REALIZATION OF THE NASA DUAL-FREQUENCY DUAL-POLARIZED DOPPLER RADAR (D3R)

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ABSTRACT

This paper describes some of the novel technologies adopted in the realization of the NASA Dual-frequency Dual-polarized Doppler Radar (D3R) system for to be used by the GPM ground validation program. A description of the transceivers and major trades that lead to a solid-state architecture is presented. Other aspects enabling the design such as the waveform design and generation and the digital receiver is also described. Data measured from a similar power amplifier was used to estimate the expected range side lobe performance. An estimate of the expected sensitivity based on the transceiver parameters also presented.

Index Terms— GPM GV, D3R, dual-frequency radar, dual-polarized radar, solid-state transmitter

1. INTRODUCTION

The Global Precipitation Measurement (GPM) mission is an international partnership aimed at two things primarily, 1) the advancement in knowledge of the global water cycle and 2) the improvement of weather, climate and hydrological prediction capabilities through more accurate and frequent measurements of global precipitation [1]. Based on its successful predecessor, the Tropical Rain Measuring Mission (TRMM), the GPM core satellite will carry a Ku-band weather radar with the addition of a Ka-band radar in order to improve snow and light rain precipitation measurements. Dual-frequency measurements will also provide the capability of measuring parameters directly related to the microphysics of precipitation such as drop size distribution (DSD).

Within GPM, a significant effort is being dedicated to the ground validation (GV) of the dual-frequency precipitation radar (DPR) onboard its core satellite. As part of the GV effort, a ground based Ka/Ku-band fully polarimetric Doppler radar system (D3R), model shown in Figure 1, is under development and scheduled for integration during the Fall of 2010. By operating at both Ka- and Ku-band, 35.56 GHz and 13.91 GHz respectively, it is expected that it will provide accurate estimates of rainfall as well as DSD parameters [2]. Furthermore, the full polarimetry capability makes D3R a unique, self-consistent cross validation tool for GPM since it will be capable of retrieving DSDs through both dual-frequency and dual-polarization techniques [3]. This paper is focused on the novel transceiver technologies required for the realization of the D3R.

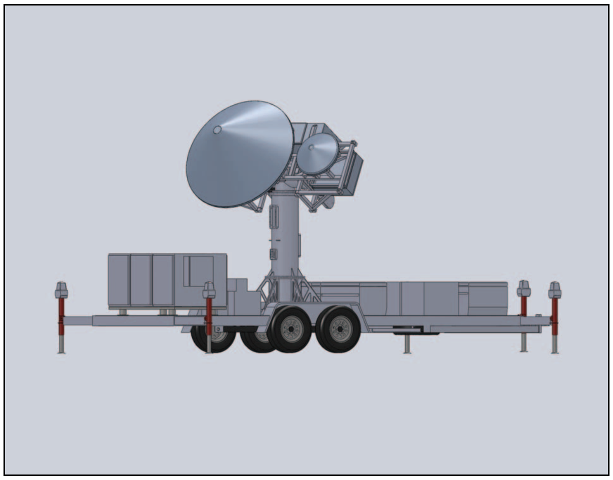

Fig. 1 Model of D3R on mobile trailer platform.

2. TRANSCEIVER DESIGN

Achieving a dual-frequency, dual-polarized mobile radar system on a single scanning platform places relatively firm size and weight constraints on the hardware used. A lightweight and compact design is required since it will allow the mounting of the RF electronics as close as possible to the antennas, which minimizes front-end losses and makes the system easier to transport between field campaigns. On the other hand, since the main purpose of the D3R is to serve as a validation tool for GPM during cold

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and warm season campaigns (operation in temperatures from -40 to 40C expected), it requires a design approach that not only minimizes size and weight but also maximizes both its reliability and stability over time and temperature.

Given the sensitivity (single pulse) requirement of -10 dBz at 15 km at both frequencies, suggests the need for a high peak power transmitter. However, recent advances in solid-state technology in the communication industry have made possible the development of rugged, light-weight, compact 55 W and 220 W power amplifiers at Ka- and Ku-band respectively. Adopting a solid-state power amplifier (SSPA) based transmitter approach requires the use of more advanced waveforms, which in turn, could not only improve the sensitivity but also the sampling capabilities of the D3R. Furthermore, it is well inline with the goal of achieving a lighter and more compact as well as reliable radar system.

2.1. Expected Sensitivity and Transmitter Selection

A detailed sensitivity analysis using the SSPAs mentioned above has been performed and results are shown in Figure 2. The waveform used in the analysis will be discussed in the following section while other parameters used are listed in Table 1.

TABLE 1
SENSITIVITY ESTIMATION PARAMETERS

Parameter	Value
Antenna Gain (Ka and Ku)	44.5 dBi
Antenna Beam Width (3dB) (Ka and Ku)	1 deg
Peak Power (Ka and Ku respectively)	40 W and 160 W
Tx Signal Bandwidth	1 MHz
Pulse Widths	1, 20 and 40 us
Range Resolution	150 m
Receiver Noise Figure (Ka and Ku respectively)	5.5 and 4.6 dB

Conventional approaches such as the use of a high peak power tube-based transmitter (e.g. extended interaction klystrons (EIK) and traveling wave tubes (TWT)) could also provide the D3R with the required sensitivity. However, these typically require the use of high voltage power supplies, which end up requiring more space and may not be as reliable when compared to SSPAs. Another point worth mentioning is the overall stability of the system. Working at relatively low power levels allows for a much better calibration loop design. The current design achieves a cal to leakage ratio greater than 40 dB for both the Ka- and Ku-band transceivers. This will allow us to keep track of transceiver gain transfer function fluctuations with 0.1 dB precision or better. For these and other reasons not mentioned above, the D3R will use solid-state technology versus a tube-based approach.

After selecting SSPAs as the transmitter technology, there are several options to distribute power between polarizations (e.g. single transmitter with 2 way splitter, single transmitter with 2 way splitter and switch). For the D3R, the requirement was to have full polarimetric capabilities therefore ruling out splitting the transmit signal without a high power isolation switch that would allow polarization selection. Now, to achieve the sensitivity shown in Figure 2 for each polarization suggests the need for a dual transmitter or else it would be lowered by 3 dB. Furthermore, we could also avoid adding the high power switch and losses associated with it, which in the long run translates to better reliability. Another benefit of having independent transmitter channels is the isolation that comes with the design approach as well as the capability of optimizing the drive power based on channel balance information obtained from the calibration loop. Hence a dual independent transmitter design approach was adopted for the D3R.

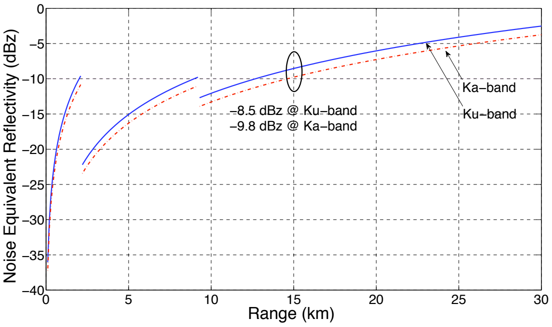

Fig. 2 D3R single pulse noise equivalent sensitivity for each polarization channel.

3. WAVEFORM DESIGN

As mentioned in the previous section, adopting a solid-state transmitter approach brings with it some challenges with regards to waveform design. However, with recent developments in digital signal synthesis and processing technologies, more advanced waveforms have become feasible. Achieving the required sensitivity of -10 dBz at 15 km with the proposed SSPAs, as shown in Figure 2, will require the use of pulse compression. Consequently, with the use of long pulse compressed waveforms come large blind ranges as well as range side lobe contamination. To overcome these, a novel waveform composed of three consecutive, non-linear FM, frequency-separated pulses, shown in figures 4 and 6, is being implemented. In this scheme, blind ranges are mitigated by optimizing the time-bandwidth product of pulses 1 and 2 to achieve the sensitivity of the middle and farthest ranges while pulse 3 (no FM) is used to sample ranges closest to the radar. On the other hand, since very large reflectivity gradients (30-40 dB/km) [4] aren't uncommon in precipitation measurements, range side lobes need to be minimized. To achieve this, a non-linear FM (NLFM) technique similar to the one described in [5] will be used.

To estimate the expected range side lobe performance, the transfer function of a similar 25 W version made by the same vendor fabricating the 55 W and 220 W SSPAs was measured using a vector network analyzer. Various input power levels were used to characterize the gain and phase transfer function of the SSPA. A sample 40 us pulsed NLFM waveform was then convolved with the measured SSPA transfer function and later used to design the compression filter. Peak side lobe suppression levels better than 75 dB were achieved. Figure 3 shows the pulse compression filter output with SSPA operating in the saturation region.

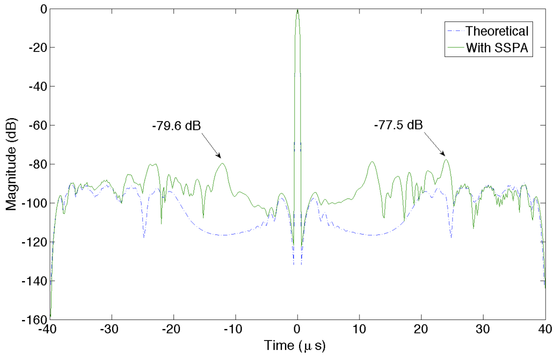

Fig. 3 Pulse compression filter output for theoretical case and including SSPA distortion during operation at the saturation region.

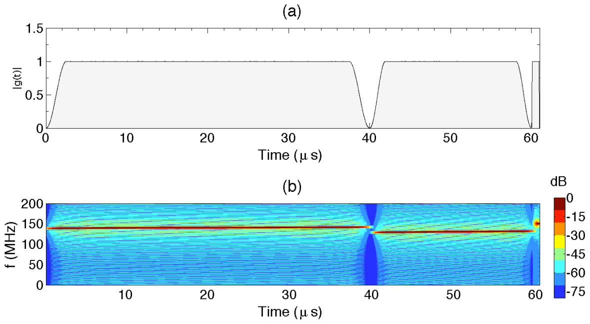

Fig. 4 D3R frequency diversity pulse compression waveform a) envelope and b) time-frequency plot [5].

3.1. Waveform Generator

As described above, a fairly complex waveform is required to achieve the -10 dBz sensitivity in the D3R. Therefore a highly flexible arbitrary waveform generator (AWG) based on digital signal synthesis was implemented. The AWG was developed at CSU for the Wideband Experimental X-band (WiBEX) radar system [6]. It consists of a Xilinx Spartan-3E FPGA controlled by a host computer which sends I and Q pairs of the pre-determined waveform to be stored in random access memory (RAM). When triggered, the waveform is then read and passed to the digital up-converter (DUC) through first in first out (FIFO) buffers. The intermediate frequency of the output of the AWG is set at 140 MHz. After this stage the transmit signal is passed to the up-conversion stage of the transceiver where it is band-pass filtered prior to up-conversion. Figure 5 shows a block diagram of the AWG.

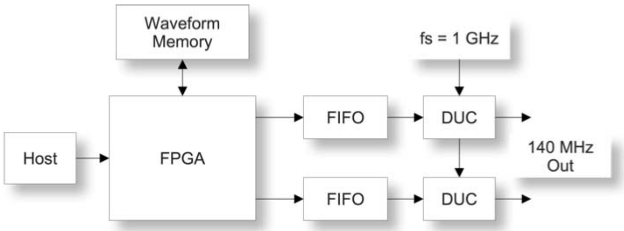

Fig. 5 Arbitrary waveform block diagram adopted from CSU WiBEX system [6].

Although not shown in Figure 5, the AWG will also handle the timing control of the system. Since many of the algorithms will be combining the acquired data at Ka and Ku-band, the synchronization of both systems is highly important. Provisions were made in the design of the AWG to implement a master-slave configuration where Ku-band system will serve as the master transmit and receive trigger for the Ka. By doing so, both Ka and Ku-band systems will be synchronized during operation. Furthermore, all clocks/oscillators within the AWG, and throughout the entire system, are locked to a 10 MHz ultra-stable local oscillator reference. Figure 6 shows a timing diagram of the transmit waveform and corresponding receiver sampling windows.

3.2. Digital Receiver

To achieve the processing of the waveform described in figures 4 and 6, an agile FPGA based digital receiver architecture based on the Xilinx Virtex 5 SX95T FPGA was chosen. The latter will have the task of filtering the incoming returns into 3 complex sub-channels as well as handling the matched filtering (shown in Figure 7).

Incoming IF (140 ±25 MHz) signals will be sampled by a 16 bit analog to digital converter (ADC) at 200 Msps followed by a three way divider to the input of each sub-channel. Each sub-channel will perform digital in-phase and quadrature (I and Q) down-conversion through the use of fully programmable numerically controlled oscillators (NCO). Each NCO will be tuned to the corresponding pulse to be processed by the sub-channel. Following the complex down-conversion, the signal will be filtered and down-sampled prior to match filtering. After match filtering the signal could be re-sampled (optional) prior to being framed, time stamped and tagged with the antenna position. Finally it is transferred over a PCI interface to the host computer.

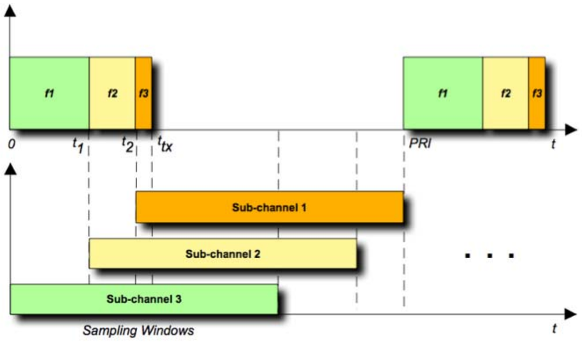

Fig. 6 D3R transmit waveform timing diagram including corresponding receiver sampling windows.

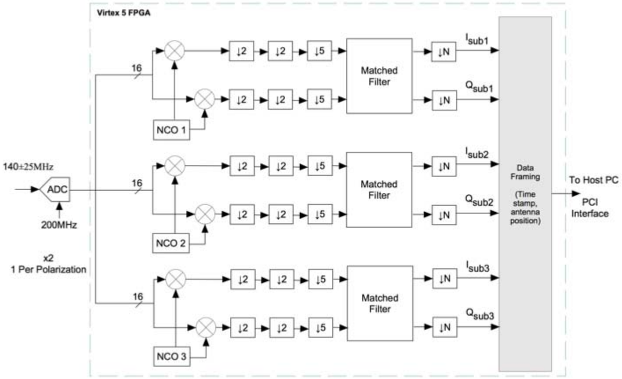

Fig. 7 Block diagram of a single channel of the sub-channeling FPGA based digital receiver implemented in the D3R.

4. CONCLUSION

The D3R system is shaping up to be a very promising system in terms of its expected performance and flexibility of the design. Its development is at its final stages. Integration and testing is scheduled to begin during the Fall of 2010. During this time, the system will undergo detailed testing at the CSU-CHILL radar facility. Data comparisons with the CSU-CHILL radar will be performed to assess the performance the D3R prior to field deployment. It is expected that D3R will participate in the Mid-latitude Continental Convective Clouds Experiment (MC3E) scheduled to take place in the Spring of 2011 in Oklahoma.

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