An Adaptive Radar Design for Small Satellite Missions

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Abstract— Space situational awareness and reliable operation require accurate and proactive detection systems onboard space satellites. Field programmable gate arrays (FPGAs) have been developed with the potential for high data processing speed, insitu parallel programming and flexibility. Also, active electronically scanned arrays (AESAs) radar with transmit/receive modules and flexible beam modes have enabled advanced aircraft target detection. This paper presents a design model that integrates FPGAs and AESA radars to achieve an on-orbit adaptive and proactive surveillance for space satellites. The model utilises microwave frequencies (L-, X-, C- and K-bands) to achieve a flexible and hybrid detection system with optimal range and resolution margins. Simulation results for the gain of the low noise amplifier subsubsystem are presented. The responses are broadband with linear gains greater than 30 dB. The proposed FPGA-AESA dual-band model promises range-independence within the operating bands, adaptive and deterministic e-scanning, high detection resolution, high data processing speed/transmission, multiple airborne target tracking and cooperative operation.

Index Terms— AESA radar, Hybrid detection, highly adaptive small satellite, surveillance.

I. INTRODUCTION

Spacecraft detection and mapping capabilities (range and resolution) have continued to evolve following advances in radar and allied technologies. Active electronically scanned array (AESA) radars, consisting of several small transmit/receive (T/R) antenna modules with distributed power capabilities, have been developed to foster multiple air-to-air and air-to-ground searching and surveillance operations onboard aircraft [1], [2]. These operations utilise four basic AESA modes: uniform coverage (standard 360^o coverage around platform and situational awareness), emphasised threat sector (focuses energy on threat sector and provides background sector coverage), dedicated threat sector (focuses all energy on threat sector and deep look) and track beams (places additional track beams on priority targets during surveillance). These modes presently work within the X-band frequencies (8 – 12 GHz) for high-resolution imagery. Multi-role electronically scanned array (MESA) has also been developed to operate within the L-band frequencies (1 – 2 GHz) for long detection range air-to-air coverage and air-to-surface coverage. Though MESA has a lower resolution, it is less affected by a bad weather condition [1]. Furthermore, increased versatility and speed, reliability and cost reduction favour field programmable gates arrays (FPGAs) for digital implementation of radar systems in realtime; a FPGA is a highly deterministic device that contains a matrix of reconfigurable gate array logic circuitry characterized by high speed, high reliability and parallel hardware [3] – [9]. A typical radar transceiver operating within a given bandwidth trade-offs between effectiveness in resolution and long detection range.

Modern spacecraft utilise dual bands, one each for radar and data transmission. With the use of frequency translation algorithms running on FPGA cores, these bands can be time-shared in realtime to achieve hybrid space surveillance. This paper presents a design model that optimises the resolution and range of AESA radar onboard small satellites using a dual-band system running on a FPGA architecture.

II. DUAL-BAND FPGA-AESA RADAR DESIGN

Hybrid or dual-band AESA radar operation depends on the ability of the system to switch between frequencies while scanning the space terrain. The phenomenon of Doppler effect is used to trigger the frequency conversions algorithms.

The proposed hybrid FPGA-AESA radar algorithm is based on the Doppler effect [9] – [10]. The relative velocity between the spacecraft and the target alters the wavelength received by the former. These are illustrated in Eqns. 1, 2 and 3:

$$\lambda_r = c/f_t + v/f_t \quad (1)$$

$$c/f_r = c/f_t + v/f_t \quad (2)$$

where λ_r is the wavelength received (m), f_t is the frequency transmitted (Hz), f_r is the frequency received (Hz) and v is the relative velocity between the spacecraft and the target (m/s). Since c >> v, Eqn. 2 becomes,

$$f_r = f_t(1 \pm v/c) \quad (3)$$

The Doppler frequency, f_d is therefore given by:

$$f_d = f_t\ v/c \tag{4}$$

Up-conversion (L-band to X-band) occurs when the target approaches the spacecraft due to a relative velocity existing between them; in this case, the received frequency is greater than the transmitted frequency and a Doppler shift occurs. Down-conversion (X-band to L-band) results when the spacecraft moves away from the object and the received frequency is less than the transmitted frequency.

III. Dual-Band Aesa Radar Modes

It is obvious from the foregoing that the proposed hybrid detection system can be applied to any AESA radar beam mode [1]. This flexibility is further enhanced by the use of message-passing interface and Agent-based systems algorithms integrated into a FPGA implementation [7].

A typical dual-band track beam mode is shown in Fig. 1. The various track beams can be of a single frequency or different frequencies. Depending on the severity of the threat sector or target, beam-frequency translation provides a better power efficiency than a dedicated band system. If a far target is sensed, the L-band excites the arrays in the direction of the threat with less emphasis on the resolution. As the object approaches the spacecraft, there is frequency up-conversion to X-band for a better resolution and clear target identification.

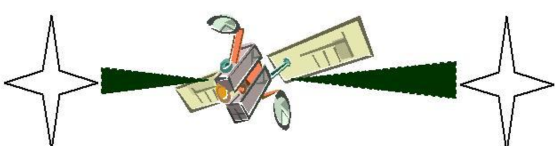

Fig. 1 AESA Radar Dual-band Track Beam Mode

The spacecraft is closer to targets 1 than 2. Hence, the X-band is excited to detect target 1 (requires high resolution) while the longer distance target 2 is probed with the L-band radar signal (lower resolution).

Fig. 2 illustrates the dual-band AESA radar in uniform coverage (UC) mode. In this mode, the small satellite can operate on both frequency bands at a time depending on the relative target's positions.

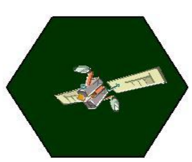

Fig. 2 AESA Radar Dual-band UC Mode

A long distance target(s) would require L-band while a closer one would trigger the X-band. A single band can also be used where the targets are approximately at the same distance from the spacecraft.

The emphasised threat sector (ETS) mode of AESA radar operation focuses much energy on the threat sector with allowance for background sector coverage. A particular band excites the arrays based on the current mission; the background sector uses a different frequency band. For instance, if the threat sector beams at the X-band, then the low energy L-band maintains background sector coverage. This is shown in Fig. 3.

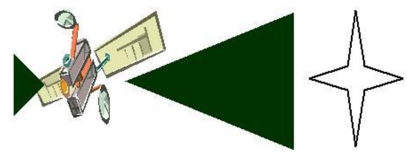

Fig. 3 AESA Radar Dual-band ETS Mode

A third type of AESA radar mode is the dedicated threat sector (DTS). Here, the entire radar signal energy is focused on the threat sector. Beam-frequency translation can still be implemented based on the radar-cross section (RCS) of the object. This type of application allows for the target to be optimally qualified and probed. Furthermore, beam energy is saved for full proximity illumination at the higher band. Fig. 4 illustrates the hybrid DTS mode.

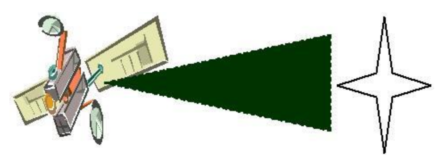

Fig. 4 AESA Radar Dual-band DTS Mode

IV. Fpga-Aesa Circuit design

Research advances in solid-state technologies have enhanced rapid developments in AESA architectures, implementation and exploitation. Though implementing advanced AESA circuitry as a technology platform for challenging radar applications still poses a great challenge, the aerospace community has made a tremendous progress.

The traditional AESA architecture employs ASIC-based logic chip for processing its beam steering signal. The design presented in this paper obviates the conventional custom-based point design by utilizing FPGA as the underlying architecture that incorporates the AESA logic chip within its transmit-receive (T/R) module. Figure 5 shows the proposed T/R module of the AESA radar that highly adaptive small satellites can accommodate for cost-effective, robust and reliable space missions.

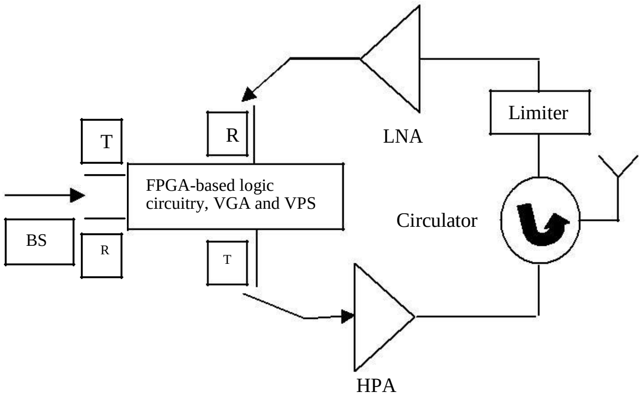

Fig. 5 A Transmit / Receive Module of an FPGA-AESA Radar

In Fig. 5, the following definitions apply: BS is the beam steering signal, T, transmitter signal, R, receiver signal, high power amplifier (HPA), low noise amplifier (LNA), variable gain amplifier (VGA) and variable phase shifter (VPS). The antenna element is connected to the circulator at the output terminal.

It is vital to note that the higher the frequency of operation, the better the signal resolution margin due to less RF activities.

A critical subsubsystem of the proposed adaptive dual-band space radar is the LNA. It is expected that the gain of the LNA be broadband over the operating frequencies. Since the presented circuit topology offers an adaptive radar operation, other microwave frequencies (such as C- and K-bands) can be time-shared. Presently, III – IV active device technologies are championing the microwave frequency applications [9], [12]. This paper reports LNA designs that have been done using the GaAs technology. The simulation results for the LNAs required for the FPGA-AESA radar in the C- and K-bands are presented in this paper. Figs. 6 [6] and 7 show the linear gains of the LNAs that would meet the stringent real-time and adaptive beamforming requirements of the FPGA-AESA radar for space satellite applications.

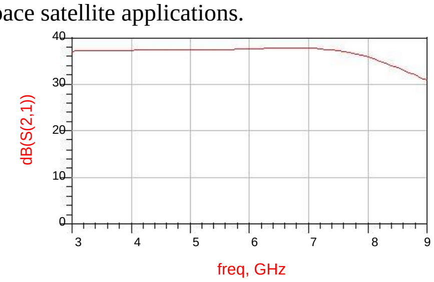

Fig. 6 The simulated gain for the FPGA_AESA Radar LNA (C-band)

The in-band ripple of the C-band LNA is less than 2 dB. This is less than the allowable minimum wideband specification (half-power gain point) for space-borne receiver front-end systems.

The in-band ripple of the K-band LNA is 0.5 dB. This presents an enormous bandwidth for FPGA-AESA radar system. Hence, the adaptive radar transceiver system can be integrated on the same technology architecture as the small satellite transponder. The beauty of the reported radar design architecture lies in its robust enhancement of the scaling strategies currently advancing space mission operations [13] – [22].

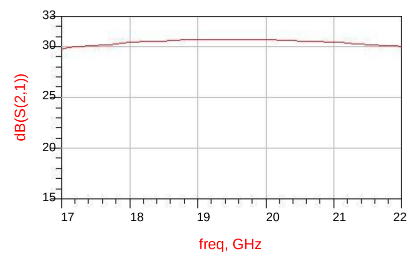

Fig. 7 The simulated gain for the FPGA-AESA Radar LNA (K-band)

Modern space missions projects are critical and complex, requiring adaptive structural and functional design paradigms. A highly adaptive small satellite (HASS) [11] system is a "reconfigurable, multifunctional and deterministic small space satellite that has capabilities for dynamic space applications and operations while retaining its designed optimal performance margins." This novel radar topology is well suited for HASS applications [5], [11], [12].

V. CONCLUSION

This paper has explained a novel radar technology called active electronically scanned array (AESA) that holds great benefits for space satellites-based applications. Four dual-band AESA radar modes have been identified and developed for an adaptive and reconfigurable space missions surveillance application. An algorithm based on the Doppler effect has been presented for the FPGA-AESA technology architecture. As a proposed advanced technology mix, it presents some implementation and benefits exploitation challenges. Yet, with the development of advanced system-level satellite technologies such as adaptive multifunctional structural units, realizing the reported AESA transmit-receive module design is possible.

This novel work has the capability to advance terrestrial and space-based radar applications by addressing key challenges such as AESA architectural design, monolithic multichannel transponder module design and implementation, deterministic digital signal/data processing, intelligent radar beam formation and steering, cooperative monitoring and surveillance of space resources.

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