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**Bryant et al.**

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(54) **SATELLITE-BASED POSITIONING SYSTEM RECEIVER FOR WEAK SIGNAL OPERATION**

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(\*) **Notice:** Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

\* cited by examiner

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(65) **Prior Publication Data**

(57) **ABSTRACT**

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**Related U.S. Application Data**

(60) Provisional application No. 60/202,464, filed on May 8, 2000, and provisional application No. 60/263,439, filed on Jan. 23, 2001.

A method, device and system for determining a receiver location using weak signal satellite transmissions. The invention involves a sequence of exchanges between an aiding source and a receiver that serve to provide aiding information to the receiver so that the receiver's location may be determined in the presence of weak satellite transmissions. With the aiding information, the novel receiver detects, acquires and tracks weak satellite signals and computes position solutions from calculated pseudo ranges despite the inability to extract time synchronization date from the weak satellite signals.

(51) **Int. Cl.**<sup>7</sup> ..... **G01S 5/14**

(52) **U.S. Cl.** ..... **342/357.1; 342/357.15**

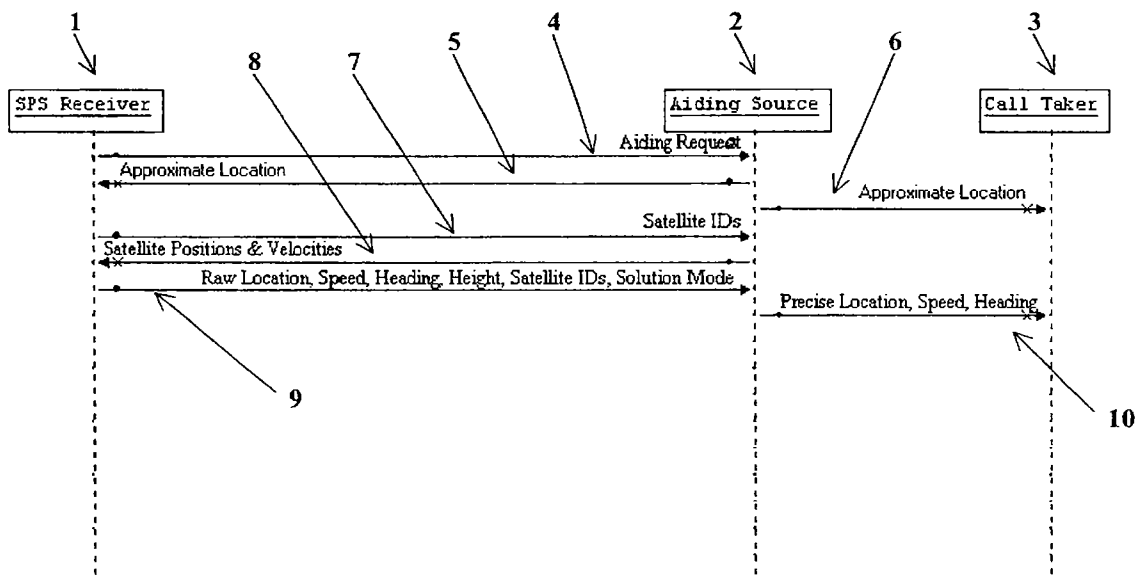
(58) **Field of Search** ..... **342/357.09, 357.15, 342/357.1**

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**32 Claims, 7 Drawing Sheets**



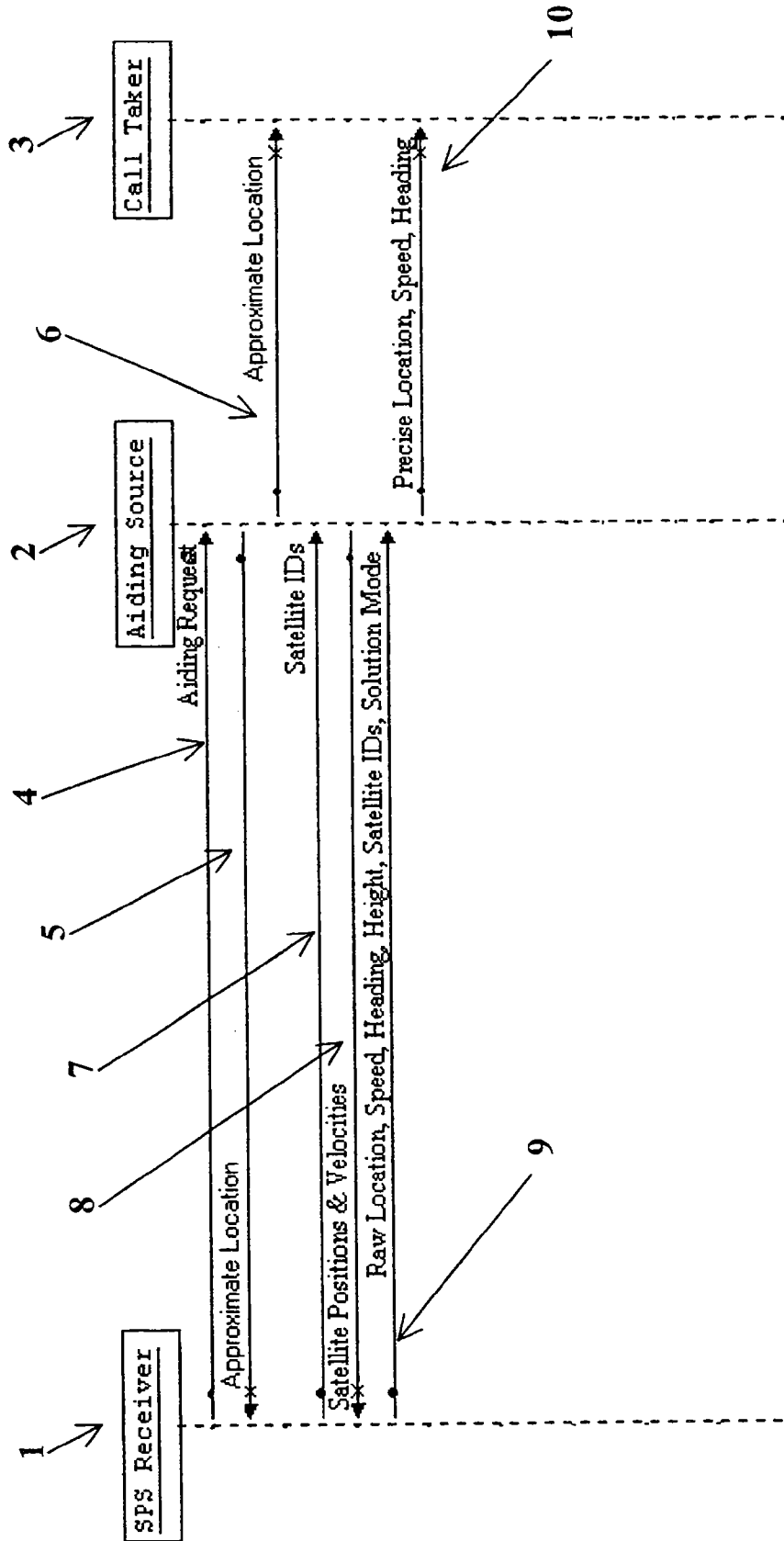


FIGURE 1

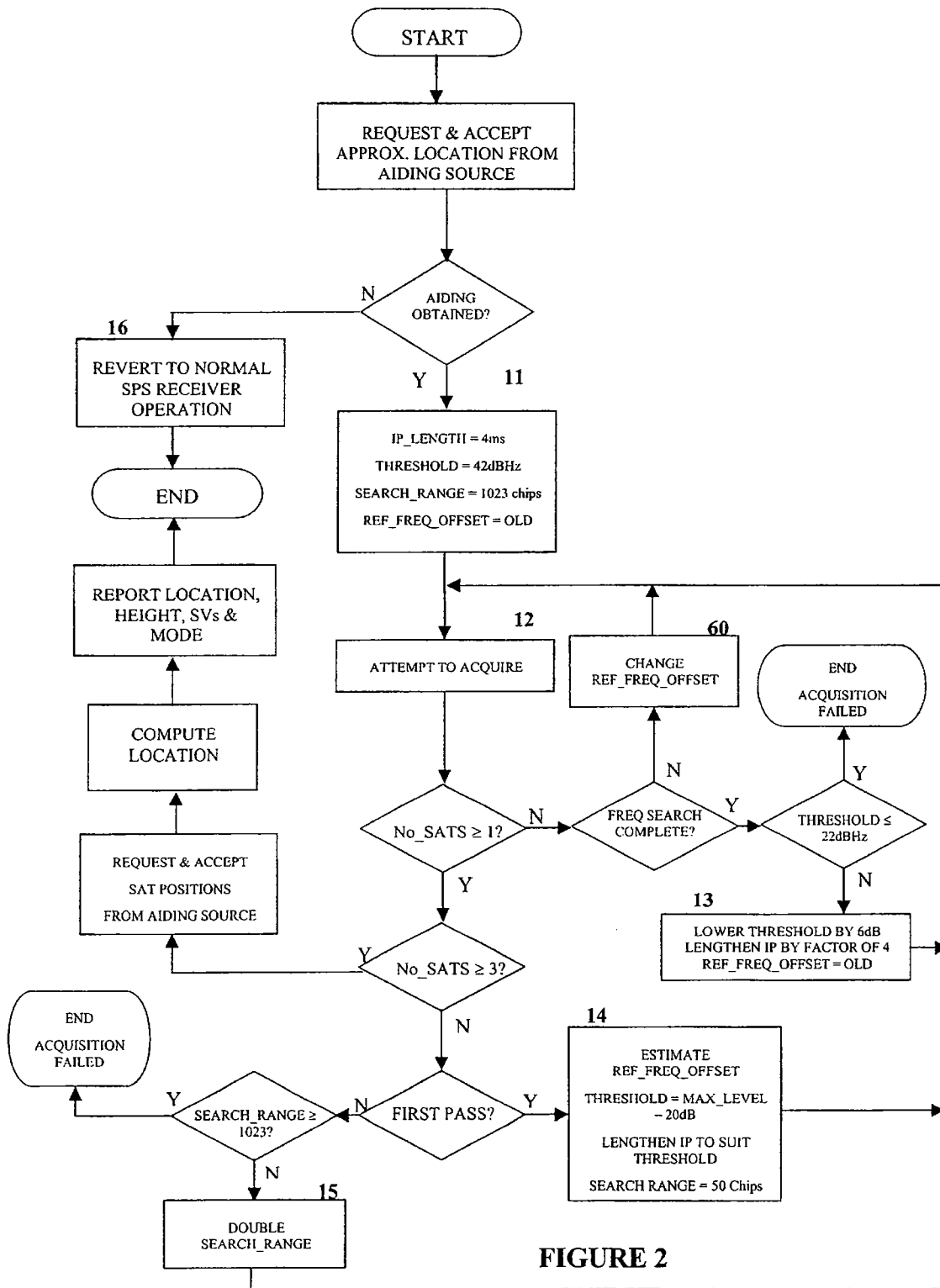


FIGURE 2

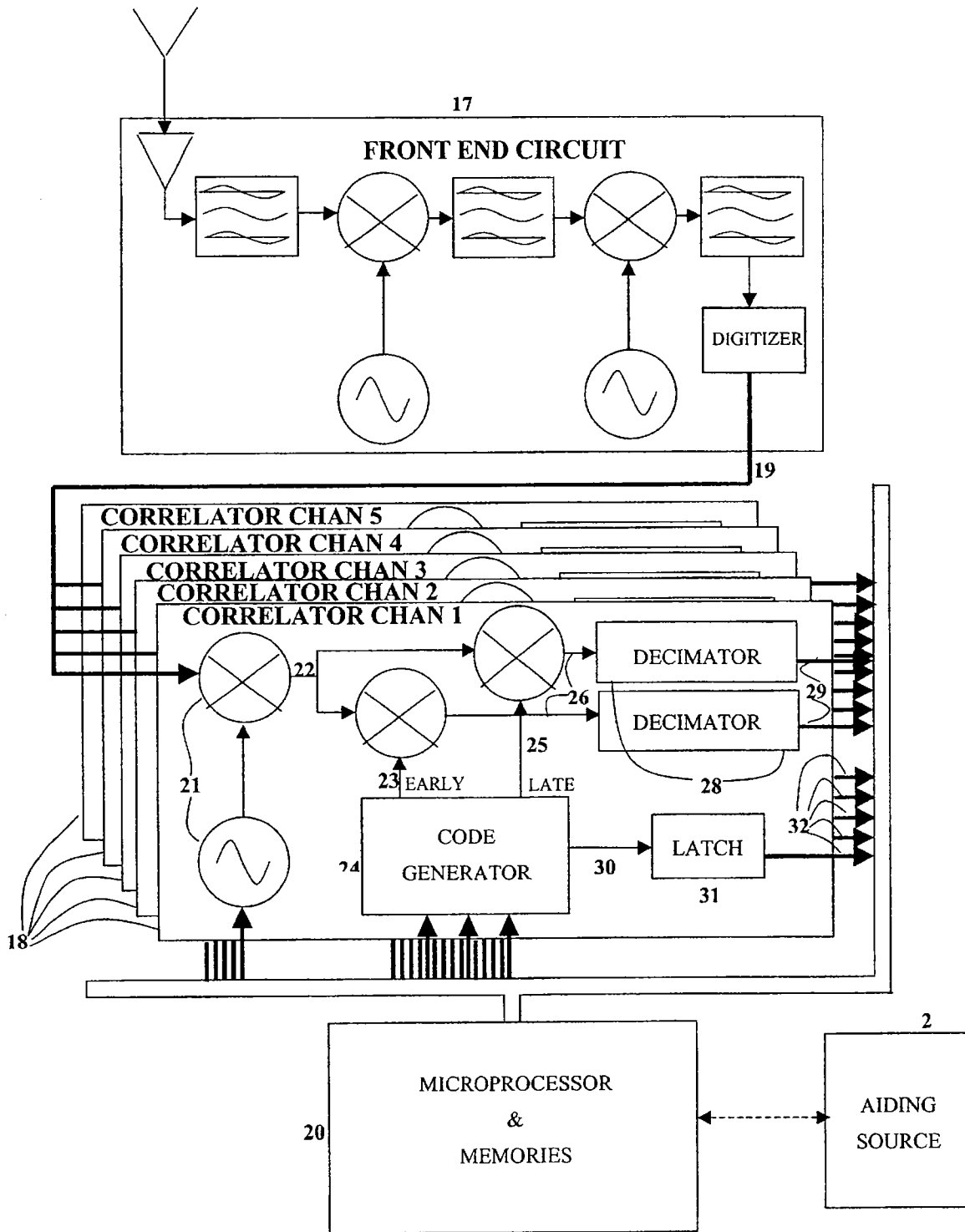


FIGURE 3

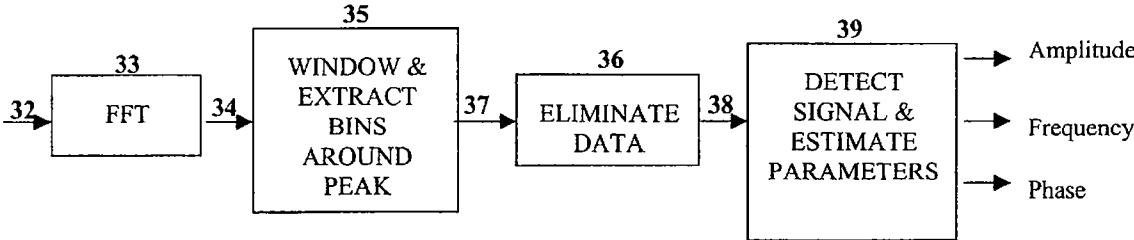


FIGURE 4

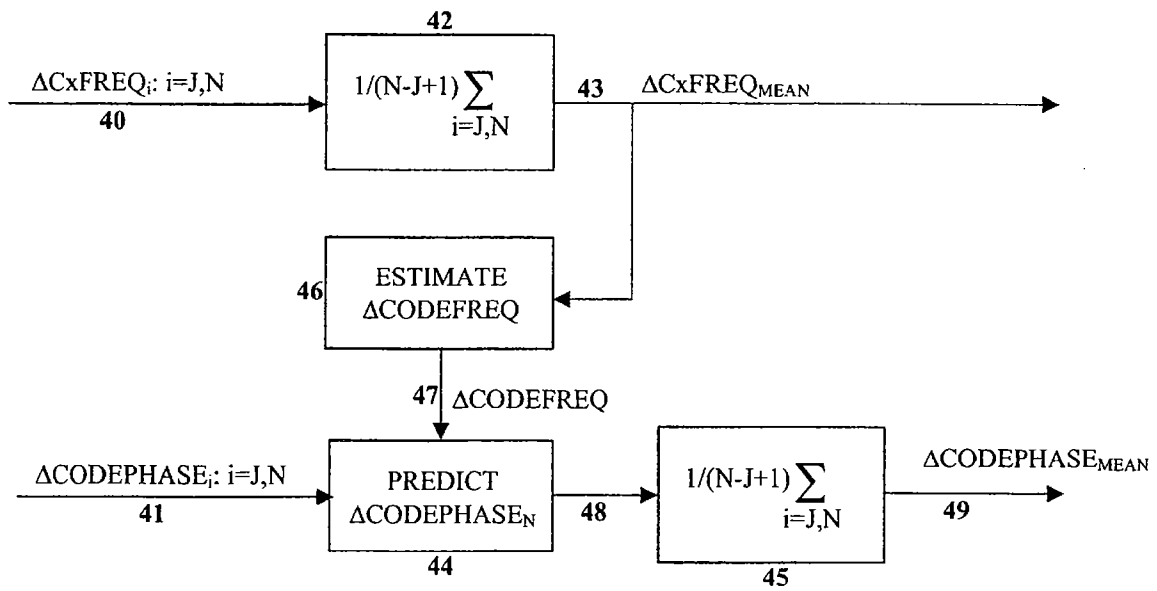


FIGURE 5

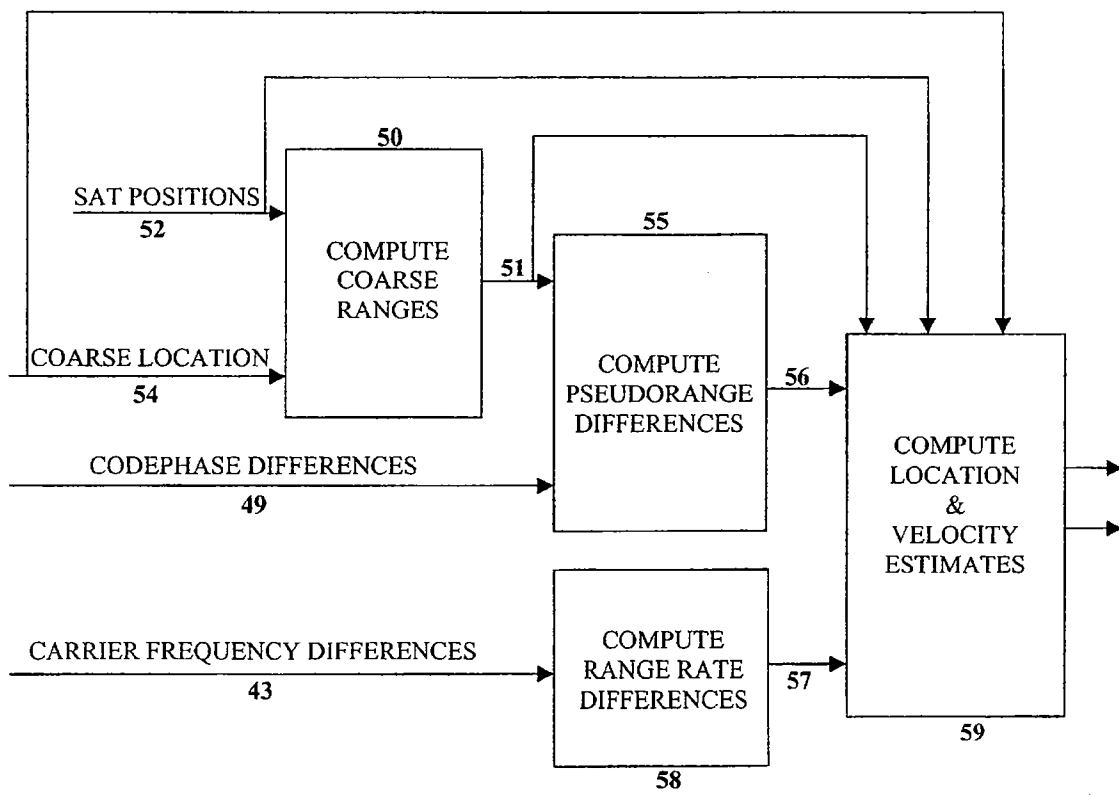


FIGURE 6

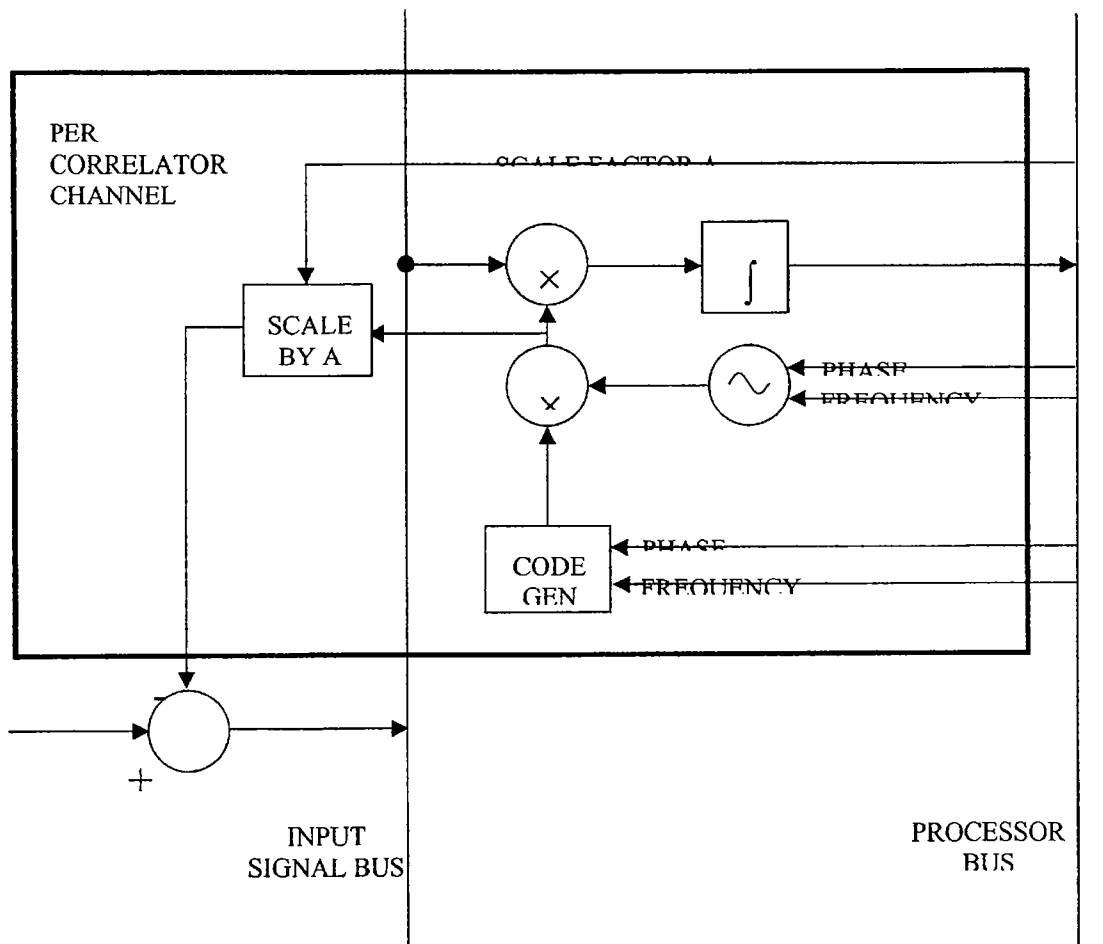


FIGURE 7

## SATELLITE-BASED POSITIONING SYSTEM RECEIVER FOR WEAK SIGNAL OPERATION

This application claims the priority filing date of U.S. Provisional Application Serial Nos. 60/202,464 filed on May 8, 2000, and 60/263,439 filed on Jan. 23, 2001.

### FIELD OF THE INVENTION

This invention relates to the design of receivers employed in satellite-based positioning systems (SPS) such as the U.S. Navstar Global Positioning System (GPS), the Russian Global Navigation Satellite System (GLONASS) and the European Galileo system. More specifically, the invention relates to methods, devices and systems for determining a receiver location using weak signal satellite transmissions.

### BACKGROUND OF THE INVENTION

Satellite based positioning systems operate by utilizing constellations of satellites which transmit to earth continuous direct sequence spread spectrum signals. Receivers within receiving range of these satellites intercept these signals which carry data (navigation messages) modulated onto a spread spectrum carrier. This data provides the precise time of transmission at certain instants in the signal along with orbital parameters (e.g., precise ephemeris data and less precise almanac data in the case of GPS) for the satellites themselves. By estimating the time of flight of the signal from each of four satellites to the receiver and computing the position of the satellites at the times of transmission corresponding to the estimated times of flight it is possible to determine the precise location of the receiver's antenna.

In a conventional SPS receiver, the process by which this is done involves estimating pseudoranges of at least 4 satellites and then computing from these the precise location and clock error of the receiver. Each pseudorange is computed as the time of flight from one satellite to the receiver multiplied by the speed of light and is thus an estimate of the distance or 'range' between the satellite and the receiver. The time of flight is estimated as the difference between the time of transmission determined from the navigation message and the time of receipt as determined using a clock in the receiver. Since the receiver's clock will inevitably have a different present time when compared to the clock of the satellites, the four range computations will have a common error. The common error is the error in the receiver's clock multiplied by the speed of light.

By using at least 4 satellites it is possible to solve a set of equations to determine both the receiver clock error and the location of the antenna. If only 3 measurements are available it is still possible to determine the location and clock error provided at least one of the receiver's coordinates is already known. Often, this situation can be approximated by estimating the altitude of the antenna.

The signals from the satellites consist of a carrier signal which is biphasic modulated by a pseudo-random binary spreading code at a relatively high "chipping" rate (e.g., 1.023 MHz) and then biphasic modulated by the binary navigation message at a low data rate (e.g., 50 Hz). The carrier to noise ratio is typically very low (e.g., 31 dBHz to 51 dBHz) at the earth's surface for a receiver with unobstructed line of sight to the satellite from its antenna. However, it is sufficient to permit the signals to be detected, acquired and tracked using conventional phase-locked loop and delay-locked loop techniques and for the data to be extracted.

The process of tracking the code of a signal in a conventional SPS receiver involves the use of a hardware code generator and signal mixer. When the locally generated code is exactly aligned with that of the incoming signal, the output from the mixer contains no code modulation at all. Hence the bandwidth of the signal is much less and it can be filtered to greatly increase the signal to noise ratio. This is usually done using a decimation filter such that the correlator output sampling rate is much lower than the input sampling rate (e.g., 1 kHz at the output compared to 1.3 MHz at the input).

Also, in the case of GPS, the precise time of transmission of this signal corresponding to any given instant at the receiver can be determined by latching the state of the code generator to get the code phase and by counting the code epochs within each bit of the data and by counting the bits within each word of the navigation message and by counting the words within each subframe of the message and by extracting and decoding the times of transmission corresponding to the subframe boundaries. A similar scheme can be used for any SPS.

However, traditional SPS receivers can suffer from troublesome lapses in position identification in the presence of weakened transmission signals. When the direct line of sight between the antenna and the satellites is obstructed, signals may be severely attenuated when they reach the antenna. Conventional techniques can not be used to detect, acquire and track these signals. Moreover, under these circumstances even if the signal could be detected, the carrier-to-noise ratio of a GPS signal, for example, may be as low as or lower than 24 dBHz and as such it is not possible to extract the data from the signals.

Prior art devices have attempted to minimize or overcome these shortcomings through the use of aiding information. In such schemes, additional information is externally supplied to the SPS receivers through various secondary transmission sources to balance the shortfall of information resulting from the attenuated signals. Examples of such devices are taught in the patents to Taylor et al. (U.S. Pat. No. 4,445,118) (aided by satellite almanac data); Lau (U.S. Pat. No. 5,418,538) (aided by differential satellite positioning information and ephemerides); Krasner (U.S. Pat. No. 5,663,734) (aided by transmission of Doppler frequency shifts); Krasner (U.S. Pat. No. 5,781,156) (aided by transmission of Doppler frequency shifts); Krasner (U.S. Pat. No. 5,874,914) (aided by Doppler, initialization and pseudorange data) Krasner (U.S. Pat. No. 5,841,396) (aided by satellite almanac data); Loomis, et al. (U.S. Pat. No. 5,917,444) (aided by selected satellite ephemerides, almanac, ionosphere, time, pseudorange corrections, satellite index and/or code phase attributes); Krasner (U.S. Pat. No. 5,945,944) (aided by timing data); Krasner (U.S. Pat. No. 6,016,119) (aided by retransmission of data from satellite signal)

However, aiding information requires additional transmission capabilities. For example, aiding information may be sent to the SPS receiver using additional satellite transmitters or wireless telephone systems. As such, it is a significant advantage to reduce the quantum of aiding information supplied to limit the use of such additional resources. For example, when the voice path of a wireless communication network is being used to communicate the aiding information, the voice communication will be interrupted by the aiding message. The aiding messages must therefore be as short as possible in order to limit the voice interruptions to tolerable durations and frequencies. Also, no matter how the aiding data is communicated, its communication will delay the operation of the receiver. In many applications the

location data is needed promptly and therefore any delay must be minimized.

#### BRIEF DESCRIPTION OF THE INVENTION

An objective of the present invention is to provide a method and device for use in a satellite positioning system that has improved performance in the presence of obstructed or weak satellite transmission signals while maintaining robust performance in the presence of strong signals.

A further objective is to improve performance of the system utilizing minimal external assistance while maintaining a graceful degradation in performance when this aiding fails.

A still further objective of the invention is to provide a device that achieves a minimal Time To First Fix (TTFF).

Additional objectives will be apparent from the description of the invention as contained herein.

Consistent with these objectives, a device made in accordance with this invention utilizes a novel signal processing scheme for detecting, acquiring and tracking attenuated satellite signals, such as those that might be received at an indoor location, and computes location solutions. The scheme makes novel use of attenuated satellite signals and minimal externally-supplied aiding information.

Under the scheme and in response to a request by the SPS receiver, an aiding source supplies two types of information in an ordered sequence. First, the aiding source provides an approximate location of the receiver preferably to within 20 km and certainly in the GPS case to within 100 km. Second, the aiding source provides precise satellite positions and velocities for the set of tracked satellites. These satellite positions and velocities are computed by the aiding source from ephemeris data for the satellites. No further aiding information is needed.

Generally, the device detects and acquires a set of satellites for tracking based upon information from internally stored almanac data and its approximate location received from the aiding source. Once acquired and in the presence of weak signals, the device relies upon the code phases of the weak satellite signals rather than the transmission time data within the weakened signal. The code phases of the signals are measured at the same instant so that there is a common time of receipt. Then, by determining the differences between the code phases, the resulting values or code phase differences, are taken as ambiguous measurements of the differences in the times of transmission of the satellite signals.

In the preferred embodiment of the invention, these code phase differences are then employed to generate pseudoranges with the assistance of the approximate location received from the aiding source. In the process, the approximate location of the receiver and the precise satellite positions are combined to determine approximate ranges to the satellites. Then, by further combining the approximate ranges with the code phase differences, precise pseudorange differences are derived. Finally, the precise SPS receiver location may be resolved using the precise pseudoranges and the precise satellite positions.

#### BRIEF DESCRIPTION OF THE DRAWINGS

This invention is illustrated by means of the accompanying drawings. However, these figures represent examples of the invention and do not serve to limit its applicability.

FIG. 1 is a sequence diagram describing the interactions between an aiding source, a call taker and a handset with an integrated SPS receiver according to one embodiment of this invention;

FIG. 2 is a flowchart describing the overall algorithm according to one embodiment of this invention for acquiring satellite signals, measuring code phases, carrier smoothing these measurements, computing pseudorange differences and computing handset location;

FIG. 3 is a block diagram of a typical SPS receiver according to this invention;

FIG. 4 is a block diagram describing the signal processing algorithm used to measure amplitude in each of an early and a late arm of each channel of the correlator according to one embodiment of this invention;

FIG. 5 is a block diagram describing the carrier smoothing algorithm used to reduce the error in the code phase measurements according to one embodiment of this invention;

FIG. 6 is a block diagram describing the algorithm used to compute the location and velocity from the code phase and carrier frequency differences according to one embodiment of this invention.

FIG. 7 depicts a hardware arrangement of the correlator.

#### DETAILED DESCRIPTION OF THE INVENTION

There are four distinct elements of the present invention, which are utilized to achieve the aforementioned objectives. The first element is the nature of the aiding information and the manner in which the SPS receiver and the aiding source interact to provide the aiding information. The second relates to a procedure for detecting, acquiring and tracking weak signals while avoiding jamming by strong signals and ensuring graceful degradation under adverse conditions. The third relates to the design of a device for tracking of multiple satellite signals to determine code phases at a common measuring instant. Finally, the fourth element of the invention involves a set of algorithms used to process a weak satellite signal in order to compute a position solution from measured code phase differences. Each of these features will be addressed in turn.

This invention relates to refinements and extensions to a commonly owned invention disclosed in U.S. Pat. No. 5,459,473. Accordingly, the foregoing U.S. patent is hereby incorporated by reference.

##### A. Aiding Source/Receiver Interaction

As previously described, the aiding data used in accordance with the present invention is limited to information that includes an approximate location for an SPS receiver and the positions and velocities of a specific set of satellites. This information is determined and provided through a request/response sequence. Satellite clock corrections should be included in the aiding data. These are provided in the satellite navigation messages and may be as large as 1 ms. Thus it is essential to apply these corrections in order to accurately compute the pseudorange differences. Instead of supplying satellite positions and velocities, the aiding source can supply corrections for the satellite positions, velocities, accelerations and/or further position derivatives computed from the satellite almanac data. This almanac data may also be used to compute coarse satellite positions, velocities and other derivatives which are corrected using aiding data for use in performing the location solution.

This is advantageous as it allows the satellite positions to be predicted for relatively long periods (eg tens of minutes) with adequate accuracy for computing the receiver location and yet remains undemanding in terms of the amount of aiding data to be transmitted to the receiver.

Because of the compact nature of this data compared to full ephemeris data and its potential longevity, it is feasible

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to structure the aiding in the form of broadcasts transmitted at regular intervals. The advantage of this is that most of the time it would be unnecessary for the receivers to request aiding and this would significantly reduce system data traffic in the direction toward the network base centre, call centre or wireless web site.

In most cases, however, the system would have to cope with a variety of issues of almanac data in the receivers. This would be handled by:

1. Broadcasting corrections for multiple issues of almanac,
2. Transmitting almanac corrections in response to requests for corrections for a specific issue of almanac, or

Broadcasting corrections for the latest one or two issues of almanac and responding to requests for corrections for other issues of almanac. A model of one embodiment of such an exchange in accordance with the present invention is depicted in FIG. 1.

A typical exchange might involve an SPS Receiver 1, an Aiding Source 2 and a Call Taker 3. For instance, the SPS Receiver 1 might be a GPS receiver embedded in or co-located with a wireless telephone or other handset. The Aiding Source 2 may be located at a call center or cell site or elsewhere in the wireless network such that the aiding data is transmitted via a wireless communication link to the handset. The Call Taker 3 may also be located at the call center or other location accessible from the wireless network. The ultimate user of the location data may be either the Call Taker 3 or the user accompanying the SPS Receiver 1. Other forms of transmission between the SPS Receiver 1, Aiding Source 2, and the Call Taker 3 may be utilized without departing from the objectives of the present invention.

To begin the exchange, the SPS Receiver 1 sends a First Aiding Request 4 to the Aiding Source 2. This would typically occur upon activation of the SPS Receiver 1 but may occur at other times as well. In response, the Aiding Source 2, sends a First Aiding Response 5 which contains the approximate location of the SPS Receiver 1. Preferably, the approximate location of the SPS Receiver 1 is accurate to better than one half of a code epoch of a satellite signal multiplied by the speed of light or about 100 km in the case of GPS. The approximate location may also be sent to the Call Taker 3 in a First Aiding Report 6.

With the received approximate location and previously stored almanac data, the SPS Receiver 1 performs its correlation search to acquire satellite signals. The almanac data and the approximate location help to constrain the initial search once at least one satellite has been acquired. Upon acquisition, the SPS Receiver 1 sends a Second Aiding Request 7 to the Aiding Source 2. The Second Aiding Request 7 includes information for identifying the specific set of satellites used by the SPS Receiver 1 in determining pseudorange differences. In response, the Aiding Source 2 determines the precise positions and velocities of the identified set of satellites from ephemeris data for the satellites. The determined positions and velocities are then sent to the SPS Receiver 1 in a Second Aiding Response 8. Since this elapsed time is known and assuming that the latency between transmission and reception of the request for aiding can be determined it is possible for the aiding source to determine the time of reception of the satellite signals to within a few tens of milliseconds.

However, if almanac corrections are to be used by the receiver then the receiver needs to determine the times of transmission (TOTs) with an accuracy of the order of 10 ms.

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Furthermore, it is preferable for the receiver to do this without requiring the estimation of the latencies as this is cumbersome, inelegant and, potentially error prone.

The aiding data can contain a timetag accurate to, say, 1 ms at the aiding source. Because of the communications latency, this accuracy will be degraded to the order of seconds for some wireless communications media such as short message services. Hence, this approach is not useful unless the latency is estimated. Instead, we can use the following facts to restrict the TOTs to a discrete set of alternatives:

- a) The boundaries of the code epochs are transmitted from the satellites at millisecond boundaries in GPS time;
- b) The time between each TOT and the preceding code epoch boundary is known as it corresponds to the measured codephase for that satellite;
- c) The Time Of Receipt (TOR) of the signals at the receiver is known to an accuracy of much less than 1 s; and
- d) The range to each satellite is known to an accuracy of below 1 ms (as required to permit the ambiguity resolution of the pseudorange differences).

The TOR and the TOTs can therefore be estimated as follows:

1. Subtract the average Time-Of-Flight (average TOF approx=70 ms) from the coarse TOR and use the almanac to compute the satellite positions at this approximate TOT.
2. Correct these satellite positions using the almanac corrections.
3. Estimate the satellite ranges to the estimated receiver location and thus the TOFs.
4. Subtract these from the coarse TOR to refine the TOTs.
5. Compute the corresponding satellite positions using the almanac and almanac corrections.
6. Iterate steps 3 to 5 until the solution converges according to some criterion.
7. Compute new TOTs as in steps 3 and 4 above.
8. Correct each TOT to the nearest possible value using a) and b) above together with the corresponding codephase measurement and clock corrections for that satellite.
9. Compute new satellite positions using the almanac and almanac corrections.
10. Compute a new receiver location estimate and a set of pseudorange difference residuals using the estimated range differences and the satellite positions obtained in step 9.
11. Calculate the mean squared value of the pseudorange residuals.
12. Enclose steps 7 to 11 in a Newton-Raphson recursion loop or similar to determine the TOR value giving rise to the smallest mean-squared residual value. This is the final TOR estimate and the difference between it and the original coarse TOR estimate may be used to correct the receiver clock. The corresponding receiver location estimate is the final receiver location estimate.

For subsequent updates of the navigation filter this process may be omitted

Therefore, under this scheme since the Aiding Source 2 provides precise satellite positions and velocities, the Aiding Source 2 rather than the SPS Receiver 1 needs to be able to determine specific time synchronization data from the satellite signals and needs to maintain or acquire ephemeris

