UDC: 623.4.023:535-15:681.586(047)=20
COSATI: 17-05, 14-02

# The improvement of single baseline passive ranging systems using target IR intensity

Goran Dikić, MSc (Eng)[1)]
Branko Kovačević, BSc (Eng)[2)]
Zvonko Radosavljević, BSc (Eng)[3)]

**In this paper, passive range estimation using the ratio of infrared energy absorbed by the sensors placed at the end of a baseline is presented. This method is adopted in situations when the target directions are collinear or nearly collinear relative to the baseline and the principle of triangulation can not be applied for range estimation. As it can be seen from simulations, in these situations the number of appropriate relative errors can be 2-4 times smaller, depending on the target range and direction, if range estimations are based on the ratio of the target IR intensity. A method presented in this paper represents a complementary solution relative to the principle of triangulation. They both have to be used in a situation when only two passive IR sensors are used for target tracking. In this way the extended tracking area is obtained.**

*Key words:* **passive IR sensor, target tracking.**

## Introduction

TARGET tracking and detection in modern combat systems is based on active radar sensing and laser illumination. However, an active sensor can be detected from a considerable distance and destroyed by homing missiles. The use of passive infrared (IR) sensors can be a better solution for a real situation on the battlefield [1,2]. They are recognized as providing a precise bearing-only target location. Through fusion of data from two or more such sensors range information can also be extracted.

Various passive ranging schemes based on the radiating characteristics of a target have been proposed. In the early 1960s several patents related to a "hot" target IR signal attenuation to the range were approved [3,4]. Both of these schemes applied the principle that the ratio of signal attenuation in two narrow IR bands, with known but nominally different atmospheric attenuation coefficients, could be related to the range. Both methods required prior knowledge of the target IR spectrum, an assumption that can be easily disqualified with today's countermeasures tactics.

The aim of this paper is to focus on the triangulation, an angle difference location technique that requires only a target unmodulated IR signature. In case when the target range estimation is obtained using two passive sensors, placed at the end of a baseline (single baseline method) there is a direction in which all precision in the triangulated target range is lost. This phenomenon is known as "geometric dilution of precision". In the intention to overcome this "geometric dilution" effect, a dual baseline scheme [5] is proposed. The baselines have been taken to be orthogonal. The individual performance of each of the baselines, when taken separately, follows the mathematics of the single-baseline model. However, the performance of each baseline is peaked along the corresponding direction for geometric dilution of the alternative baseline; thus it is possible to eliminate the geometric dilution problem by switching between baselines at performance crossing points. It is shown in [5] that the crossover points depend primarily on the ratio of the two baseline lengths. It is evident that four IR sensors must be used for the realisation of the proposed dual baseline scheme. This scheme is intended for implementation in shipboard systems. In ground-to-air scenarios an alternative solution can be obtained if IR sensors are placed in a triangle scheme. This solution may be cheaper because only three IR sensors are applied.

In this paper, a new method of range determination is introduced to overcome the "geometric dilution" effect in single-baseline passive ranging systems. In situations when the target directions are collinear or nearly collinear, relative to the baseline, the range estimation is obtained using the ratio of infrared energy absorbed by the appropriate sensors [6]. This approach is referred to as the target IR intensity ratio method. In contrast to the method presented in the literature [5] only two IR sensors would be enough for target range estimation using this method.

This paper consists of seven sections. The first one is an introduction. The second section presents the proposed method. The analysis of the range estimation areas for two methods, the triangulation principle and the method based on the ratio of the targets IR intensity is given in Sections 3 and 4. The quality of the proposed method and a suggestion for the improvement of results is presented in Section 5.

[1)] Military Academy, Ratka Resanovića 1, 11000 Beograd
[2)] Faculty of Electrical Engineering, Bulevar kralja Aleksandra 73, 11000 Beograd
[3)] Military Technical Institute (VTI), of the Yugoslav Army, Katanićeva 15, 11000 Beograd

The simulation results are given in Section 6. The last section is the conclusion.

## Presentation of the proposed method

If the origin of the tracking coordinate system is positioned in the place of the sensor $S_1$ (Fig.1) the position of the target is expressed as

$$x = \frac{d}{tan(\lambda_1) - \tan(\lambda_2)} \tag{1}$$

$$y = \frac{d\, tan(\lambda_1)}{\tan(\lambda_1) - \tan(\lambda_2)} \tag{2}$$

$$z = (x^2+y^2)^{1/2}\tan(\varphi_1) = (x^2+(y-d)^2)^{1/2}\tan(\varphi_2) \tag{3}$$

The distance between the objects $S_1$ and $S_2$ is the baseline length (d), while the angles ($\lambda_1$, $\lambda_2$) and ($\varphi_1$, $\varphi_2$) are the azimuth and the elevation from sensors $S_1$ and $S_2$, respectively. This method is frequently used in practice and is known as "the principle of triangulation". The target range estimation requires the fusion of azimuth and elevation measurements from two passive sensors placed, as shown in Fig.1, at the ends of a baseline.

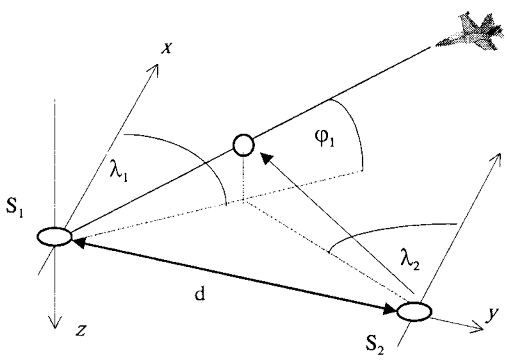


**Figure 1.** Geometry relations among target and passive sensors

The efficient estimation of other target states, velocity and acceleration, can be obtained by an appropriate algorithm as presented in [7]. As it is emphasized above, a problem arises when the target directions are collinear or nearly collinear relative to the baseline. A target movement model in a plane can be used to simplify the derivation of the appropriate relation of its range determination based on the ratio of IR intensity measured by the sensors at the end of a baseline.

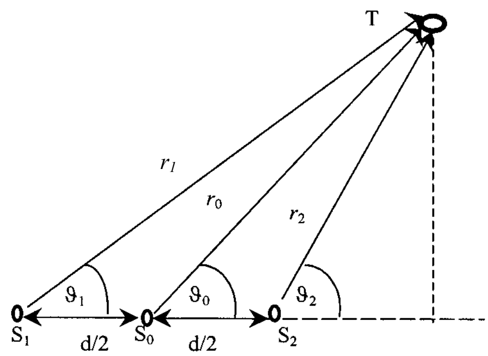


**Figure 2.** Geometry of the target tracking process in a plane

As shown in Fig.2, the points where bearing measurements are carried out, $S_1$ and $S_2$, are located at the distances $r_1$ and $r_2$ , respectively, from the target at the point T. Although the measurements are not carried out at the point $S_0$, it serves as a convenient symmetrical reference between the observation points $S_1$ and $S_2$. The target range $r_0$ is defined as a distance from the point $S_0$ to the target. For the development of the appropriate equations the next assumptions are adopted:

1. The exact baseline length is known.
2. The tolerances in the bearing measurements are known and will be denoted as $\Delta\vartheta_1$ and $\Delta\vartheta_2$.
3. The discrepancy between the horizontal-path range and the slant-path range is not significant (the target is near the horizon).

From Fig.2, it is evident that the angles and appropriate distances are related through the relations:

$$r_0 \sin\vartheta_0 = r_1 \sin\vartheta_1 = r_2 \sin\vartheta_2 \tag{4}$$

$$r_1 \cos\vartheta_1 = r_0 \cos\vartheta_0 + d/2 \tag{5}$$

$$r_2 \cos\vartheta_2 = r_0 \cos\vartheta_0 - d/2 \tag{6}$$

According to eq.(5) and (6), we get

$$\frac{r_1}{r_2} = \left(\frac{r_0 \cos\vartheta_0 + d/2}{r_0 \cos\vartheta_0 - d/2}\right)\frac{\cos\vartheta_2}{\cos\vartheta_1} \tag{7}$$

Considering that the angle $\vartheta_0 = (\vartheta_1+\vartheta_2)/2$ and using the substitution $\vartheta_2 = 2\vartheta_0 - \vartheta_1$, as well as some standard trigonometric identities, we get

$$\frac{r_1}{r_2} = \left(\frac{r_0 \cos\vartheta_0 + d/2}{r_0 \cos\vartheta_0 - d/2}\right)\left(\cos 2\vartheta_0 + \frac{\sin(2\vartheta_0)\sin\vartheta_1}{\cos\vartheta_1}\right) \tag{8}$$

From eq.(4) and (5) it follows

$$\frac{r_1}{r_1}\frac{\sin\vartheta_1}{\cos\vartheta_1} = \frac{r_0 \sin\vartheta_0}{r_0\cos\vartheta_0 + d/2} \tag{9}$$

and consequently eq.(8) can be rewritten as

$$\frac{r_1}{r_2} = \left(\frac{r_0 \cos\vartheta_0 + d/2}{r_0 \cos\vartheta_0 - d/2}\right)\left(\cos 2\vartheta_0 + \sin(2\vartheta_0)\frac{r_0\sin\vartheta_0}{r_0\cos\vartheta_0 + d/2}\right) \tag{10}$$

or alternatively

$$\frac{r_1}{r_2} = \left(\frac{\cos\vartheta_0 + d/2r_0}{\cos\vartheta_0 - d/2r_0}\right)\left((\cos\vartheta_0)^2 - (\sin\vartheta_0)^2 + \frac{\sin(2\vartheta_0)\sin\vartheta_0}{\cos\vartheta_0 + d/2r_0}\right) \tag{11}$$

A simplification of eq.(11) is possible under the condition

$$(\cos\vartheta_0)^2 >> \frac{\sin(2\vartheta_0)\sin\vartheta_0}{\cos\vartheta_0 + d/2r_0} - (\sin\vartheta_0)^2 \tag{12}$$

for $2\vartheta_0 < 10°$. In this way, a more convenient form of eq. (11) is obtained as

$$\frac{r_1}{r_2} = \left(\frac{\cos\vartheta_0 + d/2r_0}{\cos\vartheta_0 - d/2r_0}\right)(\cos\vartheta_0)^2 \tag{13}$$

The received power at the sensor entrance pupil is defined as [8]

$$W = \int_{\lambda_1}^{\lambda_2} \frac{M(\lambda,T)}{\pi} A\Omega\tau(\lambda)d\lambda \tag{14}$$

where

| | | |
|---|---|---|
| $\frac{M(\lambda,T)}{\pi}$ | – | the spectral radiance of Lambertian source in [W/(cm$^2$·sr·$\mu$m)], |
| A | – | the source area seen within the sensor FOV in [cm$^2$], |

$$\frac{\Delta r_0}{r_0} = \left(\frac{\cos\vartheta_1}{\sin\vartheta_1} - \frac{\partial v/\partial\vartheta_1}{v}\right)\Delta\vartheta_1 + \left(\frac{\cos\vartheta_2}{\sin\vartheta_2} - \frac{\partial v/\partial\vartheta_2}{v}\right)\Delta\vartheta_2 \quad (24)$$

where

$$v = \sqrt{(\sin\vartheta_0)^2[(\sin\vartheta_1)^2 + (\sin\vartheta_2)^2] - 2(\sin\vartheta_1)^2(\sin\vartheta_2)^2} \quad (25)$$

$$\frac{\partial v}{\partial\vartheta_1} = \left\{\begin{matrix}\sin\vartheta_0\cos\vartheta_0[(\sin\vartheta_1)^2 + (\sin\vartheta_2)^2] + \\ \sin 2\vartheta_1[(\sin\vartheta_0)^2 - 2(\sin\vartheta_2)^2]\end{matrix}\right\}/2v \quad (26)$$

$$\frac{\partial v}{\partial\vartheta_2} = \left\{\begin{matrix}\sin\vartheta_0\cos\vartheta_0[(\sin\vartheta_1)^2 + (\sin\vartheta_2)^2] + \\ \sin 2\vartheta_2[(\sin\vartheta_0)^2 - 2(\sin\vartheta_1)^2]\end{matrix}\right\}/2v \quad (27)$$

$$\vartheta_1 = \arcsin\left\{\frac{r_0\sin\vartheta_0}{\sqrt{(r_0\cos\vartheta_0 + d/2)^2 + (r_0\sin\vartheta_0)^2}}\right\} \quad (28)$$

$$\vartheta_2 = \arcsin\left\{\frac{r_0\sin\vartheta_0}{\sqrt{(r_0\cos\vartheta_0 - d/2)^2 + (r_0\sin\vartheta_0)^2}}\right\} \quad (29)$$

We assumed that $\Delta\vartheta_1$ and $\Delta\vartheta_2$ are zero mean random variables. If sensor performances are not identical, the coefficient $\alpha=\Delta\vartheta_2/\Delta\vartheta_1$ is introduced in eq.(24) as a mismatching measure. With this in mind, the maximum relative error is defined as

$$\left|\frac{\Delta r_0}{r_0}\right| = \left\{\left|\frac{\cos\vartheta_1}{\sin\vartheta_1} - \frac{\partial v/\partial\vartheta_1}{v}\right| + \left|\left(\frac{\cos\vartheta_2}{\sin\vartheta_2} - \frac{\partial v/\partial\vartheta_2}{v}\right)\alpha\right|\right\}|\Delta\vartheta_1| \quad (30)$$

It can be seen from eqs.(25-30) that the maximum relative error value depends on two variables, $r_0$ and $\vartheta_0$. If $r_0$ is adopted as a parameter, changing the value of the angle $\vartheta_0$ the area in which the range estimation error will not be greater than the defined maximum value of the relative error $|\Delta r_0/r_0|_{\max}$ can be obtained.

## Range estimation area for the target IR intensity ratio method

For the sake of notation simplification in the rest of the analysis the substitutions

$$k_W = \frac{W(r_2)}{W(r_1)}; \qquad k_C = \frac{c_{\tau 0}}{c_\tau} \quad (31)$$

are introduced, so eq.(19) can be rewritten as

$$r_{0M} = \frac{d}{2}\frac{(k_W k_C)^{1/2} + (\cos\vartheta_0)^2}{(k_W k_C)^{1/2} - (\cos\vartheta_0)^2}\frac{1}{\cos\vartheta_0} \quad (32)$$

In order to simplify the appropriate analysis the value of the coefficient $k_C$ =1 is introduced. So, the maximum relative error due to the measurement errors is defined as

$$\left|\frac{\Delta r_{0M}}{r_{0M}}\right|_m = \left|\frac{\partial r_{0M}/\partial\theta_1}{r_{0M}}\right||\Delta\theta_1| + \left|\frac{\partial r_{0M}/\partial\theta_2}{r_{0M}}\right||\Delta\theta_2| + \left|\frac{\partial r_{0M}/\partial W_1}{r_{0M}}\right||\Delta W_1| + \left|\frac{\partial r_{0M}/\partial W_2}{r_{0M}}\right||\Delta W_2| \quad (33)$$

where

$$\frac{\partial r_{0M}/\partial r\vartheta_1}{r_{0M}} = -\frac{(\cos\vartheta_0)(\sin\vartheta_0)}{k_W^{1/2} + (\cos\vartheta_0)^2} - \frac{1}{2}\frac{(\sin\vartheta_0)[3(\cos\vartheta_0)^2 - k_W^{1/2}]}{(\cos\vartheta_0)[k_W^{1/2} - (\cos\vartheta_0)^2]} \quad (33a)$$

$$\frac{\partial r_{0M}/\partial r\vartheta_2}{r_{0M}} = \frac{\partial r_{0M}/\partial r\vartheta_1}{r_{0M}} \quad (33b)$$

$$\frac{\partial r_{0M}/\partial W_1}{r_{0M}} = \frac{k_W^{1/2}(\cos\vartheta_0)^2}{(W_1 + W_n)[k_W - (\cos\vartheta_0)^4]} \quad (33c)$$

$$\frac{\partial r_{0M}/\partial W_2}{r_{0M}} = -k_W^{-1}\frac{\partial r_{0M}/\partial W_1}{r_{0M}} \quad (33d)$$

$\Delta W_1$, $\Delta W_2$ – the tolerances in the intensity measurement,

$\Delta\vartheta_1$, $\Delta\vartheta_2$ – the tolerances in the measurement of the appropriate angles

Through simulation it is easy to show that the change of the angle $\vartheta_0$ causes different estimations of $r_{0M}$ for the unchanged true distance $r_{0R}$ to the target. Bearing in mind this source of errors, the additional part must be introduced through the definition of the appropriate relative error

$$\left|\frac{\Delta r_{0M}}{r_{0R}}\right| = \left|\frac{r_{0M} - r_{0R}}{r_{0R}}\right| \quad (34)$$

Finally, using eqs.(33) and (34), the relative error maximum value is defined as a sum

$$\left|\frac{\Delta r_{0M}}{r_{0M}}\right| = \left|\frac{\Delta r_{0M}}{r_{0M}}\right|_m + \left|\frac{\Delta r_{0M}}{r_{0R}}\right| \quad (35)$$

From Fig.3 we can conclude that the angle difference $\Delta\vartheta = |\vartheta_2 - \vartheta_1|$ is not greater than 5° for angles $\vartheta_0$<10°, so we suppose that the appropriate error in range estimation due to different target IR radiation along the distances $r_1$, $r_2$ can be neglected.

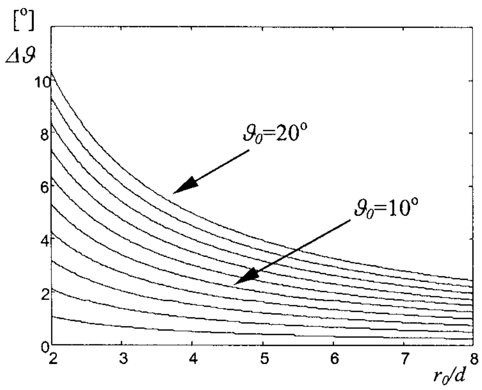


**Figure 3.** The change of $\Delta\vartheta$ relative to the ratio $r_0/d$ and the angle $\vartheta_0$

## The improvement of the target range estimation quality

Next, the sensitivity of the target range estimation $r_{0M}$ to the uncertainties in the ratio of measurement $W(r_2)/W(r_1)$ and the angle $\vartheta_0$ are considered. According to the sensitivity definition, the next expressions are obtained from eq.(32)

$$S_{k_W}^{r_0} = \frac{\partial r_{0M}}{\partial k_W}\frac{k_W}{r_{0M}} = -\frac{(k_W k_C)^{1/2}(\cos\vartheta_0)^2}{[(k_W k_C)-(\cos\vartheta_0)^4]} \tag{36}$$

$$S_{\vartheta_0}^{r_0} = \frac{\partial r_{0M}}{\partial \vartheta_0}\frac{\vartheta_0}{r_{0M}} = = \frac{\vartheta_0 \sin\vartheta_0 [k_W k_C - (\cos\vartheta_0)^4 - 4(k_W k_C)^{1/2}(\cos\vartheta_0)^2]}{\cos\vartheta_0 [(k_W k_C)-(\cos\vartheta_0)^4]} \tag{37}$$

It can be seen, from the above equations, that the sensitivity of the range estimation $r_{0M}$ may be decreased if $k_W$ is increased and $\vartheta_0$ decreased. It is evident that the value of $k_W$ may be increased if the baseline length $d$ is increased. Bearing in mind eqs.(36) and (37), it can be noted that the primary source of errors in range estimation is determined by the variation of $k_W$. Therefore, the appropriate preprocessing of the measurements $W(r_1)$, $W(r_2)$ must be introduced prior to the calculations of the value $r_{0M}$. The well-known linear Kalman filter may be used for this purpose. It is known that the target IR intensity is inversely proportional to the square of its range. So, it is reasonable to adopt intensity and its first and second derivative as a state vector in the process model

$$\boldsymbol{X} = \begin{bmatrix} W & \dot{W} & \ddot{W} \end{bmatrix}^T$$

In this case the prediction equation is expressed as

$$\overline{\boldsymbol{X}}(k+1) = \begin{bmatrix} 1 & T & T^2/2 \\ 0 & 1 & T \\ 0 & 0 & 1 \end{bmatrix} \hat{\boldsymbol{X}}(k) \tag{38}$$

The process and measurement noise are assumed to be zero-mean white Gaussian with the appropriate covariance matrices $\boldsymbol{Q}$ and $\boldsymbol{R}$, respectively, defined as

$$\boldsymbol{Q} = \begin{bmatrix} T^4/4 & T^3/2 & T^2/2 \\ T^3/2 & T^2 & T \\ T^2/2 & T & 1 \end{bmatrix} q \qquad \boldsymbol{R} = [\sigma_{W(r)}^2]$$

where $q$ and $\sigma_{W(r)}^2$ are the variances of the process and measurement noise, respectively. The appropriate measurement equation is

$$\boldsymbol{W}(k) = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix} \hat{\boldsymbol{X}}(k) \tag{39}$$

The filter suggested above requires initialisation for the automatic start. The least squares method [9] utilising n measurements should be employed to obtain the best batch estimate. If we suppose that all measurements, from the instance $t=t_i$ to $t=t_{i-n+1}$ can be described as quadratic time functions with the same initial conditions, the measurement set is defined as

$$\boldsymbol{Z}_n = \begin{bmatrix} z_{t_i-n+1} \\ . \\ . \\ z_{t_i-1} \\ z_{t_i} \end{bmatrix} = \boldsymbol{H}_n \begin{bmatrix} W_{t_i} \\ \dot{W}_{t_i} \\ \ddot{W}_{t_i} \end{bmatrix} \tag{40}$$

where

$$\boldsymbol{H}_n = \begin{bmatrix} 1 & -(n-1)T & -[(n-1)T]^2/2 \\ . & . & . \\ . & . & . \\ 1 & -T & -T^2/2 \\ 1 & 0 & 0 \end{bmatrix} \tag{41}$$

After the processing of n measurements using the least squares method, the initial estimate is obtained in a form

$$\hat{\boldsymbol{X}}_{t_i} = (\boldsymbol{H}_n^T \boldsymbol{H}_n)^{-1} \boldsymbol{H}_n^T \boldsymbol{Z}_n \tag{42}$$

The appropriate covariance matrix of errors in the estimate is of the form

$$\boldsymbol{P}_{t_i} = (\boldsymbol{H}_n^T \boldsymbol{H}_n)^{-1} \boldsymbol{R} \tag{43}$$

where the measurement noise covariance $\boldsymbol{R}$ is assumed to be constant.

## Simulation results

In the intention to compare described methods, the relative estimation errors are examined through simulations, assuming the appropriate tolerances for the angle and the intensity measurements

$$\Delta\vartheta_1 = \Delta\vartheta_2 = 10^{-3} \ \text{[radian]}$$

$$\Delta W_1 = \Delta W_2 = 0.025 W(r_n)$$

Considering that the atmospheric influence is neglected, the intensity of the target radiation is inverse by proportional to the square of the target range. In this way modeling of the intensity ratio variation $k_W$ is significantly simplified. Its value, in the presence of noise, is defined by the equation

$$k_W = \frac{W(r_2)+W(r_n)}{W(r_1)+W(r_n)} = \frac{r_2^{-2} + a r_n^{-2}}{r_1^{-2} + a r_n^{-2}} \tag{44}$$

where $W(r_n)$ and $r_n$ represent the measurement noise and the range when the SNR has the value defined by the coefficient $a$. For example, the model of the SNR=10 dB requests the value $a$=0.1. As it can be seen, the appropriate intensity values are normalised and depend only on the distances $r_1$, $r_2$ and $r_n$. So, the tolerance of the intensity measurements is adopted to be 2.5% of the intensity when the target is at the range $r_n$. The range estimation areas for both methods are presented in Fig.4. The results for the target IR intensity ratio method are obtained assuming the SNR=10dB when the target is at the range $r_n$=10km.

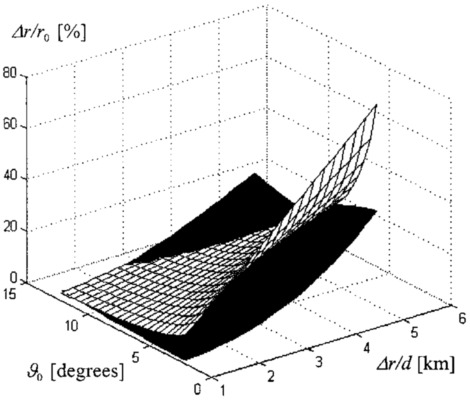


**Figure 4.** Absolute relative error of range estimation versus the angle $\vartheta_0$ and the ratio $r_0/d$ ($d$=2km); mesh surface in the case of the triangulation method; solid surface in the case of the target IR intensity ratio method.

Fig.5 represents the relative errors caused by the form of eq.(19). It is evident that the appropriate relative errors defined by eq.(34) are under 10%. The existence of optimum directions (minimum relative errors) can also be observed in this figure. By comparing Figs.4 and 5 it can be concluded that the main reason for the range estimation errors, in case of the target IR intensity ratio method, are the tolerances of the appropriate measurements.

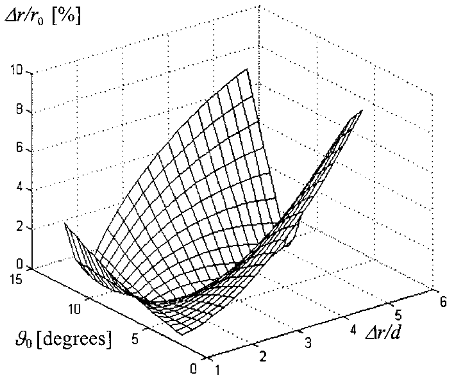


**Figure 5.** Absolute relative error of range estimation due to the form of equation

Fig.6 represents the relative errors in case of two target ranges (solid lines $r_0$=10km, dashed lines $r_0$=6km) assuming the baseline length $d$=2km. In both cases, considerable improvement can be observed if the range estimation is done using the target IR intensity ratio method when the target directions are collinear or nearly collinear relative to the baseline. The variable influence of increasing the SNR in case of different ranges can be noticed in Fig.6. The angle where the relative errors are the same for both methods becomes greater when the SNR is increased in case of the range $r_0$=10km. In case of the range $r_0$=6km the opposite is obtained. Bearing in mind the form of the diagram in Fig.5 it can be concluded that it is a consequence of equation form (19). The number of appropriate relative errors can be 2-4 times smaller (according to the target range and direction) if the target IR intensity ratio method is used in the range estimation process for the angles $\vartheta_0$ = 2-4 degrees. The results in Figs. (4-6) are obtained assuming that the minimum sensor aspect angle is 2 degrees relative to the horizon. In case of smaller angles, any other object on the horizon can be viewed as a target.

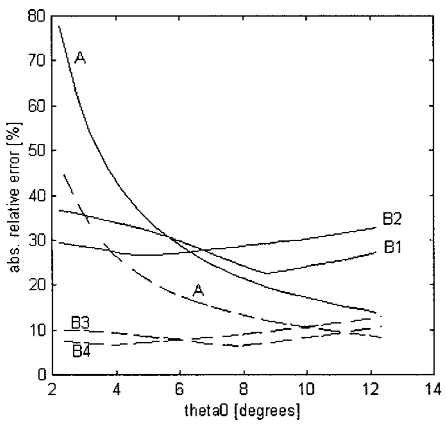


**Figure 6.** Absolute relative range estimation error versus the angle $\vartheta_0$; solid line presents the results when the target is at the range $r_0$=10km, and dashed line when it is $r_0$=6km; the triangulation method is signed as (A); in the case of the target IR intensity ratio method it is (B1-B4); in the cases (B1, B3) it is assumed that the SNR=10dB can be obtained when the target is at the range $r_n$=10km; in the case that the SNR=10dB can be obtained when the target is at the range $r_n$=20km the appropriate results are presented by (B2, B4)

With the intention to present a tracking ability of the system when the target directions are collinear or nearly collinear relative to the baseline, a flying of the target at a rate of 250 m/s, in the horizontal plane, from the point C(x,y,z) = (0.1,5,-0.1)km in a course with the angle of -91° relative to the x-axis was simulated. It is obvious that its course is nearly collinear with the y-axis direction of the coordinate system. The IR sensors are placed at the positions with the coordinates $S_1$(x,y,z)=(0,0,0)km and $S_2$(x,y,z) = (0,2,0)km. The simulation interval is chosen to be 3s with a sampling period assumed to be 20 ms. The noise energy is assumed to be at the level of 10 % of the target energy at a distance of 10 km relative to the sensor $S_1$.

The analysis of the quality of the target range estimation relative to the middle of the baseline is based on the error defined as an absolute value of differences between the estimated $r_{0M}$ and the true distances $r_0$

$$\Delta r = \left| r_{0M} - r_0 \right| \tag{45}$$

From Fig.7 it can be seen that the target range estimation is better if the coefficient $c_{r0}$ is introduced as in eq.(19).

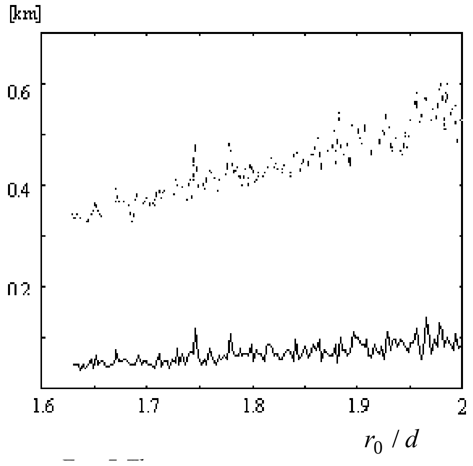


**Figure 7.** The target range estimation error, a) in the case without $c_{r0}$ (dotted line), b) in the case when the coefficient $c_{r0}$ is introduced (solid line)

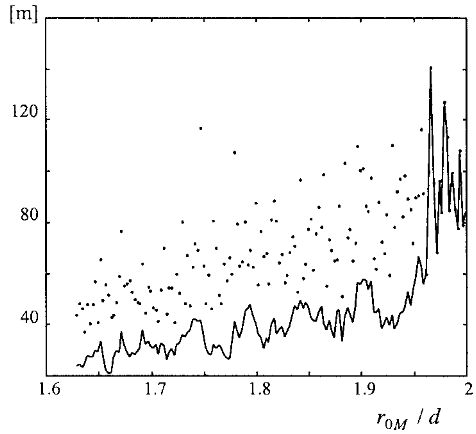


**Figure 8.** The improved target range estimation error, a) without the preprocessing of intensity measurements (dotted line), b) when the linear Kalman filter is used for the preprocessing of intensity measurements (solid line)

Fig.8 presents the mean value of the error defined by eq.(44)

$$E\{\Delta r\} = \frac{1}{n} \sum_{i=1}^{n} \Delta r_i \tag{46}$$

that is obtained through the Monte Carlo simulations (30 runs have been made). It is assumed that both coefficients, $c_{\tau 0}$ and $c_\tau$, are identical. The similar results are obtained if a small difference between these coefficients exists. It has to be mentioned that the divergence of the presented diagram in Fig.5 will be smaller if the condition ($c_{\tau 0} > c_\tau$) is satisfied. In the opposite case, when ($c_{\tau 0}<c_\tau$), a greater divergence relative to the presented diagram would be obtained [6].

## Conclusion

The use of passive sensors enables hidden target detection and tracking in the air space. However, in a situation when target directions are collinear or nearly collinear to the baseline, there is a problem known as geometrical dilution of precision (GDOP), and the triangulation method gives unacceptable range estimation errors. This problem can be overcome if full potential of passive IR sensors is explored. In case of the triangulation method only the measurement of the appropriate angles is used for the target range estimation. Considering that the tracking process is based on the target IR signature, the measurements set can be extended by the appropriate intensity measurements of the target IR radiation. Bearing in mind the extended measurements set, a new range estimation method is defined. According to the achieved simulation results, we suggest the application of this method in situations when target directions are collinear or nearly collinear to the baseline. As it can be seen from simulations, in these situations, the number of appropriate relative errors can be 2-4 times smaller, depending on the target range and direction, relative to the triangulation method.

It can be concluded that the target range estimation based on its IR intensity represents a complementary solution relative to the principle of triangulation. With this in mind, both of them, the suggested method and the principle of triangulation, have to be combined to get the extended tracking area. In the situations when the target IR intensity ratio is used for range estimation, the results are influenced by instantaneous atmospheric conditions. Better results can be obtained if an appropriate preprocessing of measurements $W(r_1)$, $W(r_2)$ is applied using, for example, the linear Kalman filter.

## References


[1] DUFOUR,F., MARITON,M. Tracking a 3D manoeuvring target with passive sensors. *IEEE Transactions on Aerospace and Electronic Systems*, July '91., pp.725-738.

[2] DIKIĆ,G., KOVAČEVIĆ,B. *Target tracking with passive IR sensors.* Proceedings of 5th International Conference on Telecommunications in Modern Satellite, Cable and Broadcasting Services, TELSIKS 2001, Nis, Yugoslavia, 2001, pp.745-748.

[3] OVREBO,J.P., WOOD,R.C. *Apparatus for passive infrared range finding.* U. S. Patent 3,103,586, Sept. 10. 1963.

[4] JENNES,J.R., SHIMUKONIS,F.J. *Apparatus for passive infrared range finding.* U.S. Patent 3,117,228, Jan. 7. 1964.

[5] PIEPER,J.R., COPER,A., PELEGRIS,G. Passive range estimation using dual-baseline triangulation. *Optical Engineering,* march 1996, vol.35, no.3, pp.685-692.

[6] DIKIĆ,G., RADOSAVLJEVIĆ,Z. *Target range estimation based on the intensity of its IR radiation.* Proceedings of IX Telecommunications Forum, Belgrade, Yugoslavia, 2001, pp.489-492.

[7] BLOM,H.A.P., BAR-SHALOM,Y. The Interacting multiple model algorithm for systems with Markovian switching coefficients. *IEEE Transactions on Automatic Control*, August '88.

[8] DRIGERS,R.G., COX,P., EDWARDS,T. *Introduction to opto-electronic systems.* Artech House, 1999.

[9] LJUNG,L., SODERSTROM,T. *Theory and practice of Recursive Identification,* Cambridge, MA: M.I.T Press, 1983.


Received: 29.11.2002

# Poboljšanje sistema za praćenje cilja pomoću pasivnih IC senzora smeštenih na krajevima bazne linije

**U radu je opisan postupak procene daljine na osnovu količnika intenziteta IC zračenja izmerenog pomoću pasivnih senzora koji su smešteni na krajevima bazne linije. Predloženi metod se uvodi u situaciji kada su smerovi cilja količine kolinearni ili približno kolinearni u odnosu na baznu liniju pa se ne može primeniti princip triangulacije za procenu daljine. Na osnovu obavljenih simulacija se vidi da odgovarajuće relativne greške mogu biti 2-4 puta manje, zavisno od pravca i daljine cilja, ukoliko se procene daljine cilja dobijaju na osnovu količnika intenziteta njegovog IC zračenja. Metod koji je prikazan u ovom radu predstavlja komplementarno rešenje u odnosu na princip triangulacije. U situaciji kada se praćenje cilja ostvaruje pomoću dva IC senzora, treba primeniti oba metoda kako bi se dobila proširena zona praćenja.**

*Ključne reči:* **pasivni IC senzori, praćenje cilja.**

# Amélioration des systèmes passives d'estimation de distance à une ligne de base en utilisant le taux de l'énergie IR de la cible

**Le papier présente une estimation passive de distance à l'aide du taux de l'énergie infraruge absorbé par les capteurs positionés au bout de la ligne de base. Cette méthode est adoptée quand les directions de cibles sont colinéaires où presque colinéaires par rapport à la ligne de base et quand le principe de triangulation ne peut pas être appliqué. Les simulations démontrent que les erreurs relatives appropriées sont 2-4 fois moins nombreuses, suivant la distance et la direction de la cible, si l'estimation de la direction est basée sur le taux de l'énergie IR de la cible. La méthode est complémentaire avec le principe de triangulation et tous les deux doivent être utilisés quand il n'y a que deux capteur IR passifs pour la poursuite de la cible. La zone de poursuite étendue est ainsi obtenue.**

*Mots-clés*: **capteur IR passif, poursuite de la cible.**