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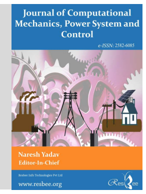

An Improve Sensor of Earth for Satellite Attitude

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Abstract: The earth horizon sensor is one of the fundamental instruments in the satellite navigation system. This sensor is required to simulate the satellite control system and to determine the satellite direction; hence, Pyroelectric detectors are employed to achieve this target. In this paper, the physical model of a Pyroelectric detector and the mathematical model of an earth horizon sensor are presented to simulate a satellite. Pyroelectric detectors are applied to calculate the step response and Field Of View (FOV), which are significant parameters to recognize the earth's horizon. To improve the detection of objects at far distances from the detector, FOV should be as small as possible. The evaluation of the device has been performed through the use of a test system that allows sensor performance to be determined. The observed results show the optimal value of FOV has decreased up to 50°. The modeling results verified that the Pyroelectric detectors are feasible to achieve functional requirements.

Keywords: Earth Horizon Sensor, Field of view, Infrared Radiation, Pyroelectric Detector, Satellite Sensor, Step Response

1. Introduction

Earth horizon sensors (EHSs) are required to determine the position of the spacecraft based on the earth's horizon and center of the earth. EHSs were often applied as a closed-loop control in the automatic control system. Additionally, these sensors used radiations between cold space (black body at a temperature of about 4°K) and the heat of the earth's horizon (black body at a temperature of about 233°K and wavelength of 15 µm) [1, 2] since those are infrared devices. Thermal detectors and photon detectors can be used to scan the earth's horizon. Thermal detectors are preferred due to their advantages. There are several types of thermal detectors including thermopile detectors, Pyroelectric detectors, and bolometers. Firstly, it is stated that the Pyroelectric effect was the best replacement for thermopiles and thermistors [3]. Generally, Pyroelectric detectors make use of moving parts to detect the earth's horizon [4]. Recently, earth sensors were employed based on thermopile detectors to determine the attitude of satellites [5].

Several researchers put forward how Pyroelectric infrared detectors have been widely applied for human detection and optical sensors [6, 7]. Pyroelectric infrared sensors have some advantages including low cost and high- performance to detect infrared radiation at 300° K (room temperature); in addition, these detectors have not required any expensive cooling system [8-10].

In order to determine the situation of the spacecraft in outer space, several references are required including the sun, earth, moon, and stars. Complex calculations according to reference's movement in space need to deduce the certain location of these objects. Earth, the sun, and a sample of stars are more interested to design the satellite control part since they are practically applied as a reference in space. In addition, the most operated satellites are deployed on the earth; hence, the application of earth sensors, especially earth horizon recognition sensors, has more attractive.

In this research, a satellite sensor was simulated based on Pyroelectric detectors. At first, the physical model of Pyroelectric detectors was examined; following that, the mathematical model of the earth's horizon was considered. Finally, the earth horizon sensor was simulated while the Pyroelectric detector was implemented. This model was applied in the simulation of satellite control systems.

Two significant parameters to determine the performance of the detector are step response and field of view of the detector, which is computed. Additionally, satellite sensors have been simulated by means of several detectors with mechanical parts which make them bulky, heavy, inexpensive, and inconvenient in space applications. The reason why the Pyroelectric detector was used in this research was that its advantages include being inexpensive, fast, and robust. Furthermore, Pyroelectric has not required any mechanical parts.

2. Research Methodology

This section elaborates on the pyroelectric detectors and mathematical models of earth horizon sensors.

2.1 Pyroelectric Detectors

Pyroelectric detectors have been attractive in several industries [11, 12] in addition to medical applications [13]. Today, these detectors were applied as the sensing element in space technologies [14, 15]. Generally, Pyroelectric detectors respond to the discrepancy in Infrared Radiation (IR) flux. This was the main limitation of Pyroelectric sensors since several instruments, including one optical chopper [16], scanning mirror [17], and more mutual among these systems, were required to detect the continuous radiation. All of these instruments need mechanical parts, which makes them huge, weighty, expensive, and inconvenient to use in space. To overcome this issue, Orvatinia and Heydarianasl [3] presented a system. In that system, Pyroelectric detectors were applied without any mechanical parts and just based on alternative cooling and heating of the detector. To achieve this target, one Peltier cooler was used that transfers heat from one side to another side when a direct current passes through it. The physical model of Pyroelectric detector system is depicted in Fig. 1. In this model, a hot object was fixed in front of the Pyroelectric sensor; on the other hand, alternative side of sensor was connected to upper level of Peltier cooler. Hot object leads to sensor was heated while the upper level of Peltier cooler is cooled by applying current. The temperature difference was created by the hot object and the Peltier cooler. As mentioned earlier, the proposed model is sensitive to temperature differences instead of connecting and disconnecting light or moving a hot object. A power supply is used to launch the system. Furthermore, the output signal of Pyroelectric detectors is very little, about 1 mm, and needs an amplifier. The signal conditioning circuit to amplify the output signal of the pyroelectric detector is depicted in Fig. 2. The output signal is amplified; then, is monitored by an oscilloscope.

In the current study, Pyroelectric detectors are applied to detect the earth's horizon which is significant to simulate the satellite sensor.

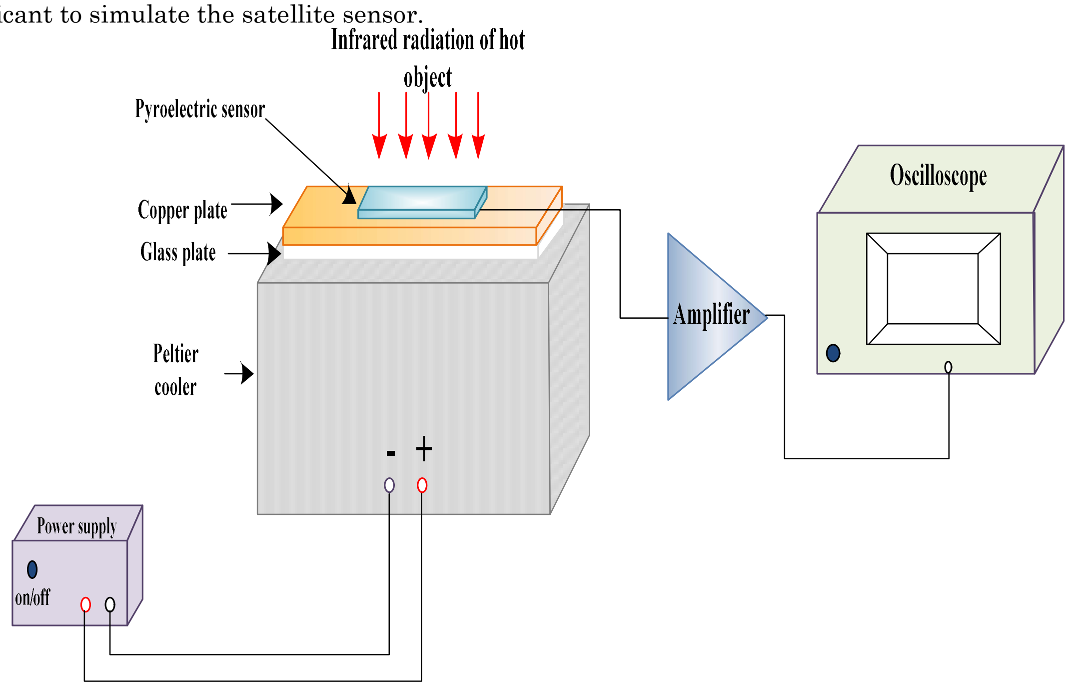

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Fig.1. *Physical Model of Pyroelectric Detector System*

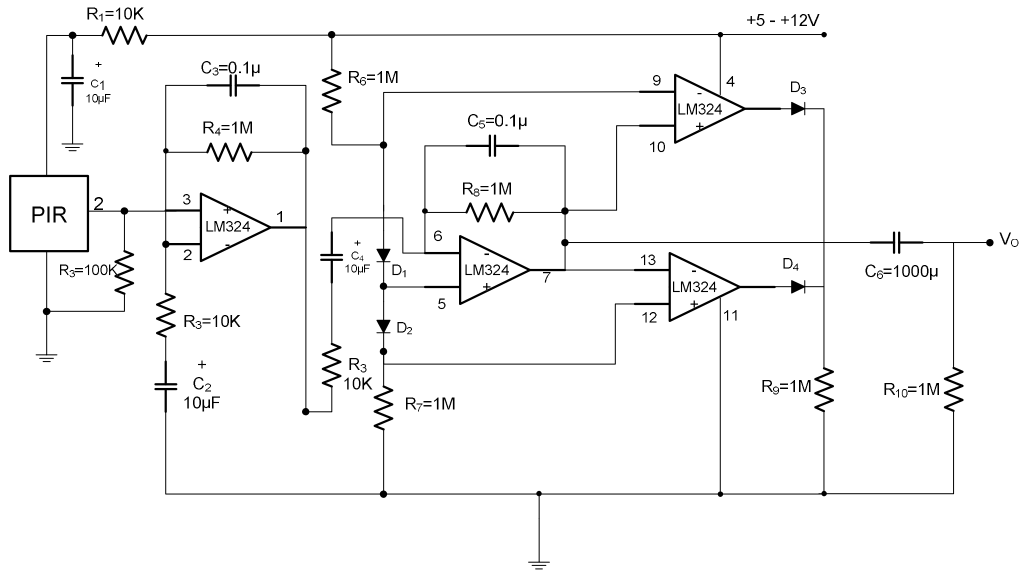

Fig.2. *Signal Conditioning Circuit to Amplify the output signal of Pyroelectric Detector*

2.2 Mathematical Model of Earth Horizon Sensor

One of the main reasons why the navigation of satellites is required is enhanced accuracy. EHSs have been applied as the major devices in the navigation of satellites. The really necessary information through sun and star sensors could be provided by the EHSs to establish the location of the satellite in space. The performance of this instrument was based upon identifying the earth as a spherical warm object in cold space and unbounded space from Infrared Radiation (IR). The earth could be recognized by control algorithms. After that, the center and horizon of the earth were also determined. Regarding the temperature difference between earth and unbounded space, several thermal infrared detectors including thermopile, bolometer, and Pyroelectric, were appropriate for the sensitive parts of the device. Earth horizon sensors are mathematically modeled, as shown in Fig. 3. Some assumptions are required for the simplicity of the mathematical model. At first, a certain height is considered. Secondly, the position of the rotation axis is assumed according to the satellite.

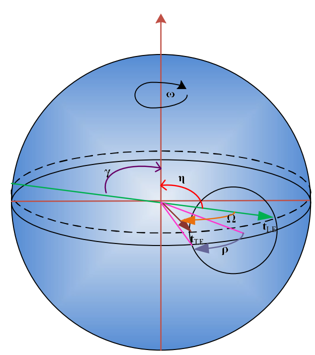

Fig.3. *Geometric design of earth horizon sensor*

According to this model, Ω is an angle that can be seen by the detector at each interval time. Hence, Ω can be calculated as follows:

$$\Omega = (t_0 - t_1)\omega \tag{1}$$

where, ω denotes the satellite rotation rate. If the earth can be seen by a detector, ΩE is stated as:

$$\Omega_E = (t_{LE} - t_{TE})\omega \tag{2}$$

where, ΩE is an angle at which the detector can realize the earth during it.

If γ is considered as an angle between the rotation axis and the earth center that it can be seen by the detector; additionally, η has denoted an angle between the rotation axis and earth center, according to Fig. 4 for a suitable spherical trigonometry, cos(ρ) can be calculated using the law of cosines:

$$\cos\rho = \cos\gamma\cos\eta + \sin\gamma\sin\eta\cos\frac{\Omega_E}{2} \tag{3}$$

where, ρ is the earth's radial angle which can be seen from the sensor position.

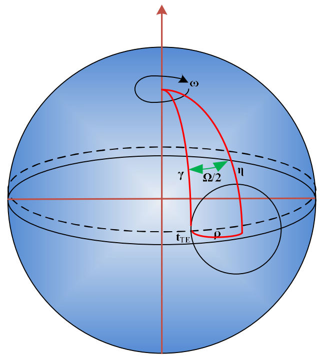

Fig.4. *Geometric design of Earth Horizon sensor using Spherical Trigonometry*

If the above equation is calculated for η, equation (4) is represented as follows:

$$\cos\rho - \cos\gamma\cos\eta = \pm(1-\cos^2\eta)^{1/2}\sin\gamma\cos\frac{\Omega_E}{2} \tag{4}$$

Then,

$$(\cos^2\gamma + \sin^2\gamma\cos^2\frac{\Omega_E}{2})\cos^2\eta - 2\cos\gamma\cos\rho\cos\eta + \ldots$$
$$+\cos^2\rho - \sin^2\gamma\cos^2\frac{\Omega_E}{2} = 0 \tag{5}$$

Equation (5) is a quadratic equation with regard to η, which can be written as follows:

$$\cos\eta = \frac{\cos\eta\cos\rho \pm \sin\gamma\cos\frac{\Omega_E}{2}(\cos^2\gamma - \cos^2\rho + \sin^2\gamma\cos^2\frac{\Omega_E}{2})^{1/2}}{\cos^2\gamma + \sin^2\gamma\cos^2\frac{\Omega_E}{2}} \tag{6}$$

To determine η, the value of γ and Ω_E is constant. Therefore, only the calculation of ρ is required. In a certain height is represented as (h) and earth radius is represented as (R_E), ρ can be easily computed.

$$\rho = \arcsin\frac{R_E}{R_E + h} \tag{7}$$

In the following, the earth horizon sensor in space is simulated based on a Pyroelectric detector.

3. Results and Discussion

Satellites lead to originate non-uniformity in the earth's radiation, which is the major source of error in the static infrared horizon recognition sensors. The occurrence of changes in the earth's radiation was in accordance with weather and seasonal changes, which are based on time and latitudinal changes. The reason why the performance of the earth's radiation in space needs to be simulated was the major objective of the current study, which was simulating a system to detect the horizon of the earth. Fig. 5 depicts the schematic of a system that shows the earth as a hot spherical object with a spatial angle, of 18 degrees, in view of the satellites situated at an altitude of 36000 km from the earth. Consequently, a metal hemisphere with a radius of 10 cm, equipped with heaters, was simulated to achieve this purpose.

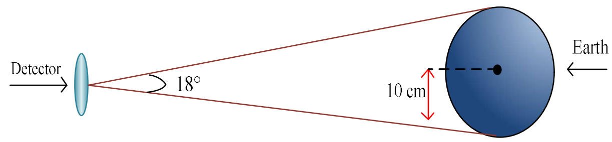

Fig.5. *Schematic of the earth in view of the satellite*

In this research, one hemisphere to simulate the earth was used, along with a Pyroelectric infrared detector that possessed circuits and equipment to detect the earth. This system included: the identification and preparation of required detectors based on the Pyroelectric effect; the simulation of ancillary circuits for converting the sensor response to electrical signals; and the simulation of an infrared source to simulate earth's radiation waves. A chopper was installed in front of the scope of the detector to show that the simulated earth was moving. The output signal of the detector was amplified by an electronic circuit. Afterward, the amplified signal was transferred to a computer by a digital oscilloscope. A block diagram of the test system in the current research is shown in Fig. 6.

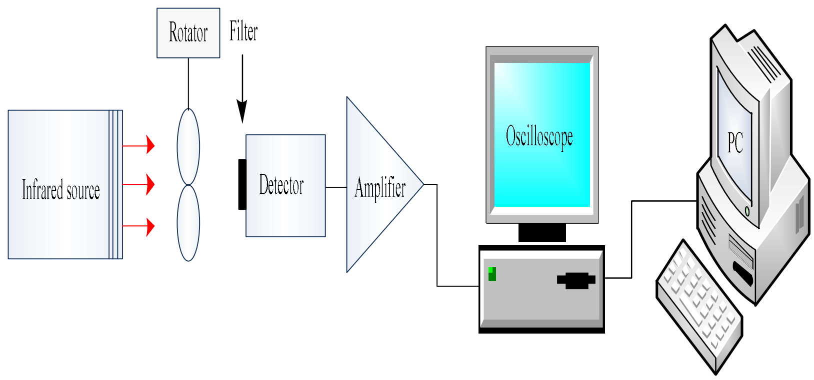

Fig.6. *Block diagram of the test system in the current study*

Additionally, these parameters must be considered to simulate satellite sensors. In this study, the field of view was calculated according to the output signals from the oscilloscope, after setting a reference position, as is shown in Fig. 7. To improve the detection of the target in far distances of the detector, FOV should be as small as possible. At first, aluminum pipes were considered to reduce FOV. Then, several tests were examined. But there were not any acceptable results for a significant decrease in the FOV of the detector by aluminum pipes. The reason for this issue was that the aluminum pipes absorb the infrared radiations and re-radiate them toward the detector. Hence, the plastic pipes were applied and some tests were performed again. The results show that the field of view of the detector is reduced from 70° to 50° by a plastic pipe with a diameter of 5 cm. Fig. 7 to Fig. 12 depicts the field of view of the detector in different target distances; for e.g. 70 cm, 125 cm, and 175 cm using aluminum and plastic pipes. According to these figures, the field of view was decreased due to increasing the target's distance. Moreover, plastic pipes have smaller FOV than aluminum pipes in the same circumstances. Additionally, FOV has been optimized to 20° in accordance with previous research by Heydarianasl and Borazjani [18].

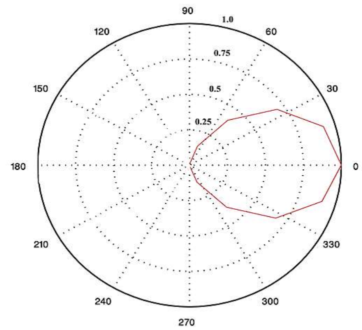

Fig.7. Detection range at a distance of 70 cm using aluminum pipe

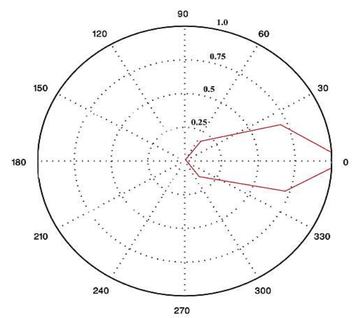

Fig.8. Detection range at a distance of 125 cm using aluminium pipe

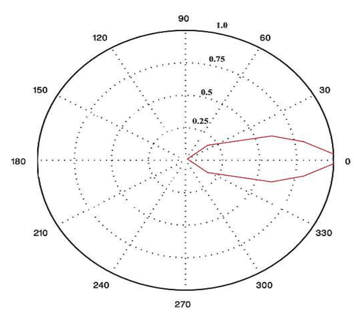

Fig.9. Detection range at a distance of 175 cm using aluminum pipe

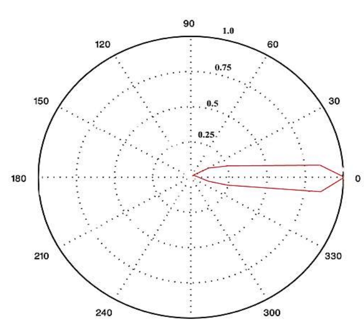

Fig.10. Detection range at a distance of 70 cm using plastic pipe

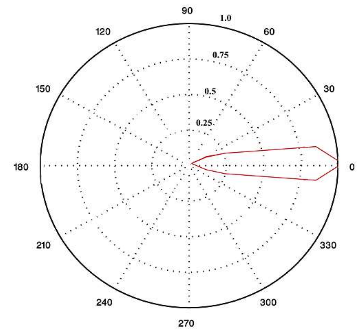

Fig.11. *Detection range at a distance of 125 cm using plastic pipe*

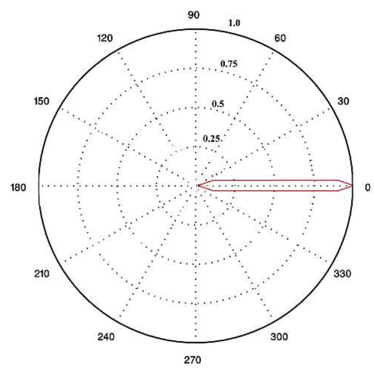

Fig.12. *Detection range at a distance of 175 cm using plastic pipe*

As mentioned earlier, another major parameter to analyze the properties of Pyroelectric detectors is defined as the step response of the detector; hence, it was calculated using a test system. To measure the step response, the detector was positioned in front of a heat source with a temperature of 50° C. The chopper was stopped for a brief moment so that the field of view would be interrupted once. The step response was plotted. Fig. 13 shows the step response of the detector using an aluminium pipe at a distance of 70 cm. Fig. 14 depicts the step response of the detector by means of a plastic pipe at a distance of 70 cm. The results illustrated that the step response of plastic pipe is better than aluminium pipe.

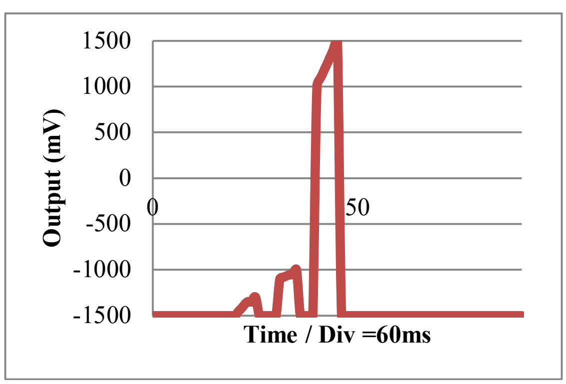

Fig.13. *Step response of detector using aluminium pipe (distance = 70 cm)*

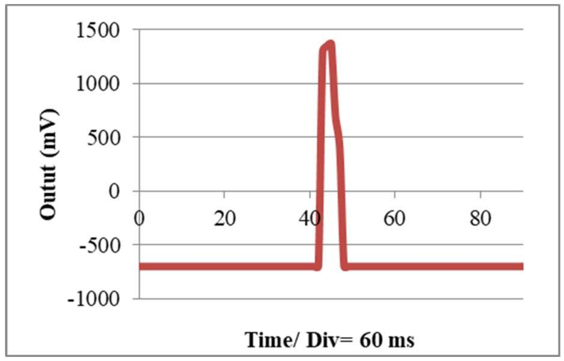

Fig.14. *Step response of detector using plastic pipe (distance = 70 cm)*

As expected, modeling results were the same with real conditions. At first, it is assumed that the target location is constant and invisible, which is shown as noise in the output of the system.

Hot objects were recognized as infrared sources in the FOV of the system. In this situation, different tests were carried out to access the system's performance. Finally, the system's performance was verified by the observed results of the digital oscilloscope. The output signal of the detector for several distances; including 70 cm, 125 cm, 175 cm, and 225 cm, is shown in Fig 15 to Fig. 18. Regarding these Figures, increasing the distance leads to a decrease in the amount of amplitude of the output signal.

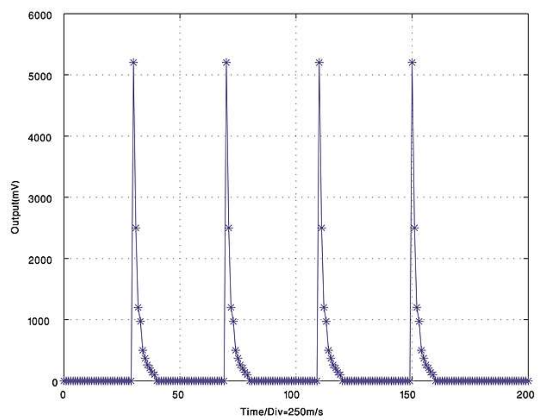

Fig.15. *The output signal of the detector at a distance of 70 cm*

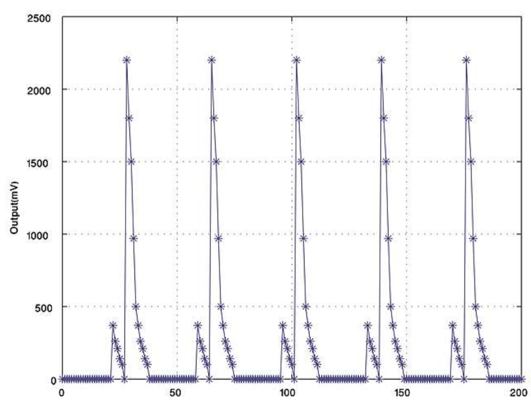

Fig.16. *The output signal of the detector at a distance of 125 cm*

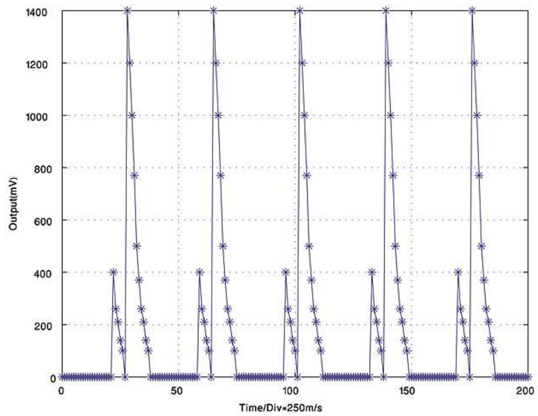

Fig.17. *The output signal of the detector at a distance of 175 cm*

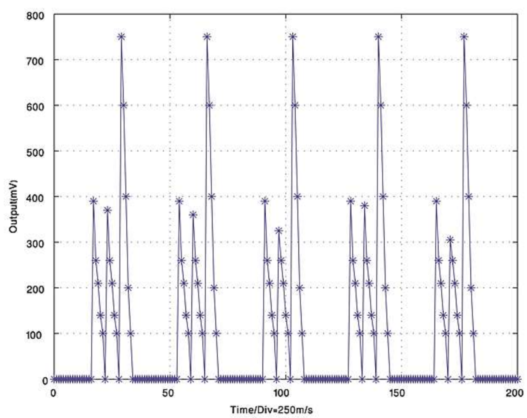

Fig.18. *The output signal of the detector at a distance of 225 cm*

Fig. 19 depicts the actual and ideal detector response. The actual detector response is the normalized response of the detector; moreover, the ideal response can be defined bya curve, where R denotes the distance. As is shown in this Figure, actual and ideal curves have significant discrepancies because of the rapid reduction when the distance is less than 1, (R<1). Besides they are similar to each other at distances larger than one, (R>1). Next, a spherical model with a specified temperature was made to simulate the earth; then, the detector response of the spherical model was analyzed. Several parameters, such as step response, the field of view of the detector, the minimum and maximum frequency of the chopper, and the minimum detectable output, were calculated and the methods were examined to reduce environmental noise. Step response and field of view of the detector were explained in detail in section 3.

The rotation frequency of the chopper is significant since the detector does not sense temperature changes at a very low frequency; consequently, it leads to restriction of the performance of the system in low- frequency of the system. On the other hand, the detector is not able to respond to temperature changes (infrared light) in too high a frequency as defined in the system, due to rapid changes in temperature by the chopper. The amplitude of the output signal decreases because of the increase in the rotation frequency of the chopper. In the field of view equal to 50°, the minimum and maximum frequency of the chopper are 5.83×10^{-2} Hz and 5.8×10^{-1} Hz, respectively.

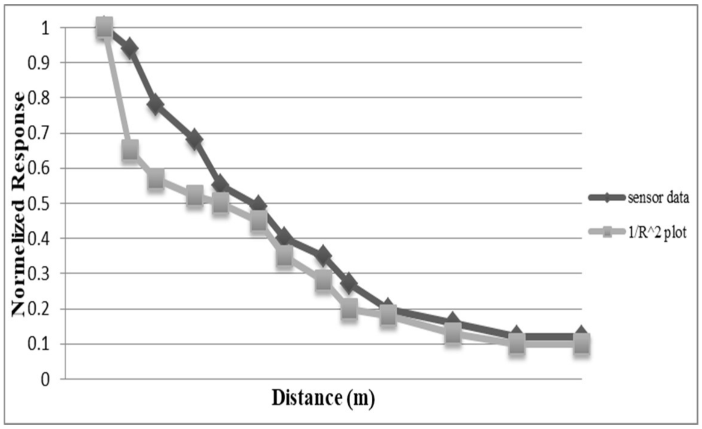

Fig.19. *Sensor response in comparison to* $1/R^2$ *curve*

4. Conclusion

The major target of the current research was the optimization of an earth sensor to determine satellite attitude. To achieve this purpose, the field of view of the detector needs to be as small as possible. First, a spherical object was considered an earth. Following that, all requirements and conditions to simulate the space were provided. Several tests were carried out in the laboratory and this system was simulated by software. Finally, the optimal value of FOV was equal to 50°, which has reduced by about 20°. At last, the experimental analysis exhibited that the pyroelectric detectors were feasible to attain the functional requirements.

Compliance with Ethical Standards

Conflicts of interest: Authors declared that they have no conflict of interest.

Human participants: The conducted research follows ethical standards and the authors ensured that they have not conducted any studies with human participants or animals.

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