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Ultra Wideband Radar Assembly Kit

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Abstract—**Ultra wideband sounding has been found to be suitable for a large number of applications in various areas. This results in a variety of different requirements concerning the measurement electronics. The article describes a conception of a measurement system, which provides for high flexibility in adapting performance to the actual need.**

I. INTRODUCTION

Ground Penetrating Radar respectively ultra wideband (UWB) sounding in general is becoming more and more interesting for quite different fields of applications. During the last years, starting from the classical geological use, UWB radar has been applied in new areas of practical applications as well as research fields such as non-destructive testing in civil engineering, surveillance (e.g. through wall radar), medical imaging, moisture sensing and many more. This development was initiated and supported by improvements in the UWB-electronics and applicators (e.g. antennas) and the considerably increased ability of sophisticated signal processing as well as the world wide endeavors for UWB radiation regulations.

Due to the increased number of different applications, the demands on the technical parameters of the electronics (and also the signal processing) may diverge considerably. This covers the operational frequency band, the ambiguity range of the radar, the number of measurement channels, the measurement speed, the transmitted power, the short and long term stability, the processing speed and complexity, the memory size, the purchase and operating costs of a measurement system, the power consumption and many others. In order to meet the dominant requirements of a specific application in the best way, it is of advantage to have choice between different measurement approaches respectively system concepts. The classical and as yet mostly used UWB-method is based on sounding fields with a short and pulse like time shape commonly termed as impulse radar. A second principle increasingly applied is emitting sine waves which are swept or stepped over the frequency band of interest. It is also reported from random noise radars, which however are of less interest for subsurface sensing purposes up to now.

The article will deal with a further approach based on Pseudo-Random Codes – the M-sequence. It tries to give an impression of the flexibility in structuring the M-sequence radar system aiming to meet the performance parameters required in the different fields of UWB research. The input for the proposed system concept was gained from the experience of 6 years work on UWB-projects which involved mine detection, through wall radar, localization, hyper sonic object tracking, moisture sensing, sounding of mobile communication channels and others. For the purpose of current UWB research, a versatile device concept that permits an adaptation of the hard- and software components to the actual need of the application as well as the opportunity to supplement user defined respectively user made sub-systems is of particular interest.

II. THE RADAR ASSEMBLY KIT

The idea to deal with an “Radar Assembly Kit” was born by summarizing the different aspects and research fields of the UWB-technique in connection with the potentialities of the M-Sequence technique. The basic idea of a M-Sequence device is known from a number of former publications. For completeness and as a starting point for the following consideration its basic approach will be shortly revised below. For deeper details, the reader is addressed to [1].

The versatility of the M-Sequence approach initiated the “Assembly Kit” idea but the measurement principle is only one side of the coin. The other side concerns data handling and processing, multi-channel capability, possibilities of device extension and completion etc. under quite different conditions as they are to be found in current research. In order to meet a wide area of application, a conception was developed which provides quite a few degrees of freedom in joining hard- and software components to a running system and to give the researcher the opportunity to adapt the device on his demand.

An essential point of the flexibility of the system is, that the user can adapt data flow at different levels following his demands. In this way the user may balance measurement speed, data throughput, noise suppression, power consumption, device costs and others.

In chapter III the M-Sequence principle is revised. Chapter IV gives a short view inside the data flow concept. Chapter V summarizes the core components currently in use and chapter VI shows some implemented radar devices.

III. THE M-SEQUENCE APPROACH

The basic concept of the M-Sequence radar is depicted in Fig. 1. The stimulus signal is a M-Sequence. It is generated by a high speed digital shift register. A M-Sequence is a special binary pseudo random code, which has a very short triangular auto-correlation function. Its FWHM-value amounts for example to 100 ps if the shift register is pushed by a 10 GHz clock. The Fast Hadamard Transform (FHT) respectively the Fast Fourier Transform (FFT) are effective means to determine the impulse response respectively frequency response function of the target from the measurement data.

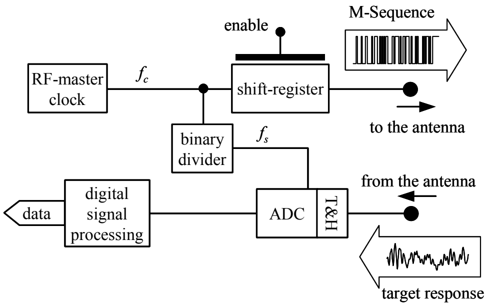

Figure 1. Basic structure of the M-Sequence measurement head. Note, that enabeling/disabeling the shift register allows a simple control of multi-transmitter systems.

In most wideband RF-systems, the data gathering is based on sub-sampling in order to reduce the data throughput, this is also the case with the M-Sequence radar. Usually the sampling time control is a challenging task but this is not the case for M-Sequence sub-sampling since a simple binary divider does this job in a very stable way by keeping an absolute linear (equivalent) time base of the captured signal. The divided pulse directly pushes the ADC and the track and hold circuit (T&H). The T&H captures the wideband input signal and provides it to the ADC which can work at a suitable low sampling rate f_s. In order to increase the signal to noise ratio, it is of advantage to apply synchronous averaging in the digital domain.

In what follows some merits of the method are summarized:

- All control signals have steep flanks and come from a common stable source. Thus the measurement head is time stable (drift, jitter, linear time base) as a matter of principle.
- The stimulation energy is distributed over the whole time avoiding signals with high peak values which are usually critical to handle. This opens some flexibility to add further RF components as amplifiers, mixers etc. into the chain.
- The operational frequency band extends from dc to $f_c/2$. Thus, the bandwidth i.e. the range resolution and the ambiguity range of the radar can be selected by the RF-clock f_c and the order of the shift register.
- The maximum target speed is adapted to the actual need by the order of the binary divider and the averaging numbers. They must be selected carefully since they largely determine the costs and the complexity of the digital processing system.

IV. THE DATA FLOW CONCEPT

The radar data flow concept is shown in Fig.2. It is partitioned into three parts:

- The RF-part,
- The radar processing unit (RPU) for high speed pre-processing, and
- The general purpose main unit (GPU).

Note, that for antenna array applications, a complete device is built from a couple of RF-parts and RPUs which work in parallel. Additionally to the radar modules, the GPU can deal with further sensor inputs (temperature, position etc.) and it can control a scanner or other actuators.

Considering the time scale of the physical processes involved in the measurement scenario, quite different requirements concerning the data throughput must be respected. This is reflected by the data flow concept. Its structure is shown in Fig.2. Four levels are distinguished respecting the speed of the running processes:

- The *interaction real time*: It concerns the time frame of the wave interaction with the target. In the case of high resolution short range radar it covers the range of some tens of nano-seconds
- The *equivalent time* refers to the time needed to capture the full data set by sub-sampling. It is a stretched version of the interaction real time. In the case of the M-Sequence radar, the stretching factor is 2^m if m corresponds to the order of the binary divider.
- The term *observation real time*, or often simply real time called, expresses the capability to follow the temporal variations of the target behavior. Observation real-time is required, if some actions need to be started immediately in dependence on the target behavior and/or position.
- In the *off-line* case, the measurement results are not subjected to a strong temporal constraint.

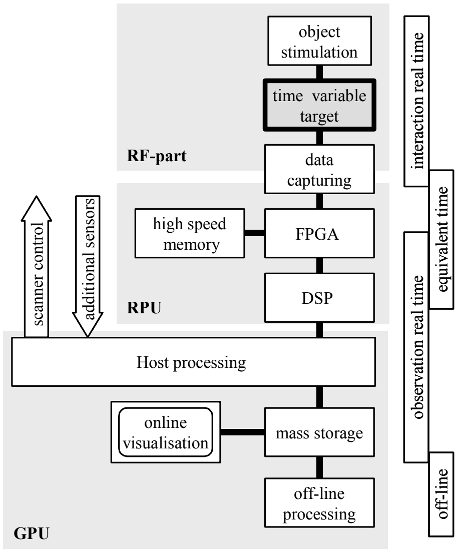

Figure 2. Data flow chart.

Considering the requirements concerning the digital system components, a critical time interval is the maximum time T_{obs} allowed to collect the data for one impulse response. Referring to the systematics of Fig. 2, it can be assigned to the observation real time. T_{obs} is limited by the temporal variability of the target e.g. the target speed v and the range resolution δ_r. A raw estimate results in:

$$T_{obs} = N\, p/f_s < 0.5\, \delta_r/|v_{max}|. \tag{1}$$

Herein, N is the number of point per impulse response function and p refers to the number of synchronous averaging. Sub-sampling deteriorates the efficiency of the data gathering and hence it increases the measurement time respectively decreases the number of averages i.e. the SNR-value gets worse but it also reduces the technical challenges with regards to signal capturing and data handling. Finally, the choice of an appropriate sampling rate f_s is a question of device cost and power consumption. State of the art video ADC's enable a reasonable compromise in that sense. However, the data rate of these ADC's is too high for general purpose digital processing units such as a PC or also a DSP as well. For this reason a high speed memory and a FPGA supporting hardware accelerated pre-processing were inserted into the data chain. This allows for the following operation mode:

- Storage of single shot data set by *external triggering*: This mode is to apply for measuring highly time variable targets with a following off-line processing.
- Storage of single shot data by *event triggering*: In that case the memory acts as a ring buffer and the gathered data are analyzed in parallel in real time with regards to specific events. If the event appears, a trigger releases the data storage (for further off-line investigations) or it initiates an action.
- Continuous *data reduction* and pre-processing: This mode is required for (observation) real time operation and/or recording of a huge data amount.

For subsurface sensing, certainly the last operation mode will be the most appropriate one. In that case the task of the RPU is aimed to perform the synchronous averaging, to calculate the FHT respectively the FFT, to provide a data statistics, to filter the data or others. This data can be visualized on-line and stored on a hard disc. However the stored data should not be manipulated too extensive by the pre-processing in order to avoid data loss for a posterior processing. After a modest pre-processing in the RPU, it is therefore recommended to split up the data flow for storage and visualization. Thus, the visualized data can be arbitrary manipulated without effect on following operations.

The radar kit considered here also covers a set of standard routines for the RPU processing, visualization and storage but the user can also introduce own software components on all levels in order to gain the flexibility in the system performance. The high-speed processing can be developed under SIMULINK and transferred to the FPGA. The on-line routines running on the host are based on CVI and the usual off-line processing is undertaken by MATLAB. In the case that further sensors (temperature, position etc.) are involved, their data are always marked by a time stamp. This facilitates the joining of data from different sources.

V. THE RADAR CORE

The core elements of the radar system are the RF-components – master clock, shift register, T&H, binary divider, low pass filters, amplifiers – and the radar processing unit (see Fig. 3).

The RF-modules are mounted on carrier-substrates which can be combined with versatility. All modules are mutually shielded resulting in an excellent suppression of cross-talk. The shift register, T&H and the synchronization unit are customer made SiGe-circuits which operate up to a clock rate of 15 GHz. In the standard case, all feeding lines are 100-Ω-symmetrically driven. The operation in a 50-Ω-grounded mode is also possible.

The RPU (see Fig. 4) can act as a stand-alone device or a number of them can be cascaded to build a larger formation as in GPR-arrays. In the last case, one RPU takes the control over the measurement procedure (master RPU) and the remaining ones are the slaves.

The RPU is able to capture the data of two receive channels in parallel. Its measurement rate is controlled by the RF-part. The maximum data throughput per channel is about 70 Msamples/s. In order to achieve high operational reliability, a temperature sensor supervises the radar electronics. The analogue output is not required in the standard radar operational mode. It is placed at the users disposal for future applications as automatic gain control, feedback sampling, active noise canceling or others. The data exchange and programming of the RPU is undertaken via Ethernet or USB. Additionally, digital I/O ports permit the exchange of time critical control and data signals as well as trigger signals.

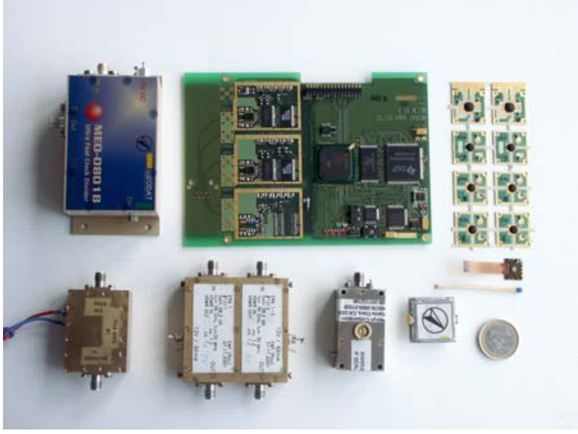

Figure 3. The core elements compared to a 1 € coin.

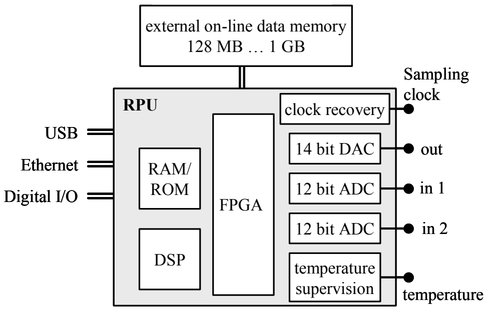

Figure 4. Structure of the radar processing unit (RPU)

The processing power of the RPU is divided up between the FPGA and the DSP. Usually, the FPGA is charged by time critical fixed point operations. The DSP performs floating point operations of increased complexity and it organizes the data flow as well as the operational mode. Subsurface sensing typically does not require hard real time conditions. In such a case, the RPU waives an external memory and it is equipped with a small FPGA. By increasing demands on the real time operation, the RPU will be up-graded with an additional memory and with a more powerful FPGA.

VI. EXAMPLES OF RADAR DEVICES

In what follows, some examples of devices of different complexity are shown which were implemented or are being built. The most simple device is the pure RF-Module. It only contains the RF-components up to the T&H output. These modules are applied if the measurement environment prohibits larger devices or if a specific digital hardware needs to be applied (see Fig. 5).

The basic device is a fully equipped radar system consisting of a power supply/battery, one RPU and a RF-module covering one transmit and two receive channels (see Fig. 5). It can be completely remote controlled via Ethernet or USB. It supposes additional means for visualization, data storage or sophisticated processing.

Figure 5. Example of the basic radar (left) and a RF-Module (right).

The user defined multi-channel radar finally opens the full complexity. The device is currently under construction. It is aimed for high resolution salt mine inspections. Its operational bandwidth exceeds 10 GHz. Multi-static and polarimetric measurements are sought and the antennas needs to be displaced by a mechanical scanner.

The task requires a fully equipped multi-channel radar system which covers the whole data flow chain as shown in Fig.2. Additionally, the RF-part needs to be extended in order to increase the operational frequency.

The device housing is based on a robust 19”-case which contains the whole electronics including host, monitor and keyboard. In dusty, dirty and aggressive environments – as in salt mines -, the case can be hermetically closed by two protection hoods. A dual circuit cooling system mounted in one of the hoods prevents overheating. In the protected mode, the man machine interface is adjusted to remote control.

The radar electronics consists of a couple of 19”-plug-ins which contain the basic radar components i.e. the RF-part and the RPU. The RF-ports and the digital I/Os are connected to the front panel in order to have free access. A further plug-in provides the RF-clock which can be distributed via coax-cable to an arbitrary number of radar modules. In order to have a running radar-array, the radar plug-ins still need to include a control procedure which is usually supervised by the DSP of the master RPU. By using two different RF-clocks, one is also able to run two independently working systems. The plug-ins are either inserted into the main frame or they are separately housed and connected via an extension cable with the main system as recommended in connection with a scanner.

The construction principle also permits to add further specialized sub-systems as demonstrated in Fig. 6. The shown example concerns a UWB up-down-converter which extends the operational band to $f_c/2 \dots 3f_c/2$ (see [2]).

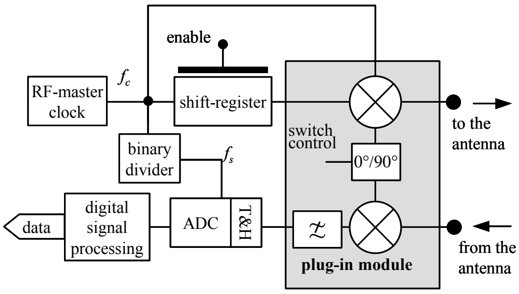

Figure 6. UWB-radar with extended operational bandwidth using a switched IQ-down conversion.

VII. SUMMARY

The concept of a versatile ultra wideband radar system was explained. The leeway to influence the system performance or to add own hard- and software components was demonstrated and some examples of implementation were shown.

REFERENCES

[1] J. Sachs, “M-sequence radar,” Ground Penetrating Radar 2nd edition, D.J. Daniels ed., IEE Radar, Sonar, Navigation and Avionics Series 15, pp. 225-237, 2004

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