GPS System Enhancement with GEO Mobile Satellites

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Abstract

An enhancement of GPS with GEO satellites is proposed. It can enhance the availability of GPS by additional satellites paths and the measurement precision by additional bandwidth. The additional GEO paths signals are precisely synchronized with GPS. The basic requirement for the proposed system is to provide additional positioning links through the earth stations with distance precision better than 1 meter without causing any serious degradation to the communication services provided by those GEO systems. Those requirements necessitate very narrow band DLL receivers both at the earth station (ES) and mobile terminal (MT). In order to shorten the acquisition time of those DLL receivers, PN correlators become essential.

1. Introduction

The GPS has fully established itself as the global positioning system. However, some problems remain; (1) As it is a system developed for military purpose, its availability depends on the policy of USA government. (2) The C/A codes open to the public is rather limited in bandwidth (1.023MHz), e.g. positioning precision. It can be improved by the proposed system with wider signal bandwidths. (3) The GPS provides only positioning and no communication service. If positioning and communication services are combined, more useful applications will become possible for users especially in those areas out of terrestrial communication services. It will be essential for emergency communications. On the other hand, Inmarsat, Thuraya, NSTAR, OPTUS, AMSC/TMI and other global and regional systems provide mobile satellite communication services with portable mobile terminals (MT). In this paper a method is proposed to add positioning services through those satellites that enhances GPS availability with additional positioning satellite links and improves the performance with distance measurement precision better than one meter and without causing any serious degradation in the communication services provided by those geo-synchronous earth orbit (GEO) satellites systems.

2. Configuration of the proposed system

As shown in Figure 1, an additional positioning link is provided for the mobile users. The positioning signal is sent from existing GEO earth stations, superimposed on the communication signals. The positioning signal is synchronized with GPS so the Mobile Terminals (MT) can establish an additional distance measurement links to those of GPS. The power of the superimposed positioning signal is set at least 15dB below that of the communication signals to avoid causing any serious performance degradation for the existing services. Two positioning signals are transmitted; one is Rate P PN code with chip rate of 10.23Mc/s and the other is Rate C/A PN code with chip rate of 1.023Mc/s corresponding to the P and C/A codes in GPS. The spectrum of the

GEO transmit signal is depicted in Figure 2.

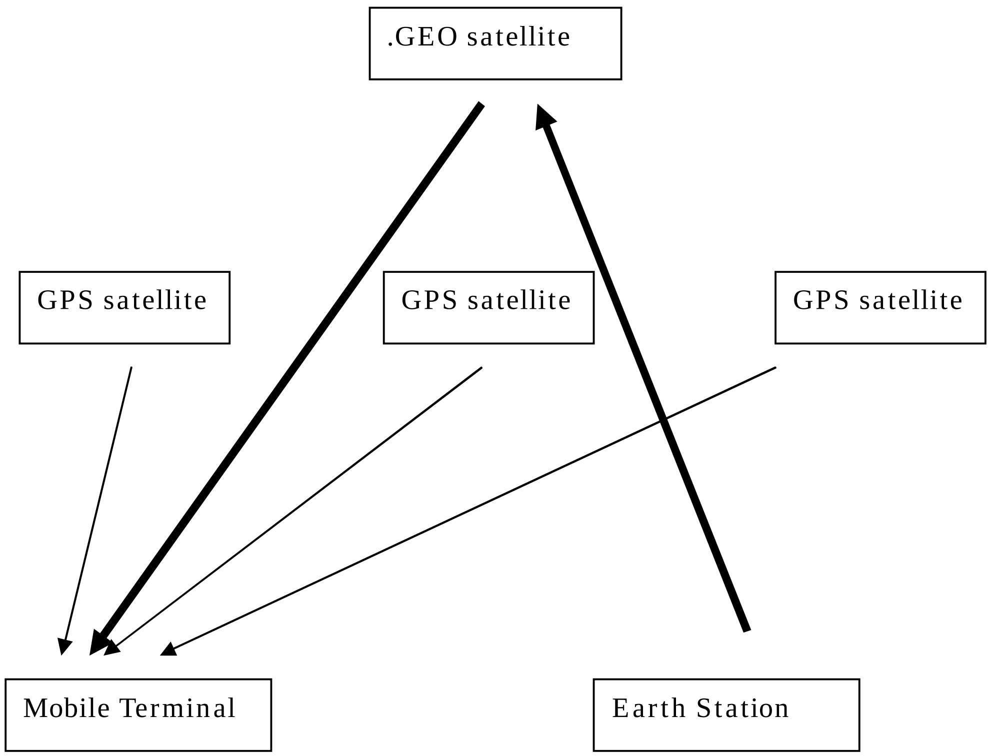

Figure 1 Overall System Configuration

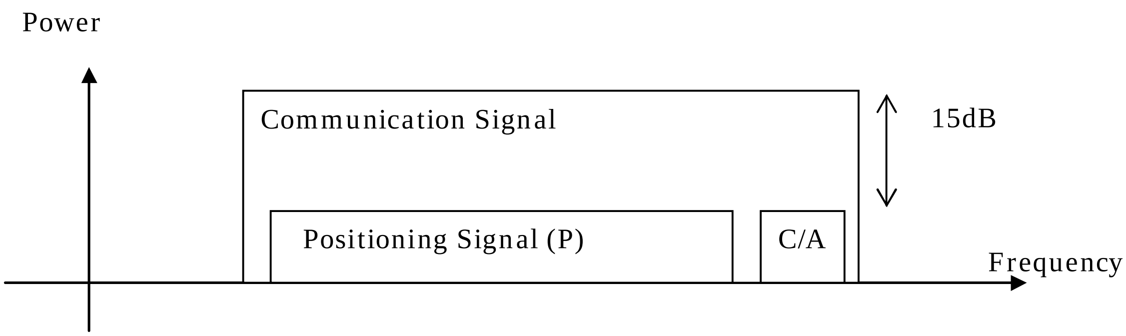

Figure 2 Positioning signal superimposed on communication signal

3. Generation of the Positioning Signal and Synchronization with GPS

Figure 3-4 give basic subsystems for the proposed system. The system timing reference is provided by the GPS system at the GEO earth station (ES). A Rate P PN signal is generated by the 10.23MHz PN Clock and 10kHz Epoch Pulse provided by the GPS system. The Positioning Data Generator combines Timing Adjust data and GEO orbit data for Positioning Data

Modulator. The Positioning Data Modulator is also spectrum spread modulated by the Rate P PN signal. The data rate of the Positioning Data sequences is set at a fraction of the Epoch Pulse frequency (10 kHz). The output of the Positioning Data Modulator is combined with the existing communication signals at a relative power level of -15dB as shown in Figure 2.

The combined signal is transmitted to the satellite and the satellite loop back signal is received and processed by the DLL and Pos.DEM which recovers the Rate P PN code, the 10kHz Epoch Pulse and the Positioning Data. Then the exact satellite loop delay is measured at the Satellite Delay Detector by comparison of the 10.023MHz PN clocks, 10kHz Epoch Pulses and the Positioning Data sequences. The timing difference can be measured in sub nano second steps. Then the GEO system can be synchronized with GPS because the exact timing delay to the satellite is now obtained. The information is included in the positioning data as Timing Adjust information. The Positioning Data also includes the satellite orbit data provided by the GEO system. With the orbit and the timing adjustment information included in the Positioning Data, the user Mobile Terminal (MT) can establish one distance measurement which can be combined with other GPS measurement for determination of its position.

The Rate C/A signal generator is the same circuitry with 1.023MHz PN clock and 1kHz Epoch Pulse. The Rate P and C/A signals are combined and transmitted as shown in Figure 2.

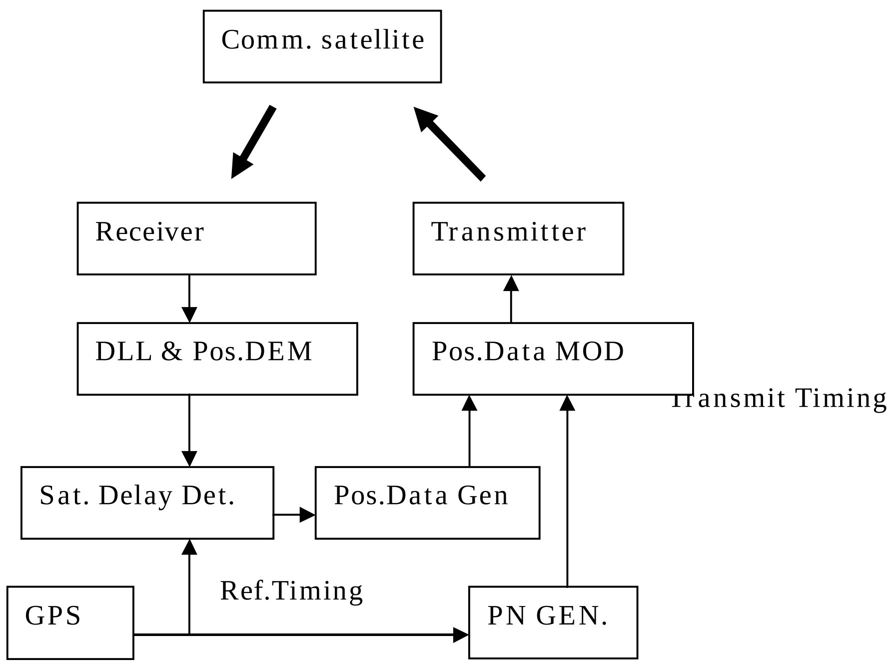

Figure 3 Synchronization circuit of the positioning signal with GPS

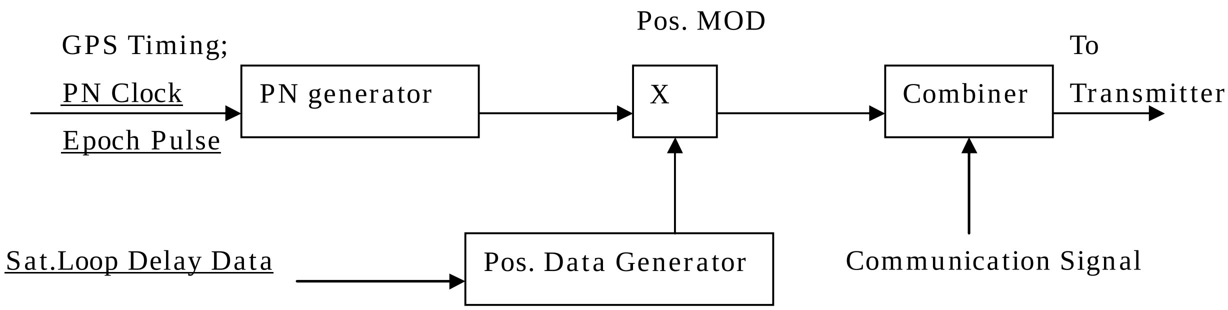

Figure 4 Generation of the positioning signal at the earth station

4. Performance of DLL and Positioning Data Demodulator

A detailed diagram of DLL and DEM is depicted in Figure 5. The circuit includes Spectrum De-spreader, Delay Lock Loop (DLL) and Positioning Data Demodulator.

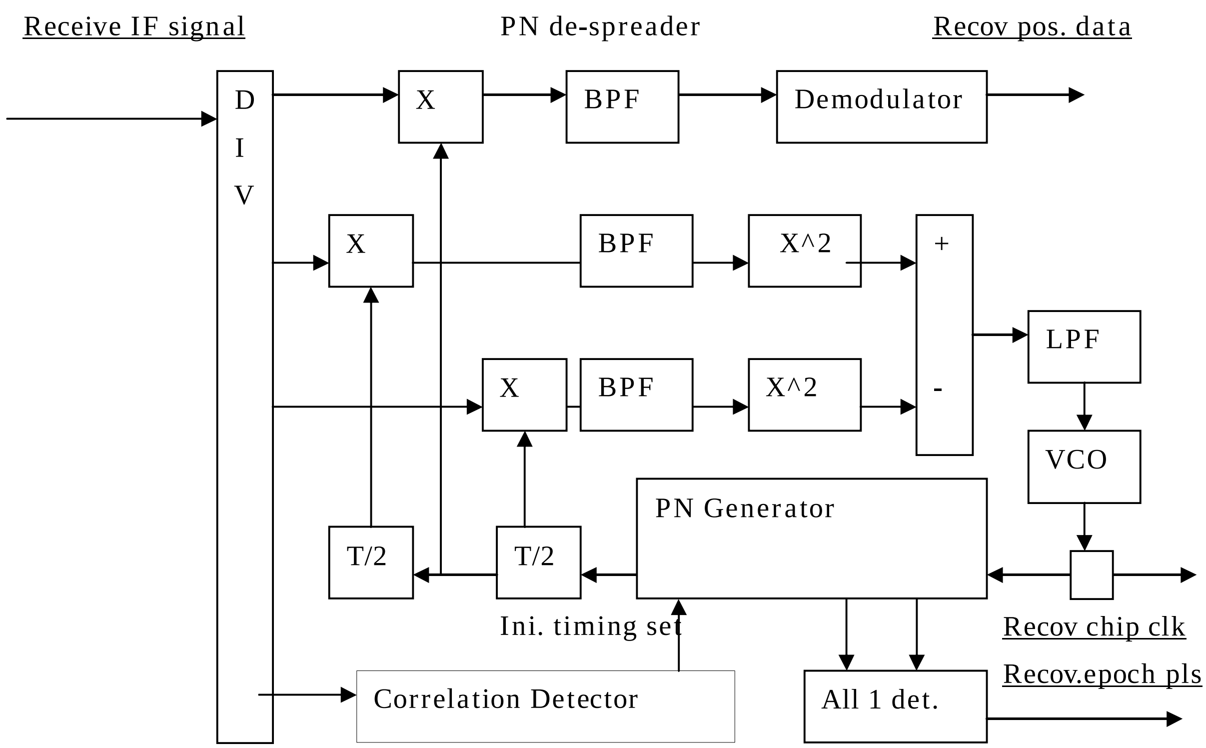

Figure 5 Delay Lock Loop (DLL) and Demodulator

Spectrum De-spreading

Let us denote the receive IF signal as

$$r(t) = c(t) + d(t).pn(t)$$

where c(t) is the communication signal, d(t) is the positioning data signal and pn(t) is the PN signal. The local PN generator generates lpn(t) driven by the recovered chip clock or recovered PN clock provided by the VCO (Voltage Controlled Oscillator) and re-spreads the receive signal by signal multiplication. The output r'(t) of the de-spreader is;

$$r'(t) = c(t) .lpn(t) + d(t).pn(t).lpn(t)$$

The amplitude of pn(t) and lpn(t) is normalized to +1,or -1. If the local PN signal lpn(t) is a perfect replica of pn(t), then pn(t).lpn(t) = 1,hence the second term in r'(t) becomes d(t). The data rate of d(t) is at most the Epoch Pulse (1kHz) which is 1/1023 of C/A code chip rate.

The communication signal c(t) is spectrum spread by multiplication with lpn(t). The frequency spectrum of c(t) is spread in the frequency domain from Fc to Fc +Fp, where Fc, Fp are respectively the occupied bandwidth of c(t) and pn(t). The power density of the spread communication signal is Pc /.(Fc + Fp) at the center of the spectrum, where Pc is the power of the communication signal. On the other hand the de-spread signal d(t) has the power density Pd / Fd, where Pd and Fd are respectively the power and the bandwidth of the positioning signal d(t). The BPF in Figure 5 limits the signal bandwidth to Fd, hence the power of the positioning signal at the BPF output is Pd / Fd * Fd = Pd, while that of the spread communication signal is Pc / (Fc + Fp) * Fd. The wanted signal at the BPF output is d(t) and communication signal is a noise . Then the S/N power ratio at the output of the BPF is

$$S/N = (Pd / Pc) * (Fc + Fp) /Fd. = (Pd / Pc) .Gp$$

The first factor Pd/Pc is the power ratio of the positioning signal to the communication service signal, which is controlled at most -15dB. The second factor (Fc + Fp) /Fd.is the process gain Gp.

$$Gp = Fc / Fd + Fp / Fd > Fp / Fd = Fp / F ep * Fep / Fd = 1023 * Fep / Fd$$

Where Fep is the Epoch Pulse frequency (10kHz) which is 1/1,023 of the P code chip rate (10.23 MHz). If the positioning data rate is 1kb/s with BPSK modulation, then Gp = 10,230. Further improvement of the process gain Gp can be achieved for lower data rate (smaller Fd).

Delay Lock Loop (DLL)

The two multipliers with local input lpn(t'-T/2) and lpn(t'+T/2) where T is the symbol duration of the local PN generator give {c(t)+d(t).pn(t)} .lpn(t'-T/2) and {c(t)+d(t).pn(t)} .lpn(t'+T/2).

Note t'= t+ ε ,where ε is the timing error of the local PN clock against the receive PN signal. The BPF in Figure 5 conducts the time averaging over time range 1/Fd, which is much larger than the correlation time of the PN signal which is 1/Fp, hence the output of the BPF will give good correlation functions. The cross correlation between c(t) and lpn(t) is very small (turns to 0 as the integration time gets infinity, because those signals are independent and uncorrelated).

Then the outputs of the BPFs are dominantly d(t).C[pn](T/2+ ε) and d(t).C[pn](T/2- ε). The auto-correlation C[pn](τ) of the PN signal is limited to T (=1/Fp), the chip duration time ; C[pn](τ) = 0 for / τ / > T. For / τ / < T, C[pn](τ) = 1 - / τ / / T.

Therefore the BPFs outputs are dominantly d(t).(1/2 + ε /T} and d(t).(1/2 - ε /T}.

The BPF outputs are square law detected and put into the differences detector as shown in Figure 5. The output of the difference detector is;

{d(t).(1/2 + ε /T})^2 – {d(t).(1/2 - ε /T})^2 = 2/d(t)/^2 . ε /T

which is linearly proportional to the timing error ε . The signal is smoothed by the loop filter (LPF) and applied to the VCO (voltage controlled oscillator) which generates the local PN clock. The local PN clock drives the local PN generator which generates the local PN signal and Epoch pulses (timing corresponding to the state of all 1 data in the PN generator of 10 stages shift register, occurs once in 1,023 states transitions).

The function of the DLL is the same as the PLL, or phase lock loops. An important difference of DLL from PLL is the very limited timing error detection ranges. As depicted previously, the timing error detector works only for / ε / < T. There is no detection of the timing error for the remaining timing : T < / ε / < 1,022T . This vast un-sensitive range poses a serious difficulty for the initial acquisition of the DLL functions. The correlator in Figure 5 can solve the problem. The PN correlator continuously conducts correlation detection of the receive signal by matching the receive signal with the designated PN sequences over the whole PN length. Thus the PN correlator can detect the PN signal and establish the timing within one PN period. The PN correlator is quite effective for very quick initial acquisition of the DLL.

5. Measurement of Satellite Link Propagation Delay

The timing between the GPS Epoch Pulse at the transmitter and the Recovered Epoch Pulse at the receiver of the ES gives fine data on the satellite loop propagation delay. The measurement can be made with sub nano second precision. The Epoch Pulses for Rate P PN codes are of 10kHz hence the measurement is ambiguous beyond 0.1ms. The ambiguity can be resolved by comparison of the positioning data sequences. The orbit data available from the GEO system can also be utilized.

6. Integration of GES into GPS

The GES system must provide the MT users with the satellite orbit data and the GPS time at the satellite at which the signal carrying the data is radiated from the satellite. The GPS time at the satellite is calculated as follows;

[GPS Time at the Satellite] = [GPS time at ES] + [Satellite Link Propagation Delay]

The satellite link propagation delay can be measured very accurately by the proposed method.

7 Precision of the Positioning Information Provided by GEO System

Now we can assess the precision of the proposed positioning system. The precision is determined by the quality of measurement of the satellite loop propagation delay, in particular the DLL.

The two correlation detected signal with timing shifted at +-T/2 and filtered by the BPFs in Figure 5 are ;

$$r''[+](t) = d(t).(1/2 + \varepsilon /T\} + 1/2.c'(t)$$

$$r''[-](t) = d(t).(1/2 - \varepsilon /T\}.+ 1/2.c'(t)$$

where 1/2.c'(t) is c(t).pn(t).lpn(t+T/2) smoothed by BPF with bandwidth Fd.

The timing error detector output is

$$Kp. \varepsilon = r''[+](t)^2 - r''[-](t)^2 = \{2d(t)^2. + d(t).c'(t)\}./T. \varepsilon$$

Kp is the PN clock phase error detector sensitivity.

Kp contains the signal component 2.d(t)^2 and the noise component d(t).c'(t). The signal power is

$$S' = < \{2.d(t)^2\}^2 > = <4 d^4> = 4Pd^2 \quad \text{;DC component.}$$

$$N' = < \{d(t).c'(t)\}^2 > = Pd.Pc.Fd/Fc \quad \text{;Continuous over bandwidth (-Fd,Fd)}$$

The second equation follows from the fact the c'(t) is c(t) filtered through the BPF with bandwidth Fd. The symbol < x > means averaging x.

The power spectrum density (Watt/Hz) of the above noise around DC is No =N/Fd.

The DLL is a PLL (Phase Lock Loop). If we denote the equivalent noise bandwidth of the DLL by BL(Hz), then the resultant S/N ratio of the recovered PN clock is;

$$S/N = S' / (N'/Fd.BL) = 4.(Pd/Pc).Fc/BL$$

The phase error ϕe of the recovered PN clock is related with the S/N by

$$/\phi e/^2 = 1/\{2.S/N\} = 1/8.Pc/Pd/Fc.BL$$

hence can be reduced by narrowing the bandwidth of the DLL.

As an example ,

BL= 10Hz,

Fc = 10 (MHz),

Pd/Pc = -15 (dB)

Then the resultant S/N is

$$S/N = 6 -15 + 60 = 51 \text{ (dB)}$$

The phase error

$$/\phi e/ = 1/\sqrt{\{2S/N\}} = 2.23 \times 10^{-3} \text{ (rad)} = 0.13 \text{(deg)}$$

The phase error corresponds to the timing and distance measurement errors

$$te = T./\phi e/ /2\pi = 0.036 \text{ (ns)}$$

$$de = c.te = 3 \times 10^8 \times 0.036 \times 10^{-9} = 0.018 \text{ (m)}$$

Thus a very accurate synchronization of the GEO system with GPS can be established.

For the above narrowband DLL the pull-in process can take quite a long time. In order to expedite the acquisition process the PN correlator is essential for the operation.

8. Operation at MT

The Mobile Terminal receives the positioning signal from the GEO Satellites, conducts the DLL and demodulation of the positioning data.

Processing Rate C/A code signal

Only C/A code is open to the general public in GPS. Therefore many users will process the Rate C/A code signal from the proposed GES system.

In order to achieve 1 m precision, the timing error must be less than 3.3 (ns). For C/A code, the chip rate is Fc = 1.023MHz. Then it is required that DLL phase error must be about 1 deg, or 0.021(rad). In order to achieve the phase error, the required S/N = 1/(2/φe/^2 = 30.6 (dB)

Then from the formula previously derived; S/N=4.(Pd/Pc).Fc/BL, the equivalent noise bandwidth of the DLL is determined by the following formula.

BL = 4.(Pd/Pc).Fc/(S/N) = 6 -15 +60 -30.6 (dB) = 20.4 (dB) = 110 (Hz)

Note Fc=1(MHz) = 60(dBHz) in the above calculation.

The PLL is fairly narrow in bandwidth and the acquisition can take a long time. Then a PN correlator will be indispensable especially for mobile users moving at high speed.

Processing Rate P code signals

The PN clock frequency is Fc=10.023MHz.and the Epoch Pulse is 10kHz. The positioning data rate can be up to the Epoch Pulse frequency. Let us assume the positioning data rate 10kb/s with BPSK modulation for which approximately Fd = 10kHz. Then the bandwidth of the DLL can be BL =1kHz. Then the performances will be;

/φe/^2 = 1/{2.S/N} = 1/8.Pc/Pd/Fc.BL = -9 +15-70+30 = -34 (dB) = 4.0 x 10^-4

/φe/ = 0.02 (rad)

te = /φe/ /2π/Fc = 3.2 x 10^-10 (Fc = 10^7)

de = c.te = 3 x 10^8 x 3.2 x 10^-10 = 0.096 (m)

Thus a very high precision can be achieved.

The PLL with BL = 1kHz will have roughly around 1ms for the pull in process. With the sweeping method the DLL will take 1,023 x 1(ms) = 1 (sec) for the acquisition process. This is too slow for mobile applications, hence a PN correlator is essential for the operation.

9. PN Correlators

Requirements;

The requirements for the PN correlators are as follows;

(1) The code length shall be 1,023 chips.

(2) The correlators shall be programmable to process variable PN codes generated by 10 stage shift registers

(3) The PN correlation detector for Rate C/A code shall operate for the chip rate 1.023MHz.
(4) The PN correlator for Rate P codes shall operate for the chip rate 10.23MHz.

Processing speed requirements for Digital correlators;

The correlation detector needs to operate BT=1,023 additions or subtractions for each samples. Normally the sampling frequency is set at 4 times the chip rates. For Rate P codes 1,023 additions must be made for every 40MHz samples, or 40G additions per second. For the Rate C/A codes, the requirement is 4 G additions per second.

PN correlators by SAW devices

A SAW device was developed that meets the Rate P PN correlator requirements by Dr. Takaya Watanabe [1] and presented at EFTF in Geneva, May/29-June/1, 2007. The device conducts continuous correlation detection for the input signal against the local PN signal which is the time inverted replica of the wanted PN sequences. For technical details, see Ref.1.

Conclusion

The developed PN correlater tells the PN timing within one PN sequence. The detected timing is used to initialize the local PN generator of the DLL. Thus a very narrow band DLL with fast acquisition capability is realized.

The proposed system can provide very accurate additional GPS links through Geo-Synchronous Earth Orbit (GEO) Mobile Satellite systems. The combined system provides better availability by the additional links and higher accuracy by the greater bandwidth of MSAT systems. Furthermore, the proposed system can provide both positioning and communication services which will be useful for the users out of the terrestrial communication service areas particularly in emergency situations.

Acknowledgement

The author deeply thank Dr. Takaya Watanabe for his development of the remarkable SAW PN correlation detector which plays the essential role in the proposed system, particularly for mobile applications.

References

[1] Takaya Watanabe, Osamu Ichiyoshi “Time and Frequency Accuracy Requirements for an Enhancement of GPS with GEO Satellites” , Paper No.7174, EFTF, Geneva May-June, 2007