Compact Scalable Multifunction RF Payload for UAVs with FMCW Radar and ESM Functionality

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Abstract—This paper describes a concept for a scalable RF sensor payload for small UAVs that can perform multiple RF functions such as synthetic aperture radar (SAR), ground-moving target indication (GMTI) and ESM. Essential to the scalable multifunction RF payload concept is the digitization of the antenna signals on transmit and receive at the antenne element level. The architecture of a technology demonstrator that can perform radar and ESM functions is described and first results of some of the various radar and ESM modes are shown.

Keywords - Radar, ESM, multifunction, UAV

I. INTRODUCTION

In current military operations, tactical sensors need to provide accurate and timely information for Intelligence, Surveillance, Target Acquisition and Reconnaissance (ISTAR) tasks. Electro-Optical (EO) sensors provide accurate information that is relatively easy to interpret but they do not perform well in environments with dust, smoke and bad weather. Radio Frequency (RF) sensors such as radar and Electronic warfare Support Measures (ESM) receivers are much less affected by environmental conditions and also provide a capability to penetrate foliage and buildings.

At the same time, a special interest of the military is in small tactical UAVs because of their small logistical footprint and quick reaction capability. However, small UAVs have severe volume, weight, and power constraints which impose a high degree of system integration and miniaturization on the sensor payload. A Scalable Multifunction RF (SMRF) system fitted with digitization at the antenna element level offers the required level of integration to deliver increased flexibility and efficiency for performing different RF functions with a single sensor payload [1].

The RF functions that are of interest for a small UAV include stripmap Synthetic Aperture Radar (SAR) and Ground Moving Target Indication (GMTI). High resolution modes like spotlight SAR and Inverse SAR (ISAR) are indispensable for target classification. In addition, an RF function that detects moving air targets may provide a sense-and-avoid capability for the platform, which is currently one of the most anticipated and critical functionalities to allow integration of UAV in (conventional) air traffic. Aside from the aforementioned ground surveillance and sense-and-avoid functionality, the inclusion of other (non-radar) functionalities in the sensor suite of a (mini) UAV is imperative. Tasks such as interception and direction finding of radar emitters (i.e., radar ESM) and data communications to a ground station can be accommodated in the SMRF concept. The combination of these widely varying RF functions in a single sensor payload will extend its applicability significantly. The purpose of this paper is to describe a novel SMRF concept that combines radar and ESM functions in a compact payload.

This paper is organized as follows. The digital SMRF concept is discussed in section II. Section III describes the various RF functions for an airborne SMRF system in more detail. The payload constraints for a small UAV are discussed in section IV. Section V describes the architecture and hardware building blocks of an SMRF system with radar and ESM functionality and some of the experimental results that have been obtained. Finally, conclusions are provided in section VI.

II. DIGITAL RF SYSTEM

The continuously increasing performance of digital circuitry, analogue-to-digital convertors, etc., combined with their decreasing size and power consumption, enables the further digitization of RF systems such as radar and ESM receivers. Digital RF systems, and in particular digital phased array systems, offer a number of distinct advantages over conventional phased array radars.

Conventional phased array radars consist of many transmit/receive (T/R) elements and extended RF manifolds. High-power components, such as the T/R elements, are usually bulky, relatively power-inefficient, and may even need special cooling measures. Traditional analogue array antennas are therefore not suited for mounting on a small UAV.

The receiver chain of a radar system equipped with a conventional phased array is schematically shown in Fig. 1. The RF manifolds are apparent. As depicted, an array is usually divided into subarrays and per subarray the beamforming is performed with phase shifters, resulting in a single receive channel for each subarray. These subarray channels are digitized for further processing. Consequently, just a single antenna beam is formed per subarray per sweep.

As can be seen in Fig. 1, the sum and difference channels can nevertheless be available concurrently. Hence, in principle, SAR modes, using the sum channel, and GMTI modes, exploiting the difference channels, can operate simultaneously. However, these modes make very different demands on

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antenna beams and waveforms, and as a result, the fully concurrent operation of SAR and MTI modes is cumbersome.

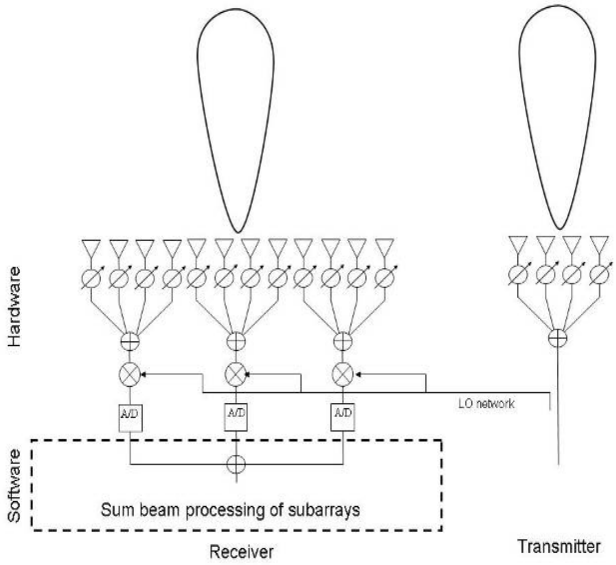

Figure 1. Conventional analog phased array with three subarray manifolds on receive.

For the true concurrent operation of different radar modes, the availability of simultaneous, independent antenna beams and orthogonal waveforms is a prerequisite. In traditional phased arrays, different beams can be formed simultaneously by realizing several arrangements of RF manifolds. With each arrangement of RF manifolds, a separate beam can be formed. When volume and weight are limited, the implementation of several arrangements of RF manifolds is not an option.

The concept of an RF system equipped with digital arrays on transmit and receive renders the RF manifolds redundant. The very special nature of such a digital RF system is realized by the fact that on transmit a digital waveform is synthesized at the element level and on receive all elements are digitized separately, as depicted in Figure 2. This approach not only renders the RF manifolds superfluous, but it also has the important consequence that completely independent waveforms and beams can be formed simultaneously. This paves the way for new, innovative mode designs. For example, the transmit array can simultaneously transmit two orthogonal waveforms, e.g. for SAR and data communications while on receive all array elements are used to perform optimal beamforming for these two functions. Note that it is implicitly assumed, that the relevant space is illuminated by a wide transmit beam.

The digital nature of the waveform generation and beamforming on transmit and receive offers the advantage that almost all building blocks of a digital RF system are defined by software and consequently can be quickly adapted to changing environments and missions. A master Local Oscillator (LO) signal (or clock signal) is still required to synchronize all elements. However, a network to distribute the master LO signal is considerably less bulky than RF manifolds.

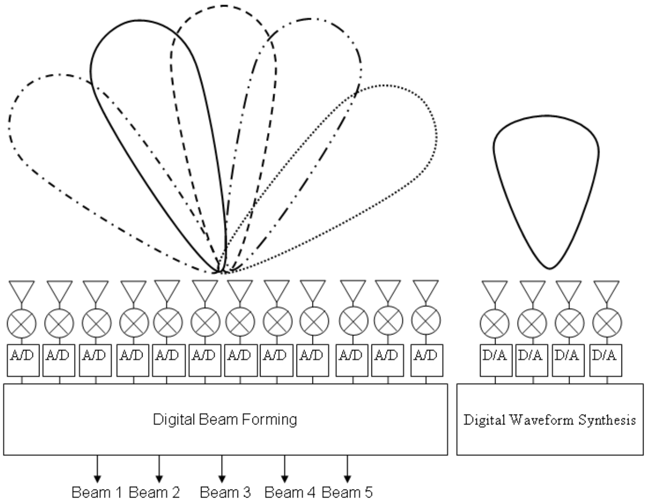

Figure 2. Digital RF system with digital waveform synthesis at the element level on transmit and digitization at the element level on receive. On transmit multiple (orthogonal) waveforms can be generated simultaneously and on receive, multiple beams can be created by digital beamforming.

In a digital RF system, a complete digital transmit and/or receive module must be installed behind each antenna element. The size of the digital elements is therefore limited by the required array element spacing. In practice, the element spacing is about half a wavelength. At X-band this is approximately 1.5 cm which is sufficient to fit a complete digital T/R module. Therefore, recent developments in digital radar concentrate mainly on X-band or lower frequency systems, e.g. [2],. Sufficiently small Ku-band components are expected to become feasible within the next few years. Ultimately a single-chip T/R module is desired.

III. RF FUNCTIONS

Some of the RF functions that may be performed by an airborne digital RF system are described in this section. While some of the functions can be performed concurrently, other functions can only be performed sequentially. If each transmit module is able to generate its own transmit signal, the array can be divided into subarrays, each performing its own dedicated task.

A. Synthetic Aperture Radar

Synthetic aperture radar can provide high resolution images of the earth's surface that are vital for detection of changes in the environment, and for surveillance and reconnaissance. High azimuth resolutions require the antenna beam to be wide. This results in a high azimuth sampling rate. The beamwidth of a single antenna element is very wide. Only after beamforming the sum beams can become narrow. High resolution stripmap modes are therefore possible with a digital RF system. A digital RF system also allows for a reduction of the azimuth sampling rate by dividing the receive array into several subarrays. This increases the effective number of samples along the azimuth per transmitted sweep and enables high resolution strip mapping modes with a low Pulse Repetition Frequency (PRF).

B. Ground Moving Target Indication

The detection of ground moving targets plays an important role for surveillance of a large area. The position and velocity measurements require a narrow beam with several subarrays for space-time adaptive processing (STAP) to achieve effective clutter reduction. The division of the antenna into the required subarrays can be performed adaptively in the digital array constituting advanced GMTI processing. Per subarray all beam directions can be obtained simultaneously. The subarray beams are no longer required to scan and each target in the transmit beam can be tracked continuously. GMTI modes favour high PRFs for unambiguous measurements of the radial velocity of the ground targets. Moreover, at close range, large unambiguous range, requiring low PRF, is not needed.

C. Maritime surveillance

For surveillance in a maritime or littoral environment specialized maritime modes are required. For detection 360° surveillance is required. After detection, Inverse SAR (ISAR) and High-Range Resolution (HRR) modes are used for target recognition. For ISAR the rotational motion of the target is used. For HRR a range profile with high resolution is obtained.

D. Sense and Avoid

A major issue for UAVs is the restricted airspace they are allowed to use. This is mainly due to the absence of a human that can intervene when another airborne vehicle is on a collision course. A sense-and-avoid sensor that detects other flying objects and can take evasive action, is a prerequisite for integration of UAVs in unrestricted airspace. Sense-and-avoid technology has not yet matured and several types of sensors are being considered. Obviously, the reaction time (under all weather conditions) is one of most important parameters in collision avoidance, which implies that radar is inherently the most suitable sensor for this task.

A forward looking digital radar with a broad transmit beam and multiple beams on receive can detect and locate moving airborne objects. The high velocities involved require a continuous monitoring and tracking of incoming objects. Because of the multiple receive beam covering the entire surveillance volume, no scanning is required for the digital radar concept. This facilitates a high update rate for the entire surveillance volume of the radar.

E. Data Communications

Both radar and data communications rely on the transmission of RF signals. A digital RF system can simultaneously transmit waveforms that are optimized for radar and communications by splitting the transmit array in two parts. Alternatively, the transmission of data can also be performed with a waveform that is suitable for radar [3].

F. Navigation

The navigation mode is very similar to an imaging mode. Assuming that low resolution suffices for the navigation, the processing will be different for the navigation mode as compared to the imaging modes using SAR. Correlation of the radar image with a map can yield a position measurement independent from GPS. Covering several directions at once, with multiple beams, allows a robust localization. This redundancy in location helps in the acceptance of UAV using unrestricted airspace. With multiple beams, Doppler centroid estimation (clutter-lock) can be effectively used to determine instantaneous platform velocity, without the directional ambiguity of one dimensional velocity estimation with a single beam. At close range, these techniques can be used to aid safe landing as well.

G. Weather Radar

The weather radar geometry is similar to the detection of airborne objects: forward looking radar. The differences lie in the velocity of the objects (the precipitation) and the conversion of radar cross section to precipitation rate. Weather features are large, so that low resolution is generally sufficient for weather modes.

H. Weapon Location

Analogous to ground-based weapon location radars that detect and track artillery shells in order to estimate their launch position, an airborne weapon location radar is of great interest. The challenge for this functionality is mainly the very low Radar Cross Section (RCS) of projectiles. In an airborne configuration, the detection of these projectiles is hampered by the presence of terrain clutter. A narrow antenna footprint minimizes the terrain clutter. Having a narrow beam and yet sufficient search volume can be potentially achieved with simultaneous beams that the digital radar concept can provide. Furthermore, vertical subarrays can be used to provide additional terrain clutter reduction, exploiting vertical separation between terrain and projectile.

TABLE I. OVERVIEW OF RF FUNCTIONS

Modes	**Characteristics**		
	PRF	***Sensitivity***	***Bandwidth***
SAR	Medium	Medium	High
GMTI	High	Medium	Low
Sea surveillance	Low	Medium/Low	Medium
Sense and avoid	High	Medium	Medium
Communications	N.A.	Medium	Medium
Navigation	Low	Low	Low
Weather radar	Low	Medium	Low
Weapon location	High	Very High	Medium
Radar ESM	N.A.	Medium	High

I. Overview

The characteristics for the various RF functions described above are clearly not compatible with conventional analogue phased array solutions. A digital RF system offers an approach in which at least several of these diverse functions can be combined. Table II gives an overview of the impact of the different RF functions on the primary RF sensor characteristics.

IV. UAV PAYLOAD REQUIREMENTS

At present, UAVs range from micro UAV to very large aircraft systems. This paper focuses on payloads for small UAVs, i.e., the category that is commonly called ‘mini-UAV’, and in particular those with typical payload weights around 10 kg . In this category, radar payloads are still feasible as shown in [4]. A wide range of UAVs exist in this category with varying performances (Luna, Observer, Viking, Mini-Vanguard, Scorpion etc). As a guideline, Table II summarizes some relevant characteristics. Most of the platforms typically carry various optical sensors.

TABLE II. MINI-UAV CHARACTERISTICS

Characteristic	**Values**		
	Typical	***Max.***	***Unit***
Payload	5 - 10	20	kg
Endurance	2 – 3	5	h
Cruising altitude	500	3000	m
Cruising speed	30 – 50	80	m/s
Electrical power	30 - 50	100	W

Both the type of operational deployment and the constraints on size and power on an RF sensor dictate close range operation. Typical radar ranges will be up to a few kilometres.

V. SMRF UAV PAYLOAD WITH RADAR AND ESM FUNCTIONALITY

A. System Architecture

To meet the stringent requirements on weight, volume and power, an SMRF UAV payload concept is proposed in this paper that is based on the Frequency Modulated Continuous Wave (FMCW) radar principle. Compared to a pulse-Doppler radar, an FMCW radar has the advantage of a low sampling rate [2]. Furthermore, FMCW radars can be completely realized in monolithic microwave integrated circuitry (MMIC) and integrated in the T/R elements. The FMCW principle requires adaptation of some processing schemes for radar functions which are typically carried out with pulse-Doppler radars.

At TNO, a compact SMRF system called EMERALD (Electronically scanned MultiplE function Radio frequency Array for Light-weight payloaDs) has been developed that allows FMCW radar and ESM functions to be performed sequentially or concurrently, see Fig. 3 [5]. The hardware architecture consists of a motherboard, eight T/R modules, two antenna arrays and a base plate for mechanical support. The EMERALD system can operate in X-band between 8.8 and 10.2 GHz.

B. Motherboard

The X-band signal for the EMERALD system can be externally supplied or generated internally. The external option, selected through a switch on the motherboard, provides the possibility to scale the RF system to multiple modules while maintaining coherent signals. The internal synthesizer uses a 155 MHz oscillator, phase-locked loop (PLL) circuit and direct digital synthesizer (DDS) to generate a software adjustable LO signal around 10 GHz. This signal is amplified, split in two and distributed to the 8 SMP connectors to connect to the T/R modules. The other branch is mixed with a baseband signal from a DDS circuit and supplied to a connector accessible from the outside. The mixer-DDS arrangement is identical to that in the T/R modules and when programmed identically it can provide a copy of the transmit signal to, for instance, a reference input of an antenna measurement set-up receiver.

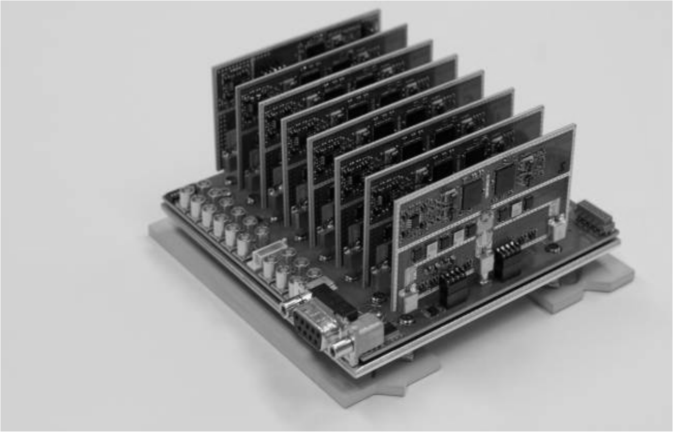

Figure 3. EMERALD SMRF system with combined radar and ESM functionality.

The Intermediate Frequency (IF) outputs of the receivers on the T/R modules are either routed to the 16 individual IQ output connectors for most flexible processing options or terminated in 50 Ω and summed without adjustable phasing to a common output. The common output relies on beam forming by adjusting the phasing of the received signals through the receiver local oscillator. Other circuitry on the mother board is a microcontroller with RS-232 interface for controlling all DDSs and switches as well as the on-board synthesizer.

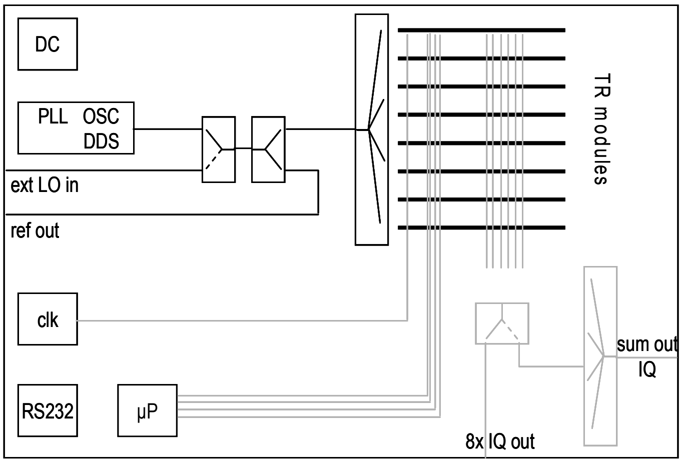

Figure 4. Schematic drawing of the EMERALD motherboard.

C. T/R modules

The T/R modules contain a single side band mixer for upconversion of the LO signal from the mother board with the signal from the transmit DDS to the swept transmit signal, see Fig. 5. After amplification to 12.5 dBm this is connected directly to the antenna elements.

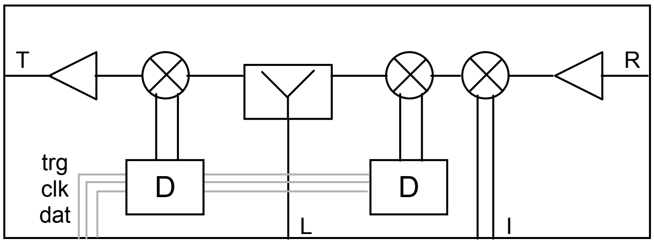

Figure 5. Schematic drawing of an EMERALD T/R module.

A total effective isotropically radiated power (EIRP) of over 2 W is obtained for an 8-element array. In the receiver chain the local LO signal is first mixed with the baseband signal from the receive DDS and subsequently used as the LO signal for down-converting the received signal (after low-noise amplification) from the antenna.

D. Antennas

The system uses two separate 8-element antenna arrays, one for transmit and one for receive, see Fig. 6. The antenna elements are pin-based cavity radiators which are fabricated on standard printed circuit board material [6]. The pitch of the antenna elements in the arrays is 14 mm and thus allows for grating lobe free scanning up to 10.7 GHz. The antenna panels have angled connectors and feeding lines on one side of the substrate and shallow slot coupled cavities, surrounded by vias, on the other side. The panels are approx. 3 mm thick. The feeding is done with microstrip coupled through a slot in the ground plane.

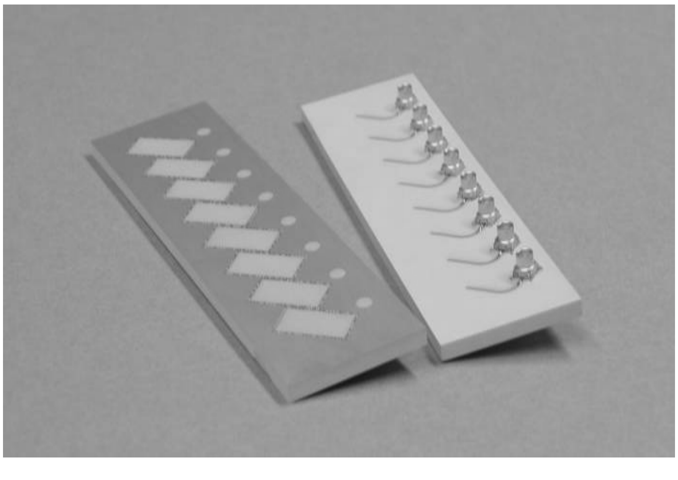

Figure 6. Antenna array with 8 pin-based cavity radiators.

The edges of the antenna arrays are close to the pin-based cavities to allow for aligning multiple substrates to built larger arrays. The element spacing will only be 1 mm larger for elements on different substrates. The transmit and receive antenna centres are approximately 80 mm apart and are on separate panels.

E. System Modes

The EMERALD system can operate in the following modes:

- radar pencil beam mode with a single narrow beam on transmit and receive (scanned)
- floodlight radar mode with wide beam on transmit and multiple beams on receive;
- ESM intercept mode with 8 receive channels in consecutive frequency bands;
- ESM direction finding mode with 8 receive channels at the same frequency.
- combined radar and ESM mode with a narrow radar beam on transmit, a single wide radar beam on receive plus 7 ESM receive channels in consecutive frequency bands for interception of X-band radars;

F. Radar pencil beam mode results

In pencil beam radar mode, the beam direction can be set using the start phase word in the DDS circuits. When each antenna has a correct starting phase beam steering is obtained as the instantaneous bandwidth is low. Both transmit and receive beams can be set in this way. The IF receive channels are summed on the motherboard and can be sampled with a single channel analogue-to-digital converter. A more flexible solution is to sample all channels independently and sum digitally. This requires more processing resources but gives the possibility of multi-beam operation.

Experiments haven been performed to test the radar pencil beam mode, especially the suppression of sidelobe scatterers on transmit and receive [7]. For the tests, the parking lot next to the TNO building has been used. A corner reflector was positioned at 17 m distance from the radar. This was the optimal distance where the influence of the environment was minimal. Four measurements were performed:

- Corner reflector in main beam with uniform weighting.
- Corner reflector in main beam with nulling.
- Corner reflector in sidelobe with uniform weighting.
- Corner reflector in sidelobe with nulling.

The results are shown in Fig. 8. The transmitted bandwidth is 70 MHz (from 10.05 to 10.12 GHz). The trigger signals are visible in the measurements. In order to reduce their influence the time signal is weighted with a Hanning window.

When the corner reflector is inside the main lobe there is only a small difference between the two measurements. Due to the amplitude weighting 0.5 dB is lost when nulling is applied. When the corner reflector is positioned in the first sidelobe, the power is reduced by 26 dB (13 dB loss in gain for both transmit and receive beam) for the uniform weighted beam. By applying (adaptive) nulling in the direction of the first sidelobe the response of the corner reflector is suppressed by an extra 16 dB. The signal at 38 m corresponds to large metallic objects positioned on the parking lot. A multipath response is visible at 50 m when the corner reflector is in the main beam.

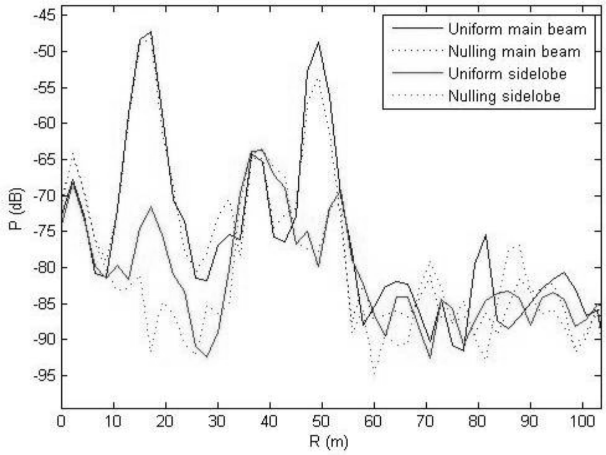

Figure 7. Results of the EMERALD radar mode with suppression of sidelobe scatterers.

G. *ESM intercept mode results*

In the ESM intercept mode, pulsed radar emitters in X-band can be detected using 8 channels that are tuned to consecutive frequency bands. With sampling of the inphase (I) signal only and an offset frequency between the channels of 10 MHz, a frequency band of 40 MHz can be simultaneously covered by the system. When IQ sampling is used, the frequency bands can each be 20 MHz wide and interference of the 10 MHz (in-band) offset frequency is greatly reduced. The pulse is detected in several consecutive channels, see Fig. 8, but with post processing the central channel can be determined. After detection of a pulse all channels will be switched to the detected frequency and the angle-of-arrival can be determined.

VI. CONCLUSIONS

In this paper, a concept for a compact scalable multifunction RF payload for small UAVs has been introduced. A (non-exhaustive) list of RF functions that can be performed with such an SMRF system has been provided. The architecture of a demonstrator that combines FMCW radar and ESM functionality in a compact system has been described. First results of some of the radar and ESM modes of this technology demonstrator show that the system performs as expected. Further experiments with SAR and GMTI radar modes and ESM intercept and direction finding modes will be performed in the near future.

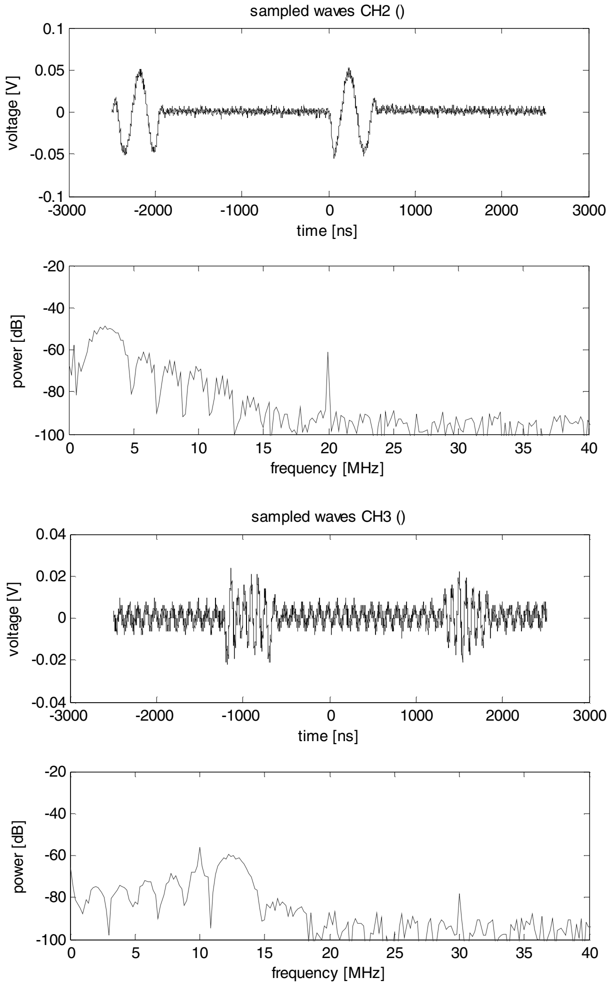

Figure 8. Results of the EMERALD ESM intercept mode

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