Implementation of DDS Chirp Signal Generator Using Phase Compensation

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Approved by

Professor Kim, Jae-Hyun

[Advisor]
위상 오차 보상을 이용한 DDS 첩 신호 발생기 연구

양 희 인

위 논문은 아주대학교 석사학위논문으로 학위논문심사위원회에서 심사 통과하였음.

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Abstract

The history of space development has been stated from when Soviet Union had launched the first artificial Earth satellite Sputnik-1 in 1957. After that more than 40 countries including U.S., Japan, Russia, and Germany are promoting the space industry and operating approximately more than 5 thousands of satellites in space. Satellites from U.S. and Russia occupy more than 90 percent of them.

As a kind of active sensor, synthetic aperture radar (SAR) that is usually loaded on satellites and uses microwave for its own illumination source. Main characteristic of SAR is that it provides high-resolution images of target in all-weather condition. Due to the property of microwave, SAR is recognized as powerful surveillance radar and several countries already have and use satellite on-board SAR. Basically it is loaded on moving-platform and the small antenna (usually 2.5 - 10 m) on satellite on-board SAR transmits and receives microwave signal in sequence. Using signal processing technique called synthetic aperture, it synthesizes its antenna length virtually during the flight time. The performance of radar system depends on antenna size. In other words, large antenna can acquire much information of target and by acquiring much information it can generate high-resolution images. However loading a large antenna increases the cost of whole satellite system and it is hard to be implemented. SAR is a kind of solution that can reduce the cost of satellite system design.

SAR is introduced in 1951 by Carl Wiley with the technique called Doppler beam sharpening (DBS) [1]. Later, during about 60-years SAR expanded its mission
not only military purpose but also other missions including environmental remote sensing, disaster monitoring, Earth observation and resource exploration. Especially in Korea, the needs of satellite on-board SAR are increasing because of the rain, clouds, and fog are frequently disturbing the observation using optical sensor.

SEASAT (launched in ’78), the first satellite on-board SAR is about 23 tons. ENVISAT (launched in ’02) is 8.2 tons, ALOS PALSAR (launched in ’05) is 3.85 tons and recent satellite on-board SAR SAR-Lupe (launched in ’08) is only 0.77 tons. The reason why these satellites has ton class of weight is they load several payloads at once. The satellite system in recent loads only mono payload and forms constellation with other satellites and it means that satellites are being minimized. However there are some limitations when designing small and light weight satellite; smaller and lighter but better performance. With the enhancement of space technology, minimization of satellite system is accelerated but still the minimization as it is remains as hard tasks. The major limitation when designing SAR system for small satellite is antenna because it occupies large weight and size. There are two types of antenna for satellite system; passive antenna which has light weight and active antenna that maximizes the performance of satellite system. In case of passive antenna, it has high-power, light weight, and low developing costs for its strong points but it is weak to beam control, wide area observation, and multi-polarization mode. Active antenna has the weak points of passive antenna as its strong points. The trade-off between these antenna should be considered when designing.

Another consideration is the resolution of SAR system. SAR system offers high-resolution from 0.5m to 10m and it is achieved by a special signal which is called
chirp. Chirp is a kind of linearly frequency modulated signal and the frequency of chirp expands linearly according to time. The reason why chirp signal is used is that it can achieve high-resolution using pulse compression technique with relatively small power.

In this paper, implementation of signal generator that makes chirp signal using direct digital synthesizer structure. Chirp signal generator discussed in this paper has phase error and consequently it degrades the performance of radar system (e.g. resolution). Conventional chirp signal generator has $-28\,dB$ lower spectrum amplitude compared to ideal chirp signal in maximum. Proposed chirp signal generator shows that is ideally eliminates spectral regrowth components then spectrum amplitude is symmetrical to ideal chirp signal. Impulse response function has been investigated to evaluate the system performance. Peak to side-lobe ratio (PSLR) has been increased $-0.0686\,dB$, integrated side-lobe ratio (ISLR) has been enhanced $0.0078\,dB$, and signal center has been compensated from 1799 to 1801 when the number of sample is 3601.
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<th>Description</th>
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<tbody>
<tr>
<td>ACS</td>
<td>attitude control subsystem</td>
</tr>
<tr>
<td>ADC</td>
<td>analog to digital converter</td>
</tr>
<tr>
<td>BPF</td>
<td>band pass filter</td>
</tr>
<tr>
<td>BW</td>
<td>bandwidth</td>
</tr>
<tr>
<td>CDS</td>
<td>command and data subsystem</td>
</tr>
<tr>
<td>CMS</td>
<td>communication management subsystem</td>
</tr>
<tr>
<td>DAC</td>
<td>digital to analog converter</td>
</tr>
<tr>
<td>dB</td>
<td>deci-bell</td>
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<tr>
<td>DBS</td>
<td>Doppler beam sharpening</td>
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<td>DDS</td>
<td>direct digital synthesizer</td>
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<tr>
<td>EPS</td>
<td>electrical power subsystem</td>
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<tr>
<td>FA</td>
<td>frequency accumulator</td>
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<tr>
<td>FCW</td>
<td>frequency control word</td>
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<td>FFT</td>
<td>fast Fourier transform</td>
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<td>FM</td>
<td>frequency modulation</td>
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<tr>
<td>FPGA</td>
<td>field programmable gate array</td>
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<tr>
<td>HPA</td>
<td>high power amplifier</td>
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<tr>
<td>IF</td>
<td>intermediate frequency</td>
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<tr>
<td>IRF</td>
<td>impulse response function</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
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<tr>
<td>--------------</td>
<td>--------------------------------------------------</td>
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<tr>
<td>ISLR</td>
<td>integrated side lobe ratio</td>
</tr>
<tr>
<td>KOMPSAT-5</td>
<td>Korea multi purpose satellite-5</td>
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<tr>
<td>LEO</td>
<td>low Earth orbit</td>
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<tr>
<td>LFM</td>
<td>linear frequency modulation</td>
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<tr>
<td>LNA</td>
<td>low noise amplifier</td>
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<tr>
<td>LO</td>
<td>local oscillator</td>
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<tr>
<td>LP</td>
<td>linear polarization</td>
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<td>LPF</td>
<td>low pass filter</td>
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<tr>
<td>PA</td>
<td>phase accumulator</td>
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<tr>
<td>PDDS</td>
<td>parallelized direct digital synthesizer</td>
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<tr>
<td>PDU</td>
<td>power distribution unit</td>
</tr>
<tr>
<td>PRF</td>
<td>pulse repetition frequency</td>
</tr>
<tr>
<td>PSD</td>
<td>power spectrum density</td>
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<tr>
<td>PSLR</td>
<td>peak to side lobe ratio</td>
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<tr>
<td>RF</td>
<td>radio frequency</td>
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<tr>
<td>RMSE</td>
<td>root mean square error</td>
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<tr>
<td>ROM</td>
<td>read only memory</td>
</tr>
<tr>
<td>Rx</td>
<td>reception</td>
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<tr>
<td>SAR</td>
<td>synthetic aperture radar</td>
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<tr>
<td>Tx</td>
<td>transmission</td>
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<tr>
<td>UAV</td>
<td>unmanned aerial vehicle</td>
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<td>VCO</td>
<td>voltage controlled oscillator</td>
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Chapter 1. Introduction

1.1 Background and Motivation

Synthetic aperture radar (SAR) is an imaging radar that uses microwave to generate the high-resolution images of target in remote area. It can be used for disaster monitoring, resource exploration, civil engineering, military purpose and etc. So several countries already have satellite on-board SAR.

SAR system is usually loaded on moving platform such as unmanned aerial vehicles (UAVs) or satellites [2]. Then it transmits and receives frequency modulated (FM) microwave signal called chirp perpendicular to its flight path. Here this type of observation is called side-looking. As it is a kind of active sensor which has its own illumination source, it can be operated regardless of day and night condition. Most significant characteristic of SAR is that this sensor uses microwave for imaging. Microwave has relatively longer wavelength than visible light which optical sensor uses for target imaging. As the wavelength of visible light is short, it scatters much in air so that visible light cannot penetrate the clouds. However, SAR sensor can acquire the images in all-weather condition. Different from optical sensor images, SAR images are shown in grey scale. An example of SAR image is presented in Figure 1.1 [3].

The pixel value of SAR image is classified to 256-level grey scale and the intensity of each pixel indicates the reflectance of target. In other words, if the target
has irregular reflection characteristics, then radar will get much of back-scattered microwave, the pixel will be shown white (pixel value = 255). However, if the target has irregular reflection characteristics (i.e. sea), the images will be shown as black (pixel value = 0).

Another characteristic is that SAR provides high-resolution images by adopting two types of post-processing techniques; pulse compression and synthetic aperture [4]. There are two types of resolution; range resolution (parallel to beam direction) and azimuth resolution (parallel to flight path of SAR sensor). Pulse compres-
tion technique is used to enhance the range direction resolution. In radar technique, as the pulse width gets narrower, range direction resolution gets better. So pulse compression compresses the pulse width virtually with post-processing using matched filter. Compared to range resolution that is affected by pulse width, azimuth resolution depends on antenna length. Figure 1.2 show the azimuth resolution according to antenna length. In case of ordinary radar, antenna is inverse proportional to beam width which is azimuth resolution. If the radar has longer antenna then its resolution gets higher. In case of SAR, it acquires the image on the moving, it synthesizes the length of antenna virtually and consequently it achieves high-resolution in azimuth direction.

![Comparison of azimuth resolution according to antenna length.](image)

In this paper, we focus on range resolution of SAR systems, especially chirp signal generator that generates wide-bandwidth signal using digital calculation.
1.2 Digital Chirp Signal Generators

An example of ideal chirp signal in time domain is presented in Figure 1.3. There are mainly two types of chirp signal generator; analog and digital type chirp signal generators. An analog type chirp generator is controlled by the linear ramp-up and -down signals of voltage controlled oscillator (VCO) [5]. Analog chirp signal generator requires a large amount of size and weight as it should be operated with workstation, oscillator, and etc. Also, as the linearity and frequency response of signal are poor it is not appropriate for to be used in SAR system that requires high-stability and -linearity. Another type of chirp signal generator is digital type and it can be classified to memory-map based chirp generator and direct digital synthesizer.
Digital chirp generator is usually implemented with digital electric components or field programmable gate array (FPGA). Compared to analog type chirp generator, memory-map and DDS generators have better frequency response, linearity, and digital compatibility. It means digital type chirp generator has better performance than analog chirp generator in the respect of signal characteristics even though the complexity of digital chirp generator is relatively high.

Memory-map based chirp generator loads pre-stored ideal chirp signal from memory ROM, and the procedure of generating the signal is easy and simple. However, if SAR system needs to generate chirp signal with wide-bandwidth, it requires a large amount of memory and it is hard to modify the signal in memory. To overcome these problems, DDS chirp generator has been proposed [6, 7]. Especially in space mission, memory unit is easily affected by space dust or radiation. When the memory unit of memory-map based signal generator gets damage from some external factors, signal purity of memory-map based signal generator will be lowered. In the mean time, Compared to memory-map chirp generator, DDS chirp generator generates phase of signal only, and according to phase address it loads pre-stored amplitude information from Sin ROM. By doing so, it depends on memory unit less than memory-map chirp signal generator and so DDS chirp generator is considered that it is much stable than memory-map chirp generator in the respect of hardware maintenance, signal characteristics, and memory dependency. Even though DDS chirp generator has more stable characteristic, it has some problems that it cannot be implemented in SAR system on space yet. SAR sensor generates images with correlation operation between transmitted signal and received signals so the transmitted
signal should be generated as ideal as possible. However, due to the digital signal generation, granular noise on sampling and truncation error because of memory insufficiency occur. These error cause that the phase of chirp signal shifts from the center. Phase error from DDS degrades signal quality and makes spectral regrowth which is unwanted side-lobe components. Consequently it degrades spectrum purity such as signal to noise ratio (SNR) because spectral regrowth increases the signal power in notch frequency. In this paper, phase error of DDS chirp generator is revealed and the algorithm that compensates the error is proposed.

1.3 Contributions

The goal of this thesis is the implementation of DDS chirp signal generator using phase error compensation algorithm. As mentioned in above, spectrum purity of chirp signal generator is important to performance of input and output signals. Therefore, phase error compensation algorithm is proposed. Proposed algorithm not only compensates phase error of conventional DDS chirp signal but also increases spectrum purity by decreasing side band signal power.

The followings are the principal contributions of this thesis:

- Structures of satellite system and SAR system are presented.
- Comparison between memory-map based chirp signal generator, DDS and PDDS chirp signal generator is presented.
- PDDS chirp signal generator has been implemented using Simulink and characteristics of parallelized DDS (PDDS) chirp signal are presented.
Phase error from DDS chirp signal generator is presented. Compared to ideal signal, PDDS chirp signal in time domain has phase error due to granular noise, truncation error, and etc. Phase error increases spectrum regrowth and consequently it leads to degradation of spectrum purity.

With the help of phase compensation, proposed PDDS signal generator has shown better performance in the respect of time domain signal, spectrum in dB scale, and impulse response function (IRF).

1.4 Overview

The remainder of this thesis is organized as follows. In Chapter 2, an overview of radar system, fundamentals of SAR system and characteristics of chirp signal generator are described. The structure of chirp signal generator, phase error from digital DDS chirp generator, and phase error compensation algorithm to enhance spectrum purity are followed in Chapter 3. Chapter 4 shows performance analysis between conventional DDS chirp signal generator and proposed idea in the respect of signal in time domain and spectrum characteristics. This thesis is concluded in Chapter 5.
Chapter 2. Related Works

In this chapter, an overview of SAR system and characteristics of chirp signal generator are presented. Also, structures of SAR system and SAR system design parameters for small satellite are presented. Block diagram of conventional radar system is shown in Figure 2.1 [8]. Radar is an abbreviation of radio detection and ranging and as its name indicates, radar system detect the location or distance of the target via time delay between transmission and reception signals. Radar system is mainly consisted of transmitter, antenna, receiver, and signal processor.

Figure 2.1. Block diagram of radar system.
Radar system first generates detection signal in waveform generator then power amplifier up-converts the transmission power. Detection signal is transmitted via antenna and back-scattered signal from target in remote area is received with time delay. Received analog signal is converted to digital signal. Next, in signal processor, the post-processing called pulse compression is operated to enhance the range resolution. With the series of signal processing, received signal is recorded in data storage. Here, the reason why the radar system uses power amplifier, antenna, and pulse compression technique is to acquire high-reliable information of targets.

### 2.1 Fundamentals of Chirp Signal

Radar detect the distance and speed of target via time delay and Doppler effects. In radar system, resolution is one of the most important factors. Resolution of radar is defined as

\[
r = \frac{cT}{2}
\]

where \( r \), \( c \), and \( T \) are range resolution, speed of light, and pulse width respectively. The definition of resolution is the minimum distinguishable distance between two adjacent targets. Equation 2.1 indicates that resolution gets better when pulse width gets narrower. Commonly Radar system transmits pulse-train type microwave signal and radar gets higher resolution when narrower the pulse width and higher the peak power of pulse. However, realizing the radar system with narrow pulse and high peak power is hard tasks so radar system adopts the technique called pulse compression
on signal processing stage [4]. In pulse compression, the radar signal passes through matched filter. Assuming the transmitted signal \( s(t) \) is given by (2.2), the back-scattered signal with a time \( t_0 \) later \( s_r(t) \) can be expressed as (2.3)

\[
s(t) = \text{rect} \left( \frac{t}{T} \right) \exp \left\{ j\pi K t^2 \right\} \quad (2.2)
\]

\[
s_r(t) = \text{rect} \left( \frac{t-t_0}{T} \right) \exp \left\{ j\pi K (t-t_0)^2 \right\} \quad (2.3)
\]

where \( t, T, \) and \( K \) are time, pulse width, and signal sweep rate respectively. When expressing the impulse function of matched filter as \( h(t) \),

\[
h(t) = \text{rect} \left( \frac{t}{T} \right) \exp \left\{ -j\pi K t^2 \right\} \quad (2.4)
\]

matched filter output \( s_{out}(t) \) can be expressed as (2.5) and it indicates rectangular signal has been transformed to sinc function.

\[
s_{out}(t) \approx T \text{sinc} \left( KT (t-t_0) \right) \quad (2.5)
\]

Finally, if we assume the 3\( \text{dB} \) beam width of sinc signal as \( \tau_{\text{comp}} \), the range resolution after pulse compression will be as

\[
r = \frac{c \tau_{\text{comp}}}{2} \approx \frac{1}{|K| T} \quad (2.6)
\]

Because \( |K| T \) is signal bandwidth, equation (2.6) indicates that resolution of radar can be enhanced when the signal has large bandwidth. To provide high-resolution images, SAR system adopts pulse compression technique and the signal called chirp which linearly enlarges its frequency with time.
Figure 2.2 shows the difference between sinusoid and chirp signals. If we assume that both two signals have the pulse width of $T$, the bandwidth of sinusoid and chirp signals are $1/T$ and $F_2 - F_1$ respectively. Here, the value of $F_2 - F_1$ is frequency difference of chirp signal. From the equation (2.2), we can define the chirp signal in SAR system. As mentioned before, SAR system uses chirp signal to enhance the range resolution. Expanding the equation with Euler’s formula, equation (2.2) can be expressed as

$$s_t = \text{rect}\left(\frac{t}{T}\right)\left[\cos\left(\pi K t^2\right) + j \sin\left(\pi K t^2\right)\right]$$

(2.7)

where $\pi K t^2$ is phase component of chirp signal. Here, cos term is called real or in-phase signal and we denote this term as I data. Also, sin term is imaginary part signal and called Q data. For simplicity, here we only consider the real term (I data) in -1 to 1 range only.

$$s_{\text{real}}(t) = |s(t)|_{-1 \leq t \leq 1} = \cos\left(\pi K t^2\right) = \cos(\phi(t))$$

(2.8)
The derivative of phase term $\phi(t)$ indicates instantaneous frequency of chirp signal and it is shown in equation 2.9.

\[
f(t) = \frac{1}{2\pi} \frac{d\phi(t)}{dt} = \frac{1}{2\pi} \frac{d}{dt} \left( \pi Kt^2 \right) = Kt \tag{2.9}
\]

Above results mean that instantaneous frequency of chirp signal is linear to time and by controlling the sweep rate or chirp rate $K$, the bandwidth of signal could be modified. Here we divide the frequency term by $2\pi$ because ordinary phase term was in radian scale. As shown in equation (2.6), if chirp signal occupies large band width the resolution of SAR system can be enhance. Thus SAR system prefer to use and generate the chirp signal with wide-bandwidth.

The remainder of this chapter is organized as follows. In Section 2.2 the architecture of satellite on-board SAR and SAR system for small satellite are described. Also, design parameters of SAR system is presented. Section 2.3 contains fundamentals of chirp signal generator including not only comparison between analog and digital chirp signal generators but also pros and cons of each type of chirp signal generators.

### 2.2 SAR System Design

#### 2.2.1 Geometry Model of Satellite On-board SAR

Satellite on-board SAR operates its mission on space orbit as depicted in Figure 2.3 [9]. Ionosphere or the air exists as propagation medium when SAR operates its mission on space.
As SAR system moves through its flight path, it transmits chirp signal perpendicular to its flight path as depicted in Figure 2.4. Here, the flight path is named as azimuth direction or cross-range direction and the direction perpendicular to azimuth is called range direction or cross-track direction [10, 11, 12, 13]. Observation modes of SAR are determined by the beam steering method and representatively there are three modes. Strip-map mode scan through the whole beam footprint while moving and spotlight mode observes designated spot or area using digital beam steering method. In addition this mode requires active radar which can steer the beam pattern. Last, there is scan mode that sweep wide area in range and azimuth direction simultaneously. Strip-map mode is considered in this paper. Also, when designing SAR system, polarization which means the difference between electric and magnetic
wave should be considered. Here, we considered that SAR system uses linear polarization (LP). Near and far range in Figure 2.4 mean the area of beam footprint on the ground. Usually, satellite on-board SAR is considered to operate its mission in low Earth orbit (LEO), about 600 km high.

### 2.2.2 Structure of Satellite on-board SAR System

Satellite system is consisted of payload, attitude control subsystem (ACS), electrical power subsystem (EPS), command and data subsystem (CDS), and communication management subsystem (CMS). SAR system is installed in payload and ACS controls attitude of satellite by using reaction wheels and torque bar. EPS distributes power to other subsystems and CDS controls the data of satellite system. Finally, CMS communicates with ground stations using S and X bands. Here, we focus on the structure of SAR systems. Figure 2.5 presents the block diagram of satellite
Figure 2.5. Block diagram of satellite on-board SAR system.
on-board SAR system.

**Attitude Control Subsystem**

ACS stabilizes the position of satellite system when it is operated on space orbit. When the attitude of satellite system is changed it controls the position using reaction wheels or actuators. Also it stores attitude information then supports satellite to perform its mission.

**Electrical Power Subsystem**

When satellite operates in space, power source can not be supplied sufficiently. EPS generates and stores electrical power during the day time from the sun and divides this power to each satellite module.

**Command and Data Subsystem**

CDS receives commands from ground station and processes it to be used for satellite mission. Main role of CDS is communication between satellite and ground station for mission operation and to do so, it collects the data from each module in satellite system and formatting the data then send it to ground station.

### 2.2.3 Structure of SAR system

Block diagram of SAR system is shown on Figure 2.6 [11, 12]. SAR system can be classified into SAR processor module, RF system module, and antenna. SAR processor module generates chirp signal and timing control unit in FPGA operates controls the systems. From the chirp pulse generator in Figure 2.6, I and Q data are
Figure 2.6. Block diagram of SAR system
generated then these digital signals are converted into analog signals. To eliminate the harmonic components of converted signal, low pass filter (LPF) is attached after analog to digital converter (ADC). Mixer up-converts I and Q data to 1.27 GHz using IF carrier source and phase shifter shifts Q data with 90 degree. Finally, through the high power amplifier (HPA), I and Q data are transmitted from transmission (Tx) antenna. Transmitted chirp signal hits the target and back-scattered signal is received at receiver (Rx) signal. Same as transmitting procedure, Rx signal passes through low noise amplifier (LNA) and IF carrier source down-converts the signal from RF stage to baseband. Baseband signal is converted to digital format using analog to digital converter (ADC) then SAR processor module stores received data.

2.2.4 SAR System Design Parameters

When designing SAR systems, several parameters should be considered such as observation modes and polarizations. First the platform of SAR system should be selected such as airplane, UAV, or satellite. Then image acquiring mode selection will be follow (i.e. strip-map mode, spotlight mode, scan mode, and etc). System requirements and design parameters will be drawn according to geometry of SAR, payload type, and image acquiring modes. Figure 2.7 shows the flow chart of system design parameter drawing procedure [10]. Basic parameters are mission parameters such as height \( h \) of payload, center frequency \( f_c \), look angle \( \gamma \), and platform velocity \( V_{st} \). After input parameters are fixed, antenna parameters are considered next. Antenna parameters define the characteristics of antenna and it contains length and width of antenna \( L, W \), temperature of antenna \( T_{am} \), beam width of range and az-
Figure 2.7. SAR system design parameter draw-out flow chart.
imuth directions ($\theta_r, \theta_{az}$). Using antenna parameters, resolution and pulse repetition frequency (PRF) can be defined. Resolution of range and azimuth directions ($\delta_r, \delta_{az}$), bandwidth of signal ($B_r$), and pulse width ($\tau_P$) are resolution parameters. When designing PRF, it is important that Tx and Rx windows not to overlap so minimum PRF ($PRF_{\text{min}}$), maximum PRF ($PRF_{\text{max}}$), and valid PRF value ($PRF_{\text{valid}}$) should be calculated. Also, using antenna beam width and look angle, maximum swath width ($Swath_{\text{max}}$) can be calculated. Azimuth ambiguity to signal ratio (AASR) and range ambiguity to signal ratio (RASR) should be considered also. Finally, SNR of SAR system will be drawn out using noise-equivalent sigma zero ($\sigma_0$), noise figure ($F$), effective antenna size ($A_{eff}$), average power ($P_{avg}$), and antenna gain ($G$).

To develop the satellite on-board SAR system, the satellite system operating on LEO (600km) using strip-map mode is considered. Table 2.1 is the preliminary design review level SAR system design parameters.
Table 2.1. SAR system design parameters.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Features</th>
</tr>
</thead>
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<tr>
<td>Operation mode</td>
<td>Strip-map mode</td>
</tr>
<tr>
<td>Altitude</td>
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</tr>
<tr>
<td>Center frequency</td>
<td>1.27 GHz (L-band)</td>
</tr>
<tr>
<td>Chirp bandwidth</td>
<td>15 MHz</td>
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<tr>
<td>Pulse width</td>
<td>$30 , \mu s$</td>
</tr>
<tr>
<td>Polarization</td>
<td>Linear polarization</td>
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<tr>
<td>Antenna gain</td>
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<td>Antenna size</td>
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<td></td>
<td>$1.8 , m$ (width)</td>
</tr>
<tr>
<td>Beam width</td>
<td>$1.962^\circ$ (azimuth)</td>
</tr>
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<td></td>
<td>$4.797^\circ$ (range)</td>
</tr>
<tr>
<td>Resolution</td>
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<tr>
<td></td>
<td>$10 , m$ (range)</td>
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<tr>
<td>Ground range resolution</td>
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<td>PRF</td>
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</tr>
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<td>Swath width</td>
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<tr>
<td>Look angle</td>
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<td>Peak transmit power</td>
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<tr>
<td>Average transmit power</td>
<td>96 W</td>
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<tr>
<td>NESZ</td>
<td>2 dB</td>
</tr>
</tbody>
</table>
2.3 Chirp Signal Generator

Chirp signal generator in SAR system works as SAR system controller. Operated with clock source, it controls timing control unit which defines Tx and Rx mode of SAR RF module. As an arbitrary waveform generator, chirp signal generator requires high-stability, -linearity, -frequency response characteristics and low FM noise [14, 15]. In SAR system, to produce the images of target, receiver needs to acquire the back-scattered signal. Pulse compression technique is used in receiver stage because Tx signal should maintain sufficient SNR value and chirp signal is used to have high pulse width and sufficient bandwidth. In this section, types of chirp generator and characteristics of DDS chirp generator will be discussed.

2.3.1 Memory-map Based Chirp Signal Generator

When designing the signal generator for satellite on-board SAR systems, the size, weight, space and etc. are considered to be as small as possible. Usually chirp signal generator is equipped with heavy and large components such as workstation, analog signal generator, and etc. to minimize the size and weight of SAR payload various digital chirp signal generator are introduced. Compared with analog chirp signal generators, digital signal generators are free from workstation that occupies large portion in chirp signal generator. Conventional satellite on-board SAR system has used memory-map based chirp signal generator. Memory-map based chirp signal generator saves the chirp waveform in ROM and loads the pre-stored signal. As this generator loads pre-stored waveform, signal generating procedure is quite simple and
accuracy of signal is relatively higher than DDS chirp signal generator. Figure 2.8 shows the structure of memory-map based chirp signal generator [16, 17].

Generally, memory-map based chirp signal generator is consisted of clock source, phase locked loop (PLL), I and Q memory ROM, and DAC modules. Memory ROM stores I and Q chirp signals respectively. Good points of memory-map based chirp signal generator is that it can generate the wanted signal if the waveform is pre-stored and pulse generating procedure is simple. However, there are some limitation in memory-map based chirp signal generator. When it needs to use the signal different from pre-stored signal, configuration of chirp signal generator is complicated. The characteristics of chirp signal such as pulse width, PRF, pulse repetition interval (PRI), and etc. vary when the detection modes of SAR change. In this case, chirp signal generator is need to provide all types of signal and memory ROM of memory-map based chirp signal generator requires large amount of memory.

2.3.2 DDS Signal Generator

DDS signal generator is introduced overcome the weak points of memory-map based chirp generator. DDS signal generator generates phase components of chirp
and matches each phase address to amplitude value stored in cos and sin look-up table (LUT). Structure of DDS signal generator is shown in Figure 2.9 [18, 16, 19].

![Figure 2.9. Structure of DDS signal generator.](image)

Tuning word in the DDS signal generator works as binary constant input. It defines step size of accumulating input and often referred as frequency control word (FCW). In the mean time, FCW indicates resolution of frequency. Phase register accumulates the input signal using unit delay component and when the phase value reaches the maximum binary value of tuning word, it overflows and reset the tuning word then finally accumulates one cycle of phase signal. This system block is called phase accumulator and if this structure accumulates frequency of output signal it is called frequency accumulator which will be discussed later. LUT which is a kind of PROM already stores the amplitude signal of sine or cosine according to the phase address that is sampled by system clock. Output of phase accumulator passes LUT and each phase address is mapped to amplitude signal in LUT. Finally to be sent to RF system constructed sine or cosine signal is converted to analog signal via DAC.
2.4 Summary

In this chapter, an overview of radar systems including the basic structure of radar and operating procedure, especially related to SAR system is presented. In Section 2.1, a special technique that radar adopt to enhance it performance, pulse compression, is introduced. Furthermore chirp signal that SAR uses for its own illumination source is discussed. Using chirp signal SAR can provide high-resolution images with relatively wide pulse and low power. SAR system design parameters, block diagram of satellite and SAR system, and requirements when design are presented in Section 2.2. Brief introduction of chirp signal generator and types of digital signal generator are explained in Section 2.3.
Chapter 3. Implementation of DDS Chirp Signal Generator

There are several satellite on-board SAR that are already launched and operated. Recently, Korea has launched Korea multi-purpose satellite-5 (KOMPSAT-5) in 2013, Germany has and operates Terra SAR-X, Italy and Japan has satellites name as COSMO-SkyMed and ALOS PALSAR-2 (Daichi-2) respectively. All of them provides high-resolution images using wide-bandwidth chirp signal generator and characteristic of these satellites is that they are large satellites (> 1000 kg). Also, they use memory-map based chirp signal generator in SAR system (still there is no satellite on-board SAR equipped with DDS chirp signal generator). Strong point of DDS signal generator is that it requires less memory than memory-map based signal generator [20]. When radar system is operated in space orbit, memory unit is easily damaged so memory-map based chirp signal generator is considered to be replaced with next generation chirp signal generator. Also as the radar system requires high-resolution output, chirp signal generator should be able to generate wide-bandwidth chirp signal. When achieving wide-bandwidth chirp signal using memory-map based chirp signal generator, it requires large memory than DDS chirp generator.

Even though that DDS signal generator has been introduced to compensate the weak points of memory-map based chirp signal generator (e.g. memory dependability, limitation of clock frequency, and etc.), DDS signal generator also has some weak
points. Representatively, the weak points of DDS signal generator are low spectrum purity due to truncation error, phase shifting property and etc. Main reason that DDS chirp signal generator could not been used in space mission is its spectrum property. However if the phase error or low spectrum purity can be improved, DDS chirp signal generator can replace the conventional memory-map based chirp signal generator with low-cost, -power consumption, and -complexity.

In this chapter, characteristics and phase error of DDS chirp signal generator and phase error compensating method will be discussed.

### 3.1 Conventional DDS chirp signal generator

DDS has first introduced in 1971 with the name as direct digital frequency synthesizer (DDFS) by Tierney [17]. It has similar structure with DDS chirp signal generator shown in Figure 2.9. Compared with DDS chirp signal generator which will discussed in this chapter, it is designed only to generate sinusoid waveform. It has only one set of counter and register that constructs accumulator. The advent of DDFS has led the flood of digital arbitrary waveform generators. Here we will discuss the Pedersen’s DDS signal generator and parallelized DDS (PDDS) chirp signal generator [18].

#### 3.1.1 Pedersen’s DDS Chirp Signal Generator

Pedersen’s chirp generator had been proposed in 1990 and it is still widely used [21]. DDS accumulates the input value with feedback loop using counter and register. If the constant value is the input, the output will be ramp signal. In the
Pedersen’s chirp signal generator is consisted of source clock, counter, accumulator, LUT and DAC [16]. The role of each block is same as DDS signal generator in Figure 2.9. The signal generating procedure as follows. First the phase of a linearly swept signal is generated in real time using counter and accumulator. Next, as the sinusoidal signal has the cycle of $2\pi$, from the total phase, mod($2\pi$) is extracted. Last,
By means of LUT Pedersen’s DDS generates desired sine or cosine swept signals.

As discussed in Chapter 2, chirp signal phase has 2nd order polynomial and by mapping the phase address to amplitude DDS can construct whole signal. Mathematical description of chirp generator will follow [7, 16]. Here we assume $f(t)$ as the instantaneous frequency of chirp signal. $f_0$ indicates the starting frequency of $f(t)$ and $K(\text{Hz/s})$ is sweep rate.

$$f(t) = 2\pi K t + f_1 \quad (3.1)$$

By integrating equation (3.1), instantaneous phase can be obtained where $\phi_0$ corresponds to starting phase.

$$\phi(t) = \pi K t^2 + f_0 t + \phi_0 \quad (3.2)$$

According to equation (3.1) and (3.2), there are two integration terms; from constant sweep rate to instantaneous frequency and from instantaneous frequency to instantaneous phase. Block diagram of Pedersen’s chirp generator is illustrated in Figure 3.2.

Here, we call the first and second integrators from the constant source as frequency and phase accumulators respectively. Because frequency and phase of chirp signal are represented as 1st and 2nd order polynomials each. As the chirp signal has linearly increasing or decreasing frequency, the phase of chirp should be 2nd order polynomial then with the constant source and two integrators we can generate the 2nd order phase. From the Figure 3.2 we assume that $\alpha$ is the constant source input, and with the help of time integration and frequency offset $\beta$, 1st order frequency term ($\alpha t + \beta$) can be drawn. 1st order frequency term is applied to second integrator with
Figure 3.2. Structure of DDS signal generator.

phase offset $\gamma$. The result is equal to $(\alpha/2) t^2 + \beta t + \gamma$. Next, with the integer $p$, 2nd order phase term is divided by sweep rate which is $2^p$. The polynomial drawn out after the sweep rate control stage is

$$\phi(t) = \left[ (\alpha/2) t^2 + \beta t + \gamma \right] / 2^p \quad (3.3)$$

After constructing the phase signal, to unwrap the $2\pi$ period signal, we take the $2\pi$ modulus of $\phi(t)$. Signal generation process will end after read the phase value from sine or cosine LUT. Each LUT has the function as

$$LUT_{\text{sin}} = \sin\left(2\pi \frac{\text{phase} \, \text{P}}{2^p} \right) \quad (3.4)$$

$$LUT_{\text{cos}} = \cos\left(2\pi \frac{\text{phase} \, \text{P}}{2^p} \right) \quad (3.5)$$

where $P$ is the bit of generator and $\text{PhaseP}$ is the address of generated phase from phase accumulator. By matching the phase address to sine or cosine value,
DDS can work as arbitrary waveform generator.

### 3.1.2 Parallelized DDS Chirp Signal Generator

The importance of resolution is already discussed in previous chapter and when designing SAR systems the bandwidth is dominant factor that affects resolution of radar. By this reason, SAR systems are desired to have wide bandwidth and to satisfy this requirements, PDDS method is introduced. Figure 3.3 depicts the example of DDS chirp signal generator structure. PDDS is consisted of DDS blocks multiplexer (MUX), counter and DAC. If we assume that source clock is $f_c$, each DDS block is driven by $f_c/4$ when using 4-DDS blocks. Through DDS A block to D, each DDS block generates same chirp signal and MUX collects the specific parts of signal from each DDS sequentially. Usually, the operation frequency of DDS limited, so
the maximum bandwidth that DDS chirp signal generator can make is also limited. However, by adding the DDS blocks in parallel, with the relatively low clock frequency, PDDS chirp signal generator can synthesize the desired bandwidth. As SAR system requires wide bandwidth (300 MHz) PDDS is recognized as next generation chirp signal generator. In this paper, PDDS chirp signal generator is implemented and simulated with Simulink. The actual PDDS block diagram in Simulink software is presented in figure 3.4 [18].
Figure 3.4. Block diagram of PDDS chirp signal generator in Simulink.
3.2 Problem Definition

Signal generation using DDS is quite simple, however due to the truncation of each accumulator frequency and phase truncation errors such as periodic error or noise occur. Due to truncation error and granular noise, the phase of DDS and PDDS chirp signal has error compared to ideal signal. Here, we only consider PDDS waveform and bi-directional chirp waveform of ideal and PDDS chirp signal in time domain is shown in figure 3.5.

![Comparison of Chirp waveform, BW=288MHz, PW=3.6µs](image)

Figure 3.5. Comparison between ideal and PDDS chirp waveform in time domain.

X axis is time and Y axis is amplitude of signal. Red line with diamond and black dashed line indicate ideal and PDDS signal in time domain respectively. Bandwidth and pulse width are 288MHz and 3.6µs respectively. Both signals are I data
of chirp so as I data has the cosine term it should be symmetrical from the signal center. Ideal chirp waveform shows cosine form from the center of signal however compared to ideal chirp waveform, the phase of PDDS waveform is shifted from the center. Due to the phase error occured by truncation error, the spectrum of PDDS signal suffers from specturm regrowth. Power of specturm in dB scale according to frequency between ideal and PDDS is shown in Figure 3.6.

![Comparison of Spectrum, BW=288MHz, PW=3.6 µs](image)

**Figure 3.6.** Comparison between phase of ideal and PDDS chirp waveform.

Here, red line and black dashed line are spectrum of ideal and PDDS signal respectively. Center frequency, bandwidth, and pulse width are 1.27GHz, 288MHz, and 3.6µs each. Spectrum of ideal chirp degrades as the frequency increases or decreases from the center and PDDS also. However, compared with that spectrum of
ideal chirp signal decreases until \(-140\, \text{dB}\), PDDS decreases only \(-60\, \text{dB}\). It is because spectrum regrowth and it affects the SNR of whole signal. Spectrum regrowth components generate spurious that increases average noise power. Even though DDS or PDDS can generate the chirp pulse with smaller memory, spurious characteristics

3.3 Phase Error Compensation

3.3.1 Extracting the Phase Error

By extracting the phase of each signal, the difference between two signals can be seen easily. To compare the phase components of each ideal and PDDS signal, we extracted its phase from time domain signal. Figure 3.7a shows the phase components of chirp signal. Red and black dashed line indicate the phase of ideal and PDDS respectively. To compare the phase precisely, magnified signal of Figure 3.7a is depicted in Figure 3.7b.

All the signal is simulated in baseband so the frequency and phase offset should be 0 because frequency and phase offset determine the starting value of center frequency and phase. The red line in Figure 3.7a, phase of ideal signal, crosses 0 point, however the phase of PDDS signal has the center around \(-4000\) below the ideal signal. The difference between two signals occurs the spurious and if it is compensated PDDS can have the similar spectrum characteristics to ideal signal. Phase component of ideal and PDDS signals as follow.
Figure 3.7. Comparison between phase of ideal and PDDS chirp signal.
\[
\phi_{\text{ideal}} = (5.903 \times 10^5) t^2 + (-6.342 \times 10^{-11}) t + (-1.033 \times 10^{-9}) \\
\approx (5.903 \times 10^5) t^2
\]  \hspace{1cm} (3.6)

\[
\phi_{\text{PDDS}} = (5.903 \times 10^5) t^2 + (-2.185) t + (-0.00747) \\
\]  \hspace{1cm} (3.7)

To extract the difference between ideal and PDDS signal, we define the phase error \( \phi_{\text{error}} \) as

\[
\phi_{\text{error}} = \phi_{\text{ideal}} - \phi_{\text{PDDS}}
\]  \hspace{1cm} (3.8)

Using equation (3.8), phase error term can be modeled 1st order polynomial.

\[
\phi_{\text{error}} = 2.185 t + 0.00747 \approx 2.185 t
\]  \hspace{1cm} (3.9)

Figure 3.8. Signal generation procedure using DDS chirp signal generator.

Similar to the DDS model introduced by Tierny et al. As shown in Figure 3.8, DDS chirp signal generator consists of three main blocks namely as frequency accumulator (FA), phase accumulator (PA), and LUT.

Each accumulator has overflowing adder and feedback register. Comparing this block with Figure 3.2. \( \alpha, \beta \), and \( \gamma \) represent constant source, frequency offset and...
phase offset respectively. Using equation (3.3), phase output before LUT can be derived as

$$\phi_{out} = \frac{\alpha}{2} t^2 + \beta t + \gamma$$  \hspace{1cm} (3.10)

Here, \( \alpha \) is constant source which defines the chirp rate of signal, \( \beta \) and \( \gamma \) decide the starting point of frequency and phase. In case of baseband signal, as the center frequency of baseband signal is 0, the frequency offset value is also set to 0. This is why the coefficient of 1st order term in equation (3.6) is 0. Phase offset is also set to 0 in same reason. Phase error has non-zero coefficient in linear and quadratic terms.

### 3.3.2 Phase Error Compensation using Polynomial Models

In section 3.3.1, phase error is modeled to 1st order polynomial and error compensation method will be discussed in this section. First, we define the error compensated phase \( \phi_{compensated} \) as

$$\phi_{compensated} = \phi_{PDDS} + \phi_{error} = \phi_{PDDS} + (\phi_{ideal} - \phi_{PDDS}) = \phi_{ideal}$$  \hspace{1cm} (3.11)

Compared to ideal signal phase the phase of PDDS signal is placed little bit below as presented in Figure (3.7b). Next, we extract the phase error and fit the curve with 1st order polynomial to verify it. Figure (3.9) shows curve fitted error and phase error between ideal and PDDS signals. In the respect of goodness of fit, R-square and root mean square error (RMSE) are 1 and 0.8711 respectively.

If there is no phase error between ideal and PDDS phase signal, the polynomial line will cross 0. However because of the truncation error occurred from \( t = 0 \), the
Figure 3.9. Curve fitted phase error with 1st order polynomial.

Phase error increases from around 0 to 8,000 according to time. Equation (??) has only the 1st order term which means frequency offset and this result shows that phase error in PDDS chirp signal generator occurs because of frequency offset. Deriving equation (3.11) again the compensated phase signal will be

$$\phi_{\text{compensated}} = \left( (5.903 \times 10^5) t^2 - 2.185t \right) + 2.185t = (5.903 \times 10^5) t^2 = \phi_{\text{ideal}}$$  

(3.12)

The simplified structure of conventional PDDS block is shown in Figure 3.10.

Figure 3.10. Block diagram of PDDS chirp signal generator.
PDDS in this paper consists of frequency accumulator, mod(In1/In2) operator, 4-DDS blocks, 4-LUTs, phase accumulator, MUX, and DAC. The system structure from the frequency accumulator to phase accumulator is same as ordinary DDS chirp signal generator. The difference is that PDDS chirp signal generator has 4-LUTs with the input from [0] to [3]. The input from [0] to [3] are combined with the output of phase accumulator and inserted to each LUT. Each number on LUT input indicates the delayed clock. First, LUT with [0] input generates the signal of 0-clock delayed, and LUT with [1] input generates the 1-clock delayed signal. In the same way, other two more LUTs generate the signal with 2- and 3-clock delayed signals. MUX collects 4-signals from LUTs and samples at the same time. In this case, 4-signals are sampled at a time, then output signal will be converted to analog value due to DAC on right end. Next consideration will be the idea how to compensate phase error. Phase error is modeled by the polynomial forms; 2nd order phase error ($\phi_{error}$). It is shown that remainder term in phase error indicates the error on frequency offset. Therefore, in this paper, the coefficient of phase error will be added after frequency
accumulator block. Figure 3.11 shows the PDDS chirp signal generator with phase error compensation block. We define the 1st order coefficient value of phase error ($\phi_{error}$) as error offset and this value will be 2.185.

3.4 Summary

The main contribution of this PDDS block is that it can generate various wide-bandwidth chirp signal with relatively low clock frequency and minimized phase error. We proposed the phase error model in PDDS chirp signal generator to reduce the spectral regrowth due to phase and frequency truncation spurs. Mathematical model shows that phase error can be eliminated by adding the error offset to frequency offset output and numerical results will show that proposed phase error compensation method enhances the performance of conventional PDDS chirp signal generator. Future work will expand the proposed PDDS chirp signal generator to replace conventional memory-map based chirp signal that is used in satellite on-board SAR systems.
Chapter 4. Performance Analysis

In this chapter, performance analysis of proposed PDDS with phase error compensation block will be discussed. In previous chapter, it has been discussed that PDDS signal has phase error compared to ideal signal and consequently phase error causes spectral regrowth. The spectrum characteristics that lower spectrum purity or increase the power of unwanted signal are called spurious or spurs. Usually spurs are occurred from frequency and phase accumulators. When accumulator generates the signal, due to the digital operation and insufficient memory the output of accumulator truncated. Truncation of digital bits can be seen as noise or error. Practical synthesizer can be modeled as ideal synthesizer with noise source. Proposed PDDS adds the truncated phase error between frequency accumulator and phase accumulator. This Chapter will show the performance of proposed PDDS chirp signal generator in the respect of signal spurs and impulse response function.

4.1 Signal Characteristics in Time Domain

To evaluate the performance of the proposed PDDS chirp signal generator using phase error compensation block, we built the PDDS simulation block using MATLAB and Simulink. Table (4.1) represents the simulation parameters. In simulation, conventional PDDS chirp signal generator is modeled with 4 DDS blocks and proposed PDDS chirp signal generator, taking into consideration the frequency offset
compensation block. PDDS and proposed PDDS generate the chirp signal simultaneously with same simulation parameters. In simulation, only I data of chirp signal is considered.

In simulations, we adapt Chebyshev filter as LPF to eliminate the unwanted harmonics. We design a 5-th order lowpass Chebyshev Type 1 filter with 0.1dB ripple in passband and a normalized passband edge frequency value of 0.9 to meet the requirements when designing chirp signal generator. Each I and Q data is divided then filtered with the filter we designed. First, we compare the chirp signal of ideal, PDDS and proposed signal in time domain to verify that proposed phase error compensation method can mitigate the phase shifting occurred from truncation error. In simulation,
PDDS signal using proposed method has shown almost same plot compared with ideal signal. Figure 4.1 represents the I data of ideal, PDDS, and proposed PDDS chirp signal in time domain. In the signal center, conventional PDDS still has the shifted phase components but proposed PDDS signal has the signal plot identical to ideal chirp waveform.

As shown in Figure 4.2, conventional PDDS chirp signal generator has the phase error of -4,000 in the center of signal. However, it is shown that phase signal of proposed PDDS traces ideal signal phase. This result shows that phase error can be compensated by adjusting the frequency offset.
4.2 Signal Characteristics in Frequency Domain

We evaluate the chirp signals in frequency domain to compare the spectral re-growth and purity. In this simulation, frequency domain signals are considered and to present the signals in dB scale, signals are modified with formula as follow. It is assumed that all the signal is up-converted from baseband to RF stage (1.27GHz) by RF carrier source. First, we take the fast Fourier transform (FFT) to convert the signal from time domain to frequency domain. The dB scale signal is defined as [6]

\[ s_{\text{ideal, dB}}(f) = 20 \log_{10} \frac{|s_{\text{ideal}}(f)|}{|s_{\text{ideal}}(f)|_{\text{max}}} \]  

(4.1)

Here, \( s_{\text{ideal, dB}}(f) \) indicates dB scale signal of ideal chirp signal generator. In previous chapter, dB scale signals of ideal and PDDS chirp signal generators are revealed. In the region of cut-off frequency, conventional PDDS chirp signal has similar characteristics, however over the cut-off frequency range, dB scale PDDS
signal shows higher value than ideal signal. This phenomenon is called spectral regrowth and it causes SNR to be lowered since the spectrum components that placed over the cut-off frequency are considered as noise. Figure 4.3 represents the dB scale signals in frequency domain.

Trace line of proposed PDDS signal in dB scale follows ideal signal case. Even though there are some ripples around 0.2, 0.6, 1.8, and 2.4GHz, we can assure that proposed PDDS can enhance the SNR property compared to conventional PDDS chirp signal generator. Also, it means spectral regrowth has been reduced by adjusting the frequency offset.
4.3 Signal Characteristics in RF Stage

4.3.1 Simulation Parameters

In previous section, signal characteristics of baseband and IF stage in time and frequency domain have been presented. As shown in Figure 2.6, to transmitted from Tx antenna signal should be processed in RF system module. SAR system module can be classified as SAR processor module which generates baseband chirp signal and DAC/ADCs, LPF stage, and RF system module consisted of mixer, transmitter, IF carrier source, and receiver. The simplified structure of SAR system is presented in Figure 4.4.

Chirp pulse output is divided into I and Q data and LPF is attached. Actual chirp pulse output is in form of sine function then Q data is modulated using 90° phase shifter which is driven by IF carrier source (1.27GHz). Both I and Q data are
Table 4.2. Simulation parameters for RF system evaluation.

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<td>Hz</td>
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<td>Integrated phase noise</td>
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<td>dBc</td>
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<tr>
<td>Phase noise floor</td>
<td>-120</td>
<td>dBc/Hz</td>
</tr>
<tr>
<td>Sampling frequency</td>
<td>2,400</td>
<td>MHz</td>
</tr>
<tr>
<td>Amplitude imbalance</td>
<td>0.1</td>
<td>-</td>
</tr>
<tr>
<td>Phase imbalance</td>
<td>$5.8 \times \pi/180$</td>
<td>-</td>
</tr>
</tbody>
</table>

combined by combiner and HPA up-converts the power of combined signal. When designing chirp signal as well as most of signal systems, basically ideal system that input and output characteristics are linear is assumed. However there are some components which makes the output non-linear though linear signal is input and consequently these components occur the error when Tx signal passes through RF stages. The error occurred in RF stages can be classified into three parts and (a) - (c) in Figure 4.4 indicate the three major error occurred in SAR RF module. In case of (a), when I and Q data from chirp signal generator pass through LPF, gain error occurs. Also, as the Q data is modulated from 90° phase shifter phase error occurs in (b). I and Q data suffers I/Q imbalance due to the phase error. (c) indicates the error from HPA and it is called HPA error. To verify the spectrum characteristics of proposed PDDS chirp signal generator, we modeled RF systems in simulation. Simulation parameters are listed in Table 4.2.
4.3.2 Simulation Results

In simulation, to enhance the analysis resolution, zero padding technique is used on ideal, PDDS, and proposed PDDS signal. Here, average transmission power and normalized power of transmission signal are defined as [6]

\[ P_{tx,\text{avg}} = \frac{\text{normized} (P_{tx})}{\text{length} (P_{tx})} \]  

(4.2)

\[ P_{tx,\text{norm}} = \left[ \frac{|P_{tx}|^2}{P_{tx,\text{avg}} \times \left(10^{2/10}\right)} \right] \]  

(4.3)

First, we investigate the time domain chirp signal characteristic occurred by RF impairments. RF impairments include the whole system abnormality in RF system and Figure 4.5a and 4.5b shows the comparison of chirp waveform due to RF impairments.

Ideal, conventional PDDS and proposed PDDS signals are compared. Amplitude of ideal signal is 1 and PDDS and proposed PDDS signals have the amplitude larger than 1. Also, amplitude of ideal signal is uniform from the start to the end however the amplitude of PDDS and proposed PDDS signals have inhomogeneities in some parts. Figure 4.5b shows magnified scope of time domain signals with RF impairments. Ideal signal is symmetrical from the signal center where \( t = 1800 \). As shown in last Chapter, PDDS still has the phase error so that this signal seems little bit shifted around 180s. In the mean times, proposed PDDS signal has negligibly small phase error compared to PDDS and ideal signals even though it has some amplitude error.
Comparison of ChirpWaveform in RF impairments, BW=288MHz, PW=1.5\,\mu s

(a) Phase of ideal and PDDS signal in time domain.

Comparison of ChirpWaveform in RF impairments, BW=288MHz, PW=3.6\,\mu s

(b) Magnified scope of figure 4.5a

Figure 4.5. Time domain signals with RF impairments.
Second, comparison of spectrum due to RF impairments is shown in Figure 4.6. Compared to Figure 4.3, PDDS and proposed PDDS have more noise component all around the frequency band. Especially, the ripple of proposed PDDS signal has been increased significantly.

The ripple noise in notch band is assumed that it is occurred from HPA error. Usually Saleh model is adopted to compensate the HPA error, however we do not consider the Saleh model in this paper. When compared to the dB scale result in previous Chapter, spurs degraded only -11 dB. Nevertheless proposed PDDS chirp signal generator shows that it can enhance the SNR and reduce spectral regrowth components.

Figure 4.6. Simplified SAR system block.
Figure 4.7. Comparison of IRF
Third, IRF has been investigated. From the IRF, we can derive resolution of signal, PSLR, and ISLR. The resolution of signal is 3 dB signal width and it is identical to actual range resolution. PSLR is the ratio between peak value of main-lobe and 1st side-lobe. If the side-lobe level is low, it is considered that this signal has low noise. Therefore maximizing the PSLR to optimal value is important factor when designing signal generators. ISLR means the ratio between peak value of main-lobe and peak value summation result of 1st to 10th null side-lobe. Figure 4.7a shows the comparison of IRF in dB unit. PSLR of conventional PDDS and proposed PDDS are $-13.5519$ dB and $-13.6205$ dB respectively. Compared to conventional structure, PSLR of proposed PDDSD chirp signal generator has been enhanced $-0.0686$ dB. Also, in case of ISLR, proposed PDDS chirp signal generator has $0.0078$ dB larger value. PSLR and ISLR can be derived from the equations below.

$$I_{PSLR} = I_{main} [dB] - I_{side} [dB] \quad (4.4)$$

$$I_{ISLR} = \frac{\int_{-1/10N}^{1/10N} |h(t)|^2 dt}{\int_{-1/10N}^{1/10N} |h(t)|^2 dt + \int_{1/10N}^{10N} |h(t)|^2 dt} \quad (4.5)$$

where $I$ is peak value of each lobe, $N$ and $h(t)$ are a number of null and impulse function respectively. For further explanation, Figure 4.7b shows magnified IRF characteristics in dB unit. Here, PSLR of PDDS and proposed PDDS have better performance than IRF of ideal chirp waveform, this is due to the sampling property in simulation. Therefore we will only consider the enhancement of proposed PDDS.
Comparison of IRF, BW=288MHz, PW=3.6 µs

Ideal, peak=3601, center=1801
PDDS, peak=3366.5458, center=1799
Proposed PDDS, peak=3606.6816, center=1801

(a) Simplified SAR system block.

(b) Simplified SAR system block.

Figure 4.8. Comparison of IRF
Table 4.3. IRF result of ideal, PDDS, and proposed PDDS chirp signal generator.

<table>
<thead>
<tr>
<th></th>
<th>Ideal</th>
<th>PDDS</th>
<th>Proposed PDDS</th>
<th>Enhancement</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSLR(dB)</td>
<td>-13.2611</td>
<td>-13.5519</td>
<td>-13.6205</td>
<td>-0.0686</td>
</tr>
<tr>
<td>ISLR(dB)</td>
<td>-10.0173</td>
<td>-10.3231</td>
<td>-10.3153</td>
<td>0.0078</td>
</tr>
<tr>
<td>Peak value</td>
<td>3601</td>
<td>3366.55</td>
<td>3606.68</td>
<td>240.13</td>
</tr>
<tr>
<td>Center</td>
<td>1801</td>
<td>1799</td>
<td>1801</td>
<td>2</td>
</tr>
</tbody>
</table>

compared to conventional chirp signal generator. Proposed PDDS traces ideal chirp signal perfectly in main-lobe and the signal centers of both signals are identical to 1801. However IRF of conventional PDDS is shifted little bit from ideal signal.

IRF plot in frequency domain is shown in Figure 4.8a to verify the peak value and phase error. In case of the peak values of ideal, conventional PDDS, and proposed PDDS are 3601, 3366.5458, and 3606.6816 each. Peak value indicates signal power of chirp waveform. In addition the center point of signals is shown. Ideal and proposed PDDS has same value of 1801, however conventional PDDS has the value of 1799. From the result of center point, it can be concluded that peak value of PDDS is lowered and center point is shifted due to truncation error. To verify the differences in frequency domain precisely, Figure 4.8b shows magnified plots of IRF. Comparison results of IRF in dB scale and frequency domain are listed in Table 4.3.

From the results above we could investigate that proposed PDDS chirp signal generator has better performance than conventional PDDS. Also, the performance of proposed PDDS has almost similar spectrum characteristics to ideal chirp waveform. We conclude that proposed PDDS chirp signal generator compensates phase error and consequently enhance the spectrum characteristics.
4.4 Summary

In this Chapter, performance analysis has been done to verify the spectrum characteristics of proposed PDDS chirp signal generator. In Section 4.1, chirp waveforms of ideal, conventional PDDS, and proposed PDDS have been investigated. Regarding that PDDS has phase shifting error compared to ideal signal, proposed PDDS compensated the phase error and it traces ideal chirp waveform perfectly by adjusting frequency offset. Signal characteristics in frequency domain has been simulated in Section 4.2. To compare the spectrum signal, we define the dB scale signals in frequency domain. Signal plots in dB scale have shown that proposed PDDS overlap the ideal chirp waveform but have little bit of ripples on 0.2, 0.6, 1.8, and 2.4 GHz. In Section 4.3, RF stage module has been presented. Following the RF model gain error from LPF, phase error from phase shifter, and HPA error from HPA have been added on simulation. For further explanation Section 4.3.2 contains simulation results in RF stage. Time domain signals with RF impairments have been presented and spectrum plot with RF impairments has been shown also. Compared to the simulation result in baseband, proposed PDDS signal suffers from noises. Nevertheless proposed PDDS shows that it has better performance than conventional PDDS chirp signal generator. Also, to verify the performance precisely, IRF characteristics are compared. Consequently proposed PDDS has better performance in the respect of PSLR, ISLR, and signal peak power. Also, it is shown that proposed PDDS compensates the center point of signal which means phase error.
Chapter 5. Conclusion

The synthetic aperture radar is a surveillance that is usually loaded on satellites to observe the earth. As it moves through its flight path, it transmits and receives microwave signal, then acquires the image of target. The characteristic of SAR is that it provides high-resolution images using LFM signal called chirp. The bandwidth of chirp increases or decreases linearly with time and it is appropriate to generate the signal with large bandwidth. There are several types of arbitrary waveform generator, in this paper DDS and PDDS chirp signal generators have been investigated which

In Chapter 2, In Chapter 3, a method that compensates phase error of PDDS chirp signal generator. There are mainly two types of DDS chirp signal generator; conventional DDS and PDDS chirp signal generators. Basically, DDS and PDDS consist of clock source, frequency accumulator which generates ramp signal, phase accumulator that accumulates ramp signal then generates 2nd order curve, LUT and DAC. Clock source is a chirp rate input that determines the bandwidth of signal. Due to the resolution of SAR systems is inverse proportional to bandwidth, designing the chirp signal generator that can drive wide-bandwidth as much as possible. Also it is shown that stability of chirp rate, in other words signal linearity, is an important consideration when designing chirp signal generator. Frequency and phase accumulators are designed with preset input, feedback loop, and register. Each accumulator delays input signal by 1-clock in series then finally the accumulated signal
has linear or quadratic form. LUT stores digitally sampled amplitude signal of the $2\pi$ period in ROM and according the address of phase signal it grants the amplitude. With the series of signal generation procedure, DDS constructs chirp signal. Similarly PDDS generates chirp signal with couple of DDS blocks. All the system components in PDDS chirp signal generator is driven simultaneously with same clock source. Each DDS block is granted the operation number [0 - 3] if we assume that PDDS has 4-DDS blocks. [0] numbered DDS starts to generate the signal from the time 0, [1] numbered DDS starts to generate the 1-clock delayed signal and other DDS(numbered with [2, 3]) work as the same. Finally MUX collects the signal output from each DDS block in sequence. PDDS chirp signal generator enables to generate the wide-bandwidth signal with relatively low clock frequency.

In DDS or PDDS architecture, chirp signal generator is operated with digital calculation and it causes granular noise and truncation errors. Usually the granular noise affects the ripple of signal and truncation error generates phase shifting in time domain chirp signals. When signal is generated from the start, small amount of truncation error occurs, however due to the propagation of error it enlarges more. Consequently it is shown that phase error is occurred within the range [0 - 8000] when the center frequency, bandwidth and pulse width are $1.27\text{GHz}$, $288\text{MHz}$, and $3.6\mu\text{s}$ respectively. When phase error exists due to the spectrum regrowth phenomenon the dB scale signal power in outer band of chirp signal lowers SNR. To eliminate the phase error, we extract the phase component from both ideal and PDDS signals and define the phase error. Phase error has the form of 1st order polynomial and as the coefficient of 1st order polynomial indicates frequency offset of frequency
accumulator in PDDS, we added this value between frequency accumulator output and \( \text{mod}(2\pi) \) operator. Successfully the phase signal has been compensated. There are several literature about DDS and PDDS however most of them only consider the implementation of DDS or PDDS chirp signal generator not the error in DDS or PDDS system. Phase compensation using polynomial model has never been proposed and performance of proposed PDDS chirp signal will follow. In the respect of time domain signal However proposed PDDS structure compensates phase error using polynomial model and dB scale signal power of it shows that the output from proposed PDDS is almost identical to ideal waveform except ripple noises outside of passband. The spectrum has been lowered \( -28dB \) in maximum.

The contributions of this thesis is as follows:

- A general model for satellite on-board SAR system has been presented.

- The structure of arbitrary waveform generator such as DDS and PDDS has been presented and signal generation procedure has been described also.

- The phase shifting phenomenon in PDDS chirp signal generator has been revealed.

- A model for phase error compensation method has been proposed and performance analysis of PDDS chirp signal generator in baseband and IF stage has been presented in the respect of time and frequency domain.

- A RF stage simulation model has been presented to evaluate the effect of RF impairments.
• An IRF characteristic of proposed PDDS signal has been increased compared to conventional PDDS chirp signal generator; PSLR = -0.0686 dB enhanced, ISLR = 0.0078 dB enhanced.

Since the proposed method considers practical DDS and PDDS chirp signal generator, and the results show considerable performance enhancements, it is expected that proposed PDDS chirp signal generator using error compensation method can be applied to conventional DDS and replace the memory-map based chirp signal generator frequently used in satellite on-board SAR systems.
References


Summary

Implementation of DDS Chirp Signal Generator Using Phase Compensation

우주개발의 역사는 구 소련이 1957년 인류 최초의 인공위성인 스푸트니크 1호를 발사하면서 시작되었다. 이후 미국, 일본, 러시아, 그리고 독일 등으로 포함한 40여개국 이상의 나라들은 우주 산업에 박차를 가하고 실제로 현재 5,000기 이상의 인공위성이 우주궤도에서 운용되고 있다. 이들 중 90% 이상이 미국과 러시아의 위성이다.

능동형 센서의 한 종류로써, 영상레이다(SAR: synthetic aperture radar)는 위성체에 실려 운용되며 전자기파를 방사원으로 사용한다. 영상레이다의 주요 특징은 전천후로 고해상도의 영상을 제공한다는 것이다. 전자기파의 특성에 의해 영상레이다는 감시위성으로 각광받고 있으며 여러 국가들은 이미 영상레이다를 탑재한 인공위성을 보유 및 운용 중이다. 일반적으로 영상레이다 탑재체는 움직이는 플랫폼에 실려 운용되며, 약 2.5에서 10m 길이의 작은 안테나를 사용하여 이동 중 전자기파를 송신하고 반사된 신호를 수신한다. 영상레이다가 이동을 하며 목표물의 영상을 획득하는 이유는 이동 중 작은 안테나 길이를 합성하여 가상의 합성개구면을 생성하고 이를 통해 영상의 해상도를 높히기 위해서이다. 레이다 시스템의 성능을 평가하는 중요한 지표 중 하나는 안테나의 크기이다. 이는 안테나 크기가 클수록 목표물에 대한 정보를 더 많이 획득할 수 있고 이를 통해 해상도를 높힐 수 있기 때문이다. 그러나 큰 안테나를 인공위성에 설치하는 것은 물리적으
로 어려우며 개발 비용 또한 막대한 자본을 필요로 하기 때문에 영상레이다는 합성 개구를 이용하여 원하고자 하는 해상도를 취득하는 방법을 채택하였다.

영상레이다는 1951년 미국의 Carl Wiley가 Doppler beam sharpening (DBS) 방법을 고안하면서 개발되었다. 이후 약 60년 간 초기의 군사용도의 목적 뿐만 아니라 지구환경감시, 재해 관측, 자원 탐사 등 여러 분야에 널리 이용되고 있다. 특히 한국에서는 영상레이다에 대한 수요가 점차 증가되고 있는데, 이는 비, 구름, 안개 등의 기상현상에 의해 원하는 지역의 영상을 얻기가 매우 어렵기 때문이다.

1978년 발사된 미국의 SEASAT은 약 23톤의 무게를 가지며, ENVISAT(2002년에 발사), ALOS PALSAR(2005년에 발사), 그리고 SAR-Lupe(2008년에 발사)는 각각 약 8.2톤, 3.85톤, 0.77톤의 무게를 가진다. 영상레이다를 탑재한 위성체의 무게가 톨게 이유는 인공위성들이 다수의 탑재체들이 실리기 때문이다. 최근의 인공위성 개발 동향은 단일 탑재체를 실어 위성의 무게와 개발 비용을 최소화하고 위성들이 성좌로 움직이며 운용되는 방법으로 바뀌어가고 있다. 그러나 위성체를 소형 경량화하며 생기는 문제점이 있다. 대표적으로 위성체의 무게와 크기를 줄이되 탑재체의 성능을 이전과 비슷한 수준 또는 더 높은 수준으로 발전 시켜야 한다는 것이다. 우주 기술의 발전에 힘입어 위성 시스템의 소형화가 가속화 되었지만 현재의 기술이 우주에서 검증되지 않은 부분이 많으므로 소형화 자체가 어려운 실정이다. 영상레이다 시스템의 경우 안테나가 가장 큰 소형화의 한계점이다. 위성시스템에서 사용하는 안테나는 크게 두 분류로 나눌 수 있는데 개별지만 부가적인 기능이 떨어지는 수동형 안테나와 무게에 중점을 두기보다 부가 기능에 중점을 둔 능동형 안테나가 그 대표적인 예이다. 수동형 안테나의 경우 고전력 공급 능력과 경량형 안테나라는 장점이 있지만 빌 조향 등에 취약하다. 능동형 안테나는 수동형 안테나와 장단점을 달리하며 이 때문에 안테나 설계 시 요구하는
시스템 성능에 따라 고려할 사항이 많다.

또 다른 고려사항은 영상레이다 시스템의 해상도이다. 최근 영상레이다는 약 0.5 - 10m의 해상도를 지원하며 이를 위해 첩(chirp)이라는 신호를 사용한다. 첩 신호는 선형 주파수 변조 방식 중 하나로 신호의 주파수가 선형적으로 증가 또는 감소하는 특징을 가진다. 영상레이다가 첩신호를 사용하는 이유는 수신탄에서 펄스 압축 기법을 이용하여 비교적 적은 전력과 구현하기 쉬운 넓은 폭의 펄스로 고해상도의 영상을 만들기 쉽기 때문이다.

본 논문에서는 DDS (direct digital synthesizer) 방식을 이용하여 첩신호를 생성하는 신호 발생기에 대해 다룬다. 또한 본 논문에서 다루는 방식의 첩신호 발생기는 위상 오차를 가지게 되는데 이에 의해 영상레이다의 품질이 떨어지게 된다. 종전의 첩신호 발생기는 이상적인 첩신호의 스펙트럼과 비교하여 최대 -28 dB의 세기 차이를 가진다. 본 논문에서 제안하는 첩신호 발생기는 주파수 재생장 성분을 제거하여 이상적인 첩신호의 스펙트럼과 같은 특성을 갖게한다. 또한 시스템 성능을 비교하기 위하여 IRF (impulse response function) 특성 또한 비교되었다. PSLR (peak to side-lobe ratio)의 경우 약 -0.0686 dB가 개선되었으며, ISLR (integrated side-lobe ratio)는 약 0.0078 dB가 개선되었다. 3601개의 샘플을 사용하는 경우 신호의 중심이 1799에서 1801로 이동되어 제안하는 첩신호 발생기가 이상적인 첩신호와 같은 특성을 갖는 것을 확인하였다.