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LASER EXPERIMENTS IN LIGHT CLOUDINESS WITH THE GEOSTATIONARY SATELLITE ARTEMIS

The geostationary satellite ARTEMIS was launched in July 2001. The satellite is equipped with a laser communication terminal, which was used for the world's first inter-satellite laser communication link between ARTEMIS and the low earth orbit satellite SPOT-4. Ground-to-space laser communication experiments were also conducted under various atmospheric conditions involving ESA's optical ground station. With a rapidly increasing volume of information transferred by geostationary satellites, there is a rising demand for high-speed data links between ground stations and satellites. For ground-to-space laser communications there are a number of impor-tant design parameters that need to be addressed, among them, the influence of atmospheric turbulence in different atmospheric condi-tions and link geometries. The Main Astronomical Observatory of NAS of Ukraine developed a precise computer tracking system for its 0.7 m AZT-2 telescope and a compact laser communication package LACES (Laser Atmosphere and Communication Experiments with Satellites) for laser communication experiments with geostationary satellites. The specially developed software allows computerized tracking of the satellites using their orbital data. A number of laser experiments between MAO and ARTEMIS were conducted in partial cloudiness with some amount of laser light observed through clouds. Such conditions caused high break-up (splitting) of images from the laser beacon of ARTEMIS. One possible explanation is Raman scattering of photons on molecules of a water vapor in the atmosphere. Raman scattering causes a shift in a wavelength of the photons. In addition, a different value for the refraction index appears in the direction of the meridian for the wavelength-shifted photons. This is similar to the anomalous atmospheric refraction that appears at low angular altitudes above the horizon. We have also estimated the atmospheric attenuation and the influence of atmospheric turbulence on observed results. The results and interpretations are presented in the paper.

Keywords: laser communication, satellite, atmosphere, clouds, scattering.

1. INTRODUCTION

Series of laser communication sessions between the geostationary (GEO) satellite ARTEMIS and the low Earth orbit (LEO) satellite SPOT-4 were conducted between April 1, 2003 and January 9, 2008 covering in total 378 hours [21]. Laser communication experi-ments in various atmospheric conditions were also performed between ARTEMIS and ESA's optical ground station (OGS) located at Canary Islands (al-titude 2400 m) [1, 15, 16, 19]. The Japanese Space Agency (JAXA) launched its own low-earth orbit satellite KIRARI (OICETS) with the laser commu-nication terminal LUCE. Successful links were es-tablished between it and ARTEMIS satellite, as well as with the optical stations in Japan (NICT) [4, 22, 23]. Similar tasks were accomplished by the Ger-man Space Agency (DLR) and TESAT Company, using two LEO satellites, TerraSAR-X and NFIRE, demonstrating data transfer rates of 5.6 Gb s^{-1} at a distance of up to 5,100 km using Binary Phase Shift Keying (BPSK) modulation [13, 14, 18].In the fol-lowing years, NASA developed a space laser commu-nication terminal (LCT) that utilizes pulse position modulation. It was used on the Lunar Atmosphere and Dust Environmental Explorer (LADEE) space-craft, which was launched on September 6, 2013. In October 2013, durinmodulationg the link from a lunar orbit to an optical ground station on Earth (beam propaga-tion distance 380000 km), data rates up to 622 Mb s^{-1} were achieved [2, 20]. Above that, the distance be-tween the lunar satellite and OGS was measured to an accuracy of 10 mm.

Currently, ESA is developing the European Data Relay Satellite (EDRS) system that will use the la-ser communication technology to transmit data from the LEO satellites Sentinel-1 and -2 to GEO satellites EDRS-A and -C (positions are 9 and 31° E, respectively). The user data rates will be up to 1.8 Gb s^{-1} at a distance of 45000 km. The satellite EDRS-A was launched on January 2016 and the launch of EDRS-C is planned for 2017 [3]. The preceding ESA project in this field, ALPHASAT satellite, with the TESAT LCT onboard for communication experiments with LEO satellites, and with OGS, was launched in 2013 (position is 25° E).

The Main Astronomical Observatory of NAS of Ukraine (MAO) developed its own laser commu-nication system for the 0.7 m AZT-2 telescope in Kyiv. The work was supported by the National Space Agency of Ukraine and ESA. The new instrument combines a highly accurate computerized tracking system for the telescope and a compact laser communication terminal LACES (Laser Atmosphere and Communication Experiments with Satellites) [9—11]. Most of the subsystems are mounted on the platform at the Cassegrain focus (F = 10.5 m) of the telescope.

All of the equipment was tested with LCT OPALE onboard of ARTEMIS. Established laser links between LACES terminal of AZT-2 telescope and OPALE LCT onboard ARTEMIS were held for 20 minutes. After the OPALE beacon scan stopped, OPALE and LACES terminals kept targeting their telescopes. The divergence of a laser beam from AZT-2 was approximately 1.5 arc seconds. Maximum signal strength achieved of OPALE was 90 nW m^{-2}. Short communication links were sustained in total 6 minutes [5, 12]. Some of the laser experiments with ARTEMIS satellite were also performed through thin cloud layers and tentative results were presented at the conference [8]. Details of these experiments and interpretation of the results are described below.

2. CONDITIONS OF OBSERVATIONS AND LASER EXPERIMENTS

2.1. Conditions of observations. Laser sessions with ARTEMIS must be programmed one week in forward and it is quite difficult to get a precise weather forecast. In case of cloudy skies, the Redu station is informed and onboard programmed sessions are stopped to save resources of the satellite. During the night on October 26, 2011, 3 sessions at 19, 20 and 21:00 UTC were recorded with a partially covered sky.

The LACES terminal includes a laser module, pointing and tracking digital cameras, which are working in a Cassegrain focus of AZT-2 telescope. The digital camera for pointing has a color CMOS sensor with a resolution of 3072×2048 pixels and a focal reducer. As a result, equivalent focus of the telescope is 2 times shorter. A field of view of the camera is 15.67×9.86 arc minutes. The tracking CCD (16-bit ADC) camera has a resolution of 752×582 pixels with a field of view 2.05×1.53 arc minutes and works at the telescope focus near to 10.85 m.

The beacon of OPALE terminal transmits in the wavelength band 797—808 nm with a beam divergence of 750 μrad. During the acquisition phase, OPALE performs spiral scanning around its initial position with a maximum radius of 3.5—3.7 mrad. During each session, two scans are performed with a duration of 3 minutes per scan. For a distance of 38100 km the spot size of the beacon on ground is approximately 29 km in diameter In addition, OPALE has a narrow (7.5 μrad) beam at λ = 819 nm. During the sessions on October 26, this narrow beam wasn't used.

Typical photometry data sample of OPALE during the beacon scans is shown in Fig. 1. Bright peaks indicate a light coming from the laser beacon of OPALE during the scans of the position of our telescope. A pixel binning scheme 2×2 for the CCD camera was used in all the sessions. The scale of the CCD is 0.327 arcsec per pixel along the $X(\alpha)$ axis and 0.316 arcsec per pixel along the $Y(\delta)$ axis.

2.2. Session 1 (19:00 UTC).

Before the session, the telescope has been pointed at ARTEMIS and began its automatic computerized tracking. The sky was partially clouded at this time.

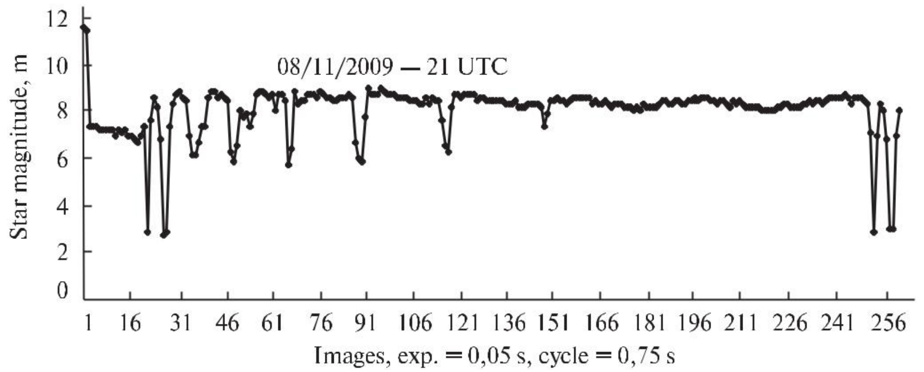

Fig. 1. Photometric data of ARTEMIS during the beacon scan

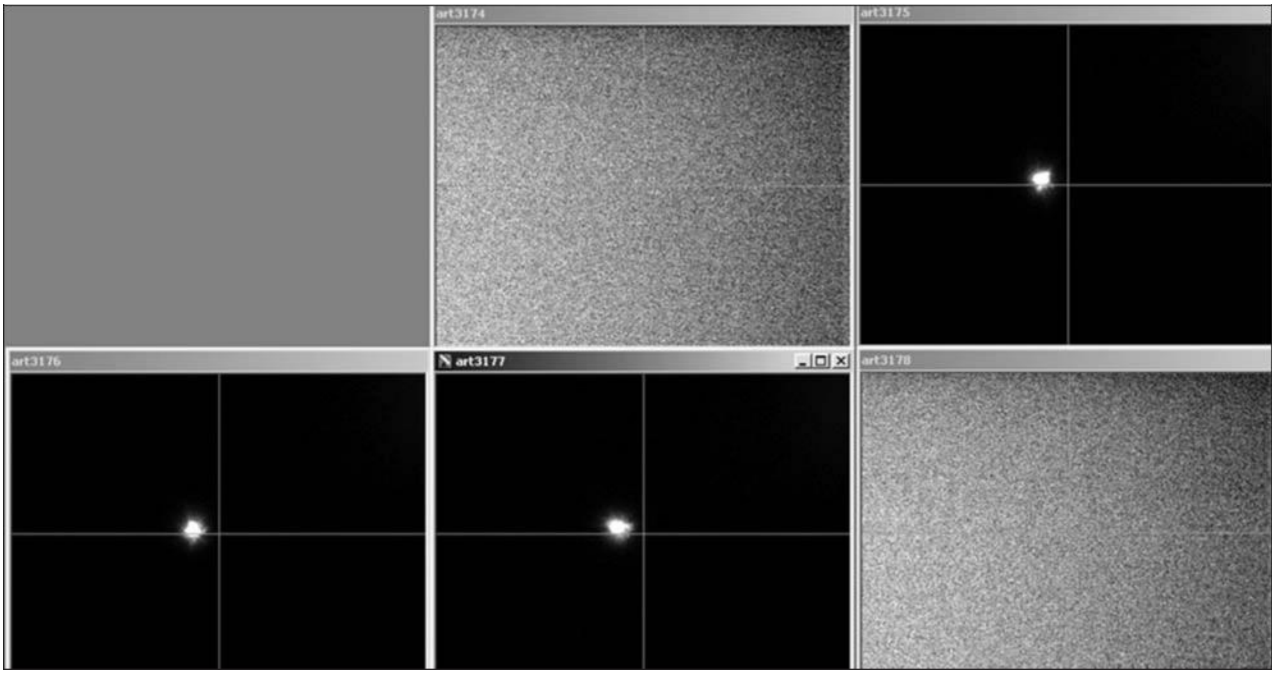

Fig. 2. Frames “art 3174” — “art 3178”. Opale laser beam through clouds: “art 3175” — “art 3177”

Table 1. **Session 1.**
ARTEMIS observation parameters

# Art-image	Time hh:mm:ss	Stellar magnitude, m	Notes
art 3174	19:02:52	—	clouds
art 3175	19:02:56	7.642	active beacon
art 3176	19:03:00	7.426	active beacon
art 3177	19:03:04	7.500	active beacon
art 3178	19:03:08	—	clouds

The exposures were 2 seconds long with a time interval of 2 seconds be-tween them, so the full duration of an image cycle was 4 seconds. The elevation angle of the satellite above the horizon was 22 degrees. The photometry data for ARTEMIS satellite during the beacon scans in light cloudiness is shown in Table 1.

Recorded images (art 3174 — art 3178) with and without the beacon beam visible through the clouds are given in Fig.2. The centre of each image is marked with a crosshair.

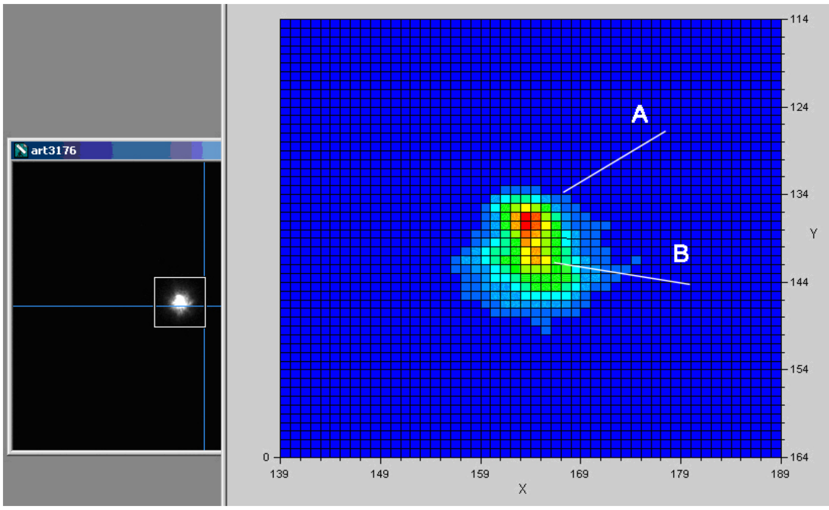

Fig. 3. The 2-D view of the frame “art 3176”

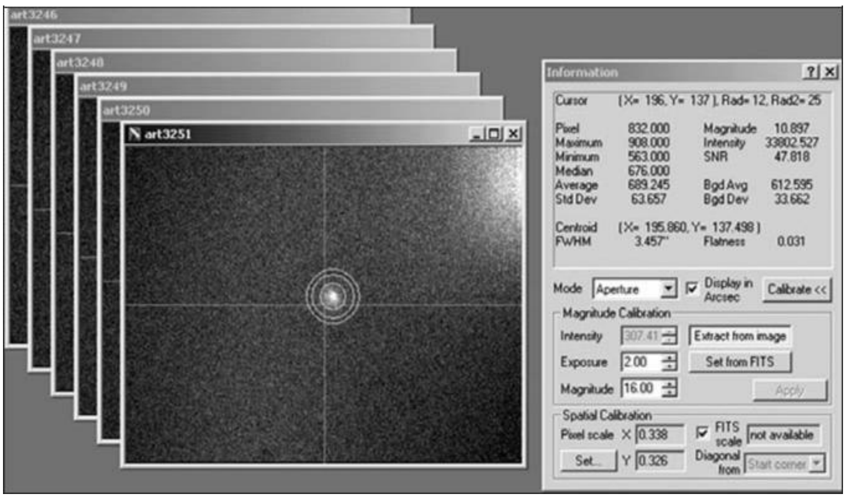

Fig. 4. Coordinate measurements of the “art 3251” frame

In the cloudy conditions the splitting of the laser beam into 2 components, A and B, is visible in the frame “art 3176” (Fig. 3). The angular separation between the components is $\Delta X(\alpha) = 0.327''$, $\Delta Y(\delta) = 1.58''$. There is no the splitting of the laser beam registered in the frame “art3177”. We did not observe wide splits of laser beacon beam during the second beacon scan.

By the end of the beacon scan, at the time period of 19:07:42 — 19:08:02 the sky cleared and the satellite became visible in the reflected sunlight. Later, the sky overcast again.

Previously, we initiated the comparative studies of the atmospheric turbulence instability for two telescopes, ESA OGS and MAO AZT-2, and different elevation angles [6]. Further, the comparative investigations of relative motion correlations of binary stars’ components to determine the local atmo-spheric turbulence were carried out. Their results are presented in [7]. The next step is the measurements of the satellite’s position on the frames obtained in reflected sunlight to estimate the possible influence of atmospheric turbulence on the results of observa-tions. An example of satellite photometric centroid

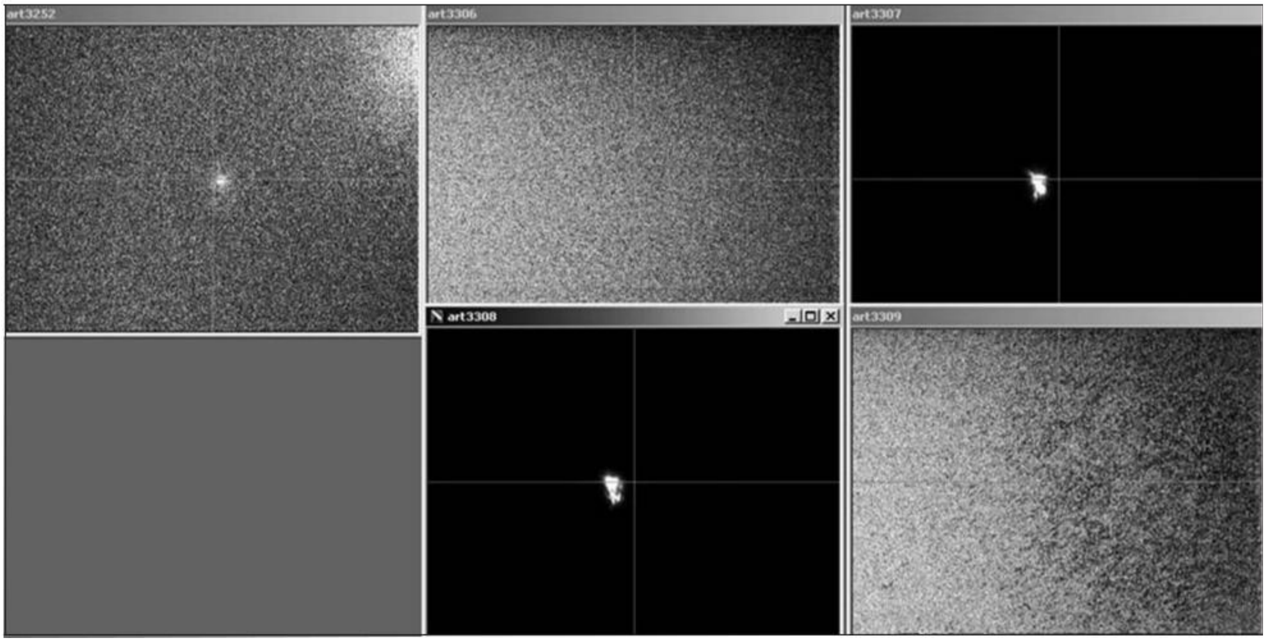

Fig. 5. Frames “art 3252”, “art 3306” — “art 3309”. ARTEMIS laser beam through clouds: “art 3307” and “art 3308”

Table 2. **Satellite coordinates’ measurements in reflected sunlight**

Image #	Time obs.	Centroid X, pixels	Centroid Y, pixels	ΔX, pixels, (arc sec)	ΔY, pixels, (arc sec)
art 3246	19:07:42	190.391	133.412	—	—
art 3247	19:07:46	191.720	133.812	1.329 (0.435″)	0.400 (0.126″)
art 3248	19:07:50	193.330	132.483	1.610 (0.526″)	—1.329 (—0.420″)
art 3249	19:07:54	192.421	134.886	—0.909 (—0.297″)	2.403 (0.759″)
art 3250	19:07:58	193.814	136.491	1.393 (0.456″)	1.605 (0.507″)
art 3251	19:08:02	195.860	137.498	2.046 (0.669″)	1.007 (0.318″)

Table 3. **Session 2.**
ARTEMIS observation parameters

# Art-image	Time hh:mm:ss	Stellar Magnitude, m	Notes
art 3306	20:03:33	—	clouds
art 3307	20:03:37	7.188	max.beacon
art 3308	20:03:41	6.318	max.beacon
art 3309	20:03:45	—	clouds
art 3349	20:06:26	—	clouds
art 3350	20:06:30	7.745	max.beacon
art 3351	20:06:34	7.776	max.beacon
art 3352	20:06:38	—	clouds

calculations performed using the Maxim DL-Pro5 software is presented in Fig. 4. The results of the measurements are in Table 2.

With the full time interval T = 20 seconds and total drifts ΔX = 5.469 pixels or 1.79″ and ΔY = 4.086 pixels or 1.29″, the drift for 2 seconds of exposure along $X(\alpha)$ axis is ΔX = 0.547 pixels or 0.179″ and the same one along $Y(\delta)$ is ΔY = 0.409 pixels or 0.129″. The last two columns of Table 2 show that deviations of photometric centroids of each image relative to the previous one are less than 0.669″ for X direction and 0.759″ for Y one. It is significantly less than the splitting in the frame “art 3176” , $\Delta Y(\delta)$ = 1.58″.

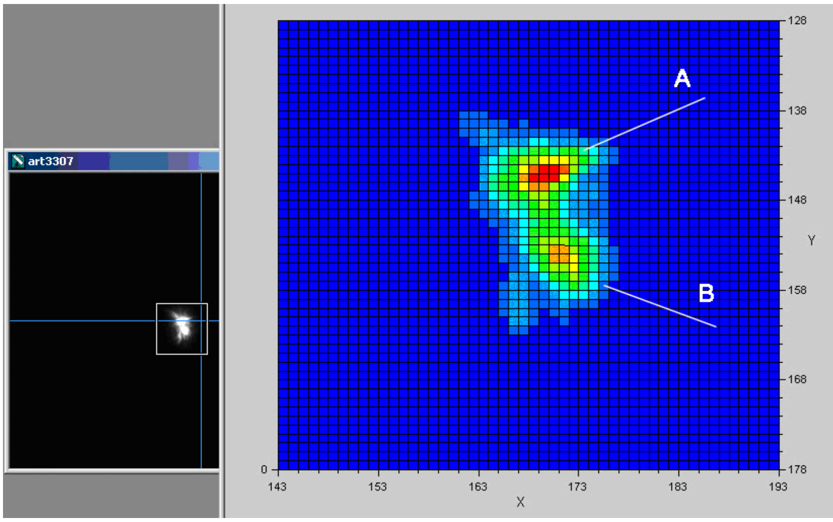

Fig. 6. 2-D view of the frame “art 3307”

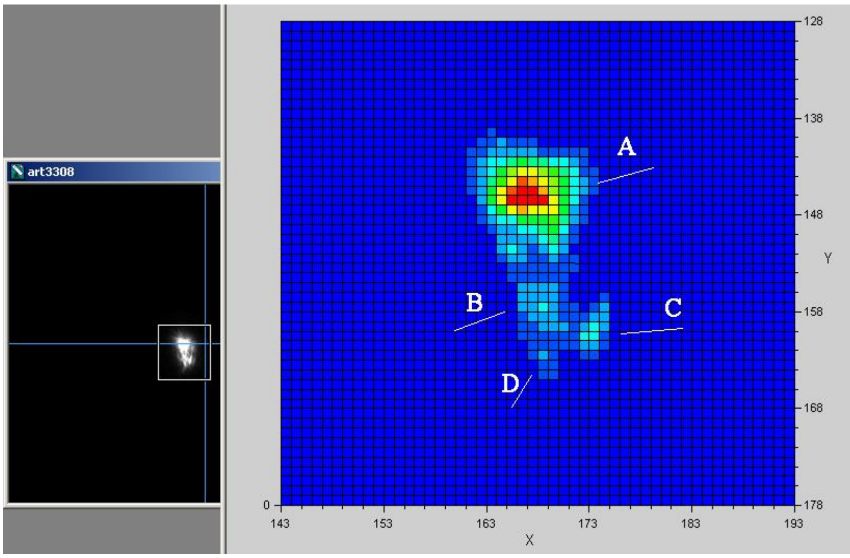

Fig. 7. 2-D view of the frame “art 3308”

2.3. Session 2 (20:00 UTC). Session 2 was also held with automatic tracking of ARTEMIS. Shortly before the start of the session, the cloudiness appeared. The recording started at $20^h00^m04^s$. The exposures were 2 seconds long during the whole session. The elevation angle of the satellite was 23 degrees. Session 2 photometry data of ARTEMIS are shown in Table 3.

The recorded images of this session are given in Fig. 5 – Fig. 10.

The laser beacon of ARTEMIS is visible through the clouds in “art 3307” and “art 3308” images. For the “art 3307” image (Fig. 6), a splitting of the laser beam was observed. The angular separation between components A and B was: ΔY = 2.844″, ΔX = 0.327″. Fig. 7 shows the large splitting along Y and a small one along X axes in “art 3308” image. The angular separation was: ΔY = 3.792″, ΔX = 0.632″ between A and B components, ΔY = 4.424″, ΔX = 1.962″ between A and C components, and ΔY= 5.372″, ΔX=0.632”

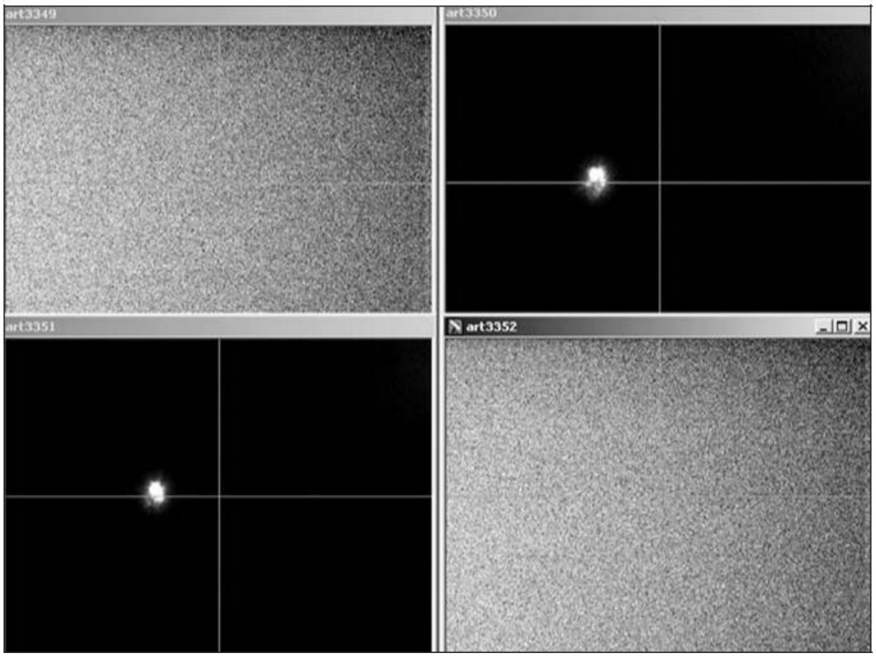

Fig. 8. Frames “art 3349” — “3352”. ARTEMIS beacon beams through clouds: “art 3350” — “art 3351”

Table 4. **Coordinate measurements of the satellite in reflected sunlight**

Image #	Time obs.	Centroid X, pixels	Centroid Y, pixels	$X(\alpha)$, pixels, (arc sec)	$Y(\delta)$, pixels, (arc sec)
art 3377	20:09:41	225.806	149.686	—	—
art 3378	20:09:45	225.693	148.918	−0.113 (−0.037)	−0.768 (−0.243)
art 3379	20:09:49	226.846	147.671	1.153 (0.377)	−1.247 (−0.394)
art 3380	20:09:53	229.585	148.639	2.739 (0.896)	0.968 (0.306)
art 3381	20:09:57	229.280	146.743	−0.305 (−0.099)	−1.896 (−0.599)
art 3382	20:10:01	228.858	142.978	−0.422 (−0.138)	−3.765 (−1.189)
art 3383	20:10:05	230.656	143.727	1.798 (0.588)	0.749 (0.237)
art 3384	20:10:09	233.365	144.516	2.709 (0.886)	0.789 (0.249)
art 3385	20:10:13	233.643	145.490	0.278 (0.091)	0.974 (0.307)
art 3386	20:10:17	233.298	143.921	−0.345 (−0.113)	−1.569 (−0.496)
art 3387	20:10:21	235.170	143.637	1.872 (0.612)	−0.284 (−0.090)

between A and D com-ponents. The next beacon peak observed hrough clouds appeared in “art3350” and “art3351” frames.

For the frame “art3350” (Fig.9), the angular separation along Y does not exceed ΔY = 2.844” and along X it reaches ΔX = 1.962”. The same data for the frame “art 3351” (Fig.10) are ΔY = 1.896” and ΔX = 1.799”.

To estimate the possible influence of atmospheric turbulence on the observed results, we also made the coordinate measurements of ARTEMIS on the frames obtained in reflected sunlight after the end of the Session 2 similar to the Session 1. The results are presented in Table 4.

With the time interval ΔT = 40 secomds, total drift ΔX = 9.364 pixels or 3.06” and ΔY = – 6.049 pixels

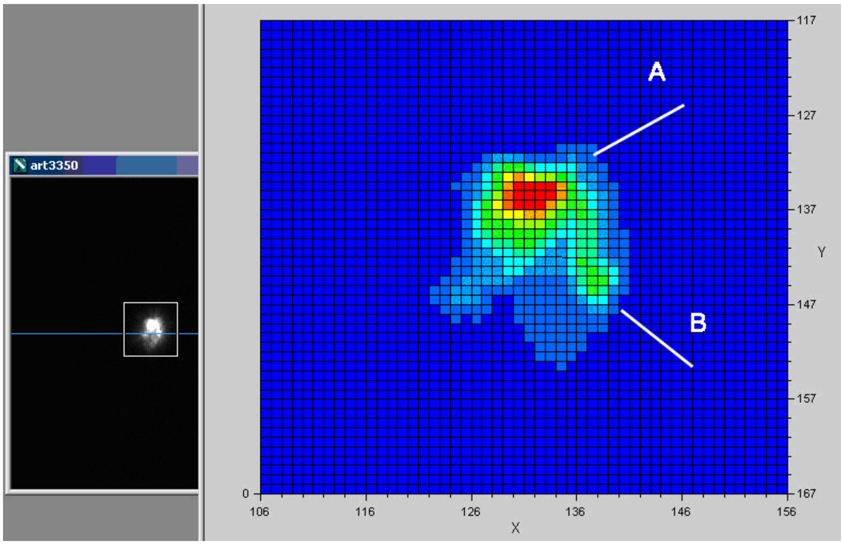

Fig. 9. 2-D view of the frame “art 3350”

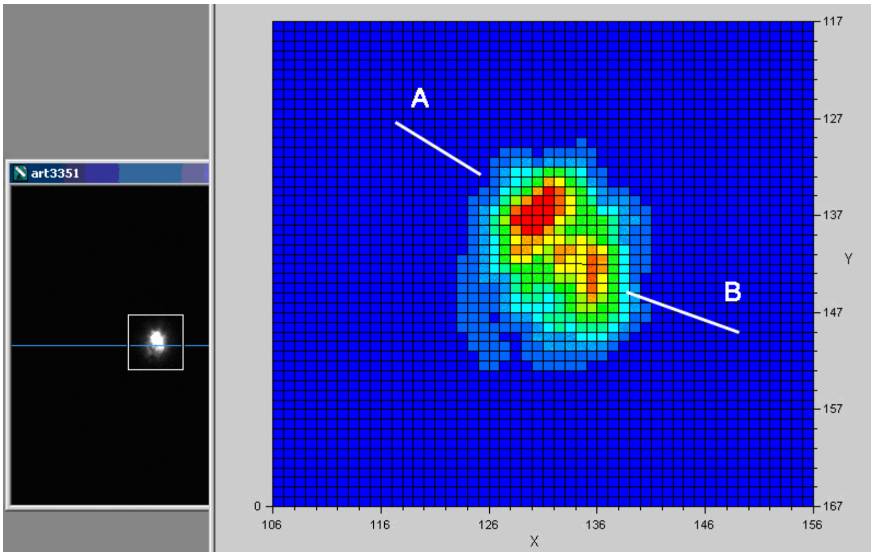

Fig. 10. 2-D view of the frame “art 3351”

or –1.91”, the drift for 2 seconds of exposition along $X(\alpha)$ axis is ΔX = 0.468 pixels or 0.153″ and the same one along $Y(\delta)$ is ΔY = 0.302 pixels or 0.096″. Last two columns of Table 4 show that deviations of photometric centroids of each image in relation to the previous image are less than 0.896″ for *X* direction and 1.189″ for *Y* direction. Both the maximum deviations are less than the splitting of the images.

2.4. Session 3 (21:00 UTC). During the session 3, the weather was clear with some mist and the exposure time was set to 1 second. The maximum beacon signals were observed at $21^h00^m35^s$ and $21^h03^m40^s$. In some exposures, our OGS laser was in operation pointing in the direction to ARTEMIS, and the photometric results were distorted (these time periods are marked as “OGS laser” in Table 5). The photometry

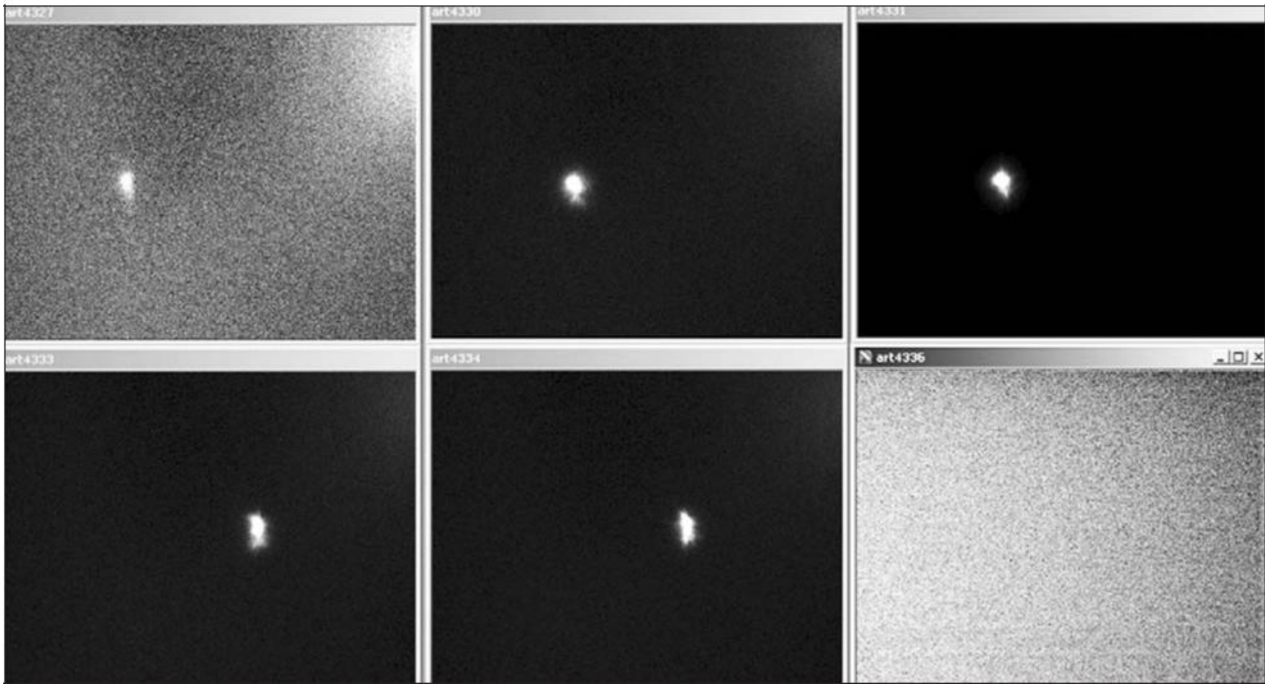

Fig. 11. Frames “art 4327”, “art 4330”, “art 4331”, “art 4333”, “art4334”, “art 4336”

results are presented in Table 5. The satellite elevation angle was 25 degrees.

The CCD frame “art 4331” (Fig. 12) was observed overexposed. The maximum separation between components was Δ*Y* = 3.476″ and Δ*X* = 1.962″. The frame “art 4388” was obtained with a very high overexposure. The area of overexposed pixels is approximately 9.5″ along the *X* axis and 10.1″ along the *Y* one. A splitting of the laser beam was not observed due to the large area of the signal from the beacon. The coordinate measurements of ARTEMIS in the reflected sunlight after the finish of the Session 3 are given in Table 6.

Table 5. **Session 3. ARTEMIS observation parameters**

# Art-image	Time hh:mm:ss	Stellar magnitude, m	Notes
art 4329	21:00:30	—	OGS laser
art 4330	21:00:32	9.018	active beacon
art 4331	21:00:35	5.601	max. beacon
art 4332	21:00:56	—	OGS laser
art 4335	21:01:10	—	OGS laser
art 4387	21:03:38	9.070	active beacon
art 4388	21:03:40	2.110	max. beacon
art 4389	21:03:43	9.050	active beacon
art 4466	21:07:22	11.992	sun reflected

With the full time interval Δ*T* = 26 seconds and total drifts Δ*X* = 7.352 pixels that is 2.400″ and Δ*Y* = 2.025 pixels or 0.640″, the drift for 1 second of exposition along *X* (α) axis is Δ*X* = 0.092 pixels or 0.030″ and the same one along *Y* (δ) is Δ*Y* = 0.078 pixels or 0.025″. Last two columns of Table 6 show that deviations of photometric centroids of each image in relation to the previous image are less than 0.879″ for *X* direction and 1.212″ for *Y* direction.

2.5. Influence of atmosphere and clouds on laser radiation.

We suggest the following possible explanation for the observed splitting of the image of the laser beam from the ARTEMIS satellite at low elevation angle. The atmosphere can be assumed as a large optical “lens” with nonhomogeneous components. The thickness of the atmosphere in the Earth’s polar regions is less than in the equatorial regions. As a result, a refraction gradient occurs in the meridian direction.

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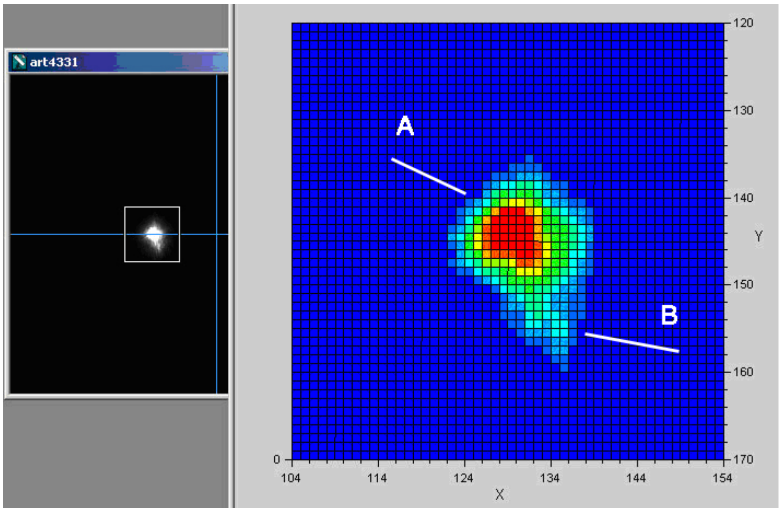

Fig. 12. 2-D view of the frame “art 4331

The beacon transmits laser radiation at the wavelength band 797—808 nm. Clouds have an additional effect on laser radiation from the satellite.

LIDAR systems are intended for the investigation of Raman scattering of the reflected laser radiation on molecules in the atmosphere. They measure the nitrogen vibration-rotation Raman signals at 387 and 607 nm. Along with them, the signals at 407 nm from water vapor molecules were observed.

The direct Raman scattering of laser radiation on molecules of water vapor is the one possible explanation of the results observed. Laser radiation at frequency ν_0 and photon energy $h\nu_0$ interacts with molecules of water vapor with energy $E(1)$:

$$h\nu_0 + E(1) \rightarrow h(\nu_0 - \nu_1) + E(2)$$

The result is $h(\nu_0 - \nu_1) < h\nu_0$ and $E(2) > E(1)$. $E(2)$ is a new, more unstable vibration-rotation energy of water vapors molecules. On the further step:

$$h\nu_0 + E(2) \rightarrow h\,(\nu_0 + \nu_1) + E(1)$$

As a result, the photons with energies $h\nu_0$, $h(\nu_0 - \nu_1)$, $h(\nu_0 + \nu_1)$ appear in clouds. For frequencies ν_0, $(\nu_0 - \nu_1)$, and $((\nu_0 + \nu_1)$ the refractive index of the atmosphere has different values. Photons change their directions after passing through the clouds, and we can observe the splitting of images of the laser beam.

***Table 6*. Coordinate measurements of sun reflected satellite**

Image #	Time obs.	Centroid *X*, pixels	Centroid *Y*, pixels	*X*(α), pixels, (arc sec)	*Y*(δ), pixels, (arc sec)
art 4466	21:07:22	210.978	149.153	—	—
art 4467	21:07:25	211.462	147.888	0.484 (0.158)	−1.265 (−0.399)
art 4468	21:07:28	210.871	148.289	−0.591 (−0.192)	0.401 (0.127)
art 4469	21:07:31	208.182	146.206	−2.689 (−0.879)	−2.083 (−0.658)
art 4470	21:07:34	208.169	150.043	−0.013 (−0.004)	3.837 (1.212)
art 4471	21:07:36	208.149	149.831	−0.020 (−0.007)	−0.212 (−0.067)
art 4472	21:07:39	208.655	149.363	0.506 (0.165)	−0.468 (−0.147)
art 4473	21:07:42	206.037	148.133	−2.618 (−0.855)	−1.230 (−0.389)
art 4474	21:07:45	204.349	149.644	−1.688 (−0.551)	1.511 (0.477)
art 4475	21:07:48	203.626	151.178	−0.723 (−0.236)	1.534 (0.485)

Raman scattering may have a strong effect on the passage of a laser beam through the atmosphere in a case of very narrow interference filters using.

CONCLUSIONS

The unique laser experiments between MAO and the geostationary satellite ARTEMIS were conducted in a partial cloudiness conditions. Some amount of laser light from the satellite was observed through the clouds by tracking CCD camera. Maxim DL-5 Pro standard software was used for image processing. The observational conditions caused the phenomenon of a high splitting of the laser beam transmitted by the ARTEMIS and received at the optical ground station at small elevation angles. One possible explanation of the obtained results is Raman scattering of laser photons on molecules of a water vapor in the atmosphere. Raman scattering causes the shift in a wavelength of laser photons. As a result, a different value of the refraction index appears for the wavelength-shifted photons in the meridian direction. This is similar to the anomalous atmospheric refraction that appears on low angular altitudes above the horizon.

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ЛАЗЕРНІ ЕКСПЕРИМЕНТИ
З ГЕОСТАЦІОНАРНИМ СУПУТНИКОМ
ARTEMIS КРІЗЬ ТОНКІ ХМАРИ

У липні 2001 р. було запущено геостаціонарний (ГЕО) супутник ARTEMIS с лазерним комунікаційним термі-налом на борту, яким вперше у світі проведено лазерні комунікаційні сеанси між супутником ARTEMIS і низь-коорбітальним супутником SPOT-4. Провадилися також лазерні комунікаційні експерименти між наземною оптичною станцією (НОС) ЄКА і супутником ARTEMIS у різних атмосферних умовах. Об'єми інформації, що надходять із ГЕО-супутників, швидко збільшуються, і виникає потреба у швидкісних каналах зв'язку с НОС на ГЕО-супутники. Для лазерної комунікації з наземної станції на супутник важливими факторами є вплив ат-мосферної турбуленції при різних атмосферних умовах і конструктивні особливості. Головна астрономічна об-серваторія Національної академії наук України розроби-ла прецизійну систему корекції руху 0.7-м телескопа АЗТ-2 і компактний лазерний комунікаційний термінал для ла-зерних атмосферних і комунікаційних експериментів с геостаціонарними супутниками (ЛАКЕС). Спеціальне програмне забезпечення дозволяє супроводжувати супутник по розрахованій орбіті за допомогою комп'ютера. Ряд лазерних експериментів з ARTEMIS проводився в частково хмарних умовах. При цьому спостерігалось сильне розщеплення зображень від лазерного маяка ARTEMIS, можливою причиною якого є раманівське розсіювання фотонів на молекулах води. Розсіювання Рамана призводить до зміни довжини хвилі випромінювання та до різних значень коефіцієнта заломлення зміщених по довжині хвилі фотонів в напрямку меридіана, подібно до аномальної атмосферної рефракції поблизу горизонту. Оцінено атмосферне ослаблення і вплив турбуленції атмосфери на спостережні результати.

Ключові слова: лазерна комунікація, супутник, атмосфера, хмари, розсіювання

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ЛАЗЕРНЫЕ ЭКСПЕРИМЕНТЫ
С ГЕОСТАЦИОНАРНЫМ СПУТНИКОМ
ARTEMIS ЧЕРЕЗ ТОНКИЕ ОБЛАКА

В июле 2001 г. был запущен геостационарный (ГЕО) спутник ARTEMIS с лазерным коммуникационным тер-миналом на борту, которым впервые в мире проведены лазерные коммуникационные сеансы между спутником ARTEMIS и низкоорбитальным (НО) спутником SPOT-4. Лазерные коммуникационные эксперименты между наземной оптической станцией (НОС) ЕКА и спутником ARTEMIS в различных атмосферных условиях также были проведены. Объемы информации передаваемые с ГЕО спутников быстро увеличивается и возникает потребность в скоростных каналах связи с НОС на ГЕО спутники. Для лазерной коммуникации с наземной станции на спутник влияние атмосферной турбуленции в различных атмосферных условиях и конструктивные особенности являются важными параметрами.

Главная астрономическая обсерватория Национальной акаде-мии наук Украины разработала прецизионную систему коррекции движения 0.7 м телескопа АЗТ-2 и компактный лазерный коммуникационный терминал для лазерных атмосферных и коммуникационных экспериментов с геостационарными спутниками (ЛАКЕС). Специальное программное обеспечение позволяет сопровождать спутник с помощью компьютера и рассчитанной орбиты спутника

Ряд лазерных экспериментов с ARTEMIS проводился в частично облачных условиях. При этом часть лазерного излучения от спутника наблюдалась через облака. Сильное расщепление изображений от лазерного маяка спутника ARTEMIS наблюдалось через облака. Атмосферное ослабление и влияние турбуленции атмосферы на наблюдаемые результаты были оценены. Возможное объяснение наблюдаемых результатов есть рассеяние Рамана фотонов излучения на молекулах атмосферы (паров воды). Рассеяние Рамана приводит к изменению длины волны фотонов излучения и до различных коэффициентов преломления для смещенных по длине волны фотонов в направлении меридиана. Это подобно аномальной атмосферной рефракции на малых углах к горизонту. Результаты наблюдений и их интерпретация изложены в статье.

Ключевые слова: лазерная коммуникация, спутник, атмосфера, облака, рассеивание