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BIDIRECTIONAL SPACE TO GROUND LASER COMMUNICATION SYSTEM FOR CUBESAT

Laser communication has potential advantages in comparison to radio frequency communication for space vehicles. The project team developed the concept of the bidirectional communication system for free space (FSO) laser communication links from space terminals (ST) at low Earth orbit (LEO) nano-, microsatellites with emphasis on CubeSat or Unmanned Aerial Vehicle (UAV) to transportable or to stationary positioned optical ground based terminal (GT) to achieve the high data rate communications. Very accurate pointing and tracking capability will be provided by options of optical auto-tracking for both ST and GT. This capability will provide fast moving of flying platforms with very precise visible movement tracking of their optical axes of telescopes and their optical alignment. Such improvement will allow optical transmission of data over a long distance while requiring fewer resources from the hardware of flying platform ST. These solutions give significant advantages compared to existing solutions. Our innovative diffraction resolution without aberration of the optical system with broad spectrum band will be used for the ST during of work of transmission, receiving, and video optical channels. The optical systems of GT embedded in the lightweight 2-axes alt-azimuthally mount with enhanced turning range will allow smooth, high-speed tracking without any gaps at zenith. All optical system axes of GT and the alt-azimuthally mount axes are controlled by an auto-collimator having unique auto-adjustment feature. The innovative stationary positioned GT is also proposed.

Keywords: *free space optics, laser, communication, space terminal, low Earth orbit, unmanned aerial vehicle, ground terminal, optical system, CubeSat, attitude determination control system.*

INTRODUCTION

We propose the concept applicable to the Free Space Optics (FSO) communication technologies suitable for flying platforms application with emphasis on CubeSat and other small size satellites. The concept takes into account the characteristics of lasers as communication signal carriers. Lasers have much more carrier frequency in comparison with radio-frequency communications. As a result, laser communications have significantly higher communication signal rates up to 100 Gbits per second (Gbps) or more per one channel in fiber or space. This property makes a promise of higher data rates than current radio-frequency communications capabilities, greater data security with reduced hardware size, weight and power (SWaP) in Space Terminal (ST). But the atmosphere of the Earth with its turbulence and clouds attenuated the laser signals more in comparison with radio-frequency signals.

The European space agency (ESO) developed the space data relay system where laser communication signals are sending from Low Earth Orbit (LEO) satellites (for example, Sentinals) to one of three Geostationary Orbit (GEO) satellites at a distant near 40000 km. Then, signals are relay to the ground sta-

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tion by radio-frequency communication channels. For this scheme, big laser power and complicated laser terminals are needed onboard the LEO and GEO satellites.

Another approach involves the scheme with laser signals from LEO satellites sent directly to the optical ground station. The proposed concept includes two tied CubeSat satellites remotely connected to each other at the common orbit. The first satellite is considered to as spacecraft for ground photo images, and the second one is the host spacecraft of FSO ST type communicating with Ground Terminal GT of the optical ground station (OGS). The other LEO nanosatellites, in particular, CubeSat or UAV (Unmanned Aerial Vehicles), could also be applied as the proposed ST.

This paper summarizes the team long experience in the development of CubeSat projects, in particular, CubeSat Athenoxat-1 [http://athenoxat.com/], as well as the development of a laser ground system for communication experiments with GEO satellite ARTEMIS [3, 6] and the development of a communication terminal LACES (Laser Atmosphere Communication Satellite experiments) for the Cassegrain focus of 0.7 m AZT-2 reflector at the Main Astronomical Observatory NAS of Ukraine (MAO NAS of Ukraine) [4, 5].

THE PROPOSED SYSTEM OVERVIEW

The System. The new prototype model of the FSO laser communication link is designed to operate at different wavelengths, 0.78/0.84 µm, 1.064 µm, and spectral range about 1.55 µm, supporting PPM (pulse position modulation) with selectable data rates from 10 to 100 Mbps and an optional capability to measure FSO signal round-trip.

The FSO laser communication link prototype model includes CubeSat spacecraft platform with ST and GT with Operational box.

Flying platform. The designed flying platform of CubeSat satellite will be equipped with the necessary navigation and altitude stabilization systems. Additional systems will have to provide the satellite operational work of ST, and the payload.

Developed FSO laser communication link can be used in various satellites and UAVs. The last ones will need to have the appropriately designed navigation and attitude stabilization systems, supplemented by the proposed ST.

Space Terminal. The ST includes the following optical systems: the telescope's main optical system with transmission, receiving, and video optical channels; a spectrum dividers and, as additional devices, a laser transmitter, an optical receiver, and a video camera. The optical systems of ST are embedded in 2-axis gimbal system. The ST devices are controlled by electronic controllers and connected by central bus to CubeSat central controller. Similarly, ST can be installed in UAV.

Ground Terminal. The GT includes the following optical systems: telescope's main optical system with transmission, receiving, and visual optical channels; a spectrum dividers and, as additional devices, a laser transmitter, an optical receiver, and a video cameras. These systems and devices are embedded in 2-axis alt-azimuthally telescope mount with actuators. The devices and systems of GT are controlled by electronic controllers and connected to Operational Center with control and FSO data processing computers. The GT telescope is placed in minibus vehicle cargo space in a transport mode and moves upper its roof in the working mode.

Operational Center. Operational Center is installed in minibus cargo space, and operators will have 2 working places equipped with control and FSO data processing computers.

SPACE TERMINAL

Optical systems. The ST telescope main optical system is made as a shortened catadioptric system. The system forms a diffraction resolution aberration-free image for spectral range 0.5...1.6 µm. It is used with a spectrum divider for transmission, receiving, and video optical channels and additional spectrum divider system at the optical data receiver. The telescope has the main aperture $D_{ST} = 85$ mm that is sufficient to provide the angle range ±1° for gimbal turning when pointing (limiting down-link laser beam auto-tracking angle range). The ST telescope gimbal and terminal devices are shown in Fig. 1 and telescope mounting on CubeSat platform in Fig. 2.

Parameters of Space Terminal optical systems. The ST main optical parameters are given in Table 1, transmitter optical system parameters — in Table 2, receiver optical system parameters — in Table 3.

Evaluated optical transmittance of ST video channels $T_{vid} = 0.97$.

Transmittance of Space Terminal optical channels. The transmittance of the beam passing through the input aperture of the ST main telescope is:

- Transmitter channel $T_{tranch} = 0.37$.
- Receiver channel $T_{recch} = 0.35$.
- Video channel $T_{vidch} = 0.59$.

Supplemented devices of ST. The spectrum divider system (Fig. 1) is the most important for obtaining optical beams from main telescope system by an optical receiver. It is used to separate spectra lines of FSO optical data laser from the rest of the spectrum range, e. g.

- 1.60 μm for laser beam upload from GT.
- 1.55 μm for laser beam download to GT.
- The spectrum divider system forms an output beam 2 × 5 μm [1] (Fig. 5) on its focal plane which is the data receiver sensor surface.

The optical output of the laser transmitter active (emitting) surface must satisfy the conditions of optical joints with the main telescope system. In other words, in this case, the estimated full radiant angle of the laser should not exceed 10° allowing to maximize the optical channel transmittance of the transmitter as well as to minimize the laser beam divergence. On the other hand, the theoretical angular resolution of the terminal telescope (θ_l) (e. g., at $\lambda_1 = 1.55$ μm laser line), defined as $\sin\theta = 1.22\lambda_1/D_{ST}$, gives an Airy circle of 4.59 arcsec or 22.25 μrad. This means that ST laser beam illuminates a circle with a diameter of 22.3 m at the best on GT at 1000 km spacecraft distance from GT.

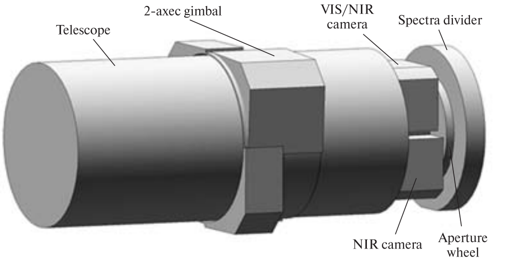


Fig. 1. Space Terminal Telescope with gimbal and terminal devices

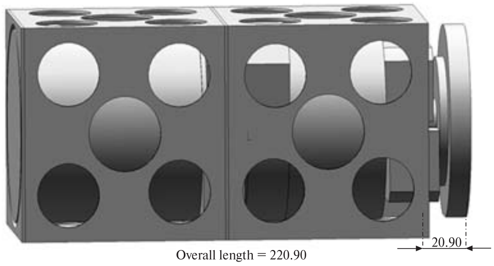


Fig. 2. Space Terminal Telescope in 2U CubeSat platform [4]

Table 1. **Evaluated parameters of ST main optical system**

Parameters	Space terminal
Geometric optical transmittance T_{mgeo}	0.75
Optical system elements transmittance T_{mop}	0.81
Main optical system transmittance T_m	0.61

Table 2. **Evaluated parameters of ST transmitter optical channel**

Parameters	Space terminal
Geometric optical transmittance T_{lgeo}	0.80
Optical system elements transmittance T_{lop}	0.80
Transmitter optical system transmittance T_l	0.64

Table 3. **Evaluated parameters of ST receiver optical channel**

Parameters	Space terminal
Spectrum divider optical transmittance T_{spgeo}	0.95
Spectrum divider elements transmittance T_{spop}	0.60
Spectrum divider transmittance T_l	0.57

Two different lasers are installed on CubeSat board — 1.55 μm and 0.84 μm as in VSOTA ST [2] where laser at 1.55 μm will be used for FSO data communication only and laser at 0.84 μm will be used as a beacon in auto-tracking mode. The laser signals at wavelength 1.55 μm will be received by InGaAs Avalanche Photo Diode (APD) having 40 nA dark current. The second laser signals with wavelength of 0.84 μm will be received by Si APD (Attitude Determination Control) System which has the dark current ~1 nA [7]. The GaAs photo diode has Noise Equivalent Power (NEP) 3×10^{-15} W/Hz$^{1/2}$ at 0.85 μm and Rise/Fall time 30 ps.

ST is equipped with 2 video cameras (see Fig. 1), NIR (Near InfraRed) and VIS/NIR (Visible/NearInfraRed), forming two ST auto-tracking signals:

- GT FSO data laser beam will form radiation position on NIR camera.

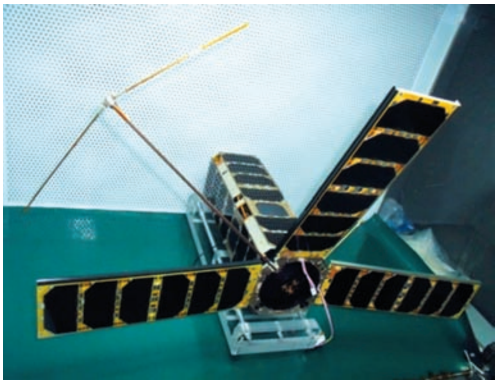


Fig. 3. Athenoxat-1, Night Vision, High Resolution CubeSat [5]

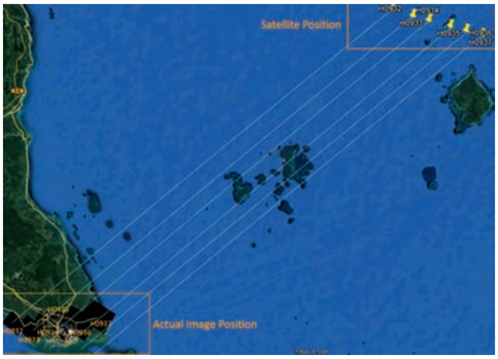


Fig. 4. Stretch of images of Singapore and Johore Bahru

- ST beacon laser beams will form position at 0.85/1.06 μm on VIS/NIR camera.

CubeSat spacecraft. The precise aiming of ST telescope optical axis to GT with its attitude control system (for laser beams aiming/tracking) needs the CubeSat axial turning angular velocity to be achieved:

- About 1.43°/s of CubeSat spacecraft at LEO height at 310 km above the Earth at nadir.
- About 0.61°/s of CubeSat spacecraf at LEO height at 710 km above the Earth at nadir.

As one can see above, the desired pointing of ST laser beam illumination circle around GT must not be worse than 1 arcsec (for both ST tracking systems: the spacecraft attitude control and a gimbal control of ST telescope).

The CubeSat spacecraft alike to Athenoxat-1 (see Fig. 3) provides the above-mentioned pointing and tracking parameters and, therefore, is suitable to be used as ST carrier.

Athenoxat-1 is the smallest spacecraft which could accommodate the proposed FSO, having nominal internal dimensions of 100 × 100 × 340 mm. It was launched in December 2015 and is still fully operative on LEO.

Athenoxat-1 has an optical payload, including sensors and image processors of dimensions comparable to the proposed FSO, occupying about 1/2 of the satellite length and using 90 mm aperture in the front of the satellite. Such high level of integration is achieved by producing in house the payload and ADC system actuators with a very compact design.

Athenoxat-1 is a very agile imaging satellite that can be easily programmed to perform observation of any visible target on the ground or in space. The off-nadir imaging is normally performed with target pointing in inertial scanning mode. The same operation modes can be adopted for the tracking of the optical GT from the satellite.

Based on Athenoxat-1 attitude and imaging results as presented for example in Fig. 4, the required platform pointing accuracy better than 1 deg is fully achievable with stability better than 0.1 deg/s and maximum slew rate of up to 10 deg/s.

The CubeSat largest energy consumer is FSO ST laser transmitter, but only for a limited time: in the worst case scenario its transit near GT zenith the CubeSat flight time cannot be greater than:

- About 130 s at LEO height at 310 km;
- About 290 s at LEO height at 710 km;

at the CubeSat trajectory visibility not more than 30° above the horizon.

GROUND TERMINAL

Optical systems. The GT telescope main optical system is made as a shortened reflector (main mirror) and Mangin secondary mirror optical system with spherical surfaces of its optical elements. The main optical system output is made non-focusing for spectral range 0.5...1.6 μm. The formed output beam is used with an image divider for transmission, receiving and video control optical channels. The main telescope aperture is selected to $D_{GT} = 400$ mm limiting main optical system weight to 14...16 kg. The GT main optical system is supplemented with diffraction resolution aberration-free field telescope with an increased field of view (FOV) with its optical axis adjusted parallel to main telescope optical axis.

GT optical systems parameters. The GT main optical system evaluated parameters are shown in Table 4, transmitter optical system parameters — in Table 5, receiver optical system parameters — in Table 6, field telescope optical parameters — in Table 7.

GT optical channels transmittance. The evaluated transmittance of beams passing through the input aperture of the telescope is:

- Transmitter channel $TR_{tran} = 0.66$.
- Receiver channel $TR_{rec} = 0.41$.
- Main telescope video channel $TR_{vid} = 0.82$.

Table 4. **Evaluated parameters of GT main optical system**

Parameters	Ground terminal
Geometric optical transmittance T_{mgeo}	0.96
Optical system elements Transmittance T_{mop}	0.88
Main optical system transmittance T_m	0.85

Table 5. **Evaluated parameters of GT transmitter optical channel**

Parameters	Ground terminal
Geometric optical transmittance T_{lgeo}	0.85
Optical system elements transmittance T_{lop}	0.90
Transmitter optical system transmittance T_l	0.77

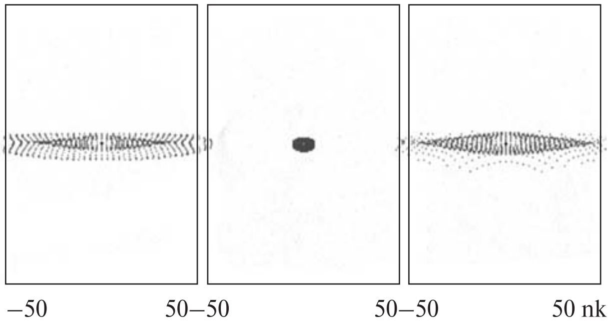
Table 6. **Evaluated parameters of GT receiver optical channel**

Parameters	Ground terminal
Spectrum divider optical transmittance T_{spgeo}	0.92
Spectrum divider elements transmittance T_{spop}	0.65
Spectrum divider transmittance T_l	0.57

The evaluated optical transmittance of ST video channels $T_{vid} = 0.97$!

Table 7. **Field telescope optical evaluated parameters (input aperture: D_{FieT} = 75 mm)**

Parameters	Field telescope
Spectrum divider optical transmittance T_{spgeo}	0.68
Spectrum divider elements transmittance T_{spop}	0.83
Spectrum divider transmittance T_l	0.57



lam = 1.55 mk	1.6 mk	1.65 mk
s = 244.8 mm	237	229
xf = 355.9482 mm	363.6269	371.5064
yf = −131.836 mm	−133.5629	−135.2888
izkl = 4.105918 mk	2.083237	4.586397

Fig. 5. Ground Terminal telescope spectrum divider image on its focal plane [1]

GT supplemented devices. The spectrum divider system (see Fig. 6) is the most important one for receiving optical data beam from ST telescope to GT optical receiver. It is intended to be used for FSO data flow near laser spectra lines, e. g.:

- 1.55 μm for laser beam downloaded from ST,
- 1.60 μm for laser beam uploaded to ST.

GT spectrum divider system is forming output beam 2 × 5 μm [6] (see Fig. 5) on its focal plane (on a receiver sensor surface) and may be used for fast sensors.

The optical output of the laser transmitter active emitting surface must satisfy the conditions of existing telescope optical joints. This means that, in this case, estimated laser *full radiant angle* should not exceed 8° allowing to maximize the transmitter optical channel transmittance as well as to minimize the laser beam divergence. On the other hand, the theoretical angular resolution of the terminal telescope (θ) (e. g., at λ = 1.60 μm laser line), defined as $\sin\theta = 1.22\lambda/D$, gives 1 arcsec or 4.85 m of GT laser illuminated circle at the best case on ST at 1000 km spacecraft distance from GT.

The GT is equipped with the video camera (NIR spectra). GT auto-tracking signals formed the position on NIR camera from ST FSO data laser beam. An additional camera on the field telescope is designed to search for a satellite.

GT Telescope Mount. The GT telescope optical elements (in Fig. 6, for visibility depicted transparent) and devices are embedded in 2-axis alt-alt telescope

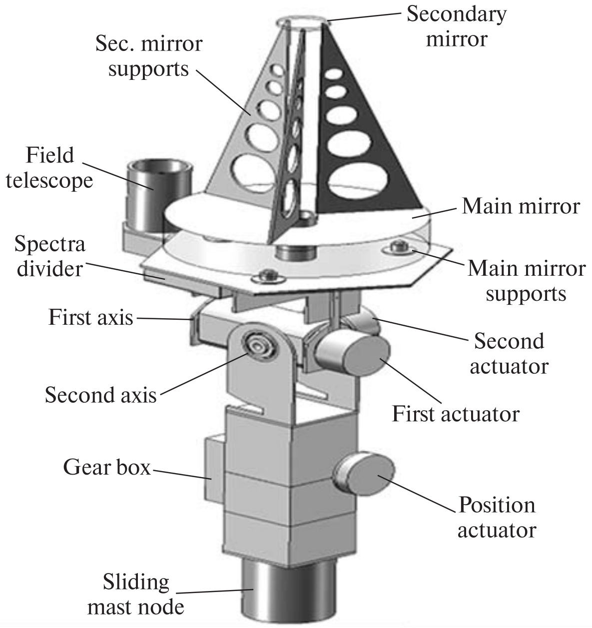


Fig. 6. Ground Terminal telescope sketch [4]

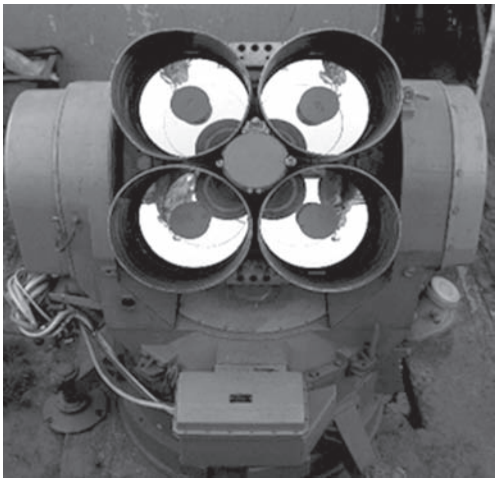


Fig. 7. Stationary positioned Ground Terminal telescope (V. Kuzkov photo, 2013)

mount with its actuators (GT telescope sketch in Fig. 6). The named GT devices and systems are controlled by their controllers and connected to Operational Center control and FSO data processing computers. In working mode, the telescope is placed on the sliding mast end, slipped over the minibus cargo roof and fixed to the initial position (see Fig. 6) with own actuator with a gear box. The other sliding mast end is fixed on the ground. The GT telescope is placed in minibus vehicle cargo space in transport mode.

Operational Center. Operational Center is installed in minibus cargo space with 2 operator's working places with control and FSO data processing computers and supplemented devices: GNSS, radio transmitter system for satellite communications, weather station, power system, climate stabilization and others.

Spacecraft ephemeris. Obtaining the FSO communication CubeSat spacecraft accurate ephemeris will be complemented by accurate GPS positioning. The aiming and tracking of the LEO CubeSat following on-board laser transmitter beam are possible only at night-time at the best.

FSO link energy balance. The LEO CubeSat FSO communication link between ST and GT can be established in the case when the transmitted data optical power is sufficient throughout all designed communications distances. As the data transmission is performed in relatively good weather conditions when the optical signal passing through the atmosphere then the signal loss could be evaluated as small: about 0.15...0.3 dB/km at 20 km distance in the atmosphere or as −3/−6 dB altogether. The greatest signal attenuation is due to geometric patterns formed by ST and GT optical systems. These signal losses can be compensated by appropriately increasing laser transmitters' power. The FSO communication link energy balance estimation is shown in Table 8.

Stationary Positioned Ground Terminal. The stationary positioned GT telescope can be upgraded as

Table 8. **FSO communication link with CubeSat spacecraft power balance**

Parameters	ST	GT
Transmittance T_{tran}, dB (transmitter channel)	–4.3	–1.6
Transmittance T_{rec}, dB (receiver channel)	–4.6	–3.9
Transmitted beam divergence γ, μrad	22.25	4.85
Geometric loss (in distance:1000 km), dB	–70.3	–69.8
Loss in the atmosphere (in distance: 1000 km), dB	–3/–6	–3/–6
Transmitted power P_t, dB	17.8	20
Received power P_r, dB	–62.5	–61.9

follows: the optical system can include 4 × 30 cm apertures of receiving telescopes and a laser transmitter optical system in the center. Next, it is possible to implement the ground receiver system with 3—4 receiving channels (separated mirrors or parts of the single mirror) to reduce the influence of the atmospheric turbulence. Other small parts of the mirrors can be used by the laser transmitters. The receiving channels supposed to be separated from the transmission communication channels [http://microspace.org/atx1.html#spec]. Similar stationary positioned GT telescope is presented in Fig. 7. The telescope is depicted during the restoration at the position in the former National Center of Space Facilities Control And Test (NCSFCT) in Crimea, Ukraine.

SUMMARY

The FSO ST communication system for CubeSat with transportable GT is being developed. The presented design and preliminary results of its operation in the space with a CubeSat satellite Athenoxat-1 show very promising chances for such very compact and efficient optical communication link.

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ДВОНАПРЯМЛЕНА КОСМІЧНО-НАЗЕМНА ЛАЗЕРНА КОМУНІКАЦІЙНА СИСТЕМА ДЛЯ СУПУТНИКІВ «CUBESAT»

Лазерний зв'язок має потенційні переваги порівняно з радіочастотним зв'язком для космічних апаратів. Проектна група розробила концепцію двобічної системи космічного лазерного зв'язку (FSO) для комунікацій між космічними терміналами (ST) нано-, мікросупутників, що перебувають на низьких навколоземних орбітах (з акцентом на «CubeSat»), або терміналами безпілотних літальних апаратів і переносними чи стаціонарними наземними терміналами (GT) для досягнення високої швидкості передавання даних. Дуже точна можливість наведення та супроводу буде забезпечена опціями оптичного автоматичного відстеження для ST та GT. Ця можливість забезпечить швидке переміщення літальних платформ з дуже точним видимим супроводом руху оптичних осей їхніх телескопів та їхнім оптичним вирівнюванням. Таке поліпшення дозволить здійснювати оптичну передачу даних на великі відстані, що вимагатиме менше ресурсів від обладнання літаючої платформи ST. Ці рішення дають значні переваги порівняно з відомими рішеннями. Наша інноваційна дифракційна роздільна здатність без аберації оптичної системи з широкосмуговим діапазоном буде використовуватися для ST під час роботи передавальних, приймальних та відеооптичних каналів. Оптичні системи GT, вбудовані в легке двовісне альтазимутальне монтування з поліпшеним діапазоном повертання, забезпечують плавне високошвидкісне відстеження без будь-яких прогалин у зеніті. Всі осі оптичних систем GT і осі альтазимутального монтування керуються автоколіматорами, які мають унікальну функцію автоматичного настроювання. Також пропонується інноваційний стаціонарний позиціонований GT.

Ключові слова: безатмосферна оптика, лазери, комунікації, космічний термінал, низька орбіта, безпілотний літальний апарат, наземний термінал, оптична система, «CubeSat», система контролю позиціонування.

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ДВУНАПРАВЛЕННАЯ КОСМИЧЕСКИ-НАЗЕМНАЯ ЛАЗЕРНАЯ КОММУНИКАЦИОННАЯ СИСТЕМА ДЛЯ СПУТНИКОВ «CUBESAT»

Лазерная связь имеет потенциальные преимущества по сравнению с радиочастотной связью для космических аппаратов. Проектная группа разработала концепцию двунаправленной системы космической лазерной связи (FSO) для коммуникаций между космическими терминалами (ST) нано-, микроспутников, находящихся на низких околоземных орбитах (с акцентом на «CubeSat»), или терминалами беспилотных летательных аппаратов и переносными или стационарными наземными терминалами (GT) для достижения высокой скорости передачи данных. Очень точная функция наведения и сопровождения будет обеспечена опциями оптического автоматического сопровождения для ST и GT. Эта возможность обеспечит быстрое перемещение летательных аппаратов с очень точным видимым отслеживанием движения оптических осей их телескопов и их оптическим выравниванием. Такое улучшение позволит осуществлять оптическую передачу данных на большие расстояния, требуя меньше ресурсов от аппаратного обеспечения летающей платформы ST. Эти решения дают значительные преимущества по сравнению с известными решениями. Наше инновационное дифракционное разрешение без аберрации оптической системы с широким спектральным диапазоном будет использоваться для ST во время работы передающих, приемных и видеооптических каналов. Оптические системы GT, встроенные в легкую двухосевую азимутальную монтировку с улучшенным диапазоном поворота, обеспечивают плавное высокоскоростное отслеживание без каких-либо пробелов в зените. Все оси оптической системы GT и оси альтазимутальной монтировки управляются автоколлиматором, имеющим уникальную функцию автоматической настройки. Также предлагается инновационный стационарный позиционированный GT.

Ключевые слова: безатмосферная оптика, лазеры, коммуникации, космический терминал, низкая орбита, беспилотный летающий аппарат, наземный терминал, оптическая система, «CubeSat», система контроля определения местоположения.