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PROPAGATION MODEL OF HARMONIC RADAR FOR DETECTION NONLINEAR CONTACTS OF THE IMPROVISED EXPLOSIVE DEVICES

PROPAGACIJSKI MODEL HARMONIČKOG RADARA ZA DETEKCIJU NELINEARNIH KONTAKATA IMPROVIZIRANIH EKSPLOZIVNIH NAPRAVA

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ABSTRACT

This paper, based on the experimental research data, analyses the improvised explosive devices (IED) detection by harmonic radar. The propagation model was applied to the spatial distribution of electric field strength of harmonic radar and IED above the flat and electrically smooth ground surface. The linear polarization for manual survey for distances up to 20–30 m is considered; the loss of spatial coverage by detection is estimated. The harmonic radar receives waves generated by nonlinear electronic components or by junctions of oxidized surfaces of different metals in IED. The detection range of the harmonic radar is limited by the nonlinearity of IED elements whose nonlinear radar cross section σ2 depends on power density [W/m2] on a target, by saturation, by oscillatory instead of monotonic decay distribution of electric field strength of electromagnetic waves. The availability of theoretic models for harmonic radar is limited to the use in free space; experimentally derived models for a limited selection of targets dominate. The needs and requirements for harmonic radars are well defined for military and security domains, but since 2014 they have been an ever-growing demand for humanitarian countermine action as well.

Keywords: *improvised explosive device, harmonic radar, nonlinear radar cross-section, nonmonotonic E distribution, loss of detection*

SAŽETAK

U radu se analizira problem detekcije improviziranih eksplozivnih naprava (IEN) pomoću harmoničkog radara, na temelju podataka iz eksperimentalnog istraživanja. Primjenjen je propagacijski model prostorne distribucije jakosti električnog polja harmoničkog radara i IEN iznad površine ravnog i električki glatkog tla. Razmatra se linearna polarizacija, za ručno izviđanje, za domete detekcije do 20 – 30 m, procjenjuju se gubitci pokrivanja prostora detekcijom. Harmonički radar prima valove koje generiraju nelinearni elektronički elementi ili kontakti oksidiranih metalnih površina IEN. Domet detekcije harmoničkim radarom je ograničen nelinearnošću elemenata IEN čija pseudo nelinearna radarska površina σ2 ovisi o površinskoj gustoći snage [W/m2] na meti, pojavom zasićenja, oscilirajućom umjesto monotono opadajućom distribucijom jakosti električkog polja elektromagnetskih valova. Za harmoničke radare je izbor teorijskih modela meta ograničen na primjenu u slobodnom prostoru, dominiraju eksperimentalno izvedeni modeli za ograničen skup meta. Vojne i sigurnosne potrebe i zahtjevi za harmoničkim radarima su dobro definirane ali od 2014. g. su se pojavile i u sve većem su porastu potrebe humanitarnog protuminskog djelovanja.

Ključne riječi: *improvizirana eksplozivna naprava, harmonički radar, nelinearna radarska površina, nemonotona distribucija E polja, gubitak detekcije*

1. INTRODUCTION

The paper, based on the data from experimental research [1],[2], analyses the problem of detection of improvised explosive devices (IED) using harmonic radar. A common name for this type of radar is a nonlinear junction detector – NLJD. Harmonic radar radiates electromagnetic waves at the frequency f, while radar target nonlinearities generate electromagnetic waves on the second $f_2=2f$ or the third $f_3=3f$ harmonic. Unlike well-known and widespread conventional linear radars, which use electromagnetic waves scattered and/or reflected from a target, harmonic radars receive the waves generated by nonlinear electronic components or junctions of oxidized metal surfaces of the target (the paper does not discuss this type of radar). The maximum distance at which linear radars detect a target (range) can be, without principled limitations, increased by increasing the power P of the radar transmitter and the gain G of the radar antennae. In contrast, the harmonic radar range is limited: a) by the nonlinearity of target components, whose nonlinear radar cross section σ_2 changes with the power density [W/m2] on a target, b) by saturation, if power density [W/m2] on the target exceeds the limit dependent on nonlinear component, c) by a spatial oscillatory distribution of electric field strength of electromagnetic waves instead of monotonic decay distribution with the distance from the source. To analyze radar targets and propagation of linear radars, there are very reliable models developed theoretically and verified in practice. For harmonic radars, the choice of theoretical models of targets is limited to the application in free space, experimentally derived models for a limited selection of targets dominate. Apart from the consequences of nonlinearity (targets, range) when using harmonic radars for IED detection on the ground, the interference of direct and ground-reflected waves dominates, which results in oscillating, nonmonotonic distribution of electric field strength E [V/m]. The need to research the use of harmonic radar above the ground surface followed the increase in terrorist activities using IEDs and ambushes. In asymmetric conflicts, military and security forces were mostly exposed the IED activities. Although the problem of actions against IEDs and ambushes

Figure 1: a), b) Manual survey includes search in the vertical and horizontal plane, after signal detection of IED, rotation of antenna matches the polarization, [1], [2]. c) Harmonic radar in development for IED detection from ground vehicles, b) antennas, NATO, [7].

was already followed before [3], [4], [5], [6], since 2014, the European Defence Agency (EDA), NATO Science for Peace Program and others responsible for the research and development of IED detection technology began a series of activities of [7], [8], [9], [10], [11]. Harmonic radars are also a part of these activities, two examples are shown in Fig. 1. Due to the security sensitivity of the topic, access to scientific and development sources and information is limited, so less reliable data or information from the Internet must be used. There is little data on the application of harmonic radar, the most recent example from Syria demonstrates a manual survey with harmonic radar [12]. In addition to well-defined military needs, new requirements for IED detection come from the civilian sector, mostly from the area of humanitarian demining, where, besides mines, and unexploded ordnance there is a need for detecting and removing IEDs [13], [14], [15]. Harmonic radars most frequently use only one or several transmitter frequencies, circular polarization for the manual survey, radiation with linear horizontal or vertical polarization, left or right circular polarization, and reception with circular polarization. Starting with the situation described above, this paper, based on experimental data on six selected examples of devices from [1] which are used to activate IEDs, analyses the issue of the manual survey of IEDs to derive an applicable model and present the impacts of several main factors. In the paper is applied a propagation model of the spatial distribution of the electric field strength for harmonic radar and IED above the surface of the flat and electrically smooth ground for linear polarization for a manual survey of the ranges up to 20 – 30 m; the losses of space coverage by detection are estimated.

2. RESULTS OF RESEARCH

The primary purpose of the research in this paper is to contribute to the development of the use of harmonic radar for the detection of IEDs in very dangerous circumstances, and the secondary is a possible contribution to the research and development of the harmonic radar technique. Due to several key limitations which are characteristic of harmonic radar and nonlinear targets, the research proceeds with empirical data collected in [1], analyzing critical aspects for the IED survey variation with the limitation to linear polarization and reflection coefficient r = -1. Data on the detection range for all six types of targets (at the heights H2 = 0 m and H2 = 1,2 m) were obtained in [1] describing the targets used (devices for IED activation). For three selected targets, data is obtained on the influence of target orientation on the detection range at two radar height variations (H1 = 1,1 m and H1 = 1,7 m), and three target heights (H2 = 0 m; 0,5 m; 1,2 m). Based on the data obtained on detection ranges for these three targets, an estimate of the nonlinear radar cross section σ2 for the second harmonic is calculated by applying a radar equation valid for the reception of harmonics in free space. In this step, it was not possible to measure the power density [W/m2] of the incident waves at the target location. Estimation of σ2 does not include the effect of interference of direct waves and waves reflected from the ground, which was separately analyzed.

2.1 Versions of the IED survey

No developed and verified methodology for harmonic radar could be adjusted to the versions of the survey: a) manual survey from a small height (Fig. 1a), (Fig. 1b), b) survey from moving ground vehicle from a great height (Fig. 1c), (Fig.1d), c) survey from small heights from a remotely controlled vehicle, d) vertical survey from remotely piloted aircraft system (RPAS). In our work, we are focused on the manual survey, the obtained results can also be applied to surveys from small heights from a remotely controlled vehicle. There is no data on the survey from vehicles and great heights (Fig. 1c), except for Fig. 7 from which we estimate the following: antenna A1 could be a transmitter antenna that allows choosing the radiation of linear horizontal or vertical polarization, left or right circular polarization. The reception is performed by circular polarization, antennae A2 receives the second, and antennae A3 the third harmonic. With this mode, it can be expected that the radar enables the detection of nonlinearity of metal oxidized surface sections, extending the possibility of detection to mines IEDs, unexploded ordnance which do not contain electronic components. With polarization selectivity, the system could operate on two (or on several) transmitter frequencies providing an increase in sensitivity over 20 dBm. Harmonic radar survey from remotely piloted aircraft system (RPAS) as a successor to helicopter survey was developed in the USA and the former USSR to detect the nonlinearity of oxidized metal surfaces of weapons and mines without electronic or electrical components. This type of survey is not discussed in this paper.

2.2 Equation of harmonic radar for nonlinear targets in free space

The basic relationship between the parameters of the linear radar and the target is described by the radar equation

$Pr = PG^2\lambda^2\sigma/((4\pi)^3R^4)$ (1)

where P[W] is the radiated power of the radar transmitter, Pr [W] is the received power at the input of the radar receiver, λ[m] is the radar wavelength, G is the gain of the radar transceiver antenna, R [m] is the distance between the radar and the target, σ [m²] is the effective radar cross-section of the target. The radar equation for the nth harmonic of the harmonic radar is taken from [15], pp. 67-69 and used in the further analysis

$P_{rn}=[G_{rn}\lambda_n{}^2(P_tG_t)^n\sigma_n]/[(4\pi)^{n+2}R^{2n+2}]$. (2)

The data selected for the analysis are as follows: radar radiates at wavelength λ_1 = 0,3583 m, receives harmonics n = 2, 3 at wavelength λ_n, λ_2 = 0,1769 m, λ_3 = 0,1179 m, the radiated power is P_t = 200 W, received power at harmonics is P_{rn} [W], noise level of radar receiver for harmonics is -125 dBm, the gain of the radar transmitting antennae is G_t = 4, the gain of radar receiving antenna at harmonics is G_{rn}, G_{r2} = 6,5; G_{r3} = 6,5; and the distance between radar and target is R[m]. The nonlinear radar cross section of the target at the wavelength λ_n is $\sigma_n = \sigma_{spec} S_n$, where σ_{spec} [m⁴/W] is a specific harmonic radar cross section, and S_n [W/m²] is the power density of the incident waves on the target. It should be pointed out that σ_n is not the target's permanent feature, it is only dependent on the power density of the target. In [1], only data for the targets with electronic and electric nonlinear components are collected, so the analysis is carried out only for n=2, the results are presented in Table 1 and Table 2.

2.3 Propagation model of harmonic radar above the flat ground surface

To analyze the spatial distribution of electric fields (Fig. 2), a general model of direct and reflected wave interference according to [16], pp. 136-138 can be applied. Electric field strength E, at the receiving point, is the result of direct wave interference the electric field strength E_D and reflected wave the electric field strength Er, $E = E_D + E_r$, where

$E_D = (60PG)^{1/2}(e^{-j\beta R}/R)F(R)$ (3)

$\beta = 2\pi/\lambda$ is the phase constant, F(R) is the value of the antenna pattern diagram in the direct wave direction in the analyzed cases F(R) ~ 1,

$E_\rho=r(60PG)^{1/2}[(e^{-j\beta(R1+R2)})/(R1+R2)]F(R1)$
(4)

r - reflection coefficient, F(R1) is the value of the antennae pattern diagram in the incident wave direction towards the ground, F(R1) ~ 1. According to Rayleigh's criterion if the ground surface roughness for the nth harmonics is $dh_n< \lambda nD/(8(H1+H2))$, the ground surface is electromagnetically smooth for the discussed λ_n. The examples from [1] meet the discussed requirements, so the approximation (3) and (4) is justified. For manual survey with harmonic radar, maximum horizontal distance D is up to 30 m, and the radar height H1 and the target H2 are H1<<D, H2<<D, so it can be approximated.

$R = (D^2 + (H1\text{-}H2)^2)^{1/2} \sim D+(H1\text{-}H2)^2/2D$,
$R1+R2=(D^2+(H1+H2)^2)^{1/2} \sim D+(H1+H2)^2/2D$

so the distance difference is R1+R2-R ~ 2H1H2/D. With F(R) ~ 1, F(R1) ~ 1, F(R2) ~ 1 follows

$E = E_D+E_R = E_D(1 + re^{-j\beta H1H2/D})$ (5)

For the area discussed, the reflection coefficient is r~-1, which results in a relation $E=2jE_D\, e^{-j\beta H1H2/D} \sin(\beta H1H2/D)$ (6)

The example (Fig. 3) presents a normalized distribution $| E/(jE_De^{-j\beta H1H2/D}) |=|\sin(\beta H1H2/D)|$ for n = 2.

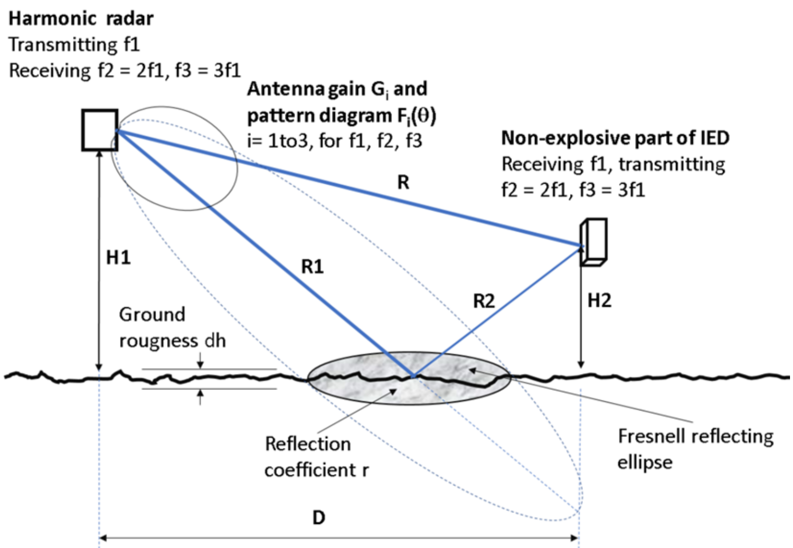

Figure 2 *The propagation model of the harmonic radar and IED above the flat ground plane and electrically smooth surface for linear polarization.*

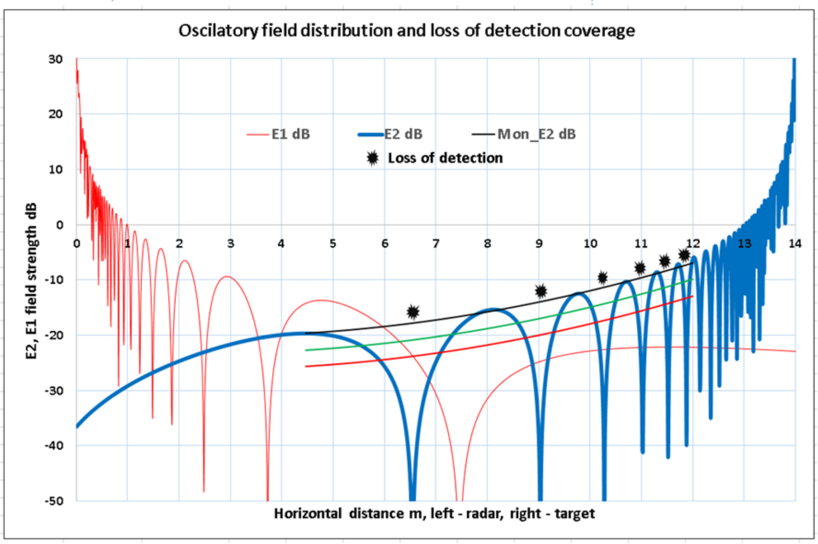

Figure 3 *Example of the spatial oscillatory non-monotonic distribution of the electrical field strength: E1 on frequency f of radar transmitter, E2 on the frequency of the second harmonic f2, radiated by electrical and electronic nonlinear elements of IED.*

Assuming that F(R2) ~ 1 and applying (6) for the second and the third harmonic, a model of spatial standard distribution is obtained. Absolute values of standard fields are denoted below by E1 (direct wave), E2 (second harmonic), and by E3 (third harmonic). Since in [1] only the targets containing electronic nonlinear components were researched, only E1 and E2 are discussed below. In the example (Fig.3) the radar is on the left side (horizontal distance 0 m), at the height H1=1,1m, and the target is on the right, at 14 m distance from the radar at the height H2 =1,2m. The target is a toy car (Fig.5a), (Fig.4). Due to the minimum field strength, in the area marked with the Loss of detection symbol, the target detection is interrupted. To estimate the width of space where the loss occurs, a maximum envelope is estimated showing a possible monotonic decay with the increase in distance of IED from the radar receiver MonE2 according to (7), (black line), below which the lines – 3dB (green) and -6 dB (red) are marked

$$MonE2=-20,2259-0,5963x+0,1417x^2 \quad (7)$$

where x is the distance at which the local maximum E2 is achieved. In the discussed case, within the range from 4m to 12 m, according to Mod_E2, detection losses at -3dB and -6dB are 45,56 % and 28,04 %, respectively. Those losses in detection capability are an indicator of the increased threat for the manual harmonic radar operator which is additionally discussed in the example (Fig.4) in which the same type of IED is located at 13m and 20m from the radar. For a more distant target, the field strength changes monotonically, and for a closer target, deep minima of the field strength appear, which leads to the loss of detection (Loss of detection symbol)

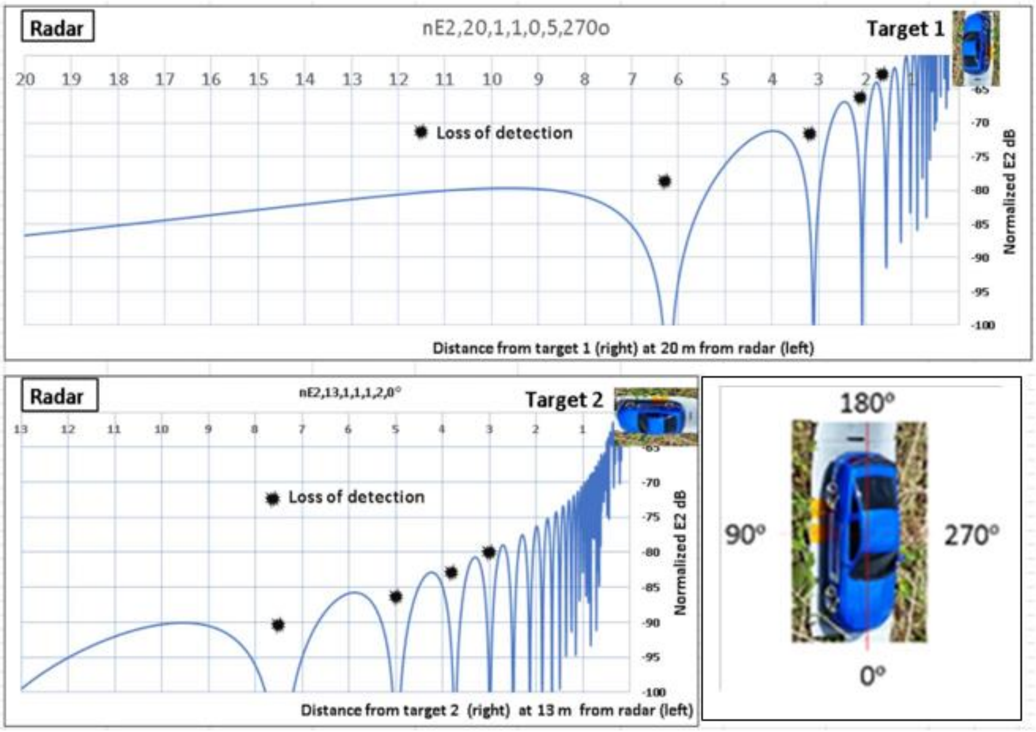

Figure 4 *The increase of threat for the operator. The same type IED on two different distances from radar a) upper diagram, D=20 m, b) lower diagram D=13 m, c) lower right image, target's orientation. The horizontal axis shows the distance from IED to the radar.*

2.4 Researched devices as used for IED activation (targets)

In [1], data were collected for targets with electronic and electric nonlinear components, and the analysis was done only for the second harmonic, n=2. The nonlinear radar cross section of the target $\sigma_n = \sigma_{spec} S_n$ is not constant but changes in proportion to the power density on the target, where σ_{spec} [m^4/W] is a specific harmonic radar cross section of the target. As there is no publicly available S_n, σ_{spec} data on the analyzed devices, Fig. 5, in 2.4 below (Table 1) presented is the data from the experimental research [1] for the detection range D for the discussed targets and measurement geometries (H1, H2), for dry and wet soil.

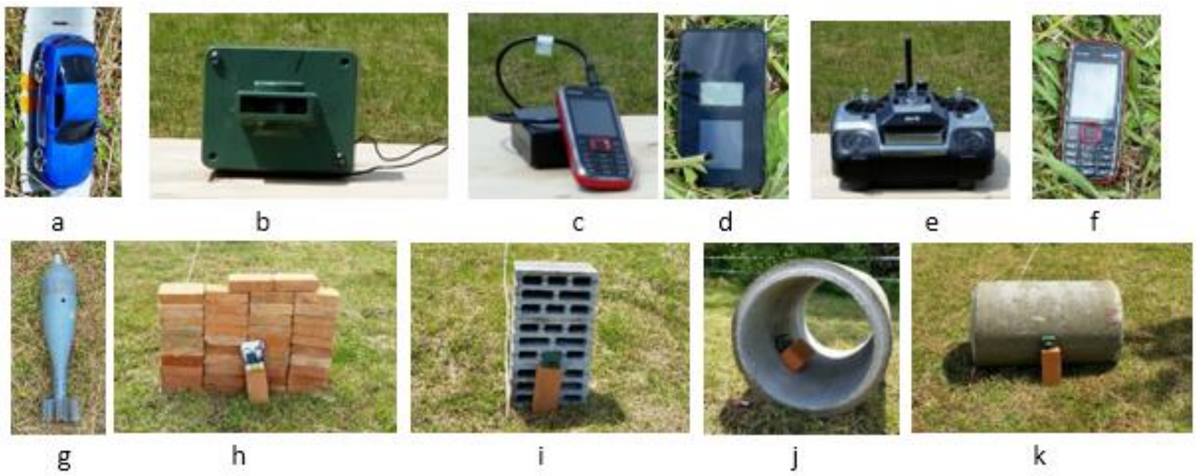

Figure 5 *Targets used in the research (Table 1). Obstacles used in the research. h) set of bricks, i) concrete blocks, j), k) concrete tube, [1].*

***Table 1** Detection distances for components of IED. Ground surface: dry, wet, [1].*

Targets	Ground	H2 = 1,2 m	H2 = 0 m	Figure
Toy Car	dry	11,5 m – 18,5 m	11 m - 14 m	5a
IR sensor	dry	20 m - 30 m	11 m – 23,5m	5b
NOKIA1616+El.switch	dry	14 m - 22m	12,5 m - 17 m	5c
Meteo station	wet	12 m -13,5 m	9 m	5d
Remote Control	wet	18,3 m - 20 m	16,5 m - 17 m	5e
Nokia5130c	wet	10,5m - 11m	7 m	5f
Mortar shell 120mm	dry	-	2-3 m	9g
λ/2 dipole, balun, diode	dry	70 m	23,5 m	
λ/2 dipole, diode	dry	76 m	21 m	

2.5 Influence of the target orientation on detection range D and nonlinear radar cross section σ_2 for selected targets

The analyzed targets showed significant variations of the range D if their orientation to the radar is changed (Fig. 5b). Three types of targets were selected for three combinations of heights H2 and four orientations: 0°, 90°, 180°, and 270°. Applying the nonlinear radar equation (2) for free space, the estimates of σ2 for each analyzed case are calculated. Data on the measured range D and an estimated amount of σ2 is shown in Table 2.

***Table 2** Influence of target orientation on D and σ2*

Target	Orientation H2 m	Range D, σ2	0°	90°	180°	270°	Difference
Toy car	1,2	D	13	11,5	15,5	13,5	4,0
		σ2	-70,34	-73,53	-65,76	-69,36	7,77
Infra-Red sensor	1,2	D	27,2	20	30	22	10,0
		σ2	-51,10	-59,11	-48,55	-56,63	10,56
NOKIA1616 & electric switch	1,2	D	14	19,3	17	18,5	5,3
		σ2	-68,41	-60,04	-63,35	-61,15	8,37
Toy car	0,5	D	17	18	16,5	20	3,5
		σ2	-63,35	-61,86	-64,13	-59,11	5,02
IR sensor	0,5	D	25,5	21	28	23	7,0
		σ2	-52,78	-57,84	-50,35	-55,47	7,49
NOKIA1616 & electric switch	0,5	D	16	19,3	22	20	6,0
		σ2	-64,93	-60,04	-56,63	-59,11	8,30
Toy Car	0	D	11	14	13	12	3,0
		σ2	-74,69	-68,41	-70,34	-72,43	6,28
Infra-Red sensor	0	D	11	14	13	12	3,0
		σ2	-72,43	-74,69	-68,41	-70,34	6,28
NOKIA1616 & electric switch	0	D	13,5	15	14	12,5	2,5
		σ2	-69,36	-66,61	-68,41	-71,36	4,75

2.6 Calibration

One of the key problems for a reliable quantitative analysis of the IED detection process on the ground by nonlinear radar is the impossibility of calibration of nonlinear radar cross-section σ2 except in very demanding laboratory conditions (measurement of thepower density at the location of IED in an electromagnetic anechoic chamber is necessary). To achieve at least a relative comparison, a thin half-wave dipole with a microwave diode was used in [1] (Figure 6).

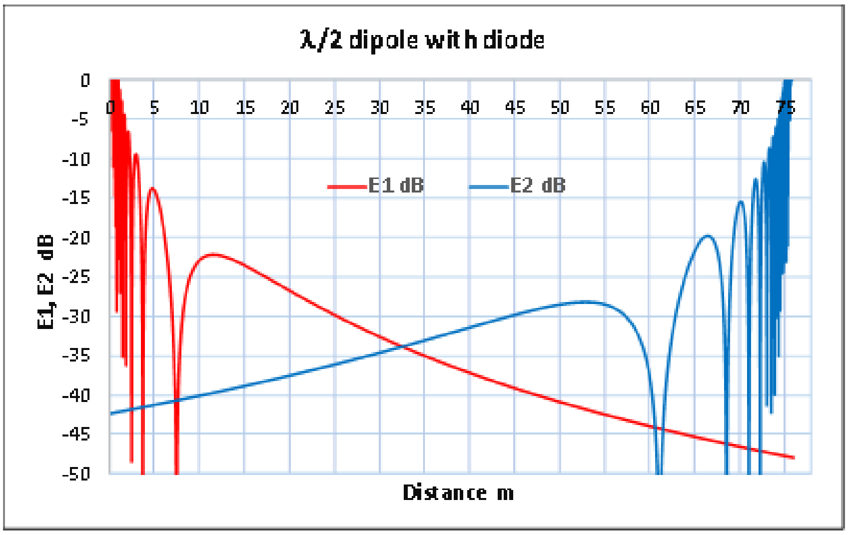

Figure 6 *The halfwave dipole with diode provides monotonic fields E2 from 53m to the radar.*

3. DISCUSSION

Nonlinear radar cross-section of the target σ_n at the harmonic wavelength λ_n is not constant but proportional to the product of the power density S_2 [W/m^2] of the radar waves on the target and specific harmonic radar cross-section of the target σ_{spec} [m^4/W], [17]. Since it was not possible to measure S_2 on the target, the data on σ2 has an indicative value (Table 2). In future work, a dipole with a diode could be used according to [19], for which data on the given specific radar cross-section σ_{spec} and optimal dimensions for the required amounts are given. The model of the loss of detection area for the manual survey was made with several assumptions that are realized on asphalt, concrete roads, and unpaved roads. For surfaces with higher electromagnetic roughness, scattering should be introduced instead of reflection and the reflection coefficient models should be adjusted.

4. CONCLUSION

Analysis of manual detection of nonlinear devices (targets) by harmonic radar on a flat electromagnetically smooth surface has confirmed the fundamental difference if compared to conventional linear radar.

Based on experimentally collected data, for six different targets, the impact of the orientation of the target towards the radar on the detection range and the estimation of the nonlinear radar cross-section was analyzed. A model was introduced for the analysis of the spatial distribution of the electric field strength E of electromagnetic waves radiated by nonlinear elements in the target. The appearance of interference of direct and reflected waves is the cause of the oscillatory instead of the monotonically decreasing distribution of the E field, which increases the danger for the radar operator during a manual survey.

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