Time and Frequency Requirements for an Enhancement of GPS with GEO 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 geo-stationary earth orbit satellites (GES) with distance precision better than 1 meter without causing any serious degradation to the communication services provided by those GES systems. Those requirements necessitate very narrow band delay lock loop (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. Correlation time $T = 100\mu s$ has been achieved in the convolver array.**

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) 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 MTs. 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 GES 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 GSO earth stations, superimposed on the communication signals. The positioning signal is synchronized with GPS so the 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 GES transmit signal is depicted in Figure 2.

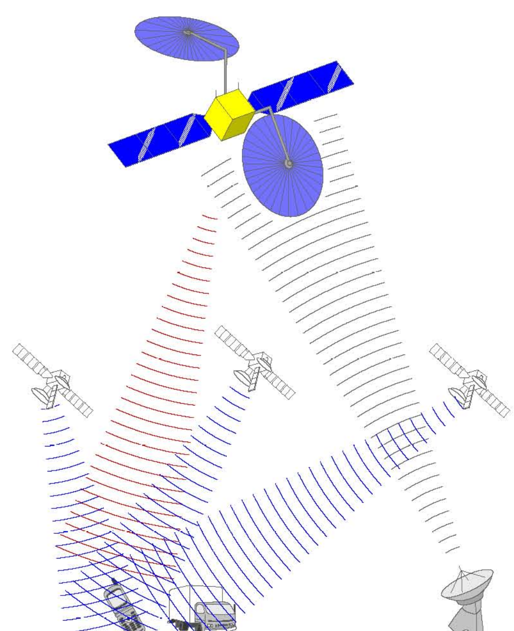


Figure 1. Overall System Configuration

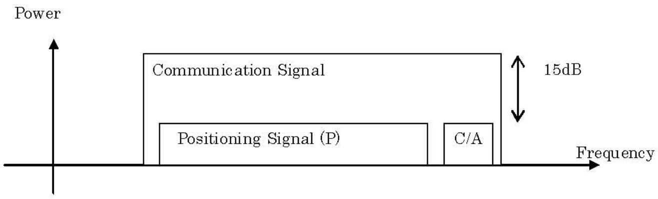


Figure 2. Positioning signal superimposed on communication signal

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 ES for GES. 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 GES 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 ($10kHz$). 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 $10.23MHz$ PN clocks, $10kHz$ Epoch Pulses and the Positioning Data sequences. The timing difference can be measured in sub nano second steps. Then the GES 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 GES system. With the orbit and the timing adjustment information included in the Positioning Data, the user MT can establish one distance measurement which can be combined with 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.

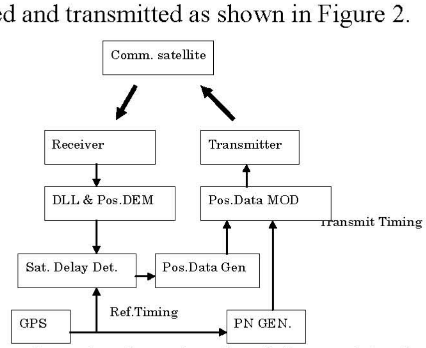


Figure 3. Synchronization circuit of the positioning signal with GPS

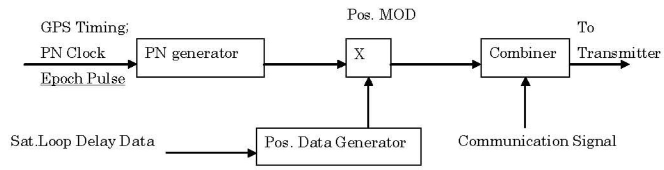


Figure 4. Generation of the positioning signal at the earth station

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, DLL and Positioning Data Demodulator.

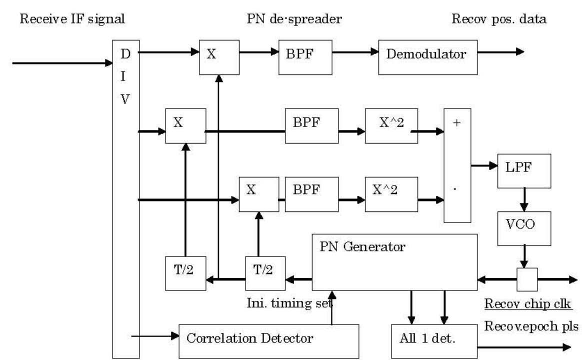


Figure 5. DLL & Demodulator

4.1. Spectrum De-spreading

Let us denote the receive IF signal as

$$r(t) = c(t) + d(t) \cdot pn(t)$$

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 voltage controlled oscillator (VCO) and re-spreads the receive signal by signal multiplication. The output $r'(t)$ of the de-spreader is;

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

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 $pn(t) \cdot lpn(t) = 1$, 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

F_c to $F_c + F_p$, where F_c, F_p are respectively the occupied bandwidth of $c(t)$ and $pn(t)$. The power density of the spread communication signal is $P_c/(F_c+F_p)$ at the center of the spectrum, where P_c is the power of the communication signal. On the other hand the de-spread signal $d(t)$ has the power density P_d/F_d, where P_d and F_d are respectively the power and the bandwidth of the positioning signal $d(t)$. The BPF in Figure 5 limits the signal bandwidth to F_d, hence the power of the positioning signal at the BPF output is $P_d/F_d * F_d = F_d$, while that of the spread communication signal is $P_c/(F_c+F_p)*F_d$. 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

$$S/N = (P_d/P_c)*(F_c+F_p)/F_d = (P_d/P_c)\cdot G_p$$

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 $(F_c+F_p)/F_d$ is the process gain G_p

$$G_p = F_c/F_d + F_p/F_d > F_p/F_d = F_p/F_{ep} * F_{ep}/F_d = 1023 * F_{ep}/F_d$$

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

4.2. 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 $\{c(t) + d(t)\cdot pn(t)\}\cdot lpn(t' - T/2)$ And $\{c(t) + d(t)\cdot pn(t)\}\cdot lpn(t' + T/2)$

Note $t' = t + \varepsilon$, 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 $1/F_d$, which is much larger than the correlation time of the PN signal which is $1/F_p$, 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 $d(t)\cdot C[pn](T/2+\varepsilon)$ and $d(t)\cdot C[pn](T/2-\varepsilon)$. The auto-correlation $C[pn](\tau)$ of the PN signal is limited to T $(=1/F_p)$, the chip duration time ; $C[pn](\tau) = 0$ for $/\tau/ > T$. For $/\tau/ < T$, $C[pn](\tau) = 1 - /\tau// T$. Therefore the BPFs outputs are dominantly $d(t)\cdot(1/2 + \varepsilon/T)$ and $d(t)\cdot(1/2 - \varepsilon/T)$.

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;

$$\{d(t)\cdot(1/2+\varepsilon/T)\}^2 - \{d(t)\cdot(1/2-\varepsilon/T)\}^2 = 2/d(t)/^2\cdot\varepsilon/T$$

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 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 $/\varepsilon/ < T$. There is no detection of the timing error for the remaining timing: $T < /\varepsilon/ < 1{,}022T$ 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. The orbit data available from the GES 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 GES

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 $\pm T/2$ and filtered by the BPFs in Figure 5 are

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

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

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

The timing error detector output is

$$K_p\cdot\varepsilon = r''[+](t)^2 - r''[-](t)^2 =$$

$$\{2d(t)^2 + d(t)\cdot c^7(t)\}/T\cdot\varepsilon$$

K_p is the PN clock phase error detector sensitivity.

K_p contains the signal component $2\cdot d(t)^2$ and the noise component $d(t)\cdot c'(t)$. The signal power is

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

$$N' < \{d(t)\cdot c'(t)\}^2 >= P_d\cdot P_c\cdot F_d / F_c$$

; Continuous over bandwidth

The second equation follows from the fact the $c'(t)$ is $c(t)$ filtered through the BPF with bandwidth F_d.

The symbol $< x >$ means averaging x.

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

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;

$$S/N = S'/(N'/F_d\cdot BL) = 4\cdot(P_d/P_c)\cdot F_c/BL$$

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

$$/\phi_e/^2 = 1/\{2\cdot S/N\} = 1/8\cdot P_c/P_d/F_c\cdot BL$$

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

As an example ,

$$BL = 10(Hz),$$

$$F_c = 10(MHZ),$$

$$P_d/P_c = -15(dB)$$

Then the resultant S/N is

$$S/N = 6 - 15 + 60 = 51(dB)$$

The phase error

$$/\phi_e/ = 1/\sqrt{2S/N} = 2.23\times10^{-3}(rad) = 0.13(deg)$$

The phase error corresponds to the timing and distance measurement errors

$$t_e = T\cdot/\phi_e//2\pi = 0.036(ns)$$

$$d_e = c\cdot t_e = 3\times10^8\times0.036\times10^{-9} = 0.018(m)$$

Thus a very accurate synchronization of the GES 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 GES, conducts the DLL and demodulation of the positioning data.

8.1. 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 $1m$ precision, the timing error must be less than $3.3(ns)$. For C/A code, the chip rate is $F_c = 1.023MHz$. Then it is required that DLL phase error must be about $1deg$ or $0.021(rad)$. In order to achieve the phase error, the required $S/N = 1/(2/\phi_e/^2 = 30.6(dB)$

Then from the formula previously derived; $S/N = 4\cdot(P_d/P_c)\cdot F_c/BL$, the equivalent noise bandwidth of the DLL is determined by the following formula.

$$BL = 4\cdot(P_d/P_c)\cdot F_c/(S/N) = 6 - 15 + 60 - 30.6(dB)$$

$$= 20.4(dB) = 110Hz$$

Note $F_c = 1(MHz) = 60(dBHz)$ 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.

8.2. Processing Rate P Code Signals

The PN clock frequency is $F_c = 10.23MHz$ 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 $F_d = 10kHz$. Then the bandwidth of the DLL can be $BL = 1kHz$. Then the performances will be;

$$/\phi_e/^2 = 1/\{2\cdot S/N\} = 1/8\cdot P_c/P_d/F_c\cdot BL$$

$$= -9 + 15 - 70 + 30 = -34(dB) = 4.0\times10^{-4}$$

$$/\phi_e/ = 0.02(rad)$$

$$t_e = /\phi_e//2\pi/F_c = 3.2\times10^{-10}(F_c = 10^7)$$

$$d_e = c\cdot t_e = 3\times10^8\times3.2\times10^{-10} = 0.096(m)$$

Thus a very high precision can be achieved.

The PLL with $BL = 1kHz$ will have roughly around $1ms$ 1ms for the pull in process. With the sweeping method the DLL will take $1{,}023\times1(ms) = 1(sec)$ for the acquisition process. This is too slow for mobile applications, hence a PN correlator is essential for the operation.

9. Simulation System

Figure 6 is Simulink function of Matlab and a telecommunication system for the DS/CDMA system. Simulink is sufficien simulation in a real parameter, and doesn't have the problem in the analysis of the essence of the system. Figure 7 is a power spectrum for doing simulation by using M-sequence as a PN code.

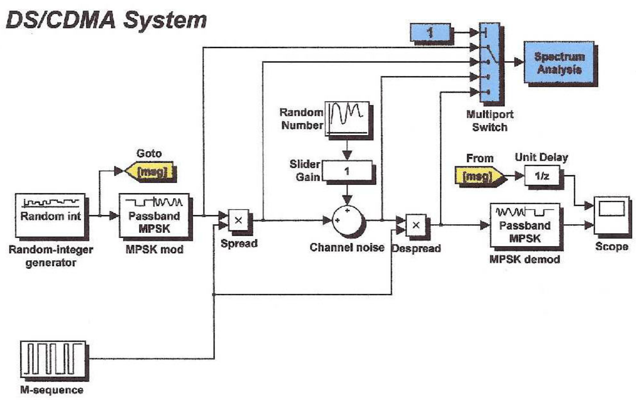
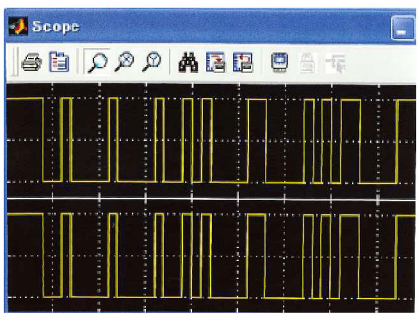
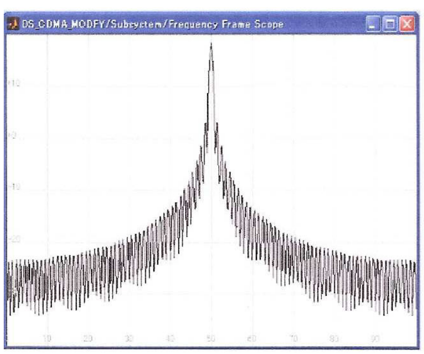


Figure 6. DS/CDMA simulation system



M-sequence



A power spectrum

Figure 7. Simulation result

10. PN Correlators

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.

10.1. SAW Elastic Convolver

PN Correlators is achieved with the SAW convolver [1]. The development target of PN Correlator is Rate P PN codes (bandwidth $B = 10.23 MHz$ and correlation time $T = 100 \mu s$). In $LiNbO_3$, the substrate size becomes $354 mm$ or more. Nonlinear coupling constant (M) is a material of comparable quality of $LiNbO_3$, and the velocity of surface acoustic wave uses half $Bi_{12}GeO_{20}$ of $LiNbO_3$.

Table1. Materials for the use of elastic convolver

Material	M(V·m/W)	v (m/s)	κ^2
$Bi_{12}GeO_{20}$	1.02×10^{-4}	1675	0.012
$LiNbO_3$	1.21×10^{-4}	3488	0.049

Preferably chirped input transducers with electrodes curved to focus the excited SAW to the waveguide ends are used. As for the width of the waveguide, it is three times wavelength because it improves efficiency. Thus the aperture of the SAW is reduced down to only a few wavelengths thereby increasing the acoustic power density. The waveguide works as an integration output electrode for the SAW. Figure 8 shows structure of the SAW elastic convolver. The chirped IDTs are tailored to obtain the appropriate frequency response and admittance for electrical broad-band matching with series tuning inductors incorporated in the device. The electrode curvature and aperture are designed to match the acoustic waveguide mode to minimize coupling loss. The output signal of the waveguide electrode is combined by a microstrip matching network from taps equidistantly distributed over the electrode. Self-convolution of the input signal by reflection at the opposite IDT is suppressed by a special dual track arrangement with IDTs connected acoustically in phase on one side and in opposite phase on the other side. Thus the reflections of the input signals are suppressed at the opposite IDTs by cancellation of the regenerated voltage. All-planar technology allows the precise reproducible design and economic mass production. The externals size has $180mm \times 15mm \times 2mm$. Various problems on the process are caused at delay time though it aimed at $100 \mu s$. Finally, $100 \mu s$ decided to be achieved by using two SAW convolvers at $50 \mu s$. Figure 9 shows a package-less $Bi_{12}GeO_{20}$ SAW convolver ($102.5mm \times 18.7mm \times 2mm$). The method by the chlorobenzene soaking method is adopted in the pattern making. The IDT electrode film thickness of the total is made $200nm$. Hafnium dopes in aluminum film for the purpose of high power resistively. In the electrode, chrome is $20nm$. To obtain high-powered resistance, hafnium is doped the aluminum film.

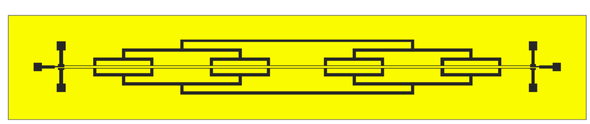


Figure 8. SAW convolver chip

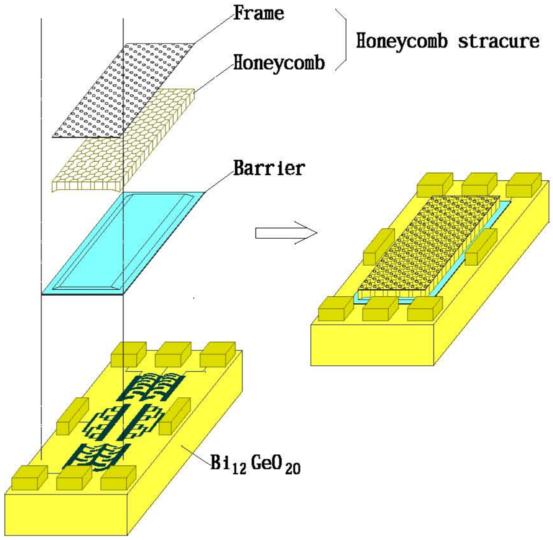


Figure 9. Package-less SAW convolver

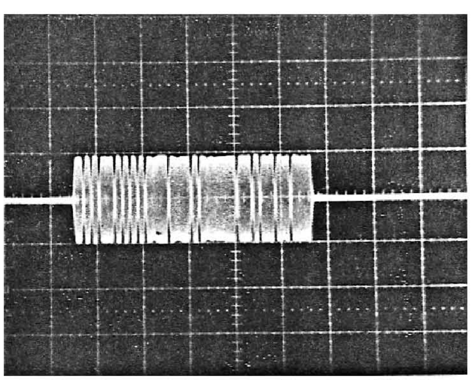
10.2. Experimental Results

The operation examination has measured by standard signal input $+30dBm$ and signal input $-20dBm$. Table 2 is a performance of SAW convolver made for trial purposes. As for F factor as elastic convolver, the one at the highest level is obtained.

Table 2. Performance summary

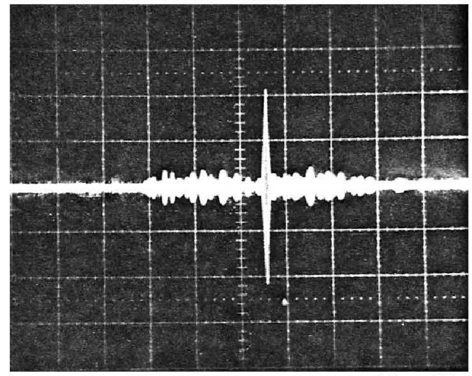
Center Frequency	300MHz
Bandwidth(3dB)	34.7MHz
Co relation time	50.8 μ s
BT Product	1762
F Fctor	-67.5

Figure 10 shows an input PN code signal waveform and the compression pulse response waveform. The correlation loss is $0.5dB$ from a compression pulse waveform.



Horizontal axis:10μs/div

(A) Input PN code (M-sequence)



10μs/div

(B) Compression pulse response waveform

Figure 10. Time domain response of SAW convolver

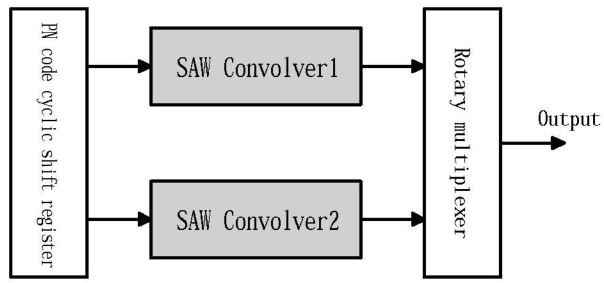


Figure 11. Proposed convolver array

Figure 11 shows two SAW parallel convolvers at $50.8\mu s$ and is a method of processing the signal. Proposed convolver array consists of the rotation type multiplexer to output the correlation value in which processing with the shift register that makes the PN code system go it as shown in Figure 10 and the convolver ends sequentially. Basic operation of the convolver array is confirmed.

11. Conclusion

The SAW elastic convolver can offer a high-speed, compact PN correlator as a device in the passive form. A nonlinear interaction and $Bi_{12}GeO_{20}$ in the material of the substrate for a long correlation time are relied on the device for the operation. Several new technologies of The SAW elastic convolver have been reported in this paper. PN correlators become essential. Correlation time $100\mu s$ has been achieved in the convolver array.

Reference

[1]. T.Watanabe, M.Morimoto, Y.Yamamoto, S.Fushimi, Y.Iwanaga and Y.Yamada, “Newest Trends of SAW Devices€ NEC Research & Development, No.88, pp.1-11, January 1988