# Antenna System Development for Radar Detection of Shallow Underground Targets

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**Abstract**. This paper presents the results of research and development of planar antennas built on tapered slot-line for ultra-wideband subsurface step-frequency radar applications. It has been shown that modification of the antenna balun and aperture area improves antenna characteristics and suppresses partially signal coupling between antennas.

## Introduction

Ultra-wideband technology covering frequency range of 3:1 and more has been widely used in subsurface radar. Possible applications include civil engineering (detection of buried pipes, inspection of bridges and roads), medical diagnostics (breast cancer detection), safety (anti-personnel land-mine detection and recognition, through-wall microwave tomography imaging) etc.

Design of broadband antennas being important component of the subsurface radar is a difficult task. The broadband antennas should satisfy general requirements such as stable enough phase center, gain weakly dependent on frequency, and low voltage standing-wave ratio (VSWR). Besides, there are several features important for the antennas used in the subsurface radar applications. So, the antenna is placed usually near the surface thus the reflection from the antenna aperture is to be low to avoid interaction between them. In the bi-static configuration, antennas are to be well isolated to reduce clutter.

The coupling between antennas can be partially suppressed by increasing the distance between antennas in the transmitting-receiving antenna pair, but at the expense of increased size of the antenna system. Shielding of closely spaced antennas is usually not effective.

As to lateral radiation from the antenna system that is of course similar to the coupling by origin, it may be important e.g. in GPR used in urban environment or non-destructive testing of structures in civil engineering. Typically, microwave absorbers are used to eliminate lateral radiation of the antenna that is rather expensive.

Radar signal should not be too sensitive to the antenna elevation over the surface of object. Optimal antenna elevation is chosen from experiments taking also into account disturbing influence of the objects located near by the antenna system, e.g. legs of operator, radar wheels that can deteriorate the image.

The antennas for subsurface radar should be also rather small, light-weight and low-cost. On the other hand, for better performance the antenna aperture should be close to the wavelength at the lowest frequency. Thus, in practice the antenna system is a result of trade-off between sizes of typical subsurface objects, the lowest frequency governing penetration depth, desired antenna gain etc.

Antennas with ultra-wideband baluns and reasonable size of radiating part are in development for more than 20 years. In this paper, the experimental and simulation results for small balanced tapered-slot antenna (TSA) in the frequency range of 0.5 to 5.5 GHz are presented. Using modified design of the balun and aperture shape, several antenna characteristics have been improved. The Zeland IE3D software helped to reveal the most critical antennas zones and to optimize a construction.

## 1. Some Aspects of Antenna Design

### *1.1 Criteria of Antenna Selection*

Antennas for wideband applications should be well matched over whole frequency band, possess stable gain and good directivity. Dispersion in antennas for step-frequency radar can be ignored as it can be accounted by calibration, but narrow radiation pattern is desired. Decrease of the size of a radiating part of the antenna results in deteriorating of many characteristics. So, at the ends of frequency range the antenna gain drops whereas VSWR and reflection of the wave from aperture increase. The radiation pattern is wide in the beginning of a frequency range while at high frequencies a lot of sidelobes arise. That is why in addition to choice of compromise between radiating properties of the antenna and its geometrical size, the frequency band of operation in design is to be a bit wider than required in the application. Then, the antenna characteristics in the frequency range of interest can be acceptable.

One of the most popular antennas for ground penetrating radar (GPR) applications is TSA. This light-weight planar structure often used in antenna arrays is rather easy for simulation and optimization. Our aim was to design antenna of reduced dimensions without considerable drop of radiating properties so that it would be competitive against other popular GPR antennas.

### *1.2 Development of Planar Balun*

There are several methods of simulating transitions for the TSA. Balun, a balanced to unbalanced line transformer, was first proposed by Marchand in 1944. The development of printed microwave baluns having Chebyshev passband response dates from middle of the sixtieth years of the last century [1]. Overlapping the frequency range of 4:1 or 6:1 is achieved easily for planar antennas. However, further expansion of the working frequency range requires additional simulation.

As TSA consist of two parts (balun and the antenna itself), we have been modeling and simulating both of them using IE3D software realizing method of moments.

We have simulated balanced TSA (with the $4^{th}$ order Marchand balun) and, for comparison, unbalanced TSA (fed by a 50-ohm cable) with different linear and exponential taper profiles overlapping the frequency range of 10:1. Balun in planar structure plays roles of impedance transformer and symmetric facility. In our case, impedance transform of 50 Ohm of the feeding cable to 136 Ohm in the beginning of the tapered slot is required. The complete picture of electric current distribution around balun and inside the antenna helps to study factors influencing on the radiation pattern and formation of sidelobes and backlobes. It had been found that the Marchand balun designed using formulas from [1], can be improved by little modification. So, better performance at low frequencies can be achieved by adjusting dimensions of the last sections of the microstrip and slotline. Further improvement of the balun characteristics at low frequencies can be achieved by expanding the slotline to an open circuit like cavity (Fig.1) [2]. In the simulation model, a triangular cavity had been selected. Unfortunately, some deterioration of the antenna properties caused by radiation from the open cavity, especially at high frequencies has been observed.

At high frequencies, the microstrip sections start to radiate, too, deforming radiation pattern of the whole antenna. To reduce the influence of an open cavity, a few radial slots had been placed near the back side of the cavity [3]. This enhanced the antenna gain approximately by 2 dB at the edges of frequency range. Besides, VSWR fell down to a value of 2, and the antenna efficiency increased by 10-15% at high frequencies of the frequency range. Modernized microstrip-slotline transition can be designed for the frequency range up to 11:1 (Fig. 1).

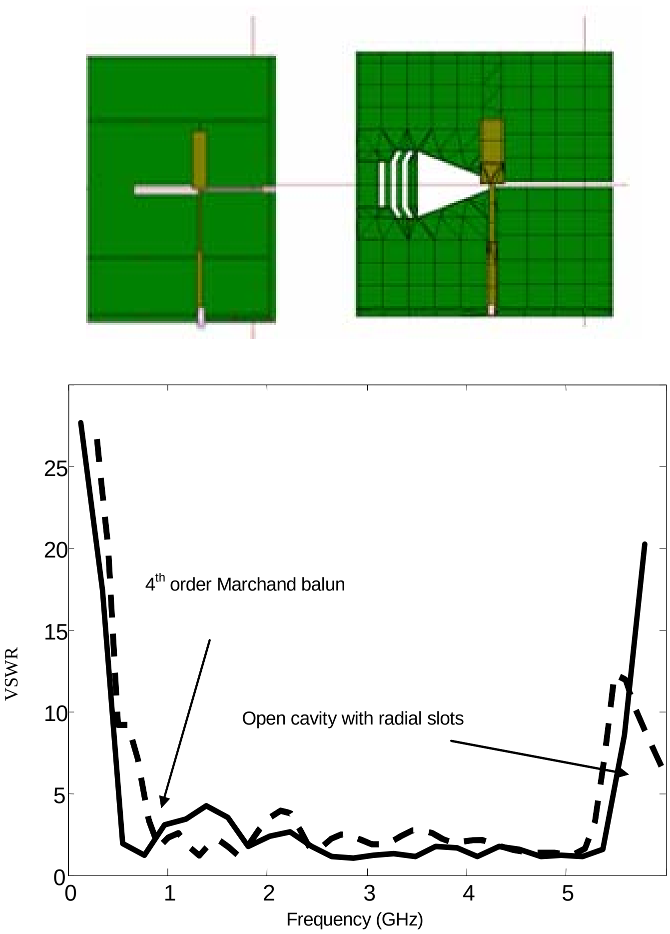
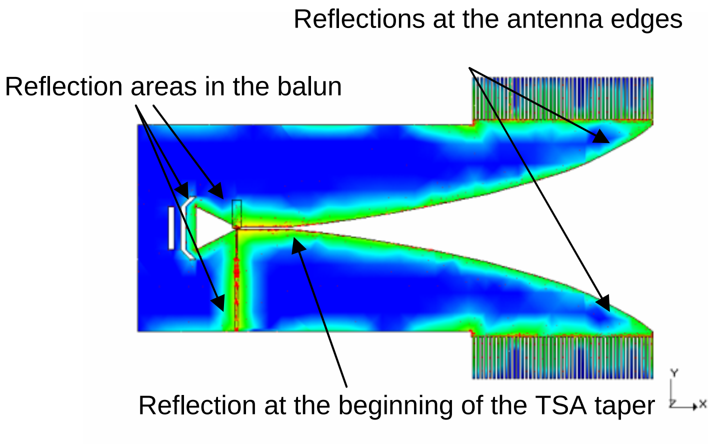



Fig.1 Wide-band antenna balun design: transformation of 4th orders Marchand balun to balun with open cavity and radial slot improves VSWR.

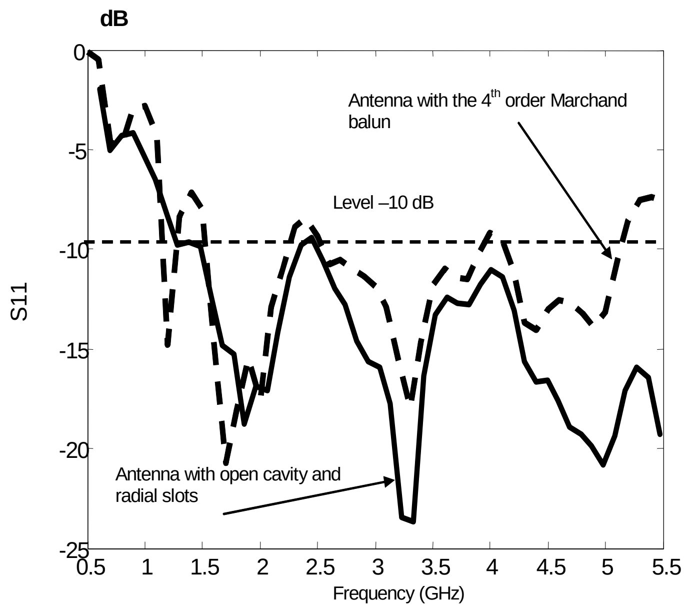
*1.3 Development of the Radiating Part*

In Fig.2, current distribution in antenna plane and S-parameters for two types of baluns and tapered section of Vivaldi type simulated at a frequency of 2.8 GHz are shown. Five most important areas of antenna structure had been determined: three of them exist in the balun, and the rest at the ends of tapered slot. As the antenna structure with balun is balanced and symmetric, the fourth and the fifth areas contribute mostly to a parasitic signal in monosta - tic configuration. First three areas contributing to full reflection of the antenna yield constant contribution to the antenna output signal as well as to internal antenna clutter appearing as a constant component for each antenna pair in the GPR antenna array. It can be accounted by data preprocessing.
Reflection at the beginning of antenna taper is reduced by as smooth as possible transition from the slotline to the aperture. To suppress reflection from the aperture, different models

of apertures edges such as elliptic brackets, corrugated edges etc. had been considered. Corrugations near antenna edges demonstrated superior performance. The alternation of strips and slots behaves like a slow-wave structure that increases effective aperture size resulting in lower reflection from the opening.




a)




b)

Fig. 2 Simulation results for full antennas Vivaldi type with different baluns and corrugated edges.
a) Current distribution in TSA of Vivaldi type computed using Zeland IE3D 10.23 software.
b) S11-parameters for antennas with different baluns.

Narrowing the aperture leads in growth of the reflection from it. It overlaps with the reflection from the air-medium interface and thus masks shallowly buried objects. Several aperture configurations had been simulated using Zeland IE3D software. Attempts of changing shape of tapered slotline and taper rate for given dimensions of the antenna as far as employing the Fermi antenna profile [4], yield rather poor results. The reflection from the antenna aperture at low frequencies can be further suppressed by applying resistive cards on the antenna flares.

Another important problem of the antenna design is the wave leakage between transmitting and receiving antennas in bi-static configuration when they are placed in one plane. This unwanted coupling diminishes dynamic range of the step-frequency radar and produces extra clutter as reflections from different objects that may be placed near by the antenna system such as wheels, borders, legs of the operator). We have found that a longitudinal cut of TSA along the aperture like in a double Vee-antenna reduces lateral coupling of antennas and sensitivity to closely situated objects especially when the antenna is elevated over the ground surface.

## 3. Experimental Results

Experimental investigation of antennas with different baluns and aperture configurations have been carried using network analyzer Agilent E5071B in the frequency range of 0.5 to 5.5 GHz. A few criteria of antenna estimation had been chosen. First, the widebandness of the antenna is naturally of interest. Second, level of unwanted reflections from the antenna aperture in mono-static configuration is the parameter that is especially important in GPR applications. Probability of masking the shallowly buried object decreases in case if the aperture reflection is low. Third, coupling between antennas in bi-static configuration had been measured. We examined three cases of relative layout of the antennas in the antenna pair: (i) the aperture is above the aperture of planar structure; (ii) the antennas are shifted by L/2 where L is the width of the aperture remaining parallel; (iii) the antennas are placed nearly in one plane. Fourth, the influence of object situated sideways from the antenna system was of interest.
Two TSA's with balun for the frequency range of 0.5 to 5.5 GHz had been simulated, designed and fabricated on dielectric substrate FR-4 with the dielectric permittivity of 4.3 and thickness of 1 mm. In the antennas, both the 4$^{th}$ order Marchand balun and modernized wideband balun had been used. The antenna dimensions are of 24 to 12 cm. The effect of the open cavity in balun at high frequencies is shown in a Fig.3.

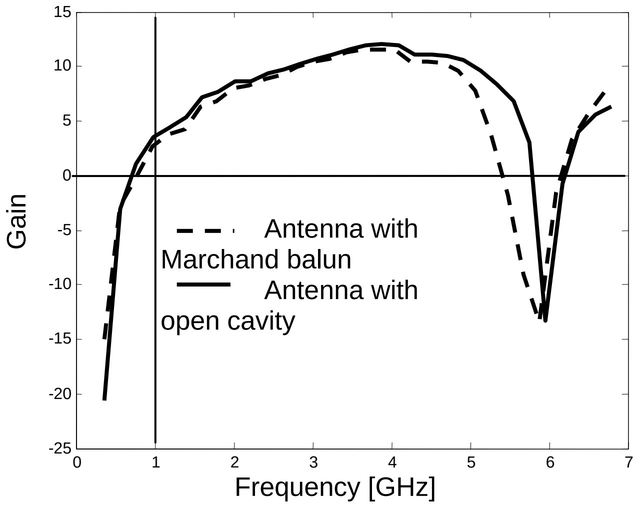



Fig.3 Measured gain for tapered-slot antennas with two different baluns – 4$^{th}$ order Marchand balun and modified balun with open cavity.

The measurements have been carried out using antenna measurement system in time-domain in a frequency range starting from 1 GHz with the horn antenna P6-23 (1-17 GHz) serving as a reference antenna. It is hard to expect good characteristics from antennas of limited size at low frequencies. Nevertheless, behavior of antennas is found stable enough. The improvement of gain is observed in the upper part of the frequency band for TSA with open cavity and radial slots.

The gain increase and influence of balun on reflection in the antenna body can be estimated in a simple experiment by a level of reflected signal from some standard object such as a metal sheet. Using Fourier transform of the frequency-domain data measured by the network analyzer, a synthetic range profile that shows reflections as a function of distance to the targets can be calculated. In Fig.4, the synthetic range profile obtained for standard TSA and TSA with open cavity in mono-static configuration are shown.

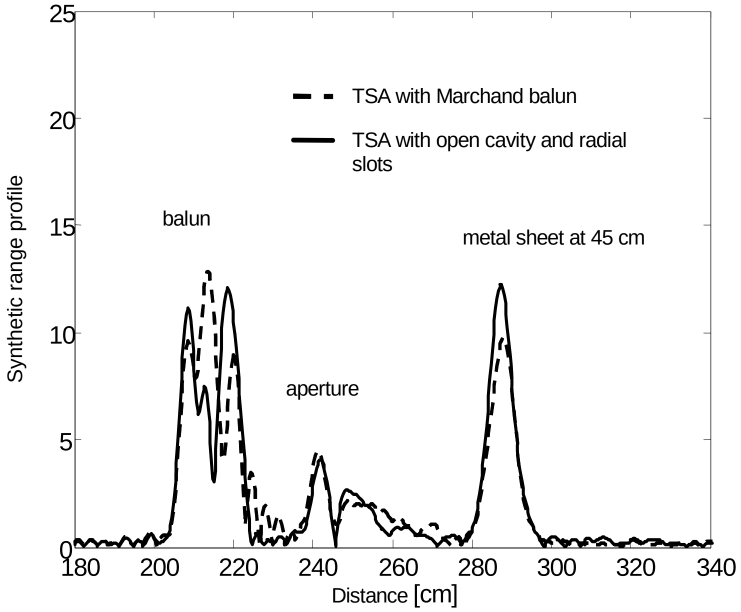



Fig.4. Synthetic range profiles obtained from metal sheet placed on distance 45 cm for antennas in mono-static configuration with two different baluns.

One can note that levels of reflection from baluns as well as levels of reflection from antennas apertures in both cases are close enough. However, there is some advantage of modernized antenna as far as reflection from object is concerned.

Consider now effects of antenna coupling and lateral radiation. The antenna coupling consists of two components: aperture coupling and coupling between upper parts of the antennas, or balun area. The coupling reduces dynamic range of the radar and produces clutter components in received signal.

To suppress coupling and lateral radiation, a simple solution was proposed, namely longitudinal cutting flares of the TSA that makes is similar to the double Vee-antenna. However, unlike the Vee-antennas, the flare in our TSA is cut so that internal part of the antenna flare is preserved while the cut follows the flare form. In this case, received signals are nearly the same as in antennas with solid flare.

In the antenna with modified radiating part, the aperture component of coupling is suppressed compared to standard antenna (Fig. 5). Distance between antennas placed in one plane was only 1.5 cm. Besides, one can see in Fig.6 that the both antennas are nearly equivalent by the level of signal received from the objects. All the parts of the building construction in Fig.6 are observed almost identically. It was noticed also that the effect of mechanical components supporting the antenna system and other objects located nearly is reduced.

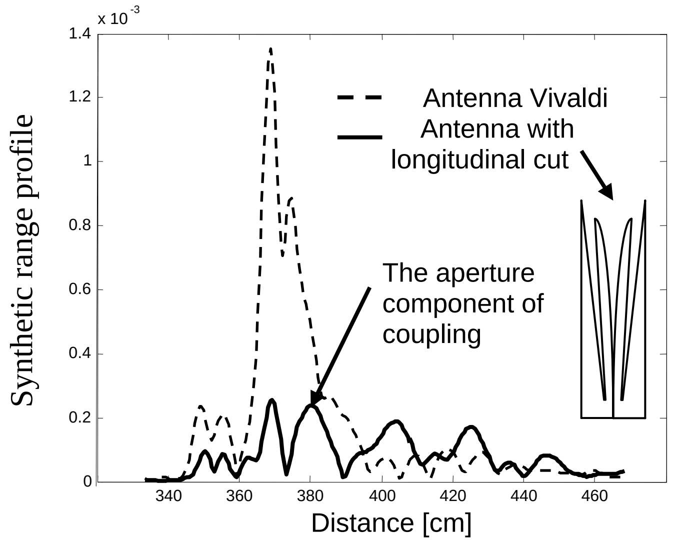



Fig. 5 Mutual coupling between TSA of Vivaldi type and antenna with modified aperture measured in free space.

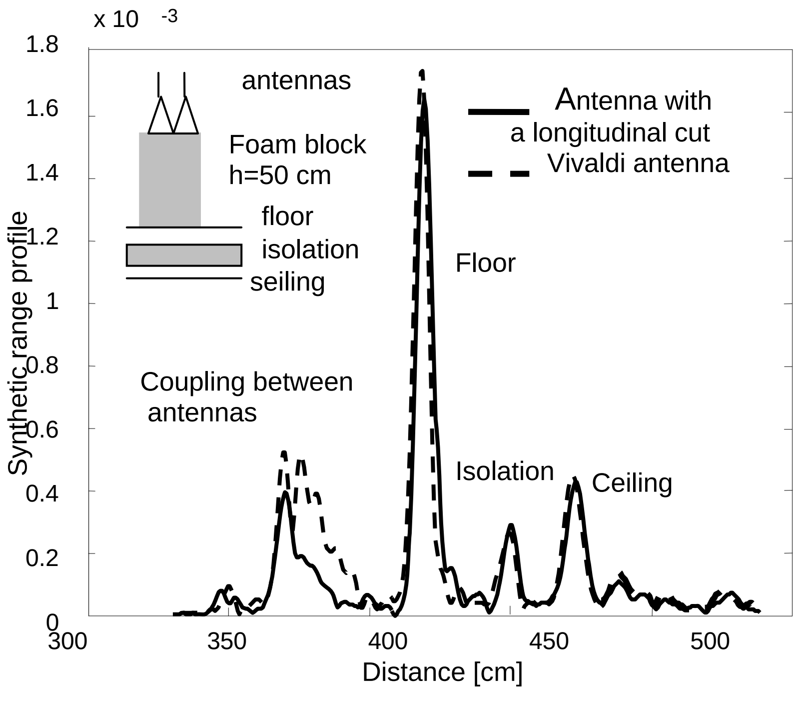



Fig. 6. Antenna comparison. Amplitude of reflected signal obtained from building construction for two types of TSA.

## 4. Conclusion

Several ultra-wideband tapered-slot antennas for the frequency range of 0.5 to 5.5 GHz had been simulated, fabricated and tested. Among new features, the microstrip-slotline balun with open cavity backed by radial slots and the antenna with longitudinal cut of flares are worth noting. The modified balun allowed somewhat widening the frequency band of antenna as well as improved antenna characteristics at its ends.

Antennas with longitudinally cut flares demonstrate reduced mutual coupling when the antennas in the array are placed closely in one plane. This suppresses partially clutter in subsurface imaging applications and results in better characteristics of the antenna system when detecting shallowly buried objects. Besides, such antennas due to lower lateral radiation are less sensitive to different objects that may be placed near the radar system.

## 5. Acknowledgements

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