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Background illumination in the guidance system for laser communication on the Impulse-1 satellite

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Abstract. Satellite laser communication requires high-precision mutual pointing between the satellite and the ground station, which is achieved by detecting a beacon laser on a tracking camera and adjusting the optical axis. Here we research the detection procedure of the laser beacon by onboard satellite camera, focusing on the relationship between laser power, beam divergence, and background illumination influenced by seasonal and geographical factors. Considering a test image from the "Impulse-1" spacecraft, we demonstrate that a 3W laser with a 3 mrad beam divergence illumination can exceed background levels by up to 20 times, improving detection as the satellite rises above the horizon, especially when positioned directly overhead.

Keywords: cubesat, spacecraft guidance, satellite optical communications, laser beacon

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Определение интенсивности фоновой засветки в системе наведения лазерной связи на космическом аппарате «Импульс-1»

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Аннотация. Лазерная спутниковая связь требует высокоточной взаимной ориентации между спутником и наземной станцией. Это достигается путем обнаружения лазерного маяка с помощью камеры слежения и корректировки направления оптической оси. Настоящее исследование рассматривает обнаружение наземных лазерных маяков бортовой камерой спутника, учитывая взаимосвязь между мощностью лазера на земле, расходимостью луча и фоновой освещенностью, зависящей от сезонных и географических факторов. Анализируя тестовое изображение со спутника «Импульс-1», показано, что лазер мощностью 3 Вт с расходимостью луча 3 мрад для показанного места и времени суток может превышать уровень фоновой освещенности до 20 раз, при пролете через надир.

Ключевые слова: кубсат, спутниковая оптическая связь, лазер, маяк

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Introduction

The orientation procedure of the satellite to the ground station is a complex and multi-stage problem, involving numerous calculations [1]. However, the final high-precision pointing is performed by using a laser beacon that illuminates the satellite from the ground station with a directed laser beam. To detect the laser beacon by the onboard camera reliably, the power of the incoming laser radiation must exceed the background illumination originating from the Earth's surface. This background noise may vary greatly depending on the time of year and the latitude of the ground station, since the station may be positioned in complete darkness or in direct sunshine. Therefore, proper selection of the laser beacon's power and beam divergence must account for the background illumination conditions, which can be assessed using images acquired by the satellite's onboard camera.

Here we provide experimental data of the background illumination detected on the camera of the Impulse-1 satellite and compare them to the irradiance expected from the beacon laser of the ground station [2, 3].

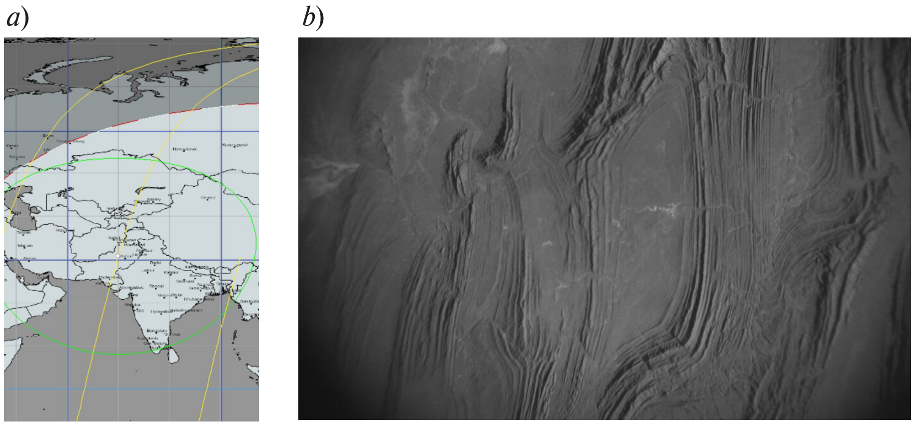

Fig. 1. Satellite’s orbit passing over Pakistan and the terminator line for this time of day (*a*); image of the Balochistan region as observed by the satellite’s camera (*b*)

Materials and methods

To enhance the contrast between the background radiation and the beacon, we use a narrowband 10 nm filter with the center wavelength of 670 nm which corresponds to a quantum efficiency of 53% for the Sony IMX 392 sensor used in the guidance camera of the “Impulse-1” spacecraft. Test image was taken with an exposure time of 3 milliseconds during clear weather while flying over the territory of Balochistan (Pakistan) on December 11, 2024, at 4:40 UTC.

Based on the known sensitivity parameters of the matrix, measured in accordance with the EMVA 1288 standard [3] as well as the parameters of the optical system of the spacecraft [4], we calculate the amount of light on each individual pixel of the sensor for a given image, considering exposure time and gain. The image is divided into 25 separate sections. For each section, the average energy value for each pixel is calculated, expressed in W/mI, along with the average number of photons that have reached the pixel. To assess the image quality, the number of overexposed and dark pixels was calculated for each section of the image.

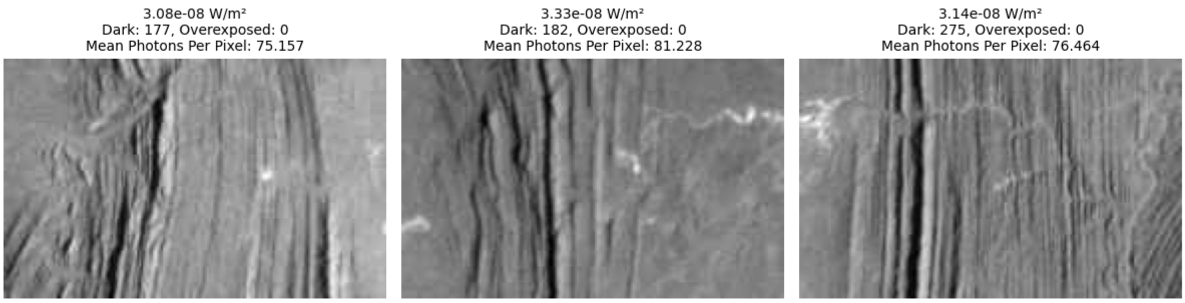

Fig. 2. Image sections with measured values of mean illumination intensity per pixel

Results and discussion

If a laser with a beam divergence (**θ**) of 3 mrad and 3W power (*P*) is stationed at the ground station, the spot size at a distance (*L*) of 500 km – 1200 km will vary from 1.5 km to 12 km, and the intensity (*I*) of the radiation will approximate values from 10^{-6} to $3 \cdot 10^{-8}$:

$$I = \frac{P}{\pi \left(\frac{\theta L}{2} \right)^2}. \quad (1)$$

Upon hitting approximately one pixel on the sensor matrix, the illumination from the laser will be 1 to 20 times brighter than the average background illumination for the given scenario. This indicates that under lighting conditions corresponding to the captured image, the satellite, as it rises above the horizon, begins to detect the laser beacon with increasing brightness, registering maximum intensity at the moment of passing directly over the ground station. To exclude additional factors complicating the calculations, only the central parts of the image are taken into account.

Conclusion

This study provides an analysis of the optical camera system aboard the "Impulse-1" satellite, specifically focusing on its capability to detect a ground-based laser beacon for precise guidance. The results highlight the critical role of laser power and beam divergence in ensuring reliable detection against varying background illumination conditions, which can fluctuate significantly based on geographical and temporal factors. Using this method, it is possible to calculate the appropriate power and beam divergence for various conditions and geographical locations. Such data may prove useful in the design of a space-based laser communication network that will possess high bandwidth and reduced energy consumption [5, 6].

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