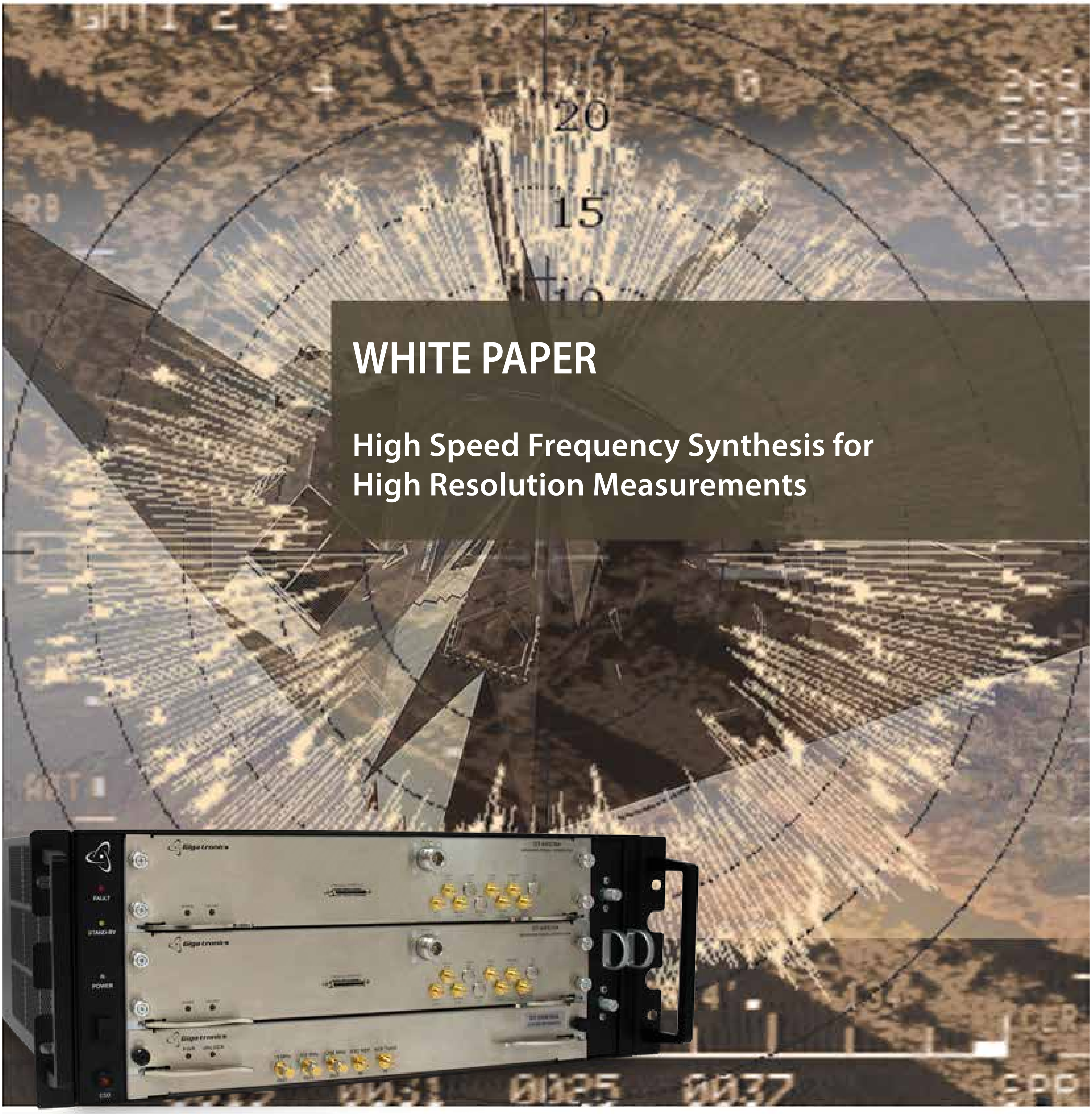

WHITE PAPER

High Speed Frequency Synthesis for High Resolution Measurements

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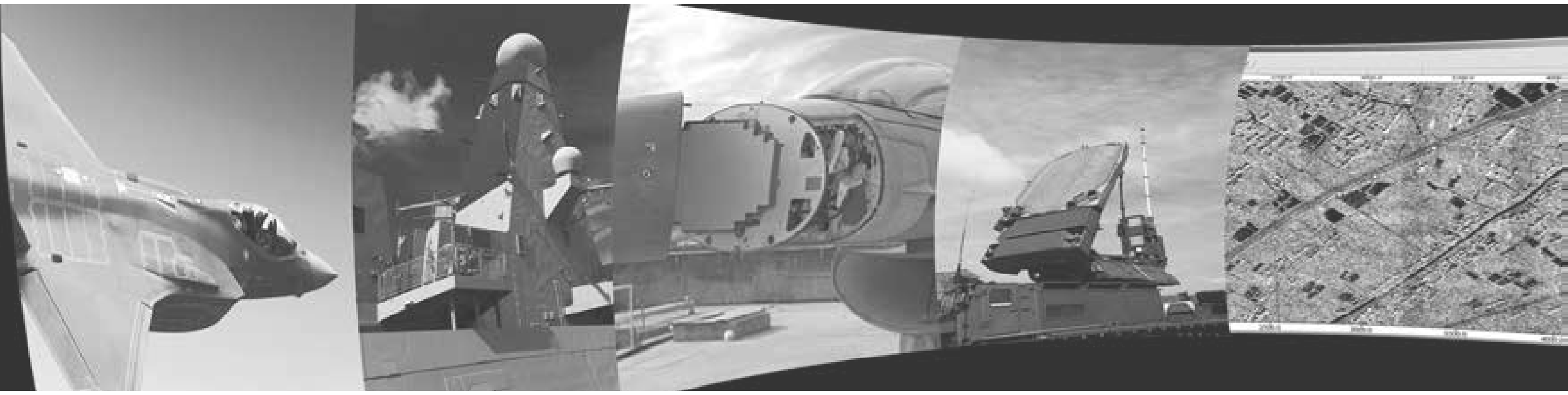
Advanced Microwave Signal Generation and Acquisition



By Mark Elo

Abstract—this paper will cover the key design attributes of a high-speed frequency switching synthesizer. It will highlight the importance of a stable reference and then go on to examine the different types of commercial high speed synthesis approaches, including advantages and disadvantages in terms of speed, frequency range, phase noise and part count. We will then explore a new hybrid approach to synthesis utilizing a lower part count commercial approach.

I. INTRODUCTION

A frequency synthesizer is a system for generating any number of frequencies from a fixed time base or reference. High-speed frequency switching wideband synthesizers have been a key element in instrumentation and radar measurement systems. Most approaches for this application use a direct synthesis method, requiring a complex design with a high part count that ultimately results in multiple failure mechanisms.

II. DESIGN ATTRIBUTES

A. Synthesizer

Synthesizer design needs to take the following five performance attributes into account: (1) Frequency Switching Speed, which can be broken down into two parts: (a) the refresh rate of the Frequency Word that controls the synthesis circuits, and (b) the time for the synthesizer to tune and settle to a specified value of amplitude and phase; (2) Coherence, or the ability to track phase while tuning to multiple frequencies; (3) Continuous tuning, or when a frequency change occurs can it be done without a break in phase (useful for generating chirp radar signals with wideband linear frequency modulation); (4) Frequency resolution - can it create small frequency increments, for example to emulate Doppler shifts; and most importantly, (5) Can it be designed in a reliable fashion, with a small part count.

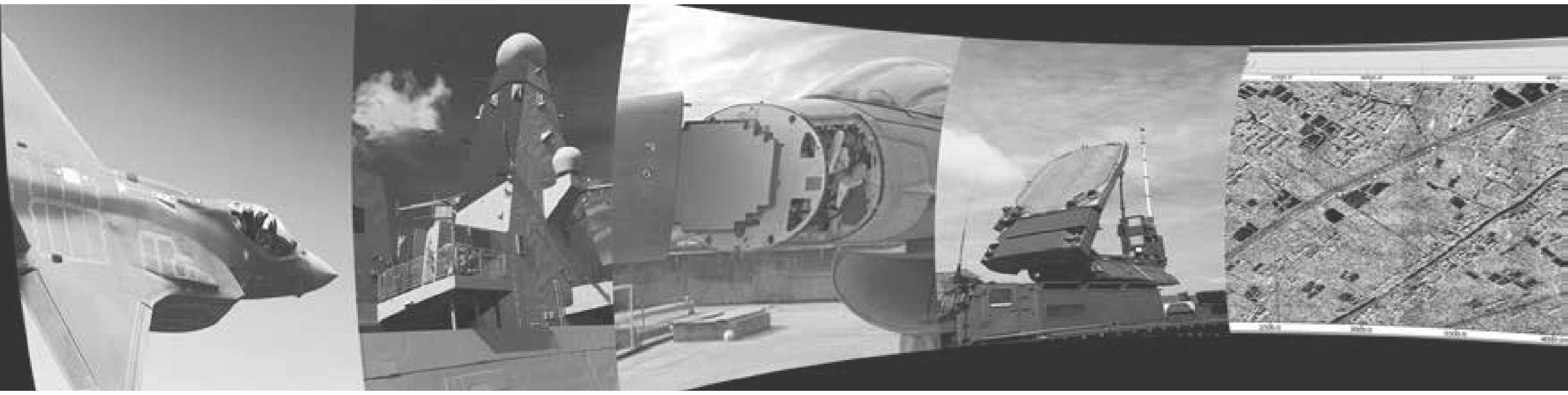
1. Frequency Switching Speed: for the purpose of this paper we shall break this down into four parameters: (1) Refresh Rate – how many times per second can the frequency be changed; (2) Latency – once a frequency change command has been received how long does it take to process; (3) Settling – how long does it take the syntheziser to settle to within a specified frequency, phase and amplitude; Finally (4) Jitter – to what uncertainty will the frequency change event happen.

2. Coherence: a synthesizer's ability to track phase. For example, defining the synthesizer initial state at time (T_0) with an initial frequency (F_0) and phase (Ø_0). If the synthesizer is tuned to an arbitrary frequency defined by F_1 then tunes back to F_0 taking time t_1 to perform the operation. The resultant phase of F_0 is as if the the synthesizer had not tuned to F_1.

3. Continuous Frequency means that as the synthesizer moves from one frequency to another, there is no break in the phase. For example a plot of phase over the frequency tune time (t_1) would result in a continuous line.

4. Frequency resolution: If the frequency resolution is 10 Hz then the synthesizer can be tuned to multiples of 10 Hz; if the resolution is 100 mHz, the synthesizer can be tuned in increments of 0.1 Hz.

5. Reliability; or the Failure Rate (Mean Time between Failure, MTBF [6]), is often predicted by counting the components used in the synthesizer and grouping them into the various component types (film capacitors for example). The number of components in each group is then multiplied by a generic failure rate and quality factor. Lastly, the failure rates of all the different part groups are added together for the final failure rate prediction.



B. Frequency Reference

All oscillators have some level of instability that causes random modulation or small fluctuations in frequency [3] [4]. In RF and Microwave design they are quantified in the single sideband phase noise measurement or plot.

A typical phase noise plot [9] shows there are specific areas of performance that relate to different types of noise sources; at the top of the curve to the left, FM walk noise is the dominant contributor; this noise is caused by the physical environment, mechanical shock, vibration and temperature. Having the best mechanical environment for the reference is important, especially in the case of discriminating small Doppler shifts. On the extreme right hand side of the curve is the broadband phase noise; this noise has little to do with mechanical or physical resonance mechanisms, and is caused predominantly by the utilization of multiple stages of amplification.

The phase noise performance is exacerbated by multiplying the signal. When this occurs an approximation can be used that for every frequency multiplication the phase noise performance will decrease by 6 dB (i.e., the LOG of 2 is 0.3, multiplied by 20 = 6). This also works in the opposite direction where the phase noise will improve by 6 dB per frequency division, until the noise floor or other system parameters become the dominant contributors.

Doppler based measurements [2] rely on the fact that returned frequency shift approximates to 2 times the velocity of target multiplied by the transmit frequency over the speed of light (wavelength). If the reference has poor phase noise or many frequency multiplication stages, then the return signal would be masked in the phase noise of the local oscillator.

For example - if a vehicle is traveling at 300 kph and a 10 GHz signal is reflected off it, the returned frequency will have shifted in frequency by 3 kHz. However, more and more sensing applications are focused around tracking slow moving targets or dismounts. So if the example is modified and the target is moving at 10 kph, we will see a frequency shift of approximately 250 Hz.

III. SYNTHESIS TECHNIQUES

A. Direct Analog Synthesis

Direct Analog Synthesis is exactly what the name implies. The frequency required is derived from the reference through a series of summing, subtraction, multiplication, and in some cases division stages.

A simple example would be as follows: to create a 2.5 GHz signal from a reference of 10 MHz would require multiplying the reference by 200 times, then summing that signal with the reference multiplied by 50.

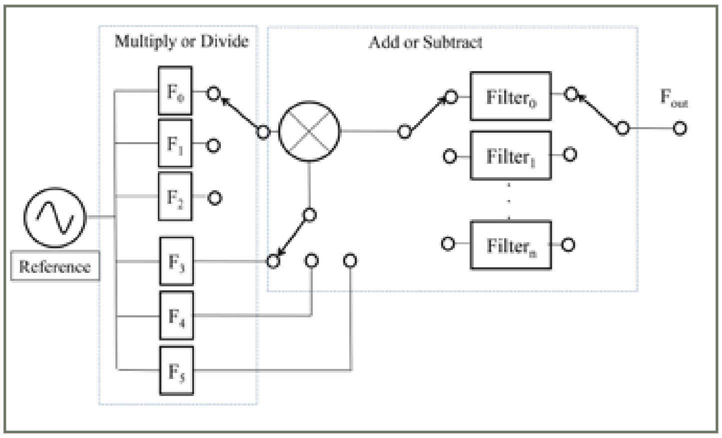
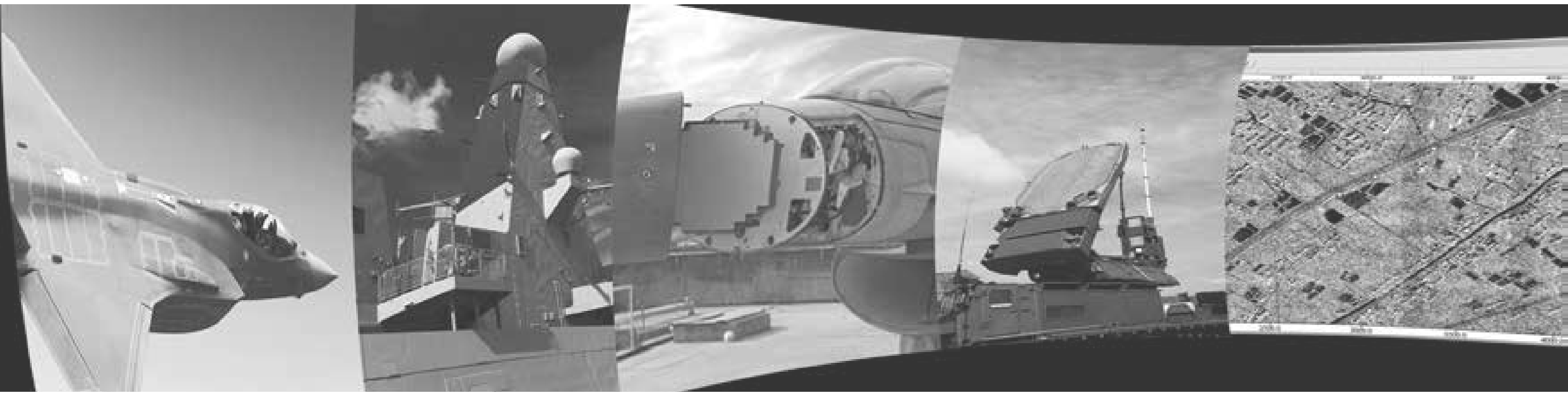


Figure 1. Example of a Direct Analog Syntheziser.

In Figure 1, F_0 would be a 200x multiplier and F_3 would be a 50x multiplier, then using the heterodyne mixing process



to sum the two signals an appropriate filter would be used to pass only the high side components, ultimately creating the desired 2.5 GHz signal.

As long as there are enough multiplication and division stages, the process of mixing and filtering can create any desired frequency.

This approach allows for very fast microwave synthesis. The synthesis speed is a function of switching between a number of multiplication and mixer blocks and sub micro-second switching is easily achieved. The design is inherently phase coherent, as physical switching between existing signal paths is employed, so when the switch returns to where it left off, the phase by default is as if it had never left.

Spectral purity in terms of phase noise is mainly a function of the reference as the only synthesis techniques employed are multiplication and mixing.

However the ability to achieve a desired frequency of sufficient resolution is severely hindered by the number of stages required to get to a desired frequency. This requires a great deal of components to realize the design. As component count directly equates to the probability of a failure (Summarized in the Mean Time between Failure Calculation), often synthesizers of this type suffer from poor reliability.

B. Indirect Synthesis

Indirect Synthesis is an alternative lower part count method of synthesis. Most commercially available high frequency signal generators today use either a Voltage Controlled Oscillator (VCO) or a YIG Tuned Oscillator (YTO) approach, or a combination of both. YTO and VCO technologies have excellent high frequency generation capability combined with excellent spectral performance. As both technologies are susceptible to temperature, we utilize the phase locked loop (PLL) technique.

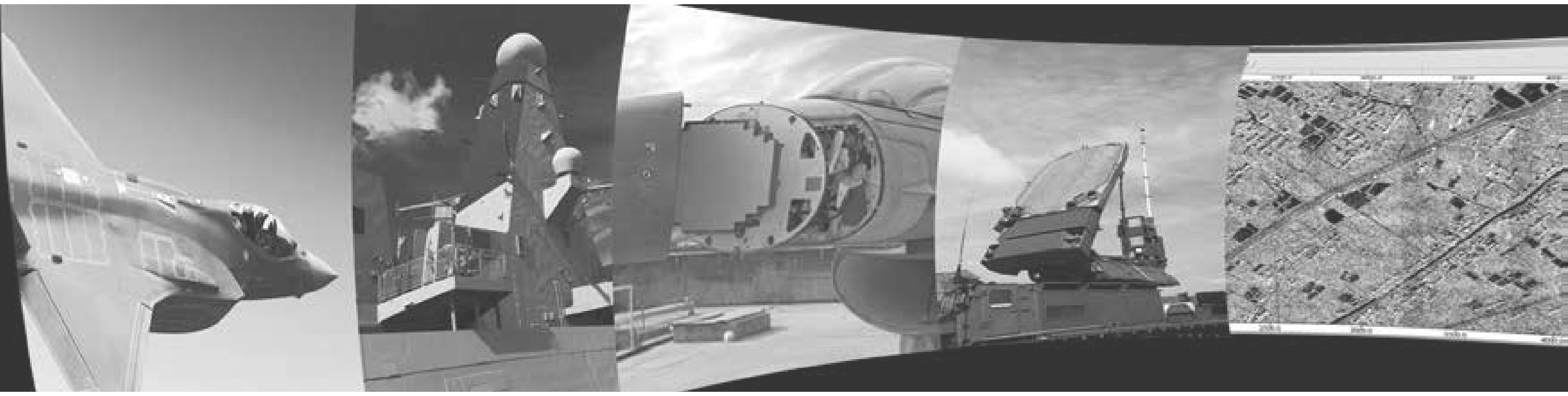
The operation of a PLL is as follows - the oscillator - VCO or YTO's output frequency accuracy is a function of the difference between the generated signal and the reference signal. If the reference signal is 100 MHz and the desired output signal is 100 MHz, then the error is zero, which means zero Hz error and zero degrees phase error. If the desired frequency is 100 MHz and the oscillator output is 100.1 MHz, then we have a 0.1 MHz error, which will translate into a phase comparison error; ultimately after filtering this translates to a correction voltage. Of course the desired signal is rarely the reference signal, so a frequency division circuit is used to reduce the generated signal frequency to that of the reference frequency, plus of course the frequency error. This example demonstrates the feedback mechanism employed has a time associated with how quickly the desired frequency can be obtained, which can hinder your ability to generate high speed signals.

Indirect VCO or YTO based synthesizers are not optimal methods for high speed synthesis as the phase locked loop associated time constant reduces the ability to tune at a sufficient speed to keep up with most applications. There is no relationship in phase when the instrument tunes to a new frequency. So coherence is very difficult if not impossible when utilizing this type of architecture.

Finally, both VCO and YTO oscillators also introduce incremental phase noise.

C. Direct Digital Synthesis

Direct Digital Synthesis [7] is fundamentally different from the previous methods of high frequency generation. To describe the operation in principle assume the DDS acts as a divider circuit, so the maximum theoretical frequency would be equal to the reference frequency. The division



function is then carried out by the three main components to the DDS – 1. a phase accumulator, 2. a lookup table and 3. the digital to analog converter.
The lookup table is a memory. Each address in the lookup table corresponds to a phase point on a sine wave from 0° to 360°. (Sometimes only a portion of the sine wave is required). The phase accumulator is a counter with variable increment sizes. In our simple example if the increment size is equal to one, then the output will equal the reference; this is because it addresses sequential points in the lookup table. If the increment size is increased, then at each clock a different address or point in the lookup table is accessed - thus creating a longer lower frequency wave. The most spectrally pure wave will be within the Nyquist band. Exceeding the Nyquist band allows higher frequencies to be extracted from this scheme, at the cost spectral purity. As the output frequency approaches the clock frequency multiple images will occur that are decreasing in amplitude (sinx)/x amplitude degradation. Using the correct filtering these images can be used to create output frequencies that exceed the frequency of the clock.

Three advantages of the DDS are: (1) it changes frequency very rapidly; (2) it can have sub-Hertz frequency resolution and, (3) as it is fundamentally a frequency divider, the phase noise will generally be less than the reference. The frequency range of these types of devices is limited especially when a wide band microwave range is required. This means that the design needs to be augmented with direct synthesis techniques, such as using a number of analog range multiplying circuits and filters to achieve the frequency required. Finally, there are many spur mechanisms that require a great deal of filtering and limit the range of frequencies you can generate.

D. Synthesis Type Summary

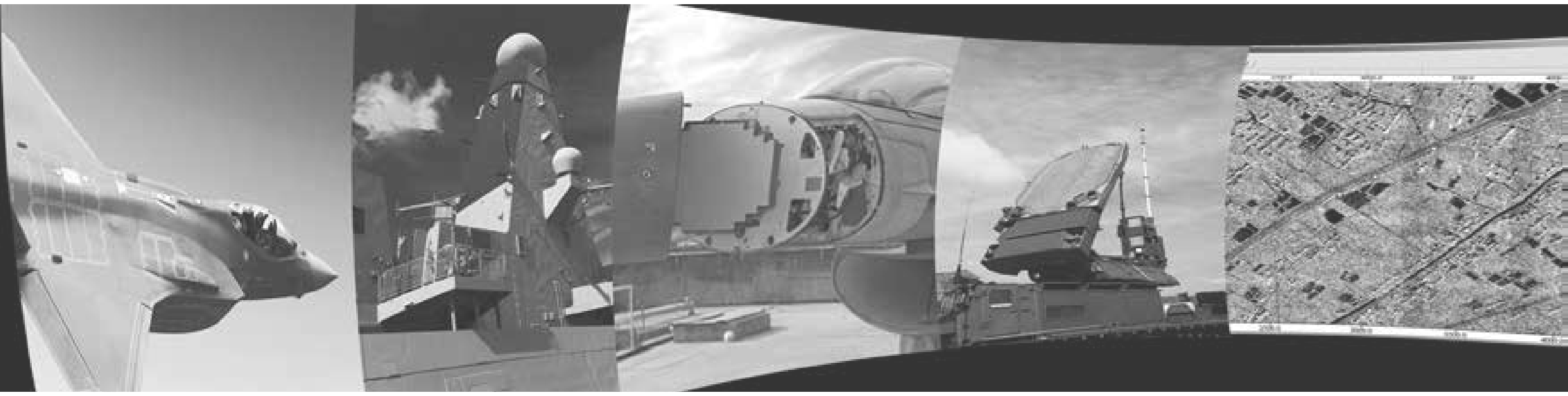
1. Direct synthesizers are coherent, high speed and have excellent phase noise. Due to their ‘brute force’ approach, the complexity of the instrument increases for higher frequency resolutions. This creates a high part count and a great deal of heat generation - meaning that the reliability of the instrument is lower.
2. While the Indirect method solves the part count and reliability problem, with very good frequency resolution (Hz), they are not coherent in their operation and have a relatively slow tuning speed.
3. Direct Digital Synthesis provides high tuning speeds, coherence schemes can be integrated into the FPGA utilized to create this synthesizer, and frequency resolution can be sub Hz. Currently DDS frequency ranges are limited, and analog multipliers are required to get to the higher frequencies. The part count is low, as the complexity of the implementation is in the FPGA - resulting in good result.

IV. HYBRID SYNTHESIS

From the discussion so far it seems like direct synthesis meets the needs of many measurement applications, at the price of reliability. Referring to Figure 1, the switching speed is determined by how quickly the synthesizer can actually ‘switch’ between different banks of oscillators. Adding more oscillators adds a greater frequency range and more importantly increases the frequency resolution.

If a Comb generator is used to replace one bank of filters and another bank is replaced with a VCO, then with the correct filtering this configuration could be coarsely tuned to produce frequencies that are multiples of the comb teeth. For example, if the comb teeth are 1 GHz apart, tuning would be achieved by selecting an appropriate tooth and then using the VCO to tune or mix up to whatever frequency required. This reduces the part count at the expense of resolution.

A DDS can be used to provide the fine tuning. The DDS



scheme needs to be architected so the frequency range of the DDS is limited enough to minimize spurious, then a number of extra filters are required to eliminate the rest of the spurious. The VCO, however, is an indirect synthesis method and is not coherent, also the phase noise is a combination of the VCO phase noise and the reference phase noise.

It is possible to add a VCO cancellation loop to the synthesizer [5], and eliminate the phase noise contribution of the VCO, thus making the system phase noise dominated by the phase noise of the reference. As we have effectively canceled out all contributions of the VCO, coherence no longer becomes an issue as the coherence is a function of the comb (which implicitly is coherent as each tooth is derived from the same source) and the DDS, which has been designed to support coherent tuning.

Comparing the plot of the reference at 10 MHz in Figure 2A, and the plot of the phase noise at the frequency synthesizer output when tuned to 10 GHz in Figure 2B, the contribution of the VCO has been eliminated and the main contributor to the system phase noise is from the multiplication of the reference. Figure 3A and 3B follow the same profile, demonstrating the VCO cancellation.

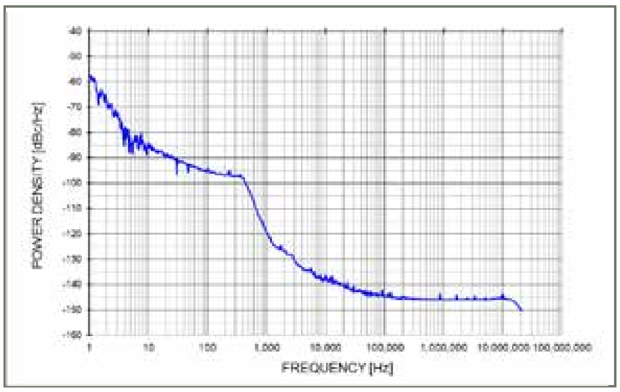


Figure 2a. 10 MHz Reference Single Sideband Phase Noise Plot

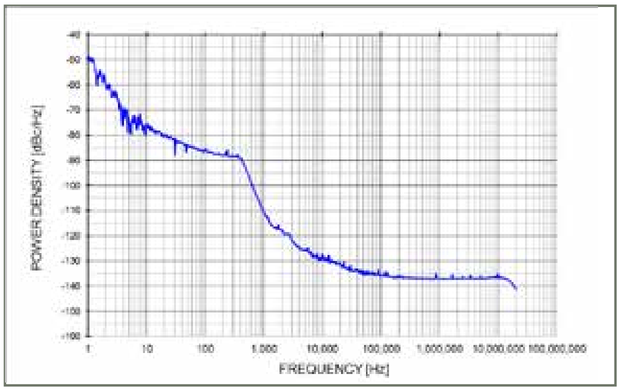
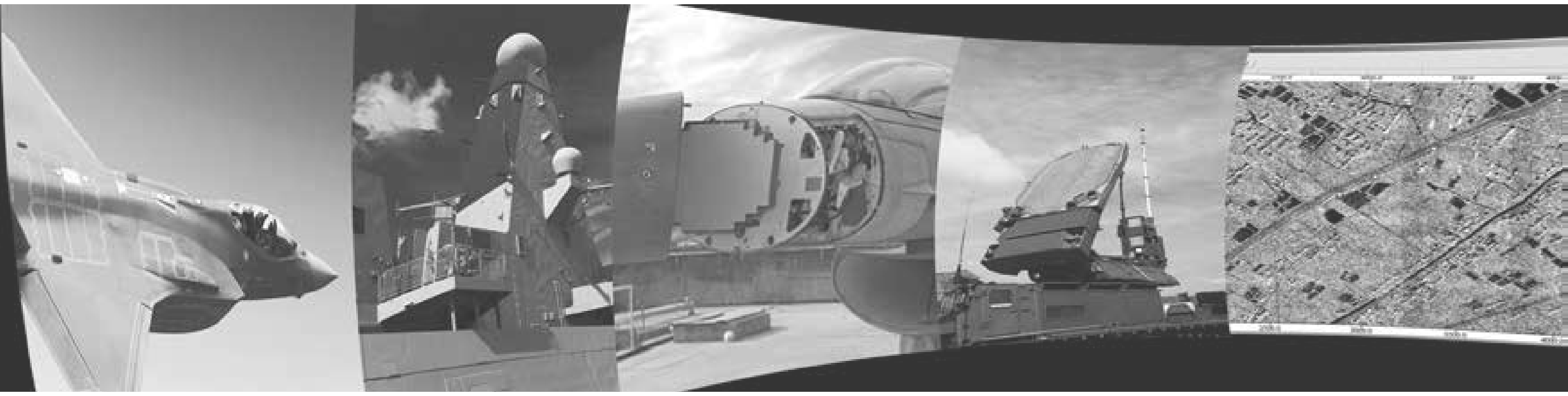


Figure 2b. 10 GHz Reference Single Sideband Phase Noise Plot

CONCLUSION

In conclusion the hybrid method modifies the block diagram of the direct synthesizer, eliminating oscillator banks by using a Comb generator and a VCO. The VCO introduces a phase noise pedestal, is not coherent and has a slow frequency settling time – however it does have a broad tuning range allowing the selection of a large range of comb teeth. The negative contributions of the VCO can be eliminated by using a VCO cancelation loop, and course tuning quickly. This creates the synthesizers coarse tuning structure. For fine tuning, a DDS structure is utilized allowing sub-Hz of resolution for Doppler applications. The DDS frequency range is limited and heavily filtered ensuring that spurious signals are kept to a minimum.

Finally the hybrid method reduces the part count for this type of synthesis, thus improving the reliability and reducing the footprint of this type of high performance synthesis technology.



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