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# Transmitter/Receiver Pulse-Driven Antenna Array with Near-Field Beam-Forming for UWB Subsurface Imaging Radar

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***Abstract*: The paper is devoted to design of impulse or equivalent ultra-wide band array antenna for subsurface radar system. Receiving elements of this antenna are arranged in array with small physical aperture and polarimetric features. Two transmitting element support two polarization states for radiating signals. The radar antenna provides down-looking scanning in subsurface medium for small areas covered by array aperture and big areas due to synthetic aperture processing when array moves in 2-D plane along scanning lines. Operation in proximity to a rough dielectric interface affects significantly on radar operation. This and other factors are involved in array antenna design to get enough 3-D spatial scanning with the maximum resolution and range for the available bandwidth. Results of such array analysis, numerical simulation and experiments are presented and discussed.**

## 1. Introduction

Subsurface radar or ground-penetrating radar (GPR) technique is widely applied as a powerful technology of remote sensing and microwave imaging in many fields of science and engineering [6,7]. Among different schemes of building of GPR systems there are two dominant ones. The first schema is impulse or equivalent ultra-wide band (UWB) radar that operates in time-domain (TD). The second one involves stepped frequency or synthetic-pulse GPR and operates in frequency-domain (FD). The both radar have some mutually excepting benefits and drawbacks as well as different design approaches to radar antennas [6]. Relative simplicity and inexpensive way of TD-GPR implementation are practically preferable for some applications. Due to this reason the UWB array antenna for TD schema of GPR is a subject of the presented study.

Principal engineering aspects of subsurface radar design involve mostly signal processing and antennas besides other topics [6]. Signal processing opportunities evolves with progress in computational software/hardware and digital signal processing. At the same time antennas designers are still situated in the rigid frame of physical limitations. The last are caused due to inherent and inaccessible features of impulse antennas loaded by the subsurface interface. Such features include ringing, impedance mismatching and so on. They cause degradation of radar performances and GPR antennas are more critical system component than in air-operated radar [3]. Another sufficient peculiarities of GPR antenna design are originated from necessity to employ UWB signals for good range resolution and operation in the near-field range of radar antenna [7].

There are generally two viable approaches for subsurface radar design. The first way, a designer has to reduce antenna internal reflections and other unwanted phenomena as much as possible, thereby simplifying signal-processing problem for radar. The second way that realized here is to live with a certain amount of antenna internal reflections and take those out in signal processing [6]. Therefore some optimal combination of efforts in antenna design and signal processing technique should be done for each specific system. In our early attempts [3] we explored behavior of single impulse transmitting (Tx) and receiving (Rx) antennas in free space and near the air-ground interface. The impulse array antenna with Rx polarimetric features and two cross-polar Tx channels is a final goal of array design project described in this work.

The presented array antenna is a principal component of UWB subsurface down-looking radar for non-destructive testing of concrete structural elements. Such GPR should be installed on a robotic platform with remote control for operation on the radioactive polluted territories near the Chernobyl destroyed nuclear reactor, Ukraine, in the frame of the big project that is in progress now. This radar should be employed for detection in thick concrete environment the metallic inclusions and non-uniform internal regions. Other missions involve offset 3-D image formation in bistatic 2-D geometry with small base as well as using synthetic aperture radar (SAR) technique for big survey areas.

The reminder of this paper is organized in the following order. Section 2 gives a glance on key aspects of antenna design for GPR. Some numerical results with approximated TD simulation technique are reviewed in Section 3. Design of UWB antennas with Rx array including single antenna elements, monostatic antenna pair, 2-element Rx array antenna and end-point array antenna project are discussed in Section 4. In Section 5 basic algorithms for array data processing with TD near-range beam-forming for physical aperture, synthetic aperture and polarimetric techniques are considered. Some experimental results are shown in Section 6. Final conclusions and reference list are at the end of this paper.

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## 2. Basic Principles of Impulse Antenna Design

Let consider principal aspects of antenna design affected on radar performances. Firstly, antenna position with respect to sounding medium must be specified. There are three possible geometrical arrangements such as stand-on, stand-over and stand-off, Figure 1. Stand-on antenna operation for GPR system is chosen and considered here because in this case down-looking GPR provides maximum available coverage of sounding media. This feature is evident from the angular spectrum compression shown schematically in Figure 1. This effect takes place when low dielectric half-space is sounding from higher air-filled medium due to evident background physics of the Snell's Law [7]. In this case refraction at the surface tends to compress the angular extent of the wave number space (k-space) spectrum into a nearly plane wave.

At the same time in down-looking case the close coupling antennas to the ground produces effects that are not of concern for stand-off applications. These effects of stochastic nature include rough surface disturbance and impedance mismatch between antennas and Rx/Tx front-ends. The last can cause up to -20 dB degradation of GPR performance factor [3]. In this case among other problems GPR needs in a wide dynamic range receiver. However energy transfer through subsurface interface is most effective for stand-on operation when radar antennas are laid on the border between two media, i.e. the upper air-filled and the lower subsurface interior. Also impact of electromagnetic interference (EMI) signals on radar performances with stand-on antennas is minimum.  The final argument for choice a stand-on antenna schema for GPR is based on the requirements to radar to operate in some space-limited conditions with low-height ceiling etc.

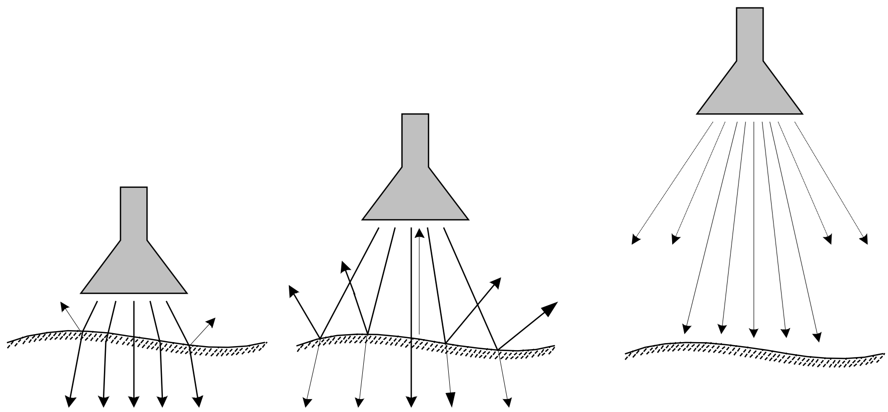

Figure 1. Basic arrangement of radar antenna position with respect to sounding media: stand-on, stand-over and stand-off or quasi-plane wave operation.

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The most fundamental choice in GPR design is a center frequency and a bandwidth of the radar. Low frequencies provide deeper penetration; the higher frequencies give better range resolution. The system designer should successfully resolve this common tradeoff. There are many factors governing the choice of central frequency related to targets to be detected and electrical properties of environment where radar to be employed like attenuation in some kind of soils etc. [4]. Furthermore even for high-resolution subsurface radar a low-frequency part of spectrum is important too. If high-frequency spectrum provides target shape and its consistence in detail, the low-frequency one enables target detection [4]. Evidently here is a practical limitation of low-frequency performance of GPR antenna determined by its maximum dimension. Note that the near-range field of pulse antenna contains dominant low-frequency spectrum.

Generally range resolution of the radar is governed by the used bandwidth. We will show later that the designed array antenna covers 0.2-0.9 GHz band at -20 dB reference level, which is an optimal one for detection of deep and shallow targets in concrete. The key antenna candidates to be employed in the designed array are shown schematically in Figure 2 including dipole, bow-tie, V-shape, TEM-horn, exponential horn and tapered slot antennas. The choice among those antennas to be used in radar is based on the following main criteria:

1) accessible bandwidth due to definite geometry;
2) pattern features including directivity and cross-polar level;
3) efficiency of antenna coupling to sounding environment;
4) loading performances to be terminated to Tx/Rx front-end devices;
5) implementation feasibility including printed circuit technology;
6) effectiveness of distributive resistive loading to prevent long ringing signals;
7) simplicity of introducing of antenna shielding for interference immunity.

Actually large number of unknowns from environmental conditions to radar parameters exists in the GPR array antenna design. Application of simulated data gives parametric estimations useful for array design. Some numerical simulations of such kind based on computing of approximated models will be demonstrated in the next section. Due to complexity of overall design of UWB array antenna with pulse excitation we introduce here some heuristic consideration. Thus qualitative comparison of antenna types, Figure 2, with respect to formulated above criterion is presented in Table 1. It is mostly based on our own experience as well as known literature data [3,6,7]. As followed from Table 1 the bow-tie antenna is more preferable for Rx mode while TEM or exponential horn is the best choice for powerful Tx devices where low input impedance is needed. For low-power Tx antenna bow-tie configuration is also suitable. For some Rx cases TEM horn and tapered slot antenna can be interesting.

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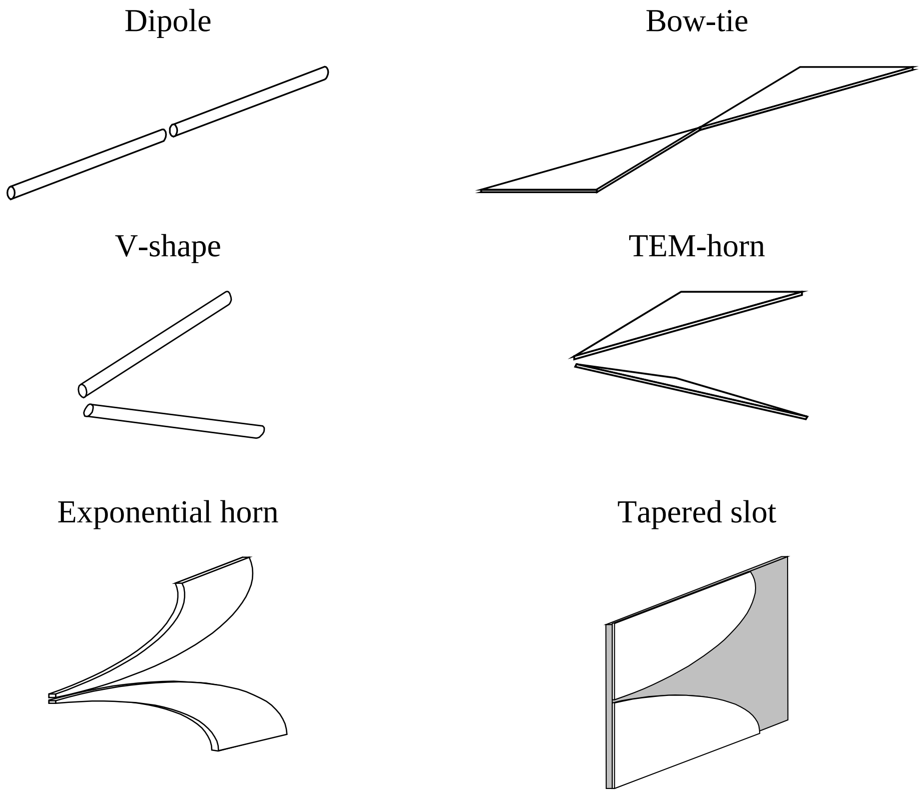


Figure 2. Basic antenna configurations to be chosen for array implementation.

Table 1. Comparison of antenna types for application in UWB GPR.

| | Dipole | bow-tie | V-shape | TEM horn | Exponential horn | Tapered slot |
|---|---|---|---|---|---|---|
| Relative Bandwidth | Low | Middle | low | wide | wide | very wide |
| Pattern Directivity | low | Low | middle | high | high | high |
| Cross-polar Level | middle | high | middle | Middle | low | middle |
| Coupling Factor | low | very high | low | low | low | low |
| Input Impedance | high | high middle | high | low | low middle | middle high |
| Production Complexity | high | low | high | middle | high | low |
| Resistive Loading | difficult | difficult | difficult | difficult | difficult | difficult |
| Shielding Possibility | easy | easy | difficult | difficult | difficult | difficult |

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## 3. Antenna Analysis in Time Domain

For antenna analysis TD waveform transformations and equivalent FD spectrum presentation are considered. Both approaches are mathematically equivalent to be connecting through the Fourier transform. However due to UWB signal nature and transient antenna operation the TD mathematical modeling is more relevant and numerically effective. Also experimental TD technique gives broadband information for test environment that is more simple than using the FD measurement in an anechroic chamber for much frequency points [3]. Finally we will consider array beam forming algorithm, which has the best implementation in TD [12] rather than common FD techniques with k-spectrum presentation [5].

Note that the most of known studies present transient antennas operated in far-field range while practically sufficient operation range of subsurface radar is related to the near-field range. There are some principal effects to be carefully treated for antenna and especially for array antenna due to specific features of energy distribution in space and time [13] that are different from those presented in literature for far-filed range operation. In many studies presented in literature rather than considering the signal waveform and its transformations, analysis and design are concentrated around the expected spectrum of the return signal after its propagation to the target, reflection, and propagation back to the radar antenna. However quality of imaging technique in GPR can be easy estimated by using TD waveforms, i.e. by specification how long in time its late-time history of radar response or/and how predictable is waveform transformation. Thus TD presentation is very useful and informative besides traditional FD data.

Ordinary for the transient electromagnetic problems, including antennas, numerical approaches like FD or TD method of moments or FDTD are applied. Besides Carl Baum [2] developed analytical approaches with the Laplace transform for some asymptotic cases. Generally widely used numeric studies have principal drawback followed from sufficient programming and computing efforts. Finally the physical meaning of the most numerical solutions is not enough evident and tedious verification is required. Therefore we developed simple mathematical models, which enable numerical simulations with universal mathematical software like Maple, Mathcad, Matlab etc. The result of such simulations will illustrate the major points of our study. The necessity of such consideration follows from the fact that TD technique in UWB antenna thoery did not receive yet features of engineering discipline.

To give a glance on the principal choices made in array design we illustrate some fundamental waveform and spectrum transformations for signal in UWB

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antennas of GPR. Skipping numerous details of mathematical modeling and numerical simulation, which require special consideration, let present the fundamental results on signal transformations in pulse driven Tx and Rx antennas like those in Figures 3 and 4 respectively. Bow-tie antennas are under treatment here. They are center-excited in double passing mode [3] when they are matched in the driven point only. Note that for Tx and Rx antennas the specific driven pulses are applied. These antennas are laid on air-dielectric ($\varepsilon = 5$) interface and their properties are studied in the intermediate range where the effect of the near-field is clear visible and discussed later.

One can observe in Figures 3 and 4 typical waveforms of driven signals in pulse antennas and other waveform variations versus direction of radiation/reception. Basically the effect of the near field resulted in broader spectrum in its low-frequency part. If the distance to observation point decreases the spectrum is broader spread to lower frequencies and DC component appears. The changing in TD waveforms and frequency spectrum transformations is also clear visible when reflector is employed in both Tx and Rx antennas. Basically the reflector shifts slightly spectrum to higher frequencies. Also signal in antenna with reflector has slightly more duration and amplitude gain up to 6 dB. As followed from Figures 3 and 4 such antennas demonstrate dominant broadside radiation where amplitude of signal has maximum value and registered waveform has specific shape to be useful for its discrimination. At the same time the antenna pattern is wide spread and special signal processing techniques can improve it.

Let consider finally a classical wireless channel to present basic peculiarities of transient excitation. For far-field range system formed by pair of center-fed, pulse-driven, linear dipole elements (one terminated to transmitter and other to receiver) Zialkowski [13] introduced the equivalent network presentation where main feature is a specific number of time derivatives applied to input waveform.

So far we concentrated on the near-field range effects in antenna we present transient radio channel model with three same dipole antennas operating in transmitting, scattering and receiving modes without any limitations concerning near or far range, antenna type and its excitation. Such generalized system is shown in Figure 4 and can be simulated with mentioned above models. Its own transformation operators A1,2,3 characterize each antenna in Figure 4. For example, Figure 5 demonstrates results of Mathcad simulation with respect to the notations in Figure 4. In this case we have three center-fed dipole antennas with double passing excitation and the effect of near-field range is observable in these data.

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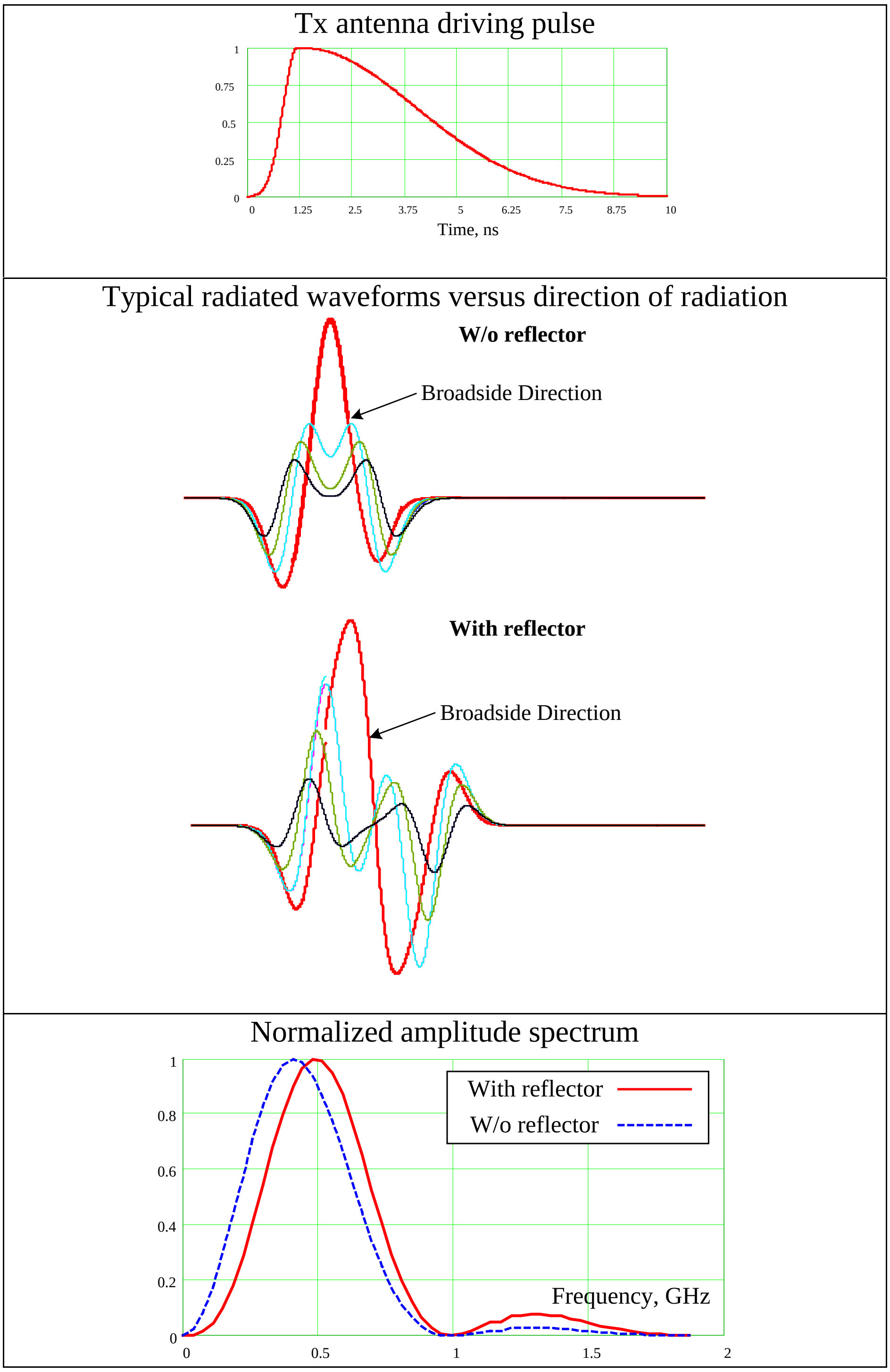


Figure 3. Waveform and spectrum transformations in Tx bow-tie antenna.

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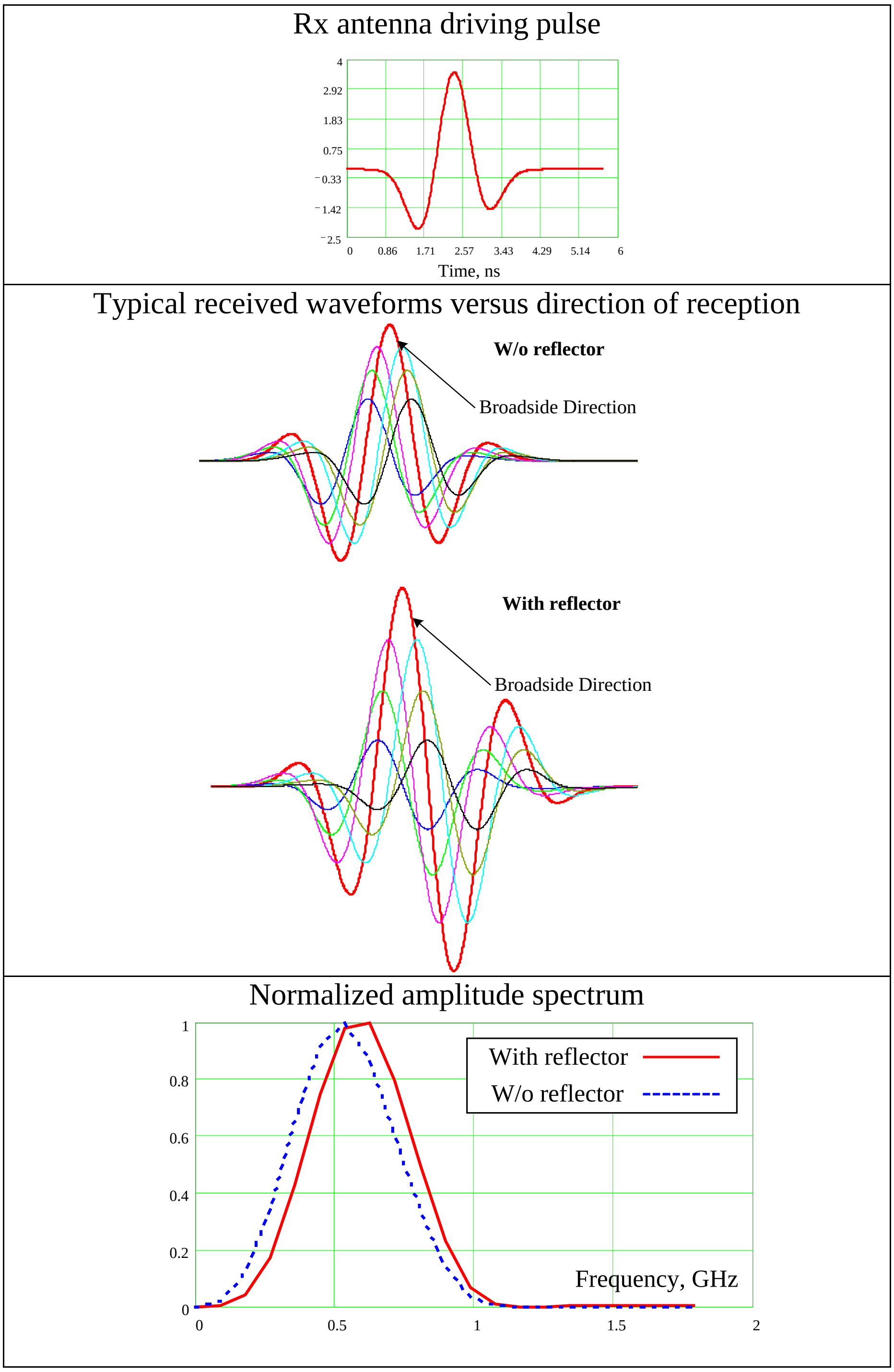


Figure 4. Waveform and spectrum transformations in Rx bow-tie antenna.

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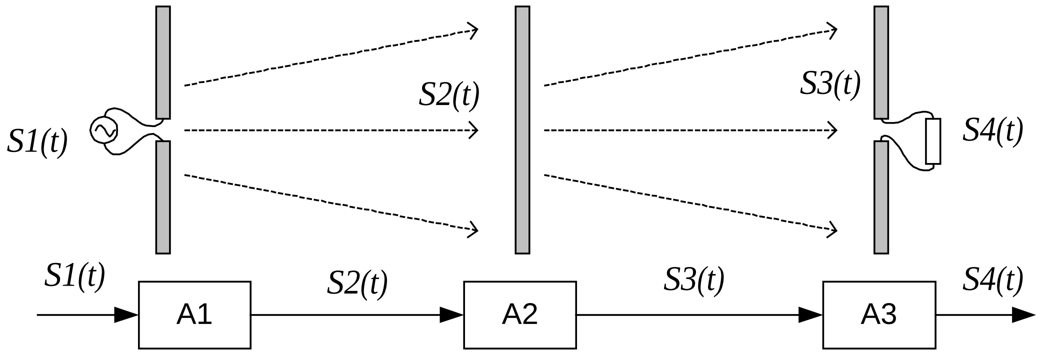


Figure 5. Network presentation of signal transformation passed consequently between transmitting – scattering – receiving center-fed dipole antennas.

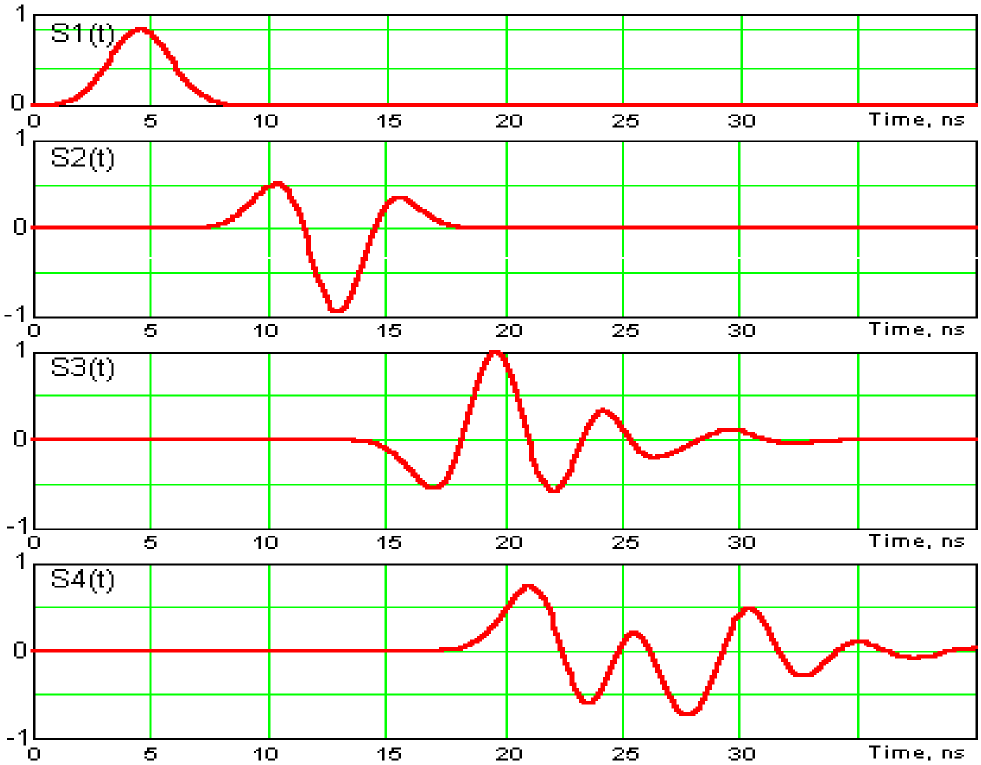


Figure 6. Mathcad simulated waveform transformation with the near-field effects for the system in Figure 5.

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## 4. Antenna Array Design

### 4.1 Single antenna element design

Waveform and bandwidth having been chosen, the GPR designer must implement an antenna commensurate with bandwidth. As stated above the antenna design becomes particularly critical for radar operation near the surface of the sounding media. In this case some preventing measures are needed to minimize antenna mismatching and ringing effects. Pure antenna matching can cause multiple reflections between the antenna and the surface (or within radar itself), and such "ringing" can hide target returns. Other problems caused by the proximity of Earth's surface are distortion of the antenna pattern and near-field effects. Both make it more difficult to predict what the GPR should see and hence make more difficult the interpretation of results.

One of the ways to minimize ringing effect in antenna is implementation of its resistive loading. However we use antenna without resistive loading rather antenna with double passing excitation [3]. The reasons are low energy efficiency and technical difficulty to put in practice resistive loading for big size antennas. It is easy to show that energy efficiency of such antenna with complete suppression of wave reflected from opened antenna end will be at least -20 dB lower than in antenna with double passing of exciting pulse. Also we do not use here impedance matching technique studied before [3] due to its complexity. Of course for such design preference we have additional lobes in signal and its stretching in time but we follow here our general design strategy to make simple antenna design and improve quality of radar imaging as more as possible by signal processing.

Another problem to be treated in design of single antenna element is minimization EMI effects and false alarm rate due to scattering in upper half-space. One of the approaches is based on introducing adsorbing materials which fill some volume above antenna to adsorb electromagnetic energy in above half-space. But this method being complex for its realization does not give practically valuable results as followed from our experience and some published data. Moreover if difference between electrical properties of sounding media and adsorbent material increases the radar performances can degrade and be worse than in antenna without adsorbent material. The more preferable way is using antenna with simple reflector. Whole antenna is placed in metallic box with one open face as an aperture. Additionally about 3dB rise of antenna directive gain is reached. Note some changing in spectrum take place also as followed from results of simulation in Section 3.

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Special attention should be paid to optimization of Tx/Rx units with respect to waveforms in them or equivalent effective spectrum. All discussed above topics and chosen design preferences have initially been verified with simple antenna design including monostatic antenna pair, and two Rx and one Tx channel array antenna. The last one is described at the next section.

The monostatic antenna pair, Figure 7, includes a pair of the same bow-tie antennas mounted on the base plane and directly terminated to the Tx/Rx front-end units. Being put on the air-ground interface these antennas have broadside radiation features. Really their pattern is disturbed due to interface influence. Such antenna layout has been studied before [3].

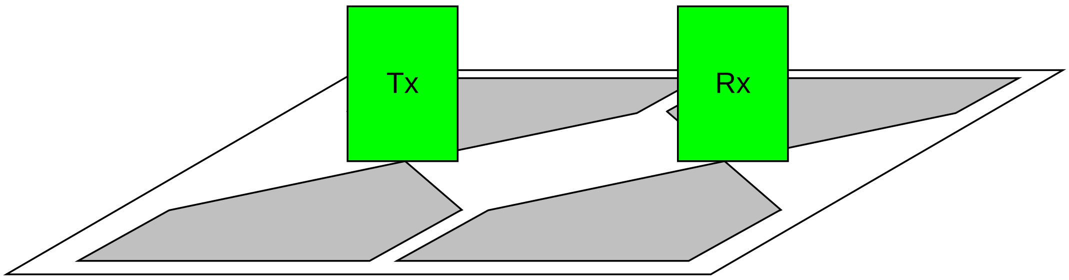


Figure 7. Design of monostatic antenna pair with terminated to Tx/Rx front-ends bow-tie antenna elements.

Transmitter electronics is based on bipolar transistor switchers with following leading edge sharpening by step-recovery diode (SRD). The Tx module is built with two identical step voltage stages either terminated with Tx antenna's arms. The main trouble of the scheme is necessity of mutual delay reduction between two outputs step voltage. Transmitter electronics provides pulse excitation similarly to that in Figure 3 above with 0.5 - 1 ns rise time and 30-60 Volts peak voltage. Pulse repetition rate is 100 kHz.

Receiver consists of wideband low-noise input RF amplifier, sampling circuit and buffer amplifier. Total input bandwidth is up to 10 GHz. Spectral transformation rate or equivalent time-sampling is approximately $10^6$.

Synchronizer unit executes control functions and interface board provides communication with the main PC unit. Block diagram of the GPR with single Tx/Rx antenna pair is shown in Figure 8.

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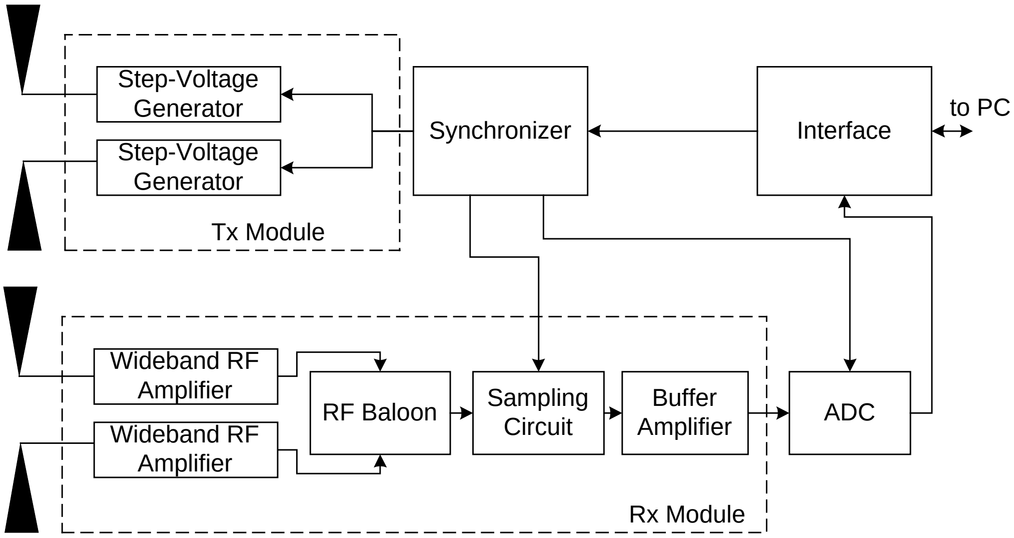


Figure 8. Block diagram of the GPR with single Tx/Rx antenna pair.

### 4.2. Two Rx and one Tx module antenna array

The next step of our research and design efforts is to build multi-element impulse array antenna. It includes two-Rx and one-Tx element array. Draft picture of this array antenna and accompanied electronics mutual arrangement is shown in Figure 9.

This array is assembled in a single box that forms simultaneously a shielding package and reflector for whole array antenna. Its inner space is filled by closed-cell foam plastic. This solution provides simple mechanical support and reciprocal disposition of antennas, shields and electronics. In order to improve directivity properties like V-dipole antennas are used instead of bow-tie antennas.

This design is realized with the same Rx and Tx modules, as described above. The main goal of the construction was simultaneous data acquisition from several Rx antennas for the principal algorithm examination. Note that considered data collection strategy assumes replacement of wide-band controlled time-delay units to computer processing of acquired data. Thereby it eliminates any problems connected with necessity to compensate mutual delay between different antenna elements. A block diagram of the GPR with described antenna array design is shown in Figure 10.

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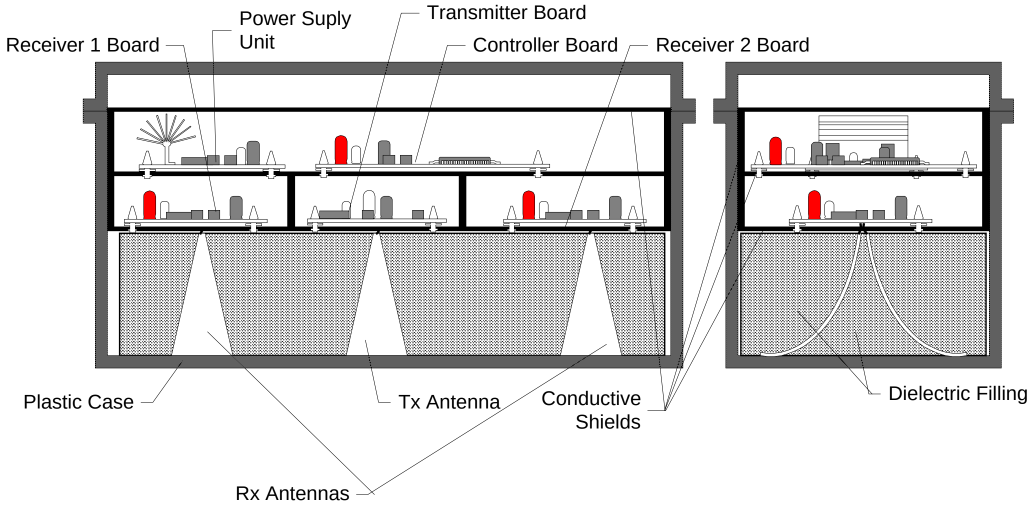


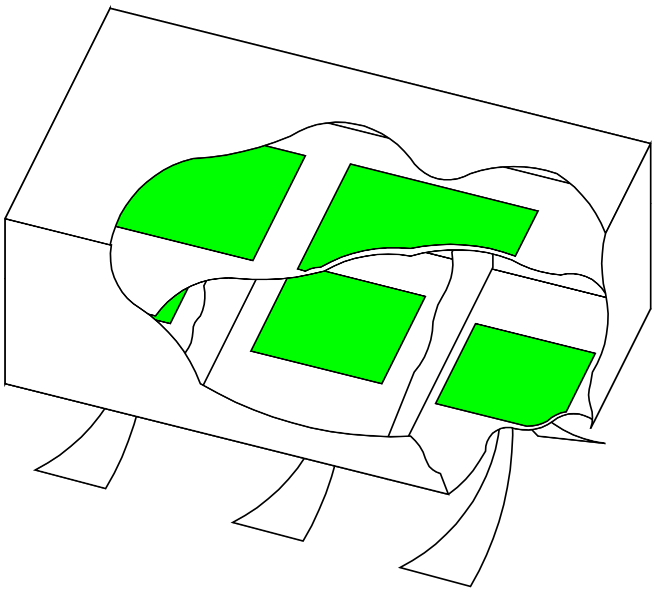

Figure 9. Design of antenna array with one Tx and two Rx modules.

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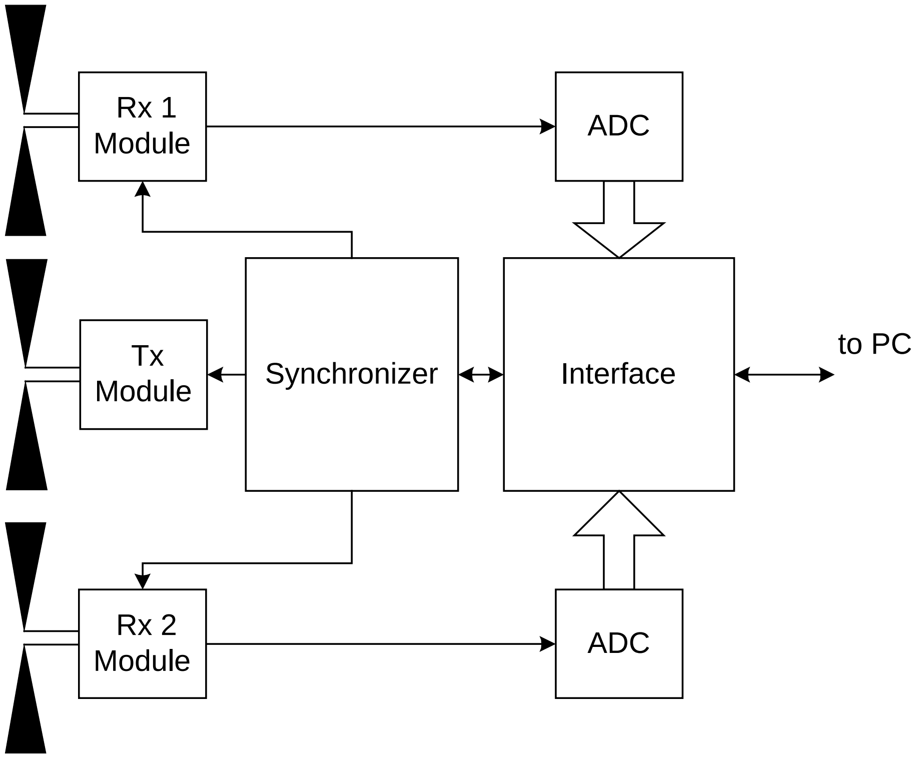


Figure 10. Block diagram of the GPR with Tx/2Rx antenna array.

### 4.3 Basic endpoint array configuration

Two versions of the basic design of array with two cross-polarized transmit antennas and 8 receive ones (4 and 4 per each E- and H-polarized direction in cross-down range) are shown in Figure 11. The first version, Figure 11 a, includes low-power Tx units connected to bow-tie antennas. Each Tx/Rx unit in array is presented as a separate module. Generally this design version allows array antenna with flexible reconfiguration opportunities by using new frame with separated Tx and Rx modules. The second version, Figure 11 b, has a rigid functional structure with low configurability. In this version a cross-polar antenna pair for each Rx and Tx elements are used. Bow-tie Rx antenna cross-polar pair is shown in Figure 12 a and exponential horn Tx antenna pair in Figure 12 b, accordingly.

The transmitter and receiver electronics modules are directly terminated to the antenna array elements. Receiving electronics is the same as the previous described one.

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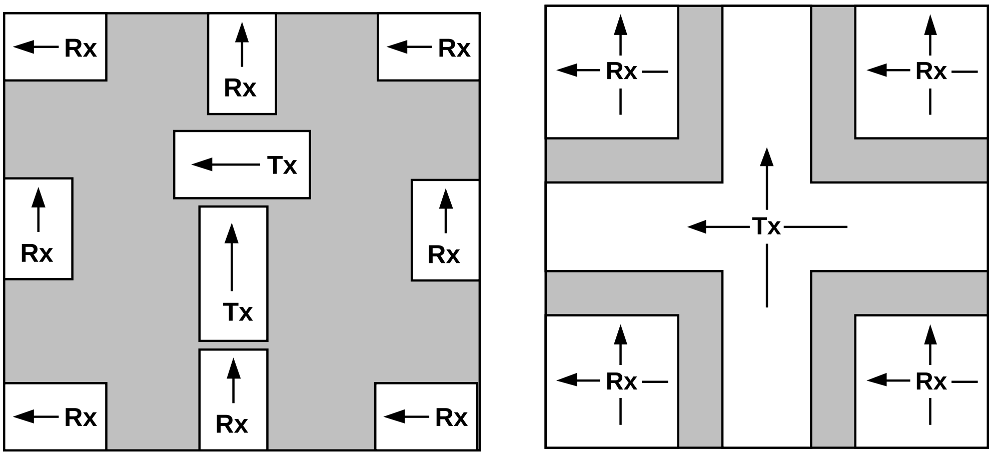
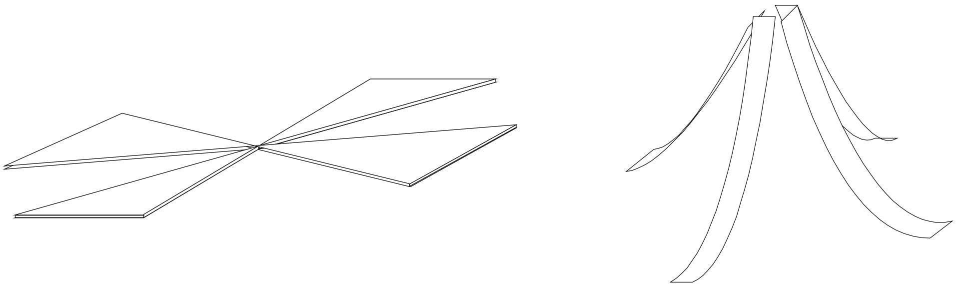



a) b)

Figure 11. Array configurations: (a) separate Tx/Rx modules, (b) cross-polar one.



a) b)

Figure 12. Antenna cross-polar elements: (a) bow-tie, (b) exponential horn.

At the same time it was utilized a new transmitter unit. In order to improve the GPR performance factor of high power nanosecond generator has been designed [9]. It forms impulse 1.5-2 ns rise time and peak voltage up to 550 V on 50-Ohm loading. Maximum pulse repetition rate reached up to 25 kHz. Power consumption was less than 6 W (500V @ 20 kHz conditions). Transmitter design combines power MOS-FET technology with drift step-recovery diode (DSRD) sharpener abilities. Note that the DSRD is the most suitable active element for solid-state up to 1 MW and more nanosecond impulse generation. Thanks to simple design, high output power, efficiency and stability, relatively durability and high repetition rate, based on DSRD Tx modules can be applied in various UWB radar design [1,8].

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The array covers 0.2-0.9 GHz at -20 dB level as can be predicted from simulation results in Figures 3 and 4. As discussed above the whole array antenna has upper shielding for improving system interference immunity and low false alarm rate. The array antenna width is 1 m on each side. This array antenna employs ground contact or nearly ground antenna positioning with elevation 0.05-0.2 m above ground to compensate some surface roughens on the searching areas. For the sake of enhancing array's performances achieved with physical aperture its size can be bigger than 1.0x1.0 m.

Such chosen size of the antenna is dictated by requirement to the designed GPR to be able to operate in some rooms to investigate their underground environment. Typically these rooms have entrances of 75x150-cm size. From the other hand implementation of SAR technique allows to have bigger equivalent aperture. Technically this solution is less expensive and simple than implementation of specialized UWB array antenna with big physical aperture. Finally SAR approach enables variety of scenarios of data collection including variable cross-range resolution. The price paid for these advantages are a relatively slow data-collection rate [6] that is not principal topic for slow moving robotic platform where the designed GPR with array antenna will be housed.

In the case of the designed radar there is necessity to employ array antenna with definite physical aperture because the SAR technique can not be effectively applied anywhere. The most important sites of the searching territory near the destroyed Nuclear Power Plant Unit in Chernobyl are located on so-called Cascade Walls. Strong edge effect there as shown in Figures 13 does not give possibility to employ SAR technique there. Efficiency of resulted SAR procedure computed by estimation of available length of scan lines is shown in Figure 14. Thus application of some physical aperture in antenna is too necessary.

### 4.4 Array control and data collection subsystem

Block scheme in Figure 15 consists of two Tx and eight Rx modules, synchronizer, data acquisition and interface units. All Rx modules sample and digitize input signals simultaneously. Mutual delays are removed during primary digital processing or later. Synchronizer is a “heart” of the system. It forms control signals for all modules and allows to realize any scanning algorithm under main computer control. Using digitally controlled sweep-generator and Rx time-varying gain-control (TVGC) amplifiers allows executing flexible GPR control.

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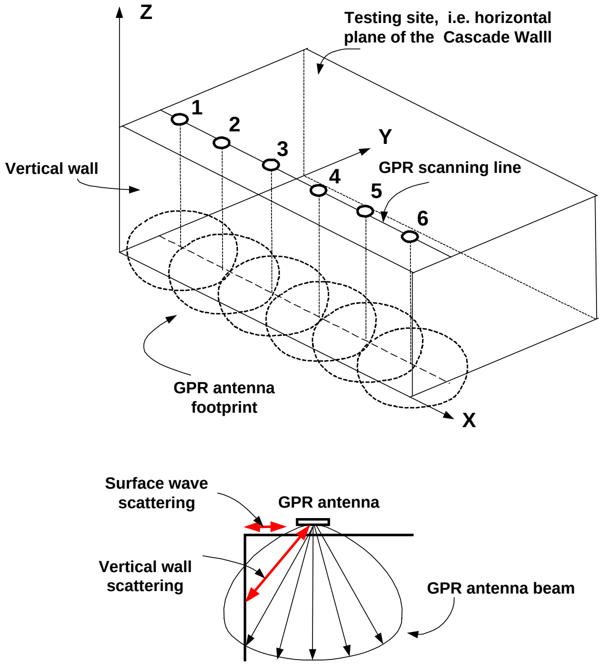


Figure 13. Schematic presentation of the GPR measurement on the Cascade Wall.

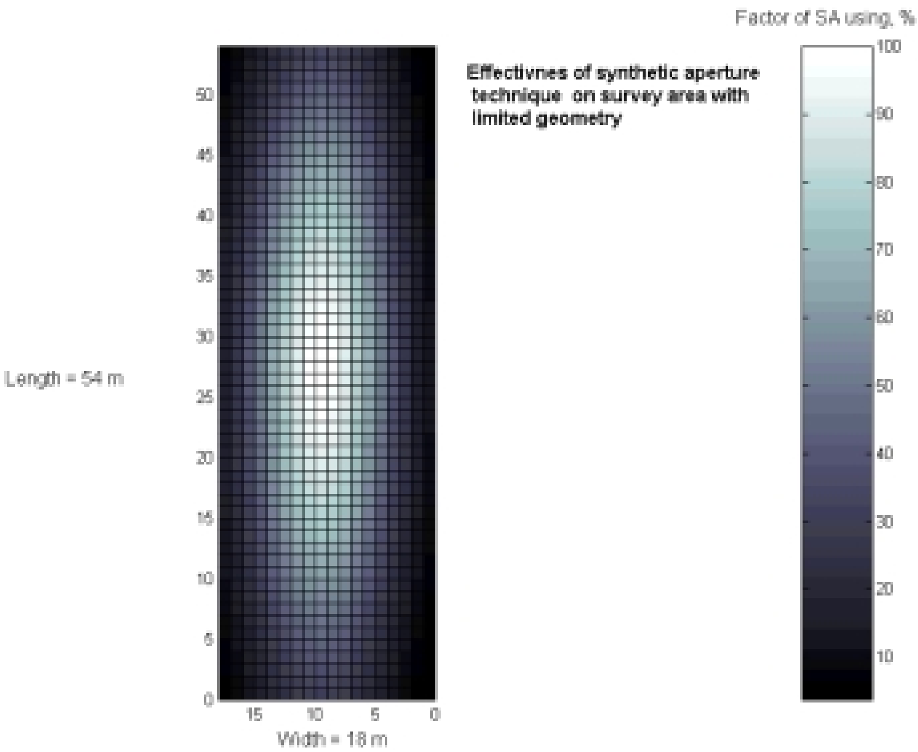


Figure 14. Effectiveness of SAR technique due to geometrical factor.

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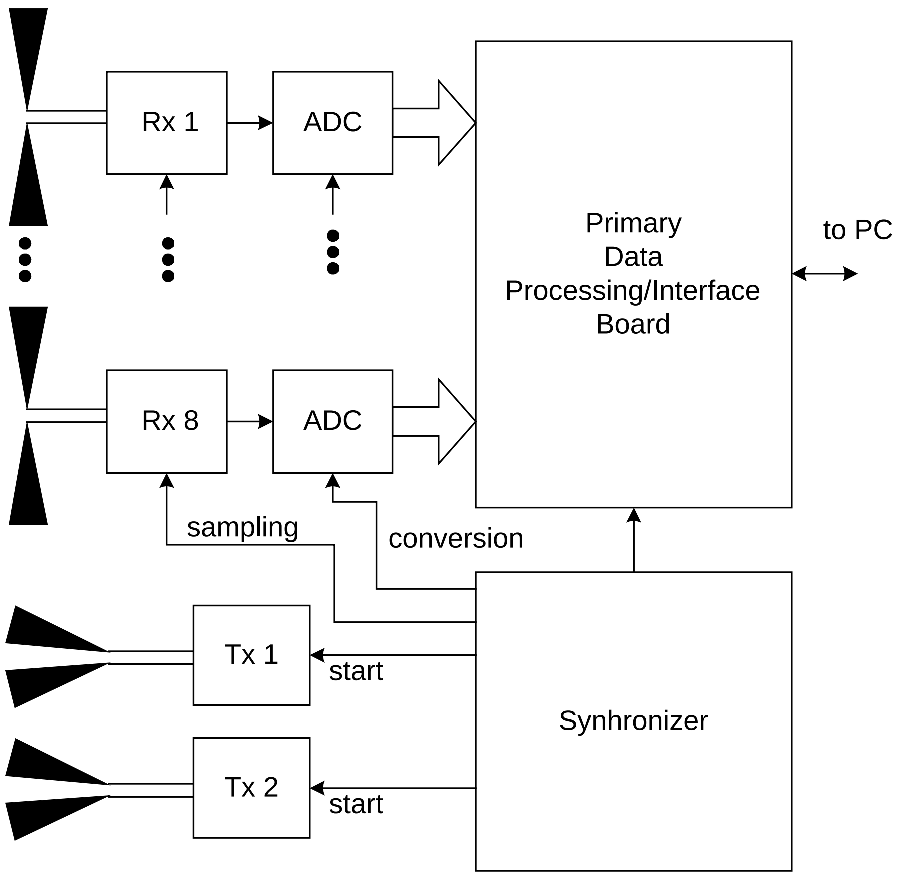


Figure 15. Block scheme of the GPR with 2Tx/8Rx full polarization antenna array.

Strategy of the GPR sounding is prepared by the main PC unit and pass to the GPR as an instructions set. Synchronizer executes these instructions in series and gives acquisition data back to the PC. This design allows determining the GPR tuning up to each sounding trace. Besides there is not any limitation on total amount of the Rx modules and its reciprocal arrangement.

## 5. Signal Processing of Antenna Array Collected Data

As stressed before the design of antenna for GPR system is some optimal “state-of-art” balance between efforts in antenna design and signal processing technique. This is more urgent for radar with array antenna where special array processing technique should be present. Generally a set of signal processing methods implemented in advanced GPR includes:

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1) 1-, 2-, 3-D filter procedures in original, spectrum or combined (F-K) spaces;
2) velocity analysis for common midpoint gathers and velocity migration [10];
3) array signal processing for physical aperture for in-situ image focusing;
4) synthetic aperture processing technique;
5) full polarimetric data processing.

Inherently beam pattern of subsurface radar antennas is widely spread and to improve its physical aperture and SAR techniques are applied that are subject of items 3-4. In order to overcome of such existing GPR technique limitations as in a hand-held radar, we will combine physical aperture technique with SAR opportunities.

**5.1 Antenna beam forming with physical aperture**

One should distinguish two kind of antenna beam forming methods implemented in the presented array antenna project. The first technique is 'in-situ' image focusing method in TD while second one is implemented by SAR processing. Note that antenna features effect strongly on such both beam-forming techniques. The basic idea of implemented algorithm of array beam-forming in TD is schematically shown in Figure 16. This beam forming technique is introduced by adjusting time delay magnitudes in Rx channels of array. In this way an array beam is focused on a definite space point (really spot) inside volume covered by array antenna [10,12]. There is a set of limiting factor on the size of array focusing spot due to decorrelation of signals in different Rx channels forced by the difference in antennas features and practical inhomogeneousty of real sounding media. There are some finite errors in estimation of velocity propagation, which quantity is used inherently in beam forming algorithm.

Actually array structure in Figure 16 implements post-processing array technique for radar imaging with improved signal-to-noise ratio [12]. Some inter-channel correlation processing can be algorithmically introduced with threshold estimation of resulted signal correlation products in fixed element of scanning volume. Generally it gives effective suppression of interference signals with out of interesting arriving.

The Rx antenna elements in Figure 16 are spaced at the distance of about 90-cm. The higher frequency in spectrum is about 800-900 MHz that corresponds to wavelength about 35 cm in free space and at least two times more in sounding media with typical $\varepsilon \geq 4$. For such elements spacing the grating lobe can be observed at the scan angle $22^0$ in free space and $52^0$ in sounding media. The scan angle is measured from the antenna broadside direction, which is normal to the

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array aperture plane. But this effect of grating lobes is not principal for down-looking radar systems with maximum scan angle equals to 10-15$^0$, i.e. array antenna looks through space covered by its aperture. Practically smallest insufficient elements of radar images can be distorted.

Moreover for the central frequency of used spectrum the grating lobe appears at 52$^0$ in air and absent in subsurface media. Note that same differences in E- and H-planes scanning will take place but these effects are high-order ones. Also here is some blindness effects in the H-plan due to specific features of pattern of pulse antenna in this plan. This effect is revealed in radar images as some artifact distorted radar signature of target. It must be subject of detailed next studies including the some specificity of pulse array antennas loaded by subsurface interface

Computational requirements for implementing antenna beam forming algorithm are low due to its realization as a post-processing algorithm. It processes the signals registered by each single Rx channel element and stored in computer memory. This algorithm has been successfully tested with two-Rx-one-Tx pulse array antenna in Figures 9 and 10 will be under experimental examination soon in the complete 8-Rx and 2-Tx array antenna.

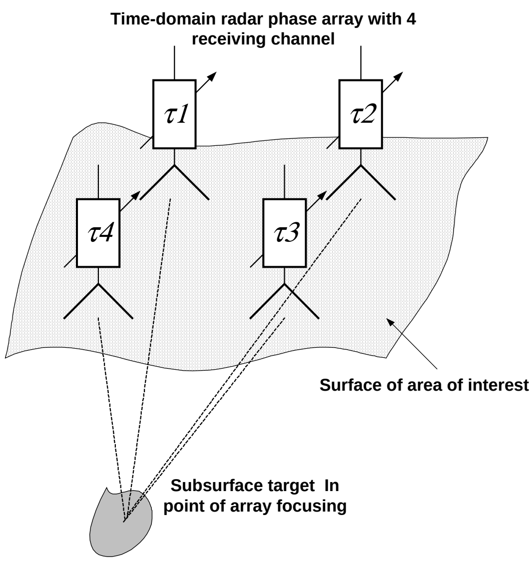


Figure 16. Schematic presentation of array antenna TD beam-forming algorithm with focusing in the cross-track and down-track directions.

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### 5.2. Synthetic aperture processing

Generally SAR processing is well-established method to transform the data collected along a scan trajectory of electrically small real aperture to data collected with big virtual aperture. Fourier transform is mostly used for such mathematical operation to transfer from wave-number space (kx, ky, kz) to Cartesian coordinate space [12]. The broader supports in k-space, i.e. longer scan trajectories, the finer impulse response in transform space. Practically it requires enough long scan line for 2-D imaging and enough scanning areas for 3-D radar imaging. This SAR technique is widely applied in GPR with single monostatic antenna pair like that in Figure 7.

Practically the strong influence of antenna properties takes place on the reconstructed SAR images including some defocusing phenomena to focus simultaneously early and late time response [12]. These affects require special detailed consideration and are outside frame of the paper. Also as illustrated in Figures 13-14 the SAR technique has sometimes very limited opportunities when GPR system must be applied on the sites limited by their areas.

### 5.3. Polarimetric processing with array antenna

To collect all available information about target the complete polarimetric technique is employed when two orthogonal polarizations are consequently transmitted and simultaneously received. Employing coherent radar, the polarization scattering matrix (PSM) is processed to provide target shape information [11]. Real problem should be carefully treated is a level of polarization isolation of antennas, especially in the near-field range. Our own results as well as the data in literature indicate about problematic of this issue for real GPR system especially for shallow target. At the same time this technique is promising for deeper target. Also using of cross-polarized antennas tends to discriminate against the surface clutter return. We do not have at this time enough experimental data on this issue that should be done soon.

Generally the radar polarimetric technique enables potentially target characterization by fixing the difference in the phase/amplitude/waveform of signals registered for different polarization states of transmitting Tx1…2 and receiving Rx1…8 antennas (Figure 15). The scattering matrix for each receiving element presents measured scattered signals of both polarization $E^{S}_{R1,2}$ versus those incident transmitted signals $E^{I}_{T1,2}$

$$\begin{bmatrix} E_{R1}^{S} \\ E_{R2}^{S} \end{bmatrix} = \begin{bmatrix} S_{11} & S_{21} \\ S_{21} & S_{22} \end{bmatrix} \cdot \begin{bmatrix} E_{T1}^{I} \\ E_{T2}^{I} \end{bmatrix}$$

Separated radar Rx antennas simultaneously operate in the both polarization states resulting in four measurements of the co-polar ($S_{11}$, $S_{22}$) signals and cross-polar ($S_{12}$, $S_{21}$) ones.

Let note that consequent scanning in two opposite linear polarization does not make possible target classifications by its polarimetric features. In this case at least only the $S_{11}$ and $S_{22}$ members of the scattering matrix can be estimated. It is not enough for a proper target characterization that is important issue for highly clattered media around the Chernobyl destroyed reactor where the designed radar should be employed.

## 6. Some Results of Experimental Investigations

Some experimental studies have been conducted with 2-Rx-1-Tx antenna for GPR design as a prototype of complete 8-Rx-2-Tx array antenna that is in progress now. The presented experiments are not directly associated with the Chernobyl radar project but give useful information for our endpoint design. Firstly additional opportunities of GPR system based on array antenna with respect to ordinary GPR with monostatic antenna pair to detect and discriminate the target with specific shape have been explored.

Figure 17 presents simulated and SAR measured data for square metal plate as a buried target. On the left in Figure 17 a is a 2-D geometry for simplest subsurface scattering problem to help communicate to next figures. Note that simulated image at the right of Figure 17 a does not present geometrical shape of target rather than its signature with specific edge effect expressed in hyperbolic leading and edge tails [7]. Since radar visualization of internal regions is inherently more qualitative than quantitative, one must concentrate on the signature of target than its exact geometrical shape that can not be reconstructed in details. In the context of our array antenna project we will consider here the effects of antennas on radar signatures.

In Figure 17 b one can observe the presence of two shallow targets like that in Figure 17 a. In contrast to simulated data the image of real medium is different. Here is a direct coupling signal between Tx and Rx antennas [3] as well as ringing effects at the right side of picture. A ringing effect inside sounding media is produced by internal interface in it with strong scattering and can be partially removed from image by some processing technique. This effect is often very unwanted for GPR because such clutter obscure valuable information, can overload internal circuits of receiver and decrease radar dynamical range. There are no receipts in antenna design other than application full-polarimetric and other enhanced signal processing techniques that can be effective for some cases.

The application of TD beam-forming technique is illustrated in Figure 18 for 2-D scan implemented with 2-Rx-1-Tx radar array antenna. The final image in this Figure is a result of post processing technique applied to focus image covered by array aperture. Radar antenna was moved along the straight scan line and the focused image is computed in broadside direction as cross-correlation of delayed signals in the Rx channels. Some threshold level was being adjusted to improve focusing and cut signal tails. We observe here absence of hyperbolic curves but image has finite level of focusing due to multi-lobe structure of signals. At the same time some artifacts are present but major reflections are strongly stressed, which correspond to internal objects should be detected. One can conclude that this technique is not perfect enough. However we expect that for such case like the Cascade Wall in Figure 13 it can be useful.

Results of radar imaging of specific subsurface target received with simple 2-Rx and 1-Tx array are shown in Figure 19. At the right one can see horizontal slice of cylindrical shallow subsurface target and the left picture presents its vertical slice. This target is like a antitank landmine at the depth of 30 cm and has the 35-cm diameter and the 15-cm height. Horizontal slice has been obtained as a set of linear scan over searching area.

The presented images do not give of course exact geometrical shape of target being defocused and with artifacts. At the same time to get best quality of radar images is very problematic. From the point of view of strong physical limitations it is impossible to obtain better imaging because wavelengths in the used signal spectrum are comparable with geometrical features of target and phased information is partially lost. Disturbance effect of medium on antenna and some uncertainty of signal velocity force the last factor too.

However the results in Figure 19 demonstrate evidently that using of "non-ideal" antennas in radar with some "ringing" etc. and coherent processing enables obtaining valuable visualization of subsurface media with GPR. Generally signal-processing component as sufficient part of design efforts is very important here and this issue is finally discussed in conclusion section.

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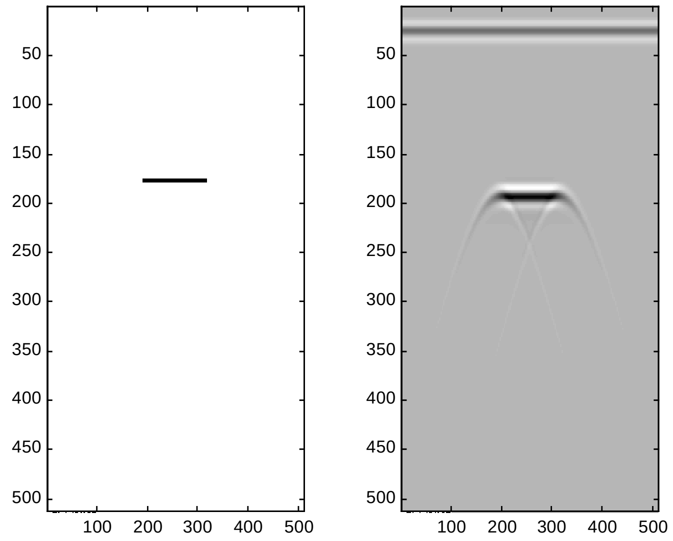
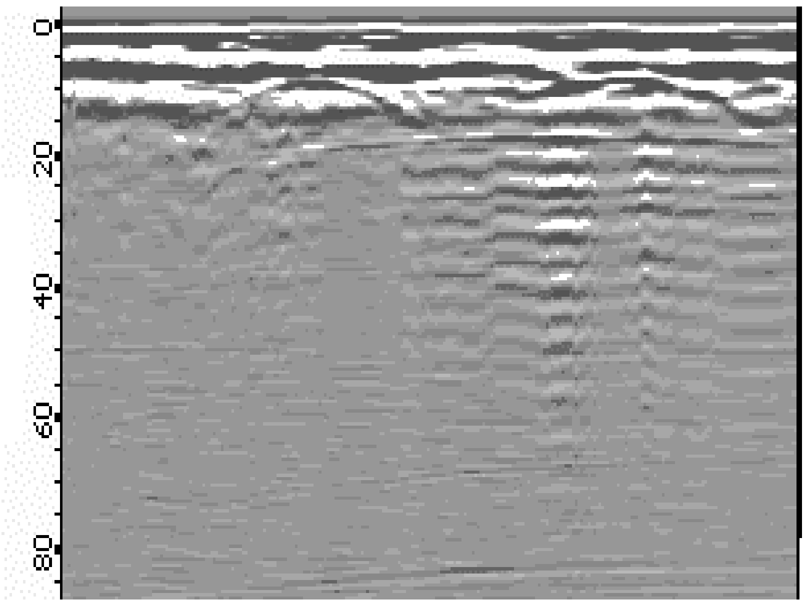



a)




b)

Figure 17. (a) simulated and (b) experimental radar image of subsurface with specific shaped target.

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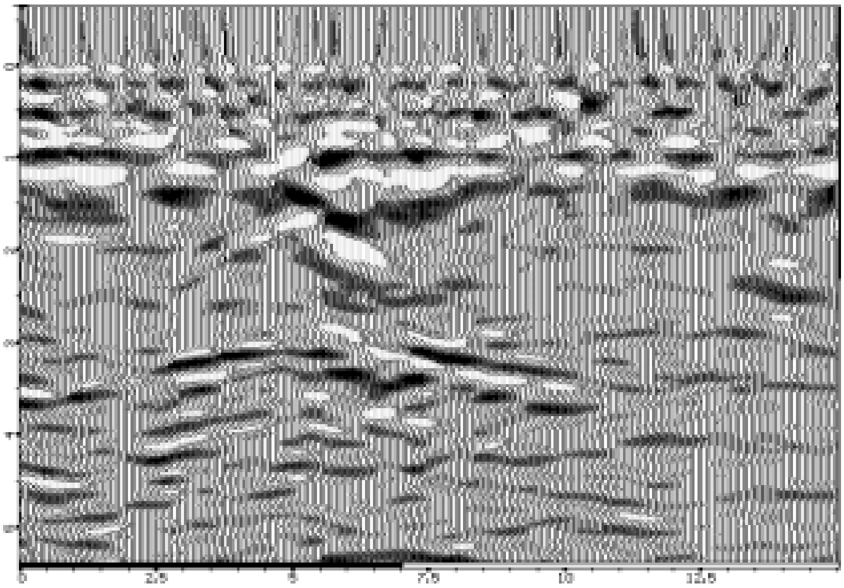
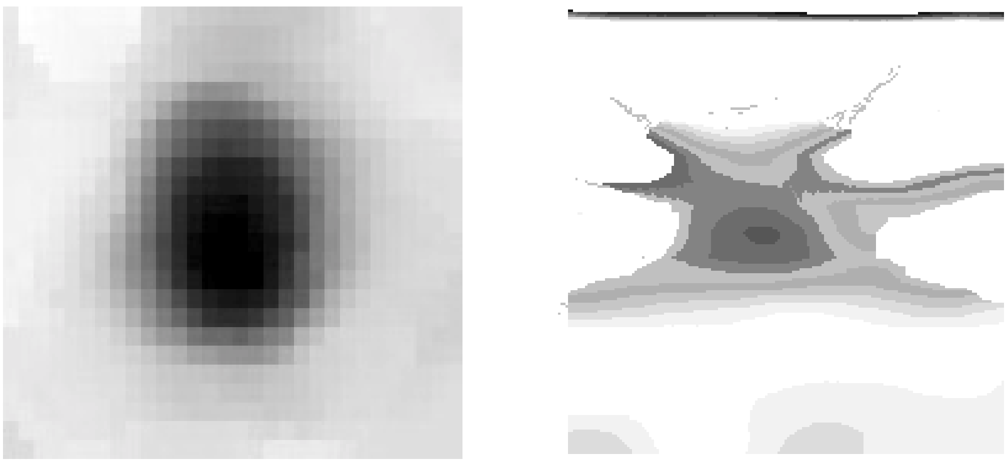



Figure 18. Radar 2-D vertical scan imaging of subsurface region obtained with 2-Rx array antenna and application of TD beam forming data processing.



a) b)

Figure 19. Vertical and horizontal slices for GPR imaging of cylindrical shallow target.

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## 7. Conclusions and Summary

It is expected that sufficient two-dimensional spatial scanning in down-looking GPR system, where physical aperture with SAR and polarimetric processing are combined, provides maximum 3-D resolution that can be achieved by the given bandwidth. The last factor is limited due to rigid background physics of electromagnetic propagation inside matter and antenna features to radiate and receive broadband or UWB signal with < 100% relative bandwidth.

Besides limitations in antennas UWB properties there are many problems in design Tx/Rx electronics with fine time accuracy and resolution or equivalent high sampling frequency as a jitter problem. Practically it is difficult to maintain operation over 5-10 GHz operation frequency. In this case FD techniques with UWB signal synthesis seems more promising.

Finally the practical distribution in array antenna design efforts tends towards to dominant role should be played by signal processing technique. As we found the potential in antenna design are sufficiently limited. Employment of antenna array adds some flexibility in GPR system design by introducing the advanced processing/imaging opportunities.

Additionally scanned antenna/array allows additional capabilities to produce synthetic aperture imaging. Doing so, however, requires careful attention to knowledge of antenna position and correction of propagation effects within soil. The last factor limits the performances of real GPR system. Note that array antenna with some spacing between its element enables potentially some calibration procedures to estimate velocity of signal propagation inside media. It is interesting opportunity to be subject of next research efforts.

Fundamentally signal processing and imaging/display options in subsurface radar are strongly driven by signal waveform choice and its implementation taking into consideration inherent signal transformation in antennas like simulated data shown in Figure 3-6. Thus relevant choice of antenna types, array configuration are important issue of overall GPR system design.

Presented results have been obtained into the frame of some subsurface radar projects for archeology and landmine detection. Now the array antenna for the advanced GPR system to be applied near the Chernobyl nuclear power plant is in focus of research and design efforts. Most of components of radar system have been designed and tested including prototype of antenna array.

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