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Case study analysis of linear Chirp and Multitones (OFDM) radar signals through simulations and measurement with HYCAM-Research test bench

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***Abstract*—This paper presents a experimental platform that allows comparing objectively any radar waveforms. This is realized by equating radar characteristics, using the same test-bench HYCAM-Research, the same signal processing and also insuring the reproducibility of the experiments. The experimental measurements on linear chirp and multitones are analyzed through distance and velocity imaging.**

Keyword: OFDM, Multitones, Chirp, active radar, Ultra Wide Band, Measurements, distance-velocity image

I. Introduction

Over the past few years the active-radar community has taken an interest in the multicarrier signals originally designed for telecommunications. Copying telecommunication signals to mask radar activity is of the utmost importance for radar Low Probability of Interception. This also facilitates the insertion of the signal into the overcrowded spectrum. Also it would facilitate the implementation of multifunction radar e.g. dual use of telecommunication and radar functions. To date, multitones as active radar signals have been mostly studied through simulations. Levanon et al. in [1][2][3] studied crest factor reduction by phase modulation and ambiguity function optimization. Prasad et al. in [4] simulate target detection capabilities of multicarrier signals. Franken et al. in [4] simulate the Doppler tolerance of OFDM-coded signals. Some experimental results can be found in [5][6][7][8] collected with HYCAM-RCS measurement system and HYCAM-Research version 1. This paper will present the HYCAM-Research version 2. The primary function of this test-bench is to validate experimentally that multitones can be used as radar signals. The particularity of version 2 is that it can operate with any waveforms. Hence it will allow comparing multicarrier signals with the chirp which is the reference in radar. First of all, in order to analyze the differences in performance of different signals, it is essential to start by establishing a waveform-independent equivalence. Then the experiment plan and the test-bench will be described. Finally an analysis of the experimental results will be presented.

II. Establishment of the Equivalence Between different radar waveforms

The equivalence will be established through radar principles and technical issues.

A. Radar Principles

A basic description of a radar system is given by the distance ambiguity ΔR, the distance resolution δR, the velocity ambiguity Δv, the velocity resolution δv, the Pulse Compression Factor (PCF) and the Power Budget (PB). To obtain an equal description for different waveforms implies that the pulse repetition period T, the pulse width T_e, the Bandwidth B, the centre frequency f_c, the number of pulse integrations N and the mean power P_{mean} have to be equal in the different signals.

B. Technical issues

Since the analysis is based on radar waveforms and not the radar itself, the radar set-up HYCAM-research will be strictly identical for all the measurements. Also since it wasn't possible to measure the different signals simultaneously, the experiments will have to be reproducible.

III. Presentation of HYCAM-Research test bench

The test bench is designed to test arbitrary signal waveforms with a bandwidth up to 800MHz thus reaching submetric distance resolution. HYCAM-Research in its current configuration emulates a X-band radar. It can be broken down into three distinct parts. The DA/AD interface is the core of the radar reconfiguration capability. It also dimensions the RF hardware necessary to emit the signal and receive the echoes. These echoes are then processed to extract a distance-velocity image.

A. DA/AD Interface Description

The signal generator is a Tektronix AWG7102. It is equipped with two 10-bits DAC channels and has a sampling frequency f_{SDAC} of 10GHz. This device has an analogue bandwidth of 5.8GHz. The digitizer is a Tekmicro Neptune II.

It is equipped with two 10-bits ADC channels and has a sampling frequency f_{SADC} of 2GHz. This device has an analogue bandwidth of 3.3GHz. Because the AD/DA interface can't generate X-band frequencies directly, the radar frequency plan is defined with Intermediate Frequencies (IFs). Also before digitization an anti-aliasing filter is necessary to reject the frequencies outside the useful bandwidth. The IFs are defined in the second Nyquist band of the ADC (figure 2) to take advantage of the performance of band pass filters in higher frequencies and also avoid the flicker noise in the digitizer [5]. Hence IF ranges from 1.1GHz to 1.9GHz. The signal being in the second Nyquist band implies that the frequencies will be downsampled. Since the Nyquist-Shannon sampling theorem is respected $f_{SADC} > 2B$, there is no information loss. However downsampling means that the frequencies are mirrored around half the f_{SADC} as shown in figure 1. Knowing the IF, the radar hardware can be dimensioned.

B. HYCAM-Research hardware description

A simplified schematic of the radar hardware implementation is shown in figure 2. The AWG7102 generates the 10MHz synchronization signal for all the devices and the triggers enabling generation and digitization. The local oscillators LO1 and LO2 are respectively HP8671B and HP8672A VCO frequency synthesizers. They are both set at $f_{LO} = 8.9GHz$. This frequency was chosen in order to reject spurs up to the 5^{th} order outside the bandwidth of interest both for upconversion and downconversion. The IF generated are upconverted to Radio Frequencies RF ranging from 10GHz to 10.8GHz and its mirror image around f_{LO}. The RF are filtered and amplified through a Low Noise Amplifier (LNA1). At the LNA output, a 20dB directional coupler is placed. The coupled output leads to the reference path and the direct path leads to the transmitter (Tx) 20dB horn antenna. At the receiver (Rx) front end is another 20dB horn antenna. The signal in the Rx path is then amplified by a second LNA2 and filtered. Then both the reference signal and the received signal are downconverted to their original IF and are filtered to avoid aliasing before digitization. The acquired data are then stored on a computer for off-line signal processing. However before hand, the signals to be analyzed will be defined.

C. Radar signals under study

The radar operates in continuous-wave (CW) mode, with the following basic signal parameters $T = T_e = 0.5\mu s$, $B = 800MHz$, $f_c = 10.4GHz$. This implies $\Delta R = 75m$, $\delta R = 0.1875m$, $\Delta v = 28846m/s$, and $PCF = 26dB$. The pulses will be integrated over 0.2s, thus a theoretical integration gain of $N = 56dB$. However the digitizer is limited in memory, so the data acquisition is gated to be able to observe slow targets. The gate repetition period is 5kHz thus $\Delta v = 72m/s$ and $N = 30dB$. The radar waveforms, studied in this paper, are the Linear Chirp (C) and the Newmann Phase Coded Multitones (MT). Their analogue equations are respectively:

$$C(t) = \exp\left(i \cdot 2 \cdot \pi \cdot \left(f_I + \frac{B}{2 \cdot T} \cdot t \right) \cdot t \right) \quad (1)$$

$$MT(t) = \sum_{k=0}^{K-1} \exp\left(i \cdot 2 \cdot \pi \cdot (k_0 + k) \cdot \delta f \cdot t + \phi_k \right) \quad (2)$$

where $\phi_k = \frac{\pi \cdot k^2}{K}$ is the Newmann Phase Code [6]. $t \in [0;T[$, T is the pulse width and is known as the orthogonal period for MT. $B = K \cdot \delta f$, $\delta f = T^{-1} = 2MHz$ is the MT's frequency step and $K = 400$ is an integer number of carriers. T in the case of MT is known as the orthogonal period. Since the MT signal has to respect signal orthogonality to get the best pulse compression (PC) performance, the discrete-time form of (2) contains only integers except for the phase coefficient. Rewriting the equations in discrete time, (1) and (2) become respectively (3) and (4).

$$C(m) = \exp\left(i \cdot 2 \cdot \pi \cdot \left(k_0 + K \cdot \frac{m}{2 \cdot M} \right) \cdot \frac{m}{M} \right) \quad (3)$$

$$MT(m) = \sum_{k=0}^{K-1} \exp\left(i \cdot 2 \cdot \pi \cdot \left((k_0 + k) \cdot \frac{m}{M} \right) + \phi_k \right) \quad (4)$$

where m is the sample number and belongs to [0,M[.

Now that the signals are equivalent with respect to time and frequency, the equivalence in Signal-to-Noise Ratio has to be established. For this, the mean power P_{mean} of both signals needs to be equalized. Only the real part of the complex signal is generated through the DAC, meaning that the available power is limited as well as a limited dynamic range. Also only the real part of the complex signal is generated. Thus it is essential to minimize the Peak-to-Mean Power Ratio (PMEPR) to maximize the output P_{mean}. For a quantized signal $s(m)$ with M samples

$$PMEPR(s) = 10 \cdot \log_{10}\left(\frac{\max|s(m)|^2}{\frac{1}{M} \cdot \sum_{m=0}^{M-1} |s(m)|^2} \right) \quad (5)\ [7]$$

The PMEPR is calculated using quantized samples of a normalized signal. The nominal PMEPR value of the linear Chirp is 3.01dB and 5.43dB for the multitones. Depending on the number of bits, the PMEPR variations are shown in figure 3. It shows that from 6bits, both signals are well represented with regard to PMEPR. From 6bits, the error between the simulated and nominal values of PMEPR is less than 0.15dB. To confirm these simulations, measurements were performed for both waveforms with pulse length [0.5µs, 5µs, 50µs, 500µs, 1ms] and bandwidth [1MHz, 10MHz, 150MHz, 800MHz]. The PMEPR with respect to pulse length, bandwidth and number of bits was measured and confirmed the fact that after 6 bits the signals are well represented with respect to PMEPR. For our example $T = T_e = 0.5\mu s$, $B = 800MHz$ the signals are normalized:

$$\frac{P_{mean}(MT)}{P_{mean}(C)} = \frac{PMEPR(C)}{PMEPR(MT)} = -2.4dB \quad (6)$$

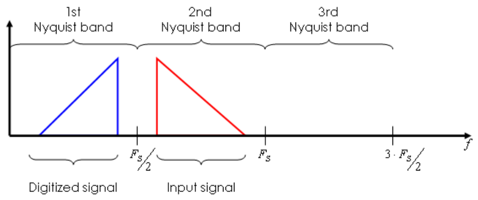

Figure 1 downsampling effect on the digitized spectrum

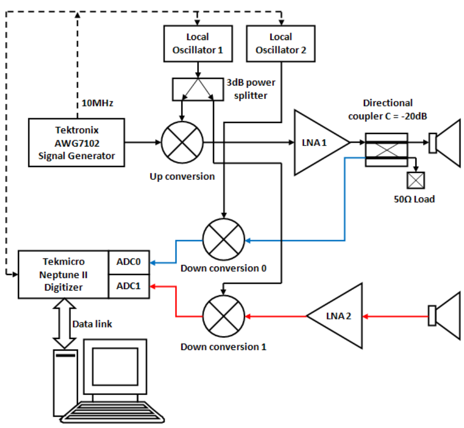

Figure 2 simplified schematic of the HYCAM-Research radar

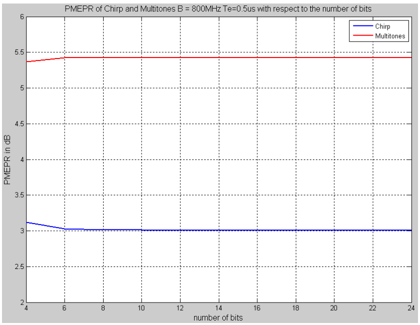

Figure 3: PMEPR of Chirp and Multitones function of the number of bits

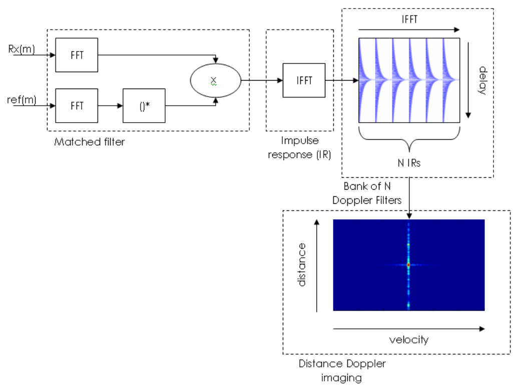

Figure 4. description of HYCAM-Research signal processing

This means that when generating a C, the DAC output peak voltage will be set at 75.8% of the peak voltage used for the MT signal. This will guarantee the equivalence of both waveforms with respect to SNR for DACs having at least 6bits. A value of 76.2% was found experimentally with power meter readings at the Tx LNA1 output. This means that the chirp exploits the DACs better than the multicarrier in linear. Now that the signals are equivalent, this will theoretically give equivalent results on the same targets through the same signal process.

D. Description of the Signal Processing

The signals under study could be considered as narrowband since the fractional bandwidth $\eta=0.077$. In [9], the UltraWideBand definition specifies a minimum of *0.25*. Hence the narrowband approximations for Doppler shift f_d is apparently valid in this case. However a calculation of the Doppler shifts at 10GHz and 10.8GHz shows a difference varying linearly with velocity $\Delta=5.33\cdot v$. At $v = 10m/s$, $\Delta= 53.33Hz$. Hence with an integration time of 0.2s and thus a frequency resolution of 5Hz, the signals can't be considered as narrowband with respect to this signal process. Currently, only one technique is implemented to process the data which is developed originally for narrowband signals. Knowing the process is not optimum, it doesn't change a thing for the analysis as long as both signals are computed in the same way. The data processing is shown in figure 4. The reference and received samples have their spectrum calculated over a orthogonal period T by Fast Fourier Transform (FFT). Then the reference spectrum complex conjugate is computed, thus obtaining the matched filter transfer function. It partially takes into account amplitude and phase distortions caused by hardware. These two spectra are then multiplied term by term. The result is the matched filter impulse response (IR) in frequency domain. Then it is transposed back in time domain by an Inverse FFT (IFFT), thus giving an IR with respect to delay. N IRs are accumulated and an IFFT is applied across the IR for every delay. It generates N Doppler filters centered at $f_{dn} = n/(N{\cdot}T)$ when n belongs to $[0,N-1]$. The result is a delay-Doppler image easily converted into distance-velocity. The equivalence in data processing has been established, now only remains the description of the experiment environment and target.

E. Description of the experiment

The HYCAM-Research experiment was done inside ONERA's premises. The parking area shown in Figure 5 is useful to test the radar because it has low clutter radar cross section $RCS = -12dB/m^2$. The area is radiated with two Horn antennas separated by 0.5m (bistatic angle < 1.5°) and with radiation absorbent material (RAM) to improve the isolation between the Tx and Rx antenna. Their isolation without RAM is -70dB and with RAM -76dB. They are positioned at a height $H = 16.68m$, the azimuth is -70°, and the elevation is 35°. The antenna footprint is approximately 560m^2. The trihedral reflector (TR), positioned at the center of the scene, is distant

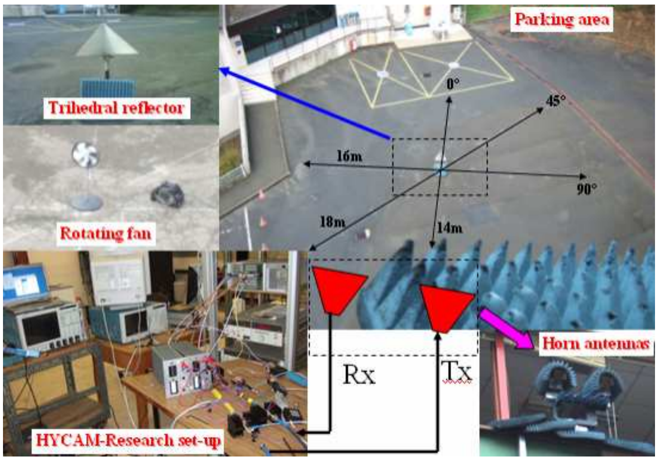

Figure 5: HYCAM-Research and the experiment environment and targets

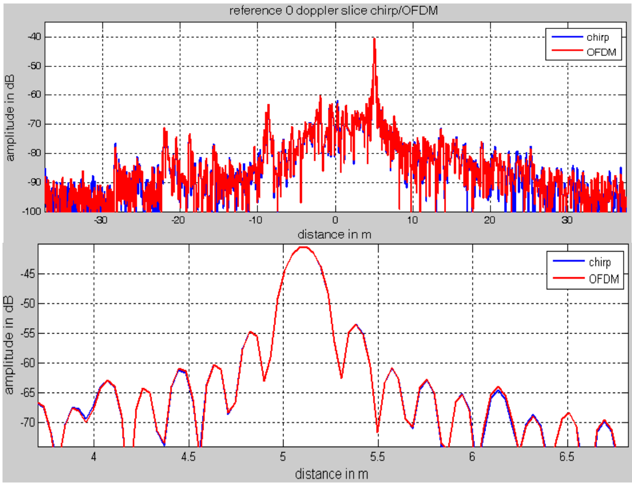

figure 6: zero velocity cut of the distance-velocity image for a 30-dB TR

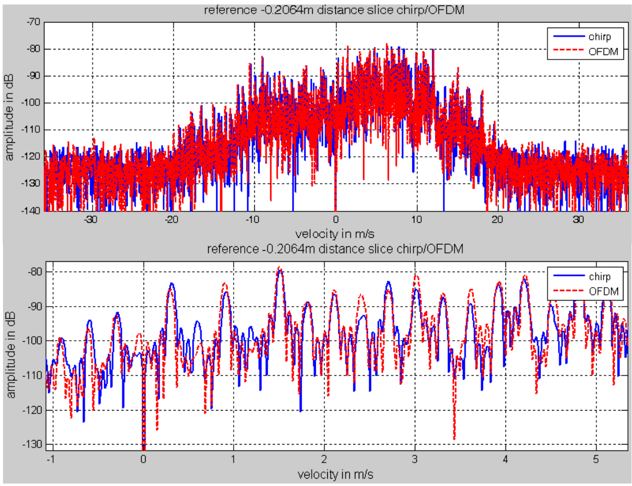

Figure 7: -0.2m distance cut of the (d,v) image for a metalized fan

of D = 27.75m. It has a RCS = 30dBm2 thus giving a contrast of approximately C = 59dB between the reflector and the clutter. This configuration is used to calibrate the radar meaning to set the phase origin and deduce the RCS of other targets from the RCS of the reflector. The other target was a plastic fan. These two targets allow for reproducible experiments since the reflector is a static target and the fan always rotates at the same velocity. Now that all the parameters are set, the measurement results will be analyzed.

IV. Analysis of the Measurements

Two kinds of measurements were performed. The first consists in measuring a static 30dB-TR to analyse the distance impulse response of both waveforms. The second consists in measuring a rotating fan to analyse the resistance of both waveforms with respect to velocity. Also in both cases the received signal was processed with the measured replica and the theoretical replica. After analysis, the difference in measurement between both processes is 0.1dB max. Thus only the measurement with a measured replica will be studied next. These results show that when the Tx LNA is used in linear mode, the reference channel isn't necessary.

A. Trihedral reflector measurement

The TR has an RCS of 30dBm^2 and is placed at 30.95m from the antennas. First, an observation of figure 6 shows very similar behaviours. On the main peak and sidelobes, the amplitude variations between the Chirp and Multitones response is less than 0.1dB. This experience along with another involving two TR reflectors were repeated over three days always yielding the same performances. Since the TR appears to the radar as a punctual target, the 3dB-width can be measured. For both waveforms, its value is 0.188m which is consistent with the theoretical values of 0.1875m. Also the distance between the calibrator and the target can be measured 5.121m which is coherent with the distance measured physically 5.197m.

B. rotating fan measurement

The rotating fan is placed at 25.75m from the antennas. For this measurement, it was very windy. Despite the weather, figure 7 shows that the chirp and multi-tones responses in velocity display the same velocity peaks. However the differences in amplitude reach up to 5dB sometimes in favour of the chirp and sometimes in favour of the OFDM.

V. CONCLUSION

The use of Multitones as a radar signal has been validated experimentally. It was shown that the chirp thanks to its low PMEPR exploits fully the DAC's available average power as opposed to multitones which has a higher PMEPR in our example the difference with the chirp is about 2dB. It was also determined through theory and validated experimentally that both waveforms were sufficiently well represented with 6bits with respect to PMEPR. The HYCAM-Research test-bench has been tested successfully with both chirp and multicarrier signals and the results obtained in linear amplification are very similar for both waveforms. For the specified settings, the differences noted are up to 0.1dB in range and up to 5dB in velocity. However in order to explain in a detailed manner those differences more analysis are required and also more experiments. Upcoming experiments involve changing the Tx amplifier by a 10W solid-state amplifier and 200W travelling wave tube amplifier to study the distortion tolerance of both waveforms. The range of operation will also be extended from 50m up to 2.5km.

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