

Ultra-Wideband Polarimetric GPR-Array stimulated by Pseudo Random Binary Codes

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Abstract— Due to improvements in RF-electronics and digital data throughput, ultra-wideband arrays become of increasing interest in Surface Penetrating Radar applications. This is not only for faster scanning but also because of the ability to gather more information from test objects. Arrays enable to the capture of multi-offset and polarimetric data. Different array structures and scanning procedures are applicable which result in a mixing of synthetic and real array data processing schemes. An adequate antenna array, a stable and fast acquisition electronics as well as a powerful digital system are the prerequisites to implement an UWB array. The article describes some basic issues with regards to a large UWB-array.

Antenna-Array, Polarimetry, M-Sequence, Ultra-Wideband, Mine detection, Surface Penetrating Radar

INTRODUCTION

It is well known that the scattering from objects depends upon frequency, wave polarisation and the angle of the incident and the scattered wave. The higher their degree of diversity, the higher the quantity of gathered information will be. Consequently, the chance will increase at least theoretically to recognize and respectively to classify unknown objects by their scattering.

There are two basic prerequisites to approach this goal. One of them is to capture the appropriate data. The second refers to the processing so that in the end the desired information can be extracted from the measured data. It is a technical challenge to meet both requirements not least because of the amount of data to be gathered and processed. This presentation will address exclusively the first point, the technical aspects of gathering polarimetric scattering data over a large bandwidth and different aspect angles by a linear antenna arrangement. For the second point refer to [1] of these proceedings. The research and development activities were mainly initiated by promoting the detection of landmines by GPR methods. There are however a great deal of other applications of such techniques for e.g. non-destructive testing in civil engineering, medical applications, through wall imaging and others.

In what follows the basic concept of the UWB-array will be successively considered by starting with the general system layout via the structure of the measurement modules up to the basics of the data gathering conception. The latter is based on a M-sequence approach which permits a monolithic integration of all RF-components, stable operation and a simple control of the gathering process.

SYSTEM CONCEPT

The design goal was to build a large UWB-array which would allow a high degree of flexibility concerning the configuration of measurement channels and measurement procedure. We wanted to be able to operate different antenna configurations without changes in the electronics and the required bandwidth was beyond 3 GHz. While designing a large antenna array, one immediately becomes aware of the challenges concerning hardware expense, measurement rate, data throughput and time stability of the RF hardware. In order to meet these requirements a M-sequence approach was applied for data gathering. It will be described below.

The chosen antenna configuration - one of many other possible variants - opened up the opportunity to combine different methods of data processing (combination of synthetic and physical array processing, polarimetry) as well as an effective scanning of large areas. Fig. 1 provides an impression of the antenna arrangement forming a dense, uni-polar, linear array and a linear, polarimetric array.

The conception of the overall system was determined by a high degree of flexibility and extensibility. Fig.2 shows its structure. The array is assembled from identical basic modules (compare also Fig.1), which can be arbitrary cascaded. All modules are controlled by the same, stable master clock. It was provided by a 9 GHz DRO (dielectric resonance oscillator). The data exchange is handled by a serial LVDS bus allowing a data throughput of up to 25 Mb/s. The continuously provided measurement data has to be spooled in the acquisition buffer in

order to avoid data loss during the transfer onto the hard disc of the host computer. The current hardware version was not designed for on-line processing. By that a Windows operating system and MATLAB for data processing gave a reasonable performance and experimental flexibility. However during data recording, a selected sub-set of pre-processed data are continuously monitored to supervise the procedure of data capturing. For that purpose, every basic module is equipped with two FPGAs and two DSPs.

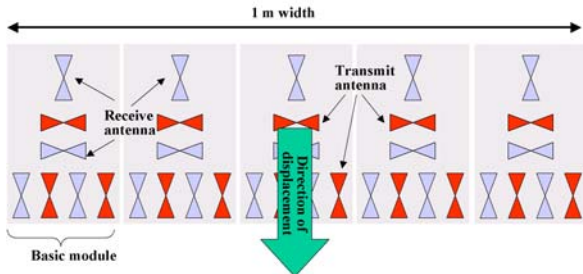


Figure 1. Configuration of the polarimetric antenna array. The actual array covers five modules.

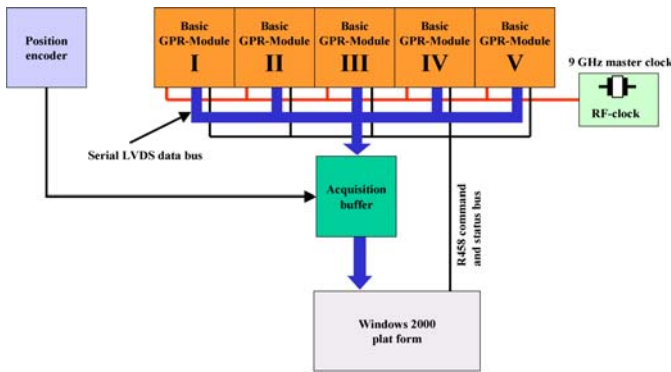


Figure 2. Hardware configuration of the polarimetric UWB-Array.

The measurement process can be configured in an arbitrary way before the measurement starts. The control commands and status messages are handled by a RS485 bus. Every basic module is able to provide the measurement data of two receive channels in parallel. This means that, for the shown configuration, a maximum of ten receive channels can operate at the same time. On the other hand, only one transmitter may be active at a pre-defined time in order to avoid cross channel interference. In summary, the current system has 20 receive and 15 transmit ports (antennas) at its disposal, thus a total up to 300 different transmission channels could be established. Actually, only a small subset of the possible variants are usual in connection with the array configuration according to Fig.1.

A position encoder finally provides the information on the advancement of the array displacement. The current software version is limited to a linear displacement but there are no restrictions to adapt it to an arbitrary curved movement by introducing a sophisticated positioning system.

Fig. 3 shows two photos of the polarimetric UWB-array. The sensor box contains all system components with exception of the acquisition computer.

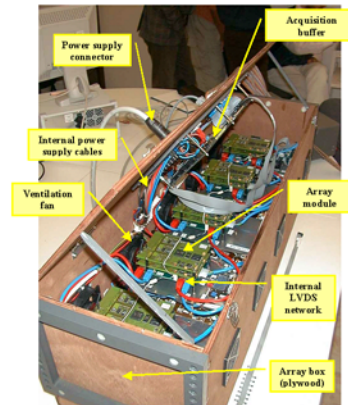
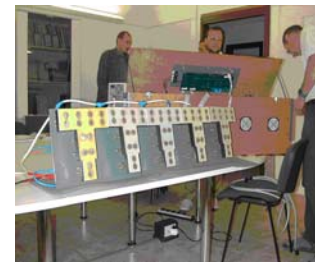


Figure 3. Photo top: Disassembled UWB-array showing the antenna plan and the housing in the background. Photo bottom: Assembled sensor box with open lid seen from the top.

MODULE CONCEPTION

The basic module structured as in Fig.4 is able to handle 3 transmit and 4 receive ports. Every transmit port is equipped with its own signal generator all synchronized by the central master clock. A select signal enables the generators successively in such a way that only one is active within the whole chain. The bandwidth of the feeding signal is from 20 MHz to about 4 GHz. The average power is about 0 dBm provided by a peak voltage never exceeding 300 mV at 100 Ohms symmetrical load.

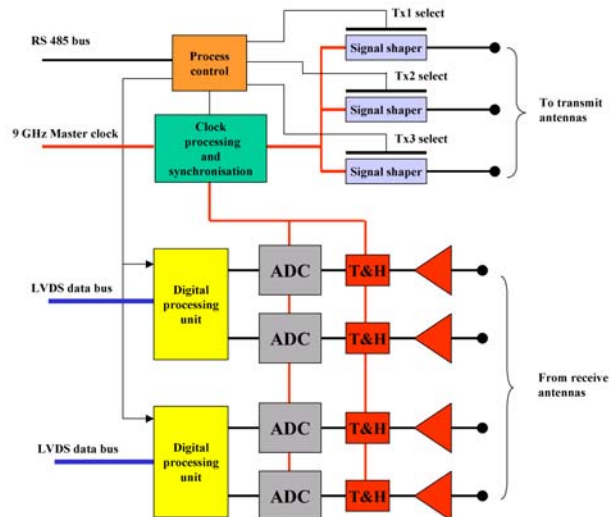


Figure 4. Structure of the basic module.

The four receiver chains work in parallel. The data is sampled at a rate of about 17 MHz applying a sub-sampling approach. The digital processing units average the incoming data in order to increase the signal to noise ratio and to reduce the data rate. Furthermore, they perform an impulse compression (see next chapter) of the averaged data. The digital impulse compression operates on one data channel within a digital unit. Thus, the data of two receiver ports per module can be forwarded simultaneously.

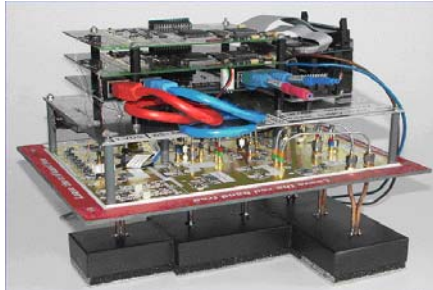


Figure 5. Photograph of the basic module.

The receiver input lines are also symmetrically driven with 100 Ohms impedance. The concept of 100 Ohms symmetrical impedance for either transmit and receive port provides a high flexibility in antenna feeding, as it can be applied to both balanced and unbalanced antennas. In the present case, the antennas are loaded bow-ties mutually shielded in order to reduce cross-coupling. Antenna cross-coupling is critical since it generates the strongest signal and cannot be gated out during data recording because: 1) the roundtrip time of the wave is too short (1 ns or less) and; 2) the radar is of continuous wave type. See [2] for further antenna information.

Fig. 5 shows a photo of a basic module. The modules form compact units. Theoretically, an arbitrary number of them can be linked by cascading the LVDS and RS 485 lines and the RF-master clock is distributed via star wiring.

M-SEQUENCE RADAR PRINCIPLE

The prerequisite for operating a large UWB-array outside laboratory conditions, is the availability of adequate measurement heads which provide a high data rate, high timing stability, compactness, robustness, and simple controllability at reasonable costs. The M-Sequence approach was selected as the favorable solution. The basic principle of a M-Sequence radar was first published in [3]. The basic reason to leave the classical approaches of impulse radar or step frequency radar are to be seen in the above mentioned requirements which, in sum, are not met by either methods.

The elementary structure of a M-sequence unit is summarized by Fig. 6. It is divided into three parts:

- The RF-clock: It provides the clock for all further sub-components. Only one clock unit exists within the whole array. Its jitter and drift determines the time stability of all channels.

- The UWB-front end: It provides the RF stimulus and captures the back scattered waves. It is the only part, which is dealing with analog signals. The key components are customer designed monolithic RF-IC in SiGe:C technology. Input and output amplifiers and anti-aliasing filters are not shown for simplicity. Fig.7 represents some design examples of the RF-components.
- Digital processing unit: It performs a fast pre-processing of the digitized data. In multi-channel applications (i.e. arrays), it also handles the measurement procedure and inter-module operation.

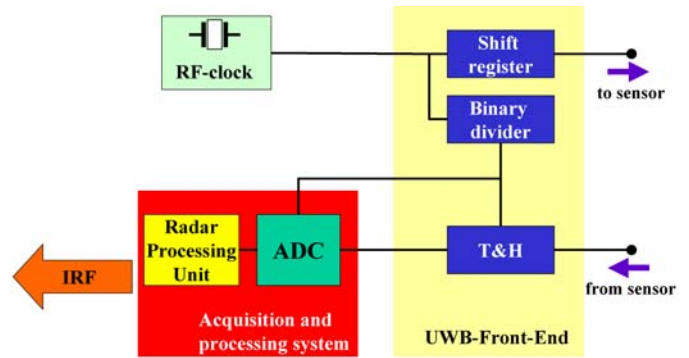
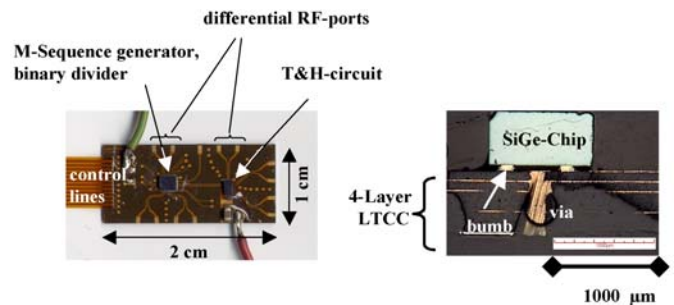
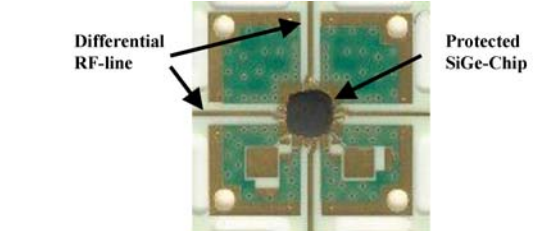


Figure 6. Block schematic of a M-Sequence measurement head.

The functioning principle is as follows. A digital shift register is pushed by an RF-clock of frequency f_c . In the case of a suitable internal feedback, the shift register periodically creates a maximum length binary sequence or in short an M-Sequence at its output. A M-Sequence is a special kind of a pseudo random binary code. It has a very short auto-correlation function, i.e., it spreads its energy over a wide spectral band. Thus in principle, it is very well suited to stimulate a device under test for impulse response measurements.



a) RF front end mounted on LTCC by flip chip technique



b) Universal RF board for M-Sequence IC, T&H IC and divider IC

Figure 7. Design examples of the RF components.

Compared to a pulse with the same mean power, the magnitude of an M-Sequence is quite low. This simplifies the handling of RF-signals and permits monolithic integration in a low-cost semiconductor technology.

The reaction of the device under test at the M-Sequence, i.e., the sensor response is captured by a track&hold (T&H) circuit and digitized. The first processing step synchronously averages the digitized data. In order to gain a high data throughput, the averager was implemented within a FPGA (field programmable gate-array) by a specific hardware structure. In the present case, a fixed number of 256 averages were calculated resulting in 256 fold reduction of the data rate for the following processing steps and a 24 dB improvement of the signal to noise ratio.

The FPGA is followed by a DSP which allows for a high flexibility in further processing steps. Usually it performs additional averaging (if required) and above all it must determine the impulse response function (IRF) of the scenario under test.

It is well known from linear system theory, that the system IRF equals the cross-correlation function between its output and input signals as long as the bandwidth of the stimulus is larger compared to the test object. For simple purposes, one can consider the stimulus as an ideal M-Sequence. In such a case the cross-correlation can easily be determined via a fast Hadamard-Transform (FHT) by the DSP. The FHT algorithm is closely related to the FFT algorithm but simpler to implement. For details see [4]. The correlation procedure as mentioned above, is also often called matched filtering or impulse compression. Although the proposed method is not unusual in the field of radar technique, it was never applied before on an UWB radar exceeding a bandwidth of some gigahertz.

Nearly 80 % of the spectral energy of an M-Sequence is located below $f_c/2$. Thus a loss in system performance by cutting the stimulation band at $f_c/2$ is not to be feared. Consequently, the Nyquist-theorem requires the sampling rate f_c , i.e., one sample per chip of the M-Sequence. By doing so, one gathers the information without redundancy. This is a very important point in multi-channel (array) applications in order to avoid processing overload. However by displaying the impulse response calculated from such data, the operator of a classical impulse radar will be disappointed since the typical quasi-continuous course of the signals is missing (a common sampling rate for impulse GPR is Nyquist 4). However this can be removed by interpolating the data for graphical visualization.

Data sampling at the clock rate f_c (9 GHz !) is hard to achieve but fortunately, the M-Sequence is a periodic signal. Thus sub-sampling may be applied, so that the real data gathering rate may be quite lower than the clock rate. Although

sampling at the clock rate is technologically feasible, the choice of sub-sampling the M-sequence must ultimately be evaluated balancing between measurement speed and system cost and efficiency. Sub-sampling is a usual technique but it requires a sophisticated timing control. As seen from Fig. 6, the M-Sequence approach allows a tricky solution by introducing a binary divider between shift register clock and sampling clock. Since the number of chips N of a M-Sequence is one less of a power of two ($N = 2^n - 1$; n – length of shift register), it will always be possible to capture from all chips one data sample whatever the number of stages in the binary divider is (see also [4]). The M-Sequence radar is noted for its high stability which is mainly due to by the binary divider and the stable mono-tone RF-clock.

Measurements have shown, that the background subtraction of antenna cross-talk results in a 40 – 50 dB reduction for medium term calibration. That is, the array was re-calibrated after a few hours. In order to estimate the drift of the system, it was compared to a virtual impulse radar. Its transmit signal was modeled by a differentiated Gaussian impulse having the same bandwidth as the antenna cross talk of the actual UWB-array. The peak value of the difference of two slightly shifted pulses of such form does not exceed –40 dB if their mutual shift is less than 0.5 ps. Thus the medium term stability of the actual UWB-system must be of the same order. It should be noted, that the geometrical cable expansion due to temperature variations also contribute to the medium term stability.

CONCLUSIONS

The implementation of a large, i.e., multi-element UWB array requires proper consideration of the antenna performance, array configuration, RF-electronics and data throughput to be handled. The RF-electronics must operate stably and in a real multi-channel mode in order to provide good quality data in a reasonable time. Currently, the management of the data throughput is the bottleneck of UWB array applications. Consequently, the processing, in particular the pre-processing, has to be distributed over a number of DSPs and the data forwarded to the main algorithms should have as little redundancy as possible.

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- [2] S.Sensani, A. Sarr, R. Cioni, G. Alli, "A combined measurements and simulation based design of a novel polarimetric array for demining applications," AMTA 2002 Conference proceedings
- [3] J. Sachs, P. Peyerl, "A new principle for sensor-array-application," Proceedings of 16th IEEE Instrumentation and Measurement Technology Conference, IMTC/99, Venice, Italy, May 24-26, 1999, p. 1390-1395
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