PROBLEMY MECHATRONIKI
UZBROJENIE, LOTNICTWO, INŻYNIERIA BEZPIECZEŃSTWA

ISSN 2081-5891 **8, 3 (29), 2017, 95-108**

PROBLEMS OF MECHATRONICS
ARMAMENT, AVIATION, SAFETY ENGINEERING

Proving Ground Testing of an Anti-Aircraft Artillery Evaluation System

Jan PIETRASIEŃSKI, Dariusz RODZIK*, Stanisław GRZYWIŃSKI, Jakub MIERNIK

Military University of Technology, Faculty of Mechatronics and Aerospace
2 gen. S. Kaliskiego Street, 00-908 Warsaw, Poland
* *Corresponding author's e-mail address: dariusz.rodzik@wat.edu.pl*

Received by the editorial staff on 6 July 2016.
The reviewed and verified version was received on 25 February 2017.

DOI 10.5604/01.3001.0010.4114

Abstract. This paper is an elaboration of the design, operating principle, and a selection of proving ground test results of an anti-aircraft artillery acoustic evaluation system. The correct location of projectiles in flight with the acoustic detection and tracking method was verified with a specially designed optical firing observation system (OFOS).
Keywords: metrology, acoustic locator, optical head

1. INTRODUCTION

The Military University of Technology has completed a development project for the security and defensive capability of Poland titled *Development of an anti-aircraft artillery evaluation system* and financed with the funds of Polish National Centre for Research and Development 2012-2016.

This work has been compiled from the paper presented during the 11th International Armament Conference on Scientific Aspects of Armament and Safety Technology, Ryn, Poland, September 19-22, 2016.

The essence of this project was to develop a mobile air defence shield capable of determining the spatial coordinates of mid-flight projectiles around an Air Target (AT) [1, 2].

The correct operating performance of this air defence shield was verified during combat fire missions of air defence units at the Central Air Force Testing Grounds (Ustka, Poland), between 8 and 11 March 2016.

The objective of this paper is to present a selection of proving ground test results for an anti-aircraft artillery acoustic evaluation system, henceforth referred to as "TP".

2. DESIGN AND OPERATING PRINCIPLE OF THE TP SYSTEM

The TP system has been designed for the detection and determination of flight coordinates of projectiles relative to an AT position, real-time visualisation of fire mission results, and recording of fire missions.

2.1. Design of the TP system

The developed TP system comprises two main components (Fig. 1):

- an acoustic locator with a mobile section of the RF link;
- a ground unit with the stationary section of the RF link.

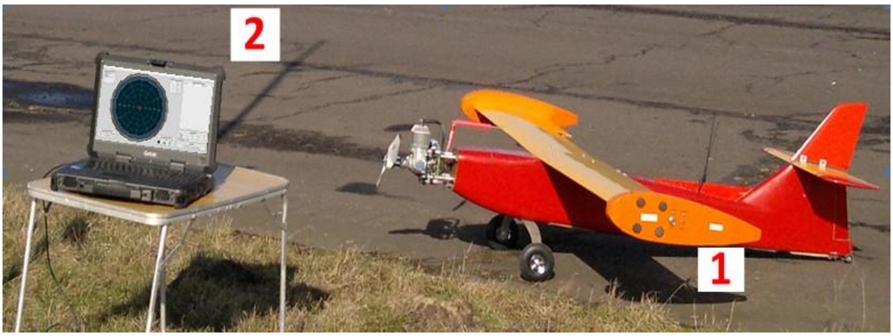

Fig. 1. Main system components: the acoustic locator (1); the ground unit (2)

The acoustic locator (AL) detects and measures the parameters of sound pressure waves generated by the supersonic movement of projectiles in mid-flight. The Air Force Institute of Technology (Warsaw, Poland) built an AT called "EKO 3" for the purpose of the project. The AL was installed on EKO 3.

The ground unit (GU) is the receiver and processor of the telemetry data of the sound pressure waves transmitted from the AL to the GU via an RF link. The GU then calculates the coordinates of the projectiles in flight relative to the AT.

The TP system is supervised, monitored and controlled by a dedicated software package installed on a PC of the GU to manage the TP system, determine the fire mission effects on the AT, and visualise, record and print the fire mission results.

2.2. Operating principle of the TP system

The operating principle of the TP system is shown with the functional diagram in Fig. 2.

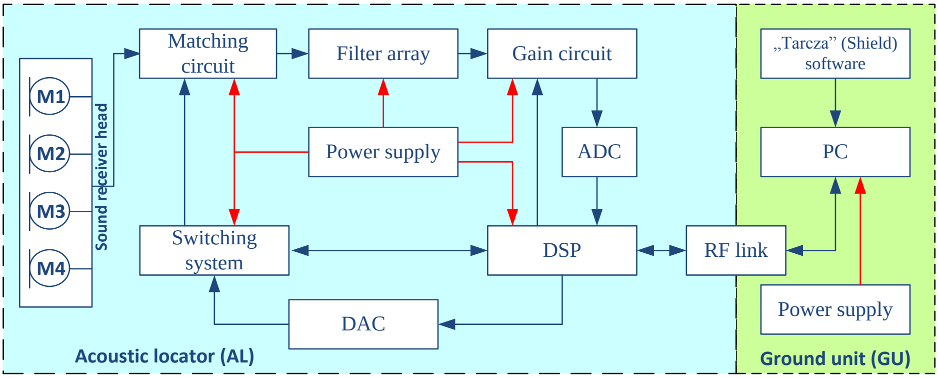

Fig. 2. Functional diagram of the TP system:
→ – data; → – power

The interference caused by sound pressure waves are detected by the sound receiver head of the AL. The sound receiver head features an array of measurement sensors. The measurement sensor outputs are data signals which are filtered, amplified and converted to digital data which is then processed by the signal CPU. The CPU applies a detection algorithm to seek in the registered signal data the characteristic properties of interference patterns generated by projectiles flying at supersonic speeds. If an interference pattern is found in the data, the CPU attempts to analyse the parameters of the detected interference. The data input to the CPU is classified to verify that the data signals match the preprogrammed interference patterns, or acoustic signatures. Next, the CPU encodes the determined sound pressure wave parameters and relays them over the RF link to the GU. The GU is tasked with measurement data acquisition and the estimation of the angular and distance coordinates of the detected projectiles relative to the AT. Based on this, the GU develops an evaluation of the fire mission, with the results and the evaluation score displayed on the PC screen.

Technical specification of the TP system:

– AL weight:	< 1.5 kg;
– Detected projectile calibres:	14.5-57 mm;
– Maximum firing rate:	600 shots/min.;
– Projectile detection range radius:	15 m;
– Distance measurement error:	5%;
– RF link range:	5 km;
– Time to deploy in standby:	1.5 h;
– Time to resume standby:	0.5 h.

3. PROVING GROUND TESTING OF THE TP SYSTEM

The objective of proving ground tests was to evaluate the correct performance of the applied design, functional and utility solutions, and to test the operation of the TP system under training ground conditions of fire missions.

3.1. Verification methodology of the TP system performance

The proving ground test consisted of determining the coordinates of the AT in flight and the coordinates of the projectiles fired by an anti-aircraft gun with the aid of the OFOS, followed by comparison of the OFOS-derived results with the results derived from the TP system.

The basic geometrical variables and relationships of this verification method are shown in Fig. 3.

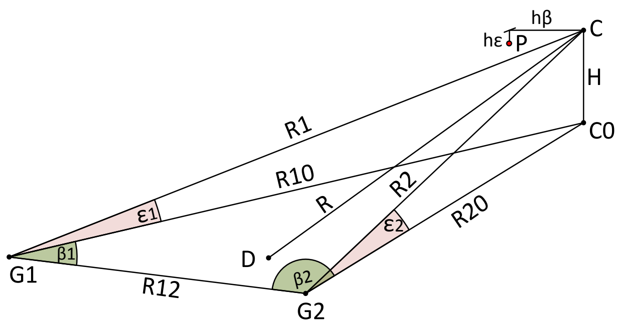

Fig. 3. Designations and geometrical relationships of the applied verification method: G1, G2 – OFOS optical head; C – AT point; C0 – horizontal projection of the AT point; D – anti-aircraft gun; P – projectile; H – altitude; h_β, h_ε – horizontal and vertical offset; R, R1, R2, R10, R12, R20 – distances between the characteristic points; β_1, β_2 – azimuth angle of the OFOS optical head; ε_1, ε_2 – elevation angle of the OFOS optical head

The distance R12 between G1 and G2 is the system baseline. The coordinates of a projectile and the AT were determined in relation to the local coordinate system of each OFOS optical head. The local coordinate system is related to the direction of the system baseline and the horizontal plane.

The determination accuracy of the flying projectile distance Δr_{TP}, is determined by the TP system. The determination accuracy was derived from the following relationship:

$$\Delta r_{TP} = r_{TP} - r_G, \tag{1}$$

where:

r_{TP} – the distance of the flying projectile determined by the TP system;

r_G – the distance of the flying projectile determined by the OFOS.

The images of the AT and the projectile registered by the OFOS optical heads were used to determine the angular offset $\Delta\beta$ and $\Delta\varepsilon$ of the flying projectile with the following relationships:

$$\Delta\beta = \Delta\beta_o/f \cdot \Delta x/a \tag{2}$$

$$\Delta\varepsilon = \Delta\varepsilon_o/f \cdot \Delta y/b \tag{3}$$

where:

$$\Delta x = x_p - x_{AT}, \quad \Delta y = y_p - y_{AT}, \tag{4}$$

- x_{AT}, y_{AT}, x_p, y_p – the determined coordinates of the AT and the projectile (Fig. 4):
- $\Delta\beta_o$, $\Delta\varepsilon_o$ – OFOS-head focal length dependent angles;
- f – OFOS lens focal length aspect ratio;
- a, b – horizontal and vertical resolution of the OFOS head optical array.

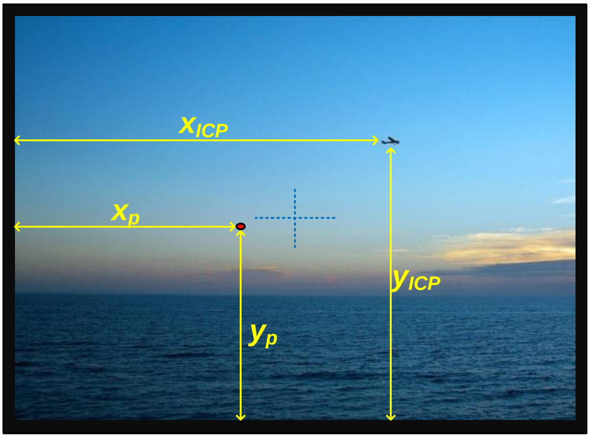

Fig. 4. The adopted principle of determining the coordinates of the AT and the projectile in the images recorded by the OFOS optical head

The offsets h_β and h_ε of the flying projectile were determined with the following relationships:

$$h_\beta = \Delta\beta \cdot r_G \text{ [m]} \tag{5}$$

$$h_\varepsilon = \Delta\varepsilon \cdot r_G \text{ [m]} \tag{6}$$

The flying projectile distance r_G to the AT is equal to:

$$r_G = r_r = \sqrt{h_\beta^2 + h_\varepsilon^2} \text{ [m]} \tag{7}$$

3.2. Optical firing observation system (OFOS)

The OFOS was developed to verify the determination accuracy of the TP system for the coordinates of flying projectiles relative to the AT as the target of the projectiles. Specifically, the OFOS is intended to:

- record the AT image;
- determine the AT flight trajectory;
- record the trace images of AA gun projectiles;
- determine the AT firing offset.

The OFOS is a portable device, comprising two optical heads and a portable PC, as shown in Fig. 5.

Fig. 5. View of the optical head with the portable PC (7): lens (1); camera (2); display (3); pan and tilt mechanism (4); angle reading system (5); tripod (6)

Each OFOS optical head comprises the lens, a slow-motion camera, a display, a pan and tilt mechanism, an angle reading system, a tripod, a power adapter, and a wiring kit. Each OFOS optical head may have its lens replaced with another; the lens selection depends on the distance of the objects to be monitored and the required image resolution of the OFOS optical head. The real-time image from the OFOS optical heads is displayed on a generic 10" VGA display screen. Each OFOS optical head is oriented with a three-motion axis mechanism (Fig. 6).

An important component of each OFOS optical head is the angle reading system which reads the pan and tilt axis angles. The angle reading system includes two rotating encoders with a resolution of 5000 pulses/revolution, installed on the pan and tilt axes, and an instantaneous pan/tilt angle decoder (Fig. 7). During operation of the OFOS optical head (i.e. observation of various visual targets), the camera's optical angle position is relayed to a microchip controller of the OFOS optical head.

Fig. 6. MN400 pan and tilt mechanism [3]

Fig. 7. Hohner series 59 encoders

The portable PC helps program the operating conditions of the OFOS optical head camera, record images, control the OFOS optical head work modes, and monitor the operating status of the OFOS optical head. The portable PC is equipped with a software package for post-processing of the recorded visual measurement data in order to estimate the coordinates and determine the trajectories of the AT and projectiles. The end result of these post-processing calculations are the linear offsets h_β and h_ε for firing at the AT.

3.3. Test conditions and course

During the test, the telemetric data output by the TP system was recorded with the images generated by the OFOS cameras, and the flight parameters stored in the AT autopilot memory module. The recorded data helped to determine the coordinates of the projectiles, and the flight paths and profiles of the AT.

Figure 8 shows a test deployment layout of the ZU-23 anti-aircraft (AA) gun, the TP system GU, and the OFOS (G1 and G2).

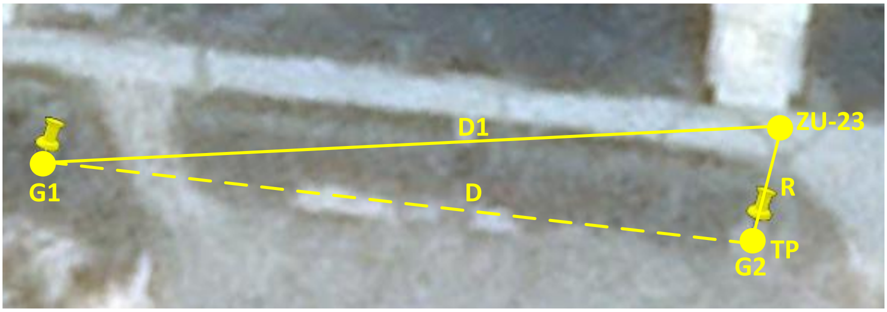

Fig. 8. Test deployment layout of the ZU-23, the TP GU and the OFOS optical heads

The distances marked in Fig. 8 were, respectively: D = 75.2; D1 = 78.5 and R = 16.4 m. The GPS-derived coordinates of the AA gun and the OFOS cameras are shown in Table 1.

Table 1. GPS coordinates of the test deployment layout

Object	Latitude	Longitude
G1	54˚ 33’ 54.3310”	16˚ 39’ 58.8482”
G2	54˚ 33’ 54.6333”	16˚ 40’ 3.2514”
ZU-23	54˚ 33’ 54.9355”	16˚ 40’ 3.3433”

The altitude of the AT was determined with this GPS data to be at 255 ± 3 [m] in the combat flight firing zone. A total of 40 projectiles were fired during the combat flights. The OFOS recorded 7 tracers. The TP system detected 23 projectiles and determined their coordinates.

The test results produced were complemented by the 23 mm calibre projectile characteristics (Fig. 9 and 10) [4] that were used to determine the time a projectile took to reach a defined distance.

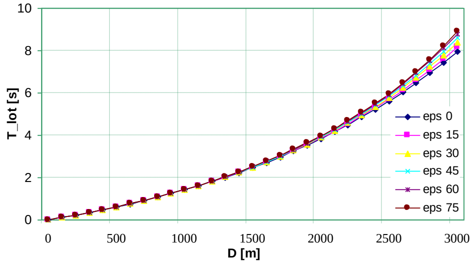

Fig. 9. Time a 23 mm calibre projectile took to reach distance D

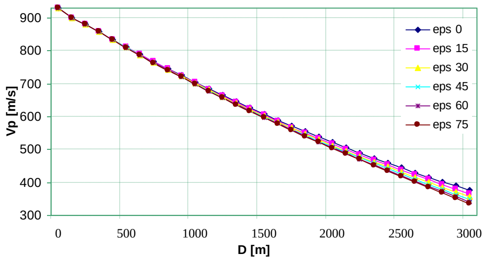

Fig. 10. 23 mm calibre projectile velocity vs. distance D

3.4. Fire mission recording results for the OFOS

The combat flights were recorded at 100 frames per second by both OFOS optical heads equipped with 200 mm focal length lenses. Due to the unfavourable lighting conditions during the tests, the recorded images of the AT and the projectiles provided poorly discernible details. It was necessary to post-process the images with accumulative filters that accounted for the projectile kinematics. This procedure enabled the detection of the images of the projectiles in flight and provided the location of the projectiles in relation to the AT. Figure 11 shows examples of the recorded frames.

a) b)

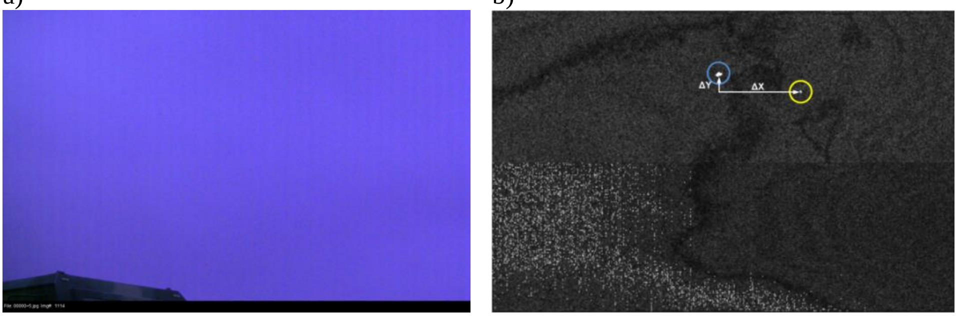

Fig. 11. A selected video frame recorded by the OFOS optical head during the tests: (a) original recorded frame; (b) the recorded frame after accumulative filtering; O – AT; O – projectile

For the projectile images, the times of tracer ignition were determined, which helped determine the projectile distance from the AA gun at the time of tracer ignition, and the AT firing azimuth values AT β_x for each recorded projectile.

Given the determined AT firing azimuth values β_x, the AT flight coordinates recorded in the AT autopilot memory module were determined, from which the distance values *R* were determined for the distance between the AA gun and the AT. With the projectile velocity and the distance to tracer ignition known, the video frames corresponding to the distance *R* were identified. The relative positions of the AT and the projectile in each identified video frame helped determine the offset angular components ($\Delta\beta$ and $\Delta\varepsilon$) of the projectile flight path relative to the AT. Given the distance *R*, the linear offset values (h_β and h_ε) were determined for the projectile flight path. The determined values are listed in Table 2.

Table 2. Results of the ATS fire mission produced with the OFOS

Fire mission parameters	Projectile number						
	1	2	3	4	5	6	7
β_x [˚]	10,0	15,1	40,4	39,8	33,7	14,2	13,8
R [m]	804,9	828,8	1121,5	1115,7	998,7	815,4	813,2
h_β [m]	20.4	22.8	4.5	20.1	9.1	-8.0	3.3
h_ε [m]	-4.3	1.6	-3.9	-14.0	-14.5	-6.3	-6.2
r_{GO} [m]	20.9	22.9	5.9	24.5	17.1	10.2	7.0

3.5. Recording results for the TP AL

The AT fire mission results recorded with the TP system were displayed in real time on the GU PC screen.

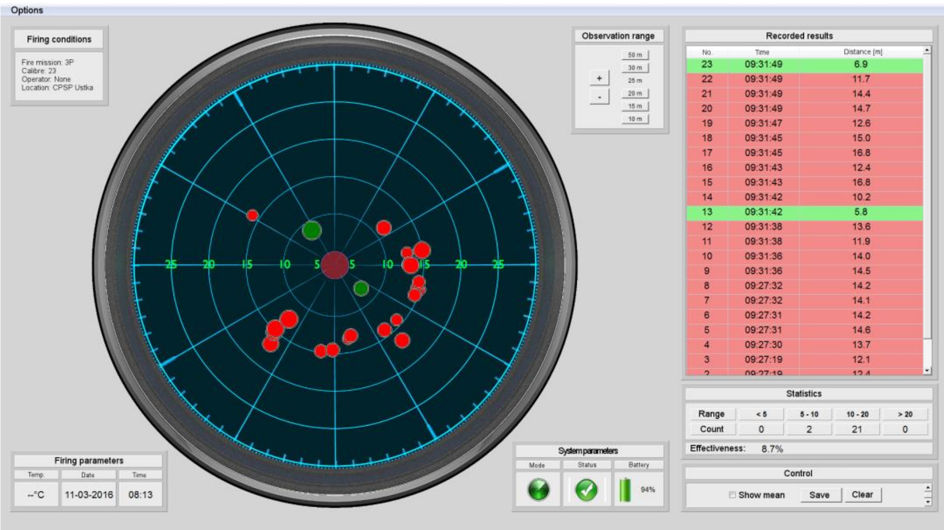

Fig. 12. Results of the TP system indications in the “Tarcza” software package [5]

The major part of the PC screen was occupied by the firing result visualisation pane in the form of a type P scope, which displayed virtual "bullet holes" for each detected projectile. The flying projectile coordinates were also displayed in an on-screen table in the Recorded Results pane. This table listed the sequential numbers of recorded projectiles, the time of detection, and the projectile distance to the AT.

The proving ground test results recorded by the TP system are shown in Fig. 12.

3.6. Comparison of the proving ground test results

The TP system detected 23 projectiles in total and determined their coordinates. All projectiles detected by the OFOS and within a distance to the AT that was less than the TP system detection range were detected by the TP system. Table 3 lists 4 pairs of projectile traces detected by the TP system and the OFOS at the same time.

Table 3. Pairs of simultaneous projectile traces detected by the OFOS and the TP system

OFOS	Projectile 3	Projectile 5	Projectile 6	Projectile 7
AL	Projectile 13	Projectile 15	Projectile 22	Projectile 23

Table 4 lists the values of the linear offsets h_β and h_ε with the distance of projectile flyby (miss) to the AT ($r_r = r_G$) for the grouped projectile trace pairs.

Table 4. Comparison of the AT firing results from the OFOS and the TP system

	h_β [m]	h_ε [m]	$r_r = r_G$ [m]	β [°]
OFOS (3)	4.5	-3.9	5.9	-41
AL (13)	4.4	-3.7	5.8	-40
OFOS (5)	9.1	-14.5	17.1	-58
AL (15)	10.8	-12.9	16.8	-50
OFOS (6)	-8.0	-6.3	10.2	-142
AL (22)	-8.8	-7.7	11.7	-139
OFOS (7)	-3.3	6.2	7.0	-62
AL (23)	3.6	-5.9	6.9	-59

(x) – recorded projectile number

4. COMPARISON OF THE PROVING GROUND TEST RESULTS

The TP system showed 100% effectiveness in the detection of the projectiles in flight at distances within the TP system detection range. All detected projectiles had their distance and angular coordinates determined. The proving ground tests found that the determination accuracy of projectile flight coordinates is better than 5%.

The practical application of the development project deliverables provide a new means for assessing and evaluating air defence fire missions. This may be a key component of training verification for military units, operators, and artillery crews during training range fire missions involving air defence against air targets. The anti-aircraft artillery assessment system enables the detection and determination of the coordinates of projectiles in flight and within a calibre range up to 57 mm. Moreover, the anti-aircraft artillery acoustic evaluation system provides statistical data about fire mission effectiveness results as required for a cumulative assessment of fire mission performance. The anti-aircraft artillery acoustic evaluation system may be used during the firing range missions of the air defence artillery units of the Army, the Air Force, and the Navy.

The paper contains the results of research work financed by the Polish National Centre for Research and Development 2012-2016.
Scientific Fund, Project no. O ROB 0068 03 01

REFERENCES

[1] Rodzik Dariusz i inni. 2016. *Sprawozdanie końcowe z realizacji projektu rozwojowego nr O ROB 0068 03 01 pt. „Opracowanie systemu oceny strzelań do celów powietrznych”*. Warszawa: Wydawnictwo Wojskowej Akademii Technicznej.
[2] Podciechowski Maciej, Dariusz Rodzik, Stanisław Żygadło. 2014. Przegląd metod i rozwiązań technicznych systemów oceny strzelań do celów powietrznych. *Materiały VIII Konferencji Naukowej nt. Kierowanie ogniem systemów obrony powietrznej (przeciwlotniczej) KOSOP 2014*. Gdynia: Wydawnictwo AMW, 95-108.
[3] http://www.cyfrowe.pl/aparaty/manfrotto-400-glowica-z-przekladniami-zebatymi.html/2016
[4] Pietrasieński Jan, Dariusz Rodzik, Stanisław Grzywiński, Paweł Siergiejuk. 2013. „Wyznaczanie współczynników kierunkowych charakterystyk ruchu pocisków w badaniach symulacyjnych fali typu *N*”. *Mechanik* 86(7) : 659-666.

[5] Rodzik Dariusz, Jan Pietrasieński, Stanisław Grzywiński, Jakub Miernik. 2016. „Komputerowe wspomaganie procesu oceny strzelań do celów powietrznych". *Mechanik* 89(7) : 810-811.

Badania poligonowe Systemu Oceny Strzelań do Celów Powietrznych

Jan PIETRASIEŃSKI, Dariusz RODZIK, Stanisław GRZYWIŃSKI, Jakub MIERNIK

Wojskowa Akademia Techniczna, Wydział Mechatroniki i Lotnictwa
ul. gen. S. Kaliskiego 2, 00-908 Warszawa

Streszczenie. W pracy omówiono budowę, zasadę działania i wybrane wyniki badań poligonowych akustycznego systemu oceny strzelań do celów powietrznych. Do weryfikacji poprawności metody akustycznej lokalizacji pocisków wykorzystano specjalnie zaprojektowany optyczny zestaw obserwacji strzelań.

Słowa kluczowe: metrologia, lokator akustyczny, głowica optyczna