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REALIZATION OF LASER EXPERIMENTS WITH ESA'S GEOSTATIONARY SATELLITE ARTEMIS

A laser communication system was developed for space-to-ground laser-link experiments between the geostationary satellite ARTEMIS (orbital position is 21.5° East, orbital inclination is more than 7.2°) and optical ground-based station in Kyiv. The main elements of the system were implemented into the technology platform located at the Cassegrain focus (F = 10.5 m) of a 0.7-m astronomical telescope. The pointing and spatial correction system of the telescope was developed for tracking unstable geostationary satellites. A short description of the laser terminal of the ground-based telescope and the results of first tests for the beacon beam of the OPALE laser terminal of the satellite are presented.

Introduction. Within the ESA contract and continuing the previous activities [1–4, 7–9], the Main Astronomical Observatory of Kyiv (MAO) developed [5] some technologies to establish an optical communication link with the geostationary satellite ARTEMIS (orbital position is 21.5° East, inclination equals 7.2°). The developed technologies include the satellite tracking system for an astronomical 0.7-m aperture telescope. The telescope tracking system, which is automatically controlled (with the help of micro-step motors), follows the satellite using its calculated coordinates. The rms error of tracking was measured to be less than 0.68 arcsec along the hour axis and less than 0.34 arcsec along the declination axis during 5.2 min of tracking time. These tests were performed while observing ARTEMIS in reflected sunlight (a stellar magnitude of 12) using digital cameras mounted on the technology platform [6].

The digital cameras of pointing and tracking of the satellite, receiving avalanche photodetector (APD) module, laser diode transmitting module, and additional optical, mechanical components such as atmosphere turbulence compensation optical elements, polarization elements for separation between transmitting and receiving beams are implemented on the technology platform located at the Cassegrain focus ($F = 10.5$ m) of the AZT-2 telescope.

Short descriptions of developed modules and subsystems as well as the results of first tests of the beacon beam of the OPALE (Optical Payload Laser Experiment) laser terminal of the ARTEMIS satellite are presented in the paper.

An overview of the satellite and ground-based systems. At present ARTEMIS is a geostationary satellite with the increasing inclination. Its position on the sky is currently fluctuating up to ±7.2° in the North – South direction.

ARTEMIS is a multipurpose communication satellite with radio frequency communication terminals of the Ka, Ku, S, L bands and OPALE laser communication terminal onboard. Table gives the general parameters for the OPALE terminal.

The ground-based laser communication terminal is bound to receive signals from the OPALE terminal (Table) and to send a narrow laser beam in 843–853 nm spectral band with none or 49.3724 Mbps NRZ modulations and left-hand circular polarization.

AZT-2 of the MAO is a reflector-type telescope. The primary telescope mirror is 700 mm in diameter. The diameter of the secondary hyperbolic mirror of the Cassegrain system is 215 mm. The equivalent focus of the Cassegrain system is 10500 mm. The telescope is equipped with the refractor guide having an objective of 200 mm and a focus distance of 2500 mm.

The technological platform with implemented individual components for performing laser communication experiments with the ARTEMIS satellite is

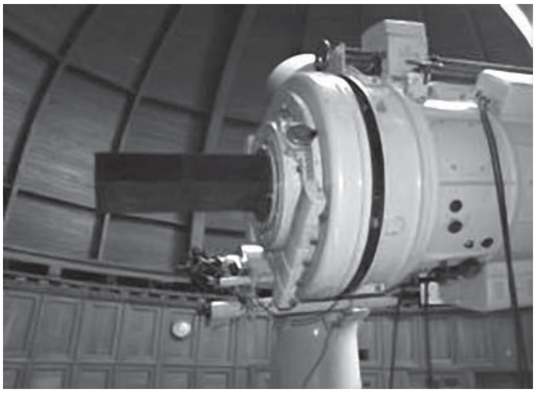

Fig. 1. The AZT-2 telescope with the technological platform in its Cassegrain focus

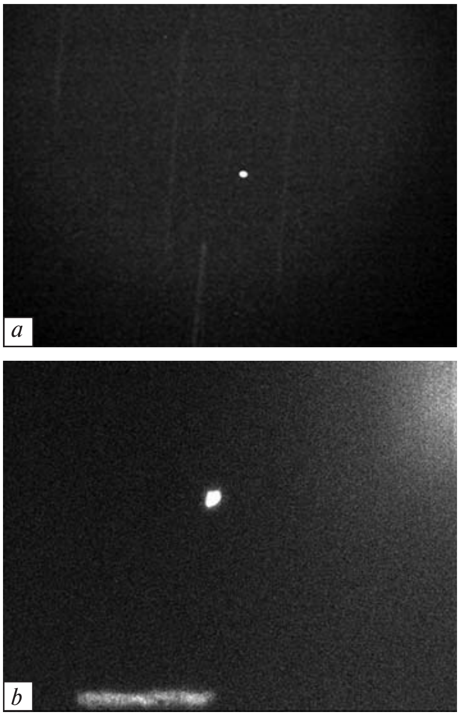

Fig. 2. ARTEMIS and star track images obtained with the use of the pointing camera (*a*) and the tracking of ARTEMIS by CCD camera (*b*)

connected with the Cassegrain focus of the AZT-2 telescope. Fig. 1 gives the common view of the technological platform connected with the telescope.

Pointing and tracking digital cameras. Digital cameras for pointing and tracking of the satellite are implemented on the technology platform. Pointing digital camera works with the focal reducer (from 10 m to 5 m), it has the CMOS sensor with 2000××3000 pixels and its field of view is 10.6×16 arcmin. It can operate with time exposures from 1/1000 to 30 s and more. The focal reducer for the Cassegrain focus was constructed and installed on the technology platform. The following picture shows an example of the ARTEMIS images pointed with the use of this camera.

Another small digital CCD camera (ADC is 16 bits) for tracking of the satellite works without any focal reducer. It has thermoelectrically cooling of a CCD sensor (596×795 pixels) and its field of view is equal to 1.6×2.3 arcmin. The noise level is 0.02 e-/pixel/second and the exposure lies in the range from 1/1000 s to several hours. Fig. 2 gives an image of tracks of the ARTEMIS and a star.

A receiving module. The receiving module is implemented on the technology platform and uses an avalanche photo detector (APD) cooled to a temperature of 4° C and low-noise electronic amplifiers. The sensitivity of the APD system is 0.15 nW in a bandwidth of 8 MHz [3].

Laser transmitting modules. The laser transmitting system uses a laser diode module, which is thermoelectrically stabilized in the temperature range from 8 to 25°C. The laser diode power is 150 mW, wavelength equals 851 nm. Laser modulation is possible with data rates up to 50 Mbps. The electronic module of power and thermoelectric stabilization is situated outside the technology platform.

Oscillators and a BER test module. The electronic module for generation of 49.3724 MHz, PRBS-15

General Parameters of OPALE Terminal

Beam	Beam divergence (FWHM)	Irradiation at Ground Station	Wave-length	Modulation	Polarization
Beacon beam	750 µrad	5 nW/m^2	801 nm	none	none
Communication beam	5.5 µrad	30 nW/m^2	819 nm	none or 2.048 Mbps NRZ	Left-hand circular

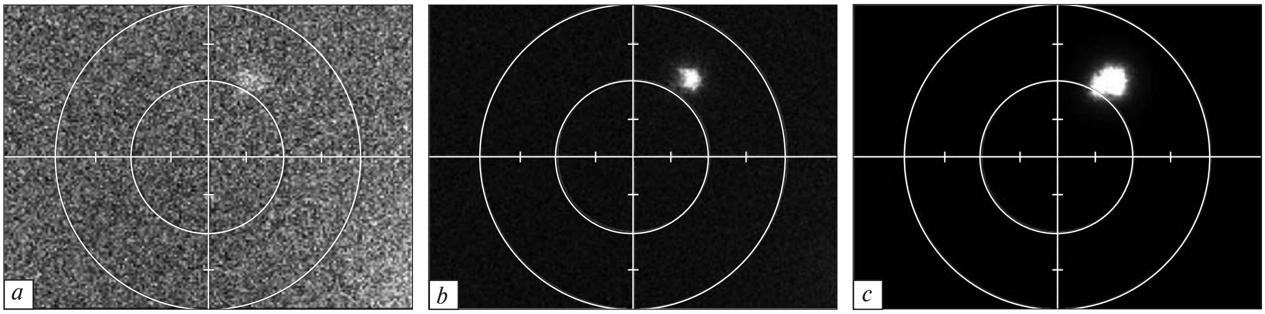

Fig. 3. *a* — ARTEMIS before the beacon start, *b* — the signal after the beacon start, *c* — the beacon signal maximum

(Pseudo Random Bit Sequence) signals and BER (Bit Error) test scheme was produced. To achieve 49.3724 Mbps, the 100 MHz oscillator with the temperature stability less than 5 ppm in the temperature range from –10° C to +60° C and a digital synthesizer is used. This electronic block with a generator and PRBS-15 modulation for a laser beam was produced and adjusted. The frequency was measured and turned out to be 49372320 Hz. The deviation from the nominal frequency is 80 Hz, that equals 1.6 ppm. This value is acceptable for the communication link. The BER test scheme for receiving and testing of 2.048 Mbps laser signals from OPALE was produced in the same module.

Precision of tracking and turbulence compensation. For the precision of tracking of the satellite and for turbulence compensation, the multi-element (six elements) quadrant photodetector (QPD) module was developed. It operates with the laser moving module. The electronic module of power and precision tracking is situated outside the technology platform.

A quarter wave plate (QWP). To transform the linear polarization of the laser module into the necessary left-hand circular polarization, we use an achromatic in a 840–855 nm band λ/4 wave plate. [4].

Additional optical elements. Some additional optical elements such as beam splitters, filters and lenses were also implemented into the technology platform.

OPALE beacon test. There were three sessions of the OPALE beacon scanning during each night on 9 and 10 November. Each scanning started at 19, 20 and 21 UTC and extended over 6 min. The OPALE beacon performed the scanning in a double spiral (3+3 min) during each session. All the sessions of beacon scanning of the first night (9 November) were recorded.

We calculated some part of the beacon images recorded at 21:00 on 9 November. Altogether, 478 images during 6 min of beacon scanning were obtained. We received the beacon signal during all the scanning time (6 min) beyond the time when the beacon beam was oriented to our telescope. We assume that it was a result of the scattering of the beacon beam by atmosphere aerosols. The first maximum of the beacon signal was received within 15 s after turning on the beacon. The second maximum was seen within 19 s after turning on the beacon. This situation repeated 3 min later.

We started observations of ARTEMIS in reflected sunlight before the start of the beacon with an exposure of 0.05 s. We observed bright beacon peaks and a small peaks when the beacon passed close to us. Fig. 3 gives the ARTEMIS images before and after the start of the beacon operation. The exposure was stable during all the observations and was equal to 0.05 sec. Fig. 3a shows an image of ARTEMIS before the beacon start (3.4×10^{-5} nW). Fig. 3b illustrates an image of the beacon beam after the start ($1.3 \times \times 10^{-3}$ nW). Fig. 3c shows the maximum of the beacon signal (2 nW) when the beacon passed across the observatory position.

We did not calculate all beacon images. Fig. 4 shows the brightness of the beacon during the first scan and after the start of the second scan. We observed similar not bright beacon peaks when the beacon was close to us.

Fig. 5 gives coordinated deviations of the beacon beam during the first scan. A calculated mean devia-

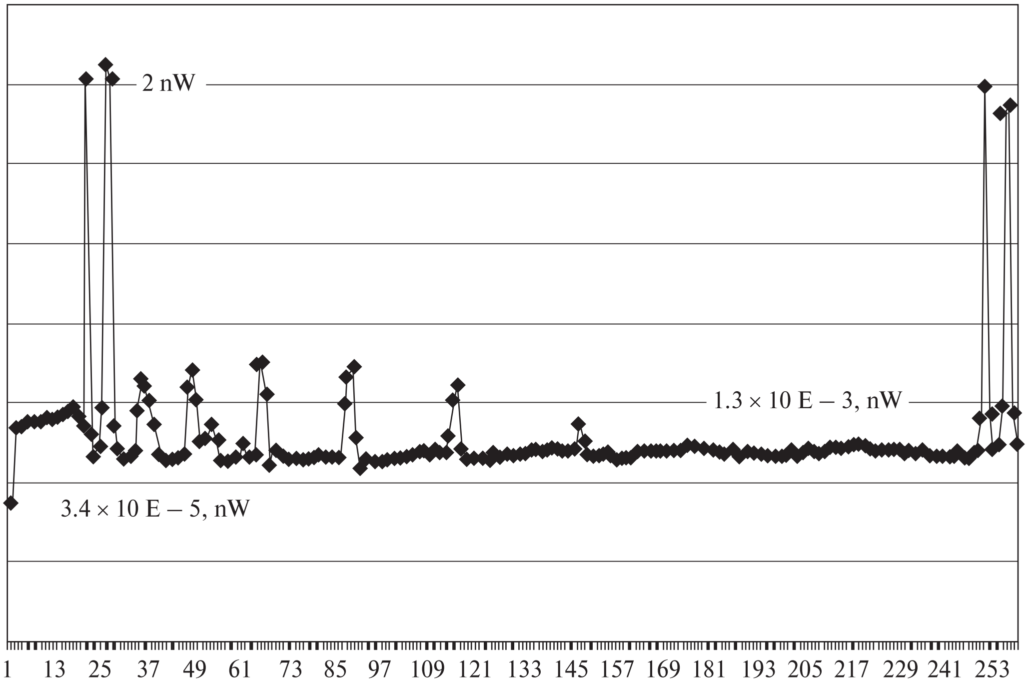

Fig. 4. Photometric data on the first beacon scan and a part of the second scan (258 images) from 21:00 UTC Quarter moon period. Exp. is 0.05 s, cycle is 0.78 s

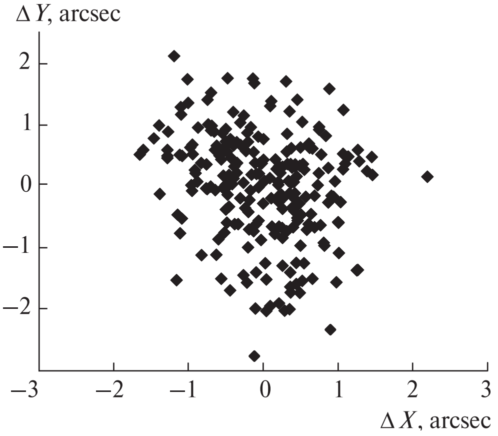

Fig. 5. A deviation of the ARTEMIS position during the first beacon scan. 236 images from 21:00 UTC, 9.11. 2008

tion for the beacon beam (Fig. 5) was $X = 0.56$ arcsec and $Y = 0.69$ arcsec.

The ARTEMIS beacon beam (750 micro radians) intensity on the Earth's surface is 5 nW/m^2.

According to the attenuation by the telescope and optical elements, the maximum beacon signal observed by the CCD camera was approximately 2 nW (the exposure was 0.05 s). From calculating the ARTEMIS signal before the beacon start, we estimated the signal/noise ratio for the maximum beacon signal of the CCD camera (the exposure was 0.05 s) as 5.9×10^4 while the beacon passed across the telescope position.

The ARTEMIS communication beam (5.5 micro radians) intensity on the Earth's surface is 30 nW/m^2. The expected power at APD level after passing the signal across the telescope and optical elements is 9 nW. The APD receiving block sensitivity is 0.15 nW in the frequency band from 0 to 8 MHz. The calculated signal/noise ratio for the communication signal is about 30 for a 0.7-m telescope.

Conclusions. A laser communication system was developed for space-to-ground laser-link experiments between the ARTEMIS satellite and optical ground-based station in Kyiv. The main elements of the system were implemented into the technology platform located at the Cassegrain focus ($F = 10.5$ m) of a 0.7-m astronomical telescope. The first laser experiments with the ARTEMIS satellite were performed. The OPALE laser terminal of ARTEMIS performed spiral scanning of the MAO optical ground-based station. The receiving system detected the beacon during all the period while the beacon was operating (6 min for every time). We assume that it was the scattering of the laser beam by atmosphere aerosol particles. The first maximum of the beacon signal was received within 15 s after turning on the beacon. The second maximum was received within 19 s after turning on the beacon. This situation repeated 3 min later. The mean deviation of the beacon beam position during the beacon scan was $X = 0.56$ arcsec and $Y = 0.69$ arcsec. The signal/noise ratio for the maximum beacon signal was 5.9×10^4 for an exposure of 0.05 s of the CCD tracking camera. The expected signal-to-noise ratio for the communication signal is about 30. Signals are suitable for performing laser link experiments with the ARTEMIS satellite.

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РЕАЛІЗАЦІЯ ЛАЗЕРНИХ ЕКСПЕРИМЕНТІВ ГЕОСТАЦІОНАРНИМ СУПУТНИКОМ ЄКА ARTEMIS

Розроблено лазерну комунікаційну систему для експериментів між геостаціонарним супутником ARTEMIS (положення на орбіті 21.5° с. д., нахил орбіти 7.2°) і наземною оптичною станцією в Києві. Головні елементи системи вбудовано в технологічну платформу, розташовану у фокусі Кассегрена ($F = 10.5$ м) 70-см астрономічного телескопа. Розроблено систему наведення і корекції руху телескопа для супроводження нестабільних геостаціонарних супутників. Дається короткий опис лазерного терміналу наземного телескопа і результати перших тестувань лазерного маяка супутникового лазерного терміналу.