Performance Analysis of a High Resolution Airborne FM-CW Synthetic Aperture Radar

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Abstract - Compact FM-CW technology combined with high resolution SAR techniques should pave the way for a small and cost effective imaging radar. A research project has been initiated to investigate the feasibility of FM-CW SAR. Within the framework of the project an operational airborne FM-CW SAR demonstrator is being implemented. Furthermore, a detailed system model is being developed in order to analyze and estimate the performance of the demonstrator.

1. INTRODUCTION

In the field of airborne earth observation there is growing interest in small, cost effective imaging radar systems of high resolution. Such radar systems should consume little power and be small enough to be mounted on small, possibly even unmanned, aircraft. Additionally, there is a special interest in radar systems which have fast imaging capability, for example in the field of civil crisis monitoring. Cost effectiveness and rapid employability are crucial if such systems are to be successful. Existing imaging radars are usually based on coherent pulse radar technology being neither low cost nor very compact. Pulse radar systems are therefore less suitable for mounting on small aircraft or for applying to civil earth observation.

Frequency modulated continuous wave (FM-CW) radar systems are, on the other hand, generally compact, relatively cheap, and they consume little power. Consequently, FM-CW radar technology seems to be of interest to (civil) airborne earth observation, particularly in combination with high resolution synthetic aperture radar (SAR) techniques. The combination of FM-CW technology and SAR techniques should lead to the development of a small and cost effective, high resolution imaging radar.

SAR techniques have already been successfully applied to coherent pulse radar systems. The feasibility of FM-CW SAR, however, is not evident due to the different radar principles. In pulse radar systems the radar platform is assumed to be stationary during the transmission and reception of a pulse. This so-called *stop-and-go approximation* is valid because pulse radar systems transmit very short pulses. FM-CW radars transmit relatively long sweeps; the *stop-and-go approximation* may therefore not be valid. In such a case the additional phase change due to the platform motion should be taken into account. Furthermore, pulse radar systems measure range in the time domain, whereas FM-CW radars measure range in the frequency domain. Conventional SAR algorithms may therefore not be readily applicable. A research project has been started to investigate the feasibility of FM-CW SAR.

A detailed description of the project and the demonstrator system will be given in the following section. In the subsequent section the CNR will be derived.

2. PROJECT DESCRIPTION

In order to investigate the feasibility of FM-CW SAR in the field of airborne earth observation a research project has been initiated. Within the framework of the project two main subjects are focused upon: the design and implementation of a low cost FM-CW SAR demonstrator system and the development of special SAR signal processing algorithms.

Table 1: The specifications of the FM-CW SAR demonstrator system.

Carrier Frequency:	35 GHz	Antenna Gain:	24 dB
Frequency Sweep:	500 MHz	Antenna Isolation:	52 dB
PRF:	1000 Hz	Beamwidth Azimuth:	6°
Transmitted Power:	18 dBm	Beamwidth Elevation:	28°
Phase Noise at 1 MHz:	-93 dBc/Hz	Platform Velocity:	25 m/s
Phase Noise at 3 MHz:	-100 dBc/Hz	Altitude:	300 m
IF Band:	1 to 3 MHz	Near Range:	400 m
Noise Figure:	7 dB	Far Range:	820 m
System Losses:	1.5 dB	Ground Swath:	500 m

The demonstrator system should prove the feasibility of FM-CW SAR under operational circumstances and provide experimental test data. A detailed system model is currently being developed in order to analyze the performance of the demonstrator system. The developments include a thorough analysis of the power budget and the implementation of a computer simulation, [1], [2]. A Stemme S10 motorglider is available for experimental flights, see Fig. 1. The first airborne experiments are scheduled for the second half of 2003. The performance of the demonstrator system will be evaluated after the airborne experiments. The findings of this evaluation will be used to improve the system models. The improved system models should facilitate the design of a future higher performance FM-CW SAR system.

The demonstrator system will operate in strip-mapping mode. Initially the resolution in range as well as azimuth will be 1 m. In the course of the project this will be augmented to the maximum obtainable value of 30 cm in both range and azimuth direction. The specifications of the FM-CW SAR demonstrator system are summarized in Table 1.

2.1. The FM-CW SAR Demonstrator System

The central part of the demonstrator system is a PXI chassis manufactured by National Instruments, [3]. This chassis contains, among others, a 1.26 GHz Pentium III embedded controller, a 10 MHz, 12-bit A/D converter board, a 100 kHz, 16-bit A/D converter board, a wide ultra SCSI board, and a 40 MHz, 12-bit arbitrary waveform generator. The control software of the PXI chassis is developed in LabVIEW, [4]. The block diagram of the complete FM-CW SAR demonstrator is presented in Fig. 3.

The 35 GHz FM-CW front-end is manufactured by Epsilon-Lambda Electronics. The frequency sweep and the type of modulation are both controlled by the arbitrary waveform generator and they are both software selectable. The IF-band of the front-end is 0 to 3 MHz. The expected beat frequencies are 1.3 MHz for near range up to 2.7 MHz for far range. The radar data are sampled at 6.7 MHz. The 12-bit samples are stored as 2 bytes, resulting in a data rate of approximately 12.7 Mbytes/s.

In order to be able to estimate the position and attitude of the motorglider, three gyroscopes, a tri-axial accelerometer and a Global Positioning System (GPS) receiver are attached to the demonstrator system. The motion sensors have analogue outputs which are sampled at 1000 Hz. The GPS receiver has an RS232 output. It gives its position once every second. The GPS readings are necessary to update the position estimates made with the aid of the motion sensors because the motion sensors exhibit a considerable drift over time.

A digital camera has been added to the system in order to compare the radar images with pictures of the imaged area. The camera is controlled via a USB link. Pictures are taken automatically at regular intervals.

For the motorglider standard certified pods that can be attached under the wings are available. These pods have a diameter of about 35 cm and a length of 80 cm, excluding the aerodynamic fairings. The maximum payload is 50 kg. The complete FM-CW SAR demonstrator has been fitted in such a pod. The

Fig. 1: The motorglider with pods attached under the wings.

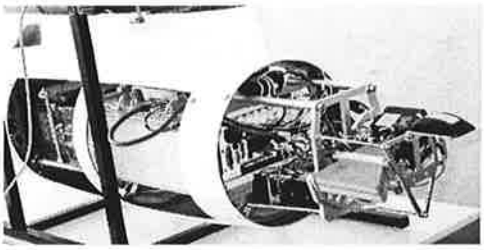

Fig. 2: The FM-CW SAR demonstrator system installed in the standard pod.

demonstrator system installed in the pod is shown in Fig. 2.

With the aid of a pocket PC the demonstrator system can be monitored and controlled from the cockpit. The pocket PC and the demonstrator system are connected by means of a network connection.

The complete system is fed by a 12 V battery which is also placed inside the pod. The system can operate for approximately 2.5 hours on the battery.

2.2. FM-CW SAR Signal Processing

Because pulse radars measure range in a different domain, conventional SAR algorithms may not be readily applicable to FM-CW systems. One of the main topics addressed during the project is therefore the development of new processing algorithms which take the characteristics of FM-CW signals into account, [5], [6]. In the course of the project the possibilities for moving target indication will be investigated and furthermore a study of real time processing using off-the-shelf parallel computer boards will be carried out.

3. CLUTTER-TO-NOISE RATIO

The two main contributors to the noise floor of the FM-CW SAR demonstrator are the thermal noise and the oscillator phase noise. Within the context of oscillator phase noise, the direct coupling between the transmitting and the receiving antenna is a well-known problem in FM-CW systems. After demodulation the direct-coupled signal will be close to dc. The phase noise sidebands of the demodulated direct-coupled signal may, however, extend well into the beat spectrum. This is an important issue because the direct-coupled signal is generally much larger than the echo signals coming from targets. Thus, the phase noise related to large (unwanted) echo signals effectively raises the receiver noise floor. An inventory of the noise sources has already shown that the sensitivity of the FM-CW SAR demonstrator is limited by oscillator phase noise rather than thermal noise. Of course the phase noise level is mainly determined by the quality of the RF oscillator. Having chosen for a low cost approach, increased phase noise levels cannot be avoided.

If it is assumed that the direct coupling is the main contributor to phase noise, the phase noise power follows as:

$$N_p = \frac{P_c N_{osc}(f_m) B_n}{\chi}, \tag{1}$$

in which P_c is the power at the carrier frequency, $N_{osc}(f_m)$ is the oscillator phase noise at an offset frequency f_m from the carrier, B_n is the noise bandwidth, and χ is the antenna isolation. In FM-CW radar systems the noise bandwidth equals the sweep repetition frequency, [7].

The phase noise power is evaluated for far range corresponding to a beat frequency of 3 MHz. At an offset frequency of 3 MHz the oscillator phase noise is -100 dBc/Hz. In that case the phase noise power related to the direct coupling N_p is around -134 dBW. The thermal noise power N_t is -166 dBW.

If part of the transmitted signal is used as local oscillator in the receiver the effect of phase noise is reduced (the so-called *range correlation effect*, [8]-[12]). That is because in this case the local oscillator's

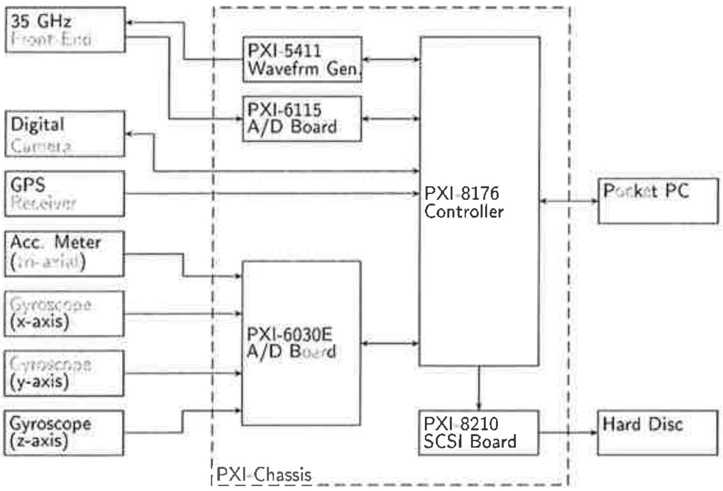

Fig. 3: The block diagram of the FM CW SAR demonstrator system.

phase noise is correlated with the phase noise of the received signal. The range correlation factor is given as:

$$K^2 = 4\sin^2(\pi f \Delta t), \tag{2}$$

where Δt is the total delay time between transmission and reception. As can be seen from (2), the reduction of phase noise is significant if the delay time is very short. This is particularly true for the direct coupling. For the phase noise related to the direct coupling K^2 is -31 dB.

The received power from a resolution cell filled with clutter is given as:

$$P_r = \frac{P_t G^2 \lambda^2 \sigma_{sar}}{(4\pi)^3 R^4}, \tag{3}$$

where P_t is the transmitted power, G is the antenna gain, λ is the carrier wavelength, σ_{sar} is the clutter radar cross section, and R is the range. The clutter radar cross section is -12.4 dBm^2, [2]. The received clutter power is -167 dBW.

After SAR processing the clutter-to-noise ratio (CNR) can be written as:

$$CNR = \frac{n P_r}{N_t + K^2 N_p}, \tag{4}$$

where n is the number of sweeps that is coherently integrated. For far range the CNR is 24 dB assuming the coherent integration of 1000 sweeps. In practice the CNR will be lower since the received clutter power will not be fully coherent from sweep to sweep, [1]. It is nevertheless expected that the CNR will be satisfying even under operational circumstances.

4. CONCLUSION

System models are currently being developed in order to estimate the performance of an FM CW SAR demonstrator system. A first inventory has shown that the sensitivity is limited by oscillator phase noise. Therefore, a study on the effects of phase noise has been carried out.

If part of the transmitted signal is used as local oscillator in the receiver, the effect of phase noise is reduced significantly due to the *range correlation effect*. In that case the noise floor is raised about 3 dB by the phase noise associated with the direct coupling between the transmitting and receiving antenna.

After SAR processing of 1000 sweeps the expected CNR is 24 dB for far range assuming coherent integration. In practice the CNR will be lower since the clutter power will not be fully coherent from sweep to sweep. It is however expected that the CNR will be satisfying even in operational conditions. In the second half of 2003 experimental results will become available.

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