HIGH RESOLUTION W-BAND UAV SAR

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ABSTRACT
A miniaturised millimetre wave radar, MIRANDA, to be used as Synthetic Aperture Radar onboard a small UAV was designed, built and tested onboard of an unmanned helicopter. The design followed the FM-CW principle, to get the highest possible average transmit power and thus the best range performance. The experiments described here were conducted at a centre frequency of 94 GHz. An inertial system of high quality, based upon a fibre optic gyroscope maintained the necessary precision, to allow high resolution SAR imaging. The raw data are transmitted to the ground station using an ordinary analogue data link, where they are A/D converted, pre-processed and finally undergo a real-time SAR-focusing algorithm. Additionally to the quick-look processing the data are stored to be able to apply further high quality SAR processing. The paper describes the design principles and gives results from the flight tests.

Index Terms— Synthetic Aperture Radar, mm- waves, UAV, High Resolution

1. INTRODUCTION

Remote Sensing nowadays is able to rely on a very broadband inventory of sensors ranging from visible and IR to radar. Different applications as well routine survey of areas for agricultural or traffic monitoring as urgent requirements for remote sensing like over disaster areas can only be served by airborne sensors. Different physical effect, which allow to sense specific features of the earth’s surface as requirements concerning the environmental conditions or technical demands are determining factors for the choice of a certain sensor type or frequently a sensor suite, which has to be taken into consideration. Also unmanned operation over dangerous terrain may be essential as the Fukushima nuclear accident shows and which is evident for many military applications. Radar is one of the sensor types, which are under consideration for airborne remote-sensing. Bandwidth and frequency of operation are key parameters, which are determining resolution, antenna-size, available output power and sensitivity for specific features on the ground. Millimeter-wave radar allows a compact set-up, using MMIC technology and allows to use small antennas with adequate gain. Further, millimeter-wave radar is very sensitive to small-scale variations of the scattering surfaces and gives information on small-scale changes, which are not visible for classical radars at more traditional frequencies like X-band. Currently a range of other applications, mainly concerning automotive applications and security and safety, can be served by mm-wave radars. This means, that a technology is available, which allows miniaturization of radars where only a limited payload is possible. Moreover also broadband performance can be realized with up-to-date solid-state technology, which is the key parameter for high-resolution radars. Additionally low noise performance allows to reduce transmit power without loosing signal to noise ratio and thus avoids expensive and heavy transmitter technology.

2. THE MIRANDA UAV RADAR

With this technological background, it is possible to develop miniaturized millimetre-wave Synthetic Aperture Radars, able to be used onboard on-board a small UAV with real-time SAR processing. W-band is the optimum choice for all applications, where small-scale features or chances have to be observed as the physical properties of scattering, result in a better contrast and lower speckle. The scattering characteristics of targets and background in this frequency region are mainly governed by the increased relative roughness of all scattering surfaces. Sensitivity to small-scale features and changes is a prominent characteristic of this frequency band. A miniaturized millimeter-wave radar, MIRANDA, to be used as Synthetic Aperture Radar onboard a small UAV was designed, built and tested with an unmanned helicopter [1]. The design followed the FM-CW principle, to get the highest possible average transmit power and thus the best range performance. A very flexible principle of operation, based upon multiplication of baseband frequencies allows an easy adaption to different bands of operation in the millimetre-wave region. An inertial system of high quality, based upon a fibre optical gyroscope [2] maintained the necessary precision, to allow high resolution SAR imaging. The raw data are transmitted to the ground station using an ordinary analogue data link, where they are A/D converted, pre-processed and finally undergo a real-time SAR-focussing algorithm. Additionally to the quick-look processing the data are stored to be able to apply further high quality SAR processing.

2.1. RF Front-End
The front-ends is based upon multiplication of a DDS-generated waveform around 7 GHz using a times-12 multiplier. This gives the advantage to be able to use
conventional hardware with microstrip technology, while only a few millimeter-wave components in the input- and output stages are required [3]. The high frequency components, namely the frequency multiplier, the W-band mixer with integrated low-noise amplifier (LNA) and the high power amplifier (HPA), were developed at Fraunhofer IAF and represent the most advanced state of the art. To maintain a low over-coupling between transmitter and receiver, a separate antenna in a special arrangement is used for each of both. The low over-coupling is mandatory to give a high dynamic range, which is necessary to detect indirect signatures. Fig. 1 shows a block diagram of the system. The photo of Fig. 2 illustrates the mechanical outline and Tab. 1 summarizes the performance data.

The waveform-generator module was especially designed for use with these components. The generator is developed using an AD 9910 DDS (Direct Digital Synthesizer). Fig. 3 shows a photo of the DDS building block.

![Photo of DDS Building Block](image)

To avoid sidelobes in the spectrum, this chirp generator covers the range from 87 MHz to 164 MHz, giving a maximum bandwidth of 77 MHz at this low frequency stage. The DDS is synchronized by an ultra-stable master clock, which also drives other components of the front-end. This technique allows a fully coherent and stable operation, which is important to ensure the coherency within both a single chirp and series of chirps and thus enabling high resolution SAR processing over long range. The output of the waveform generation module synchronizes a signal between 7.68 GHz and 7.99 GHz. The desired output frequency is maintained by subsequent up-conversion and multiplication. For the MIRANDA UAV-SAR the 94-GHz band is realized.

2.2 Inertial System

Key parameters for the SAR imaging are the inertial informations on heading, roll and pitch as well as the exact GPS information.

After experiments with commercial MEMS-based inertial systems, which did not deliver sufficient accuracy to generate high quality SAR images, the AEROCONTROL inertial system of IGI GmbH has been introduced into the SAR system.

The AEROCONTROL incorporates a high precision GPS system, three axis interferometer fibre-optic gyroscope (IFROG) and a processor unit. Tab. 2 summarizes the performance data.

Additionally the measurement data can be extracted in real-time via a RS232 bus, which is necessarily used for the quick-look real-time SAR processing. An off-line SAR
processing with higher quality inertial data can be done later.

<table>
<thead>
<tr>
<th>Quantity</th>
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<tbody>
<tr>
<td>position accuracy</td>
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<tr>
<td>velocity accuracy</td>
</tr>
<tr>
<td>roll / pitch</td>
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<tr>
<td>true heading</td>
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<td>chirp length</td>
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<tr>
<td>weight</td>
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<td>Power consumption</td>
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Tab. 2: Performance Data of Inertial System

2.3 Data Acquisition Unit

The data acquisition unit is designed around the National Instruments high speed 32-bit I/O-card NI 6534. The card is linked to a PC operated under LINUX. The IMU data from the aircraft are linked to the complex radar data and transmitted to the ground station via an analogue data link. A second GPS unit is also integrated into the ground station and can be used for further evaluation purposes. For instance the system time is derived from these data. All data acquired by the ground station PC are available for other computers, as the SAR processor PC, via Ethernet. The calibrated raw data, which are transmitted by the broadband data link, are stored on hard disk, which can be exchanged for further detailed off-line processing. In parallel a real time SAR processing is done on this ground station PC. The whole set-up is mounted into a transportable box.

2.4 Airborne Carrier

Tests were done with the copter-UAV NEO S-300 of SwissUAV, operated bei ESG [4] over the proving ground Storkow (Brandenburg, Germany), where the airspace could be cleared for use of a UAV.

Figure 4. NEO S-300 Copter on Ground and in Operation with the UAV-SAR

| Size                                          | 275x95x86 cm³  |
| Weight max.                                   | 85 kg          |
| Payload max.                                  | 35 kg          |
| Diameter rotor                                | 3 m            |
| Speed max.                                    | 120 km/h       |
| turbine                                       | 12 kW          |

Tab. 3: Technical Parameters of NEO S-300

3. DATA PROCESSING

The variation of the instantaneous slant-range introduced by the continuous motion during the ramp period for a FM-CW radar is not negligible since the conventional start-stop approximation does not hold. Conceptually, this approximation assumes that any transmitted signal experiences a delay time, which is constant during the pulse duration and only varies from pulse to pulse (range migration), whereas generally leading edge and trailing edge of any transmitted pulse experience different delay times introduced by the variation of the slant range with time. Processing of FM-CW SAR data differs from the conventional pulsed SAR as the range walk term and an additional range–azimuth coupling is introduced by the continuous motion of the antenna during transmission and reception of the radar signal. Consequently conventional SAR algorithms cannot directly be applied and the range-Doppler algorithm has to be modified to focus FMCW SAR data [5].

Figure 5. Principle of Mosaic Processing for UAV SAR Data

The SAR signal processing for a radar onboard lightweight carrier platform has to take into account, that such platforms exhibit quite rapid changes in the direction of their trajectory. This makes it quite difficult or even impossible to use a conventional strip-map process, as the related motion compensation algorithms can only handle relatively slow motion gradients. A back-projection algorithm would be able to handle such data, but usually it is quite time consuming and not really suited for a real time imaging approach. The solution for the quick-look real-time image is to subdivide the flight path into a great number of
effectively straight path segments. Each segment can be processed separately, and the image is formed by mosaicking of the segments as demonstrated in Fig. 5.

5. EXAMPLES OF UAV SAR IMAGES

The measurements onboard the copter UAV showed that flight stability has a big influence on image quality. Especially critical is the yaw movement, which occasionally gives reason for a too low sampling of parts of the terrain. Fig. 6 gives such an example.

Figure 6. Example for UAV SAR Image with strong Yaw Movement of Copter

Flights under calm weather conditions or using a fixed wing aircraft results in good images with the theoretical resolution determined by the radar bandwidth. Fig. 7 and Fig. 8 show examples for urban and rural terrain.

6. CONCLUSIONS

Research at Fraunhofer FHR could demonstrate, that a miniaturized Synthetic Aperture Radar at 94 GHz, is well suited to be operated on board of a small UAV, like the NEO S300 copter or for ease of operation on board of any small air vehicle, like a microlite aircraft. The capability to do real time SAR processing with high resolution at a ground station at a remote location could also be demonstrated. In comparison with other radar sensors at lower frequencies like X-band, millimetre-waves have numerous advantages which make them especially suitable for investigation of small scale features [6], like sensing of crops also under adverse environmental conditions. They do not suffer from any dust, smoke or bad weather like EO and IR sensors do. They are also ideally suited to give the necessary guidance to ground based systems.

REFERENCES
