High-Resolution Imaging mmW-Sensors for Target Reconnaissance and Tracking Onboard of Light-Weight UAVs and Missiles

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ABSTRACT

Highly miniaturized mmW-Sensors, especially designed for target reconnaissance and tracking applications onboard of small tactical UAVs and ground surveillance missiles provide high-resolution radar-images in near-photographic quality in day and night operations. Penetrating clouds, rain, fog and smoke, mmW-Sensors will offer a true all-weather capability, along with real-time onboard target acquisition and tracking functionality. Small size, light weight and low prime power requirements, given in small airborne platforms will be met.

The presentation deals with requirement analysis in defined scenarios and applications, outlines radar design rationales and addresses technology aspects. Realized and verified mmW-sensors will be discussed.

The following features characterize the sensor design:

- *High-resolution SAR-imaging mode*
- *MTI mode for detection and tracking of moving objects*
- *Automatic target recognition, based on polarimetric target signatures*
- *Monopulse target tracking*
- *Radar-based platform navigation*
- *Real-time signal- and data processing*

Successful demonstration flights were conducted in different fixed and rotary wing aircrafts. A miniaturized SAR-sensor was successfully tested onboard of a mini-UAV. Based on experiences, gathered in numerous flight tests, the sensor systems have been continuously improved.

Finally, the presentation will show examples of the latest flight tests results.

1.0 INTRODUCTION

Small size UAVs are increasingly used for environmental monitoring, pipeline surveillance, border patrol and airborne reconnaissance missions. While electrooptical sensors provide a high-quality imaging capability in good weather conditions, their usage in case of low clouds, fog, rain or smoke is severely limited. A **S**ynthetic **A**perture **R**adar **SAR** instead or in addition to the E/O sensor could significantly enhance the efficiency of the UAV by enabling all-weather operation and the collection of additional information like radar reflective properties, object location or **M**oving **T**arget **I**ndication **MTI**. However,

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the integration of SAR sensors into small UAVs is difficult for various reasons which are described in the following chapters.

2.0 RECONNAISSANCE SAR SENSOR

2.1 System Requirements

Complex air to ground missions require high-resolution imaging sensor systems which perform in all-weather, adverse battle-field environments, like dust, smoke, fire and countermeasures. High-performance target classification and even identification are of utmost importance in order to avoid collateral effects. In this respect, multi-sensor configurations will play an important role. In modern scenarios it is very much requested to operate from stand-off ranges in subsonic, as well as supersonic missiles or drones. In modern "man in the loop" concepts, a bi-directional datalink is a key feature to operate the sensor system remotely, that is, to command the recce platform and get target images back to monitor the mission effectiveness. Small volume, light weight and low prime power consumption are severe constraints in small airborne platforms. Not to forget, affordable sensor costs are very important.

2.2 System Concept Overview

The requirement for an all-weather capability in adverse air to ground applications favours a high-resolution imaging SAR concept. Moreover, powerful Moving Target Indication MTI is another key radar characteristic, which will extend the system performance. An overview of potential sensor modes are illustrated in fig. 1. SAR-Stripmap, Spotlight-SAR and Doppler Beam Sharpening mode are standard modes of operation. In addition, a forward looking MTI-Mode is very effective in detecting moving targets.

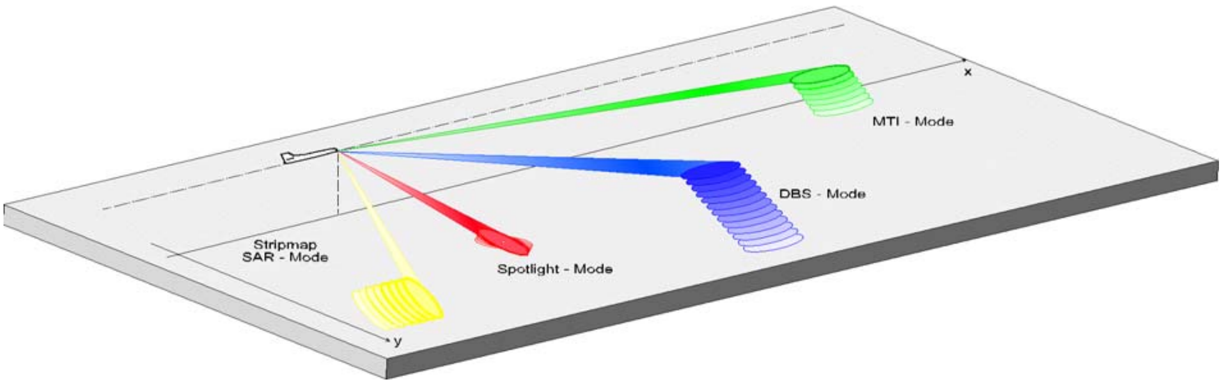

Figure 1: Sensor modes of operation in airborne platforms.

Long-term experience in radar design for small, light-weight airborne platforms revealed, that mmW-radar systems using FMCW-waveforms show impressive advantages in terms of performance, simplicity, miniaturization aspects and cost. A simplified block diagram of a generic SAR sensor is shown in figure 2, which will provide all the radar modi indicated in fig. 1 on software basis.

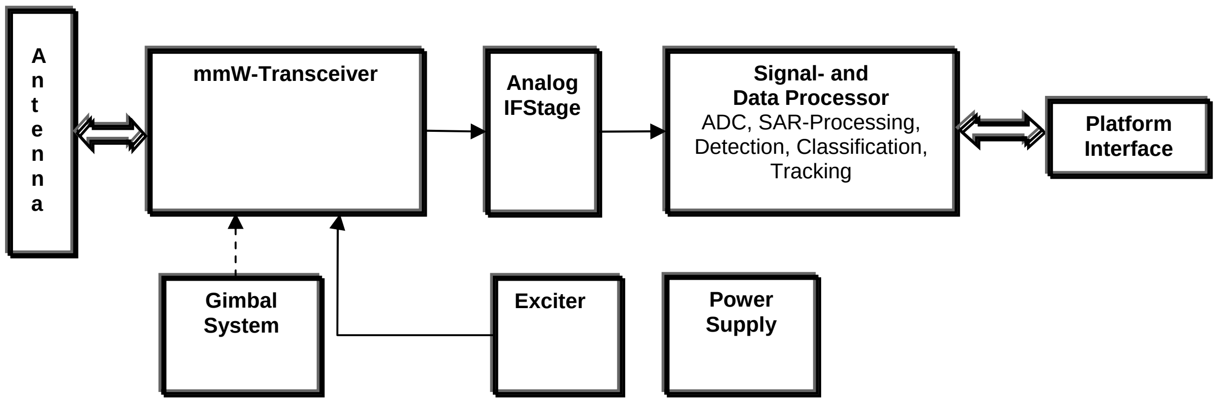

Figure 2: Simplified sensor block diagram.

A dual-horn or multi-feed cassegrain antenna offers signal transmission and reception in a common aperture, likewise showing excellent transmit/receive isolation, which is an important feature in all FMCW radar systems. The Ka-band FMCW transceiver is arranged behind the antenna system. Deramped narrow-band signals are tranferred via coax cables - thus avoiding lossy rotary joints - to the analogue baseband stage for further amplification and filtering. The compact RF-frontend is mounted on a 2-axis gimbal system, which allows wide angular antenna pointing in azimuth and elevation. Decoupling the antenna from platform motion, called antenna stabilization, is based on the strap-down principle, which involves an IMU, angular pick-offs and a NAV-computer. Analog/digital conversion and digital I/Q-demodulation in conjuction with data rate decimation provide multi-channel complex time data for SAR processing.

2.2 SAR Processing

The SAR processing itself is indicated in fig. 3. Range resolution, corner turn memory, azimuth processing and motion compensation are basic processing steps. It turned out, that motion compensation, purely based on inertial data was not sufficient. Thus an autofocus algorithm was designed to assist the focussing process.

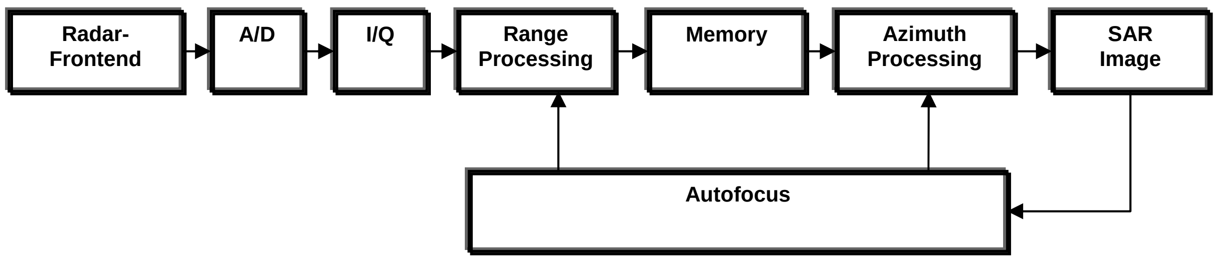

Figure 3: Fig. Block diagram of the SAR-image generation process.

2.3 Detection and Classification

Target detection, classification and tracking is based on high-resolution SAR images as indicated in fig. 4. The detection process is a type of two-dimensional CFAR, where special care is taken to avoid mutual masking of strong radar reflexions. The classification process is based on statistical pattern recognition techniques, where radar features related to the SAR-signatures and multistage classification algorithms discriminate predefined target classes.

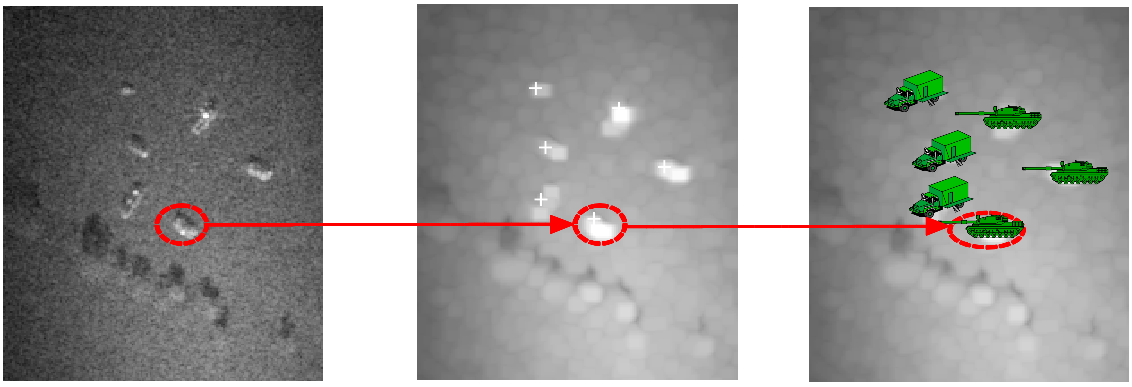

Figure 4: Target Detection and Classification Process:
SAR-Image (left), Detection (middle) Feature calculation and Classification (right).

3.0 SAR-SENSOR FOR SMALL UAVs

3.1 SAR Onboard Segment

To provide a SAR capability for small UAVs, where size, weight and power consumption of the onboard sensor payload are strongly limited, a miniaturised SAR sensor was designed and developed [1, 3]. The overall objective was to design a SAR sensor which can be integrated even in the smallest UAVs currently operated on a regular basis. The payload weight was restricted to 4kg. For data transmission from the UAV to the ground control station, only a standard analogue video datalink was available. Due to their low weight, such UAVs are heavily affected by wind and turbulences which lead to frequent sudden movements of the air vehicle and prevent it from following an exact straight flight path. The airspeed of the UAVs is in the order of 20m/s to 50m/s with highly varying associated ground speeds according to wind conditions. This flight dynamics posed severe problems on antenna stabilization and motion compensation in the context of SAR-imaging.

The highly miniaturised SAR sensor is based on a Ka-band FMCW radar frontend. The radarsensor consists of an onboard segment and a ground segment. The onboard segment delivers an analogue radar raw signal with associated motion data to the ground segment. Digitisation of the radar signal and realtime SAR processing is done in the ground segment.

The structure of the onboard segment is shown in fig. 5 The transmit path comprises the digital waveform generator, a 35GHz cavity oscillator for upconvertion into Ka-band, a solid state power amplifier and the transmit antenna. The receive path has a seperate receive antenna for optimum transmitter-to-receiver isolation which is followed by a LNA, a mixer for the deramp-on-receive operation and the baseband filter chain. At the output of the filter chain, the analogue radar raw signal is available. The transmit and receive antennas are mounted in a 2-axis gimbal system. The gimbal is positioned by the antenna control subsystem which is made up of a motion sensor interface and the antenna control unit. The motion sensor data is furthermore multiplexed with the radar raw data and transmitted to the ground segment via the analogue UAV datalink. Fig. 6 shows photographs of the MISAR onboard segment demonstrator and the MISAR-A model realization.

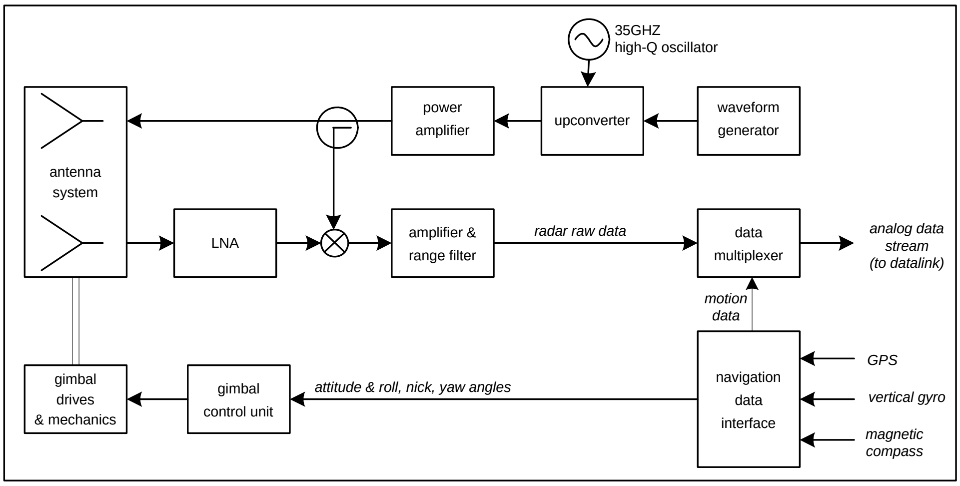

Figure 5: Block Diagram of the sensor onboard segment.

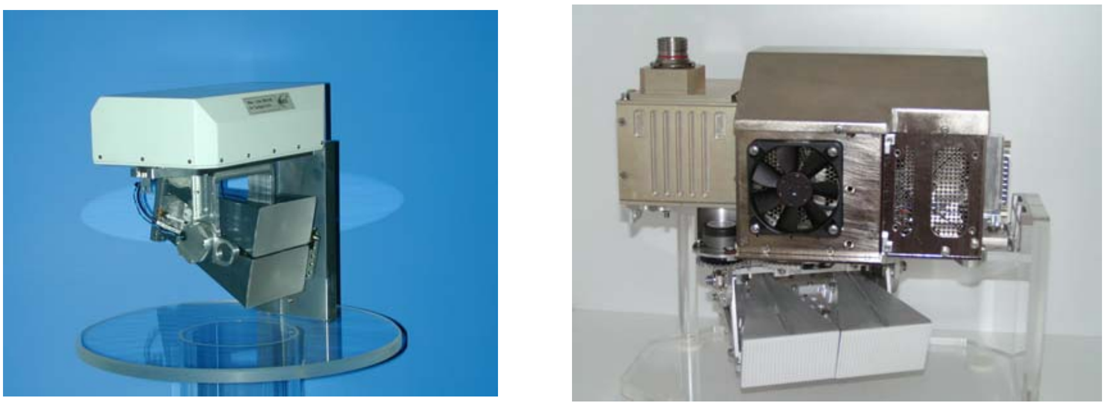

Figure 6: MISAR Realization: Demonstrator (left), improved MISAR-A Model (right).

3.2 Ground Segment: SAR and MTI Processing

The concept of operation of small UAV platforms is different from the one of the large carrier platforms where SAR sensors are traditionally employed. SAR applications in large aircraft mainly rely on exactly preplanned flight paths and mission profiles, and evaluation of the sensor data is in most cases done offline after landing. In contrast, small UAVs have traditionally been equipped with electro-optical sensors which provide their imagery in real-time. The ground-based operator can observe the image sequence and immediately react by changing the flight path, e.g. to observe an object from different aspect angles or review an area of special interest. As a consequence, the concept of operation of small UAVs needs real-time image generation as well as flexible flight paths without the contraints of preplanning or flying a straight path, as required in stripmap SAR mode. As a consequence, a snapshot SAR imaging mode was proposed. This is essentially a time-successive generation of spot SAR images, where the images have a spatial overlap in the order of 90%. As a result, a movie-like sequence of SAR images can be provided in realtime which is very similar to the output of the traditional electro-optical sensor systems.

Especially in applications like border patrol or wide area surveillance, automated detection of moving objects was found to significantly enhance mission effectiveness. As a consequence, two possible modes for MTI were proposed for MISAR. The first one is given inherently by the spapshot SAR processing mode as described above. The object movement, i.e. the change of location over time, can be visually detected by the operator in the SAR image sequence. An alternative MTI mode is based on autonomous exo-clutter detection and tracking of moving objects. Especially in forward looking conditions moving objects will show up in the clutter-free area of the range/doppler domain.

The sensor ground segment is entirely made up of commercial 19‘‘ rack-mounted PC components. The intrinsic SAR processor unit is a 2.8GHz Dual Xeon workstation which is linked by a gigabit ethernet switch to two peripheral workstations for data preprocessing and data storage. The interface to the UAV datalink is given by a standard PCI A/D converter board.

4.0 SAR-SENSOR TECHNOLOGY

4.1 mmW-Technology

To fullfil the requirements wrt weight and size of a radar frontend and to achieve a high level of integration a RF multilayer technology is mandatory. Possible solutions are: HTCC (High Temperature Cofired Ceramic), LTCC (Low Temperature Cofired Ceramic) or a multilayer made of a soft substrate material like glass microfiber reinforced composites of PTFE (Poly Tetra Fluoro Etylene). LTCC is preferred because there are a lot of advantages which make it to a key technology in Ka-band frontend design [2]. The LTCC-realization of the MISAR receiver is to be seen in fig. 7.

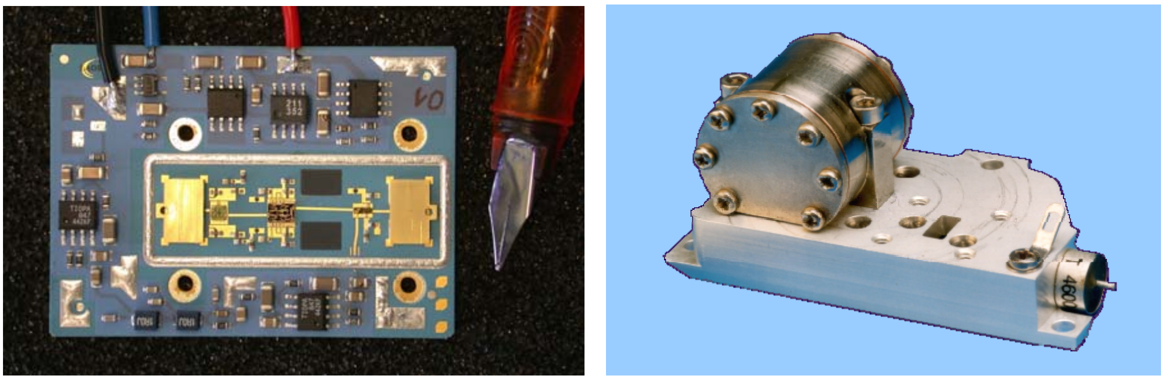

Figure 7: LTCC-Receiver (left) and High-Quality Oscillator (right) of MISAR frontend.

A further key item in all SAR sensors is a high quality RF-source. The spectral purity of the mmW-oscillator dominates the range and resolution performance of the sensor. A cavity-stabilized oscillator, also shown in fig. 7, is the preferred solution because of its low phase noise in the order of < -140dBc/Hz at 1MHz off the carrier.

4.2 Waveform Generation, Real-Time Processing

Broadband, coherent and flexible waveform generation is of utmost importance in SAR systems. Nowadays, there is digital solution available, which is based on the Digital Direct Synthesis DDS concept. The realization applied in MISAR is shown in fig. 8.

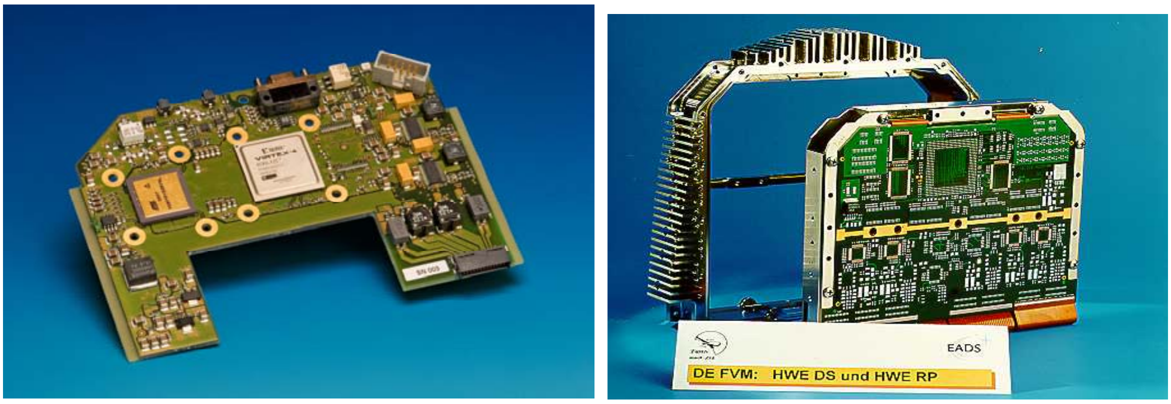

Figure 8: Photograph of a digital waveform generator (left), signal & data processor (right).

In another program, a real-time onboard SAR processor was developed and successfully demonstrated in numerous flight tests. On 2 boards (see also fig. 8) 4-channel SAR-processing, target detection, classification and tracking was realized.

5.0 FLIGHT TEST RESULTS

Numerous flight tests where conducted in the past onboard a Dornier DO-27 fixed-wing airplane, in a Bell UH1 helicopter and in the small UAV Luna (see fig. 9), proving impressively the overall SAR sensor concept. During the flight tests, strong deviations from the ideal preplanned flight path and rapid platform movements caused by turbulence and wind were observed. This behaviour can be considered typical for small airborne platforms. In this respect, the designed stabilized antenna concept and the implementation of a sensor-specific NAV-system turned out to be very important.

Figure 9: MISAR integrated in DO27 (left) and in UAV-Luna (right).

The design goals in terms of range, image resolution and swath as well as the UAV constraints like onboard size, weight and prime power demand were fully met. The sensor produced SAR images with a very high overall quality (see fig. 10). The Ka band sensor proved to be very well suited for the detection of man-made objects and for reproducing surface textures. The sensor hardware proved to be extremely reliable and robust, especially when considering the impacts of UAV launch accelerations and parachute landing shocks. These tests clearly revealed, that is is possible to integrate a SAR sensor into small UAVs and to obtain high-quality SAR images in realtime.

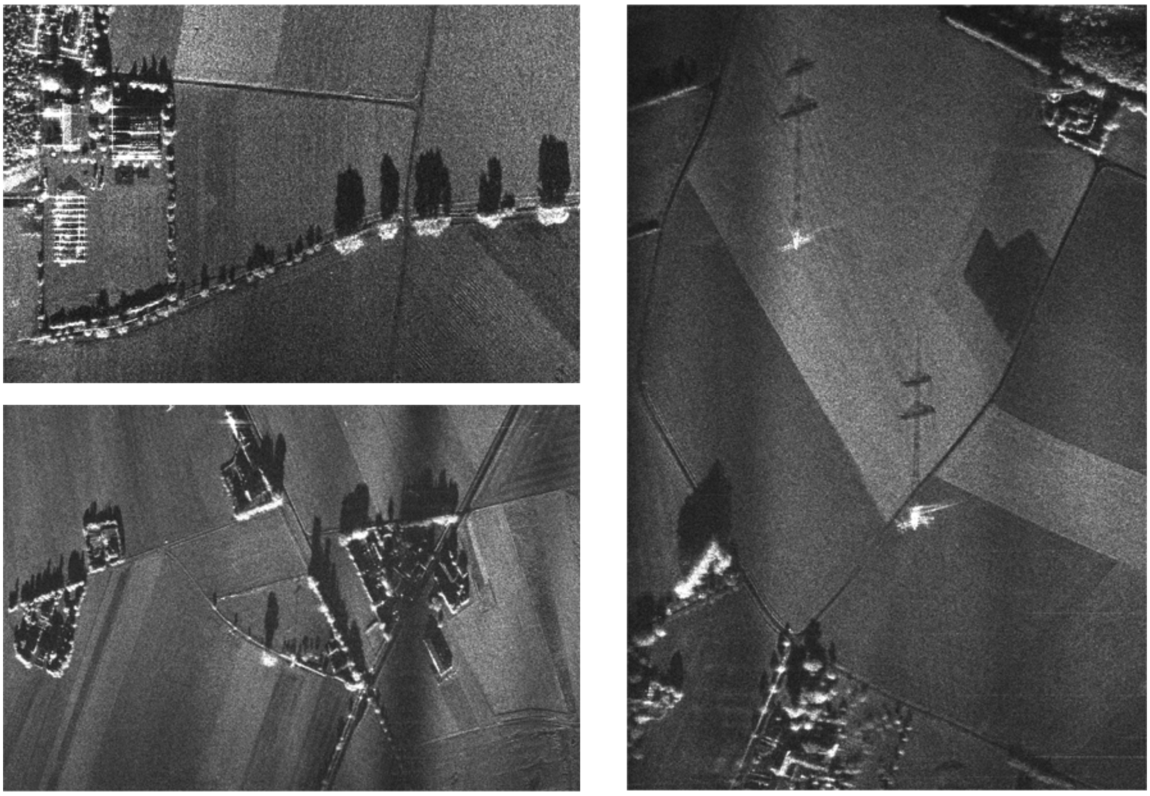

Figure 10: Examples of MISAR Images.

6.0 SUMMARY

The design and development of the highly miniaturised mmW-SAR sensors for application in small size UAVs and missiles was discussed. It shows that a solution based on a FMCW approach in Ka-band is well suited for the airborne radar frontend. The performance of this sensor was extensively evaluated in multiple flight test campaigns in both manned aircraft as well as in a typical small UAV. The results show that the design goals with respect to range, geometrical resolution, image quality as well as size, weight and prime power could be fully achieved. Typical problems SAR sensors will face on small airborne platforms were identified and solutions found. Currently, a second generation of the MISAR sensor system is being tested and will shortly be available for operational use.

7.0 REFERENCES

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[3] Edrich, M.: "Ultra-Lightweight Synthetic Aperture Radar based on a 35GHz Sensor Concept and Online Raw Data Transmission", IEE Proceedings Radar, Sonar and Navigation, Special Issue on Adavances in Synthetic Aperture Radar, Vol. 153, No. 2, pp. 129-134, April 2006.