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(57) Abstract

A GPS receiver for use with the NAVSTAR global, satellite-based radio navigation and time transfer system wherein transmission from each of a plurality of satellites includes C/A code signals comprising a code and data modulated carrier, said receiver comprising means for receiving C/A code signals transmitted from at least four satellites and means to process the signals including an open loop estimator of signal parameters for phase-coherent estimation of a plurality of signal parameters including code delay, carrier frequency, carrier phase, carrier phase acceleration, data value and data delay.

G P S RECEIVER

The invention relates to a radio receiver and in particular to a GPS receiver for use with the NAVSTAR Global Positioning System.

The NAVSTAR Global Positioning System is a global, satellite-based radio navigation and time transfer system using the satellite constellation of the US Department of Defence. This constellation will comprise at least 21 satellites positioned in a plurality of orbital paths at a predetermined distance above the Earth and arranged so that, at any time, at substantially any position on the Earth, there will be at least four satellites above the horizon. There is a satellite control station which, inter alia, controls highly accurate clocks in the satellites, synchronises the clocks, determines the orbits or the satellites and uploads orbital information to the satellites for retransmission to users.

Each satellite in the constellation transmits two unique direct-sequence spread spectrum messages in phase quadrature on each of two L-band frequencies. The receiver described here only processes the C/A (Coarse/Acquisition) code message on the L1(1575.42 MHz) carrier; but the principles discussed also apply to the P (Precise) code signals on L1 and L2. The direct sequence code signal, which has a frequency of 1.023 Mchips/sec, and a code epoch repetition rate of 1kHz, modulates the carrier in a binary phase shift keyed (BPSK) manner. This spread signal is further BPSK modulated by a 50 bps data signal. The data includes information which allows the receiver to measure the range between the receiver and the satellite, i.e. data which allows modelling of the spacecraft orbit (ephemeris) and timing information referenced to the precise satellite clock. The receiver clock will always have an offset with respect to the satellite clock, so these range measurements are known as pseudoranges. To perform a position solution, four pseudorange measurements are required - to solve for the four variables x, y, z and the local clock offset. To further enhance the accuracy of the position solution more measurements can be made - over time (several measurements from the same satellites), over a larger satellite set, or over a wider range of satellite signal variables, such as phase and phase rate.

A position reporting system employing NAVSTAR GPS satellite signals is described in our co-pending Australian application No. 63995/90.

Many factors influenced the basic design of the GPS receiver of the invention. In addition to particular customer requirements, several design desiderata were identified.

Firstly, the receiver design should be flexible enough to be used in many applications. This implies a modular design with individual modules being interchangeable. In addition, the proportion of the receiver functionality to be provided by software should be optimised, with the software written in modular form, preferably in a high-level language.

Secondly, the receiver design should be suitable for a variety of potential environments. This implies the use of appropriate margins and packaging for the hardware design. More important is the ability of the signal processing to operate under various dynamic conditions, such as those due to vehicle manoeuvring dynamics, or vibration and intermittent blocking of the satellite signals.

Thirdly, a high performance low cost receiver implies the minimisation of production costs which may be achieved by minimising hardware, either by maximising the functionality provided by software, or by using a high-density packaging technique, or both. In addition, the receiver is designed to use the C/A code, as opposed to the more complex P code.

Fourthly, using C/A code, a receiver can be almost as accurate as a P code receiver, when it is used in the differential mode. This requires an accurately-positioned base station to provide systematic error corrections of the pseudoranges to the receiver. The receiver must measure the pseudoranges (and any other parameters) to the resolution and accuracy required for the accurate solution, and thus the measurement error and resolution must be much less than the systematic errors which are being removed.

Fifthly, for portability and convenience, the receiver must be designed for minimum mass and volume. In addition, as many proposed applications are for remote, portable use, with power supplied by batteries, power consumption should be minimised. Again, high-density packaging techniques are important.

A known GPS receiver of the closed loop type employs two loops: a code-locked loop which extracts the code delay estimate (pseudorange), and a phase-locked loop (typically a

Costas loop) for extraction of the data. The Costas loop may also be used to make ongoing measurements of carrier parameters such as phase and phase rate. In the code-locked loop, a replica of the satellite code is used to despread the received signal, and a data-modulated carrier replica is used to coherently demodulate the despread signal. The resultant energy in each of the early and late channels is balanced in order to align the replica with received signal. In the Costas loop, the data is demodulated by coherent demodulation.

This phase-locked approach only approximates optimality. Another problem is its susceptibility to loss-of-lock and cycle-slips in low signal to noise ratio (SNR) situations such as in the presence of high noise or vibration or under jamming conditions. The code-locked loop also suffers degraded performance, but is less significant with respect to total receiver performance. The problem is prevalent in dynamic conditions. However, even in low dynamic conditions such as for high accurate surveying applications, cycle-slip probability becomes significant since the relevant measurements take long periods of time.

Another type of GPS receiver employs an open loop estimator of signal parameters. In particular, a generic correlation receiver may be used to be the maximum likelihood estimator of signal parameters. Estimates are made of a selection of signal parameters which are processed to provide a position solution.

The dynamic performance of an open loop design is superior to that of a closed loop design because the former is not subject to the phenomena of cycle slipping and loss of carrier lock. It follows from this that open loop receiver designers have more freedom to vary parameters to meet varying application requirements. Furthermore, an open loop design many be implemented more cost-effectively because of the modularity of the basic processes and because the designer is far less constrained in terms of allowable processing delay.

A high dynamic global positioning system receiver is described in U.S. Patent No. 4578678 by W.J. Hurd. Unlike the Hurd receiver, the receiver of the invention operates phase coherently. This results in a significant improvement in SNR. Further, without a phase coherent approach, the carrier phase parameter cannot be measured. It also allows an increased number of parameters to be used in a position solution leading to greater accuracy. Whereas Hurd used the P code, the receiver of the invention uses the

C/A code leading to a significant simplification of the hardware and processing software. The Hurd design relies on application-specific hardware and software. Because the processing is performed in software, the receiver of the invention is more flexible catering for many different applications simply by changing the algorithms of the receiver software. Another advantage over Hurd, is the control the processor has over the frequency of the local code generator which allows optimisation of the measurements made of the signal parameters.

The GPS receiver according to the invention produces estimates of code delay, carrier frequency, carrier phase, carrier phase acceleration, data value and data delay. It produces these estimates using open-loop correlation techniques. By using multiple optimal parameter estimates, the receiver is highly accurate. The open-loop nature of the receiver makes it comparatively immune to high vibration or high dynamics environments and allows it to operate reliably under intermittent signal blocking. In addition, with the majority of the signal processing being performed in software, the receiver is both low cost and versatile.

Accordingly, the invention comprises a GPS receiver for use with the NAVSTAR global, satellite-based radio navigation and time transfer system wherein transmission from each of a plurality of satellites includes C/A code signals comprising a code and data modulated carrier, said receiver comprising means for receiving C/A code signals transmitted from at least four satellites and means to process the signals including an open loop estimator of signal parameters for phase-coherent estimation of a plurality of signal parameters including code delay, carrier frequency, carrier phase, carrier phase acceleration, data value and data delay.

Receivers incorporating the principles of the invention may be designed for many various applications which may involve a variety of environmental and dynamic conditions. So as to provide a more detailed illustration of the invention, one embodiment thereof will be described with reference to the accompanying drawings, in which:-

Figure 1 illustrates a functional block diagram of one receiver in accordance with the invention;

Figure 2 illustrates raw pseudoranges on the Correlation Diagram; and

Figure 3 is a block diagram of the Kalman Filter.

For ease of estimation of the signal parameters, and for the elimination of systematic errors, three of the parameters are not estimated directly, but as differences between the selected satellites. Rather than producing four estimates of the four pseudoranges, the shortest pseudoranges is nominally assigned the value zero, and the others are thus assigned the value by which they exceed this one. This has been shown to introduce no errors in the position solution, since one of the variables for which solution is required is the clock offset. This method of estimation effectively sets the value of the clock offset to the value of the shortest pseudorange. Not only are errors common to each channel eliminated by this approach, but the number of bits required to describe the pseudoranges is reduced by more than one quarter, which reduces the size of the message required to be sent to the base station when differential positioning is being used. For the phase, phase rate (frequency) and phase acceleration parameters, differences are also estimated. This eliminates errors common to the estimates from different satellites such as those due to reference oscillators phase fluctuations.

HARDWARE

Figure 1 illustrates the architecture for the receiver of this embodiment. The functional blocks are divided between hardware and software performed by a digital signal processor. The hardware performs amplification, downconversion and filter functions, all of which are "normal" functions to be performed in hardware. The down-conversion is "pseudo-single-stage", i.e. the carrier is converted down to a frequency only slightly (with respect to the carrier frequency and signal bandwidth) above dc. This offset permits self-detection products and local oscillator feed-through products to be filtered out. Because the offset is very small compared to the signal bandwidth, it is necessary to generate in-phase and quadrature components.

In this embodiment, the code generation and mixing are also performed in hardware under control of the main processor. A further downconversion is also performed at this point using a hard-limited "complex" local oscillator. The local oscillator frequency is controlled from the processor to allow for drift and predictable Doppler shift thereby increasing the effective range of carrier frequencies that the receiver can handle. Mixing is performed digitally, in a binary way, the received signal being hard-limited, i.e. it is represented by a binary "1" if positive, and "0" if negative. Hard-limiting results in a loss in SNR, but the simplifications that it allows in the hardware outweigh this disadvantage.

Code mixing results in a signal of bandwidth roughly twice the code frequency, i.e. = 2 MHz, unless the codes are "perfectly" matched. This signal is sampled at 5 MHz and is then low-pass filtered and downsampled to 9768 Hz, which is low enough for software to be used for processing. This filter/downsampler is realised as an integrate-and-dump, integrating(counting) a number of input samples and providing a single output sample. An integrate-and-dump filter has a sinc-function frequency response which has its first zero at the sampling frequency. This means that there is a significant amount of the passband above the Nyquist frequency. Signal and noise frequency components in this region are thus passed as noise due to aliasing. This problem can be simply solved if, for the same output sampling rate, twice as many input samples are integrated. This means that a given output sample is the sum of the previous two integrate-and-dumps. This second summing, known as the anti-aliasing filter is performed in the hardware.

MAIN PROCESSOR

Up until this point, the receiver functional blocks have been operating either continuously, or if sampled, each sample has had no special meaning with respect to its position in time. In the main processor, all of the algorithms are based around a time unit known as the "integration period", =25ms. Certain algorithms are performed each integration period; others are performed once every 3 or 54 integration periods, as shown in Figure 1.

Also, some of the main processor algorithms are performed according to the acquisition status of the receiver, i.e. whether a satellite has been acquired or not. The incoming signal is transformed into the frequency domain by the use of a Fast Fourier Transform (FFT). Each bin in the FFT is checked for magnitude. If no bin exceeds a threshold, the satellite signal is assumed to be not acquired, and the main processor waits for the next integration period. If the threshold is exceeded, the bin in which the maximum occurs is downconverted to the zero Hz bin, and a narrow low-pass infinite impulse response (IIR) filter is applied in the time domain. The signal at this stage is the carrier, spread by the 50 Hz data.

The unwrapped phase of this signal is determined, and is differentiated across the integration period. This allows detection of the data bit transitions (180° phase transitions). Once the locations of a string of transitions have been located, the data can be decoded. This operation looks for the repeated framing information, which, once acquired, removes the polarity ambiguity, and the rest of the data can be decoded. The aims of this decoding are to establish the time of transmission of the data transitions, and to extract the ephemeris data, which describes the satellite orbit to a high degree of precision.

Based on these detected transitions, the signal is despread by multiplication by a replica of the detected data. Optimum detection can be guaranteed by performing several of these despreading operations around the detected transitions, and picking the peak of the correlation function for the data delay parameter. Once the signal has been despread with respect to data, nominally leaving only the carrier, the phase is measured once again. A linear fit is made to this phase function. This produces a least-squares estimate of the phase rate over the integration period. The phase of the signal is then rotated using the transform by which the line produced by the linear fit is transformed to the real axis. The sum of the real values of this rotated signal is effectively the phase-coherent correlation of the signal. One of these correlation values is produced each integration period. A threshold set on the correlation value may also indicate that a satellite has not been acquired.

In order to measure the pseudoranges, an estimate of the code delay must be made. In this receiver, pseudoranges are not measured directly but as differences between satellites. One satellite is assigned the value zero, the others are assigned the difference between this pseudorange and the pseudorange in question. By measuring differences, the receiver is simplified in that a high-resolution clock is not required, and communications with the base station are simplified.

The code delay is estimated by setting the code generator at three different "phases" for three successive integration periods. These three phases are "locked" (i.e. local and satellite codes are aligned), part of a chip early, and part of a chip late. From these three code phases, the correlation function can be reconstructed. The optimum way to reconstruct the correlation function, and pick the peak is to correlate the measured correlation function, sampled at the three points, with the expected correlation function, which can be measured a priori. By using this double-correlation technique, raw pseudo-range estimates are produced. The use of this second correlation is necessary to optimise the use made of the three integration times contributing to the measurement. Each of the three correlation samples is produced by observing the signal for one integration period only but the total measurement time is three integration periods. The noise on the samples is independent between samples. Therefore this sampled correlation curve is sub-optimal. Correlating it with the expected correlation function maximises the correlation signal-to-noise ratio, thereby restoring the optimatlity of the process, and allowing the samples to be interpolated.

In order to meet the requirements for accurately measuring the pseudorange differences, phase differences, frequency differences and phase acceleration differences, the signal must be observed for a much longer period than an integration period (the length of which is set by signal detection requirements). In other words, the raw estimates must be combined in some optimal way in order to generate a more accurate estimate. The method selected for combining the estimates is to use a Kalman filter. Inputs to the filter are the estimates of pseudorange, frequency and phase differences, and the pseudorange corrections from the base station. This filter models the receiver position, satellite and receiver motion, and receiver oscillator drift. From these models and the inputs, it produces not only smoothed but uncorrected pseudoranges, for transmission to the base station, but also estimates of the receiver position to the user. These estimates are presented to the user in a standard reference system, which requires a geometric transformation.

CORRELATION

The Maximum Likelihood (ML) estimator is a correlation detector. The signal parameters of interest are code value, signal delay (measured using code delay and data delay), carrier frequency, carrier phase, and data value. The receiver must effectively perform a six-dimensional correlation and pick its peak to determine the optimal estimates of all parameters, in order to derive the optimal position solution.

Two other parameters that arise in the estimation process are the local oscillator drift, and the code generator frequency. The oscillator drift is of interest since all of the measurements of time made in the receiver are made with reference to the one oscillator, which is used for the local oscillator and sampling clocks. The Kalman filter output is used to produce an estimate of oscillator frequency, which can be used to correct the setting of the code generator frequency. Correction of the code generator frequency allows the close tracking of the satellite code, optimising the correlation shape and value and maximising SNR. It is not estimated as a separate parameter (i.e. the correlation is not performed against it) because it is directly proportional to the satellite signal carrier frequency, which is already estimated.

CODE VALUE

Code value selection simply entails the selection of a satellite code to be used for each channel of the receiver. Each satellite has a code of epoch length 1023 chips, which it repeats at an epoch rate of 1KHz. In the receiver, each satellite channel generates a replica of the code for the satellite from which it is to receive data. The locally-generated code is multiplied by the received satellite signal. If the local code has been delayed such that the codes are matched, the received signal is despread from the 2MHz spread-spectrum bandwidth to the 100MHz data bandwidth.

DATA VALUE ESTIMATES

The data value is determined by searching for data transitions. The correct polarity of the data is established in the data decoding algorithm. For the purposes of the signal processing, the data value is estimated as inverted or non-inverted, with the actual data, "1" or "0" being determined at a later stage. Transitions are located in time by filtering the phase of the data-modulated carrier with a filter matched to a transition. Peaks in the matched filter output occur in the region of data transitions. Matched filtering is an optimal method of locating transitions and is accurate to within a small number of samples. Code epochs can be used to unambiguously locate the transitions, given the initial estimate from the matched filter. Since the matched filter locates the transitions to within a few samples (i.e. within hundreds of micro-seconds), and the data transitions always correspond to transitions of code epochs, which occur every 1ms, unambiguous location of the transitions is possible if the locations of code epoch boundaries within an integration period are known. This is the method used in the receiver.

When the data transitions have been located and decoded, the information in the data contributes to other measurements. The timing information in the data is used to set time-of-week and allows the receiver to calculate the time of transmission of the edge used for pseudorange measurement. The ephemeris data is used to accurately locate the satellites, given the time of transmission.

PHASE, PHASE RATE (FREQUENCY) AND PHASE ACCELERATION ESTIMATES

The estimate of frequency in each of the satellite channels is simply the sum of all of the downconversions used to coherently detect the signal. Nominally, there are four such downconversions - in the analogue hardware (via the LO), in the digital hardware and two in the main processor (one prior to the IIR filter and one via the phase rotation, both in the time domain). Each of these conversions is nominally smaller than the previous one. Also, the measured value of each is proportional to the LO frequency. This is because the frequencies of the downconversions performed in the hardware and in the processor are all in terms of the sampling frequency, which is derived from the same source as the LO. In other words, LO drift causes a multiplying error in this measurement. However, due to the estimation of frequency differences, the first LO frequency offset is eliminated, and the drift only multiplies the downconversions performed in software.

The optimality accorded to the frequency estimate relates only to the last two downconversions - the first two are effectively "constants". The FFT is a correlation in frequency, so estimating frequency for the first downconversion in the main processor via the FFT provides a ML estimate. The phase processing which uses averaging for the estimates of frequency and phase can be shown to be an optimal interpolation of the complex FFT estimates.

If the phase is measured at integration period boundaries, its measurement is also optimal. The phase contribution by the first LO is eliminated by the use of phase differences. Both the downconversion in the digital hardware and the FFT downconversion contribute zero phase to the signal at integration period boundaries. This is due to these downconversion "oscillators" having integral numbers of cycles in an integration period, and being initialised to zero. This means that the phase estimate is the average value estimated during the phase processing. To remove phase ambiguity the phase estimate must be "unwrapped" with respect to 2.

The phase acceleration is not optimal because it does not use all of the available information. It only uses the early and late integration periods, both of which will generally have lower SNR than the punctual.

DELAY ESTIMATE (PSEUDORANGE)

The estimate of delay is more complex than the others, but it is the most fundamental to the determination of receiver position. As discussed earlier, only differences between pseudoranges are estimated. The estimate requires input from both the estimate of code delay (which has a 1ms ambiguity, but can be estimated easily since the code is known) and data delay (which has no ambiguity but is not known). A data transition that occurs in each channel is used for time-tagging the pseudorange measurement. This locates the data transition to within one sample, as described for the data value estimation. A data transition always coincides with a code epoch transition. Interpolation between samples is made possible by sampling the "phase" of code at the beginning and end of the integration period, to sub-chip accuracy. Given that the local code frequency is "locked" to the received code frequency to a degree that can be estimated, the point between samples where the transition occurs can be interpolated. If the local code was perfectly matched (in delay) to the received code, and there was no noise in the system, this interpolated pseudorange measurement would be perfectly correct.

However, the requirements to both maintain code lock and make an accurate estimate despite the system noise dictate that two further processing steps be taken. The first of these involves the picking of the correlation peak for the delay parameter, and the second involves the combination of a series of measurements taken over an observation period that ensures that the accuracy requirement is met.

The pseudorange estimates made using the above method have been called "raw pseudoranges". These estimates are not optimal because there is no relationship between these estimates and the correlation in the delay parameter. This is addressed by making three such estimates in three successive integration periods, each estimate being made for a different "phase" of the code. One of the integrations is made with the code set at the "best estimate" of the code phase (i.e. as close as estimable to "locked"). The other two are made at points part of a chip early and part of a chip late, giving a set of measurements as shown in Figure 2. In order to find the accurate peak of the correlation, and thus correct the pseudorange measurement made at the "best" estimate, these three points must be used to reconstruct the correlation function shape. The optimal method of reconstruction is to correlate the three points with the expected correlation shape (dotted in Figure 2.). This estimate of pseudorange has been called "interpolated pseudorange", and is an optimal estimate, since correlation has been used (twice, effectively, since two estimates are made - one of correlation shape and one of correlation peak) in the estimate generation. However, despite the optimality of each estimate, they are still not accurate enough. Several (nominally at least 18) of these interpolated pseudoranges feed into the Kalman filter, which produces the final estimates of pseudorange and position. The phase and frequency estimates, as inputs to the Kalman filter, also contribute to the refining of the pseudorange estimate.

KALMAN FILTER

The function of a Kalman filter is to track the "state" of a linear dynamic system by processing observations in an iterative least-squares fashion. The state of the system is described by a vector of system variables which must be related to each other by a known set of linear equations. Typically, the state vector consists of one or more sets of derivatives and hence the equations relating them are differential equations describing the dynamics of the system. The observations are made by measuring observables which must be known linear functions of the state variables.

Figure 3 illustrates the operation of the Kalman filter. The observation vector, Y, consists of the three pseudorange differences and the three phase differences. The state vector is X, and consists of the receiver position, velocity and acceleration in three co-ordinates, and the rate of change of the local clock offset. The "hats" denote estimates or predictions.

The transition matrix ϕ is multiplied into $\hat{X}$ to obtain the estimate of the state vector for the next time interval. That loop is known as the state transition loop. Every N transitions an observation is made and a correction is made to $\hat{X}$. So, between observations, the transition matrix models the predicted dynamic behaviour of the receiver.

The corrections are made by comparing the predicted observation vector, $\hat{Y}$, to the observation vector, Y, and processing the prediction error vector that results. The latter is multiplied by the so-called Kalman Gain Matrix, K. The latter is computed via a stochastic modeling technique involving the state covariance matrix, P, the observation error covariance matrix, R, the system noise convariance matrix, Q, and the observation matrix, M. The observation matrix relates the measurement vector to the state vector.

The presence of subscripts on the matrices defining the model (e.g. ϕ, Q, and M) indicates that these matrices must be updated regularly as they are not time-invariant. These matrices depend on the positions of the satellites and the receiver. In addition, Q and R may be estimated from the observations in various ways allowing the filter to adapt to changes in the dynamic behaviour of the receiver. Another way the filter may be caused to adapt is by multiplying it by a scalar factor related to the trace of an estimate of the prediction error concerned. Specifically, the scalar factor is $1+\alpha$ where α is linearly related to a sub-trace of the matrix $<(Y-\hat{Y})(Y-\hat{Y})T> - (MPMT+R)$.

An observation in the context of this Kalman filter is an input from the pseudorange interpolation algorithm, and an input from the frequency and phase estimators. After the required number of observations have been made, the estimated value of position can be output directly from the predicted state vector to the user. Similarly, the estimates of pseudorange differences to be transmitted to the base station under differential operation can be extracted directly from the predicted observation vector. When pseudorange corrections are available from the base station, these can be utilised to produce the more accurate position by feeding into the filter as illustrated in Figure 3.

POSITIONING ALGORITHMS

The positioning algorithms used in this receiver are performed within the Kalman filter.

It is emphasised that the invention is not restricted to the embodiment described. Many changes and modifications may be made within the broad concepts described. The receiver design may be enhanced in several ways.

The generic concept as described here is relevant to receivers with four or more channels, known as "multi-channel" receivers.

With little effort the concept could be extended to applications such as three-channel marine receivers or single-channel multiplexing receivers. For the single-channel receiver, the important difference would be that absolute measurements of pseudorange, phase, and so on, would be required, rather than differences.

Other changes and modifications are envisaged to cater for particular applications and for special environmental conditions.

CLAIMS

1. A GPS receiver for use with the NAVSTAR global, satellite-based radio navigation and time transfer system wherein transmission from each of a plurality of satellites includes C/A code signals comprising a code and data modulated carrier, said receiver comprising means for receiving C/A code signals transmitted from at least four satellites and means to process the signals including an open loop estimator of signal parameters for phase-coherent estimation of a plurality of signal parameters including code delay, carrier frequency, carrier phase, carrier phase acceleration, data value and data delay.

2. A receiver according to Claim 1, characterised in that the open loop estimator is a correlation detector.

3. A receiver according to Claim 1 or 2, characterised in that means are provided to select at least four satellites from which the C/A code signals are to be received.

4. A receiver according to Claim 3, characterised in that at least one of the signal parameters is estimated as the difference between one and the remaining selected

satellites.

5. A receiver as claimed in Claim 4, characterised in that a difference estimate is made of code delay.

6. A receiver as claimed in Claim 4 or 5, characterised in that a difference estimate is made of carrier frequency.

7. A receiver as claimed in Claim 4, 5 or 6, characterised in that a difference estimate is made of carrier phase.

8. A receiver as claimed in Claim 4, 5, 6 or 7, characterised in that a difference estimate is made of phase acceleration.

9. A receiver according to any preceding claim, characterised in that means are provided to extract information from the signals transmitted from a satellite to enable the receiver to measure the range between the receiver and said satellite.

10. A receiver according to any preceding claim, characterised in that means are provided to extract timing

information from the signals transmitted from a satellite to enable the receiver to measure the clock offset of a clock in the receiver and a precise clock in said satellite.

11. A receiver according to any preceding claim, characterised in that the means to process the signals includes a digital signal processor.

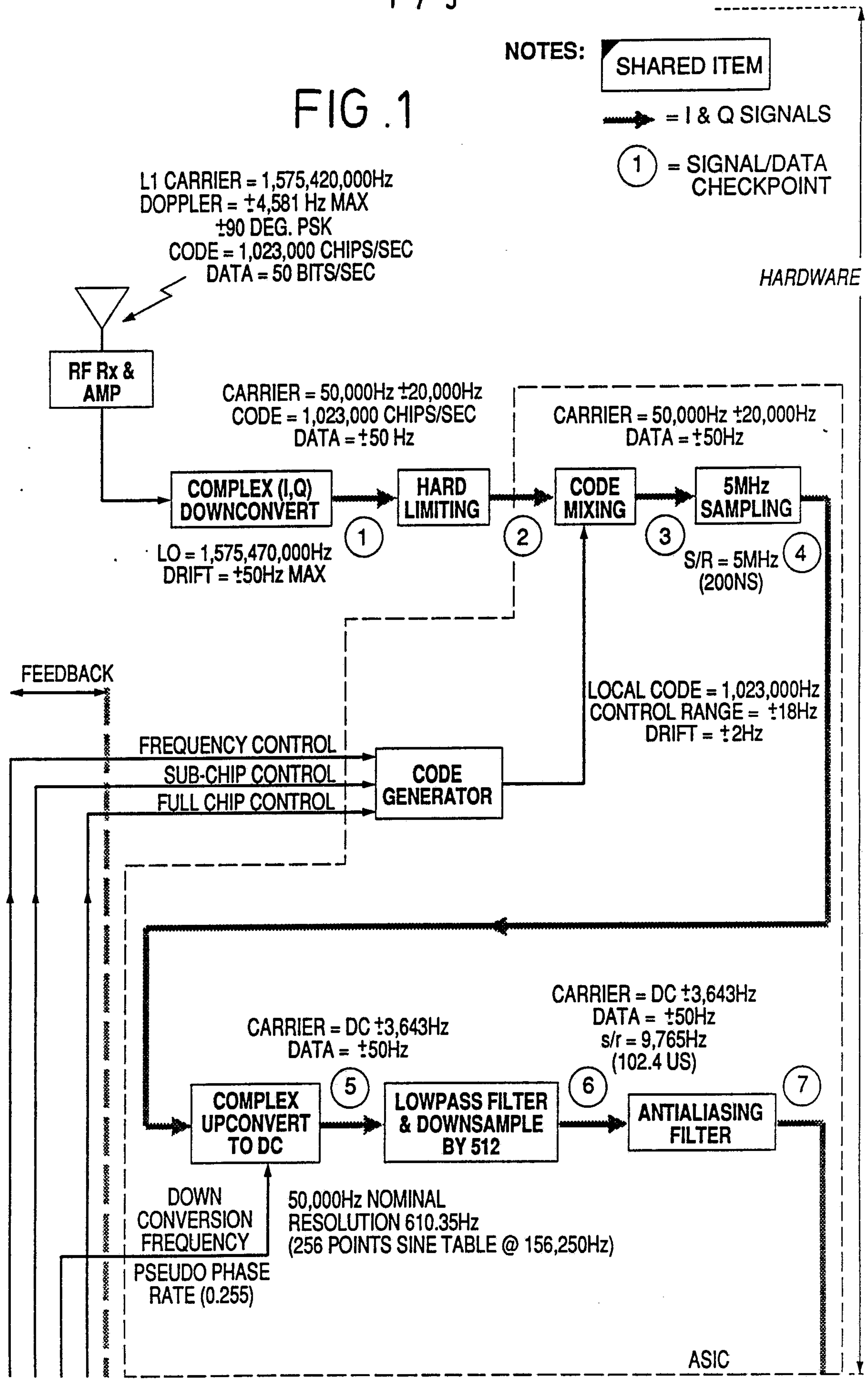
12. A receiver according to Claim 11, characterised in that the receiver functions are performed in hardware and software.

13. A receiver according to Claim 3, characterised in that the receiver includes at least four channels, each channel corresponding to a particular one of the selected satellites.

14. A receiver according to any preceding claim, characterised in that the receiver is a modular design with individual modules being interchangeable.

15. A GPS receiver substantially as herein described and illustrated in the accompanying drawings.

FIG .1


NOTES:
SHARED ITEM
= I & Q SIGNALS
1 = SIGNAL/DATA CHECKPOINT
L1 CARRIER = 1,575,420,000Hz
DOPPLER = ±4,581 Hz MAX
±90 DEG. PSK
CODE = 1,023,000 CHIPS/SEC
DATA = 50 BITS/SEC
HARDWARE
RF Rx & AMP
CARRIER = 50,000Hz ±20,000Hz
CODE = 1,023,000 CHIPS/SEC
DATA = ±50 Hz
CARRIER = 50,000Hz ±20,000Hz
DATA = ±50Hz
COMPLEX (I,Q) DOWNCONVERT
HARD LIMITING
CODE MIXING
5MHz SAMPLING
LO = 1,575,470,000Hz
DRIFT = ±50Hz MAX
S/R = 5MHz
(200NS)
FEEDBACK
LOCAL CODE = 1,023,000Hz
CONTROL RANGE = ±18Hz
DRIFT = ±2Hz
FREQUENCY CONTROL
SUB-CHIP CONTROL
FULL CHIP CONTROL
CODE GENERATOR
CARRIER = DC ±3,643Hz
DATA = ±50Hz
CARRIER = DC ±3,643Hz
DATA = ±50Hz
s/r = 9,765Hz
(102.4 US)
COMPLEX UPCONVERT TO DC
LOWPASS FILTER & DOWNSAMPLE BY 512
ANTIALIASING FILTER
DOWN CONVERSION FREQUENCY
50,000Hz NOMINAL
RESOLUTION 610.35Hz
(256 POINTS SINE TABLE @ 156,250Hz)
PSEUDO PHASE RATE (0.255)
ASIC

2 / 3

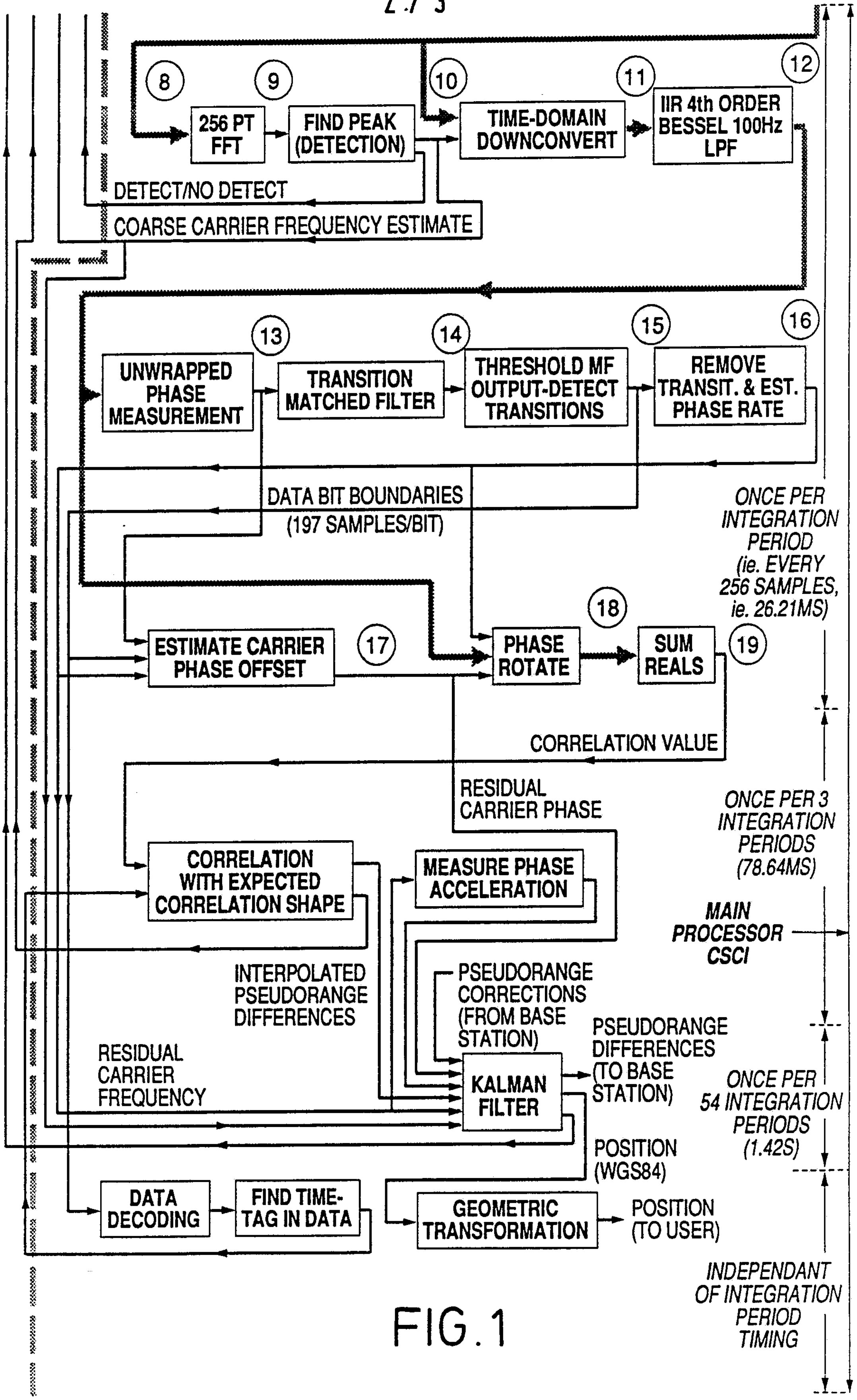
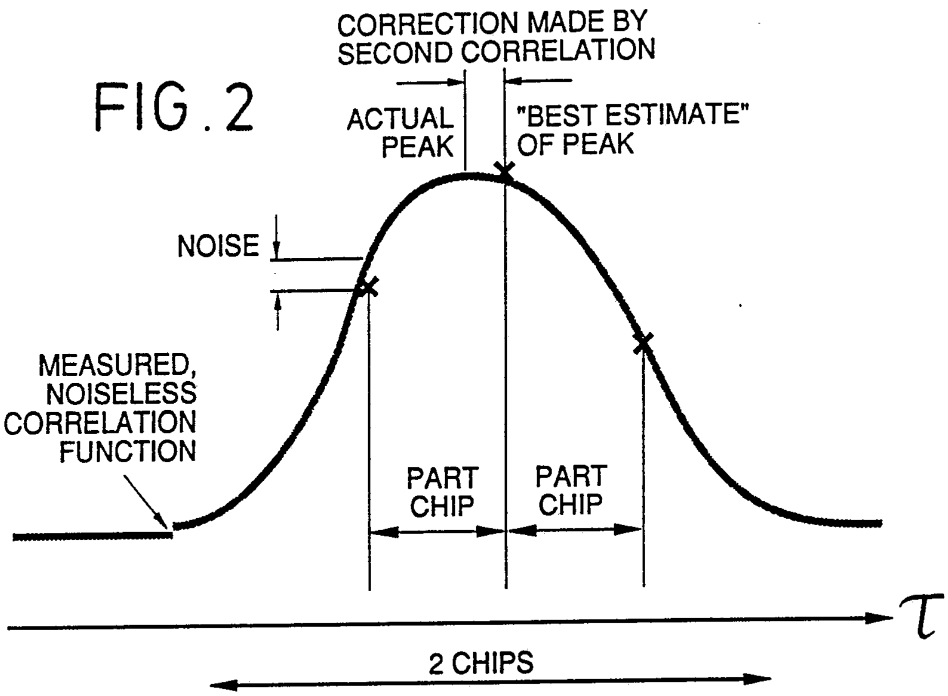

8
256 PT FFT
9
FIND PEAK (DETECTION)
10
TIME-DOMAIN DOWNCONVERT
11
IIR 4th ORDER BESSEL 100Hz LPF
12
DETECT/NO DETECT
COARSE CARRIER FREQUENCY ESTIMATE
13
UNWRAPPED PHASE MEASUREMENT
14
TRANSITION MATCHED FILTER
15
THRESHOLD MF OUTPUT-DETECT TRANSITIONS
16
REMOVE TRANSIT. & EST. PHASE RATE
DATA BIT BOUNDARIES (197 SAMPLES/BIT)
ONCE PER INTEGRATION PERIOD (ie. EVERY 256 SAMPLES, ie. 26.21MS)
ESTIMATE CARRIER PHASE OFFSET
17
PHASE ROTATE
18
SUM REALS
19
CORRELATION VALUE
RESIDUAL CARRIER PHASE
ONCE PER 3 INTEGRATION PERIODS (78.64MS)
CORRELATION WITH EXPECTED CORRELATION SHAPE
MEASURE PHASE ACCELERATION
MAIN PROCESSOR CSCI
INTERPOLATED PSEUDORANGE DIFFERENCES
PSEUDORANGE CORRECTIONS (FROM BASE STATION)
PSEUDORANGE DIFFERENCES (TO BASE STATION)
RESIDUAL CARRIER FREQUENCY
KALMAN FILTER
ONCE PER 54 INTEGRATION PERIODS (1.42S)
POSITION (WGS84)
DATA DECODING
FIND TIME-TAG IN DATA
GEOMETRIC TRANSFORMATION
POSITION (TO USER)
INDEPENDANT OF INTEGRATION PERIOD TIMING

FIG. 1

FIG. 2


CORRECTION MADE BY SECOND CORRELATION
ACTUAL PEAK
"BEST ESTIMATE" OF PEAK
NOISE
MEASURED, NOISELESS CORRELATION FUNCTION
PART CHIP
PART CHIP
τ
2 CHIPS

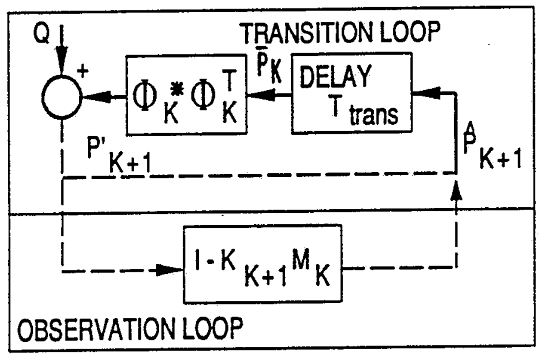
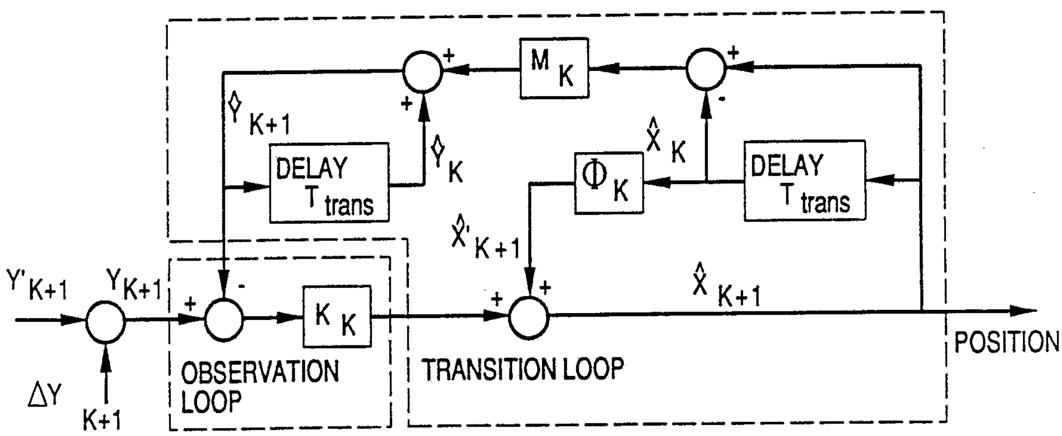

Q
TRANSITION LOOP
DELAY T trans
P'K+1
P̂K+1
I - K K+1 M K
OBSERVATION LOOP

FIG. 3


M K
K+1
DELAY T trans
K
X̂ K
Φ K
DELAY T trans
X̂' K+1
Y'K+1
YK+1
K K
X̂ K+1
POSITION
ΔY K+1
OBSERVATION LOOP
TRANSITION LOOP

ANNEX TO THE INTERNATIONAL SEARCH REPORT ON INTERNATIONAL PATENT APPLICATION NO. GB 9101555 SA 51154

This annex lists the patent family members relating to the patent documents cited in the above-mentioned international search report.
The members are as contained in the European Patent Office EDP file on 11/05/92
The European Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US-A-5019824	28-05-91	None	
US-A-4959656	25-09-90	None	
US-A-4578678	25-03-86	None	

EPO FORM P0479

For more details about this annex : see Official Journal of the European Patent Office, No. 12/82

INTERNATIONAL SEARCH REPORT

International Application No PCT/GB 91/01555

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all)[6]

According to International Patent Classification (IPC) or to both National Classification and IPC

Int.Cl. 5 G01S5/14

II. FIELDS SEARCHED

Minimum Documentation Searched[7]

Classification System	Classification Symbols
Int.Cl. 5	G01S

Documentation Searched other than Minimum Documentation to the Extent that such Documents are Included in the Fields Searched[8]

III. DOCUMENTS CONSIDERED TO BE RELEVANT[9]

Category °	Citation of Document, [11] with indication, where appropriate, of the relevant passages [12]	Relevant to Claim No.[13]
A	US,A,5 019 824 (KUMAR) 28 May 1991 see the whole document ---	1,4,9, 11,12,15
A	US,A,4 959 656 (KUMAR) 25 September 1990 see the whole document ---	1,4,9, 11,12,15
A	US,A,4 578 678 (HURD) 25 March 1986 cited in the application see the whole document ---	1,3,4,9, 11,12, 13,15
A	POSITION LOCATION AND NAVIGATION SYMPOSIUM 1986, November 4-7, 1986, Las Vegas, NV, US; OULD ET AL: "The Modular Digital Approach to GPS Receiver Design", pages 162-168. see the whole document ---	1,14

° Special categories of cited documents : [10]

"A" document defining the general state of the art which is not considered to be of particular relevance

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"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

IV. CERTIFICATION

Date of the Actual Completion of the International Search	Date of Mailing of this International Search Report
11 MAY 1992	16.06.92
International Searching Authority	**Signature of Authorized Officer**
EUROPEAN PATENT OFFICE	HAFFNER R.D.R. R.D.R. Haffner

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