Development of a Small Phased Array SAR-MTI System for Tactical UAV

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ABSTRACT

A small SAR-MTI system is being developed at TNO, aimed at deployment on tactical UAV, such as the SPERWER, in use with the Royal Netherlands Army. The system makes use of modern front-end technology, to provide flexible SAR imaging and MTI modes. Major design goals are 40 kg weight, 500 W power consumption and 50 cm resolution in order to comply with typical tactical UAV constraints and applications. The use of an active phased array antenna has several distinct advantages, not yet found in existing SAR-MTI systems of this small size. The active electronically steered array (AESA) antenna allows the system to be fixed-mounted on the platform, eliminating the need for gimbals, and enables simultaneous SAR- and scanning MTI modes. The prototype will have a single receive channel, while provisions for extension to 3 parallel receive channels are made, enabling the antenna to be divided into sub-apertures: this will allow advanced MTI processing techniques (STAP) to be applied, increasing MTI sensitivity, target localisation accuracy and lowering of minimum detectable velocity (MDV). A podded version will be demonstrated in flight on a motorglider platform. Apart from the front end, maximum use is made of COTS components for system development. This paper describes the system concept and main components, projected operational capabilities and processing aspects.

1.0 INTRODUCTION

The proposed SAR-MTI system is designed for use as an all weather, day and night sensor on board of tactical UAV or small aircraft. Since these platforms have limited resources for the payload, the system has to be compact, lightweight and low power. Still, a high resolution and a covered swath width as large as possible are necessary. Beyond that the system should also cover different modes of operation amongst which Stripmap SAR modes, also known as swath SAR modes, Spotlight SAR modes and Moving Target Indication (MTI) modes. The latter should preferably be able to cover a large area frequently, such that moving targets can be detected and tracked. If possible, an MTI mode should be combined with an imaging mode in order to capture moving as well as stationary targets in the scene simultaneously.

The SAR system is designed to accomplish just these tasks. For this purpose the system uses an Active Electronically Scanned Array (AESA) front end which can be split into three subarrays allowing for a very sensitive MTI mode. The use of AESA facilitates the possibility to interleave different modes due to the inertia-free beam steering. For example, Stripmap SAR and scanning MTI can be interleaved.

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The primary system requirements are popularly referred to as the 50^n-requirements: weight below 50 kg, volume below 50 litre, resolutions better than 50 cm and power consumption below 500 Watt (i.e. 50 “deca-Watt”).

Owing to the large proposed swath and needed antenna gain, the swath and beam width are closely coupled. The unwanted motion of the beam induced by platform motion then needs to be compensated. This can be achieved by using the Active Electronically Scanned Array. A two-dimensional AESA can compensate for both the roll and yaw. The pointing angle of the beam can be set to different values for different modes. The ability to steer in azimuth can be used for scanning purposes needed for scanning MTI and Spotlight SAR.

The use of a lightweight, small AESA makes this system unique, novel, and beneficial for the user.

In the next paragraph an historical overview of TNO’s involvement in SAR-MTI systems and processing will be given. Paragraph 3 states the starting points and requirements for the system, followed by the design considerations. The subsequent two paragraphs deal with the RF and data chain. The final image quality relies heavily on the motion data errors. Therefore, in paragraph 7 the motion sensors are investigated with some detail. The paper is finalized with some concluding remarks in paragraph 8.

2.0 HISTORICAL OVERVIEW

TNO has long-standing experience in the development of phased-array radar systems, and has gained extensive experience in Synthetic Aperture Radar with the PHARS and PHARUS systems. The PHARUS (Phased Array Universal SAR) system was developed by TNO in co-operation with the National Aerospace Laboratory and the Delft University of Technology. PHARUS is a polarimetric, active phased array SAR system that has been operated in a large variety of SAR and MTI modes [1]:

- Stripmap SAR modes;
- Spotlight mode;
- Sliding-spotlight mode, providing a trade-off between coverage (Stripmap SAR) and resolution (Spotlight SAR);
- MTI modes: single-beam MTI and DPCA;
- Extended bandwidth (double-pulse) mode.

In these various modes, PHARUS was flown at altitudes from 3000 ft up to 33000 ft. Furthermore, PHARUS has been used for repeat-pass interferometry, placing additional demands on beam steering, and processing accuracy.

Processing capabilities have been developed for the above modes, including full motion compensation for the fixed-mounted antenna (no gimballing), meaning that all aircraft motion must be compensated during processing. Polarimetric processing capabilities have been developed for various applications, ranging from target classification to contrast enhancement and land use classification. A polarimetric image is shown in figure 1.

Figure 1: Polarimetric Image of TNO Defense, Security and Safety, location The Hague.

The experience gained in building and flying the PHARUS system is instrumental in the definition of the novel SAR concept and its design, resulting in a third-generation phased array SAR concept. Since the emphasis is on low power and the need for high resolution, polarimetry, which requires additional power, was considered of lower priority than resolution, and is therefore not included in the current SAR concept.

3.0 STARTING POINTS AND REQUIREMENTS

The SAR design is based on a number of starting points that were determined at a very early stage of the project. They are:

- Pulsed system, operating in X-band;
- Resolution down to 30 cm, in future 15 cm Spotlight mode;
- Non-polarimetric, only VV channel is foreseen;
- Active phased array antenna;
- Azimuth and elevation steering;
- Front-end setup with three panels consisting of eight T/R modules each;
- One SAR and three MTI receiver channels;
- Small, lightweight platform.

The architecture is designed for platforms with standard optical ring for camera mounting, mounted in a pod or elsewhere. A demonstrator system will be implemented on a motorglider, see figure 2.

Figure 2: Example of a Motorglider, the Stemme S8. A mock-up of a SAR inside the pod is shown in the insert.

With the use of a number of scenarios, several operating modes were computed in an iterative process, where initial estimates for technical constraints and operational parameters were evaluated. These modes are the main required modes against which the system design is evaluated, and which serve as a guideline for design decisions. In practice, all other modes that remain within the technical constraints are also possible.

The scenarios are characterized as follows:

- The military SAR modes at near, mid, and far range are defined for use of the system on a platform comparable to the Sperwer (i.e. a tactical UAV). In these modes high resolution SAR imagery can be acquired at different ranges. Compression of raw data is necessary due to the limited bandwidth of the data link. The swath covered is thus maximized. At large range the resolution is limited to 50 cm in order to achieve sufficient sensitivity;
- A civil SAR wide area mode is a wide swath mode with moderate resolution (50 cm) for efficiently imaging relatively wide swaths (4000 m) alongside the aircraft track for cartographic purposes. It is operated at relatively low altitudes (1500 m). The data is stored on board of the aircraft, while the processing is performed on the ground;
- A civil SAR steep mode is created with steep incidence angles in order to reduce shadowing effects. In this mode the swath is reduced to 2000 m.

Table 1 shows the radar parameters defined by the above-mentioned scenarios. Since a large bandwidth is required for the military SAR modes at near and mid range, the bandwidth is transmitted in a double pulse mode, thus reducing the ADC sampling rate of the foreseen data-acquisition system.

Table 1: Radar Settings for the Different Modes

Item	SAR	MTI	Unit
PRF	4 to 10	3	kHz
pulse length	6 to 12,5	8	µs
Bandwidth	300 to 600	10	MHz
double pulse (1 or 2)	1 or 2	1	
Altitude	1 to 3,5	3,5	km
near range	2 to 7	4 to 7	km
ground swath	1 to 6	1 to 8	km
far range	3 to >15	5 to >15	km
duty cycle	2 to 10	2	%
Incidence angle	45 to 75	55 to 75	deg
ground resolution	0,3 to 1,0	10 to 20	m

The following features will not be implemented within the current project, but the architecture is designed with their future implementation in mind:

- Radio data link to send data to the ground segment;
- Extra front end for cross-track interferometry (XTI);
- Snapshot processor.

4.0 DESIGN CONSIDERATION

It was decided to concentrate the timing and control intelligence for all aspects of sending and receiving radar pulses in a single unit and have other modules behave as slaves that receive commands and settings for every radar pulse. This facilitates the implementation of intricate pulse schemes, such as for simultaneous interleaved modes, whereas the large concentration of control logic and the extra communication needed in this scheme prove no problem with current technology.

Some modes require more bandwidth than can be realized in a single chirp within the applicable constraints, therefore a multiple pulse scheme can be implemented. The local oscillator is then switched between two or more fixed frequencies in order to enhance the effective bandwidth.

Digital I/Q demodulation was chosen in favour of an analogue scheme because of its superior performance in terms of linearity, inherent amplitude and phase matching and absence of quadrature error over the wide frequency range associated with high resolution. This benefit more than compensates for the drawback of the higher sample frequency and additional digital logic that are needed.

Many actions in the system must be tightly coordinated in time. They encompass the control and timing of the following modules:

- Chirp generator;
- Front end;
- Acquisition;
- Preprocessing;
- TX/LO module;
- RX modules.

A synchronization scheme is employed which accomplishes the exact synchronization between the chirp generator and acquisition module(s) without the need for additional high-speed logic. This is achieved by internal dividers in both modules which divide the 1 GHz input clock to a more relaxed 25 MHz timing grid. These grids are synchronized upon initialization, giving a fixed, up to the ns, relation between chirp generator and acquisition.

5.0 RF CHAIN WITH ANTENNA

A fixed sample frequency of 1 GHz was chosen for all modes, even when some modes could in theory do with a lower sample frequency. This choice simplifies the RF chain and negates the need to switch frequencies and analogue filters depending on the mode. The RF chain is shown in figure 3.

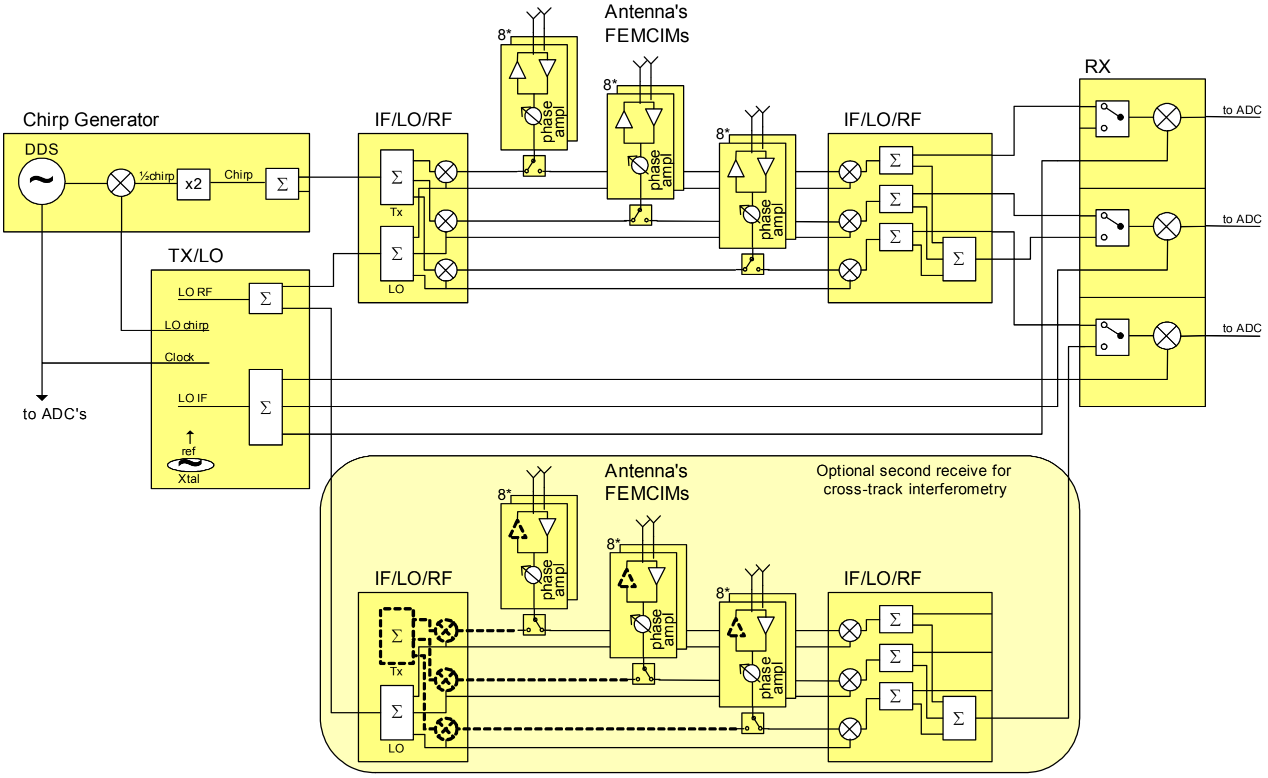

Figure 3: RF Chain with Optional Second Front End for Interferometry.

The chirp generator is the source of the RF signal. Owing to the requirements for linearity and repeatability, a Direct Digital Chirp Synthesiser (DDCS) is chosen. The selected DDCS has the following characteristics:

- Single chip, single supply DDCS with on-board DAC;
- Freely programmable chirp function;
- Possibility to generate a 125 – 375 MHz chirp with the 1 GHz clock.

With the use of this DDCS, a mixer and proper filtering it is possible to generate a 250 MHz chirp pattern around the first LO frequency. This signal is doubled in frequency using a x2 multiplier to the actual 500-MHz wide chirp at the chosen IF.

An FPGA receives programming data for the DDS chip from the timing and control unit. The chirp parameters can be set on a pulse to pulse basis, e.g. to support double pulse scenarios with asymmetrical chirp shape with respect to the LO frequencies used. The data for a given radar pulse is sent via the radar bus in a synchronous serial fashion during the previous pulse.

The TX/LO module is used to generate all necessary LO frequencies for the complete radar system (TX and RX), in particular the chirp generator clock, the 1st LO for upconversion to IF and the 2nd LO for up/downconversion to/from RF. For the demonstrator system, the LO can be switched between two frequencies 500 MHz apart, allowing the use of a doubled bandwidth when using a double pulse scheme. The TX/LO module also generates the 1 GHz clock for the acquisition module. To obtain a coherent RADAR system all the above given frequencies are derived from one reference frequency, which is part of this module.

The IF/LO distribution module is used to convert the TX/RX signals from IF to RF and back using the 2nd LO signal and to distribute or combine the RF signals to and from the active array panels of the front end. Because there are three front-end panels and one to three RX modules, it provides both the downconverted outputs of the individual antenna and the combined output of the three panels. For SAR functionality, the combined output is used. For the MTI function it is also possible to receive signals from each front-end panel separately, provided three receiver chains are implemented. Within the RX module the choice can be made between the sum channel and the individual RX channels.

The front end is formed by an active electronically scanned array (AESA) antenna consisting of three Transmit/Receive panels, each consisting of eight individual Transmit/Receive modules with associated signal distribution, gain and phase control and power conditioning electronics. These State of the Art panels are designed for non-airborne applications and are optimized for series production, which significantly lowers the costs of the AESA. The actual antenna is based on a flared waveguide array antenna with a fan beam with beam width of 25° in elevation and 8° in azimuth and a scanning capability of +/-15° in elevation and +/- 40° in azimuth. The antenna array is arranged in three segments of 2 x 4 elements each.

The RX module transfers the IF RX signal to the required frequency band which can be handled by the acquisition module; given the 1 GHz sampling rate the receive signals are centred at 250 MHz, allowing easy downconversion to base band I and Q data streams in the data chain. It also provides the adequate amplification of the RX signals in order to obtain maximum dynamic range for the 8-bit ADC input range of the acquisition module. Finally, it provides the function of selection between the RX summation and the individual RX channels of the front end.

6.0 DATA CHAIN

Digitization is performed by an 8-bit ADC clocked at 1 GHz. The ADC contains an internal demultiplexer, which delivers 2x8-bit data at half the sample rate. The ADC is followed by a demultiplexer which converts the 500 MHz/16 bit bus from the ADC to a 125MHz/64 bit bus that can be handled more easily by digital hardware.

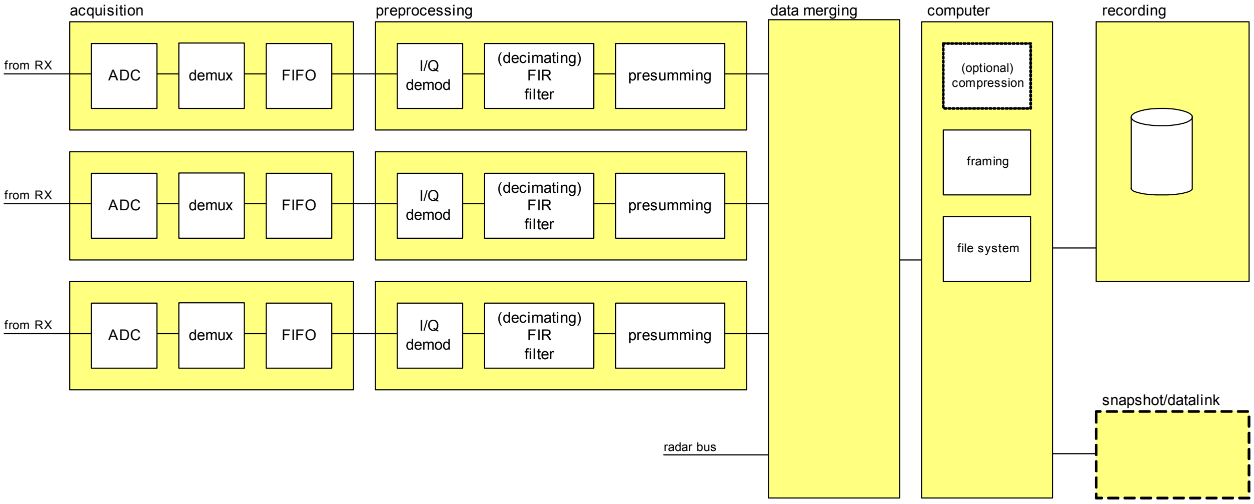

Figure 4: Data Chain.

Because the acquisition module contains a buffer and the maximum sampling duty cycle is significantly lower than 100 %, the average data rate is well below 1 GB/s. Following the I/Q-demodulation, both branches feature low pass filters that are basically identical. These filters serve the following purposes:

- Remove the undesired frequency components around -2 times the centre frequency;
- A further reduction of bandwidth in low resolution modes, e.g. MTI modes, whilst decimating the data;
- Equalization of the RF-curve.

Presumming, or azimuth filtering, serves the following purposes:

- Limit the bandwidth and optionally decimate the azimuth spectrum;
- Increase signal to noise ratio;
- Optionally shift the azimuth spectrum (advantageous for Spotlight SAR and large-squint processing).

The presummer is implemented as a programmable decimating FIR filter in azimuth direction.

The settings to be used for the current radar line are received via the radar bus on every PRI cycle, allowing very flexible control over pulse schemes. The items that can be set are:

- Range window;
- Filter sets;
- Azimuth line number;
- Azimuth mixer frequency;
- Data channel (for double pulse schemes);
- Others.

All demultiplexing and preprocessing after the ADC are implemented in a Field Programmable Gate Array (FPGA).

The processing system is based on COTS components. The CompactPCI standard is chosen for its wide support, and within this standard the 3U form factor is used for its compactness and mechanical robustness. The processor boards are general purpose boards based on the Mobile Pentium IV processor, because this architecture has a good power versus performance ratio and good software support.

The figure below shows an overview of the location of parts of the demonstrator system.

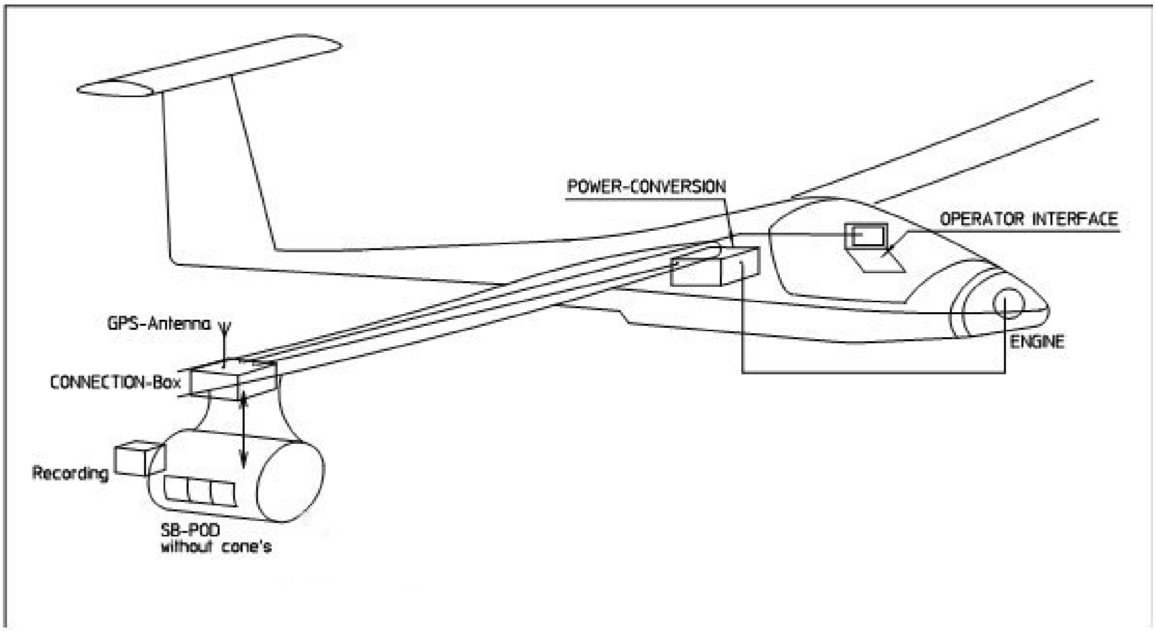

Figure 5: Component Locations for Demonstrator System.

7.0 MOTION COMPENSATION SYSTEM

The decision to design and implement a new navigation system from scratch, instead of using one off the shelf, was motivated mainly by the volume, weight, and power budgets and projected system cost. Opting for this solution also increases the freedom of changes to the navigation system, facilitating an easier and more flexible integration with the radar.

The main idea behind the complete development process of the navigation system was to start from a basic configuration and step by step improve it until the final goal, to comply with all the SAR requirements, is reached. Flexibility to the available GPS observables was one of the main requirements imposed to the INS. The capacity to process different types of GPS observable was used to mark the separate development phases, as explained in [2]. The last goal was to tightly integrate the inertial sensors (3 accelerometers and 3 gyroscopes), the magnetic sensor (3 axes magnetometer) and the dual frequency GPS carrier phase double differences observables, as introduced in [3]. An Iterative Extended Kalman Filter is under development and is used to integrate the unprocessed measurements from the GPS and magnetometer, and the raw inputs from the IMU. This type of filter was chosen because it is proven to have a superior performance in this type of applications, [4]. A smoother trajectory is also available when the Smoothing version of the filter is used. This type of filter uses both past and future data to produce a better estimation.

The motion sensor data are digitized using three boards each using three ADCs, which are connected to the pulse control module using a Serializer/Deserializer (SERDES) that combined a number of digital signals over a single LVDS pair. This setup allows very short differential analogue wiring to be used in order to minimize interference and supply current feedthrough in the measurements. Separate converters allow true synchronous acquisition of all sensor channels, and also minimize inter-channel coupling that hampers some multiplexed setups. The serial LVDS interface minimizes cabling and reduces sensitivity to interference (with respect to direct interfacing to the ADC chips). Each board contains its own isolated power supply converter. Data acquisition is controlled from the pulse control module, thus enabling tight synchronization between motion data and radar data.

The following motion requirements are based on the following assumptions:

- The requirements apply to the motion compensation system as a whole, i.e., the final accuracy achieved with the combined sensors, unless otherwise stated;
- The requirements apply to the motion of the SAR antenna itself. Any distance between the positions of measurement (sensors) and the antenna must be taken into account within the motion compensation system.

Table 2 shows the results for the different types of motion errors.

Table 2: Maximum Value for Different Motion Errors and their Effects on the SAR Image

Error type	Result	Image effect
Difference between actual and measured ground speed	0,0373 m/s	Defocus
Velocity error along line-of-sight (cross-track)	0,002 m/s	Image shift
Acceleration error along line-of-sight (cross-track)	0,00195 m/s^2	Defocus
Vibration amplitude (high frequency)	0.15 mm	Peak sidelobes (ghost images)

Roll, pitch and heading errors are much less critical than the displacements in a SAR system: the main purpose of their measurement is to know where the antenna beam is pointing, within a fraction of the beam width. The roll and pitch angles are known with a different precision than the heading angle. This is due to the fact that absolute roll and pitch angles estimation accuracy is directly dependent on the estimation of the accelerometer biases. Errors in roll and pitch will cause gravity to be misinterpreted, causing apparent horizontal accelerations that integrate into ramping velocity and quadratic position errors when compared to GPS. However, an accelerometer bias will also produce the same error signature, so the Kalman filter will only be able to estimate the roll and pitch error down to the level where the misinterpreted gravity cancels out the accelerometer biases. Precisions better than 0.1^{o} are expected for roll and pitch angles.

Heading angles, when no magnetic sensor is available, are observed through the accelerations. During straight-and-level flight with little or no accelerations, the heading error will grow at a rate defined by the gyro noise and residual gyro bias. As soon as a significant acceleration is experienced, the heading angle will be observed and the error reset. Hence in order to maintain heading accuracy to the maximum level, it is important that a manoeuvre be performed periodically. The time between manoeuvres is dependent on the quality of the IMU. When a magnetic sensor is present, the heading angle error will be bounded, even when no manoeuvres are performed, by the precision of the used sensor. This yields a typical maximum error of 0.5^{o} when properly calibrated.

8.0 CONCLUDING REMARKS

The presented SAR-MTI system is compact, lightweight and low power. Yet, the system has high resolutions and a large swath. The system uses a lightweight, small Active Electronically Scanned Array (AESA) front end which can be split into three subarrays allowing for a very sensitive MTI mode. The use of AESA facilitates the possibility to interleave different modes due to the inertia free beam steering.

Digital I/Q demodulation was chosen in favour of an analogue scheme because of its superior performance in terms of linearity, inherent amplitude and phase matching and absence of quadrature error over the wide frequency range associated with high resolution. It was decided to concentrate the timing and control intelligence for all aspects of sending and receiving radar pulses in a single unit and have other modules behave as slaves that receive commands and settings for every radar pulse. A synchronization scheme is employed which accomplishes the exact synchronization between the chirp generator and acquisition module(s) without the need for additional high-speed logic.

A fixed sample frequency of 1 GHz was chosen for all modes. The chirp generator is the source of this RF signal. The front end is formed by an active electronically scanned array (AESA) antenna consisting of three state-of-the-art Transmit/Receive panels, each consisting of eight individual Transmit/Receive modules. The actual antenna is based on a flared waveguide array antenna with a fan beam with beam width of 25° in elevation and 8° in azimuth and a scanning capability of +/-15° in elevation and +/- 40° in azimuth.

The data chain digitizes the signals at 1 GHz. After I/Q demodulation the data is filtered and decimated in both the range and azimuth direction. For the demonstrator system the data is stored onboard.

The final image quality relies heavily on the motion data errors. The decision was made to design and implement a new navigation system from scratch. This decision was motivated mainly by the volume, weight, and power budgets and projected system cost. Opting for this solution also increases the freedom of changes to the navigation system, facilitating an easier and more flexible integration with the radar.

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