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Structure of Direct RF Sampling Receivers for GNSS Signals

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ABSTRACT

A direct RF sampling method refers to a technique that directly converts a passband signal to an intermediate band or a baseband without using a mixer. This method is less complicated than an existing RF receiver because a mixer is not used. It uses digital processing after sampling, and thus can flexibly process signals in a number of bands using software. In this process, it is important to select an appropriate sampling frequency so that a number of signals can be converted to an intermediate band that is easy to process. In this study, going beyond previously studied direct RF sampling frequency selection methods, conditions that need to be additionally considered during receiver design were examined, and the structure of a direct RF sampling receiver that satisfies these conditions was suggested.

Keywords: GNSS, direct RF sampling receiver

1. INTRODUCTION

Software defined radio (SDR) is a technique that processes existing functions that have been processed in analog circuits in the digital domain by implementing most roles of a radio communication system using software (Tuttlebee 1999). Accordingly, SDR has high flexibility of system implementation because only the software needs to be changed depending on the communication system. On the other hand, an SDR system processes most signals in the digital domain, and thus, analog-to-digital converter (ADC) should be arranged as close to an antenna as possible. One of the methods for implementing SDR is a method using direct RF sampling, which performs the sampling of RF signals (Vaughan et al. 1991). In direct RF sampling, a passband signal is converted to an intermediate band or a baseband through direct sampling. In this regard, if the sampling frequency is more than twice the signal bandwidth, the signal can be restored without a distortion even though the sampling is performed using a frequency that is much lower than the carrier frequency of the signal (Vaughan et al. 1991).

When signals in a number of bands are to be received by one receiver such as the case of the global navigation satellite system (GNSS), the direct RF sampling method can perform simultaneous processing using one ADC. This method has a simple receiver configuration and has the advantage of reduced processing capacity when compared to a general IF sampling receiver that uses a number of mixers for the processing of multiband signals. For this reason, many studies on the direct sampling of RF signals have been performed (Akos et al. 1999, Alonso et al. 2008, Huang & Lin 2010, Barrak et al. 2011).

Based on the two systems of global positioning system (GPS) and global navigation satellite system (GLONASS), Akos et al. (1999) suggested a method for determining a sampling frequency that can simultaneously receive two GNSS signals. For the simultaneous reception of GPS and GLONASS, Barrak et al. (2011) suggested a method that alleviates the condition of an anti-aliasing filter regarding adjacent signal bands as one band.

In this study, conditions that need to be considered during the design of a direct RF conversion receiver in addition to previously suggested conditions were examined. Also, based on these conditions, the structure of a direct RF conversion receiver for receiving GNSS signals (e.g., GPS, GLONASS, and GALILEO) was suggested.

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2. DESIGN CONDITIONS OF A DIRECT RF SAMPLING RECEIVER

To design a direct RF sampling receiver, the sampling frequency of ADC needs to be first determined. A theoretical direct RF sampling frequency is determined by the carrier frequency and bandwidth of a passband signal. However, to process a number of signals in multibands using one ADC (i.e., one sampling frequency) such as the case of GNSS, additional conditions are required. Also, to actually design a receiver, several conditions need to be additionally considered besides the determination of a sampling frequency. The additional considerations include the relation between intermediate frequency (IF) and sampling frequency, aliasing noise, and the interpolation and decimation for obtaining an intermediate band sample frequency.

Condition 1. Direct RF sampling frequency for a single band

If the sampling of a continuous signal in the time domain is performed, the spectrum of an original analog signal is repeatedly observed at every sampling frequency (f_s). This repeated spectrum is called aliasing. In a direct RF sampling receiver, a demodulated signal is obtained so that the aliasing is located at the intermediate frequency (f_{IF}) or the baseband. In this regard, the sampling frequency needs to be determined so that aliasings do not overlap each other, and the following condition should be satisfied (Akos et al. 1999).

$$\frac{2f_H}{N} \le f_s \le \frac{2f_L}{N-1}, \qquad 1 \le N \le \left\lfloor \frac{f_H}{B} \right\rfloor \tag{1}$$

where N is the number of aliasings that are between the intermediate frequency of the passband signal and 0 Hz; f_H and f_L are the maximum and minimum frequencies of the passband signal, respectively; and B is the bandwidth of the passband signal ($B = f_H - f_L$).

In addition, the aliasing located at f_{IF} should not overlap with 0 Hz and $f_s/2$. This is because if it exceeds 0 Hz, it overlaps with the symmetric spectrum in the negative frequency domain; and because if it is larger than $f_s/2$, the signal cannot be restored due to the Nyquist theorem. This can be expressed as follows (Akos et al. 1999).

$$0 < f_{IF} - \frac{B}{2}, \; f_{IF} + \frac{B}{2} < \frac{f_s}{2} \tag{2}$$

Condition 2. Direct RF sampling frequency for multibands

In the case of multiband direct RF sampling, the spectra of a number of signals are converted to within $f_s/2$ through one ADC, and thus, the aliasings of each signal coexist in the domain within $f_s/2$. Therefore, a distortion does not occur when the aliasings do not overlap each other. This can be expressed as Eq. (3) (Akos et al. 1999).

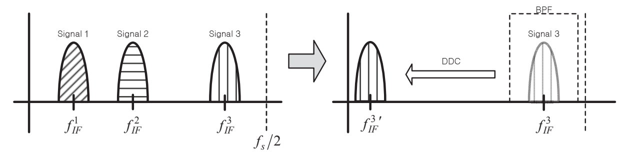

Fig. 1. Operation of baseband aliasing and DDC for multiband signals.

$$\left| f_{IF}^i - f_{IF}^j \right| \ge \frac{B^i + B^j}{2} \tag{3}$$

where i and j are the indices that represent the f_{IF} of different signals.

Condition 3. Relation between intermediate frequency and sampling frequency

After direct RF sampling, the spectrum of the signal is repeated every sampling frequency, and the f_{IF} of aliasing that is within $f_s/2$ is determined by the sampling frequency and the carrier frequency of the signal, as shown in Eq. (4).

$$if \left\lfloor \frac{f_c}{f_s/2} \right\rfloor is \begin{cases} even, & f_{IF} = rem(f_c, f_s) \\ odd, & f_{IF} = f_s - rem(f_c, f_s) \end{cases} \tag{4}$$

where f_c is the carrier frequency of the passband signal,   is the floor function, and rem (a,b) represents the remainder obtained through dividing a by b. In this process, f_{IF} needs to be larger than the bandwidth of the signal, but it is desirable to select a sampling frequency as close to 0 Hz as possible. This is because when f_{IF} decreases, the intermediate band sample frequency necessary for digital signal processing can be reduced.

For the sampling of a single band signal, it is not difficult to determine a smpling frequency that locates f_{IF} close to 0 Hz. However, in the case of the direct RF sampling for multibands, the aliasings of each band signal exist within $f_s/2$, and these aliasings should not overlap. Therefore, at least one aliasing is located relatively far from 0 Hz. In this case, after obtaining desired aliasing through a bandpass filter, it needs to be moved close to 0 using a digital down converter (DDC), as shown in Fig. 1.

Condition 4. Interpolation and decimation

In the case of a general IF sampling receiver, a passband signal is lowered to desired f_{IF} through a mixer. Then, it goes

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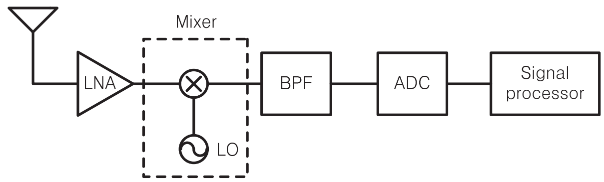

Fig. 2. Structure of a general IF sampling receiver.

through a bandpass filter, and sampling is performed at ADC, as shown in Fig. 2. In general, the sample frequency of ADC is set to about four times the f_{IF}. This is to easily restore the inphase-quadrature (I-Q) components from the received signal using the characteristics of the I-Q components that are orthogonal to each other. For the same reason, in the case of a direct RF sampling receiver, it is also desirable to select a sample frequency so that it is about four times the f_{IF}. For direct RF sampling, this sample frequency can be obtained from the sampling frequency through interpolation and decimation, and the implementation is easy when the interpolation and decimation are performed in an integer multiple. Therefore, the initial sampling frequency needs to be determined so that an intermediate band sample frequency can be obtained from the sampling frequency through integer multiple interpolation and integer multiple decimation.

Condition 5. Aliasing noise

A representative disadvantage of direct RF sampling is aliasing noise. This is a phenomenon where noise increases significantly due to the overlapping of the spectrum of noise that exists in out-of-signal bands as the spectrum of an analog signal is repeated due to sampling. To avoid aliasing noise, sampling needs to be performed after the noise in out-of-signal bands is eliminated through a bandpass filter in the RF band. To pass only a desired signal band in the RF band, a sharp filter (i.e., a filter with a high Q-factor) is required. However, a filter with a high Q-factor is difficult to implement, and is expensive.

Another method that can reduce aliasing noise weakening the sharp characteristics of a filter is to reduce the number of noise aliasings by decreasing the number of overlapped spectra (i.e., N in Eq. (1)). This is enabled by widening the interval of aliasing through increasing the sampling frequency during direct RF sampling. In other words, if the sampling frequency is increased, the magnitude of aliasing noise can be reduced even though the bandpass filter is not sharp. Therefore, to reduce aliasing noise, the sampling frequency needs to be determined considering the Q-factor of the bandpass filter.

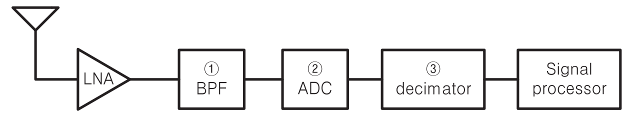

Fig. 3. Structure of a single band direct RF sampling receiver.

Table 1. Direct RF sampling frequency and intermediate frequency for the GPS L1 band.

Band	Carrier frequency (MHz)	BPF bandwidth (MHz)	Sampling frequency (f_s) (MHz)	Intermediate frequency (f_{IF}) (MHz)	f_s / f_{IF}
GPS L1	1575.42	5	16.3676	4.1304	3.9627
			40.268	5.007	8.0423

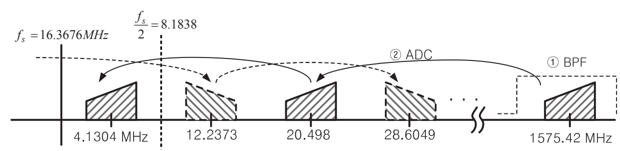

Fig. 4. Spectrum of the direct RF sampling of the C/A signal for the GPS L1 band f_s = 16.3676 MHz.

3. STRUCTURE OF A DIRECT RF SAMPLING RECEIVER FOR GNSS SIGNALS

In this study, a direct RF sampling receiver for GNSS signals was designed. This direct RF sampling receiver can be classified into a single band direct RF sampling receiver and a multiband direct RF sampling receiver depending on the number of target GNSS signals. A single band direct RF sampling receiver is used for only one signal among a number of GNSS signals, and a multiband direct RF sampling receiver can be used when GNSS signals in a number of bands are simultaneously received.

3.1 Single band direct RF sampling receiver

Fig. 3 shows a single band direct RF sampling receiver. A direct RF sampling receiver for the C/A signal of single band GPS L1 that satisfies the receiver design conditions described in Chapter 2 is as follows. First, the carrier frequency of the L1 band is 1575.42 MHz, and the cut-off bandwidth of the bandpass filter was set to 5 MHz. In this case, based on Eq. (1), there are about 315 sampling frequencies that are capable of direct RF sampling (N = 2,3,…,315). If the lowest two frequencies are selected considering the design conditions explained in Chapter 2, 16.3676 MHz and 40.268 MHz can be obtained (Table 1).

First, when f_s = 16.3676 MHz, the repetition of the spectrum can be expressed as shown in Fig. 4. As shown in the figure, after the bandpass filter, the spectrum is repeated

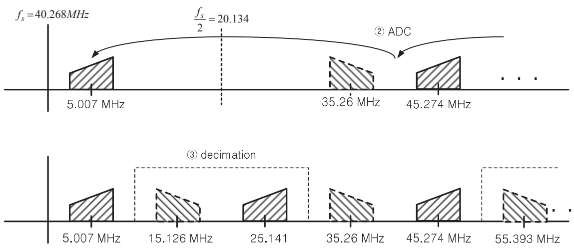

Fig. 5. Spectrum of the direct RF sampling of the C/A signal for the GPS L1 band f_s = 40.268 MHz.

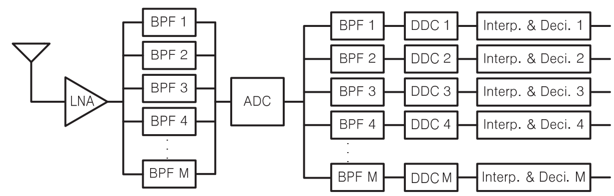

Fig. 6. Structure of a direct individual RF band sampling receiver for multiband signal.

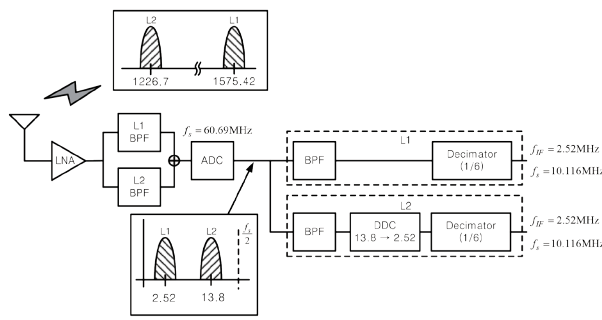

Fig. 7. Structure of a multiband direct individual RF sampling receiver for the L1 and L2 signals.

through the ADC sampling. The spectrum and arrow shown in dotted lines represent the aliasing that came from the negative frequency domain through repetition. In this case, the intermediate frequency of the intermediate band signal, f_{IF}, is 4.1304 MHz, and the sampling frequency is about 3.96 times the f_{IF}. Thus, the signal can be restored without decimation. However, for this sampling frequency, if the cut-off bandwidth of the bandpass filter is larger than 8.1 MHz, the signal cannot be restored due to the overlapping of aliasings. Therefore, a larger sampling frequency is required.

In the case of f_s = 40.268 MHz, the spectrum is observed as shown in Fig. 5, and the f_{IF} is 5.007 MHz. The sampling frequency is about 8.04 times the f_{IF}, and the sampling frequency is lowered by decimation by 2. This has the same effect as a case in which the sampling frequency decreases by half, and indicates that the interval of spectrum repetition in the frequency domain also decreases by half. In other words, a new spectrum is formed between the repeated spectra in the frequency domain as shown in the figure. After the decimation, the sample frequency becomes 20.134 MHz, and this is about 4.02 times the f_{IF}. Also, the cut-off bandwidth of the bandpass filter can be applied up to about 20 MHz.

3.2 Multiband direct RF sampling receiver

Methods for the direct RF sampling of multiband GNSS signals can be classified into two categories depending on the setting of the zone. In the first method, all GNSS signal bands are processed by dividing them into each separated pass signal (direct individual RF band sampling receiver for multiband signal). In the second method, a number of adjacent GNSS bands are bound together and are processed as one large band (direct integrated RF band sampling receiver for multiband signal)

3.2.1 Direct individual RF band sampling receiver for multiband signal

Fig. 6 shows the structure of a direct individual RF band sampling receiver for multiband signal. All the target GNSS bands (M bands) are divided into each separated band through bandpass filters, and all the signals are converted to frequencies within $f_s/2$ through one ADC. Then, DDC and interpolation/decimation are performed for each signal so that f_{IF} and f_s satisfy the design conditions described in Chapter 2.

Fig. 7 shows the structure of a direct RF sampling receiver that simultaneously receives the L1 C/A and L2C signals of GPS. The intermediate frequencies of the L1 and L2 bands are 1575.42 MHz and 1226.7 MHz, respectively, and the bandwidthes of the bandpass filters, L1 BPF and L2 BPF, which select two signals, are 5 MHz. Based on this, the lowest frequency that satisfies Eqs. (1-3) and the receiver design conditions described in Chapter 2 is about 60.69 MHz. When sampling is performed using this frequency, the aliasings of the L1 C/A and L2C signals are located at 2.52 MHz and 13.8 MHz, respectively. Then, each signal is selected using a bandpass filter, and decimation by 6 is performed for the L1 signal. After the decimation, the sample frequency becomes 10.116 MHz. This is about 4.01 times the f_{IF} of L1, which satisfies Condition 3. In the case of the L2 signal, the aliasing located at 13.8 MHz is lowered to 2.52 MHz through DDC, and decimation by 6 is performed similar to the L1 signal. Then, it becomes about 4.01 times the f_{IF} similar to the case of L1, and thus, the minimum sample frequency can be obtained. However, for this direct individual RF band sampling for multiband signal, one bandpass filter is needed for every GNSS signal to be

Table 2. A number of GNSS signals and integrated bands.

Union	Frequency (MHz)	GNSS signals
1	1164-1220	GPS L5 GALILEO E5a, E5b BDS B2
2	1220-1260	GPS L2C GLONASS G2
3	1559-1610	GPS L1 C/A, L1C GALILEO E1 DBS B1 GLONASS G1

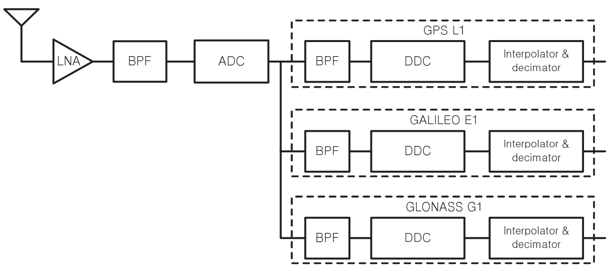

Fig. 8. Structure of a direct RF sampling receiver for Union 3 (integrated band)

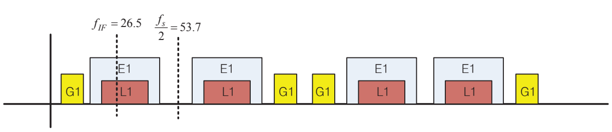

Fig. 9. Spectrum of the RF sampling for Union 3 (integrated band) f_s = 107.3 MHz.

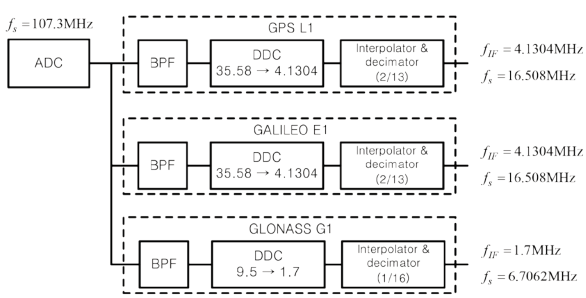

Fig. 10. Restoration of the Union 3 (integrated band) signals.

received. In particular, a filter with sharp characteristics is needed when signal bands are adjacent to each other, and a large Q-factor is needed because the intermediate frequency at which a filter operates is higher than the cut-off bandwidth. This would induce a burden on receiver design in terms of cost.

3.2.2 Direct integrated RF band sampling receiver for multiband signal

The disadvantage of a direct individual RF band sampling receiver can be overcome using the fact that the signals of a number of GNSS systems are located in adjacent bands and some signals share the same band. This is a method in which adjacent signal bands are bound together as a large band and are processed as one signal band enabling the design of a receiver using a bandpass filter with a wide cut-off bandwidth (low Q-factor). This method reduces the implementation burden of a bandpass filter, and processes the procedure of a passband that requires a sharp filter, in an intermediate band where implementation is relatively easy.

GNSS signal bands can be classified as shown in Table 2 depending on their adjacent locations (Bin et al. 2014). Fig. 8 shows the structure of a direct RF sampling receiver for Union 3 (integrated band) in Table 2. Union 3 includes the GNSS signals such as GPS L1, GALILEO E1, and GLONASS G1. To restore each signal, three branches are required in an intermediate band after ADC. Each branch consists of bandpass filter, DDC, and interpolator/decimator. The sampling frequencies for Union 3 include 107.3 ~ 107.5 MHz, 111 ~ 111.4 MHz, and 119.3 ~ 119.6 MHz. If sampling is performed using the lowest frequency (107.3 MHz), the spectrum is repeated as shown in Fig. 9. Fig. 10 shows a detailed design plan after ADC. The f_{IF} of L1 and E1 are 35.58 MHz, and the f_{IF} of G1 is 9.5 MHz. To satisfy the RF receiver design conditions described in Chapter 2, the frequencies of the L1 and E1 band signals are lowered through DDC so that the f_{IF} can be located at 4.1304 MHz. Then, the sampling frequency is lowered to 16.523 MHz by performing about 2-/13-times interpolation and decimation so that the sampling frequency can be four times the f_{IF}. In the case of the G1 signal, the f_{IF} is 9.5 MHz, and the bandwidth of the signal is about 3.2 MHz. Thus, the lowest f_{IF} becomes about 1.6 MHz. Therefore, the f_{IF} is lowered to about 1.7 MHz using DDC so that it is close to 0 Hz, and the sample frequency is set to four times the f_{IF} through the interpolation and decimation of the sampling frequency. In other words, a sample frequency of 6.7062 MHz is obtained by decimation by 16, which is about 3.96 times the f_{IF}.

4. CONCLUSION

In this study, the structure of a direct RF sampling receiver that can simultaneously receive a number of GNSS signals was suggested. In particular, the relation between intermediate frequency and sampling frequency after sampling, aliasing noise, and the proportion of interpolation and decimation were considered during the design of a receiver. The direct RF sampling receiver can be classified into three structures depending on the number of target

GNSS signal bands and the method of processing signal bands.

The first is a single band direct RF sampling receiver, which receives only one signal among GNSS signals. This receiver has simpler structure than a multiband receiver, and it is relatively easy to obtain a sampling frequency that satisfies receiver design conditions.

The second is a direct individual RF band sampling receiver, which processes a number of GNSS signals by dividing them into each separated band. This receiver requires as many bandpass filters as the number of separated bands, and all of these filters should have sharp characteristics.

The third is a direct integrated RF band sampling receiver, where adjacent signal bands among a number of GNSS signal bands are bound together and processed as one large virtual band. This receiver requires less bandpass filters than an individual band receiver, and the characteristics need not be sharp, but the sampling frequency is relatively high due to wide bandwidth.

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