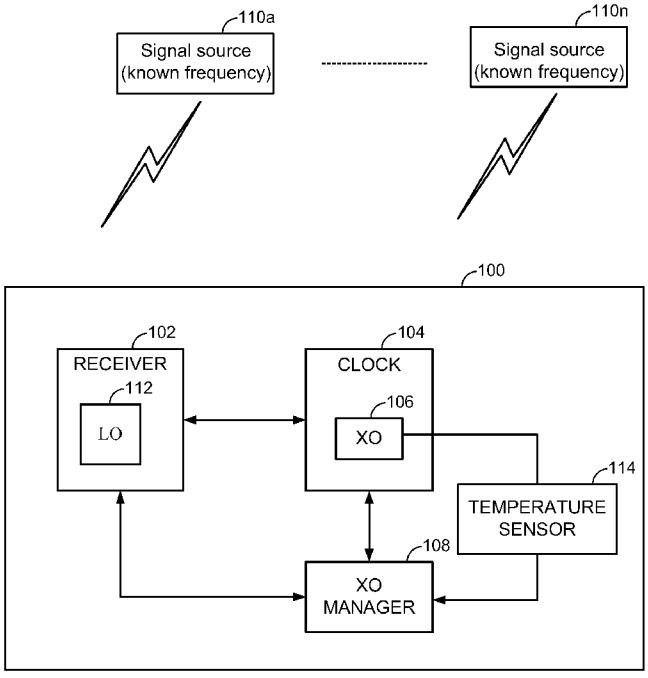

FIG. 2A

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CRYSTAL OSCILLATOR CALIBRATION

Claim of Priority under 35 U.S.C. §119

[0001] The present Application for Patent claims the benefit of U.S. Provisional Application No. 61/666,307, entitled "GNSS BASED CRYSTAL OSCILLATOR CALIBRATION" filed June 29, 2012, assigned to the assignee hereof, and expressly incorporated herein by reference.

Field of Disclosure

[0002] Disclosed embodiments are directed to field calibration of an XO, and more particularly, for temperature-calibration of an uncompensated XO using assistance from one or more wireless signals of known frequency, including satellite signals, and optionally, terrestrial signals. The uncompensated XO does not comprise built-in compensation for frequency variation with variation in temperature or voltage.

Background

[0003] Global navigation satellite systems (GNSS) are well known in applications related to tracking and positioning. GNSS systems such as global positioning systems (GPS) are satellite-based systems used for pinpointing a precise location of a GNSS receiver or object capable of tracking satellite signals. With advances in GNSS technology, it is possible to locate and track movements of an object on the globe.

[0004] GNSS systems operate by configuring a GNSS satellite to transmit certain signals which may include pre-established codes. These signals are based on a GNSS time or satellite time derived from an atomic clock or satellite clock present in the satellite. The transmitted signals may include a time stamp indicating the time at which they were transmitted. A GNSS receiver, which may be integrated in a handheld device, is timed by a local clock located at the receiver end. Ideally, this local clock is synchronized to the satellite clock (also known as the GNSS time). The device comprising the GNSS receiver is configured to estimate the GNSS time based on the satellite signals in order to synchronize their local clocks to the GNSS time. Once the local clocks are accurately synchronized, the device is configured to calculate the propagation time for the satellite signals to reach the receiver, based on a difference between the time at which the signals were received, and the time at which they were transmitted. This propagation time is an

indication of the distance between the satellite and the device, keeping in mind that factors such as atmospheric conditions may affect the propagation time.

[0005] In order to pinpoint the location of the device, the device performs the above process to calculate the distance to two or more other satellites (if altitude and/or local time of the device is known, the location can be determined with a total of three satellites, otherwise, a total of four satellites may be needed). Using the distances to the satellites, it is theoretically possible to "trilaterate" the position of the device. However, practical applications diverge from theoretical expectations due to several sources of inaccuracies inherent in GNSS based positioning.

[0006] One source of inaccuracy relates to synchronization of the local clock. In modern devices comprising GNSS receivers, time is typically maintained via a temperature-compensated crystal oscillator (TCXO), to maintain the frequency stability required for GNSS operation across varying device temperatures. Even small errors in frequency may result in large positional errors in position estimation. Thus, the TCXO and/or a voltage controlled temperature compensated crystal oscillator (VCTCXO) have been used in the art to maintain nearly constant frequency across fluctuating temperature and voltage. While the TCXO and VCTCXO may also experience some fluctuation in frequency with fluctuations in temperature and voltage, the frequency variations in an XO, i.e., a crystal oscillator without such temperature or voltage compensation, is much larger. Accordingly, the XO has historically not been used because of the large frequency variations across temperature and voltage that may prolong GNSS searches or cause them to fail.

SUMMARY

[0007] Exemplary embodiments of the invention are directed to systems and methods for calibration of an XO, and more particularly, for temperature-calibration of an uncompensated XO, in order to overcome frequency variation of the XO. In several exemplary aspects, temperature-calibration of the XO includes determining an accurate relationship between frequency and temperature of the XO using assistance from one or more signal sources.

[0008] For example, an exemplary embodiment is directed to a method of temperature-calibrating an uncompensated crystal oscillator (XO), in a mobile device during mobile device operation, the method comprising: receiving a first set of wireless signals

comprising at least a first wireless signal of known frequency, at a first temperature, estimating a first frequency of the XO at the first temperature, based on at least the first wireless signal, and temperature-calibrating the XO based on the first frequency and the first temperature.

[0009] Another exemplary embodiment is directed to a method of temperature-calibrating an uncompensated crystal oscillator (XO) in a mobile device during mobile device operation, the method comprising: receiving a first set of wireless signals comprising at least a first wireless signal, from a signal source of known frequency and known Doppler, at a first temperature, wherein a plurality of satellite signals is unavailable, estimating a first frequency of the XO at the first temperature, based on at least the first wireless signal, and temperature-calibrating the XO based on the first frequency and the first temperature.

[0010] Another exemplary embodiment is directed to a system comprising: a mobile device comprising an uncompensated crystal oscillator (XO), means for receiving a first set of wireless signals comprising at least a first wireless signal of known frequency, at a first temperature, means for estimating a first frequency of the XO at the first temperature, based on at least the first wireless signal, and means for temperature-calibrating the XO based on the first frequency and the first temperature during operation of the mobile device.

[0011] Another exemplary embodiment is directed to a system comprising: a mobile device comprising an uncompensated crystal oscillator (XO), means for receiving a first set of wireless signals comprising at least a first wireless signal, from a signal source of known frequency and known Doppler, at a first temperature, wherein a plurality of satellite signals is unavailable, means for estimating a first frequency of the XO at the first temperature, based on at least the first wireless signal, and means for temperature-calibrating the XO based on the first frequency and the first temperature during operation of the mobile device.

[0012] Another exemplary embodiment is directed to a mobile device comprising: an uncompensated crystal oscillator (XO), a temperature sensor configured to provide a first temperature, one or more receivers configured to receive a first set of wireless signals comprising at least a first wireless signal of known frequency, at the first temperature, and a processor configured to estimate a first frequency of the XO at the first temperature, based on at least the first wireless signal, and temperature-calibrate the

XO based on the first frequency and the first temperature during operation of the mobile device.

[0013] Another exemplary embodiment is directed to a mobile device comprising: an uncompensated crystal oscillator (XO), a temperature configured to provide a first temperature, one or more receivers configured to receive a first set of wireless signals comprising at least a first wireless signal, from a signal source of known frequency and known Doppler, at the first temperature, wherein a plurality of satellite signals is unavailable, and a processor configured to estimate a first frequency of the XO at the first temperature, based on at least the first wireless signal and temperature-calibrate the XO based on the first frequency and the first temperature.

[0014] Yet another exemplary embodiment is directed to a mobile device comprising: an uncompensated crystal oscillator (XO), a temperature sensor configured to provide a first temperature, one or more receivers configured to receive a first set of wireless signals comprising at least a first wireless signal of known frequency, at a first temperature, a processor, and a non-transitory computer-readable storage medium comprising code, which, when executed by the processor, causes the processor to perform operations for temperature-calibrating a crystal oscillator (XO), the non-transitory computer-readable storage medium comprising: code for estimating a first frequency of the XO at the first temperature, based on at least the first wireless signal, code for determining unknown coefficients of a polynomial equation comprising a relationship between frequency of the XO and temperature based on at least the first frequency and the first temperature.

BRIEF DESCRIPTION OF THE DRAWINGS

[0015] The accompanying drawings are presented to aid in the description of embodiments of the invention and are provided solely for illustration of the embodiments and not limitation thereof.

[0016] FIG. 1 is a graphical illustration of XO frequency as a function of temperature.

[0017] FIGS. 2A-B illustrate exemplary devices configured for XO temperature-calibration based on received wireless signals according to exemplary embodiments.

[0018] FIGS. 3A-C depict flow chart illustrations of exemplary methods of temperature-calibrating an XO based on one or more sets of received wireless signals.

[0019] FIG. 4 illustrates an exemplary wireless device configured for XO temperature-calibration based on received wireless signals according to exemplary embodiments.

DETAILED DESCRIPTION

[0020] Aspects of the invention are disclosed in the following description and related drawings directed to specific embodiments of the invention. Alternate embodiments may be devised without departing from the scope of the invention. Additionally, well-known elements of the invention may not be described in detail or may be omitted so as to not obscure the relevant details of the invention.

[0021] The word "exemplary" is used herein to mean "serving as an example, instance, or illustration." Any embodiment described herein as "exemplary" is not necessarily to be construed as preferred or advantageous over other embodiments. Likewise, the term "embodiments of the invention" does not require that all embodiments of the invention include the discussed feature, advantage or mode of operation.

[0022] The terminology used herein is for the purpose of describing particular embodiments only and is not intended to be limiting of embodiments of the invention. As used herein, the singular forms "a", "an" and "the" are intended to include the plural forms as well, unless the context clearly indicates otherwise. It will be further understood that the terms "comprises", "comprising,", "includes" and/or "including", when used herein, specify the presence of stated features, integers, steps, operations, elements, and/or components, but do not preclude the presence or addition of one or more other features, integers, steps, operations, elements, components, and/or groups thereof.

[0023] Further, many embodiments are described in terms of sequences of actions to be performed by, for example, elements of a computing device. It will be recognized that various actions described herein can be performed by specific circuits (e.g., application specific integrated circuits (ASICs)), by program instructions being executed by one or more processors, or by a combination of both. Additionally, these sequence of actions described herein can be considered to be embodied entirely within any form of computer readable storage medium having stored therein a corresponding set of computer instructions that upon execution would cause an associated processor to perform the functionality described herein. Thus, the various aspects of the invention may be embodied in a number of different forms, all of which have been contemplated to be within the scope of the claimed subject matter. In addition, for each of the

embodiments described herein, the corresponding form of any such embodiments may be described herein as, for example, "logic configured to" perform the described action.

[0024] Embodiments described herein may generally pertain to a crystal oscillator (XO) in a device configured for GNSS or GPS applications. More particularly, an exemplary XO is "uncompensated," which refers herein to an XO which lacks built-in temperature or voltage compensation (or in other words, an XO which comprises a lack of built-in compensation) to account for frequency variation, in contrast to the aforementioned TCXO and VCTCXO, which have temperature and/or voltage compensation on the TCXO and/or VCTCXO device. The description of embodiments may simply make reference to an XO, and it will be understood hereinafter that such a reference will pertain to an uncompensated XO, unless otherwise specified. Therefore, exemplary embodiments may be configured to overcome the problem associated with large frequency variation in the XO by calibrating the XO. As used herein, the term "calibration," or more specifically, "temperature-calibration," pertains to a relationship between frequency and temperature (also known as a "frequency-temperature relationship" or "FT relationship" or "FT model" or "FT curve") of the XO, formulated to a high degree of accuracy, whereby the frequency of the XO can be determined from the formulated relationship at any given temperature. While in some cases, the more general term, "calibration," may be used, it will be understood that "calibration" refers to "temperature-calibration" as it pertains to the exemplary embodiments, wherein temperature-calibration generally means determination of an FT relationship or FT model for the XO.

[0025] Moreover, temperature-calibration of the XO in exemplary embodiments may also be distinguished from precalibration of the XO during manufacture or in factory settings. Precalibration, factory-based calibration, or hereinafter, "factory-calibration," as used herein, pertains to calibration of the XO in factory settings before it is placed in the field or under operational conditions. Factory-calibration is limited to the frequency offset at nominal temperature. Calibrating each XO across a broad range of temperatures in the factory is time and cost prohibitive. Therefore, factory-calibration is generally insufficient for reliable operation of the device during operation or in field conditions. Therefore, embodiments are directed to field-calibration, or more specifically, temperature-calibration in the field, of the XO, which pertains to temperature-calibrating the XO during operation of the device comprising the XO, after the device

has left the factory, is integrated into a mobile device, and is put in use, for example, by the end user of the mobile device. Accordingly, it will be understood that the term "calibration" as used herein, refers to field-calibration, and more specifically, temperature-calibration in the field, during operation of the device, and excludes any precalibration that may exist in the XO.

[0026] With the above definitions in mind, exemplary embodiments are directed to temperature-calibration (i.e., temperature-calibration in the field) of the XO using one or more wireless signals of known frequency. As described herein, "wireless signals" (or sometimes, more generally, signals received by an exemplary receiver, or "received signals") include satellite signals from satellite sources such as GNSS. Additionally, and optionally, in some aspects, wireless signals may also include terrestrial signals from terrestrial sources (or more particularly, "calibrated terrestrial sources" which have known frequency with negligible frequency variation) such as, some wireless wide area networks (WWAN) such as code division multiple access (CDMA), and some long term evolution (LTE) networks. In general, when compared to terrestrial signals, temperature-calibration performed using satellite signals may have beneficial aspects based on relative imperviousness to user motion. In more detail, when the device is in motion, for example, transported by a user on a freeway, large variations in "Doppler," or shift in frequency, are introduced in terrestrial signals, say when the device approaches or moves away from a base station. On the other hand, the impact of user motion is significantly smaller on the Doppler of satellite signals, due to the large distances between the device and the satellites, as well as, the speed of motion of the satellites when compared to the distances traversed by the device and the velocity of the device. Therefore, temperature-calibration can be performed using satellite signals, even when the device is in motion. Moreover, due to the above beneficial aspects of satellite signals, a smaller temperature range (e.g., within a variation of 2.5^0C), at which frequencies are sampled, may be sufficient to temperature-calibrate the XO. However, it is possible to augment, or replace, satellite signal based temperature-calibration of an exemplary XO with terrestrial signals, in scenarios where terrestrial signals are available and temperature-calibration based on the terrestrial signals is feasible. In general, a common aspect of the wireless signals – both satellite signals and terrestrial signals – is that these wireless signals have known frequency. As used herein, "known frequency" of a wireless signal, particularly in the case of satellite signals, is intended to mean that

frequency of the wireless signal is predetermined or determinable, from additional information (referred to herein as "GNSS assistance information"), such as, but not limited to, GNSS Ephemeris and/or Almanac or velocity of the device. As one of ordinary skill in the art would recognize, Almanac provides a course position and time and Ephemeris provides a fine position and time for each satellite. If Ephemeris is available, Almanac may not be necessary. On the other hand, if only Almanac is available, Doppler may be estimated with the Almanac information in some cases. Each satellite broadcasts its own Ephemeris (for that satellite only) and Almanac for all of the satellites. Location servers typically have Ephemeris for all visible satellites and Almanac available for download.

[0027] For calibrated terrestrial sources, the known frequency can be obtained in a more straightforward manner, for example, based on the WWAN or CDMA transmission frequency. However, it will be understood that one or more of the wireless signals of known frequency may have an associated "Doppler" or shift from the known frequency, based on factors such as, speed or relative speed of the signal source. This Doppler would optimally be accounted for, for example, by taking multiple samples across a longer period of time, in order to determine whether there is a variation in velocity, and by determining a nominal frequency. As seen from the above, in some cases, the Doppler of a wireless signal of known frequency can be constant and of a known value. However, in some other cases, the Doppler may vary. The variation in Doppler sometimes may be known or determinable, however, in some cases, the Doppler variation may not be known and further, may not be easily determinable or predictable. The wireless signals of known frequency (or hereinafter, simply, "wireless signals") may be used to derive frequency estimates of the XO at the device. If the Doppler of the one or more wireless signals used in obtaining the frequency estimates is unknown, then a plurality of wireless signals may be used to determine and offset the Doppler values. On the other hand, a known Doppler source (e.g., a Doppler-true or zero Doppler source, such as a geostationary source) can also be used in the temperature-calibration process where a single known Doppler source would suffice (wherein a plurality would not be needed for offsetting the Doppler in calculations of frequency estimates). In either case, frequency estimates are obtained at various operating temperatures and associated with the operating temperatures to form sample points comprising frequency estimates and operating temperatures. Based on the

implementation, the number of such sample points required to temperature-calibrate the XO or form the FT model may vary.

[0028] In exemplary embodiments, signals from one or more satellites sources are used to derive a frequency estimate at a given operating temperature. The minimum number of satellite sources required to obtain the frequency estimate of the XO may be dependent on various scenarios. In general, three satellites may be sufficient to obtain the location or position of the device with an assumed altitude. With a fourth satellite, the altitude of the device can also be solved for. In some cases, location can also be obtained through other means, such as, via a cell sector center or the location of a terrestrial transmitter. In these cases, one satellite signal and known Ephemeris, or a terrestrial transmission of known and reliable frequency, may suffice for obtaining the frequency estimate of the XO. Note that in embodiments which only utilize terrestrial wireless signals of known frequency, Ephemeris, time, and location are not required. In cases where only satellite or GNSS signals are relied upon, the GNSS location fix or position fix can provide a location that may be used, along with GNSS Ephemeris information, to determine the frequency of the XO. Obtaining a position fix for the device can essentially compensate for the Doppler of the various received satellite signals, due to the motion of the GNSS satellites, and therefore, the actual frequency of the received satellite signals can be known. The actual frequency can be correlated to the frequency of the XO, and correspondingly the variation in the frequency of the XO from an expected nominal XO frequency can be calculated and associated with the temperature at which the above operation is performed. In some cases, if the altitude of the device is known, then satellite signals from three satellite sources are sufficient to obtain the fix, and therefore for estimating frequency and temperature-calibration of the XO. Similarly, knowing an approximate location of the device can also bring down the minimum number of satellites required for temperature-calibration. An approximate location may be obtained through various means. In one example, relying on terrestrial sources, a cell sector center for a serving cell can be used to obtain an approximate location. If Ephemeris and Almanac are known, they may be used, in conjunction with the location of the mobile device, to determine the Doppler shift for at least one satellite signal and, consequently, the actual frequency of the received signal may be determined to estimate the frequency of the XO. Thus, the minimum number of signal sources may vary for different embodiments, but once the device has searched for, and locked on to the

minimum number of signal sources based on particular situations and criteria, wireless signal(s) can be received from these signal sources, and frequency estimates for the XO can be derived from the received wireless signals.

[0029] In some embodiments temperature-calibration of the XO can be based on wireless signals received from at most one signal source. These embodiments may pertain to situations wherein a minimum plurality of satellite sources (e.g., three or four, depending on the scenarios described previously) required for a GNSS fix and/or terrestrial sources which can provide a GNSS fix are unavailable and/or situations wherein power levels of GNSS signals is low, requiring a longer, more time consuming search. As used herein, the term "unavailable," as it pertains to signal sources, refers to lack of availability of signals from the signal source at the device comprising the XO. For example, a signal source may be unavailable with respect to the device when it is not in the line of sight or plain view of the device, when signals from the signal source are prevented from reaching the device due to any reason, such as distance or obstructions, or when the device cannot easily receive signals from the signal source for any reason, including lack of capability for reception (e.g., the device may not be configured for WWAN and thus not be capable of receiving signals from a calibrated terrestrial source such as WWAN), or where the amount of time or power required to receive the signals is prohibitively high. Accordingly, for temperature-calibrating the XO according to these embodiments, the device may first search for signal sources and determine whether a minimum number of satellite sources and/or calibrated terrestrial sources for obtaining a GNSS fix are available (keeping in mind that in some aspects a specific search may not be required, as the device can be configured to rely on information, obtained for example, from a user, or other configuration information, in order to determine or assume that a minimum number of satellite sources and/or calibrated terrestrial sources for obtaining a GNSS fix are unavailable). Thereafter, the device may nevertheless be configured to temperature-calibrate the XO based on assistance from a single or at most one signal source when the at most one signal source has a "known Doppler." As used herein, the term "known Doppler" can refer to a signal source whose Doppler is known or can be precisely determined. In one example, the known Doppler can be zero. A zero Doppler source is also known as a Doppler-true or Doppler-accurate source. Doppler-true sources can be geo-stationary, which guarantees that their Doppler is 0Hz at all times. Doppler-true sources can also include stationary

terrestrial sources. A satellite based augmentation system (SBAS) is an example of a Doppler-true source which can be utilized in this embodiment. Another example of a known Doppler is a non-zero Doppler source, such as a GNSS satellite vehicle whose position and velocity are known (e.g., based on Satellite Ephemeris and/or Almanac), which may be utilized in these embodiments when at least a coarse location of the device is known, and further at least a coarse time at the device is known. When feasible (e.g., when a SBAS vehicle or other stationary signal source of known frequency is available), the temperature-calibration of the XO based on a single known Doppler source can beneficially reduce search time and computation time associated with the XO temperature-calibration in these embodiments. In the case where the single known Doppler signal source is a satellite source (e.g., SBAS vehicle), the device may obtain a position estimate for the device from a positioning determining entity (PDE) (e.g. as known in the art for CDMA systems), or more generally, a positioning server or location server, which covers other air interfaces. The position estimate or location of the device can also be obtained from an approximate location derived from terrestrial signals (e.g. using cell sector center of the serving cell or trilaterating terrestrial signals, wherein looking up the cell sector location can be done using a positioning server or on device 100 if it has a base station Almanac), location derived from a positioning server or a positioning determining entity (PDE) or a location server Once the location is known, using Ephemeris and time, the received wireless signal can be used to determine an effective frequency of the satellite constellation. This effective frequency derived from the received wireless signal can be compared with the frequency of the local oscillator, in order to obtain the frequency estimate for the XO. In cases where the known Doppler signal source is not a satellite source (e.g., if the signal source is a calibrated terrestrial source such as WWAN or other fixed frequency source of known frequency), and if the device is stationary, then the known fixed frequency is treated as the effective frequency which is compared with the frequency of the local oscillator in order to obtain the frequency estimate for the XO.

[0030] A detailed description of the configuration and operation of devices according to the above exemplary embodiments will now be provided with reference to the figures.

[0031] With reference to FIG. 1, the formulation of the frequency-temperature (FT) relationship (also known as, FT curve or FT model) for the XO will be discussed in detail. More particularly, the formulation of the FT model pertains to field calibration

of the XO, e.g., during mobile device operation related to GNSS-based positioning applications of an exemplary mobile device. The FT model can be expressed as a polynomial equation or function, wherein frequency is expressed as an n^{th} degree polynomial function of temperature. At least some of the parameters or coefficients of this polynomial equation are unknown quantities for an XO and accordingly, an objective of the XO temperature-calibration can comprise determining or refining the coefficients of the FT model for the XO. In general, the number of coefficients will vary proportionally with the value of "n" or the degree of the polynomial. However, in exemplary embodiments, certain constraints can be imposed to make reasonable assumptions regarding the value of one or more coefficients, such that the number of coefficients that are unknown, and need to be determined, may be reduced. The unknown coefficients are determined using the aforementioned samples of frequency estimates of the XO at associated temperatures. The number of samples required for the temperature-calibration of the XO will vary based on the number of coefficients that need to be determined. Accordingly, by reducing the number of unknown coefficients, the temperature-calibration of the XO can be performed with fewer samples, which correspondingly leads to advantages in terms of increased speed and efficiency of the temperature-calibration process.

[0032] In FIG. 1, FT curves FT1 and FT2 are based on a third degree (i.e., n = 3) polynomial equation for exemplary XOs. Each of these FT curves can be represented by the third order polynomial equation: $f(T) = c_3(T-T_0)^3 + c_2(T-T_0)^2 + c_1(T-T_0)^1 + c_0$, where $f(T)$ is the function of frequency f of the XO with variation in temperature T, T_0 is a constant, typically, room temperature (e.g., 30°C), and c_0-c_3 are the parameters or coefficients to be determined to temperature-calibrate the XO. The elements c_0-c_3 are the parameters of the polynomial equation, which are to be determined in an exemplary process. Once the coefficients are determined with a high degree of precision, FT curves such as FT1/FT2 can be plotted, and frequency of the corresponding XO can be read or determined from the FT curve for any given temperature. While the discussion herein will pertain to third degree polynomial equations for exemplary FT curves, it will be understood that the embodiments may be easily extended to polynomial equations of any degree (e.g., n = 4, 5, etc.), or for that matter, any mathematical expression or function of any order or degree for representing the FT model for exemplary XO temperature-calibration, without departing from the scope of this disclosure.

[0033] In some embodiments, the device comprising the XO can be configured to receive wireless signals from one or more satellite sources and additionally, in some cases, from one or more calibrated terrestrial sources. Based on these received wireless signals, a GNSS location can be obtained, if needed, and a frequency error in the XO can be computed, based upon at least one frequency reference. Using the nominal/expected frequency of operation of the XO and the computed frequency error in the XO, a frequency estimate, say a first frequency estimate, of the XO can be obtained. A reading of the temperature, say a first temperature, of the device is also obtained at the time when the frequency estimate is obtained, and a first sample comprising the first frequency estimate and the first temperature is formed. This process is repeated at a second, different temperature to obtain second sample comprising a second frequency estimate and a second temperature. In some cases, as low as two samples may be sufficient, based on certain constraints and assumptions pertaining to the coefficients c_0-c_3. In other cases, the process is repeated at other different temperatures to determine additional corresponding frequency estimates to refine the coefficient estimates.

[0034] In an illustrative example, the coefficients may be determined based on certain specifications related to the XO, which may be available, for example from a vendor or manufacturer of the XO. The coefficients may also be determined based on knowledge of operating conditions and expected range of variation in temperature of the device. It will be understood that the below discussion pertaining to determination of coefficients for the FT model of an exemplary XO are only illustrative, and they may be based on specific implementations and operating conditions. Accordingly, in one implementation, the coefficient c_0 may be a constant, and can be assumed to be of value zero (or precalibrated at a nominal temperature during manufacturing with a non-zero constant or known value), which reduces the number of unknown coefficients to three, i.e., c_1-c_3. This constant c_0 may be referred to as a DC offset in the art. In yet another optional implementation, the temperature variation of T from T_0 may be known in advance or may be constrained to be very small, and therefore, the contribution of the third order term, i.e., $c_3(T-T_0)^3$, to the polynomial function of $f(T)$, may be negligible, and therefore c_3 may be assumed to be zero. This could reduce the number of unknown coefficients to two, i.e., c_1 and c_2. Obtaining two sample points comprising first and second frequency estimates at corresponding first and second temperatures would then be sufficient to determine c_1 and c_2 and thus temperature-calibrate the XO.

[0035] Some specifications for the XO may also define the maximum range of acceptable error in the coefficients for the XO, which may determine the number of samples needed to obtain the coefficients to the specified degree of error. For example, acceptable error in c_0 may be specified to fall within the range of ±2 parts per million (ppm), and therefore setting c_0 to "*0,*" as described above would satisfy this requirement. The contribution of the term $c_1(T-T_0)^1$ to the polynomial function $f(T)$ may be significant in many cases, and therefore c_1 may need to be determined to a high degree of accuracy, or in other words, finely temperature-calibrated in the field. Some specifications may limit the error in c_1 to fall in the range of, -0.10 ppm/^{0}C to –0.40 ppm/^{0}C, for example. Some embodiments herein can achieve c_1 to within -0.10 ppm/^{0}C based on exemplary techniques to satisfy such stringent requirements. As previously discussed, a higher tolerance may be acceptable for error in the coefficient c_3 and sometimes, factory precalibration of c_3 may be sufficient. Some specifications may require error in c_3 to fall within a relatively relaxed range of 8.5e-5 ppm/^{0}C to 11.5e-5 ppm/^{0}C, and therefore, using factory precalibration values or even assuming c_3 to be zero may satisfy the error requirements in the specification.

[0036] In the illustrations of FIG. 1, for FT curve FT1, the coefficients are, c_1 = *-0.1* and c_3 = *11.5e-5*, and for FT curve FT2, c_1 = *-0.4* and c_3 = *8.5e-5*. In these examples, it can be seen that the total range of XO frequency, with an uncertainty in c_0 contained within an upper limit of 2 ppm/^{0}C, can be up to ±20 ppm for a temperature variation between 30°C and 90°C. Viewing FT1 and FT2, it can be observed that as this temperature range is widened, for example, between -40°C and 100°C, the uncertainty in XO frequency can be as high as ±34 ppm. Accordingly, some embodiments are configured to temperature-calibrate the XO by choosing the constraints and assumptions based on operating conditions such as the temperature range pertaining to the device operation.

[0037] With reference now to FIG. 2A, a simplified schematic of an exemplary device 100 configured for XO field calibration according to exemplary embodiments is illustrated. It will be noted that device 100 may be a mobile device or handheld device and may further comprise one or more components as known to one skilled in the art, but which are not illustrated in FIG. 2A for the sake of clarity (although FIGS. 2B and 4 provide other exemplary embodiments directed to devices similar to device 100, which illustrate certain other components which may be included in the exemplary devices). Device 100 may comprise receiver 102, which may be configured to receive wireless signals

from various sources such as, one or more signal sources 110a-n. In one non-limiting example, one or more of signal sources 110a-n may be satellite or GNSS sources capable of providing GNSS fixes. Additionally and optionally, one or more signal sources 110a-n may also be calibrated terrestrial sources, such as WWAN or CDMA, which can augment the temperature-calibration process, although it will be recalled that such features pertaining to calibrated terrestrial sources are purely optional and not required in the various embodiments. As described further in later sections, one of the signal sources 110a-n can also be a stationary satellite signal source such as an SBAS satellite, wherein temperature-calibration can be performed using a single SBAS satellite. Receiver 102 may be driven by clock 104 which can be sourced from XO 106. Temperature sensor 114 may be included in device 100 to sense temperature of XO 106 and provide XO manager 108 with operating temperature associated with XO 106. Temperature sensor 114 may be a discrete block on device 100 as illustrated, or in some embodiments, a thermistor, such as temperature sensor 114, may be integrated into one of the other blocks. Moreover, while temperature sensor 114 may be configured to measure temperature directly at XO 106 in some embodiments, it is also possible to configure a similar device/sensor to representatively measure or sense the required temperature on a printed circuit (PC) board or at a pin or lead external to an integrated circuit on which device 100 is integrated. XO manager 108 may be configured to obtain frequency estimates for XO 106 based on signals received by receiver 102. XO manager 108 may be further configured to associate operating temperatures provided by temperature sensor 114, and perform operations related to temperature-calibration of XO 106 according to the above-described techniques. While XO manager 108 is designated as a separate block in this illustration, the functionality and logic associated with XO manager 108 may be integrated in any processor, such as a digital signal processor or a general purpose processor, in device 100.

[0038] In FIG. 2A, one local oscillator, local oscillator 112, is illustrated as included in receiver 102. However, it will be understood that in the various embodiments described herein, one or more other local oscillators may be present in one or more other blocks. For example (as will be further described with reference to FIG. 4), an exemplary mobile device may comprise one or more receivers or transceivers configured for reception of satellite signals and one or more receivers or transceivers configured for other wireless signals such as WWAN signals. Accordingly, in some embodiments, each of those

receivers and/or transceivers may have one or more local oscillators. However, exemplary techniques described below with reference generally to local oscillator 112, can be easily extended to any other local oscillator which may be present in the device, based on the source of the particular wireless signal under consideration.

[0039] In one exemplary embodiment, receiver 102, along with one or more components not specifically illustrated in device 100, may search for a minimum number of wireless signal sources 110a-n to obtain a GNSS fix (keeping in mind, that in some embodiments, for example, device 400 of FIG. 4, separate receivers/transceivers and accompanying local oscillators may be configured for different types of wireless signals, such as satellite signals and WWAN signals). As previously explained, this minimum number of wireless signal sources 110a-n may be as low as one (e.g., when the Doppler of the signal source is known, such as in the case of an SBAS satellite), or may be three or four, depending on whether additional information, such as Ephemeris, Almanac, position of device 100, time at device 100, etc. are known. If the required minimum number of signal sources 110a-n is found, then device 100 locks on to these signal sources 110a-n to receive wireless signals from them through receiver 102. A position fix or GNSS fix is obtained using these received wireless signals, for example, at XO manager 108. The GNSS fix may provide information such as the location of device 100 and a frequency error of local oscillator 112. Using the GNSS fix, a frequency error of XO 106 can be calculated, using which, a first frequency of the XO can be estimated.

[0040] In one example, a first set of wireless signals comprising at least, three wireless signals, say, a first, second, and a third wireless signal, may be received by receiver 102, at an associated first temperature. The first, second, and third wireless signals may be from a first, second, and a third satellite respectively, such that a position fix or GNSS fix for device 100 may be obtained from at least the three wireless signals (e.g., by a process of trilateration). It will be recalled that wireless signals from three satellites may be sufficient to calculate location of the device comprising the XO if altitude of the device is known, but if altitude is unknown, then wireless signals from at least four satellites may be needed. Determining the location can also be based on additional information or GNSS assistance which may be derived from signal sources, such as calibrated terrestrial sources (e.g., WWAN, CDMA, etc.). Once location is determined based on the wireless signals, using Ephemeris and time, the frequency of the wireless signals can

be determined. Using a received wireless signal(s), the Doppler(s) of the wireless signals may be determined, allowing the frequency of the received wireless signal to be determined, which then allows deriving an effective frequency of zero Doppler (from a stationary source) or known Doppler (from a moving source or source moving relative to the receiver) from the wireless signal(s).

[0041] The Doppler of the wireless signals received from a satellite source can be determined through the use of Ephemeris or Almanac information and a known location, such as the location determined through a GNSS fix or a terrestrial estimate (such as the location of a visible terrestrial transceiver). Ephemeris information, when used in conjunction with a known location of the device can be used to predict the location, velocity, and heading of a GNSS satellite relative to the device and thus calculate the Doppler shift. Once the Doppler shift is known, the impact of the Doppler shift can be removed from the received signal frequency to determine the effective frequency of the wireless signal. If multiple wireless signals are used to determine a reference frequency at a given temperature (such as the nominal GNSS frequency, the effective frequency of the satellite constellation, or the frequency offset at that temperature), multiple frequency estimates derived from the multiple wireless signals may be combined into a single frequency estimate which can be utilized as the derived effective frequency. If Ephemeris and location are known, wireless signals received from a single satellite can be used to derive the effective frequency of the satellite signal. Note that the satellites in a given GNSS constellation generally broadcast at the same effective frequencies. Similarly, a single terrestrial wireless signal of known frequency can be used to derive the effective frequency of the terrestrial signal source. Effective frequency can also be derived from multiple wireless signals when Ephemeris for each GNSS satellite and location of the mobile device are known. The effective frequencies, as derived from the multiple wireless signals, can be combined in several ways to obtain a "derived effective frequency," which can be based on the effective frequency derived from one or more of the multiple wireless signals. For example, a first effective frequency can be derived from a first wireless signal, a second effective frequency from a second wireless signal, and a third effective frequency from a third wireless signal, wherein the derived effective frequency can be based on one or more of the first, second, and third effective frequencies. However, it will be kept in mind that while sometimes it may be possible to derive an effective frequency (e.g. first, second, and third effective frequencies) from

each of the received wireless signals, in some cases the effective frequency may be obtained from fewer than all of the received wireless signals (e.g., only one wireless signal in some cases). In some embodiments, multiple satellite signals may be required to determine an initial location. In other embodiments, location can be determined via a previously saved location, or via terrestrial wireless signals, such as by utilizing a cell sector center derived either locally on the device or on a location server by looking up the serving cell in a base station Almanac, or by trilaterting a position based on terrestrial signals. In any case, in embodiments utilizing GNSS signals, once a location is determined, not all of the wireless signals may be required for the purposes of estimating the frequency of the XO at a given temperature. In embodiments utilizing terrestrial signals, only one wireless signal is sufficient for estimating the frequency of the XO at a given temperature. For example, in one embodiment, once the location is determined, the effective frequency (e.g. first effective frequency) may be derived from the strongest signal and may be used as the derived effective frequency based on all of the received wireless signals. In another embodiment, frequencies (or effective frequencies when Ephemeris and location are known) may be derived from multiple wireless signals (e.g., first, second, and third effective frequencies), which may be combined as stated above to obtain an overall effective frequency, or derived effective frequency, of the multiple signals. For GNSS signals, the derived effective frequency is an estimate of the frequency of the GNSS satellite signals, which is typically shared among the satellites in the GNSS constellation. The combination can be based on schemes such as a weighted average obtained by weighting and averaging the signal frequencies such that the effective frequency derived from the strongest or several of the strongest of the received signals is/are weighted more heavily and the effective frequency derived from the weaker signals are afforded less weight. In another embodiment, the effective frequency may be derived from the frequency of the strongest of the received signals while also utilizing the frequency from each of the other received signals, which are weaker. Other combination mechanisms for obtaining the derived effective frequency of the multiple signals can include a mean, a median, a geometric mean, a least squares fit, or other pre-specified mathematical fit of the effective frequencies derived from the multiple wireless signals, such as, the first, second, and third effective frequencies. By using Ephemeris to determine predicted Doppler offset for each of the one or more signals (wherein multiple signals may be combined to obtain

a derived effective frequency), the respective Doppler shift of the signals can be corrected for to obtain each effective frequency prior to calculating the derived effective frequency. Once the Doppler of the received wireless signals is accounted for, the derived effective frequency can be obtained, which may be used to estimate a frequency error, say first frequency error, of XO 106 (a further detailed process for estimating the frequency error from the effective frequency of known or zero Doppler derived from a received wireless signal will be provided in the following sections).

[0042] XO 106 may be configured for a nominal or reference frequency, such as 19.2 MHz. A first frequency error can be an offset of the effective frequency from the reference frequency. Therefore, using the first frequency error and the reference frequency, a first frequency estimate of XO 106 can be obtained. Temperature sensor 114 can supply the first temperature at which the first frequency estimate is obtained in this manner from the three wireless signals. XO manager 108 can then form a first sample comprising the first frequency estimate and the first temperature. The process of temperature-calibrating the XO can be started with this first sample comprising the first frequency and the first temperature.

[0043] In some examples, the process of temperature-calibration can be completed with the first sample, (e.g., in a case where the degree n of the polynomial equation is low enough that one sample point can sufficiently complete the temperature-calibration process, or in a case where the factory precalibration or assumptions made for the coefficients make it possible to complete the temperature-calibration with just one sample point). However, if for example, the temperature-calibration is not completed with the first sample, (e.g., not all of the coefficients of the polynomial equation have been determined with required or desired precision), the process can comprise further temperature-calibrating the XO. As described herein, "further temperature-calibrating" comprises proceeding with or refining the temperature-calibration (i.e., determining the coefficients of the FT model) with additional sample points. Additional sample points may be obtained, for example, from a second frequency obtained using a second set of at least one wireless signal, third frequency obtained using a third set of at least one wireless signal, etc., at respective second temperature, third temperature, etc. The number of samples may be based on the number of unknown coefficients which need to be determined for the FT model pertaining to XO 106. If the FT model is a third order polynomial and c_0 is a DC value of zero as previously explained, then three such

samples may be needed to obtain the remaining unknown coefficients c_1-c_3 (keeping in mind that c_3 may be constrained to be zero in some cases, and thereby reducing the number of samples to two).

[0044] In one embodiment, the temperature-calibration of the XO can be performed using a single signal source of known Doppler, for example, in situations where the minimum number of signal sources 110a-n, as above, may not be available, or where device 100 is configured to attempt temperature-calibration with a single source of known Doppler first, if such a source is available. For example, when receiver 102, along with one or more components not specifically illustrated in device 100, searches for a minimum number of wireless signals from signal sources 110a-n to obtain a GNSS fix, it may be determined that this minimum number of signal sources is unavailable (e.g., first, second, and third wireless signals from first, second, and third satellites, as above, may not be available) and device 100 may search for a signal source with known Doppler, and if one is available, then, in this embodiment, device 100 may be configured to temperature-calibrate XO 106 based on a single signal source of known Doppler. In other embodiments, the mobile device may be configured to attempt temperature-calibration with a single signal source of known Doppler first, and if that single signal source of known Doppler is not available, then attempt temperature-calibration with multiple sources. If receiver 102 receives a first set of wireless signals which comprises a first wireless signal from a first satellite or signal source of known Doppler, the temperature-calibration may be performed based on the first wireless signal from that signal source of known Doppler. In other embodiments, if an approximate location of the device is known, the device may default to using a single GNSS signal source of known frequency in conjunction with satellite Ephemeris information and may skip a search for additional GNSS signal sources. In another embodiment, a terrestrial source of known frequency is sufficient to temperature-calibrate the XO and a location is not required. As previously explained, a known frequency signal source may be either a Doppler-true source such as a geostationary source (e.g., SBAS or terrestrial transmitter), or a non-zero Doppler source such as a GNSS or other satellite vehicle of known position (e.g., a position that may be determined utilizing Ephemeris and/or extended Almanac or other Ephemeris-related source of information), when at least a coarse position and time at device 100 is known. Accordingly, the term “known

Doppler" as used herein, can indicate a constant known value such as zero or a determinable quantity.

[0045] The process of frequency estimation of the XO will now be provided, with reference to a case where the Doppler of the received wireless signal is a constant known value or determinable quantity. It will be recalled that once the wireless signal of known Doppler (including wireless signals with zero Doppler) is received, the frequency estimation process herein is similar in many aspects to the case where the effective frequency is determined from frequencies derived from a minimum number (e.g., three) of wireless signals, such as the first, second, and third wireless signals from respective first, second, and third satellites (wherein these satellites are utilized to calculate a location of the device and wherein the frequency estimates received from each of these satellites may be combined, or selected between, in order to optimize the frequency estimate). With continuing reference to FIG. 2A, receiver 102 may be configured to search for and receive signals from, say, signal source 110a which is of known Doppler. Local oscillator 112 may be any generic local oscillator configured to oscillate at a nominal frequency such as a GPS L1 center frequency or a GPS L1 carrier frequency. Similarly, for a terrestrial wireless signal from a terrestrial source or calibrated terrestrial source, local oscillator 112 may be configured to oscillate at the expected nominal frequency of the terrestrial source, such as the standard frequency of the terrestrial wireless signal. Local oscillator 112 may be sourced from XO 106, such that a variation of frequency in XO 106 is proportionally reflected as a frequency variation in local oscillator 112. In one numerical example, local oscillator 112 may be configured for a nominal frequency of 1575.42 MHz, which will be recognized by the skilled person as a GPS L1 center or carrier frequency, or other known frequency. Further, as previously mentioned, XO 106 may be configured for a typical or reference frequency of 19.2 MHz.

[0046] In one example, signal source 110a is a Doppler-true source (e.g., a geo-stationary source, such as a SBAS satellite vehicle (SV), wherein the Doppler of received signals at receiver 102 from the Doppler-true source is zero). In an illustrative example, frequency variation of XO 106 is initially assumed to be an unknown, say "δf" parts per million (ppm). Accordingly, the frequency variation "δF" in ppm of local oscillator 112, which is sourced from XO 106 (i.e., is a multiple of the frequency of XO 106) will also be equal to δf ppm. Thus, frequency variation of local oscillator 112 can be first

calculated, based on signals obtained from the Doppler-true signal source 110a, in order to determine the value of δf. Once the frequency variation δf of XO 106 is known, the frequency of XO 106 can be estimated based on frequency variation δf and the expected reference frequency of XO 106. In this numerical example, since local oscillator 112 is configured to oscillate at the expected nominal frequency of the signal source, e.g., 1575.42 MHz, which corresponds to that of the Doppler-true signal (because there is zero Doppler or variation from the nominal frequency), a comparison of the frequency of the received signal at receiver 102 with the frequency of local oscillator 112 can reveal the frequency uncertainty of local oscillator 112. This is because the Doppler-true signal from signal source 110 is assumed to not have any frequency uncertainty of its own, and therefore, the frequency of the Doppler-true signal can be predicted as zero in the calculations pertaining to XO temperature-calibration. A band pass filter, as is known in the art (not specifically illustrated, but may be present in one of the illustrated blocks, such as, within XO manager 108), can be used to reveal the difference, "ΔF" between the measured nominal frequency of local oscillator 112 and the predicted true Doppler (i.e., zero) of the received signal from signal source 110a. In other words, ΔF provides the frequency uncertainty or the amount the frequency of local oscillator 112 deviates from the precise nominal frequency of the received signal at 1575.42 MHz. This value of ΔF can then be normalized by dividing ΔF with the nominal frequency 1575.42 MHz in order to obtain the frequency variation of local oscillator 112 as δF ppm. As previously discussed, the frequency variation δf of XO 106 and therefore, the absolute variation Δf of XO 106 from the expected reference frequency of 19.2 MHz can now be calculated. Accordingly, the frequency of XO 106 can be estimated with a high degree of precision, as, say, the first frequency estimate, and associated with the first temperature, which will be supplied by temperature sensor 114. In this manner, a first sample comprising the first frequency estimate and the first temperature can be formed, and the process of temperature-calibration or determination of coefficients of the FT model for XO 106 can be started with the first sample point. The above process can be repeated at different operating temperatures to obtain further such samples comprising frequency estimates and associated temperatures (e.g., a second frequency estimate at a second temperature, and a third frequency estimate at a third temperature, etc.) to further temperature-calibrate XO 106 or to determine the coefficients of the FT model for XO 106 with higher precision.

[0047] In another example, one of the signal sources, say signal source 110n may be determined to be a known Doppler source, whose Doppler is a non-zero value. The Doppler of such a source can be determined or predicted or "known" according to when its position is known. Position of signal source 110n can be obtained in several ways which have been previously described. For example, position of a GNSS signal source can be determined based on satellite Ephemeris, assuming that a coarse location and GNSS time is available. The position or location of device 100 may be available from a prior location fix or it may need to be determined, for example, through trilateration of GNSS or terrestrial signals or through cell sector center of the serving cell. GNSS time may be available from a terrestrial network source or may be determined directly from the GNSS satellite signals. With regard to location of device 100, while in this embodiment, device 100 is preferably stationary for purposes of temperature-calibration using signals from a signal source 110n of known position, it is possible to extend exemplary techniques to cases where device 100 is in motion, but position, as well as, relative Doppler of device 100 is precisely known. For example, a GNSS fix can be utilized to determine velocity and heading of device 100 which may be used to determine a resultant or combined Doppler due to motion of device 100 and of signal source 110n. With regard to determining a local time at device 100, a clock on device 100, such as clock 104 may need to have at least a coarse correlation to GNSS time, and/or in some cases, uncertainty in the local clock must be very low. Moreover, in some cases, temperature-calibration of XO 106 may be improved by imposing threshold requirements for quality of the wireless signals received from signal source 110n. For example, embodiments may require the received signals from the GNSS satellite vehicle (SV) to satisfy a pre-specified signal to noise ratio (SNR) and/or pass pre-specified error/parity checks, in order to utilize the received wireless signals for XO temperature-calibration. Imposing such requirements or standards on the strength and accuracy of the received signals can improve efficiency and accuracy in the temperature-calibration process.

[0048] Accordingly, when the position of signal source 110n is known (and Ephemeris, in the case of satellite sources), the position of device 100 is known, a coarse time at device 100 is known, and signals received from signal source 110n meet pre-specified quality standards, the Doppler of signal source 110 can be known (i.e., predicted or determined to high degree of accuracy). Using the known non-zero Doppler value, the process of

temperature-calibration of XO 106 is substantially similar to the process of temperature-calibration of XO 106 outlined above for the case of a Doppler-true source, with only minor variations, notably, to replace the previously used zero Doppler value with the known non-zero Doppler value (say, ΔS) in the calculations. The remaining detailed aspects of the calculations pertaining to temperature-calibration of XO 106 will not be repeated herein, for the sake of brevity.

[0049] In some cases, as an alternative to using GNSS Ephemeris, extended terrestrial receiver assistance (EXTRA) assistance (or other time-extended ephemeris information) may be used instead of the most recent GNSS Ephemeris information. For example, device 100 is in motion, EXTRA assistance, such as extended Almanac corrections, may be available, wherein, once receiver 102 becomes capable of tracking a signal source 110a-n comprising a GNSS SV, a difference in measured speed and expected speed of device 100, can be obtained. This difference can be translated to a bias in frequency of XO 106. For example, if the received signal from the GNSS SV has strong carrier to noise ratio (C/N_0), and the speed and heading (or vector speed) of device 100 can be measured with high confidence, the received GNSS signal can be used for obtaining an estimated frequency uncertainty (e.g., ΔF) of local oscillator 112. More specifically, the frequency estimate may be based on a difference between a measured Doppler of the received signal from the GNSS SV and a predicted Doppler based on the vector speed or speed and heading of device 100 (e.g., a prediction based on an expected GPS L1 center frequency and the speed).

[0050] Accordingly, it is seen that exemplary embodiments can accomplish temperature-calibration of XO 106 using only one signal source with known Doppler (of zero or non-zero value). For example, some embodiments may perform XO temperature-calibration with a single signal source, for example, in situations where a required minimum number of satellite sources or calibrated terrestrial sources for obtaining a GNSS fix are unavailable. Moreover, some embodiments may optionally determine (e.g., based on a signal search) whether a calibrated terrestrial source or a plurality of GNSS satellite signals for XO temperature-calibration are unavailable, prior to selecting and performing exemplary above-described operations pertaining to XO temperature-calibration using only one signal source with known Doppler.

[0051] Referring now to FIG. 2B, another exemplary device 200, for XO temperature-calibration using received wireless signals is illustrated. More particularly, device 200

is illustrated with components and logic elements which may be used for temperature-calibration of the XO using received GNSS signals (while it will be understood that this depiction is only exemplary, and does not limit alternative implementations which may rely on one or more of the other types of wireless signals which have been described herein for use in XO temperature-calibration). As seen, device 200 is shown with several additional components or blocks, in comparison to the depiction of device 100. The function of these additional components will be described in an exemplary configuration of device 200. In device 200, GNSS receiver 202 may be configured to receive GNSS signal 203, for example, from a GNSS satellite vehicle (e.g., signal sources 110a-n of FIG. 2A). GNSS receiver 202 may include a local GNSS clock generator 214 which may comprise a local oscillator sourced from an XO in device 200 (the local oscillator and XO are not explicitly shown in this depiction). The received GNSS signal 203 may pass through GNSS baseband processor (BP) & GPS accumulator (GACC) 204 and GNSS correlation processor (CP) & GACC 206 which may be configured to accumulate energy from searching for GNSS satellite signals, for a selected time period corresponding to a measurement duration. Measurement engine (ME) 208 can comprise measurement controller (MC) 212, channel controller 216 and adder 218. Overall, ME 208 can be configured to compile a report of all GNSS SV measurements 209 and transfer it to position engine (PE) 210. PE 210 may use measurements 209 to compute location information for device 200. If PE 210 is successful in calculating the location information, it may further provide clock frequency bias 211 to measurement controller (MC) 212, which may be applicable at a point in time corresponding to a middle of the measurement duration. Clock frequency bias 211 may relate to a variation in clock frequency or representatively, a variation in frequency of the local oscillator from its expected frequency (e.g., ΔF from the above embodiment related to device 100). XO frequency error 219 (e.g., Δf from above), can be obtained from ME 208 using MC 212 and adder 218. XO frequency at a given temperature can be calculated by ME 208 based on XO frequency error 219 and an XO frequency estimate provided by XO frequency estimation block 220. Also note that a communications transceiver, such as transceiver 440, for example, may similarly receive terrestrial wireless signals for XO temperature-calibration, as is discussed relative to FIG. 4.

[0052] In more detail, GNSS receiver 202 may be configured to use XO frequency error 219 to apply any correction as needed to front end rotators configured in GNSS BP & GACC 204. XO frequency error 219 is passed on to XO manager 228. XO manager 228 may comprise XO field calibration block 230 configured to solve the FT polynomial equation pertaining to the XO using received values of XO frequency error 219 and associating them with operating temperature received from XO & power management integrated circuit (PMIC) temperature block 234. In other embodiments, the thermistor or other temperature sensor 114 may be discrete or integrated into other integrated circuits. As a result of solving the FT polynomial, coefficients (e.g., c_0-c_3 as discussed above) can be obtained and stored in the block, XO coefficients 232. It will be understood that thermistors used in the XO & PMIC temperature block 234 can pertain to one or more XOs and can comprise any other thermistor that impact error or temperature of the XOs. Additionally, XO & PMIC temperature block 234 may be further configured to provide temperature information to both XO thermal frequency estimation block 224 (located in XO frequency estimation block 220). In some embodiments, XO temperature-calibration can optionally and additionally integrate assistance from calibrated terrestrial sources, although it will be understood that such optional assistance from calibrated terrestrial sources is not required, and exemplary embodiments are configured to perform XO temperature-calibration even in situations where such assistance is unavailable, unviable, and/or undesired. Accordingly, total frequency estimation block 222 may take into account, an input from an optional WWAN frequency assistance block 226 in some embodiments. Another input may be derived from XO thermal frequency estimation block 224.

[0053] In this manner, exemplary embodiments may implement functionality of the various above-described blocks of device 200 in order to temperature-calibrate the XO using GNSS signal 203. In some embodiments, device 200, for example, with the use of ME 208, may be selective on the received signals which are used for XO temperature-calibration. For example, selection criteria may be applied to ensure quality of received GNSS signal 203 prior to basing frequency estimation for XO temperature-calibration based on the received GNSS signal 203. One such selection criterion can involve assigning a pre-specified maximum tolerable error in clock frequency based on the received GNSS signal 203. For example, if the error in clock frequency based on a received GNSS signal 203 is above a maximum tolerable error, such as, 3ms, the

received GNSS signal 203 may not be used for assistance to derive frequency estimates. Conditions may also be imposed on other aspects, such as a maximum tolerable position error, for example, as derived from PE 210. In some embodiments, if a horizontal estimate of position error (HEPE) is greater than a predetermined threshold, such as 50m, then, XO temperature-calibration may not be performed under such conditions. Similar other conditions or criteria may be imposed to ensure quality of XO temperature-calibration.

[0054] It will be appreciated that embodiments include various methods for performing the processes, functions and/or algorithms disclosed herein. For example, as illustrated in FIG. 3A, a first embodiment can include a method of temperature-calibrating an uncompensated crystal oscillator ("XO," e.g., XO 106), in a mobile device (e.g. device 100) during mobile device operation (i.e., field calibration), the method comprising: receiving a first set of wireless signals comprising at least a first wireless signal of known frequency, at a first temperature (e.g., one or more wireless signals received by receiver 102 from signal source 110a, wherein signal source 110a may be a satellite with known frequency, such as the GPS L1 frequency, and further, in some cases, a satellite with known Doppler, such as zero Doppler when the satellite is an SBAS or geo-stationary satellite or a terrestrial source of known frequency) – Block 302; estimating a first frequency of the XO (e.g., by determining a frequency variation ΔF of local oscillator 112 sourced from XO 106 as a difference in frequency between the frequency of the first wireless signal (i.e., GPS L1 frequency) and the frequency of the local oscillator F, normalizing the frequency variation of the local oscillator based on an expected nominal frequency of the local oscillator (e.g., GPS L1 frequency or a terrestrial wireless signal's carrier frequency), determining a normalized frequency of the XO (δf) as equal to the normalized frequency of the local oscillator (δF), and determining the first frequency (f) based on the normalized frequency of the XO and an expected nominal frequency of the XO (e.g., 19.2 MHz) at the first temperature (e.g. supplied by temperature sensor 114), based on at least the first wireless signal – Block 304; and temperature-calibrating the XO based on the first frequency and the first temperature (e.g., by starting the process of formulating the FT model or polynomial equation for XO 106, for example, using logic or means in XO manager 108, using a first sample point comprising the first frequency and the first temperature) – Block 306. A frequency tolerance or maximum frequency error at a given temperature can be pre-

specified for the temperature-calibration, in order to determine whether the temperature-calibration process is completed, or in other words, whether frequency error has been determined within the pre-specified tolerance for that temperature.

[0055] Accordingly, if the temperature-calibration is complete at Block 308 (i.e., if frequency error of XO 106 meets a pre-specified tolerance), then the temperature-calibration process can end in Block 310. However, if for example, the temperature-calibration is not completed at Block 308 (i.e., if the frequency error of XO 106 falls outside the pre-specified tolerance), the method can comprise further temperature-calibrating XO 106 by repeating the methods of Blocks 302 and 304, for estimating a second frequency at a second temperature based on, for example, a second set of wireless signals comprising at least one wireless signal of known frequency; and maybe continuing on to further temperature-calibrating the XO by estimating a third frequency at a third temperature based on, for example, a third set of wireless signals comprising at least one wireless signal of known frequency, and so on. It will be understood that the various temperatures, i.e., the first, second, and third temperature above, are different from each other, in order to achieve useful frequency-temperature samples. Moreover, the temperature-calibration can be improved if the various temperatures are not too close to each other, and there is a minimum gap or separation between the temperatures. The value of the minimum gap may depend on the particular XO and desired or pre-specified tolerance in frequency error. For three samples of first, second, and third frequencies at respective first, second, and third temperatures, the temperature-calibration of the XO by the above process can be based on at least the first, second, and third frequency and corresponding first, second, and third temperatures. Moreover, it will also be understood that the three samples can be based on the first, second, and third set of wireless signals, wherein each set of wireless signals can comprise at least one wireless signal from one satellite (e.g., an SBAS or Doppler-true satellite source, see FIG. 3C) or one terrestrial source, or three or more wireless signals from three or more satellites (see FIG. 3B). For an exemplary third order polynomial equation with three unknown coefficients (e.g., $c_0 = 0$), at least three such samples may be needed in some cases, while keeping in mind that fewer or greater samples may be required based on the order or degree of the polynomial function, data available from precalibration, assumptions made based on operating conditions or specifications of the XO obtained from the vendor, etc. Once the relationship (e.g., polynomial relationship, or any other

relationship, without departing from the scope of this disclosure), between frequency and temperature has been expressed in terms of the polynomial equation, i.e., once XO 106 has been temperature-calibrated, a fourth frequency can be determined from the polynomial equation at any given temperature (e.g., a fourth temperature).

[0056] With reference now to FIG. 3B, an embodiment similar to FIG. 3A is depicted, wherein temperature-calibration of the XO is based on wireless signals received from three or more satellites. It will be recalled that wireless signals from three satellites may be sufficient to calculate location of the device (e.g., device 100 comprising XO 106) if altitude of the device is known, but if altitude is unknown, then wireless signals from at least four satellites may be needed. Once location is determined based on the wireless signals, using Ephemeris and time, the frequency of the wireless signals can be determined. Sometimes it may be possible to determine the frequency of all of the received wireless signals, but sometimes it may only be possible to determine the frequency of less than all of the received wireless signals (e.g., only one wireless signal in some cases). In any case, once the location is determined, not all of the wireless signals may be required for the purposes of estimating the frequency of the XO at a given temperature. For example, once the location is determined, only the effective frequency derived from the strongest signal may be used as the derived effective frequency of all the received wireless signals. In other examples, effective frequencies derived from the multiple signals may be combined, using schemes such as weighting signals such that effective frequency derived from the one or more of the strongest of the received signals is weighted more heavily and the effective frequencies derived from the weaker signals are afforded less weight. Other combination mechanisms such as a mean, median, least squares fit, etc. may also be used. Accordingly, if more than one such frequency (or effective frequency, when Ephemeris and location are known) is obtained, the multiple frequencies (or effective frequencies) may be combined by any suitable manner. By using Ephemeris to determine predicted Doppler offset for each of the multiple signals being combined, the respective Doppler shift can be offset from the respective effective frequencies or from the derived effective frequency. Once the Doppler of the received wireless signals is accounted for, the effective frequency can be derived, which may correspond to the GPS L1 frequency or other nominal frequency of the received wireless signals. The effective frequency (or derived effective frequency) is compared to the frequency of a local oscillator (e.g., local oscillator 112 in receiver

102 of device 100, which has been set to the nominal frequency). The comparison can be performed using a band pass filter, and the frequency deviation "ΔF" of the local oscillator from the nominal frequency can be obtained, using the frequency variation δf of the XO, and the estimated frequency of the XO at the given temperature can be obtained. More particularly, the above process is depicted in FIG. 3B as a method of temperature-calibrating an uncompensated crystal oscillator ("XO," e.g., XO 106), in a mobile device (e.g., device 100) during mobile device operation (i.e. field calibration), the method comprising: receiving a first set of wireless signals comprising at least a first wireless signal from a first satellite, a second wireless signal from a second satellite, and a third wireless signal from a third satellite, at a first temperature – Block 312; estimating a first frequency of the XO at the first temperature, based on at least the first, second, and the third wireless signals (e.g., by combining the wireless signals as described above to obtain an effective frequency, or when Ephemeris and location are known, deriving an effective frequency of the satellite constellation from a single satellite signal, and thereby deriving a first frequency error of the XO to obtain the first frequency) – Block 314; and temperature-calibrating the XO based on the first frequency and the first temperature (e.g., by starting the process of formulating the FT model or polynomial equation for XO 106, for example, using logic or means in XO manager 108, using a first sample point comprising the first frequency and the first temperature) – Block 316.

[0057] With reference to FIG. 3C, yet another embodiment similar to that of FIG. 3A is depicted, wherein temperature-calibration of the XO is based on wireless signals received from a single signal source. In the case where the single signal source is a satellite source (e.g., SBAS vehicle), the device comprising the XO (e.g., device 100 comprising XO 106) may obtain a location or position estimate for the device from, for example, using an approximate location derived from terrestrial signals (e.g. using cell sector center of the serving cell or trilaterating terrestrial signals), or location derived from a positioning server. Once the location is known, using Ephemeris and time, the received wireless signal can be used to determine the effective frequency for comparison with the frequency of the local oscillator, in order to obtain the frequency estimate for the XO, as described in the case of FIG. 3B above. In cases where the signal source is not a satellite source (e.g. if the signal source is a WWAN or other fixed frequency source of known frequency), and if the device is stationary, then the known

fixed frequency is treated as the effective frequency which is compared with the frequency of the local oscillator in order to obtain the frequency estimate for the XO. More particularly, the above process is depicted in FIG. 3C as a method of temperature-calibrating an uncompensated crystal oscillator ("XO," e.g., XO 106), in a mobile device (e.g., device 100) during mobile device operation (i.e., field calibration), the method comprising: receiving a first set of wireless signals comprising at least a first wireless signal of known Doppler (e.g., from a signal source such as a SBAS satellite or geostationary source of zero-Doppler, or a known Doppler source or a terrestrial signal source), at a first temperature – Block 322; estimating a first frequency of the XO at the first temperature, based on the first wireless signal (e.g., by determining the location of device 100 based on the processes described above, based on whether the signal source is a satellite source or a terrestrial source, and once the location is known, using Ephemeris and time, the received wireless signal can be used to determine the effective frequency for comparison with the frequency of the local oscillator, in order to obtain the frequency estimate for the XO) – Block 324; and temperature-calibrating the XO based on the first frequency and the first temperature (e.g., by starting the process of formulating the FT model or polynomial equation for XO 106, for example, using logic or means in XO manager 108, using a first sample point comprising the first frequency and the first temperature) – Block 326. Also note, in embodiments that utilize a terrestrial signal source of known frequency, Ephemeris, time and location are not required.

[0058] Those of skill in the art will appreciate that information and signals may be represented using any of a variety of different technologies and techniques. For example, data, instructions, commands, information, signals, bits, symbols, and chips that may be referenced throughout the above description may be represented by voltages, currents, electromagnetic waves, magnetic fields or particles, optical fields or particles, or any combination thereof.

[0059] Further, those of skill in the art will appreciate that the various illustrative logical blocks, modules, circuits, and algorithm steps described in connection with the embodiments disclosed herein may be implemented as electronic hardware, computer software, or combinations of both. To clearly illustrate this interchangeability of hardware and software, various illustrative components, blocks, modules, circuits, and steps have been described above generally in terms of their functionality. Whether such

functionality is implemented as hardware or software depends upon the particular application and design constraints imposed on the overall system. Skilled artisans may implement the described functionality in varying ways for each particular application, but such implementation decisions should not be interpreted as causing a departure from the scope of the present invention.

[0060] The methods, sequences and/or algorithms described in connection with the embodiments disclosed herein may be embodied directly in hardware, in a software module executed by a processor, or in a combination of the two. A software module may reside in RAM memory, flash memory, ROM memory, EPROM memory, EEPROM memory, registers, hard disk, a removable disk, a CD-ROM, or any other form of storage medium known in the art. An exemplary storage medium is coupled to the processor such that the processor can read information from, and write information to, the storage medium. In the alternative, the storage medium may be integral to the processor.

[0061] With reference now to FIG. 4, another exemplary device 400, for GNSS-based XO temperature-calibration is illustrated. As seen, device 400 is shown with several additional components or blocks, in comparison to the depiction of device 100 in FIG. 2A. In some embodiments, device 400 is implemented as a wireless communication system. Device 400 includes digital signal processor (DSP) 464 and a general purpose processor, depicted as processor 465. The above-described functions and methods related to XO temperature-calibration can be performed in DSP 464 or processor 465 or any combination of the processing elements thereof. Accordingly, in some embodiments, processor 465 may be configured to perform operations described with regard to XO manager 108, but it will be understood that some of the operations related to XO temperature-calibration can be performed in DSP 464, and moreover, these operations can be implemented in any suitable combination of hardware and software. Both DSP 464 and processor 465 may be coupled to clock 104 driven by XO 106 as previously described and to memory 432. Instructions related to related to a coder/decoder (CODEC) (e.g., an audio and/or voice CODEC) can be stored in memory 432. Speaker 436 and microphone 438 can be coupled to audio controller 434, which can be coupled to processor 465 and/or to DSP 464. Display controller 426 can be coupled to DSP 464, processor 465, and to display 428. Other components, such as transceiver 440 (which may be part of a modem) and receiver 441 are also illustrated.

Transceiver 440 can be coupled to wireless antenna 442, which may be configured to receive wireless communication signals from a terrestrial source such as WWAN or CDMA. These signals can be used to receive wireless signals from a terrestrial signal source of known frequency to be used in XO temperature-calibration. Receiver 441 can be coupled to a satellite or GNSS antenna 443, which may be configured to receive wireless signals such as satellite signals from a satellite or GNSS satellite, which, in embodiments utilizing GNSS satellite signals may also require knowledge of Ephemeris, time and location to be used in XO temperature-calibration. In some embodiments, both receiver 441 and transceiver 440 may include respective local oscillators 112 and 113, which may be sourced from XO 106. Temperature sensor 114 is also illustrated, and may be coupled to clock 104 and processor 465. Either local oscillator 112 or 113 may be used for XO temperature-calibration, depending on whether a GNSS satellite signal source, or other satellite signal source, or a terrestrial signal source is utilized. Local oscillator 112 would be used for XO temperature-calibration when one or more satellite signal source are utilized for XO temperature-calibration. Local oscillator 113 would be used for XO temperature-calibration if a terrestrial source of known frequency is utilized for XO temperature calibration. Additionally, band pass filter (BPF) 467 is also illustrated as a functional block with processor 465, but it will be understood that placement of BPF 467 in device 400 is not restricted, and thus functionality of BPF 467 according to exemplary embodiments, can be implemented anywhere within device 400. Exemplary functionality of BPF 467 can include logic/means for comparing a frequency of local oscillator 112 and/or 113 with a frequency of a signal received from receiver 441 and/or transceiver 440 respectively and logic/means for determining a frequency variation of local oscillator 112/113 based on the comparison. In a particular embodiment, DSP 464, processor 465, display controller 426, memory 432, audio controller 434, transceiver 440, receiver 441, clock 104, and temperature sensor 114 are included in a system-in-package or system-on-chip device 422.

[0062] In a particular embodiment, input device 430 and power supply 444 are coupled to the system-on-chip device 422. Moreover, in a particular embodiment, as illustrated in FIG. 4, display 428, input device 430, speaker 436, microphone 438, wireless antenna 442, GNSS antenna 443, and power supply 444 are external to the system-on-chip device 422. However, each of display 428, input device 430, speaker 436, microphone

438, wireless antenna 442, GNSS antenna 443, and power supply 444 can be coupled to a component of the system-on-chip device 422, such as an interface or a controller.

[0063] In one embodiment, one or both of DSP 464 and processor 465, in conjunction with one or more remaining components illustrated in FIG. 4, can include logic/means to perform the method of temperature-calibrating an uncompensated XO (e.g., XO 106) in device 400 during operation of device 400 (i.e., field calibration) as discussed, for example in Blocks 302-310 of FIG. 3A (or similarly, with regard to Blocks 312-316 of FIG. 3B or Blocks 322-326 of FIG. 3C). For example, one or more of transceiver 440, wireless antenna 442, receiver 441 and GNSS antenna 443 can include logic/means for receiving a first set of wireless signals comprising at least a first wireless signal of known frequency (e.g., from a first satellite), and similarly, logic/means for further receiving at least second and third wireless signals of known frequencies. DSP 464 and/or processor 465 (illustrated as comprising XO manager 108) in conjunction with input from temperature sensor 114, can include logic/means for estimating a first frequency of the XO at a first temperature, based on at least the first wireless signal, and temperature-calibrating the XO based on the first frequency at the first temperature. DSP 464 and/or processor 465 can similarly, further comprise logic/means for estimating a second frequency at a second temperature, based on a second set of wireless signals comprising at least one wireless signal of known frequency, estimating a third frequency at a third temperature, based on a third set of wireless signals comprising at least one wireless signal of known frequency, and further temperature-calibrating the XO based at least on the first, second, and third frequency and corresponding first, second, and third temperature. DSP 464 and/or processor 465 may be configured to estimate the first frequency of the XO at the first temperature based on an effective frequency of the first, second, and third wireless signals, wherein the frequencies of the first, second, and third wireless signals are offset by a first, second, and third Doppler relative to the effective frequency and derive a first frequency error of the XO based on the effective frequency. As previously described, the band pass filter BPF 467 may be configured to determine a frequency variation of local oscillator 112/113 as a difference in frequency between the effective frequency and a frequency of the local oscillator and the processor is further configured to normalize the frequency variation of the local oscillator based on an expected nominal frequency of the local oscillator, determine a normalized frequency variation of XO 106 as equal to the normalized frequency variation of the local

oscillator 112/113, and determine the first frequency based on the normalized frequency variation of XO 106 and an expected nominal frequency of XO 106. It will be recalled that the effective frequency can be, for example, equal to the strongest one of the first, second, and third wireless signals, or can be based on a combination of the first, second, and third wireless signals, wherein the combination is one of a weighted average, a mean, a median, a least squares, or a pre-specified mathematical fit of the first, second, and third wireless signals.

[0064] In some cases, the signal source can be a signal source of known Doppler, such as a geostationary source or a SBAS vehicle of zero Doppler or a terrestrial source of known frequency such as a wireless base station. At most one such signal source of known Doppler may be available in some cases, where a plurality of satellite signal sources, or calibrated terrestrial sources, are unavailable. In such cases, DSP 464 and/or processor 465 may be further configured to determine whether the wireless signal received from such signal sources satisfies a pre-specified signal to noise ratio (SNR) and/or passes a pre-specified error or parity check. If device 400 is in motion, and a satellite signal is relied upon, DSP 464 and/or processor 465 may be further configured to estimate the first frequency of XO 106 at the first temperature, based on a difference between a measured Doppler of the satellite signal and a predicted Doppler of the satellite signal based on a speed of motion of the mobile device. Temperature-calibration of XO 106 can comprise a relationship between frequency of the XO and temperature, based on at least the first frequency and the first temperature, wherein the relationship is a polynomial equation (e.g., of third order) of the frequency of the XO and temperature with a number (e.g., four) of unknown coefficients based on an order of the polynomial equation. DSP 464 and/or processor 465 may be able to perform temperature-calibration of XO 106 using a reduced number of unknown coefficients, wherein the reduced number can be based on constraints and/or assumptions, such as obtained from vendor specifications of XO 106, precalibration of XO 106 during manufacture or in the factory, and/or constraining variation in temperature.

[0065] Moreover, one or more of transceiver 440, wireless antenna 442, receiver 441 and GNSS antenna 443 can also be configured to receive GNSS assistance information such as location of device 400, GNSS Ephemeris and/or Almanac information. DSP 464 and/or processor 465 can also be configured to determine the location of device 400, for example, from the above GNSS assistance or based on a terrestrial signal or signals (e.g.

using cell sector center of the serving cell or the location of a wireless transceiver sending signals received by the device 400 or by trilaterating terrestrial and/or GNSS signals) and/or by using a positioning server.

[0066] It should be noted that although FIG. 4 depicts a wireless communications device, DSP 464, processor 465, and memory 432 may also be integrated into a set-top box, a music player, a video player, an entertainment unit, a navigation device, a communications device, a personal digital assistant (PDA), a fixed location data unit, or a computer. Moreover, such a device may also be integrated in a semiconductor die.

[0067] Accordingly, an embodiment of the invention can include a computer readable media embodying a temperature-calibrating an uncompensated crystal oscillator (XO), in a mobile device during mobile device operation (i.e., field calibration). Accordingly, the invention is not limited to illustrated examples and any means for performing the functionality described herein are included in embodiments of the invention.

[0068] While the foregoing disclosure shows illustrative embodiments of the invention, it should be noted that various changes and modifications could be made herein without departing from the scope of the invention as defined by the appended claims. The functions, steps and/or actions of the method claims in accordance with the embodiments of the invention described herein need not be performed in any particular order. Furthermore, although elements of the invention may be described or claimed in the singular, the plural is contemplated unless limitation to the singular is explicitly stated.

CLAIMS

WHAT IS CLAIMED IS:

1. A method of temperature-calibrating an uncompensated crystal oscillator (XO), in a mobile device during mobile device operation, the method comprising:

receiving a first set of wireless signals comprising at least a first wireless signal of known frequency, at a first temperature;

estimating a first frequency of the XO at the first temperature, based on at least the first wireless signal; and

temperature-calibrating the XO based on the first frequency and the first temperature.

2. The method of claim 1, wherein the uncompensated XO comprises a lack of built-in compensation for frequency variation of the XO with variation in temperature or voltage.

3. The method of claim 1, wherein the first wireless signal is transmitted by a first satellite.

4. The method of claim 3, wherein the first satellite comprises a global navigation satellite systems (GNSS) satellite.

5. The method of claim 4, further comprising receiving GNSS assistance information.

6. The method of claim 5, wherein the GNSS assistance information further comprises a location of the mobile device.

7. The method of claim 5, wherein the GNSS assistance information comprises GNSS Ephemeris information.

8. The method of claim 5, wherein the GNSS assistance information comprises Almanac information.

9. The method of claim 5, further comprising determining a location of the mobile device.

10. The method of claim 9, wherein determining the location is based on at least one terrestrial signal.

11. The method of claim 9, wherein determining the location is based on GNSS signals.

12. The method of claim 9, wherein the first set of wireless signals further comprises at least a second wireless signal transmitted by a second satellite and a third wireless signal transmitted by a third satellite.

13. The method of claim 12, wherein estimating the first frequency of the XO at the first temperature is further based on at least the second and third wireless signals.

14. The method of claim 13, wherein estimating the first frequency of the XO at the first temperature comprises obtaining the location based on at least the first, second, and the third wireless signals.

15. The method of claim 13, wherein estimating the first frequency of the XO at the first temperature comprises: obtaining an effective frequency of the first, second, and third wireless signals, wherein the frequencies of the first, second, and third wireless signals are offset by a first, second, and third Doppler relative to the effective frequency; and deriving a first frequency error of the XO based on the effective frequency.

16. The method of claim 12, wherein, estimating the first frequency of the XO at the first temperature comprises:

deriving a first effective frequency from the first wireless signal, a second effective frequency from the second wireless signal, and a third effective frequency from the third wireless signal;

determining a derived effective frequency based on one or more of the first, second, and third effective frequencies;

determining a frequency variation of a local oscillator on the mobile device, as a difference in frequency between the derived effective frequency and a frequency of the local oscillator, wherein the local oscillator is sourced from the XO;

normalizing the frequency variation of the local oscillator based on an expected nominal frequency of the local oscillator;

determining a normalized frequency variation of the XO as equal to the normalized frequency variation of the local oscillator; and

determining the first frequency based on the normalized frequency variation of the XO and an expected nominal frequency of the XO.

17. The method of claim 16, wherein the derived effective frequency is based on the strongest of the first, second, and third effective frequencies.

18. The method of claim 16, wherein the derived effective frequency is based on a combination of the first, second, and third effective frequencies.

19. The method of claim 18, wherein the combination is one of a weighted average, a mean, a median, a least squares, or a pre-specified mathematical fit of the first, second, and third effective frequencies.

20. The method of claim 3, wherein a Doppler of the first wireless signal transmitted by the first satellite is constant.

21. The method of claim 20, wherein the first satellite is geostationary and the Doppler of the first wireless signal is zero.

22. The method of claim 20, wherein the first satellite comprises a satellite-based augmentation system (SBAS) satellite.

23. The method of claim 20, further comprising determining whether the first wireless signal satisfies a pre-specified signal to noise ratio (SNR).

24. The method of claim 20, further comprising determining whether the first wireless signal passes a pre-specified error or parity check.

25. The method of claim 3, wherein the mobile device is in motion, and wherein estimating the first frequency of the XO at the first temperature, based on at least the first wireless signal further comprises estimating a difference between a measured Doppler of the first wireless signal and a predicted Doppler of the first wireless signal based on a speed of motion of the mobile device.

26. The method of claim 1, wherein temperature-calibrating the XO comprises determining a relationship between frequency of the XO and temperature, based on at least the first frequency and the first temperature.

27. The method of claim 26, wherein the relationship is a polynomial equation of the frequency of the XO and temperature with a number of unknown coefficients based on an order of the polynomial equation.

28. The method of claim 27 comprising reducing the number of unknown coefficients based on specifications of the XO.

29. The method of claim 27 comprising reducing the number of unknown coefficients based on precalibration of the XO during manufacturing of the XO.

30. The method of claim 27 comprising reducing the number of unknown coefficients based on constraining a variation in temperature.

31. The method of claim 1, further comprising:

receiving a second set of wireless signals comprising at least one wireless signal of known frequency at a second temperature;

estimating a second frequency of the XO at the second temperature, based on the second set of wireless signals, wherein the second temperature is different from the first temperature; and

further temperature-calibrating the XO based on the second frequency and the second temperature.

32. The method of claim 31, wherein further temperature-calibrating the XO comprises determining a relationship between frequency of the XO and temperature, based on at least the first frequency and the first temperature and on the second frequency and the second temperature.

33. The method of claim 31, further comprising

receiving a third set of wireless signals comprising at least one wireless signal of known frequency at a third temperature;

estimating a third frequency of the XO at the third temperature, based on the third set of wireless signals, wherein the third temperature is different from the first temperature and the second temperature; and

further temperature-calibrating the XO based on the third frequency and the third temperature.

34. The method of claim 33, wherein further temperature-calibrating the XO comprises determining a relationship between frequency of the XO and temperature, based on at least the first frequency and the first temperature, the second frequency and the second temperature, and the third frequency and the third temperature.

35. A method of temperature-calibrating an uncompensated crystal oscillator (XO) in a mobile device during mobile device operation, the method comprising:

receiving a first set of wireless signals comprising at least a first wireless signal, from a signal source of known frequency and known Doppler, at a first temperature, wherein a plurality of satellite signals is unavailable;

estimating a first frequency of the XO at the first temperature, based on at least the first wireless signal; and

temperature-calibrating the XO based on the first frequency and the first temperature.

36. The method of claim 35, wherein the signal source is a satellite.

37. The method of claim 36, wherein the satellite is geo-stationary with zero Doppler.

38. The method of claim 37, wherein the satellite is a satellite based augmentation system (SBAS) satellite.

39. The method of claim 36, further comprising obtaining a location of the mobile device from an approximate location using cell sector center of a serving cell, from a trilateration of terrestrial signals, from a positioning server, or from a base station Almanac on the mobile device.

40. The method of claim 39, further comprising determining an effective frequency of the first wireless signal based on Ephemeris and time at the mobile device.

41. The method of claim 40, wherein, estimating the first frequency of the XO at the first temperature comprises:

determining a frequency variation of a local oscillator on the mobile device, as a difference in frequency between the effective frequency and a frequency of the local oscillator, wherein the local oscillator is sourced from the XO;

normalizing the frequency variation of the local oscillator based on an expected nominal frequency of the local oscillator;

determining a normalized frequency variation of the XO as equal to the normalized frequency variation of the local oscillator; and

determining the first frequency based on the normalized frequency variation of the XO and an expected nominal frequency of the XO.

42. The method of claim 36, further comprising determining whether the first wireless signal satisfies a pre-specified signal to noise ratio (SNR).

43. The method of claim 36, further comprising determining whether the first wireless signal passes a pre-specified error or parity check.

44. The method of claim 35, comprising receiving the first set of wireless signals from a calibrated terrestrial source.

45. The method of claim 44, wherein the calibrated terrestrial source is one of a wireless wide area network (WWAN), code division multiple access (CDMA) network, or long term evolution (LTE) network.

46. A system comprising:

a mobile device comprising an uncompensated crystal oscillator (XO);

means for receiving a first set of wireless signals comprising at least a first wireless signal of known frequency, at a first temperature;

means for estimating a first frequency of the XO at the first temperature, based on at least the first wireless signal; and

means for temperature-calibrating the XO based on the first frequency and the first temperature during operation of the mobile device.

47. The system of claim 46, wherein the uncompensated XO comprises a lack of built-in compensation for frequency variation of the XO with variation in temperature or voltage.

48. The system of claim 46, wherein the first wireless signal is transmitted by a first satellite.

49. The system of claim 48, wherein the first satellite comprises a GNSS satellite.

50. The system of claim 49, further comprising means for receiving GNSS assistance information.

51. The system of claim 50, wherein the GNSS assistance information further comprises a location of the mobile device.

52. The system of claim 50, wherein the GNSS assistance information comprises GNSS Ephemeris information.

53. The system of claim 50, wherein the GNSS assistance information comprises Almanac information.

54. The system of claim 50, further comprising means for determining a location of the mobile device.

55. The system of claim 54, wherein the means determining the location utilizes at least one terrestrial signal.

56. The system of claim 54, wherein the means for determining the location utilizes GNSS signals.

57. The system of claim 54, wherein the first set of wireless signals further comprises at least a second wireless signal transmitted by a second satellite and a third wireless signal transmitted by a third satellite.

58. The system of claim 57, wherein the means for estimating the first frequency of the XO at the first temperature is further based on at least the second and third wireless signals.

59. The system of claim 58, wherein the means for estimating the first frequency of the XO at the first temperature comprises means for obtaining the location based on at least the first, second, and the third wireless signals.

60. The system of claim 58, wherein the means for estimating the first frequency of the XO at the first temperature comprises: means for obtaining an effective frequency of the first, second, and third wireless signals, wherein the frequencies of the first, second, and third wireless signals are offset by a first, second, and third Doppler relative to the effective frequency; and means for deriving a first frequency error of the XO based on the effective frequency.

61. The system of claim 57, wherein, the means for estimating the first frequency of the XO at the first temperature comprises:

means for deriving a first effective frequency from the first wireless signal, a second effective frequency from the second wireless signal, and a third effective frequency from the third wireless signal;

determining a derived effective frequency based on one or more of the first, second, and third effective frequencies;

means for determining a frequency variation of a local oscillator on the mobile device, as a difference in frequency between the derived effective frequency and a frequency of the local oscillator, wherein the local oscillator is sourced from the XO;

means for normalizing the frequency variation of the local oscillator based on an expected nominal frequency of the local oscillator;

means for determining a normalized frequency variation of the XO as equal to the normalized frequency variation of the local oscillator; and

means for determining the first frequency based on the normalized frequency variation of the XO and an expected nominal frequency of the XO.

62. The system of claim 61, wherein the derived effective frequency is based on the strongest of the first, second, and third effective frequencies.

63. The system of claim 61, wherein the derived effective frequency is based on a combination of the first, second, and third effective frequencies.

64. The system of claim 63, wherein the combination is one of a weighted average, a mean, a median, a least squares, or a pre-specified mathematical fit of the first, second, and third effective frequencies.

65. The system of claim 48, wherein a Doppler of the first wireless signal transmitted by the first satellite is constant.

66. The system of claim 65, wherein the first satellite is geostationary and the Doppler of the first wireless signal is zero.

67. The system of claim 65, wherein the first satellite comprises a satellite-based augmentation system (SBAS) satellite.

68. The system of claim 65, further comprising means for determining whether the first wireless signal satisfies a pre-specified signal to noise ratio (SNR).

69. The system of claim 65, further comprising means for determining whether the first wireless signal passes a pre-specified error or parity check.

70. The system of claim 48, wherein the mobile device is in motion, and wherein the means for estimating the first frequency of the XO at the first temperature, based on at least the first wireless signal further comprises means for estimating a difference between a measured Doppler of the first wireless signal and a predicted Doppler of the first wireless signal based on a speed of motion of the mobile device.

71. The system of claim 46, wherein the means for temperature-calibrating the XO comprises means for determining a relationship between frequency of the XO and temperature, based on at least the first frequency and the first temperature.

72. The system of claim 71, wherein the relationship is a polynomial equation of the frequency of the XO and temperature with a number of unknown coefficients based on an order of the polynomial equation.

73. The system of claim 72 comprising means for reducing the number of unknown coefficients based on specifications of the XO.

74. The system of claim 72 comprising means for reducing the number of unknown coefficients based on precalibration of the XO during manufacturing of the XO.

75. The system of claim 72 comprising means for reducing the number of unknown coefficients based on constraining a variation in temperature.

76. The system of claim 46, further comprising:

means for receiving a second set of wireless signals comprising at least one wireless signal of known frequency at a second temperature;

means for estimating a second frequency of the XO at the second temperature, based on the second set of wireless signals, wherein the second temperature is different from the first temperature; and

means for further temperature-calibrating the XO based on the second frequency and the second temperature.

77. The system of claim 76, wherein the means for further temperature-calibrating the XO comprises means for determining a relationship between frequency of the XO and temperature, based on at least the first frequency and the first temperature and on the second frequency and the second temperature.

78. The system of claim 76, further comprising

means for receiving a third set of wireless signals comprising at least one wireless signal of known frequency at a third temperature;

means for estimating a third frequency of the XO at the third temperature, based on the third set of wireless signals, wherein the third temperature is different from the first temperature and the second temperature; and

means for further temperature-calibrating the XO based on the third frequency and the third temperature.

79. The system of claim 78, wherein the means for further temperature-calibrating the XO comprises means for determining a relationship between frequency of the XO and temperature, based on at least the first frequency and the first temperature, the second frequency and the second temperature, and the third frequency and the third temperature.

80. A system comprising:

a mobile device comprising an uncompensated crystal oscillator (XO);

means for receiving a first set of wireless signals comprising at least a first wireless signal, from a signal source of known frequency and known Doppler, at a first temperature, wherein a plurality of satellite signals is unavailable;

means for estimating a first frequency of the XO at the first temperature, based on at least the first wireless signal; and

means for temperature-calibrating the XO based on the first frequency and the first temperature during operation of the mobile device.

81. The system of claim 80, wherein the signal source is a satellite.

82. The system of claim 81, wherein the satellite is geo-stationary with zero Doppler.

83. The system of claim 82, wherein the satellite is a satellite based augmentation system (SBAS) satellite.

84. The system of claim 81, further comprising means for obtaining a location of the mobile device from an approximate location using cell sector center of a serving cell, from a trilateration of terrestrial signals, from a positioning server, or from a base station Almanac on the device.

85. The system of claim 84, further comprising means for determining an effective frequency of the first wireless signal based on Ephemeris and time at the mobile device.

86. The system of claim 85, wherein, the means for estimating the first frequency of the XO at the first temperature comprises:

means for determining a frequency variation of a local oscillator on the mobile device, as a difference in frequency between the effective frequency and a frequency of the local oscillator, wherein the local oscillator is sourced from the XO;

means for normalizing the frequency variation of the local oscillator based on an expected nominal frequency of the local oscillator;

means for determining a normalized frequency variation of the XO as equal to the normalized frequency variation of the local oscillator; and

means for determining the first frequency based on the normalized frequency variation of the XO and an expected nominal frequency of the XO.

87. The system of claim 81, further comprising means for determining whether the first wireless signal satisfies a pre-specified signal to noise ratio (SNR).

88. The system of claim 81, further comprising means for determining whether the first wireless signal passes a pre-specified error or parity check.

89. The system of claim 80, comprising means for receiving the first set of wireless signals from a calibrated terrestrial source.

90. The system of claim 89, wherein the calibrated terrestrial source is one of a wireless wide area network (WWAN), code division multiple access (CDMA) network, or long term evolution (LTE) network.

91. A mobile device comprising:

an uncompensated crystal oscillator (XO);

a temperature sensor configured to provide a first temperature;

one or more receivers configured to receive a first set of wireless signals comprising at least a first wireless signal of known frequency, at the first temperature; and

a processor configured to estimate a first frequency of the XO at the first temperature, based on at least the first wireless signal, and temperature-calibrate the XO based on the first frequency and the first temperature during operation of the mobile device.

92. The mobile device of claim 91, wherein the uncompensated XO comprises a lack of built-in compensation for frequency variation of the XO with variation in temperature or voltage.

93. The mobile device of claim 91, wherein the first wireless signal is transmitted by a first satellite.

94. The mobile device of claim 93, wherein the first satellite comprises a GNSS satellite.

95. The mobile device of claim 94, wherein at least one of the receivers is further configured to receive GNSS assistance information.

96. The mobile device of claim 95, wherein the GNSS assistance information further comprises a location of the mobile device.

97. The mobile device of claim 95, wherein the GNSS assistance information comprises GNSS Ephemeris information.

98. The mobile device of claim 95, wherein the GNSS assistance information comprises Almanac information.

99. The mobile device of claim 5, wherein the processor is further configured to determine a location of the mobile device.

100. The mobile device of claim 99, wherein the processor is configured to determine the location based on at least one terrestrial signal.

101. The mobile device of claim 99, wherein the processor is configured to determine the location based on GNSS signals.

102. The mobile device of claim 99, wherein the first set of wireless signals further comprises at least a second wireless signal transmitted by a second satellite and a third wireless signal transmitted by a third satellite.

103. The mobile device of claim 102, wherein the processor is further configured to estimate the first frequency of the XO at the first temperature based on at least the second and third wireless signals.

104. The mobile device of claim 103, wherein the processor is configured to estimate the first frequency of the XO at the first temperature based on a location of the mobile device determined from at least the first, second, and the third wireless signals.

105. The mobile device of claim 103, wherein the processor is configured to: estimate the first frequency of the XO at the first temperature based on an effective frequency of the first, second, and third wireless signals, wherein the frequencies of the first, second, and third wireless signals are offset by a first, second, and third Doppler relative to the effective frequency; and derive a first frequency error of the XO based on the effective frequency.

106. The mobile device of claim 102, further comprising at least one local oscillator sourced from the XO, wherein the processor is configured to derive a first effective frequency from the first wireless signal, a second effective frequency from the second wireless signal, and a third effective frequency from the third wireless signal, and a derived effective frequency based on one or more of the first, second, and third effective frequencies;

a band pass filter configured to determine a frequency variation of the at least one local oscillator as a difference in frequency between the derived effective frequency and a frequency of the local oscillator; and

the processor is further configured to normalize the frequency variation of the local oscillator based on an expected nominal frequency of the local oscillator, determine a normalized frequency variation of the XO as equal to the normalized frequency variation of the local oscillator, and determine the first frequency based on the normalized frequency variation of the XO and an expected nominal frequency of the XO.

107. The mobile device of claim 106, wherein the derived effective frequency is based on the strongest of the first, second, and third effective frequencies.

108. The mobile device of claim 106, wherein the derived effective frequency is based on a combination of the first, second, and third effective frequencies.

109. The mobile device of claim 108, wherein the combination is one of a weighted average, a mean, a median, a least squares, or a pre-specified mathematical fit of the first, second, and third effective frequencies.

110. The mobile device of claim 93, wherein a Doppler of the first wireless signal transmitted by the first satellite is constant.

111. The mobile device of claim 110, wherein the first satellite is geostationary and the Doppler of the first wireless signal is zero.

112. The mobile device of claim 110, wherein the first satellite comprises a satellite-based augmentation system (SBAS) satellite.

113. The mobile device of claim 10, wherein the processor is further configured to determine whether the first wireless signal satisfies a pre-specified signal to noise ratio (SNR).

114. The mobile device of claim 110, wherein the processor is further configured to determine whether the first wireless signal passes a pre-specified error or parity check.

115. The mobile device of claim 93, wherein the mobile device is in motion, and wherein the processor is configured to estimate the first frequency of the XO at the first temperature, based on a difference between a measured Doppler of the first wireless signal and a predicted Doppler of the first wireless signal based on a speed of motion of the mobile device.

116. The mobile device of claim 91, wherein the temperature-calibration of the XO comprises a relationship between frequency of the XO and temperature, based on at least the first frequency and the first temperature.

117. The mobile device of claim 116, wherein the relationship is a polynomial equation of the frequency of the XO and temperature with a number of unknown coefficients based on an order of the polynomial equation.

118. The mobile device of claim 117, wherein the processor is further configured to temperature-calibrate the XO using a reduced number of unknown coefficients, wherein the reduced number of unknown coefficients is based on specifications of the XO.

119. The mobile device of claim 118, wherein the reduced number of unknown coefficients is based on precalibration of the XO during manufacture of the XO.

120. The mobile device of claim 118, wherein the reduced number of unknown coefficients is based on constraints in variation of temperature.

121. The mobile device of claim 91, wherein,

the one or more receivers are further configured to receive a second set of wireless signals comprising at least one wireless signal of known frequency at a second temperature;

the temperature sensor is configured to provide a second temperature, wherein the second temperature is different from the first temperature; and

the processor is further configured to estimate a second frequency of the XO at the second temperature, based on the second set of wireless signals and further temperature-calibrate the XO based on the second frequency and the second temperature.

122. The mobile device of claim 121, wherein the further temperature-calibration of the XO comprises a relationship between frequency of the XO and

temperature, based on at least the first frequency and the first temperature and on the second frequency and the second temperature.

123. The mobile device of claim 121, wherein

the one or more receivers are further configured to receive a third set of wireless signals comprising at least one wireless signal of known frequency at a third temperature;

the temperature sensor is configured to provide a third temperature, wherein the third temperature is different from the first temperature and the second temperature; and

the processor is further configured to estimate a third frequency of the XO at the third temperature, based on the third set of wireless signals and further temperature-calibrate the XO based on the third frequency and the third temperature.

124. The mobile device of claim 123, wherein the further temperature-calibration of the XO comprises a relationship between frequency of the XO and temperature, based on at least the first frequency and the first temperature, the second frequency and the second temperature, and the third frequency and the third temperature.

125. A mobile device comprising:

an uncompensated crystal oscillator (XO);

a temperature configured to provide a first temperature;

one or more receivers configured to receive a first set of wireless signals comprising at least a first wireless signal, from a signal source of known frequency and known Doppler, at the first temperature, wherein a plurality of satellite signals is unavailable; and

a processor configured to estimate a first frequency of the XO at the first temperature, based on at least the first wireless signal and temperature-calibrate the XO based on the first frequency and the first temperature.

126. The mobile device of claim 125, wherein the signal source is a satellite.

127. The mobile device of claim 126, wherein the satellite is geo-stationary with zero Doppler.

128. The mobile device of claim 127, wherein the satellite is a satellite based augmentation system (SBAS) satellite.

129. The mobile device of claim 126, wherein the processor is further configured to obtain a location of the mobile device from an approximate location using cell sector center of a serving cell, from a trilateration of terrestrial signals, from a positioning server, or from a base station Almanac on the mobile device.

130. The mobile device of claim 129, wherein the processor is further configured to determine an effective frequency of the first wireless signal based on Ephemeris and time at the mobile device.

131. The mobile device of claim 130, further comprising a local oscillator sourced from the XO and a band pass filter configured to determine a frequency variation of the local oscillator as a difference in frequency between the effective frequency and a frequency of the local oscillator, and wherein the processor is further configured to normalize the frequency variation of the local oscillator based on an expected nominal frequency of the local oscillator, determine a normalized frequency variation of the XO as equal to the normalized frequency variation of the local oscillator, and determine the first frequency based on the normalized frequency variation of the XO and an expected nominal frequency of the XO.

132. The mobile device of claim 126, wherein the processor is further configured to determine whether the first wireless signal satisfies a pre-specified signal to noise ratio (SNR).

133. The mobile device of claim 126, wherein the processor is further configured to determine whether the first wireless signal passes a pre-specified error or parity check.

134. The mobile device of claim 125, wherein the one or more receivers are configured to receive the first set of wireless signals from a calibrated terrestrial source.

135. The mobile device of claim 134, wherein the calibrated terrestrial source is one of a wireless wide area network (WWAN), code division multiple access (CDMA) network, or long term evolution (LTE) network.

136. A mobile device comprising:

an uncompensated crystal oscillator (XO);

a temperature sensor configured to provide a first temperature;

one or more receivers configured to receive a first set of wireless signals comprising at least a first wireless signal of known frequency, at a first temperature;

a processor; and

a non-transitory computer-readable storage medium comprising code, which, when executed by the processor, causes the processor to perform operations for temperature-calibrating a crystal oscillator (XO), the non-transitory computer-readable storage medium comprising:

code for estimating a first frequency of the XO at the first temperature, based on at least the first wireless signal;

code for determining unknown coefficients of a polynomial equation comprising a relationship between frequency of the XO and temperature based on at least the first frequency and the first temperature.

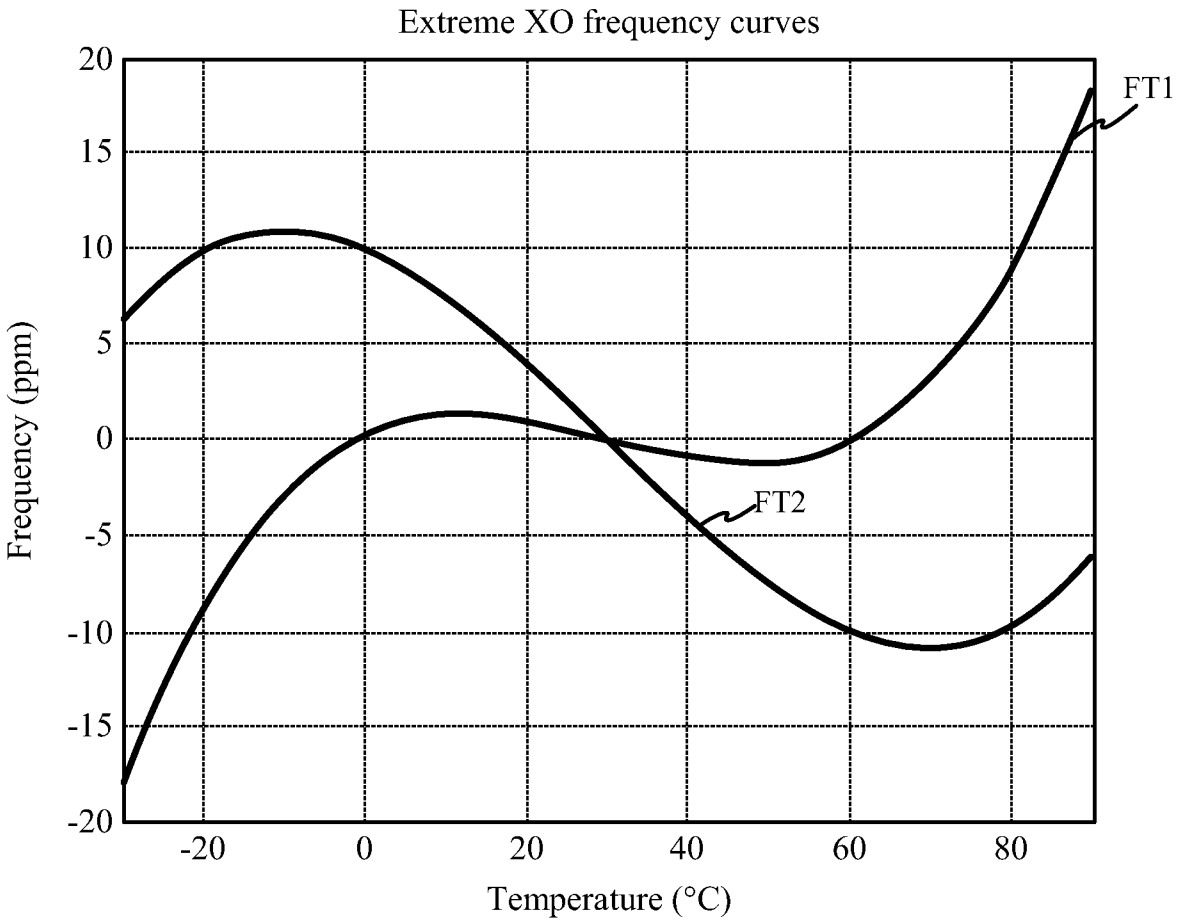
Extreme XO frequency curves
20
15
10
5
0
-5
-10
-15
-20
Frequency (ppm)
-20
0
20
40
60
80
Temperature (°C)
FT1
FT2

FIG. 1

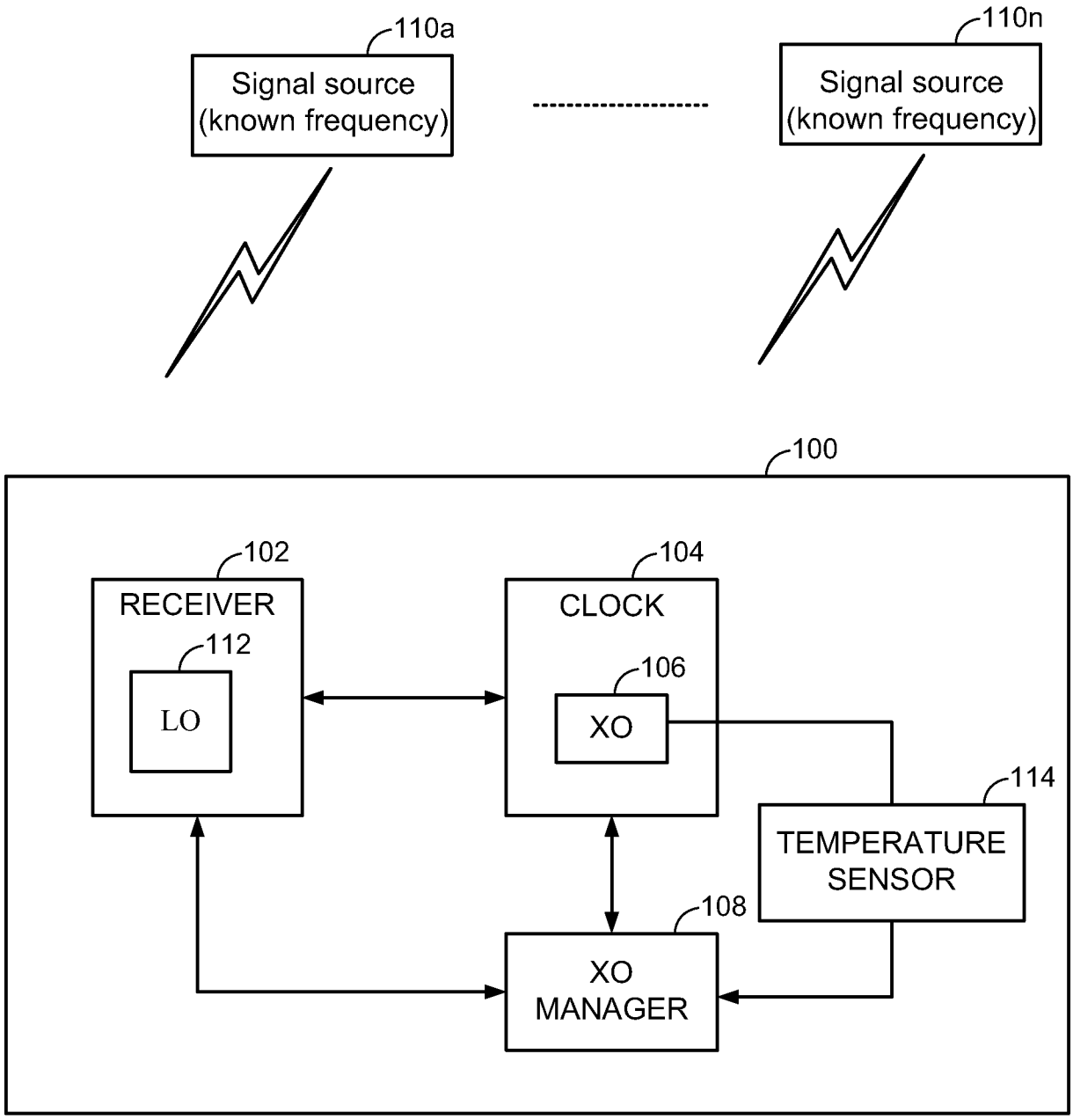
110a
Signal source (known frequency)
110n
Signal source (known frequency)
100
102
RECEIVER
112
LO
104
CLOCK
106
XO
114
TEMPERATURE SENSOR
108
XO MANAGER

FIG. 2A

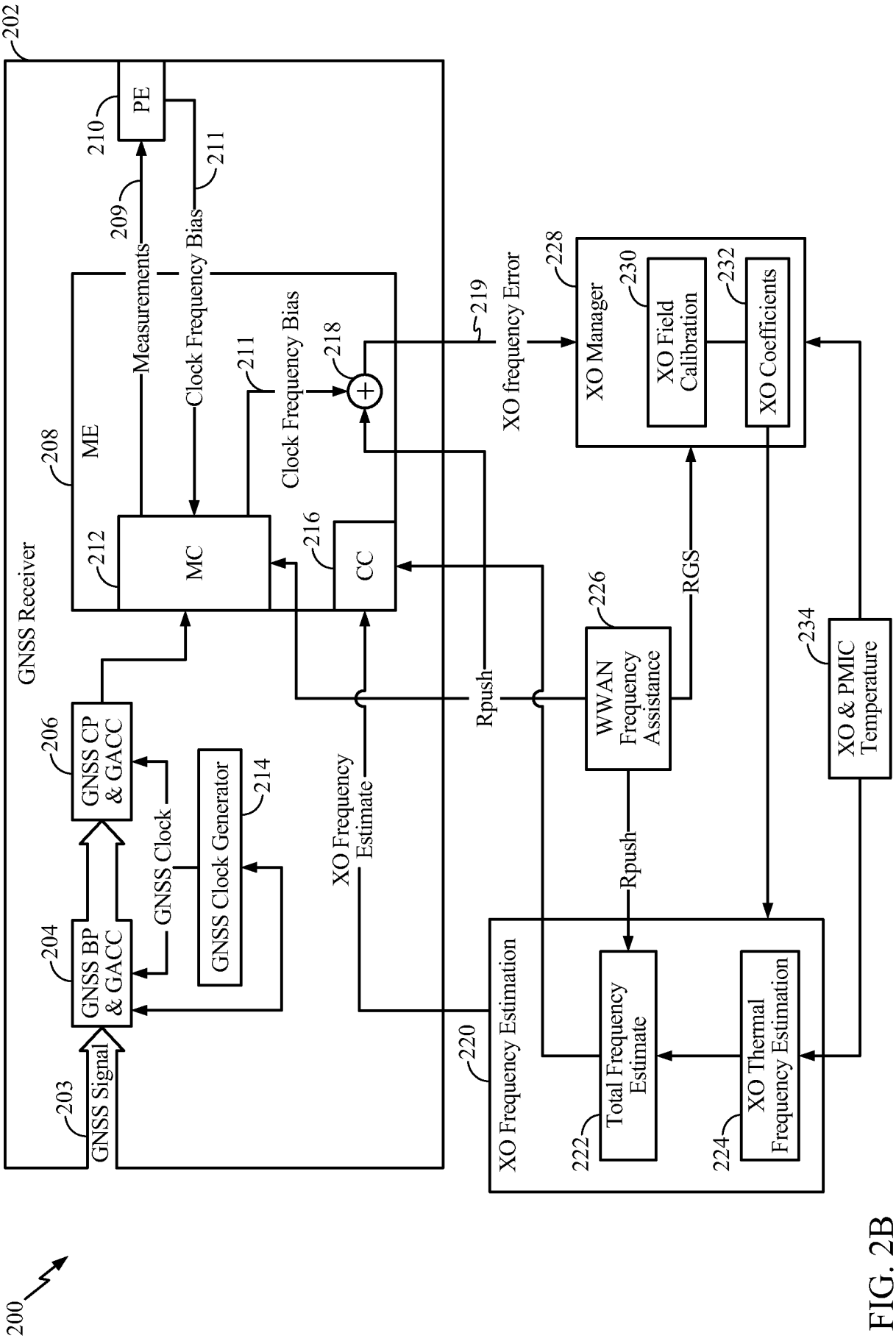
200
202
GNSS Receiver
PE
210
211
209
Measurements
Clock Frequency Bias
ME
208
212
MC
216
CC
218
211
Clock Frequency Bias
219
XO frequency Error
228
XO Manager
230
XO Field Calibration
232
XO Coefficients
GNSS CP & GACC
206
GNSS Clock
GNSS Clock Generator
214
GNSS BP & GACC
204
203
GNSS Signal
XO Frequency Estimate
Rpush
WWAN Frequency Assistance
226
RGS
234
XO & PMIC Temperature
Rpush
XO Frequency Estimation
220
Total Frequency Estimate
222
XO Thermal Frequency Estimation
224

FIG. 2B

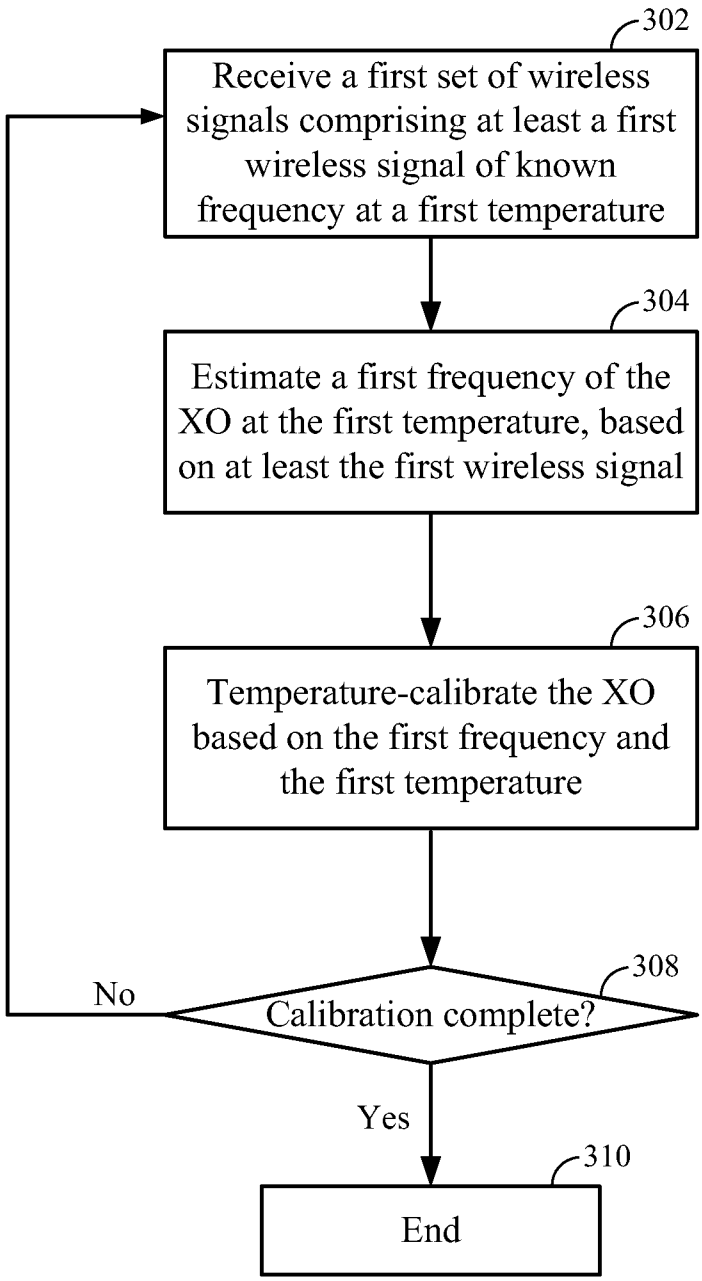
302
Receive a first set of wireless signals comprising at least a first wireless signal of known frequency at a first temperature
304
Estimate a first frequency of the XO at the first temperature, based on at least the first wireless signal
306
Temperature-calibrate the XO based on the first frequency and the first temperature
308
Calibration complete?
No
Yes
310
End

FIG. 3A

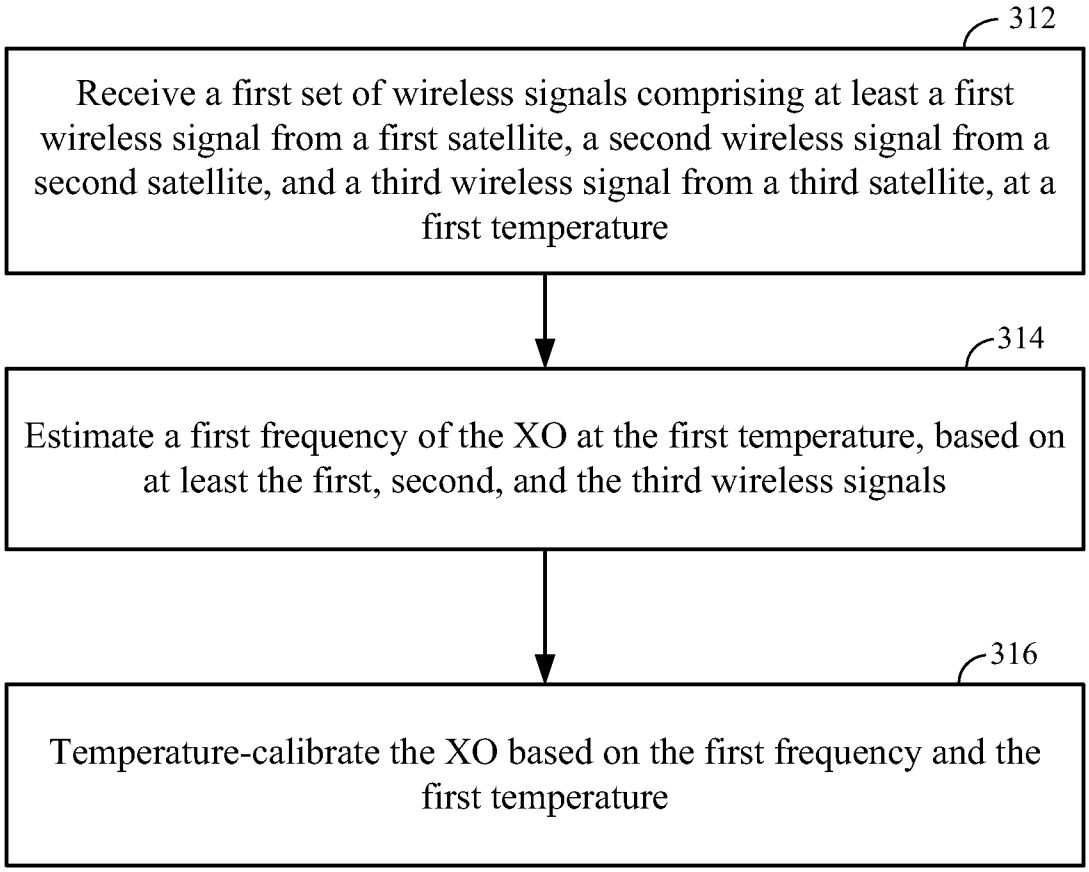
312
Receive a first set of wireless signals comprising at least a first wireless signal from a first satellite, a second wireless signal from a second satellite, and a third wireless signal from a third satellite, at a first temperature
314
Estimate a first frequency of the XO at the first temperature, based on at least the first, second, and the third wireless signals
316
Temperature-calibrate the XO based on the first frequency and the first temperature

FIG. 3B

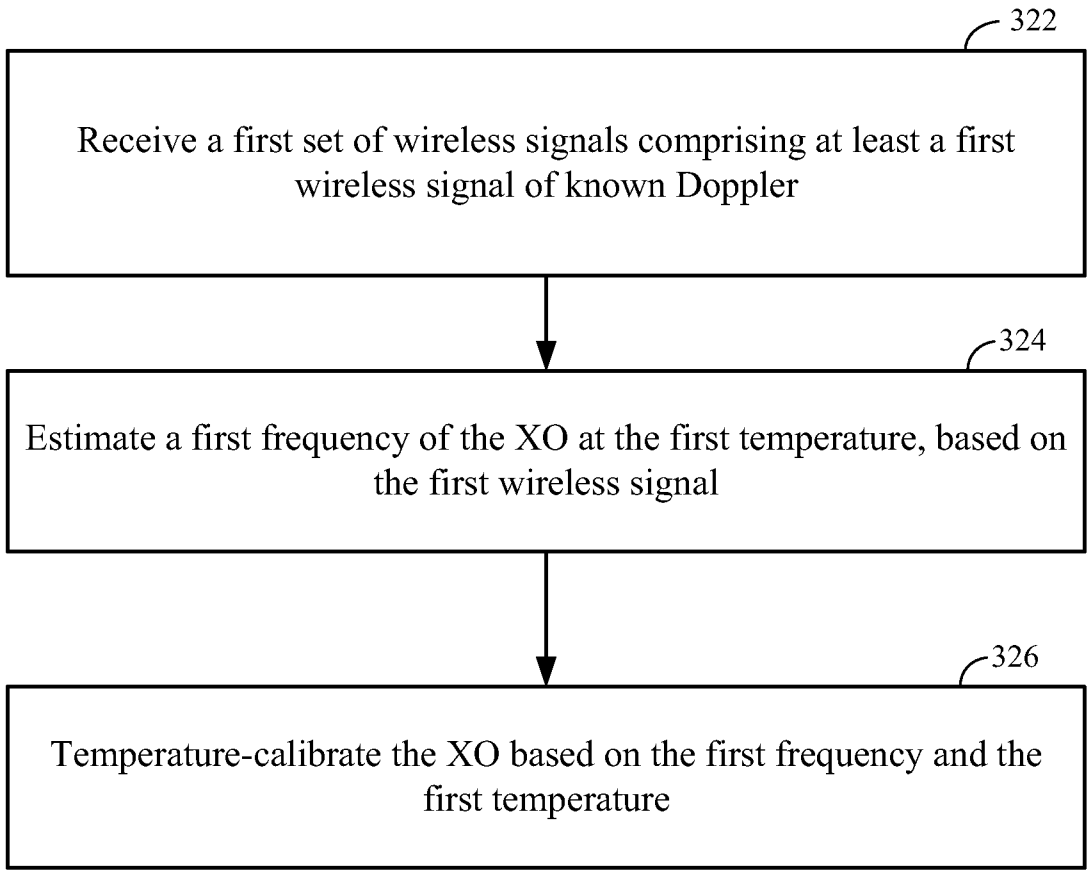
322
Receive a first set of wireless signals comprising at least a first wireless signal of known Doppler
324
Estimate a first frequency of the XO at the first temperature, based on the first wireless signal
326
Temperature-calibrate the XO based on the first frequency and the first temperature

FIG. 3C

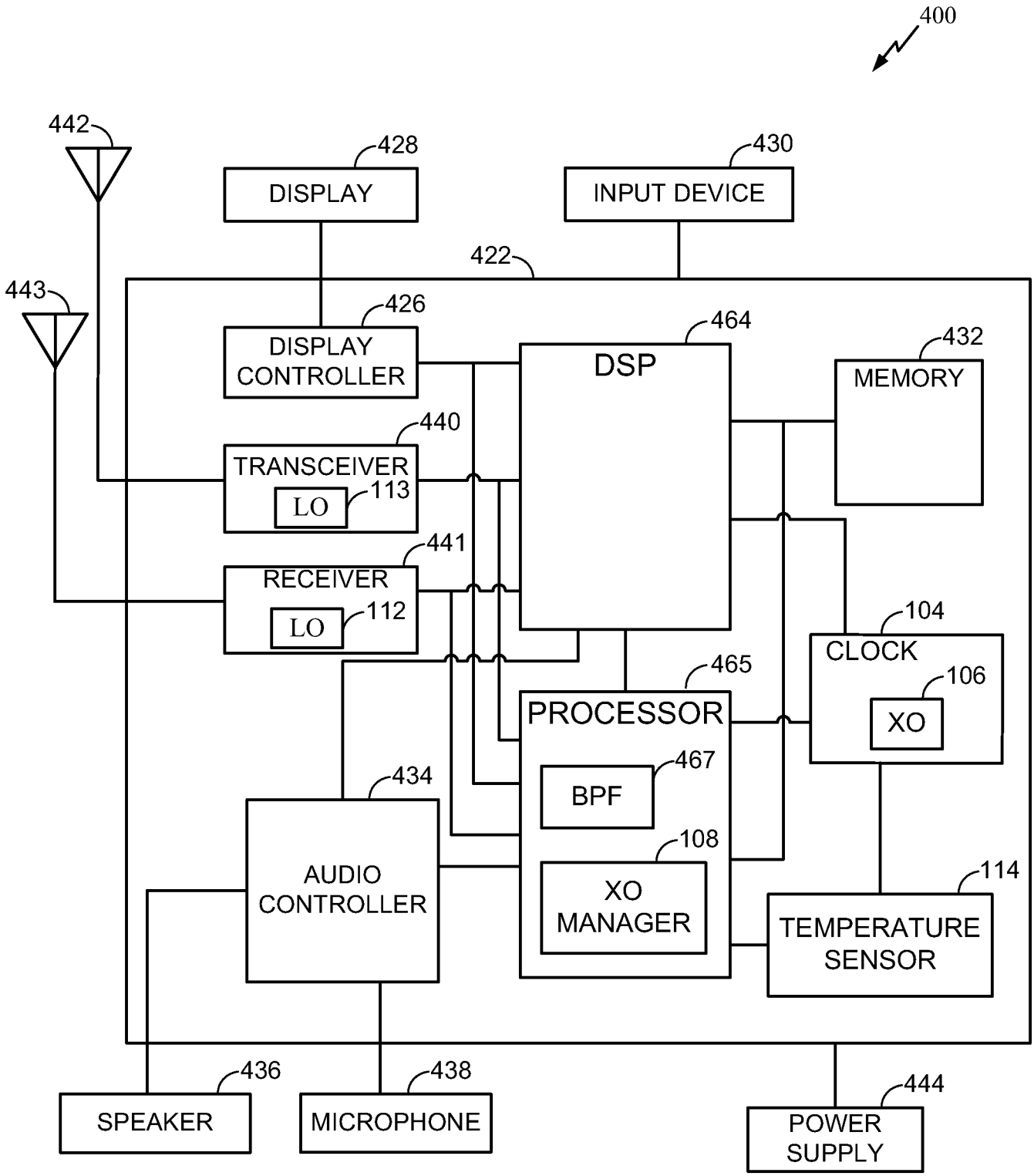
400
442
428
DISPLAY
430
INPUT DEVICE
422
443
426
DISPLAY CONTROLLER
464
DSP
432
MEMORY
440
TRANSCEIVER
LO
113
441
RECEIVER
LO
112
104
CLOCK
106
XO
465
PROCESSOR
467
BPF
434
AUDIO CONTROLLER
108
XO MANAGER
114
TEMPERATURE SENSOR
436
SPEAKER
438
MICROPHONE
444
POWER SUPPLY

FIG. 4