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Experimental quantification of solar panel power activation delay post-illumination with metrological analysis

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Abstract: The issue of solar panel power activation delay is significant when modeling processes that change rapidly. This assessment enables the correct decision to either neglect the generated electrical power if it is minimal or to include it in the model. Resolving this issue experimentally is often the most straightforward approach due to the considerable nonlinearity of transient electrical processes, which requires the development of complex mathematical models. The primary objective of this research is to experimentally estimate the delay time for solar panel power activation. The methodology involves direct measurements of the voltage produced by the solar panel. A metrological model of the experiment has been developed, allowing for the estimation of errors in the measurement of the solar panel's turn-on delay time. Experiments were conducted using three solar panels from different manufacturers. The results obtained are slightly lower than the values provided on the manufacturers' official websites. The methodology and metrological model presented can be utilized to accurately simulate the temperature shock experienced by spacecraft solar panels.
Keywords: *Metrological model of the experiment, Power activation delay, Solar panel.*

1. Introduction

Solar panels are currently very widespread. Solar energy makes a significant contribution to the development of technologies for generating electric energy for various needs [1-3]. While terrestrial efficiency depends on weather conditions [4-6] they remain indispensable in space applications [7-9]. Since the dawn of space technology [10-12] solar panel designs have been continuously optimized for mission-specific requirements [13-15].

The rise of small spacecraft has intensified focus on mass reduction [16-18] energy efficiency [19-21] and resilience against space environmental factors [22-24]. Mass reduction of the solar panel led to the emergence of extremely flexible designs [25-27] which – as demonstrated by experiments with panels like ROSA [28] – exhibit greater susceptibility to external influences and more pronounced effects on the angular motion dynamics of a small spacecraft [29-31]. Such influence reduces the efficiency of some target tasks as remote sensing of the Earth [32] or the implementation of gravity-sensitive processes [33].

One of the significant disturbing factors affecting the relative motion of solar panels is temperature shock[34-36]. It occurs when a small spacecraft immerses itself in the Earth's shadow or leaves the shadow. Thus, during an experiment with the ROSA solar panel on the international space station, the relative motion of the panel due to temperature shock did not allow it to be folded as planned. As a result, it was shot off in an unfolded form [28]. Therefore, studying the temperature shock effect on the relative motion of a solar panel is very important for the development of space technology.

According to classical problems, the deflections of solar panel points are related to its temperature field [37-39]. Therefore, the correctness of the dynamics description of these deflections largely depends on the formulation and solution of the heat conduction problem. Common approaches to

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modeling the solar panel involve either approximating it as a thin homogeneous plate for analytical solutions [30] or building a finite element model [40-42].

However, the generated energy issue in the heat conduction equation remains open. On the one hand, it is significant when the solar panel reaches its calculated power of electricity generation. On the other hand, how quickly does this process of reaching the calculated power occur compared to the temperature shock itself? Such an account is certainly necessary to study thermally induced vibrations of the solar panel. Nevertheless, how important is it at the stage of the temperature shock itself within the first second after the spacecraft leaves the Earth's shadow? There are few studies on this topic. There is an opinion that the photoelectric effect itself occurs almost instantly after the rays hit the surface of the photocell [43]. However, one can find on the website of solar panel manufacturers an indication that "The time it takes for a solar panel to generate electricity is approximately 1 to 3 seconds after the first exposure to sunlight..." [44]. This delay is negligible for the vast majority of tasks. However, this is not the case in the task of correctly describing a temperature shock, the active stage of which does not exceed 1 s.

Thus, the purpose of this work is to establish the value of the electricity generation delay in reaching the calculated power experimentally with the construction of a metrological model.

2. Materials and Methods

Three solar panels of different power and different manufacturers were used to conduct the experiment (Figure 1).

a) b) c)

Figure 1.
There is an external appearance of the tested solar panels.

The main characteristics of the solar panels used in the experiment are given in Table 1.

Table 1.
There are the main characteristics of experimental samples of solar panels.

Parameter, Dimension	**Panel № 1 (a) fig. 1)**	**Panel № 2 (b) fig. 1)**	**Panel № 3 (c) fig. 1)**
Maximum power, W	0.24	2.00	1.50
Maximum current, mA	120	400	125
Maximum voltage, V	2	5	12
Brand	Ruichi, China	SKI Solar Energy, China	Mistaha, China

A digital multimeter of the DT9208A series was used as a means for measuring the volt-ampere characteristics of the solar panel (the parameters are presented in Table 2).

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Table 2.
There are the main characteristics of the measuring instrument DT9208A.

Parameter	Dimension	Meaning
Voltage sensitivity threshold	μV	100
Current sensitivity threshold	μA	100
Number of measurements per second	-	3
Voltage error	%	±0.5+1 unit of account
Current error	%	±1.5+1 unit of account

A matte LED lamp A60-12W-4000-E27 (luminous flux - 1300 lm, color temperature - 4000 K, color rendering index - 80%) was used as a light source.

The data derived during the experiment are processed using standard methods of statistical processing of simple homogeneous samples [45].

3. Results

3.1. Methodology And Metrological Model of the Experiment

3.1.1. The Experimental Setup Description

The experimental setup (Figure 2) consists of a solar panel (1), a light source (2), a multimeter (3), a stopwatch (4), a video camera (5), conductors (6), and a switch (7).

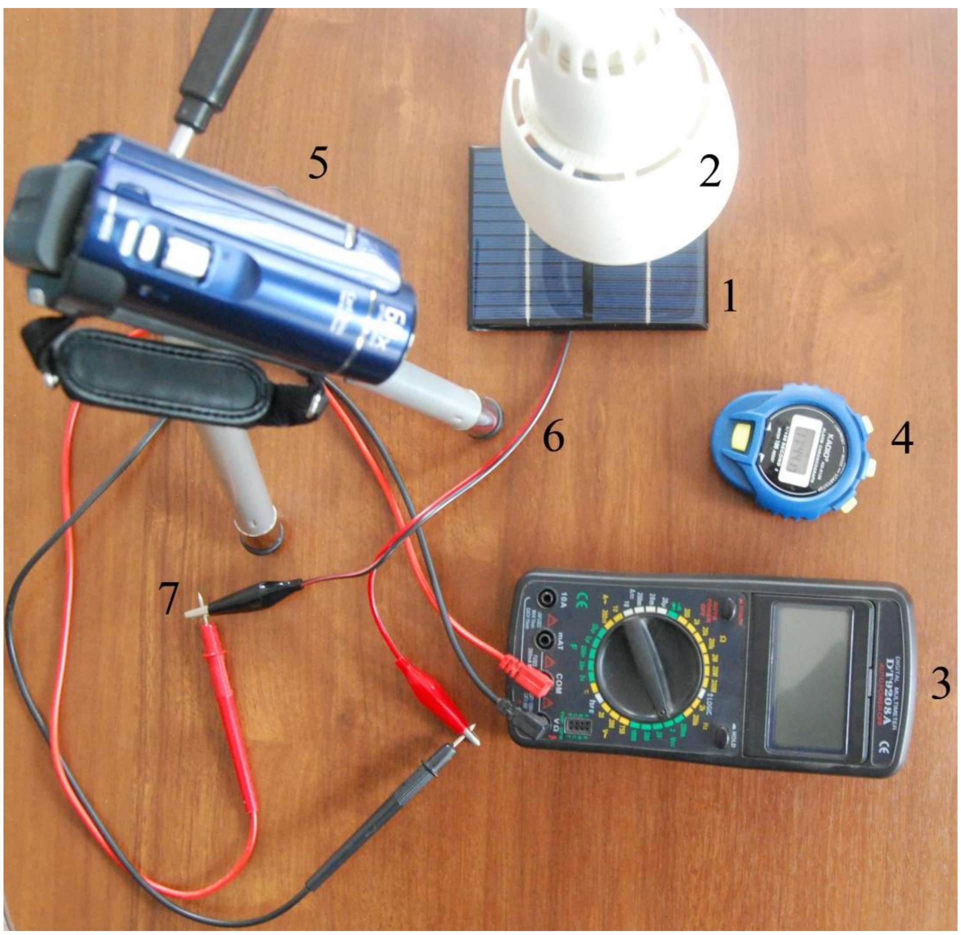

Figure 2.
There is a photo of the experimental setup.

3.1.2. The Experiment Progress

The light source is switched on under conditions of negligible background radiation (the multimeter records zero values of voltage and current). Then, using a multimeter, stopwatch, and video camera, the dynamics of voltage and current changes in the circuit are recorded. All experiments are conducted under the same conditions to obtain a uniform and equally accurate sample of the delay time values for turning on the solar panel after exposure to radiation.

3.1.3. Description and Analysis of Stochasticity Sources

The measured value will be affected by the following sources of stochasticity during the implementation of the experiment.

3.1.3.1. Background Radiation

It is obvious that zero illumination of a solar panel is practically unattainable. Therefore, it is correct to speak about negligible illumination, which is not recorded by measuring instruments. This stochasticity source leads to the appearance of an additive error δ1. This error affects the initial conditions of the experiment (zero initial illumination). Its maximum value corresponds to the sensitivity threshold of the measuring instrument (Table 2). Thus, the initial value of the current or voltage will be in the range $[0, \delta_1]$.

3.1.3.2. Voltage and Current Measurement Error

This stochasticity source is the DT9208A measurement error, which is added to the measured values during the experiment. It is considered to be a normally distributed random variable ($N(0, \delta_1)$).
Error in sampling of voltage and current measurements.

This stochasticity source characterizes the error in the time estimating at which the measurements were made. In this paper, the maximum value of this error is estimated as 10 % of the discretization step ($\delta_2 = 0.033$ s). Thus, this error is an additive error in time measurement with a normal distribution law $N(0, \delta_2)$.

3.1.3.3. Time Measurement Error

This stochasticity source is the measurement error of the stopwatch, which is added to the measured values during the experiment. It is considered a normally distributed random variable ($N(0, \delta_3)$). The value of δ_3 is determined by half the least significant digit of the measuring instrument and is $\delta_3 = 0.005$ s.

3.1.3.4. Error in Synchronizing Measuring Instrument Parameters Via Video.

This stochasticity source generates an additive error in time measurement when synchronizing the DT9208A and stopwatch measurements using video information. This error is considered to be a normally distributed random variable ($N(0, \delta_4)$). The value of δ_4 is determined by the least significant bit of the measuring instrument and is $\delta_4 = 0.01$ s.

3.1.3.5. Non-Instantaneous Switching on of the Light Bulb

It is obvious that the process of the light source reaching maximum illumination occurs in a short time interval. However, it is not instantaneous and varies for different light sources. This stochasticity source mainly affects the first measurement after switching on. Considering it seems to be quite difficult. Therefore, in this paper it is assumed that the influence of this stochasticity source on the measurement results is negligible.

Thus, the analysis of the stochasticity sources showed that the data with the following errors will be obtained during the experiment.
Current strength:

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$$i = I + \Delta_1, \quad (1)$$

where i is a measured value; I is a true meaning, $\Delta_1 = \pm 100$ μA (Table 1).
Voltage on solar panel:

$$u = U + \Delta_2, \quad (2)$$

where u is a measured value; U is a true meaning, $\Delta_2 = \pm 100$ μV (Table 1).
Measurement time:

$$t = \tau + \Delta_3, \quad (3)$$

where t is a measured value; τ is a true meaning, $\Delta_3 = \pm(\delta_2 + \delta_3 + \delta_4) = \pm 0.045$ s.
All errors Δ_1, Δ_2 and Δ_3 are normally distributed random variables.

We derive the required sample size to construct confidence intervals (β = 0.95 and β = 0.99) for the mean measurement time, based on (3) [46]:

$$n > \left(\frac{s \cdot t_{n-1,\,\beta}}{|\Delta_3|} \right)^2 + 1, \quad (4)$$

where s^2 is mean sample variance; $t_{n-1,\,\beta}$ is a Student's t-distribution quantile.

Since the mean sample variance is unknown before the experiment, the required sample size n to achieve an accuracy of $\Delta_3 = \pm 0.045$ s will be determined by the following expression:

$$n > 493.83 s^2 t_{n-1,\,\beta}^2 + 1. \quad (5)$$

The value of the required sample volume will be estimated using inequalities during the experiments, according to the constructed metrological model (5). This is necessary to achieve the highest possible accuracy of the delay time estimate, taking into account the analyzed measurement errors.

3.2. Experimental Results and Their Statistical Processing

The following data were derived during the experiment and are presented in Table 4. The average sample value was estimated using the classical maximum likelihood method. To determine the sample variance, its unbiased estimate was used [46]:

$$s^2 = \frac{1}{n-1} \sum_{i=1}^{n} \left(x_i - \bar{x} \right)^2. \quad (6)$$

The boundaries of the confidence interval were determined using known formulas for the mathematical expectation of a normally distributed random variable:

$$\Delta \bar{x} = \pm \frac{s}{\sqrt{n-1}} t_{n-1,\beta}. \quad (7)$$

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Table 4.
There are experimental results

Parameter, Dimension	Panel № 1 (a) fig. 1)	Panel № 2 (b) fig. 1)	Panel № 3 (c) fig. 1)
Sample of 10 measurements			
Sample mean, s	0.433	0.540	0.363
Sample variance, s^2	0.001	0.001	0.001
Confidence interval (β = 0.95)	0.433±0.029	0.540±0.022	0.363±0.024
Confidence interval (β = 0.99)	0.433±0.041	0.540±0.032	0.363±0.035
Required sample size to ensure precision ±0.045 s (β = 0.95)	5	4	4
Required sample size to ensure precision ±0.045 s (β = 0.99)	9	6	7
Sample of 20 measurements			
Sample mean, s	0.425	0.538	0.371
Sample variance, s^2	0.001	0.001	0.001
Confidence interval (β = 0.95)	0.425±0.016	0.538±0.013	0.371±0.018
Confidence interval (β = 0.99)	0.425±0.022	0.538±0.018	0.371±0.024
Required sample size to ensure precision ±0.045 s (β = 0.95)	4	3	4
Required sample size to ensure precision ±0.045 s (β = 0.99)	6	4	7
Sample of 30 measurements			
Sample mean, s	0.427	0.535	0.371
Sample variance, s^2	0.001	0.001	0.002
Confidence interval (β = 0.95)	0.427±0.013	0.535±0.010	0.371±0.017
Confidence interval (β = 0.99)	0.427±0.018	0.535±0.014	0.371±0.024
Required sample size to ensure precision ±0.045 s (β = 0.95)	4	3	6
Required sample size to ensure precision ±0.045 s (β = 0.99)	6	4	9

All the corresponding confidence intervals overlap for samples of different sizes as can be seen from Table 4. This indicates the correct operation of the measuring instruments and the correct application of statistical processing methods. The estimated required sample size to obtain the achievable accuracy (±0.045 s) shows that the studied samples are representative for estimating the mathematical expectation of the turn-on delay time.

Thus, taking into account the achievable accuracy (Δ_3 = ±0.045 s,), it can be stated that with a probability greater than 0.99, the mathematical expectation of the delay time for turning on the panels is 0.427 s, 0.535 s and 0.371 s (respectively, for panels No. 1, No. 2 and No. 3).

4. Discussion

The experiments revealed an overestimation in the delay time for solar panel activation reported on official websites (for example, [45]). Accounting for achievable accuracy, this delay did not exceed 0.6 s (versus the cited 1–3 s), based on experimental results. This finding is critically important for modeling temperature shock in spacecraft solar panels. The characteristic duration of the temperature shock's active phase is estimated at 0.75 s [30]. While data from Skipper and Skipper [45] suggest neglecting heat converted to electrical energy is justified, experiments demonstrate otherwise. For panel No. 3, it is appropriate to neglect generated electrical energy only during the initial 0.2 s. Beyond this interval, it must be included in the heat conduction equation. Furthermore, accurate quantification is complicated by multiple stochastic factors: the angle between the panel normal and solar direction, natural panel oscillations, spacecraft rotation, etc. Consequently, these new experimental results necessitate a revision of temperature shock modeling methodology. The active phase should be divided into two intervals:

1. Initial phase (≤0.2 s): Generated electrical energy may be omitted from the heat conduction equation.

2. Subsequent phase: This energy must be accounted for — either by measuring spacecraft battery recharge current/voltage or via modeling using statistically averaged current/voltage values.

In either approach, a new source of stochasticity must be incorporated into the methodological model, and the estimated modeling error increased. This outcome significantly enhances the efficiency of spacecraft mission operations.

5. Conclusions

Thus, this work derived new experimental results estimating the activation delay time of solar panels following sunlight exposure. A metrological model of the experiment was developed, enabling determination of the achievable accuracy in estimating this delay time. The required sample size was calculated based on experimental data.

These results demonstrate that published delay time estimates on some manufacturers' websites are overestimated. Consequently, when modeling rapidly evolving phenomena (e.g., temperature shock), experiments must utilize the specific solar panels intended for deployment to ensure model fidelity. The authors propose the specific values derived in this study (ranging from 0.371 s to 0.538 s) as preliminary reference data. Notably, this range exhibits a spread exceeding 44 % relative to the lower value. Therefore, to determine case-specific delay times, the authors recommend implementing the experimental methodology outlined in this work. Concurrently, applying the proposed metrological model provides a quantitative basis for deciding whether to include or exclude panel-generated energy in simulations at the required accuracy level.

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Transparency:

The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

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