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SYNTHETIC APERTURE RADAR (SAR) SIGNAL GENERATION

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Abstract—This paper outlines the trend of signal generation in synthetic aperture radar particularly chirp (linear FM signal) generation using digital approach. A study in fundamental of FM signal and typical analog FM signal generation is highlighted. Various signal generation in SAR using digital techniques is discussed and finally the some of the digital chirp generators are presented.

1. INTRODUCTION

Radar has long been used for military and non-military purposes in a wide variety of applications such as imaging, guidance, remote sensing and global positioning [1]. Airborne and spaceborne radars, capable of producing images of ground, have been developed and extensively used in remote sensing applications. In the 1950s, Real Aperture Imaging Radar (or Side Looking Airborne Radar, SLAR) was developed to produce better quality images for military use. Large antenna that produces narrow radiation beamwidth must be used for scanning of the earth terrain in order to achieve the required resolution. However, the image formed by SLAR is poor in azimuth resolution. The recent development in Synthetic Aperture Radar (SAR) technology has made possible a much higher resolution to be achieved using a small antenna. The advantages of SAR have been detailed in many books and journals, which record the concrete proof and support behind the blossoming of SAR systems in worldwide [2]. Among them includes fine resolution achievable that made headline when the technique first came to light, often credited to Carl Wiley of Goodyear Aerospace in 1951 [3]. SAR has been shown to be very useful over a wide range of applications, including high resolution geological and topological mapping, snow monitoring [4], military surveillance, mining [5], hydrology, oil pollution monitoring [6], classification of earth terrain [7] etc. The potential of SAR in a diverse range of application led to the development of a large number of airborne and spaceborne SAR systems.

One breakthrough in technology made up the advancement of SAR development is to take the digital approach towards designing and developing of the transmitter for SAR. The idea of taking the digital approach is rooted in the belief that, as for most contemporary radar systems designs, digital electronics offer better stability, repeatability, and flexibility over an equivalent analog upshot. This revolution in radar designs has over the decades justified the common perception of many radar designers about radar system, that unlike early radar systems that consisted entirely of analog circuits, digital techniques can now be employed too for optimization purpose. In fact, there are several other advantages of digital circuits in comparison with analog circuits, such as, digital circuits are less affected by noise and it can be regenerated to achieve lossless data transmission. Also, digital operations interface well with computers and are easy to control with software. This is particularly advantageous because timing circuits that could be interfaced with control unit of SAR system are needed to properly control chirp start frequency in an effort to preserve the coherency of SAR system. SAR being a coherent system requires both the magnitude and the phase of the echo samples to be preserved, which implies that the system pulse-to-pulse phase must be stable as the essential information lies not in the magnitude but the phase of the received data. Apart from that, information storage by digital method is much easier than using analog methods and this is a plus for radar receiver whereby data storing is involved.

Nevertheless, despite the many advantages offered by digital circuitry, generation of chirp signal directly at the intermediate frequency (IF) by digital method was in the olden days possible but not popular. This was due to the limitation in the speed of the digital circuitry as well as the demand for high clock frequency to meet the Nyquist Theorem. Nyquist Theorem states that a signal must be sampled at least twice as fast as the bandwidth of the signal to accurately reconstruct the waveform; otherwise, the high-frequency content will alias at a frequency inside the spectrum of interest, which is the so-called passband. Although a lowpass filter could be adopted in an effort to prevent aliasing in the passband, in that it limit the frequency content of the input signal above the Nyquist rate, but the best is still to have sampling rate twice as that of the bandwidth for best performance.

These two constraints had long remained restrictive to SAR design in the past, until very recently the restriction is lifted when they have been proven neither insurmountable nor insuperable because the speed of digital circuitry has increased remarkably following advances in digital technology. Though it is often uncertain whether technology or customer demand is driving the other, technology advancement is no doubt an essential part of SAR technology and hence its development. That explains why generation of chirp signal directly at baseband is today favoured for it avoids the difficulties of building a precision single-sideband modulator with high suppression of carrier and unwanted sideband.

In reality, for the past 30 years or so a large proportion of the innovation in radar systems arose from the use of digital technology in radar systems design, notably among them is in data processing. Indeed in recent years many radar designers have been switching — if not already switched — to the adopting of digital techniques that further contributed to the mushrooming of various digital techniques in SAR application all across the globe. This trend is expected to continue, with advances in radio frequency (RF) technology and antennas, besides digital technology. In brief, a digital world beckons.

The digital approach taken to construct the chirp generator is limited to the state-of-the-art in digital components in the market. It relies heavily on the best components the market has to offer, in terms of speed, precision and resolution (for instance, that of DAC). However digital circuits are also subject to the following limitations:

- Digital circuits are more likely to include human error as they are more complex. That explains why much of the modern art of designing digital systems consists of analyzing them into smaller parts that can be perfectly solved with some form of automated design system.
- Digital systems can be fragile, in that the lost or misinterpretation of a single piece of digital data can result in a thorough change of meaning of large blocks of related data. Anyhow, this problem can be mitigated by designing the digital system for robustness. A crucial issue is to remove unused logic signals in minimizing the numbers of states.
- Quantizations errors may be present as the analog signals from the real world are translated into a storable, regenerable digital form. Yet this problem can normally be mitigated by storing more digital data within practical limit.
- Digital system could use subtle features to store digital states that digital systems errors are difficult to be regenerated accurately. In most digital circuits, these problems show up as “glitches”,

vanishingly-fast pulses that may trigger some logic but not others, "runt pulse" that do not reach valid switching (threshold) voltages, or unexpected ("undecoded") combinations of logic states.

- Digital circuits are slower to perform calculations than analog circuits using similar components.
- Digital circuits are sometimes more expensive, especially in small quantities.

Nonetheless, despite the limitations discussed above, digital technology has been proven time and again to be of great significance in stirring the innovations in radar systems design especially in recent years. Literally, these limitations can be overlooked as they do not affect the kernel of the system. After all, many of the limitations described above have their own alternatives to overcoming it, which further reduces the impact of its weak points. Thus, exaggerating the limitations of digital circuitry under microscope is unnecessary.

2. CHIRP SIGNAL ANALYSIS

In general, chirp is a typical phase coding or modulation applied to the range pulse of imaging radars designed to achieve high time bandwidth product (TBP). The resulting phase is quadratic in time, which has a linear derivative, hence the name linear frequency modulation, or linear FM. There is a solid reason as to why linear FM has become so dominant and widely adopted in various SAR systems design all over the world today. Early radar systems transmitted a strong pulse of RF energy after which it displayed reflections of the pulse on the familiar circular display screen, the scanning beam of which matched the angle of the rotating dish antenna. The phosphor blip, which is a spot of light on the radar screen indicating the position of a detected object, appeared at a radial distance from the screen center directly proportional to delay time of the reflected signal, and therefore its distance. Their peak power levels and pulse widths however, limited range and resolution of these fixed-frequency pulse systems respectively. Although resolution could be improved by narrowing the pulse, but this reduced the outgoing peak energy resulting in compromised range performance, and also required wider bandwidth operation for both the transmitter and receiver systems. This morass had remained baffling for some time, until pulse compression technique came to light.

Pulse compression is a technique that helps overcome the above mentioned limitations in an effective manner. It is no wonder this technique is used in virtually all radar systems nowadays, not just in SAR. Instead of a fixed frequency pulse, the transmitted pulse is modulated by a specific phase or frequency pattern during a wider pulse interval. The receiver uses a pulse-matched filter to pass reflected pulses that match the pattern of the outgoing pulse and reject noise and other signals. In other words, a form of correlation is implemented by the pulse-matched filter in the receiver to produce a narrow output pulse only when the received signal contains the exact frequency chirp pattern in the transmit pulse. Since the transmitted pulse is wider, a lower peak power output stage can deliver the same amount of transmitted pulse energy to maintain range performance. In this way, the wide transmitter pulse is effectively compressed to a narrow pulse at the output of the correlator. The ratio of the transmitted pulse to the compressed pulse, known as the pulse compression ratio, is equal to BW·PW, where BW is the bandwidth of the sweep and PW is the transmitter pulse width.

To avoid confusion however, it must be pointed out that pulse compression technique does not make up to pulse modulation. Instead, it constitutes to frequency modulation, with the name chirp, or linear frequency sweep. Typically there are three basic modulation schemes in radar system, namely pulse, linear FM (LFM) chirp, and phase coded. Frequency modulation is conventionally selected over pulse modulation for its easier signal processing and simpler yet economical hardware implementation. Unlike pulse radar that separates the transmitted and received signals in the time domain, the LFM radar transmits chirp signal at lower power yet processes the received signal in frequency domain, thereby eliminating the need for proper and very precise timing circuitry. Also, LFM radar has no need of a high power source as in pulse radar to generate a short burst of electromagnetic energy. In fact the same average transmitting power can be achieved with lower peak amplitude in typical LFM radars. As a matter of fact, the use of frequency modulation to obtain range information in radar is almost as old as radar itself, dating back to 1924 when Appleton and Barnett used this technique for ionospheric sounding [8].

In the time domain, an ideal linear FM signal or pulse has a duration T seconds with a constant amplitude, a center frequency f_{cen} Hz, and a characteristic phase component $\theta(t)$, which varies with time in a specific manner [9]. Physical "probing" systems often transmit pulses of this form. For linear frequency modulation, the phase is a quadratic function of time. When f_{cen} is set to zero, the complex form of the signal is

$$s(t) = rect\left(\frac{t}{T}\right)\exp\left\{j\pi Kt^2\right\} \tag{1}$$

where t is the time variable in seconds, while K is the linear FM rate in hertz per second. Each of the real and imaginary parts oscillates as a function of time, and the oscillation frequency increases away from the time origin.

On the other hand, the phase of the pulse is given by the argument of the exponential expressed in radians

$$\phi(t) = \pi K t^2 \tag{2}$$

This equation is a quadratic function of time.

As for the instantaneous frequency, it is the derivative with respect to time expressed in Hz, implying that the frequency is a linear function of time t, with the slope K expressed in hertz per second.

$$f = \frac{1}{2\pi}\frac{d\phi(t)}{dt} = \frac{1}{2\pi}\frac{d(\pi K t^2)}{dt} = Kt \tag{3}$$

The bandwidth is defined as the range of frequencies spanned by the significant energy of the chirp, or the frequency excursion of the signal (for real signals, only positive frequencies are considered in this definition). The bandwidth is the product of the chirp slope and the chirp duration, expressed in Hertz, and it governs the obtainable resolution.

$$\mathrm{BW} = |K|T \tag{4}$$

Another signal parameter is the time bandwidth product (TBP), which presents the product of the bandwidth $|K|T$ and chirp duration T (a dimensionless parameter).

$$\mathrm{TBP} = |K|T^2 \tag{5}$$

The TBP of the baseband linear FM signal in (1) can be measured by counting the number of zero crossings of the real or imaginary part of the time-domain signal. When $f_{cen} = 0$, the number of zero crossings in the signal is close to one-half of the TBP. For T of 20 us and bandwidth of 20 MHz, it gives a TBP of 400.

In short, a linear FM signal has a quadratic phase, where its frequency is a linear function of time. The frequency slope is the linear FM rate. A linear FM signal is often called a chirp, in analogy with a bird's call. When the slope is positive, the signal is called an up chirp; whereas for a negative slope, the signal is called a down chirp. Yet the direction of the chirp, which is embedded in the sign of K, will not affect the analysis.

2.1. Spectrum of the Linear FM Pulse

Most pulse compression radars require a drive signal for the power amplifier which has an essentially rectangular envelope. For a linear FM signal the associated frequency spectrum is also approximately rectangular, based on a derivation of the Fourier Transform of the signal. The exact derivation is not straightforward, but a convenient approximate expression can be obtained by the Principle of Stationary Phase (POSP).

There are a couple of important properties that can be derived from the complex spectrum of a linear FM pulse. First, the real and imaginary parts of the spectrum have a similar linear FM structure as the real and imaginary parts of the time domain signal. The differences are a $\pi/4$ phase change, and a change in the sign of the FM rate, compared to the time domain. Second, the envelope of the magnitude of spectrum is approximately the same as the rectangular envelope of the time domain signal. In other words, the envelope is approximately preserved between the two domains. And third, the phase of the spectrum is approximately quadratic in the frequency domain, as it is in the time domain. This implies that the frequency versus time relationship is $f = Kt$, showing that there is a linear, one-to-one relationship between time and frequency in linear FM signals.

This problem statement stems from the limitations revolving analog FM modulation technique that has been in use worldwide for at least two decades, due to its simplicity and low cost implementation. Traditional FM exciter technology makes full use of a modulated oscillator approach to FM generation. In principal, a FM signal is obtained by forcing an oscillator to move in proportional to a modulation frequency, which is normally done by applying a modulation signal to a varactor that is part of an oscillator's tank circuit. The varactor is a semiconductor device in which the capacitance is sensitive to the applied voltage at the boundary of the semiconductor material and an insulator. As for the tank circuit, its center frequency changes as the modulation voltage changes. The frequency of oscillation will then change too following changes in the center frequency. An equation that describes the resultant signal can be stated as below:

$$FM(t) = A\cos\{[\omega_c + k_f f_m(t)]t + \theta_0\} \tag{6}$$

A close examination on the above equation reveals that it resembles very much the equation used to digitally generate FM signal. In this equation, A refers to the amplitude of the FM signal or peak voltage output of the oscillator. The center frequency of oscillation can be obtained from $\omega/2\pi$, while the constant k_f has units of rad/sec/volt and relates to how much the frequency changes for a given voltage input. As for θ_0, it represents the initial phase of the signal while $f_m(t)$ speaks for the modulation signal.

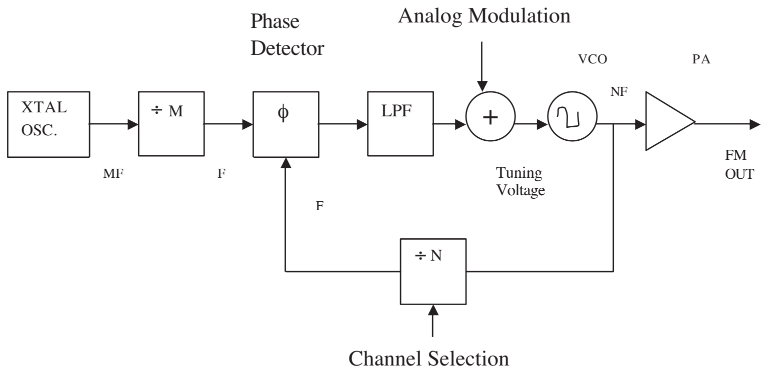


Figure 1. A basic block diagram of a traditional analog FM modulation oscillator.

Figure 1 above illustrates a basic block diagram of a conventional analog FM modulation oscillator. A crystal oscillator is divided down by M to obtain the minimum frequency increment of the modulated oscillator. Manufactures typically provide 10 kHz spacing that requires $M = 1000$ for a 10 MHz crystal reference. The reference frequency set by M is multiplied by a factor N to obtain the desired FM channel. Channel selection is therefore made by changing N and possibly M. The final output frequency being calculated by:

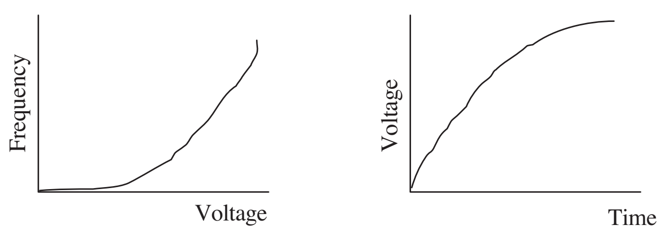
$$F_{out} = F_{clk}N/M \tag{7}$$

where F_{clk} is the reference oscillator frequency. The VCO receives an error voltage from the phase detector which keeps the oscillator on frequency should it start to drift. Modulation is also applied at the VCO input, changing the frequency proportionally. This change in frequency is sensed by the phase detector, which produces a voltage equal to the modulation, but opposite in phase. This signal must be filtered by the low pass filter to keep the modulation from being canceled. Hence the low pass filter must attenuate all modulation frequencies, which in turn requires a cutoff frequency of well below 20 Hz. Even though this is essential for modulation, it provides little noise reduction and inhibits fast loop response. Slow loop response is usually overcome by using a faster loop to obtain lock, then switching to the narrow band loop. The modulated oscillator phase noise is therefore only slightly better than the phase noise of the VCO. Also, since lower frequencies are attenuated less, its response is degraded. Another problem due to the narrow bandwidth of the modulation oscillator is susceptibility to microphonics. Unless adequate mechanical isolation is provided, microphonic frequencies above a few Hertz will impact system noise performance.

Additionally, system performance is impacted by the non-linearity in the VCO itself. The transfer function of the VCO can be described by the following equation:

$$K_0 = \Delta F_{out}/\Delta V_m \tag{8}$$

where ΔF_{out} is the change in output frequency or deviation, and ΔV_m is the change in modulation voltage. It can be seen that if the transfer curve were exactly linear then K_0 would be constant. But all analog VCOs exhibit some non-linear characteristic mostly due to varactor nonlinearity. Therefore, K_0 changes as V_m changes. Lower order nonlinearity cause deviation levels to change across the FM band (as shown in Figure 3 by $\Delta\varepsilon$) while higher order nonlinearity cause distortion within the signal itself.



(a) VCO response (b) Compensation Tuning Voltage

Figure 2. Nonlinear frequency response of a VCO (a) and the required compensation tuning voltage (b).

Figure 2 shows the nonlinear frequency response of a VCO due to a linear tuning voltage while Figure 3 shows an exaggerated plot of a non-linear VCO transfer function. Frequency sweep nonlinearity is considered a limiting factor in SAR range resolution and a contributor to spectral clutter in the range compressed signal. Many different methods have been attempted to achieve high linearity in the FM signal with varying degree of success. Some of these methods, though offering compensation for high linearity in the FM signal, introduce phase errors due to large drifts in the center frequency of the chirp on the order of MHz. Phase error, however, is unbearable as it puts a serious threat to the coherency of SAR system. Hence the development of a digital chirp generator for LFM generation is timely and advantageous

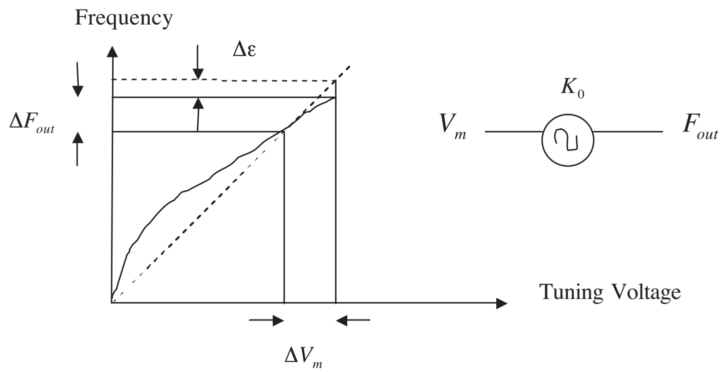


Figure 3. VCO transfer function.

as it not only overcome the shortcomings of VCO but also preserves the coherency of SAR system.

In summary, Table 1 gives the advantages of direct digital modulation over analog modulation in a tabular form.

Table 1. Analog modulation vs. direct digital modulation.

System Performance	Analog FM	Direct Digital FM
FM noise	Good.	Good.
Frequency Response	Good.	Excellent.
Linearity	Good (requires tuning).	Excellent.
Microphonics	Poor (requires mechanical isolation).	Excellent.
$N+1$ Compatibility	Degraded performance.	Excellent.
Spurious	Minimum fltering.	Requires fltering.
Complexity	Low.	Moderate to High.
Digital Compatible	No.	Yes.

3. STATE-OF-THE-ART IN SAR TRANSMITTER

The trend of development of SAR is being from large to small in recent years. This trend — which has been taking increasing force — exists not just by chance. Size, weight and power are long known as the critical factors for airborne and spaceborne application. Logically, smaller and lighter SAR systems can be more readily accommodated in small spacecraft and launch vehicles that enable significantly reduced total mission costs. Not withstanding the same common goal, which is to achieve lower weight, volume, power and data rates, the methods for constructing the transmitter of SAR vary from institution to institution. In general, there are four approaches towards constructing the transmitter of SAR, namely the FPGA firmware method, the Direct Digital Synthesizer (DDS) method, Monolithic Microwave Integrated Circuits (MMIC) method, and RF Electronics method.

3.1. FPGA Firmware

Field-Programmable Gate Array (FPGA) has been recognized as one of the resources that can boost radar system performance. It has, over the course of time, found its way to become one of the building blocks in advanced radar platforms, among other available options. FPGA enhances radar system performance levels through optimized intellectual property (IP) core implementations for critical compute-intensive digital signal processing algorithms such as pulse compression and Fast Fourier Transform (FFT).

Basically, FPGA is a semiconductor device containing programmable logic components and programmable interconnects. As for firmware, it is a combination of software and hardware, of which software refers to programs or data that has been written onto read-only memory (ROM) to control the system hardware. The programmable logic components of FPGA can be programmed to duplicate the functionality of basic logic gates (such as AND, OR, XOR, INVERT) or more complex combinatorial functions such as decoders or simple math functions.

In order to define the behavior of FPGA, the user provides a schematic design or a hardware description language (HDL) such as Very High Speed Integrated Circuits (VHDL) and Verilog. Following that, a technology-mapped netlist is generated using an electronic design automation tool. The netlist can hence be fitted to the actual FPGA architecture by a process called place-and-route, normally performed by the FPGA company's proprietary place-and-route software. This imply that the user usually will not have much to do with the hardware construction, but will instead validate the map, place and route results via timing analysis, simulation, and other verification methodologies. Upon the completion of design and validation process, the binary file generated along with the FPGA company's proprietary software is used to configure the FPGA device.

One recent example of such SAR transmitter developed taking FPGA resources is the Radar Digital Unit (RDU) of South African

Synthetic Aperture Radar II (SASAR II) in May 2004, by the Department of Electrical Engineering, University of Cape Town [10]. This RDU — which is a subsystem of SASAR II — further contains one Digital Pulse Generator (DPG), Sampling Unit (SU) and Timing Unit (TU). The firmware is designed and written using Mentor Graphics HDL Designer — a tool specifically used for firmware development. ModelSim then simulates the firmware after the writing process while Synplify synthesizes the firmware after simulation of the design.

Notwithstanding the advantages that FPGA bring, such as the improved performance and increased speed, there are also certain trades-off associated with FPGA inevitably. FPGA is generally more expensive and difficult to program as the programming involved is not just writing a program but creating hardware. Also, it is less versatile and less flexible in that once written, or modified, the FPGA is tough to change again. Still, FPGA has found its place in applications like sonar, medical, baggage scanning, and radar — which includes SAR. The bottom line could be drawn, therefore, that FPGA is good for applications where they sit on the front end, quickly doing compute-intensive work with simple algorithms.

3.2. Direct Digital Synthesizer

The Direct Digital Synthesizer (DDS), which is also known as the Numerically Controlled Oscillator (NCO), is seen adopted in modern radar systems. DDS is a technique that uses digital-data and mixed/analog-signal processing blocks as a means to generate real-life waveforms that are repetitive in nature. In principle, DDS is an electronic method for digitally creating arbitrary waveforms and frequencies from a single, fixed source frequency. A basic DDS circuit consists of an electronic controller, a random-access memory, a frequency reference (normally a crystal oscillator), a counter and a digital-to-analogue converter (DAC).

DDS grew out of the military necessity for different kinds of radar able to sweep a frequency. Historically the military used DDS, yet their brand of DDS was an expensive, large, rack-mounted instrument that would dissipate 50 watts. Then from radar applications DDS worked its way into becoming used as a general local oscillator in communications systems. The DDS characteristics that most attract radar-system designers are precision frequency-tuning, phase offset control, and linear chirp capability. Since DDS is in basic a technique for creating a waveform in digital domain, it can generate waveform of any arbitrary nature — not just the common sine wave. Meaning waveform can be created and put into an algorithm or a lookup table that will then be made repetitive. This accounts for the beauty of DDS as it gives its designers control over every aspect of the waveform they are generating.

One such example of the radar transceiver developed by this method, among many others, is the chirp synthesizer developed by the Electronic Communications Laboratory of the University of Florida, United States, in 1995 for applications in various radar configurations [11]. This synthesizer allows the generation of waveforms with a wide range of carrier frequencies, chirp rate, pulse widths, and pulse repetition frequencies. The variation of these parameters allows the radar to transmit different waveforms to achieve various missions such as target acquisition, tracking, or classification. This synthesizer's flexible waveform control provides a means for motion compensation, reducing ambiguities, and correction of nonlinearities in the transceiver's frequency response.

In short, DDS promises precise, agile control of output waveforms; but is limited in frequency and spurious performance. In other words, DDS has limited operating ranges and limited spectral purity due to numerical distortions and actual realization. Other applications of DDS beside radar include satellite communications, broadband networking, test and measurement, and instrumentation.

3.3. MMIC Technologies

The use of Monolithic Microwave Integrated Circuits (MMIC) in space hardware is becoming more widespread lately. Besides, it has also successfully made its presence noticeable in automotive radar applications and in its transceiver design. MMICs are integrated circuit (IC) devices that operate at microwave frequencies, which typically perform functions such as microwave mixing, amplification, and tuning. In essence, a MMIC is a microwave circuit in which the active and passive components are fabricated on the same semiconductor substrate. The frequency of operation can range from 1 GHz to 100 GHz, and a couple of different technologies and circuit approaches can be used. The additional term 'monolithic' is needed to distinguish them from the established microwave integrated circuit (MIC), which is a hybrid comprising a number of discrete active devices and passive components integrated onto a common substrate using solder or conductive epoxy adhesive.

There are certain advantages and disadvantages associated with MMICs. MMICs are cheap in large quantities and hence economical for complex circuits. Also, they are small and light, reliable, and less parasitic (more bandwidth); besides having very good reproducibility. Reproducibility is excellent for MMICs because the active and passive components are produced by the same well-controlled fabrication steps, using the same photolithographic masks. Nevertheless, despite offering strings of advantages, MMICs have very limited choice of component, require long turn around time (approximately 3 months) and are very expensive to start up. Furthermore, most MMIC devices have to be tailored to volume production and tend not to give state-of-the-art performance. This can be a serious problem for design that demands excellent performance, such as the design of Low Noise Amplifier (LNA) and Power amplifier (PA).

The applications of MMICs are wide, with military and space applications being the major driving force behind MMIC technology. For instance, the Advanced RF & Optics Group at Matra Marconi Space Systems Portsmouth, United Kingdom, has designed one T/R Module for their Advanced Synthetic Aperture Radar (A.S.A.R) using GaAs MMIC circuits in 1998 [12]. This T/R Module that operates at 5.3 GHz consists of a low noise receiver and a transmitter that provides peak output power of nominally 7.2 Watts. The T/R Module operates between a single RF port and two radiator ports, namely that of vertical and horizontal polarization. Since physical size and mass are equally important, GaAs MMICs have been incorporated in the areas of phase, amplitude control, switching, and transmit channel amplification. Additionally, this project has also pioneered the use of ceramic packaging technologies that aimed at reducing mass.

Other applications of MMICs beside radar are in communications satellites, mobile phones, electronic warfare, radiometers, global positioning (GPS) and many others. It is interesting to be pointed that there are a variety of applications for microwave/millimeter wave devices in the consumer automotive arena. These include forward looking radar for collision warning and cruise control, side radar for lane change maneuvers, rear radar for backing aid, parking aid, air bag arming, and security systems.

3.4. RF Electronics

The RF Electronics method has been receiving warm welcome especially of late as it allows better creativity for the users to make do on the current technology available besides keeping the cost low. Recognizing that maintenance costs could be reduced by reliability improvements, ways of improving the installation's transmitter systems of radar have been studied in supporting the aging technology into the future. Engineers have determined that reliability, supportability, and reliability gains in the transmitter system could be realized through modern design approaches, like in the case of phased-array radar, high-power vacuum tubes are replaced with RF power transistor and integrated electronic technology. Apart from that, microcontroller with high integrated features can be employed to minimize assembly complexity and parts count. All these account for the fundamental advantage of electronic control, which is the speed.

One fine example that illustrates a transmitter brought about by this method, among many others, is the low cost, FM/CW transmitter developed by the Microwave Earth Remote Sensing Laboratory of Brigham Young University, in 2000 for use from 2 to 18 GHz with a transmit bandwidth of up to 1 GHz [13]. This design includes a microcontroller aided by a 10 bit digital to analog converter (DAC), a microwave VCO, a 4 bit counter, several radio frequency (RF) prescalers, and a passive coplanar microwave circuit. The microcontroller communicates with a host using a RS232 serial port, enabling the users to set parameters such as center frequency, bandwidth and repetition count. A trigger is used to synchronize receiver analog to digital conversions with the transmitted signal. This transmitter is adopted in a railway hazard detection system, a SAR, and an altimeter.

There are a variety of electronic technologies in the development of upgrades or brand-new design of the transmitter of radar systems. For instance, high-voltage and high-power electronics, power grid tubes, RF power transistors, analog/digital electronics, RF signal processing electronics, electronic packaging, and PC-based instrumentation are all at hand. In most cases, circuits are engineered using standard electronic components; but in some cases, like RF amplifiers, commercial industry can be solicited for custom-developed products built to Institute's specifications. As for RF signal processing components, they can be represented by power dividers, mixers, filters, fixed attenuators, current-controlled variable attenuators, RF amplifiers, voltage-variable phase shifter, and some others. Device connections can be made on a printed circuit board with microstrip circuit traces designed for 50-Ω transmission line impedance.

4. CHIRP GENERATOR IN SAR TRANSMITTER

Before applying chirp generator into the transmitter of SAR system, the selection of choice to developing the transmitter is first to be made after careful examination of the state-of-the-art in SAR transmitter, as presented in Section 3. This was so as the method chosen has direct effects on the method to developing chirp generator in the later stage.

Nevertheless, in spite of the selection made, it is crucial to be pointed out that the question of which is the better technology, or which performs the better does not arise. Each technology has its place — a place determined by the application and by individual needs.

Co-existence, rather than competition, is deemed the way forward. Each technology, be it FPGA, DDS, MMIC, or RF electronics, has its advantages and disadvantages and each is capable, according to the application, of outperforming the other. It doesn't matter which technology has been chosen, so long as it is capable to meet the design needs. All the more so when the said technology can contribute to improving the performance, target acquisition, and tracking and identification of the targets, like what many modern radar system engineers are working on and seeking after.

4.1. State-of-the-Art in Chirp Generator

Chirp generator, which is also known as the Linear Frequency Modulation (LFM) generator, has witnessed the increasing usage of itself in recent years. Chirp pulses are required for a number of earth remote sensing such as SAR, and Radar Altimeter (RA). Also, it may find its usage in planetary remote sensing spaceborne instruments such as SAR, RA, and microwave sounder. To name a few, a Canadian National (CN) Railway funded project uses a LFM generator at C-band, or to be more exact, at 5.7 GHz to 6.0 GHz together with interferometry to measure terrain profiles [14]. Besides, a NASA funded project uses the chirp transmitter that operates between 14.2 GHz to 14.4 GHz to analyze the mean sea level EM bias in a prototype altimeter [15]. In fact, the increased usage of radar for commercial products has shed light into the radar field thereby bringing higher demand for a cost-effective chirp generator.

The performance requirements of chirp generator for different applications vary remarkably from 5 MHz/5 msec chirp rate for planetary research, to 320 MHz/300 μsec chirp rate for earth observation advanced radar altimeter. This altimeter is commonly used for determining elevation, especially an aneroid barometer used in aircraft that senses pressure changes accompanying changes in altitude. Though the performance requirements of chirp generator may be different, but the basic operation is the same in all applications. Hence, the development of a single unit that can be configured to meet a range of requirements is advantageous and timely.

Study has revealed that a digital-based chirp generator has advantages of stability, repeatability and flexibility over an equivalent analog solution. Principally, there are three basic approaches to digitally generating chirp pulses, namely dual adder, RAM/ROM based (pre-stored waveform), and single bit methods.

4.1.1. Dual Adder Method

The dual adder method has reasonably low mass and power, which meets the trend of radar design as discussed in Section 3. Also, the start frequency implemented by this method can be properly controlled. Yet, though this method offers great flexibility and low implementation size for long pulses, but it offers limited bandwidth due to the implementation technology. High bandwidth, however, is essential in this work as range resolution of SAR can be made arbitrarily fine by increasing the pulse bandwidth within practical limits.

4.1.2. Single Bit Method

The single bit method, being simple in nature, requires less designing and developing time. Also, it allows very high bandwidth. Yet, it has unacceptable phase performance for it generates large phase errors at high frequencies. Apart from that, chirp start frequency of this method is uncontrollable, which makes designing a coherent SAR system impossible. A point to be borne in mind when considering which method to adopt is that, the clock frequency of the to-be-designed chirp generator will be derived from a single source, in this case from Stable Local Oscillator (STALO). In other words, control over the start frequency of chirp signal is mandatory.

4.1.3. RAM/ROM based Method

The RAM/ROM based method is also known as the pre-stored waveform method. This method promises low mass or power for simple chirps. Though the characteristic of low mass or power might be restrictive for fine control of chirp start frequency or long pulses. The pre-stored waveform approach gives maximum performances for short pulses; yet as the length of pulses increases, the memory size will increase linearly. In addition, the RAM/ROM based method offers high bandwidth which will improve with the speed of memory technology. Apart from that, non-linear ramps can be achieved with this method, besides linear ramps.

4.2. Selection of Choice

Having surveyed the implementation of high time bandwidth chirp pulses using three basic digital techniques, it can therefore be concluded that by comparison the RAM/ROM based method outshines all others in that it offers high bandwidth and linear ramps yet puts no threat to the coherency of SAR system. Also, though the memory size increases linearly with the length of pulse, but for short pulse length SAR system makes the disadvantage of this method fades away. On the other hand, the dual adder method is not preferred because it provides lower bandwidth than the RAM/ROM method. The single bit method is also not being considered because it has unacceptable phase performance and its chirp start frequency cannot be controlled. This drawback is intolerable as it gets to the core of the transmitter design, threatening the coherency of SAR system, which is a crucial characteristic that must be preserved for it spells the difference of SAR from other radar systems, such as SLAR. Hence, RAM/ROM based method is more preferable over the other two methods. Table 2 below summarises the pros and cons of the three discussed methods.

Table 2. Summary of three basic methods for digital chirp generation.

Method	Pros	Cons
Dual Adder	- Moderately low mass and power. - Fine control of start frequency .	- Non-linear ramps impossible. - Lower bandwidth than RAM/ROM method.
RAM/ROM Based	- Low mass/p ower for `simple' chirps. - Non-linear ramps possible. - High bandwidth that will improve with memory technology.	- Low mass/power for fine control of long pulses. - Greater load on instrument computer.
Single Bit	- Simple system. - Very high bandwidth.	- Large phase errors at high frequencies. - Uncon trollable chirp start frequency .

4.3. Parameter Selection

Selection of SAR transmitter architecture and chirp generator technique is project dependent and survey is done to determine a few crucial parameters surrounding the chirp generators of notable and newborn SARs worldwide. Among the SARs surveyed include Airborne SAR (AIRSAR) by NASA (National Aeronautics Space Association) of the US [16], European Remote Sensing Satellites (ERS) in 1991 [17], South African SAR II (SASAR II) in 2004 [18], CCRS by the Canada Centre for Remote Sensing in 1986 prior to the launching of RADARSAT-1 in 1995 [19], the Japanese Earth Resources Satellite-1 (JERS-1) in 1992 [20], and the Shuttle Imaging Synthetic Aperture Radar (SIR) in 1978 [21], which is a cooperative space shuttle experiment between NASA, the German Space Agency (DARA), and the Italian Space Agency (ASI).

Table 3. The specifications of various chirp generators developed worldwide.

Parameters	Micro wave Band	Bandwidth (BW)	Pulse Width (PW)	Data Format	Sampling Frequency
AIRSAR (NASA)	P-Band	20/40 MHz	10 or 5 us	8-bit	45/90 MHz
	L-Band	20/40 MHz	10 or 5 us	8-bit	45/90 MHz
	C-Band	20/40 MHz	10 or 5 us	8-bit	45/90 MHz
SAR (ERS)	C-Band (5.3 GHz)	15.55 MHz	37.1 us	8-bit	18.96 MHz
SASARII	X-Band	50 MHz (I &Q each)	3-5 us	8-bit	220 MHz
CCRS	C-Band	26.3 MHz (I channel) 8.3 MHz (Q channel)	7 us (I channel) 8 us (Q channel)	8-bit	37.5 MHz (I channel) 10.0 MHz (Q channel)
	X-Band	31.2 MHz (I channel) 7.5 MHz (Q channel)	15 us (I channel) 30 us (Q channel)	8-bit	37.5 MHz (I channel) 10.0 MHz (Q channel)
JERS-1	L-Band	15 MHz	35 us	3-bit	30 MHz (60 Mb/s)
SIR	L-Band	40 MHz	33.8, 16.9, 8.5 us	8,4 bits/word	90 MHz
	C-Band	40 MHz	33.8, 16.9, 8.5 us	8,4 bits/word	90 MHz
	X-Band	10&20 MHz	33.8, 16.9, 8.5 us	8,4 bits/word	45 MHz

From Table 3, it is observed that the parameters such as microwave band, bandwidth, pulse width, data format and sampling frequency resemble yet vary among the chirp generators developed by various institutions.

For microwave band, the popular ones frequently selected by radar designers are that of P, L, C and X. The selection of microwave band goes hand in hand with the objective of the radar systems. For illustration, the Microwave Earth Remote Sensing group at Brigham Young University (BYU) has developed a number of SAR systems over the past few years, ranging from BYUSAR, YSAR, YINSAR, to the latest BYμSAR in December 2002 [22–24]. BYUSAR was first developed in hopes to have an instrument capable of mapping archaeology sites and so the frequency was set at 10 GHz. The YSAR next to BYUSAR was designed specifically to target archaeological sites and so the frequency was lowered to 2.1 GHz for greater ground penetration. In a separate development later, YINSAR was brought about on a Cessna 337 N Skymaster reconnaissance plane owned jointly by the BYU and Utah State University. And the frequency was raised back to 9.9 GHz again, approaching 10 GHz like that of BYUSAR for mapping archaeology sites.

On the other hand, bandwidth and pulse width of the chirp generator determine range resolution and the location of the detectable targets respectively. Higher bandwidth allows for better range resolution while wider pulse width increases the minimum distance at which targets can be detected. This is so as wilder pulse delivers more energy and results in stronger signal return for the receiver. As for the data format, although higher bit can result in better resolution, for instance 36-bit data yields better resolution than an 8-bit one, but one remark can be drawn from Table 3, that generally, data format of 8 bits would be sufficient. The last parameter to be noted is the sampling frequency — it should preferably be set at a value to fulfill the Nyquist Theorem for good performance.

5. CONCLUSION

With the development of modern integrated circuits technology, the technique for signal digitally generation are evolving rapidly to maturity. The digital radar transmitter can obtain much higher precision and stability than analog ones. Furthermore it can retain the extreme flexibility of digital techniques. The advent of digital radar transmitters is an evolution of modern SAR transmitter technology. This paper provided a brief introduction to the various architectures employed in SAR transmitter design and digital technique used in chirp generation. The merit and demerit for each of the digital generation technique has been discussed and each is capable, according to the application, of outperforming the other.

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