Proc. International Conference on Space Optical Systems and Applications (ICSOS) 2014, S4-4, Kobe, Japan, May 7-9 (2014)

Laser Experiments with ARTEMIS Satellite in Cloudy Conditions

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***Abstract*—In July 2001, the ARTEMIS satellite with laser communication terminal OPALE on board was launched. 1789 laser communications sessions were performed between ARTEMIS and SPOT-4 (PASTEL) from 01 April 2003 to 09 January 2008 with total duration of 378 hours. In addition ESA's Optical Ground Station (OGS) performed laser communication experiments with OPALE in various atmospheric conditions.**

Since the launch of ARTEMIS, the amount of information handled by geostationary telecommunication satellites has increased dramatically and so has the demand for data rate that needs to be transmitted from ground. With limited bandwidth allocations in the radio frequency bands interest has grown for laser communication feeder link technology. In this respect there is interest to compare the influence of atmosphere conditions in different atmospheric regions with respect to laser transmission. Two locations are being compared, namely ESA's OGS (located in an altitude of 2400 m above sea level) and the Main Astronomical Observatory of Ukraine (MAO) (located at an altitude of 190 m above sea level).

In 2002 MAO started the development of a ground laser communication system for the AZT-2 telescope. The MAO developed compact laser communication system is called LACES (Laser Atmosphere and Communication Experiments with Satellites) [1] and the work was supported by the National Space Agency of Ukraine and by ESA. The beacon laser from OPALE was occasionally detected even in cloudy conditions and an anomalous atmospheric refraction at low elevation angles was observed. The main results of laser experiments with ARTEMIS through clouds are presented in the paper.

Keywords—optical ground station; laser communications; laser experiments; atmosphere; clouds

I. INTRODUCTION

The ARTEMIS satellite with the OPALE laser communication terminal onboard was launched on 12 July, 2001. Laser communications sessions were performed between ARTEMIS and SPOT-4 (PASTEL) with bit rate 50 Mbps by using on-off keying modulation. Regular laser communication experiments between ESA's Optical Ground Station (OGS) at the Canary Islands (in an altitude of 2500 m) and ARTEMIS were performed in various atmosphere conditions [1-6].

The Japanese Space Agency (JAXA) launched in 2006 the KIRARI (OICETS) satellite with a laser communication terminal called LUCE. Laser communication links between KIRARI and ARTEMIS were successfully realized and international laser communications experiments from the KIRARI satellite were also successfully performed with an optical ground station in Japan owned by the National Institute for Information Technology (NICT) [7-10]

The German Space Agency (DLR) and TESAT Spacecom performed laser communication tests between two Low Earth Orbiting (LEO) satellites (TerraSAR-X and NFIRE), demonstrating data rates of 5.6 Gbit/s by using Binary Phase Shift Keying (BPSK) modulation at link distances up to 5,100 km [11-13]. Tests were also performed between the satellites and ESA's optical ground station.

The Alphasat satellite with an upgraded Laser Communication Terminal (LCT) from TESAT Spacecom on board was successfully launched in 2013. The LCT will be used for inter-satellite and space to ground laser communication links with data rates of 1.8 Gbps and link distances up to 45,000 km.

ESA is now developing the European Data Relay Satellite (EDRS) system, which will use laser communication technology to transmit data from the Sentinel 1 and Sentinel 2 satellites in LEO to two geostationary satellites (EDRS-A and EDRS-C) at data rates of 1.8 Gbps.

NASA launched the Lunar Atmosphere and Dust Environmental Explorer (LADEE) spacecraft on 6 September 2013 with a laser communication module on board and demonstrated data rates up to 622 Mbps from lunar orbit back to Earth. Due to the data up link capability ranging was also demonstrated with an accuracy to better than 10 mm.

As the data handling capabilities of state-of-the-art telecommunication satellites in GEO increase so is the demand for the feeder-link bandwidth to be transmitted from ground. This is why there is an increasing interest in developing high bandwidth ground-to-space laser communication systems working through atmosphere.

Therefore there is interest to investigate the influence of the atmosphere on laser beam transmission and the quality of communication in different atmospheric regions.

In 2002 the Main Astronomical Observatory (MAO) started to develop its own laser communication system for its 0.7m aperture AZT-2 telescope, located in Kyiv, Ukraine in an altitude of 190 meters. The work was supported by the National Space Agency of Ukraine and by ESA. MAO developed a highly accurate computerised tracking system for the AZT-2 telescope and a compact laser communication package called LACES (Laser Atmosphere and Communication Experiments with Satellites). The LACES instrument includes a camera for the pointing and tracking subsystems, a receiver module, a laser transmitter module, a tip/tilt atmospheric turbulence compensation subsystem, a bit error rate tester module and other optical and electronic components. The principal subsystems are mounted on a platform, which is located at the Cassegrain focus (f = 10.5 m) of the AZT-2 telescope. All systems were tested in laser communication experiments with ARTEMIS and the data analysis was supported by telemetry received from the ARTEMIS payload control centre in Redu (Belgium). The first laser link between LACES terminal of AZT-2 telescope and OPALE terminal of ARTEMIS was achieved in 2011 [14 - 20].

II. TESTS IN CLOUDY CONDITIONS

Laser sessions with the ARTEMIS satellite have to be scheduled at least one week in advance and it is quite difficult to get precise weather forecast. The ARTEMIS orbital data is entered into a computer which performs the tracking of the satellite before, during and some time after the session. In cloudy weather conditions the session is canceled by telephone call to Redu to save resources on the satellite. During the sessions of 26 October 2011 (19:00 UTC, 20:00 UTC, 21:00 UTC) the sky was partly clouded and the weather conditions were unstable. The AZT-2 telescope was pointed at ARTEMIS, but close to the start of the link it clouded over and it was too late to cancel. The sessions were recorded automatically but assumed to be unsuccessful. Some weeks later when browsing through the images the beacon laser beam from OPALE was found to be visible through the clouds.

The OPALE laser communication terminal on-board ARTEMIS transmits a beacon beam with a wavelength of λ = 801 nm and a communication beam with a wavelength of λ = 819 nm. It receives data in a wavelength range between λ = 845 – 852 nm from other satellites or of from ground stations.

The interest was to determine the atmospheric extinction ration at the beacon wavelength (λ = 801 nm).

The solar irradiance and atmospheric components near 801 nm observed through the atmosphere is given by "An Atlas of the Photospheric Spectrum from 8900 to 13600 cm^{-1} (7350 to 11230 A)" by L. Wallace and K. Hinkle Kitt Peak National Observatory and W.Livingston National Solar Observatory and is presented in Figure 1.

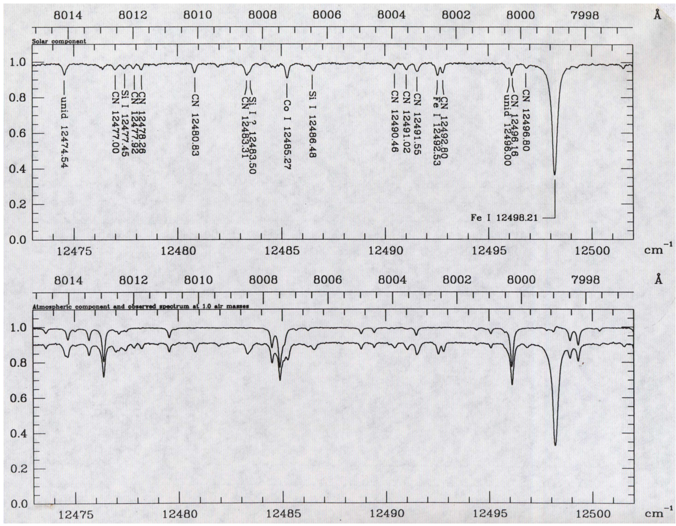

Figure1.Solar spectra of atmosphere in the 797 – 801.5 nm band.

Fig.1 shows that deep atmospheric components and solar lines not exist near 801 nm except for 799.9 nm. The main attenuation of a laser beam would come from H_2O water vapor in clouds and to a lesser extent from scattering on aerosols in the atmosphere. Atmospheric turbulence comparisons with ESA OGS have been previously performed [15-16].

III. POINTING AND TRACKING SUBSYSTEMS

The pointing and tracking digital cameras are implemented in the laser communication terminal called LACES (Laser Atmosphere and Communication Experiments with Satellites), which is located at the Cassegrain focus (f = 10.5 m) of the 0.7 m AZT-2 telescope. An acquisition camera works with a focal reducer (focal length reduction from 10 m to 5 m) and has a CMOS sensor with 2000 x 3000 pixels. The camera's field of view is 10.6 x 16.0 arc minutes and it can operate with exposure times from 1/1000 up to 30 seconds and more. The focal reducer for the Cassegrain focus was constructed and integrated into the technology platform.

Another small digital (CCD 2) camera (16 bit ADC) for satellite tracking works without a focal reducer. CCD2 has a thermoelectric cooling of its sensor (596x795 pixels with pixel size 8.3 μm x 8.6 μm), its field of view is 1.6 x 2.3 arc minutes, the noise level is 0.02 e-/ pixel/second and exposure times are from 1/1000 second up to several hours.

IV. Laser Sessions with ARTEMIS

A. *Session 1 (26 October 2011)*

The ARTEMIS beacon beam divergence is 750 μrad, leading to a 28.5 km beacon beam diameter on the Earth's surface at a distance of 38000 km. The typical optical power from ARTEMIS received in the Cassegrain focus of the AZT-2 telescope during a beacon laser scan is shown in Figure 2. The received power from reflected sunlight amounts 0.034 pW, with change to about 1.3 pW at active laser beacon situation and is increased up to 2 nW when the beacon laser beam passes the OGS position..

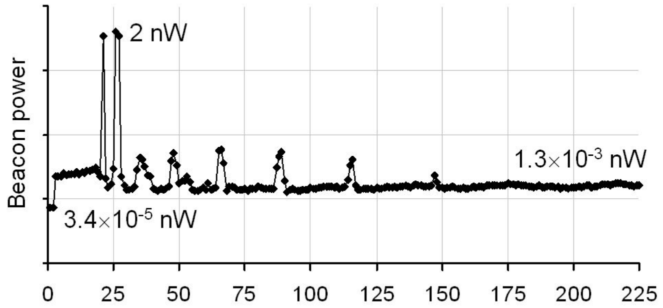

Figure 2. Brightness of ARTEMIS during a single beacon scan

The following operational parameters were recorded:

- Pixel binning: 2x2
- Camera scale: X (α) = 0,338 ″/ pixel and Y (δ) = 0,326 ″/ pixel
- Expose time: 2 seconds
- Elevation angle: 22 degree
- Start of recording: 19h01m19s
- 19h02m56s to 19h03m04s: beacon observed.
- 19h03m08s to 19h06m29s: clouds.
- 19h06m33s to 19h06m41s: beacon observed.
- 19h06m45s to 19h07m38s: clouds.
- 19h07m42s to 19h07m58s: ARTEMIS observed in reflected sun light.

Some results of the ARTEMIS photometry are presented in Table 1.

TABLE 1. ARTEMIS OBSERVATIONS PAREMITERS.

# Art – image	Time hh:mm:ss	Stellar magnitude m	Exposure s	Notes
art 3174	19:02:52	-	2	Clouds
art 3175	19:02:56	7.642	2	active beacon
art 3176	19:03:00	7.426	2	active beacon
art 3177	19:03:04	7.500	2	active beacon
art 3178	19:03:08	-	2	clouds
art 3228	19:06:29	-	2	clouds
art 3229	19:06:33	7.705	2	active beacon
art 3230	19:06:37	7.782	2	active beacon
art 3231	19:06:41	7.839	2	active beacon
art 3232	19:06:45	-	2	clouds
art 3245	19:07:38	-	2	clouds
art 3246	19:07:42	11.763	2	sun reflected
art 3247	19:07:46	11.662	2	sun reflected
art 3248	19:07:50	11.676	2	sun reflected

Table 2 shows the ARTEMIS orbital parameters as determined from ephemeris data via a specially designed software. The precision of the calculation is 1 arc seconds along the declination axis and 1.5 arc seconds along the hour angle. Data obtained from the table is converted into a file which is used by the pointing and tracking subsystems of the AZT-2 telescope.

TABLE 2. ARTEMIS OBIT PARAMITERS

Kyiv AZT-2. 26 October 2011. Satellite ARTEMIS							
Date	Time UTC, hh:mm:ss	Declination, dd:mm:ss	Hour angle, hh:mm:ss	El., deg	D_m, deg	Speed α, arcsec	Speed δ, arcsec
26 Oct	19:00:00	-17 06 59	00 39 11.6	22	122	-0.199	0.635
26 Oct	19:01:00	-17 06 20	00 39 10.8	22	122	-0.198	0.646
26 Oct	19:02:00	-17 05 41	00 39 10.0	22	122	-0.197	0.657
26 Oct	19:03:00	-17 05 01	00 39 09.2	22	123	-0.196	0.669
26 Oct	19:04:00	-17 04 21	00 39 08.5	22	123	-0.195	0.680
26 Oct	19:05:00	-17 03 40	00 39 07.7	22	123	-0.194	0.691

Table 2: ARTEMIS orbit parameters: date, time, declination, hour angle, El. elevation, D_m angular distance from the Moon, angular speeds along hour angle and declination axes.

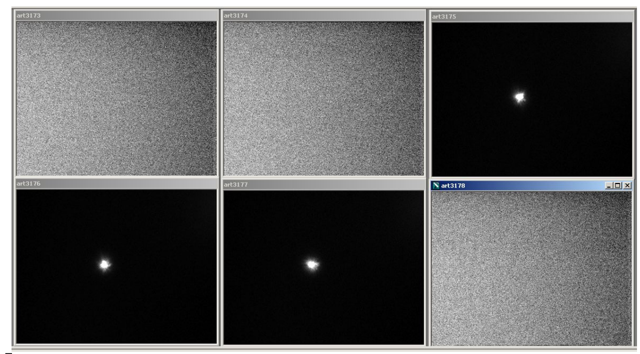

Figure 3. Images art 3174 –art 3178. Laser beacon from ARTEMIS via clouds art 3175 – art 3177

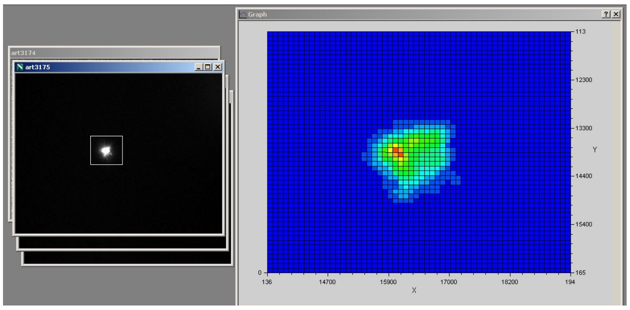

Figure 4. Image art 3175. 3D view of laser beacon from ARTEMIS via cloud

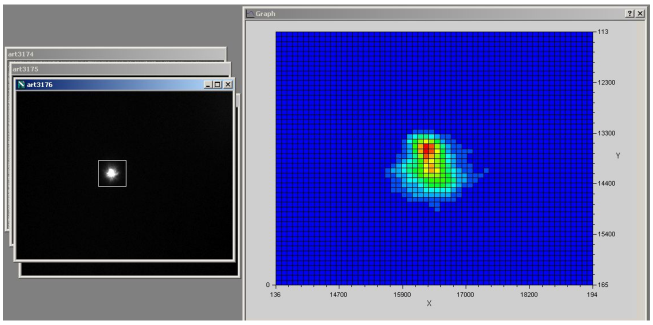

Figure 5. Image art 3176. 3D view of laser beacon from ARTEMIS via clouds art 3176.

In cloudy conditions a split in two components A and B was observed in image art 3176. Their angular separation was measured to be:

$\Delta X = 0.338''$; $\Delta Y = 1.304''$

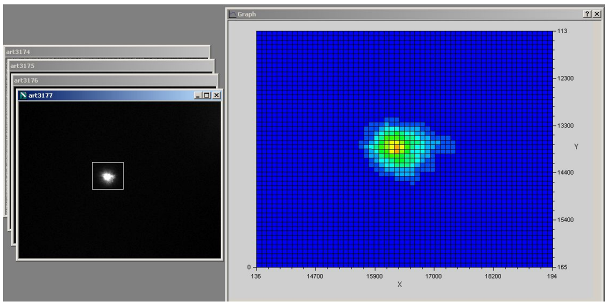

Figure 6. Image art 3177. 3D view of laser beacon from ARTEMIS via clouds

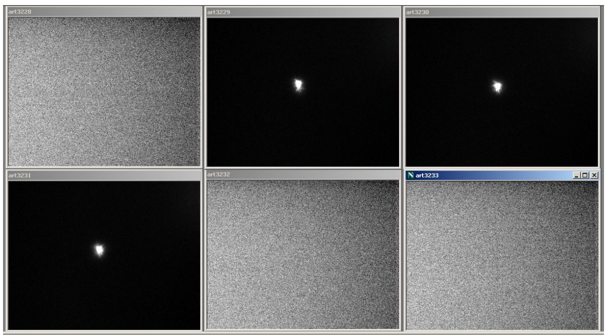

Figure 7. Images art 3228 – art 3233. Laser beacon from ARTEMIS via clouds art 3229 – art 3231

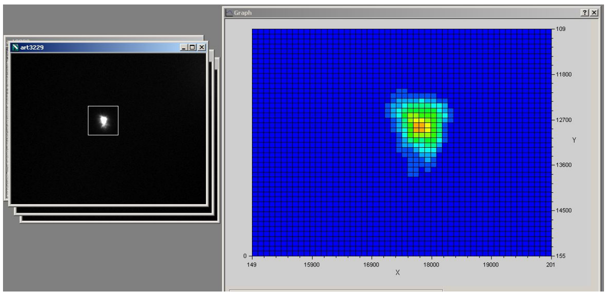

Figure 8. 3D image art 3229

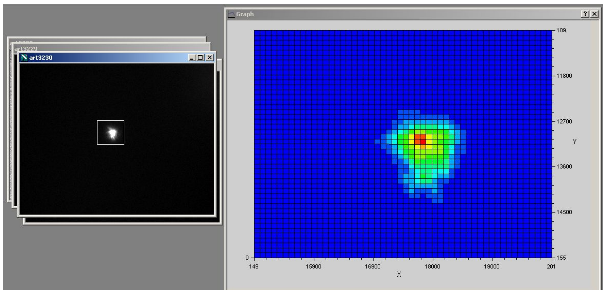

Figure 9. 3D images art 3230

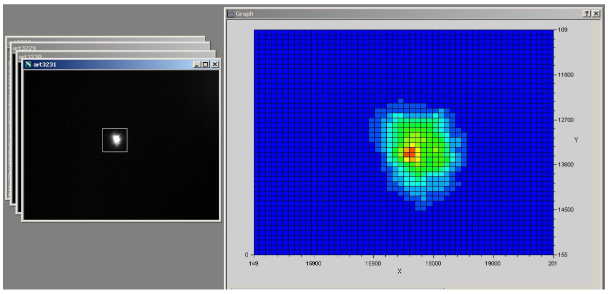

Figure 10. 3D image art 3231

The split was not observed in images art 3229 – art 3231.

Sometime after the end of Session 1, ARTEMIS was observed in reflected sunlight when the laser was not active.

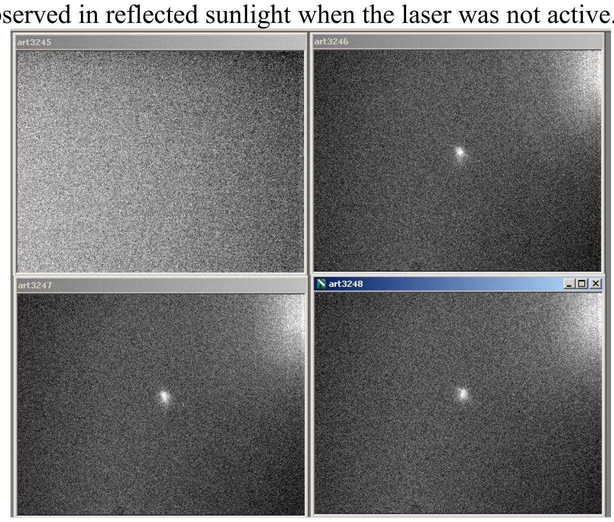

Figure 11: Images art 3245 – art 3248. ARTEMIS laser is not active art 3246 – art 3248

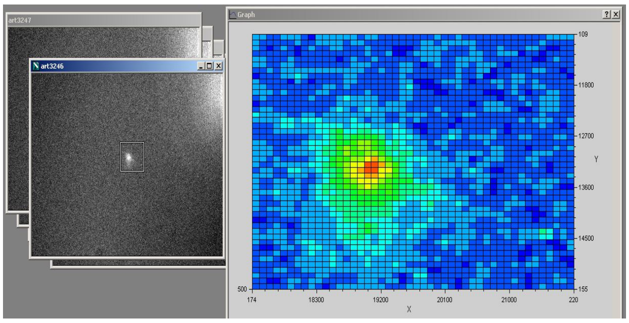

Figure 12. 3D image art 3246. ARTEMIS laser is not active

Two components were not observed in reflected sunlight from ARTEMIS in wide band sensitivity of CCD camera.

B. Session 2 (26 October 2011)

Automatic tracking of the ARTEMIS satellite without active beacon is recoded in the images of Session 1 up to 19h08m02s. Shortly before the start of Session 2 the sky became cloudy and recording started at 20h 00m04s:

- 20h00m04s to 20h03m33s: cloudy.
- 20h03m37s to 20h03m41s: beacon observed.
- 20h03m45s to 20h06m26s: cloudy.
- 20h06m30s to 20h06m34s: beacon observed.
- 20h06m38s to 20h07m03s: cloudy.

TABLE 3. ARTEMIS OBSERVATIONS PAREMITERS

# Art – image–	**Time hh:mm:ss**	**Stellar magnitude m**	**Exposure, s**	**Notes**
art 3253	19:08:02	12.389	2	sun reflected
art 3254	20:00:04	-	2	clouds
art 3306	20:03:33	-	2	clouds
art 3307	20:03:37	7.188	2	max.beacon
art 3308	20:03:41	6.318	2	max.beacon
art 3309	20:03:45	-	2	clouds
art 3349	20:06:26	-	2	clouds
art 3350	20:06:30	7.745	2	max.beacon
art 3351	20:06:34	7.776	2	max.beacon
art 3352	20:06:38	-	2	clouds
art 3358	20:07:03	-	2	clouds

Altitude above the horizon equal 23 degree.

Image processing performed by program Maxim DL-5 Pro.

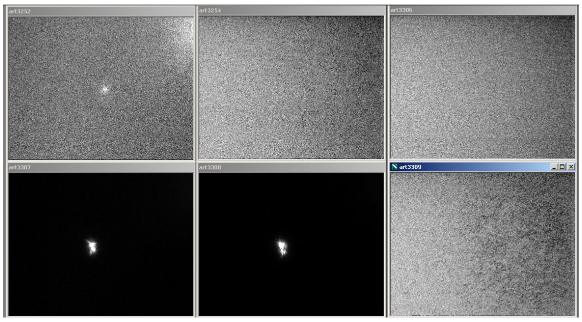

Figure 13. Images art 3252, art 3254, art 3306 – art 3309. Laser beacon beams of ARTEMIS via clouds: art 3307 – art 3308

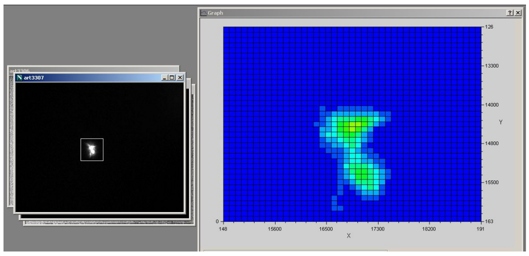

Figure 14. 3D image art 3307. ARTEMIS laser beacon beam via clouds

The angular separation between components A and B was measured to be:
$\Delta Y = 1{,}956\,''$. $\Delta X = 0{,}676\,''$.

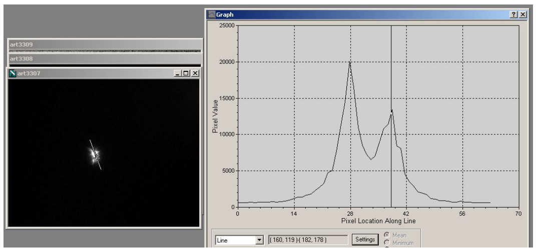

Figure 15. Image art 3307. Line slice of laser beacon beam via clouds

The first peak has the amplitude of 20000 ADC counts and the second peak has the amplitude 13500 ADC counts, 1.48 times smaller. The 16 bit CCD camera has a maximum of 65536 ADC counts.

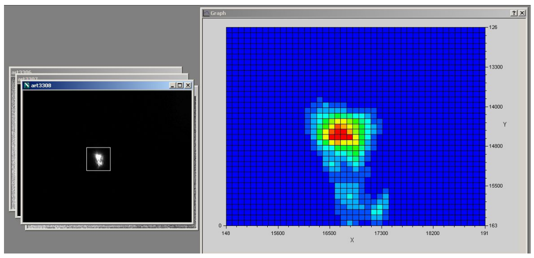

Figure 16. 3D image art 3308. ARTEMIS laser beacon beam via clouds

The angular separation between components A and B was measured to be:
$\Delta Y = 4.564''$. $\Delta X = 1.69''$.

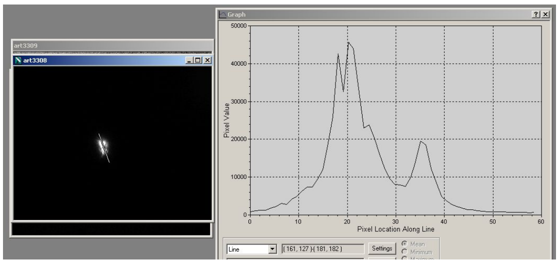

Figure 17. Image art 3308. Line slice of laser beacon beam via clouds

The first peak has the amplitude of 45000 ADC counts and second peak has the amplitude of 19000 ADC counts, 2.37 times smaller.

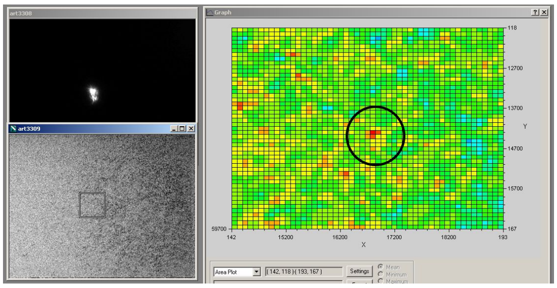

Figure 18. 3D image art 3309. ARTEMIS is laser active via clouds

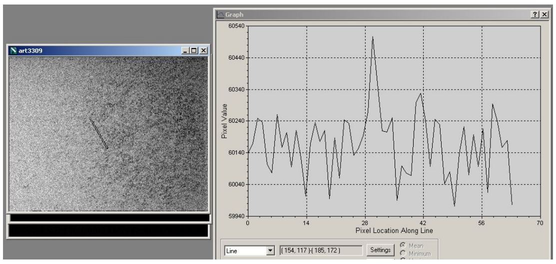

Figure 19. Image art 3309. Line slice of laser active ARTEMIS via clouds

At Figure 19 we see low level image of laser active ARTEMIS via clouds with signal comparable with noise of clouds.

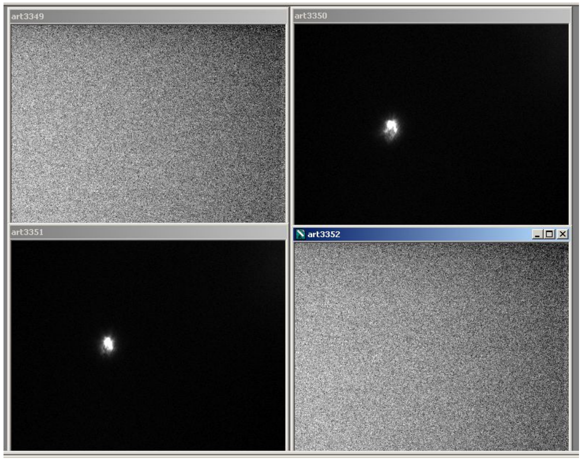

Figure 20. Images art 3349 – 3352. ARTEMIS laser beacon beams via clouds art 3350 – art 3351

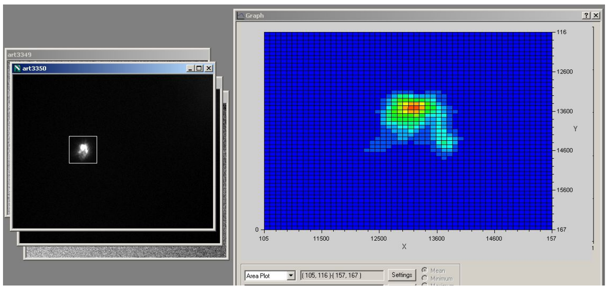

Figure 21. Image art 3350. ARTEMIS laser beacon beam via clouds

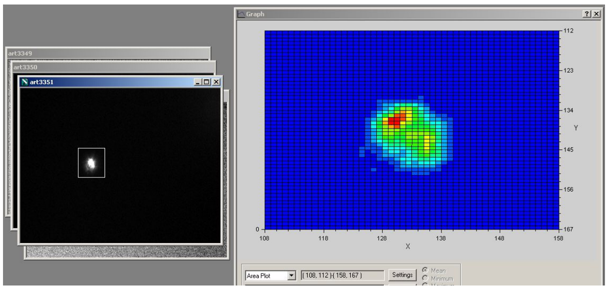

Figure 22. Image art 3351. ARTEMIS laser beacon beam via clouds

In images art3350 and art3351 as well as in art3307 and art3308 two components were observed.

C. Session 3 (26 October 2011)

Session 3 was cloud free and the camera exposure time was set to 1 second. The time schedule is presented in Table 4. The maximum beacon signal was observed at 21h00m35s and 21h03m40s.

TABLE 4. SESSION 3. ARTEMIS ORBIT PAREMITERS.

# Art – image	**Time hh:mm:ss**	**Stellar magnitude m**	**Exposure s**	**Notes**
art 4327	20:59:59	11.607	1	sun reflected

art 4328	21:00:22	-	1	OGS laser
art 4329	21:00:30	-	1	OGS laser
art 4330	21:00:32	9.018	1	active beacon
art 4331	21:00:35	5.601	1	max. beacon
art 4332	21:00:56	-	1	OGS laser
art 4333	21:01:04	9.042	1	active beacon
art 4334	21:01:07	8.941	1	active beacon
art 4335	21:01:10	-	1	OGS laser
art 4378	21:03:12	-	1	OGS laser
art 4379	21:03:15	8.573	1	active beacon
art 4380	21:03:18	8.157	1	active beacon
art 4387	21:03:38	9.070	1	active beacon
art 4388	21:03:40	2.11	1	max. beacon
art 4389	21:03:43	9.050	1	laser active
art 4466	21:07:22	11.992	1	sun reflected

Altitude above the horizon equal 25 degree

Figure 23. Images art 4327, art 4330 – art 4334, art 4336

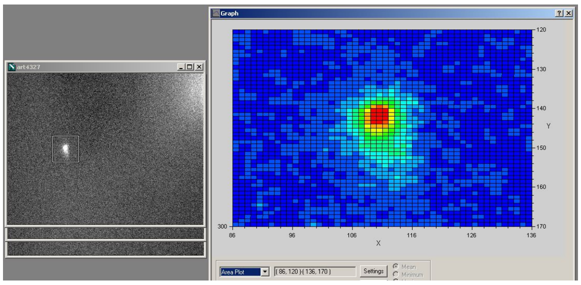

Figure 24. Images art 4327 before active laser of ARTEMIS

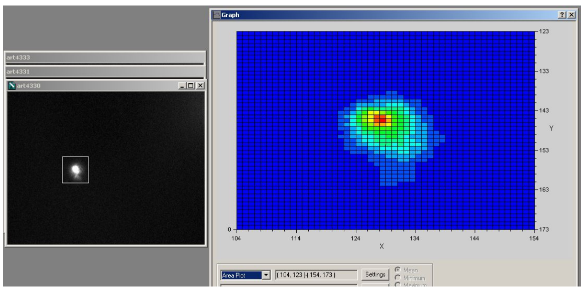

Figure 25. Images art 4330 with active laser of ARTEMIS

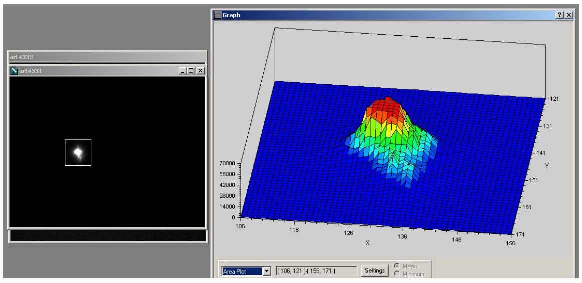

Figure 26. Images art 4331 with maximum beacon laser of ARTEMIS

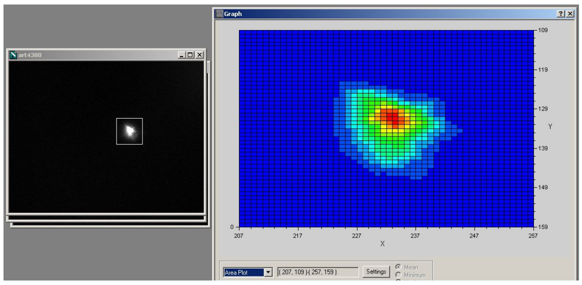

Figure 27. Images art 4380 active laser of ARTEMIS

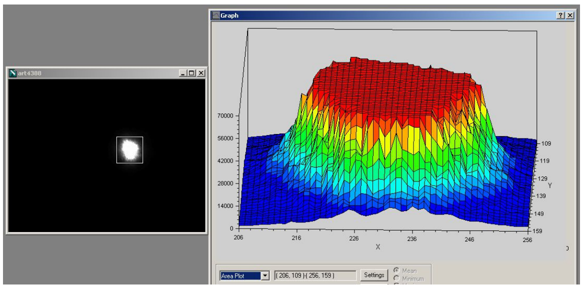

Figure 28. Images art 4388. The maximum beacon laser from ARTEMIS

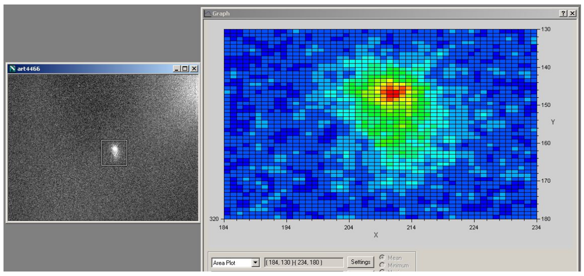

Figure 29. Images art 4466. Sun reflected light from ARTEMIS

V. INFLUENCE OF CLOUDS ON LASER RADIATION

The following possible explanations for observing two images of the laser beam from the satellite instead one (at low elevation angles) are proposed:

1. The atmosphere is an optically non homogeneous system. Two parallel atmospheric layers with different temperatures and different concentrations of water vapor can result in the split of a laser beam. If a laser beam passes these layers it is

split in two components with different directions (Figure 30) and two images appear on the CCD camera.

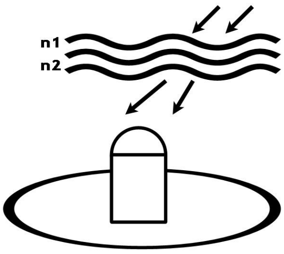

Figure 30. Laser beams via clouds

2. A second possibility is combinatorial scattering of laser radiation on molecules of water vapor. If one assumes laser radiation at frequency ν_0, then the photon with energy $h\nu_0$ interacts with molecules of water vapor with energy E(1):

$$h\nu_0 + E(1) \rightarrow h\nu_c + E(2)$$

The result is $h\nu_c < h\nu_0$ and E(2)>E(1). E(2) has more vibration energy of water vapors molecules.

During next step:

$$h\nu_0 + E(2) \rightarrow h\nu_a + E(1)$$

This results in photon energies $h\nu_a$, $h\nu_c$ at frequencies ν_a and ν_c where the refractive index of the atmosphere has different values for these two frequencies.

This combinatorial scattering can affect the passage of a laser beam through the atmosphere and can result in carrier frequency changes of the received laser light. The effect may impose restrictions on the bandwidth of narrow band-pass interference filters in terrestrial communication terminals, which are needed for operation in daytime conditions, in conditions of high background and thin clouds

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