LOW COST MULTI-CHANNEL GPS RECEIVER

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ABSTRACT

An investigation was conducted on compact, multi-channel GPS receivers. The code generator and correlation equipment were simplified, taking into consideration to avoid downgrading the properties possessed by multi-channel receivers as far as possible, and the error-increasing factors caused by such modification were examined. As a result, it was concluded that the simplificaton can be put into full practical application if enough consideration such as error compensation processing, etc. are performed.

INTRODUCTION

GPS receivers have proved to have applications in a wide range of fields such as navigation, survey and time calibration. In particular, these receivers are highly effective as the absolute position sensor in an automobile navigation system [1]. For GPS receivers used for this purpose, the following conditions are required:

1. the ability to withstand the interruption of satellite radio waves caused by buildings, etc.,

2. compact size and low price, and

3. the ability to accommodate the acceleration of a vehicle.

As a method for realizing condition 2, the sequential system is already known. However, the system has the disadvantage of not fulfilling condition 3. Therefore, a multiplex system meeting conditions 2 and 3 has been proposed and put into practical use [2]. Using this system, low-cost receivers have been realized which can withstand the high acceleration of aircraft, etc. Although the system can receive radio waves from more than one satellite almost simultaneously, it is difficult to simultaneously receive all data such as Ephemeris and Almanac which are being sent from these satellites. Further, since satellite radio waves are frequently interrupted in the case of receivers for automobiles, such receivers may experience difficulty in receiving subframes, the packet unit of data from a satellite, which cannot be received without continuous reception from the receiver for 6 seconds or more. Therefore, for condition 1 to be fulfilled, it is preferable for the receiver to be able to simultaneously receive satellite data from all of the satellites from which the receiver is receiving data (data collection). For this purpose, a multi-channel system is suitable. However, multi-channel receivers often do not meet condition 2.

In order to develop a small-sized, inexpensive multi-channel receiver, it is important to simplify the demodulation section, which requires more than one channel and consists of code tracking and carrier tracking. As the means for realizing this, the following methods can be considered:

1. simplification of the configuration of the detection circuit, and

2. digitalization of the detection circuit.

Although method 2, digitalization of the detection circuit [3], [4], is effective in itself, we have first dealt with method 1, simplification of the configuration, because the results of such simplification can then be applied to method 2, digitalization.

From the above standpoints, we proposed simplification of the detection circuit, produced a trial GPS receiver based on the proposal, conducted vehicular running tests, and reported the results [1].

This report describes the results of a more-detailed investigation on the detection circuit and receiver.

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In the section entitled Receiver Configuration, comprehensive measures taken to lower the cost and simplify the receiver are explained, as well as points particularly concerned with its use in automobiles, overall operation, etc. Next, in the Tracking Procedure section, the configuration, operation and control method of the simplified detection circuit are described. Finally, in the section on Performance, the results of evaluation of the detection circuit and the consideration of error factors are discussed.

RECEIVER CONFIGURATION

Basic Structure and IF

As described in the Introduction, the receiver is so designed that it has 4 channels and receives signals with frequency L1 and C/A code only.

The overall configuration of the receiver is shown in Fig. 1. As the first intermediate frequency, 266 MHz was selected from the frequency band which is easily obtained by the SAW filter. As the second intermediate frequency, 4,092 MHz was selected from the frequency band in which the characteristics of the double-balanced mixer are easily obtained by the analog IC. For the case where the receiver is mounted in a vehicle, a frequency synthesizer was not incorporated since this component requires countermeasures against vibration, and instead frequency multiplication and frequency dividing was employed for all basic signals. In order to control frequency oscillator errors, only one reference oscillator was used.

Detector

In the detection section, the individual receiving channels are independent from each other, and the 1 channel is simplified as shown in the block diagram in Fig. 2. The detector is explained in detail in the Tracking Procedure section.

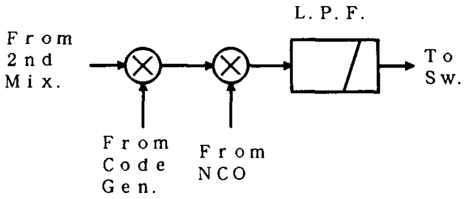

Fig. 2 Detector Block Diagram

Code Generator

The code generator inputs a constant standard clock pulse of 8.184 MHz and outputs a code line synchronized with the clock timing. The receiver controller sets the phase codes which have been quantized taking the standard clock pulse as the unit. Therefore, the code phase can be set in the unit of 1/8 chip, or 37 m in distance. However with a unit of quantization this large, sufficient accuracy for the measurement of position cannot be obtained. Thus we employed a method of conducting code tracking at a finer phase unit equivalent to that of the quantized phase. We consider that this method will also be effective in the next stage of digitalization.

As described above, an NCO is not used in the code generator, and the code phase can be changed over in a very short period of time (1/8 chip). Each channel has an independent code generator of this type.

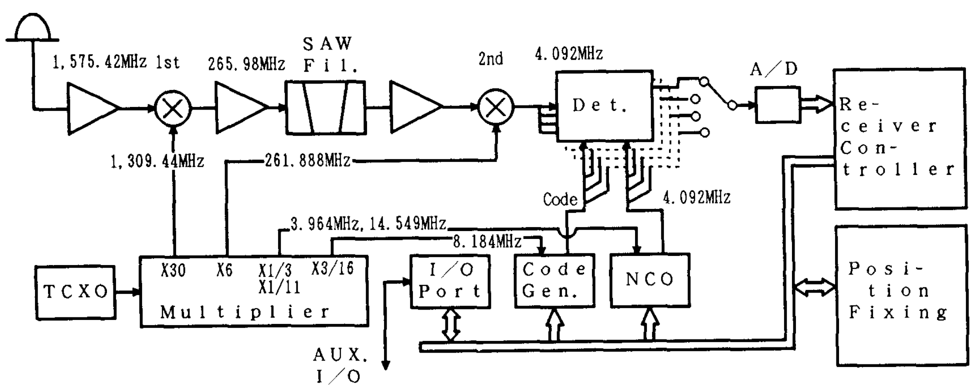

Fig. 1 GPS Receiver Block Diagram

NCO

For the carrier regeneration of the satellite signals, an NCO is used. The NCO, similar to the code generator, inputs a clock pulse of a constant frequency to control the phase of the regenerated carrier. The fineness of the controllable phase is $3 \times 10^{-5}\pi$, providing a sufficient degree of accuracy. The NCO is controlled by the receiver controller, and is possessed by each channel independently. The NCO clock signals and local signals of frequency conversion are generated by a common reference oscillator. By using the same reference signals and synchronizing the regeneration carrier with the satellite signals, the frequency can be compared between the reference signals and satellite signals, and during position measurement, receiver controller can estimate the difference of the reference signal frequency with a high degree of precision. This is useful for receiving satellite signals as well as for securing the accuracy of the fixing position.

Receiver Control

The receiver part controls all channels using an ordinary 16-bit microprocessor. Further, in this control part all processing except for the calculation of position measurement is carried out, such as external input/output processing, control related to the satellite direction, calculation of GDOP or HDOP, selection of the satellite from which data are to be received, and control of data such as Almanac and Ephemeris.

Position Fixing

This part performs the process of calculating the position using the data obtained from the receiver control part. It uses the same 16-bit microprocessor as that used by the receiver control part, but does not employ any external operation unit. The operational accuracy is limited to the level which is sufficient for the calculation of position fixing, in order to reduce processing time.

TRACKING PROCEDURE

Concept

In order for the NCO and code generator to track satellite signals, it is necessary to detect the carrier and phase difference of the codes. The τ-dither system is recognized as a simple system for detecting the phase difference of codes, and one of the features of our receiver is that this system has been expanded to incorporate the detection of the carrier phase as well as data receiving and processing by time division. By synchronizing this changeover timing with the timing of the data transmitted from satellites (50 bps), stable tracking is ensured. Therefore, the detector, as shown in Fig. 2, has been highly simplified.

Also, as explained under the heading Code Generator in the Receiver configuration section, the simplification of this part has greatly reduced the quantity of hardware required per channel. This another feature of our receiver.

Thus, in spite of the simplification of each channel's hardware, all four channels can simultaneously receive satellite data because of their independent operation from each other.

Control Timing

Fig. 3 shows the phase of the signals which are input to the mixer of the detector in Fig. 2. At timings 1, 2, 11, 12, 19 and 20, data are received, and the in-phase signals of the carrier-tracking

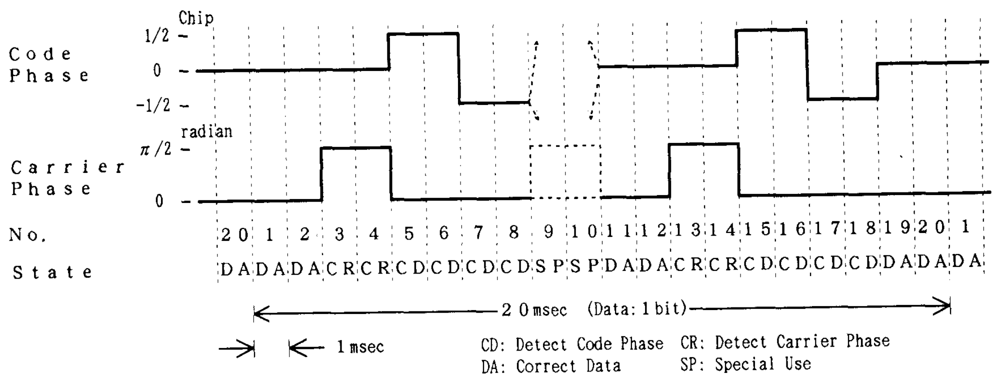

Fig. 3 Timing Chart

are detected. At timings 3, 4, 13 and 14, the quadrature-phase signals of the carrier-tracking are detected. At timings 5, 6, 15 and 16,, correlation of the advanced phase codes is detected, while at timings 7, 8, 17 and 18, correlation of the delayed phase is detected. Timings 9 and 10 are used for special purposes such as direct current bias detection of the mixer, etc. The code phase in Fig. 3 establishes the values quantized at 1/8 chip. One timing corresponds to approx. 1 msec and timings 1 through 20 execute phase inversion among 1, 2, 11, 12, 19 and 20, so that they conform to the transmission timing of the data sent from satellites.

The A/D converter in Fig. 1 performs A/D conversion of the filter output of each channel in sequence at a clock timing of approx. 100 kHz.

The results are divided in the pretreatment circuit into each channel, and with the above mentioned 1 msec timing of each channel as the unit, are filtered and sent to the receiver controller. The receiver controller feeds back the correlation results through the carrier and code tracking filter to the code generator and NCO.

Code Phase Estimation

The code phase is quantized at 1/8 chip to establish the phase. If this quantized code phase is left unchanged, quantization noise in the measurement of the pseudo range with satellites becomes very large at a value of around 20m. Therefore, the error in the estimated value of the code phase is given as the value obtained by subtracting the error with quantization from the phase error obtained in the code phase which has been established by quantization.

When the output phase of the code tracking filter is t_n, which is quantized to give T_n, and the quantization error is d,

$$t_n = T_n - d \qquad (1)$$

$$(1/16 > d \geq -1/16)$$

The code phase is measured for $T_n + 1/2$ and $T_n - 1/2$, and the correlation results are represented as a_n^+ and a_n^-, respectively. When the response characteristic of the correlation part consisting of the mixer and filter is $f(\tau,A)$, where is the phase difference of code τ_n, and A_n is the input amplitude, the following relation holds:

$$\begin{cases} a_n^+ = f(\tau_n + 1/2, A_n) \\ a_n^- = f(\tau_n - 1/2, A_n) \end{cases} \qquad (2)$$

Further, if only the range in which the linear property of the mixer and filter applies is used, and $f(\tau,A)$ can be expressed as $Af'(\tau)$, the relation can be expressed as:

$$\begin{cases} a_n^+ = Af'(\tau_n + 1/2) \\ a_n^- = Af'(\tau_n - 1/2) \end{cases} \qquad (3)$$

Therefore,

$$\frac{a_n^+}{a_n^-} = \frac{f'(\tau_n + 1/2)}{f'(\tau_n - 1/2)} = F(\tau_n) \qquad (4)$$

If the function $F(\tau)$ is a single-value function, the solution can be obtained. For actual receivers, however, it is practical to use a table to obtain the solution.

The code phase difference Δt_n between the filter output t_n and the received signals can be determined as:

$$\Delta t_n = \tau_n - d \qquad (5)$$

which, as the measurement result, is then input to the tracking filter.

The function $F(\tau)$ is influenced by the overall characteristics of the SAW filter, mixer and code generator. These characteristics can be determined from their design values by means of simulation, etc., or actually-measured values can be used. Their relations are shown in Fig. 4.

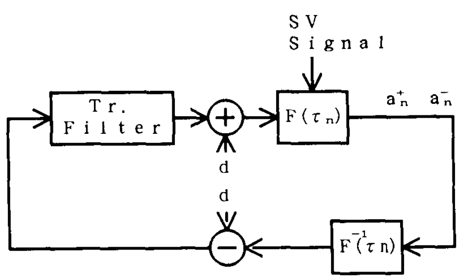

Fig. 4 Code Tracking

PERFORMANCE

Characteristics

A principal feature of the simplified detection system is that satellite data can be simultaneously received by all of the channels. Other advantages and disadvantages are described below.

Firstly, when it is necessary, an increase in the number of channels can be made in the unit of one channel, because each channel consists of individual hardware. Since the code-phase difference is measured with the same mixer for both the advanced phase and delayed phase, errors caused by a difference in sensitivity do not occur. Further, since the direct current bias is always measured, measurement error caused by this factor also does not occur. However, since the delay error between channels does not disappear, a self-correction function must be provided, or hardware with less delay error must be designed.

The deterioration of the S/N ratio, resulting from simplification, in the measurement of the code phase and carrier phase is approx. -7dB, since the ratio of the measurement time against that of the original multi-channel system is 1:5. However, since the deterioration of the S/N ratio in data receiving, by similar calculation, is about -5dB, the level can be improved to around -5dB if the timing for changing over the phase in Fig. 2 is modified to obtain a mode whose main purpose is to measure the phase difference of the codes.

Evaluation

Experimentation was carried out to evaluate the accuracy of code-phase estimation. Fig. 5 shows the results of measurement of the correlation characteristics of the experimental receiver. The y-axis shows the correlation values, and the x-axis the relative phase difference of the codes. The experimental receiver has excellent SAW filter characteristics and linearity of the mixer. The characteristic curve measured by taking the relative strength of the input signals as a parameter is almost a similar figure, if the parts corresponding to noise are removed. This shows that the phase difference of the codes changes almost linearly in the vicinity of ± 0.5 chip. The point at which the left and right straight lines cross near the center is almost the same code phase regardless of the parameters. Further, the left and right straight lines with different parameters cross at -1.04 chip and 1.02 chip respectively. Therefore, it is demonstrated the correlation characteristic $f(\tau,A)$ changes almost linearly, provided that the vicinity of the point at which is $\pm$ 1/2 chip is approximated with these straight lines. The positions of the left and right points of intersection depend upon the characteristics of the filter, and if these are expressed as $-K^-$ and K^+,

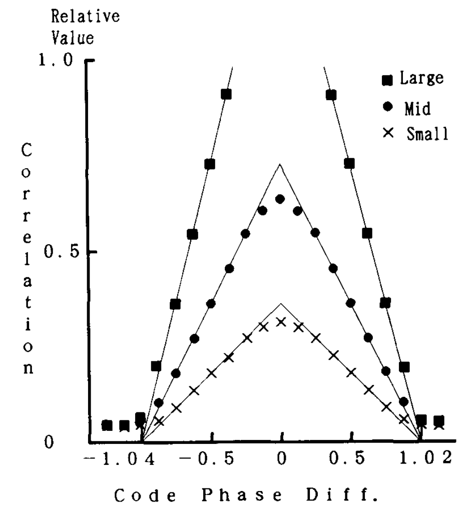

Fig. 5 Correlation Structure

$$f'(\tau) \simeq \begin{cases} 1 - \tau/K^+ & \tau \text{ is in the vicinity of } 1/2 \\ 1 + \tau/K^- & \tau \text{ is in the vicinity of } -1/2 \end{cases} \quad (6)$$

$$F(\tau_n) = \frac{K^-}{K^+} \cdot \frac{K^+ - 1/2 - \tau_n}{K^- - 1/2 + \tau_n}$$

provided that τ_n is close to 0 (7)

Then the code phase difference is calculated from

$$\tau_n = \frac{(a_n^+K^+ - a_n^-K^-)/2 - (a_n^+ - a_n^-)K^+K^-}{a_n^+K^+ + a_n^-K^-} \quad (8)$$

This equation is effective only when τ_n is sufficiently small, but during tracking, τ_n is around the maximum value of the quantization error, 1/16 chip, giving sufficient accuracy.

Fig. 6 shows the tracking results corresponding to the test signals. The response frequency of the tracking filter corresponding to the codes is approx. 0.5 Hz and the input signal level is -125dBm. The fluctuation of the measured phase caused by quantization noise is 1m or less in 1σ. If the gradient error of the approximate straight line is 0.02, the quantization noise becomes 0.4m. Therefore, it is considered that the noise element arising from factors other than quantization accounts for the larger part. This result indicates that the quantization of the code phase of 1/8 chip is sufficient for application in sensors for an automobile navigation system.

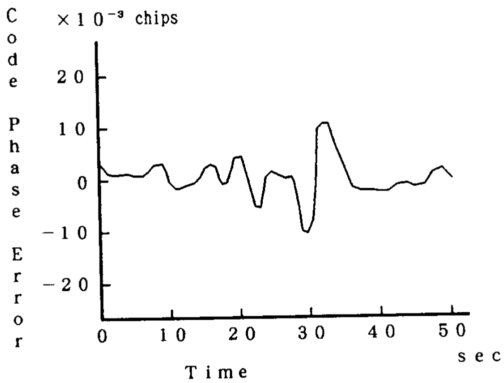

Fig. 6 Tracking Error

Next, in order to measure the phase difference of codes with time division, the error caused by the time difference of measurement is estimated. If the measuring interval is 2 msec, the change in distance from the satellite during that period would be 2m or less, and even if the speed of a car is 200 km/h, the distance travelled is about 0.1m. The change in distance from the satellite can be quite accurately estimated, and is proportional to the Doppler shift. The frequency deviation of the reference oscillator which is built into the receiver has an equivalent effect to the Doppler shift of satellite signals. This can be determined, because the frequency is controlled by using a single reference oscillator. Since the Doppler shift of satellite signals and the code phase measurement error caused by the frequency deviation of the reference oscillator are semi-stable shifts and can be estimated, they can be reduced by error compensation.

SUMMARY

As a means of simplifying the hardware of the multi-channel receiver, phases with a unit of 1/8 chip were established in the code generator. Each channel was provided with a circuit for determining correlation, and the phase differences of the carrier and the code were measured by time division. It was confirmed that sufficient accuracy of measurement can be obtained even if such simplification is carried out.

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