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FUNCTIONAL TESTING OF THE CAMERA WITH ACTUATOR FOR THE EXPERIMENTAL DETERMINATION OF THE POLARIZATION OF LIGHT BY MEASURING THE STOKES PARAMETERS

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Abstract

The article presents the results from the functional tests of cameras with actuator for determining of Stokes parameters. The aim of the tests is to investigate the possibility for the cameras in question to work in the space. Positive results are obtained, which allow the cameras to be used for measurements in free space.

Introduction

The polarization of light is a process that occurs in interaction of light waves with matter. According to Maxwell's electromagnetic theory light waves are electromagnetic (EM) transverse wave: the vibration of the electric and magnetic vector is carried out in directions perpendicular to the direction of propagation of light.

The light can be considered as electromagnetic radiation from a large number of atoms belonging to a given source. Since every atom of the source emits vibrations independently of the other, in total EM radiation is characterized by the kinds of equally possible orientations of the electric vector $\bar{E}$, which is also called a light vector.

In the radiation from majority of sources the direction of the electric vector is in general not defined but changes continuously and randomly over extremely short time intervals. Such radiation is called unpolarized or natural light.

If the light reflected or passed through the dielectric, the electric vector of light waves can vibrate only in one plane – the so-called full or linear polarization plate, or, due to a more complex interaction with the substance, the electric vector vibrates in a sequence that can be illustrated with a vector rotating spiral with "step" equal to the wavelength λ. If during this rotation the amplitude of the electric field is kept constant in all directions perpendicular to the direction of propagation, the polarization is circular. If the amplitude is changed and is different in two orthogonal directions, the tip of the vector will describe an ellipse and the polarization is elliptical [1], [2].

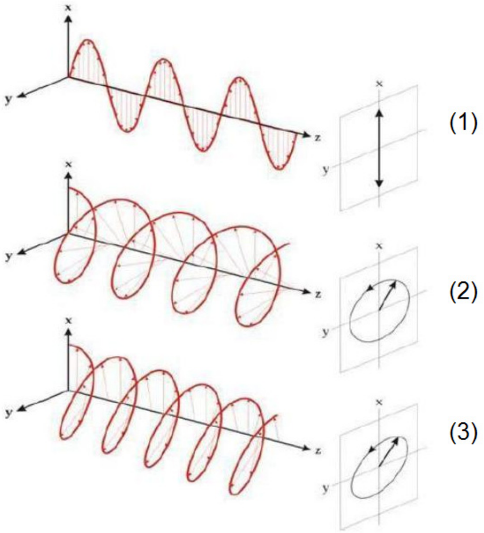


Fig. 1. Schematic representation of a linearly (1), a circularly (2) and an elliptically (3) polarized light

The state of polarization of light is described completely by the four Stokes parameters, which contain complete information on the intensity, the extent, and the form of polarization of light. They are real numbers with dimension of intensity and can be expressed by the Cartesian components of the electric field (E_x и E_y) by the following equations [3]:

(1) $\mathbf{I} = S_0 = I(0°) + I(90°) = <|E_x|^2> + <|E_y|^2>$

(2) $\mathbf{Q} = S_1 = I(0°) – I(90°) = <|E_x|^2> – <|E_y|^2>$

(3) $\mathbf{U} = S_2 = I(45°) – I(135°) = Re<E_xE_y>$

(4) $\mathbf{V} = S_3 = I_{\mathbf{RHC}} – I_{\mathbf{LHC}} = Im<E_xE_y>$

Where the brackets "< >" indicate averaging over a long time.

The first parameter S_0 gives us the total light intensity; S_1 indicates the difference between the components of the wave which is horizontally (+) or vertically (–) polarized; S_2 indicates the difference between the components of the wave which is polarized at –45 and +45 degrees; S_3 gives the difference between the circular components with intensities $I_{\mathbf{RHC}}$ and $I_{\mathbf{LHC}}$ of right and left rotating polarization.

The polarization state is completely determined by the three ratios known as relative Stokes parameters:

(5) $P_1 = S_1/S_0$

(6) $P_2 = S_2/S_0$

(7) $P_3 = S_3/S_0$

They have possible values between (–1) and (+1).

The following equations are used to calculate the degree of polarization – the ratio of the polarized light to the total intensity.

Degree of polarization P:

(8) $P = sqrt (S_1^2 + S_2^2 + S_3^2)/ S_0$

Degree of linear polarization P_L:

(9) $P_L = sqrt (S_1^2 + S_2^2)/ S_0$

Degree of circular polarization P_C:

(10) $P_C = S_3/ S_0$

P_C is positive for right-handed circular polarization and negative for left-handed circular polarization.

Experimental measurements and results

The aim of the experimental measurements is the determination of Stokes parameters and the state of polarization of a light source by using photodiode and a prototype of the onboard camera.

A *He-Ne laser* with a wavelength of 633 nm and an output of 5 mW is used as a light source. A linear polarizer is utilized for the determination of Stokes parameters and the rotating of the plane of polarization, and a photodiode and a camera – for measurement the signal. The silica photodiode with active area size 2.5 x 2.5 mm is mounted in a metal protective housing and connected to an amplifier. The black/white camera is selected with high light sensitivity (4.8 V/lux.s), dynamic range >110 dB and relatively high resolution (752 x 480). It also has the property to average by hardware (as analogue level) pixels in areas up to 4 x 4 in the whole frame, which additionally increase the signal to noise ratio.

In order to determine Stokes parameters, a certain sequence of steps is followed. First, the linear polarizer has to be placed in front of the photodiode/camera. By rotating of the position of the polarizer at 0 and 180 degrees, the intensity has to be measured and the result to be averaged. Similar measurements have to be made at 90 and 270 degrees. By these measurements S_0 and S_1 will be determined. The averaging of the readings will give a more accurate value. In a similar manner S_2 has to be determined with the polarizer at 45 and 135 degrees. By equations (1–4) Stokes parameters can be calculated.

Three series of measurements were made. Images of the experimental setup of the first series are shown in Figure 2.

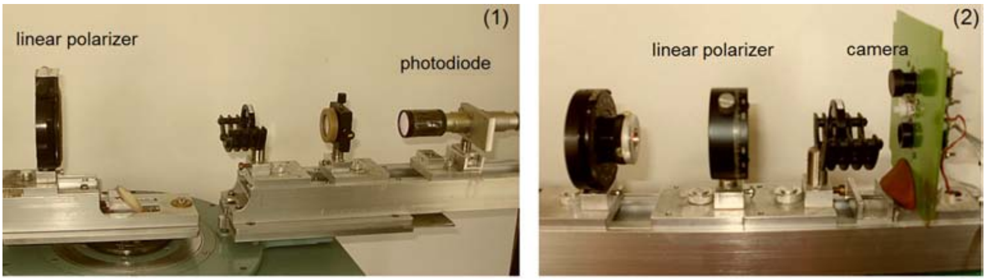


Fig. 2. Experimental setup for measurement Stokes parameters by using He-Ne laser as a light source

In this series of experiments, a difficulty in measuring the signal with the camera occurs. In spite of the use of attenuators, the signal from the laser was outside the dynamic range of the camera, which prevents the measurement. This required a change of the light source.

The second series of experiments aimed assembling a setup with a source light-emitting diode (LED), which emits unpolarized light in the red range of spectrum and is fitted with a potentiometer for adjusting the brightness of the light. The experimental setup is shown in Figure 3.

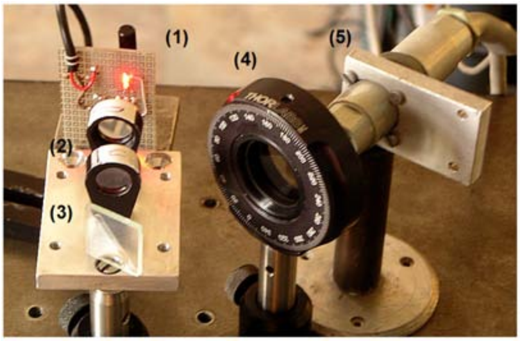


Fig. 3. Experimental setup for measurement Stokes parameters by LED as a light source: 1) LED, 2) lens system, 3)glass plate,4) polarizer, 5) photodiode chip

The light from the LED passes through a lens system and reaches the glass plate. The reflected light is polarized, and the state of polarization depends on the angle of incidence and, repectively, on the angle of reflection from the plate. [4] After reflection from the plate, the light passes through a polarizer and falls on the photodiode chip.

The aim of the third series of experiments is to determine Stokes parameters by LED as a light source and to compare the measurement results of the camera with those of photodiodes. The following pictures show the configuration of the experimental setup with a photodiode and a camera.

In this series of experiments, measurements were divided into several groups depending on:

- the angle of incidence/reflection of light from the glass plate – 30 and 40 degrees;
- the step of rotating the position of the polarizer – in our case 30 and 45 degrees.

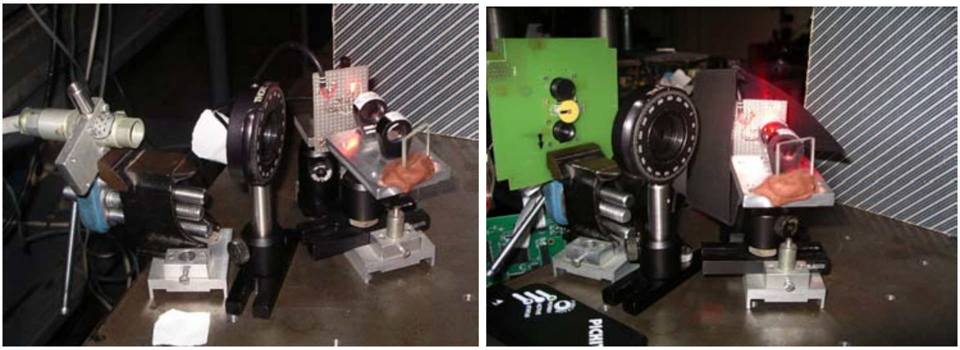


Fig. 4. Pictures of the experimental setup for measurement of Stokes parameters by a photodiode (left side) and a camera (right side) in source LED

The normalized results from measurements of light intensity using a photodiode and a prototype of the onboard camera are presented in the following tables. They are received in a step of rotating the position of the polarizer 30 degrees (Table 1) and 45 degrees (Table 2) and a reflection angle of the glass plate 30 degrees.

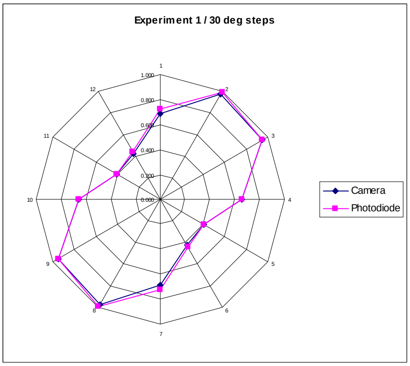
Table 1. Results of measurements of the intensity of light: step of rotating the position of the polarizer 30 degree; reflection angle of the glass plate 30 degrees

Experiment 1		
deg	**camera**	**photodiode**
30	0.686	0.725
60	0.971	0.992
90	0.948	0.950
120	0.656	0.658
150	0.401	0.400
180	0.425	0.442
210	0.686	0.725
240	0.971	0.992
270	0.948	0.950
300	0.656	0.658
330	0.401	0.400
0	0.425	0.442

Table 2. Results of measurements of the intensity of light: step of rotating the position of the polarizer 45 degree; reflection angle of the glass plate 30 degrees

	Experiment 1	
deg	**camera**	**photodiode**
0	0.640	0.675
45	1.000	1.000
90	0.712	0.700
135	0.365	0.367
180	0.640	0.675
225	1.000	1.000
270	0.712	0.700
315	0.365	0.367

The diagrams below (Figure 5) present the state of polarization of light by comparing the results of the first two experiments.



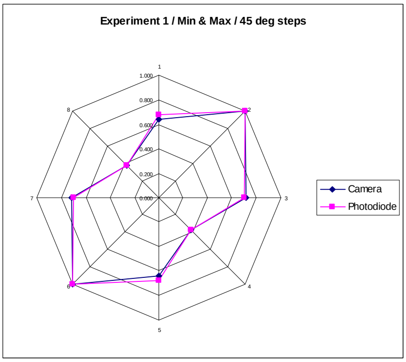


Fig. 5. Diagram of the state of polarization at step 30 degrees and 45 degrees and a reflection angle of the glass plate 30 degrees

The normalized results of the measurements of the light intensity at a reflection angle of the glass plate 40 degrees are shown in the following tables. They are received in the step of rotating the position of the polarizer 30 degrees (Table 3) and 45 degrees (Table 4).

Table 3. Results of measurements of the intensity of light: step of rotating the position of the polarizer 30 degree; reflection angle of the glass plate 40 degrees

Experiment 2		
deg	**camera**	**photodiode**
30	0.757	0.753
60	0.941	0.955
90	1.000	0.981
120	0.815	0.801
150	0.617	0.592
180	0.595	0.573
210	0.757	0.753
240	0.941	0.955
270	1.000	0.981
300	0.815	0.801
330	0.617	0.592
0	0.595	0.573

Table 4. Results of measurements of the intensity of light: step of rotating the position of the polarizer 45 degree; reflection angle of the glass plate 30 degrees

	Experiment 2	
deg	**camera**	**photodiode**
0	0.722	0.715
45	0.982	1.000
90	0.825	0.820
135	0.585	0.554
180	0.722	0.715
225	0.982	1.000
270	0.825	0.820
315	0.585	0.554

The following diagrams (Figure 6) present the state of polarization of light by comparing the results of the last two experiments.

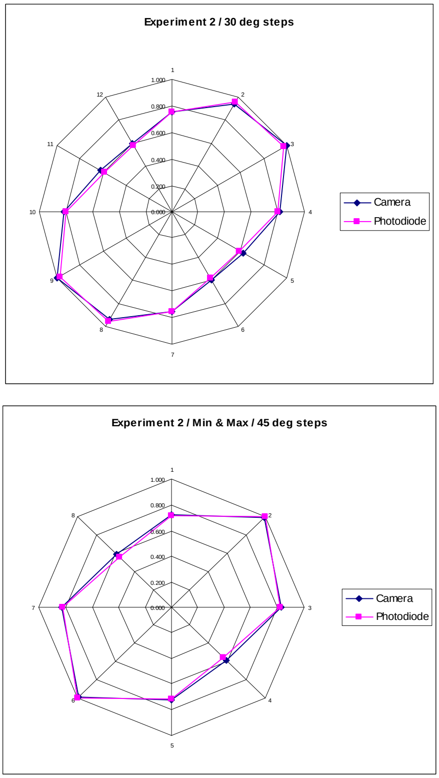


Fig. 6. Diagram of the state of polarization at step 30 degrees and 45 degrees and a reflection angle of the glass plate 40 degrees

Using the experimental results and formulas (1–7) given in the theoretical part, Stokes parameters S_0, S_1 and S_2 are calculated. Calculations are made with normalized intensity values. The results are presented in the following tables. The *Experiment 1* corresponds to the case of the reflection angle of the glass plate 30 degrees and the *Experiment 2* – to the case of the reflection angle of the glass plate 45 degrees.

Table 5. Measurement results and calculated Stokes parameters using a photodiode

No	I(0°)	I(90°)	I(45°)	I(135°)	S_0	S_1	S_2	P_1	P_2
Exp. 1	0.675	0.700	1.000	0.367	1.375	-0.025	0.633	-0.018	0.460
Exp. 2	0.715	0.820	1.000	0.554	1.535	-0.105	0.446	-0.068	0.291

Table 6. Measurement results and calculated Stokes parameters using a camera

No	I(0°)	I(90°)	I(45°)	I(135°)	S_0	S_1	S_2	P_1	P_2
Exp. 1	0.640	0.712	1.000	0.365	1.352	-0.072	0.635	-0.053	0.469
Exp..2	0.722	0.825	0.982	0.585	1.547	-0.103	0.397	-0.067	0.257

The percentage difference between the readings of the photodiode and a Δk camera is calculated on the basis of the data from two different measurements. The normalized results of the first calculation are shown in Table 7.

Table 7. Difference between the readings of the camera and the photodiode from the first measurement

angle	camera	photodiode	difference (%)
0	0.414	0.442	-6.180
30	0.686	0.725	-5.408
60	0.971	0.992	-2.083
90	0.948	0.950	-0.249
120	0.656	0.658	-0.324
150	0.401	0.400	0.358
180	0.425	0.442	-3.797

A difference between the readings of the camera and those of the photodiode for angles from 0 to 180 degrees is given in the last column of Table 7.

The percentage difference Δk is given by the formula:

(11) $$\Delta k = (I_{max} - I_{min})/2$$

In this case, after the due calculations, we obtain 3.27% for Δk.

The results of the second test are shown in Table 8.

In this case we obtain Δk = 3.46% after calculations.

We can conclude from them that the results received by the camera coincide with those obtained by photodiode with an accuracy of about 3.5%, which is evident from the diagrams given in Figures 5 and 6.

Table 8. Difference between the readings of the camera and the photodiode from the second measurement

angle	camera	photodiode	difference (%)
0	0.604	0.573	5.455
30	0.757	0.753	0.503
60	0.941	0.955	-1.464
90	1.000	0.981	1.908
120	0.815	0.801	1.684
150	0.617	0.592	4.194
180	0.595	0.573	3.759

Illustration of the results from the camera – the change in the intensity as a function of the angular position of the polarizer (from 0 to 180 degrees) is shown in Figure 7.

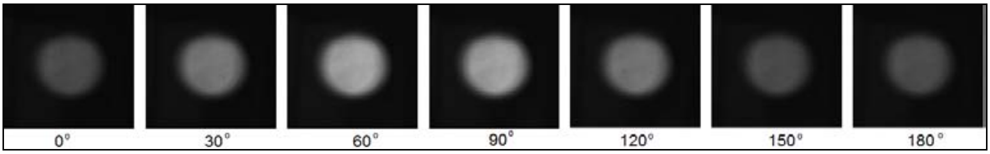


Fig. 7. Change in intensity of light as a function of the angular position of the polarizer

We can conclude from the calculations of Stokes parameters (Table 5 and 6), the diagrams in Figure 5 and 6, and the photos from Figure 7, that the tested light is elliptically polarized.

Sources of errors in measurements

The magnitude of the error in the experimental measurements depends both on the accuracy of the instrument and the natural fluctuations in the values, which can be a result from accidental causes.

Errors in the performed experimental measurements can accumulate each element presented in the setup: LED, the polarizer, the photodiode and the camera.

The change of LED’s power can be a source of error. To account this change, the power was repeatedly measured as a function of time. The power changed by less than 1% within 120 minutes, which has no significant influence on the measurements.

The accuracy of measurement of the polarization depends on the smallest division of the holder, in which the polarizer is placed and by which the plane of polarization of the light can be changed. In our case, it is 2 degrees and hence the measurement error is ±2°.

The smallest change in measuring by photodiode signal is 0,001 V. Therefore, the error that can occur is ± 0,001 V. The average dark signal is 0,000 V.

Testing of the camera with actuator in a vacuum. Incorporation of the equipment for 30 min in a vacuum – 2.10^{-3}mbar

Upon reaching a vacuum value of 2.10^{-3}mbar (Figure 8), the equipment was turned on for checking of its functionality. Deflection in the power supply and in the operating mode as well as a mechanical displacement of the cameras were not found.

Fig. 8. Incorporation of the equipment for 30 min in a vacuum - 2.10^{-3}mbar

The captured test images show the normal functioning of both cameras (Figure 9 and 10).

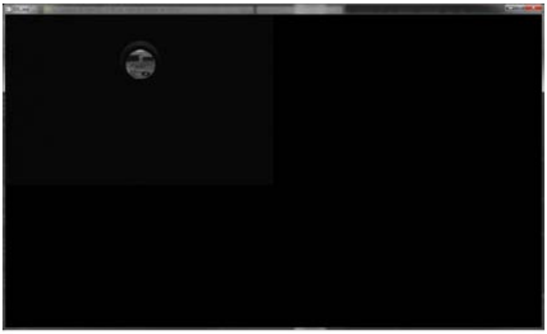


Fig. 9. Test image in vacuum at 2.10^{-3} mbar captured without outside backlight conditions

Fig. 10. Test image in vacuum at 2.10^{-3} mbar captured with outside backlight condition.

Turning on the equipment for 10 min in a vacuum at 9,4.10^{-6} mbar (Figure 3, 4, 5).

After the completion of the tests described above, the equipment was turned off without being removed from the thermo-vacuum chamber. The thermo-vacuum chamber reached a values 9,4.10^{-6} mbar for 40 min. After reaching the maximum values, the equipment was turned on, in order to explore its functionality. Deflection in the power supply and in the operating mode as well as a mechanical displacement of the cameras were not found.

The captured test images show the normal functioning of both cameras (Figure 11, 12, 13).

Fig. 11. Reaching the values 9,4.10^{-6} mbar of vacuum thermo chamber

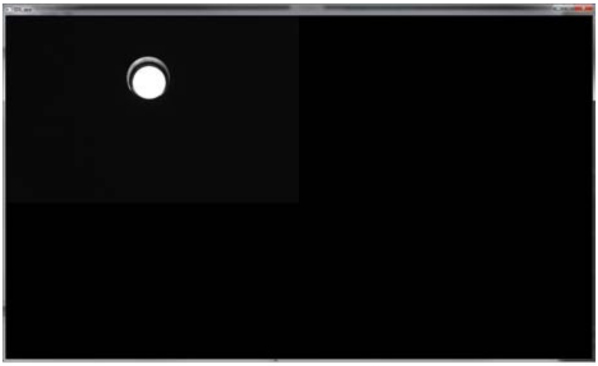


Fig. 12. Test image in vacuum at $9,4.10^{-6}$ mbar captured with outside backlight conditions

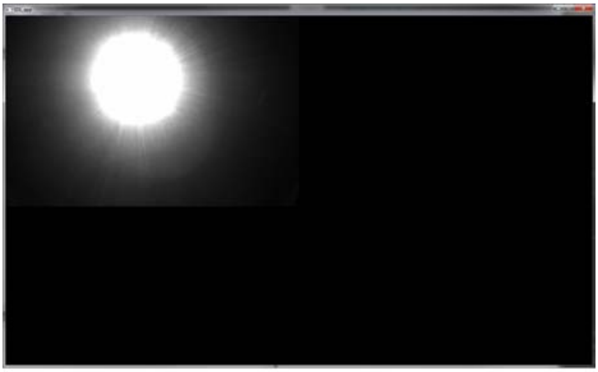


Fig .13. Test image in vacuum at $9,4.10^{-6}$ mbar captured with outside backlight conditions

Conclusion

On the basis of the results obtained from the thermo- and vacuum tests of the equipment, it can be concluded that it meets the general technical requirements for operation in a vacuum of a value of $9,4.10^{-6}$ mbar.

Acknowledgements

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ФУНКЦИОНАЛНО ТЕСТВАНЕ НА КАМЕРА СЪС ЗАДВИЖВАНЕ ЗА ЕКСПЕРИМЕНТАЛНО ОПРЕДЕЛЯНЕ НА ПОЛЯРИЗАЦИЯТА НА СВЕТЛИНАТА ЧРЕЗ ИЗМЕРВАНЕ НА ПАРАМЕТРИТЕ НА СТОКС

Ж. Железов, Р. Недков, Д. Теодосиев, М. Биволарска, Н. Георгиев, И. Лилов, Г. Чамов, С. Янева

Резюме

В настоящата работа са представени резултати от проведени функционални тестове на камери със задвижване, с помощта на които се определят параметрите на Стокс. Целта на тестовете е да се изследва възможността за работа на камерите в условията на открития космос. Получените резултати са положителни, което дава възможност те да бъдат използвани при измервания в условия на открит космос.