Exploitation of direct digital synthesis for sweep generation in FMCW radar

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Abstract: Continuous wave radars, unlike their pulsed counterparts, cannot intrinsically determine target range and need to modulate their transmissions in order to do so. Frequency modulated continuous wave radars (FMCW) discern target range by cyclically ramping the output frequency and calculating range from the frequency difference between the transmitted and received signals.

Voltage controlled oscillators (VCOs) have traditionally provided a cost effective solution to provide frequency modulation. This paper addresses a solution based on direct digital synthesis (DDS) and discusses the impact of both these solutions in radar performance terms.

I. Introduction

The Tarsier T1100 programme at QinetiQ has addressed the development of a high resolution, FMCW radar that is suitable for foreign object detection (FOD) on runways [1]. The radar specification is put forward in Table 1; it can be seen that the need to spot extremely small targets has driven the design towards minimising the clutter footprint. This has been achieved by both a narrow azimuthal beamwidth of the antenna and a high range resolution.

Parameter	**Value**
Centre frequency	94.5GHz
Modulation	FMCW 600MHz sawtooth
Transmit power	100mW
Sweep time	3.28ms
Transmit polarisation	RHC
Receive polarisation	RHC and LHC
Azimuth beamwidth	0.2^{O}
Elevation beamwidth	2.0^{O}
Scan time	3^{O} / s typical
Range resolution	0.25m
Instrumented range	2048m
Receiver noise figure	6.5dB

Table 1: T1100 radar parameters

The high range resolution has placed a stringent specification on the frequency modulation of the radar. Although it currently uses a VCO based solution, the advances in DDS technology have made it particularly attractive for this application.

II. Frequency modulation and key parameters

FMCW radars rely on a swept (or frequency modulated) output to discern target range. Although there are many techniques for achieving this, a cost effective solution that does not compromise system performance is to perform the modulation at lower frequency and then up-convert to the transmission frequency. The performance of the oscillator used to generate the frequency sweep will impact on system parameters.

The first parameter is the oscillator bandwidth. In FMCW terms, the broader bandwidth provides finer range resolution. It can be calculated that 600MHz of bandwidth is required to achieve a range resolution of 0.25m. Future system development may address reducing the clutter cell size further; hence ideally bandwidths in excess of 1GHz would be desirable.

The oscillator spectral purity is key to overall system performance. Ideally an oscillator output would contain only the desired signal, however two sources of corruption are encountered. A typical oscillator output is shown in Figure 1 (left) and shows both discrete, unwanted signals (spurs) as well as the unwanted phase noise “shoulders”. Spurs are discrete signals that can usually be traced to unwanted coupling of other signals (clocks, power supply switching products etc) and can be minimised with careful design. Phase noise appears as a collection of random phase fluctuations, caused by thermal and flicker noise within the oscillator, whose power spectral density decays with separation from the carrier.

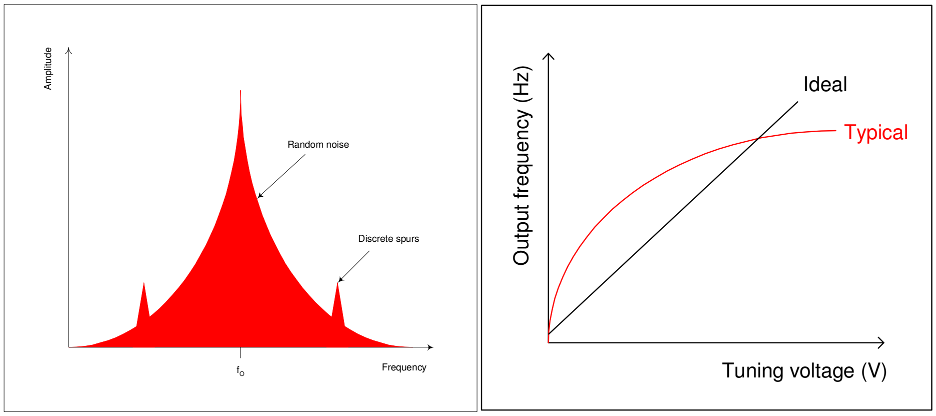

Figure 1: Spectral purity (left) and typical tuning sensitivity (right).

Whereas the presence of spurs can lead to false target returns within the radar, phase noise will lead to a reduction in receiver sensitivity in the presence of high target returns. A practical example of the effects of phase noise is shown in Figure 2 (left) and shows a measured plan position indicator (PPI) display. The T1100 unit shown in Figure 2 (right) was deployed alongside a runway and used to scan the environment. The runway and associated taxiways can clearly be seen along the top, however metal structures with powerful radar returns have raised the receiver noise floor at certain angles, resulting in the bright “spokes” that are visible in the display. The radar will suffer reduced sensitivity at these bearings.

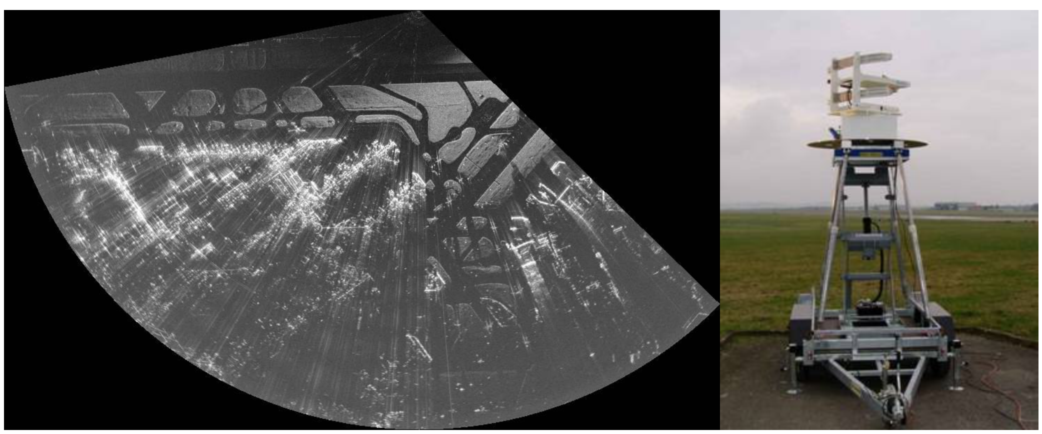

Figure 2: PPI scan showing the effects of phase noise (left) for T1100 airfield deployment (right).

Another parameter to consider is sweep linearity: the linearity of the rate of change of frequency with respect to time. Most oscillators do not exhibit a linear relationship in tuning sensitivity with respect to frequency, see Figure 1 (right). Any non-linearity of the sweep will result in a “smearing” of the target with range.

III. Description of VCO based solution

The VCO is an oscillator whose output frequency can be modulated proportionally to an applied DC voltage. The devices themselves are well understood [2] and represent a good compromise between cost and performance. The tuneable bandwidth is usually limited to an octave and has to be compromised against the phase noise performance and tuning linearity. The modulation sensitivity is not linear and generally follows the profile shown in Figure 1 (right). The phase noise is a function of numerous factors: the quality factor of the resonator, the quality factor of the varactor diodes and the active device used in the oscillator. However VCO phase noise also degrades due to noisy power supplies, poor grounding and unwanted coupling onto the modulation port.

The device chosen was a Mini-circuits ROS-1710-1. This device has a tuneable bandwidth of over 600MHz and a phase noise of -120dBc at 100kHz. The VCO was configured as shown in Figure 3. The control of the VCO is performed digitally using a look-up table of desired values stored on a programmable device. The periodic sweep is divided into discrete time increments and a corresponding value stored for each increment. Synchronously clocked counters address the programmable device, which then uses its table of desired values to set the output voltage of the digital to analogue converter (DAC).

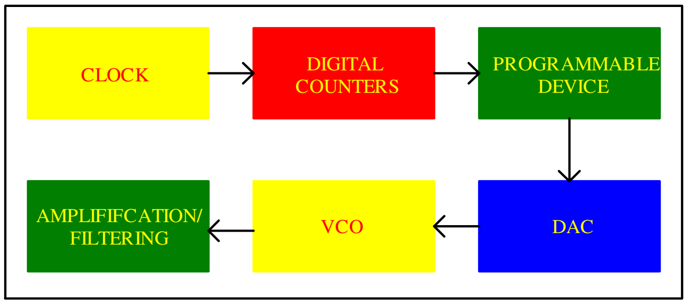

Figure 3: VCO configuration

An exploded diagram of the physical implementation of the VCO solution is shown below in Figure 4 (left) and a photograph of the final unit is shown in Figure 4 (right). Both digital and analogue components are implemented on a single laminate, although they are physically separated and shielded from one another by the conformal enclosure.

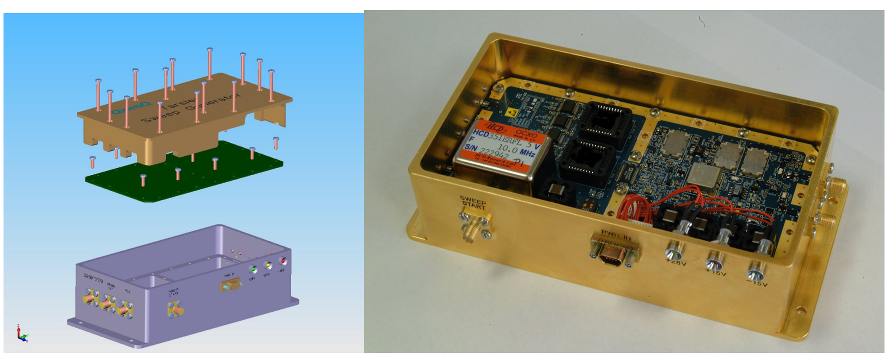

Figure 4: VCO implementation

The phase noise and sweep linearity of this solution will be discussed in the results comparison. The spectral output does however contain some coupling from the 10MHz clock for the digital circuitry at -45dBc.

IV. DDS solution

A simplified DDS architecture is shown in Figure 5 for a typical integrated circuit with support circuitry [3]. An external reference is provided to both the phase accumulator and the DAC. The phase accumulator may be thought of as a numerically controlled oscillator, which derives its output from the reference clock. The phase accumulator will generate appropriate phase increments for the desired output frequency. A phase to amplitude conversion algorithm is then required to interface the output of the accumulator to the DAC.

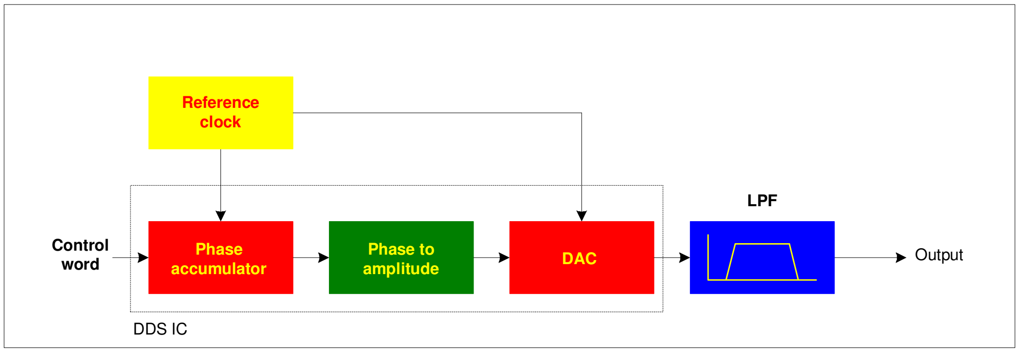

Figure 5: Simplified DDS architecture

DDS was investigated for future development as it offered a number of advantages. Principally these are:

- Frequency sweep is linear (but discrete)
- Lower phase noise
- Potentially more robust to vibration and temperature variations.

The DDS may have comparatively good phase noise but its output contains numerous sources of spurs: quantisation spurs (from the imperfect digital representation of an analogue signal), phase accumulation spurs (approximation to the desired phase increments in the phase accumulator), image responses (which appear at differences between the clock frequency and output frequencies), clock feed through etc. The primary concern with adopting a DDS solution is that these spurs could lead to numerous false targets being generated.

An experiment was undertaken using available laboratory components to generate a DDS solution that was broadly equivalent to that of the VCO. A block diagram of the set-up is shown in Figure 6. The DDS chip used was the Analog Devices AD9858 [4].

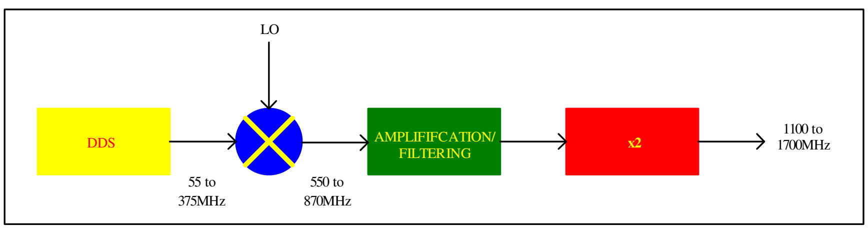

Figure 6: DDS solution architecture

The low frequency range of the DDS is overcome by up-converting the output and then doubling the bandwidth. Since no bespoke filtering was available, inter-modulation of the leaked LO signal with the wanted signal caused a number of spurs in the final output (see Figure 7). Although undesirable, the results of the next section will show what effect that this has on radar performance.

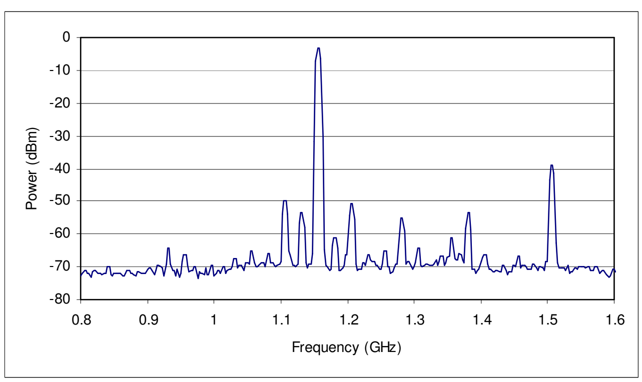

Figure 7: Typical output spectrum of up-converted DDS output

V. Results comparison

A comparison of the phase noise of the VCO and DDS solutions are shown below in Figure 8. The VCO solution exhibits about 5dB worse performance than desired at 100kHz. The DDS solution can be seen to offer noticeably better performance up to 1MHz. Further investigation showed that the DDS trace is dominated by the performance of the synthesiser used as the local oscillator in Figure 6 and could therefore be improved with a higher quality alternative. The third trace is the performance of the millimetric local oscillator of the radar and it can be seen that above 30kHz, it is considerably worse than either solution and will hence dominate the overall profile. Although the DDS can be seen to be better, it will only offer overall improvement close to the carrier frequency.

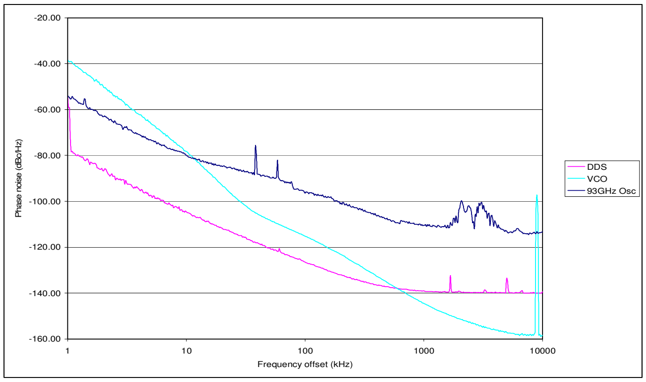

Figure 8: Phase noise comparison

A comparison of the linearity results are shown in Figure 9. Due to the high frequency of operation, the results were generated using a fixed delay line and mixing the output with the delayed version of itself. If the rate of change of frequency is constant, the low frequency output should also remain constant with time across the length of the sweep. The VCO is broadly linear over much of the band but exhibits some overshoot at the beginning whereas the DDS is as expected, linear across the sweep.

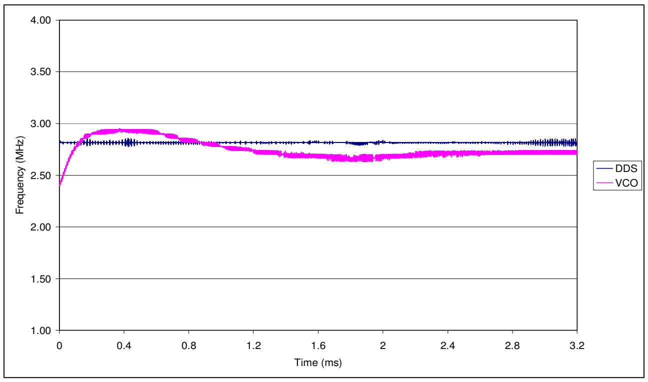

Figure 9: Sweep linearity comparison

The “A” scope is commonly used in radar to display raw data in terms of target return against range. Figure 10 shows raw data for the VCO and DDS against a known (but uncalibrated) target at 255m. Inspection of the trace confirms earlier results in regards to phase noise and spurs. The DDS solution has lower phase noise around the peak target return up to a distance of 30m (which corresponds to a 35 kHz separation from carrier). However there can clearly be seen to be a number of unwanted returns in the profile.

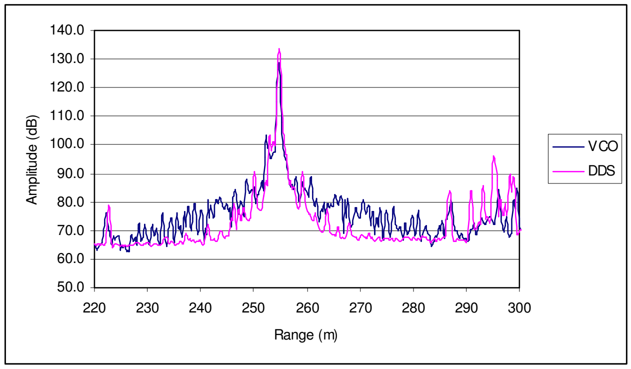

Figure 10: "A" scope comparison of target returns

VI. Conclusions

DDS can be seen to offer a viable alternative to the VCO for broadband FMCW radar. The results show that there are clear advantages in terms of sweep linearity and close in phase noise but there is still work required to address the issue of spurs.

References:

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