International Conference on Space Optics—ICSO 2022

Dubrovnik, Croatia

3–7 October 2022

Edited by Kyriaki Minoglou, Nikos Karafolas, and Bruno Cugny,

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International Conference on Space Optics — ICSO 2022, edited by Kyriaki Minoglou, Nikos Karafolas,
Bruno Cugny, Proc. of SPIE Vol. 12777, 1277779 · © 2023 ESA and CNES · 0277-786X · doi: 10.1117/12.2691383

Design of the setup for testing optical telemetry ranging including turbulence simulator for the Earth-to-satellite communication link

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ABSTRACT

Despite numerous challenges optical communication offers faster data transmission than its radio-frequency (RF) counterpart, enabling implementation of technologies requiring high transmission rates. In the satellite communication precise determination of the distance between the ground station and the satellite is needed to properly estimate and control the parameters of its orbit. Several different satellite ranging techniques basing on traditional RF communication has been proposed[1–3], including sequential, pseudo-noise and telemetry ranging. However, significant improvement of the ranging accuracy can be expected when switching to the optical methods[4]. Nevertheless, the feasibility and performance of free-space optical communication protocols, including ranging, depends on the overall optical power loss, which is heavily conditioned on the atmospheric turbulence[5]. In this paper we present the design of the laboratory setup to test a variant of optical telemetry ranging protocol[6] implemented in an optical modem in the presence of atmospheric turbulence, with the expected ranging accuracy of 3 cm. The simulator capabilities include simulation of typical effects occurring as a result of atmospheric turbulence mainly optical scintillation while also studying the Doppler effect due to satellite's motion relative to ground station[7,8]. The optical channel simulator is based on fiber optics with electro-optical intensity modulator controlled by arbitrary waveform generator.

Keywords: optical ranging, optical scintillation, temporal fading.

1. INTRODUCTION

The switchover from the traditional RF to optical frequencies was brought on by the increasing requirement for higher bandwidth in telecommunication. Over the years various optical links were tested, with different wavelengths or transmission spectral windows, including high-speed fiber optic technology over short distances and free-space optical links between two ground stations as well as for the 'last mile' communication. The satellite-based free-space optical communication has been studied in recent years both for the orbital communication and for the application in deep space environment, *e.g.* in projects like NASA's Laser Lunar Communication Demonstration (LLCD)[9], OPALS[10], MESSENGER spacecraft[11] and ESA's European Data Relay System (EDRS)[12]. Our study focuses on developing a breadboard to test the performance of the satellite optical ranging protocol based on optical modem utilized for different orbits in the situation when the optical channel is affected by atmospheric turbulence causing temporal fading.

2. TELEMETRY RANGING SYSTEM DESIGN

Satellite ranging is a procedure to determine the distance between a ground station and a spacecraft or between two spacecrafts. It is typically done by exchanging electromagnetic signals between the two objects and measuring

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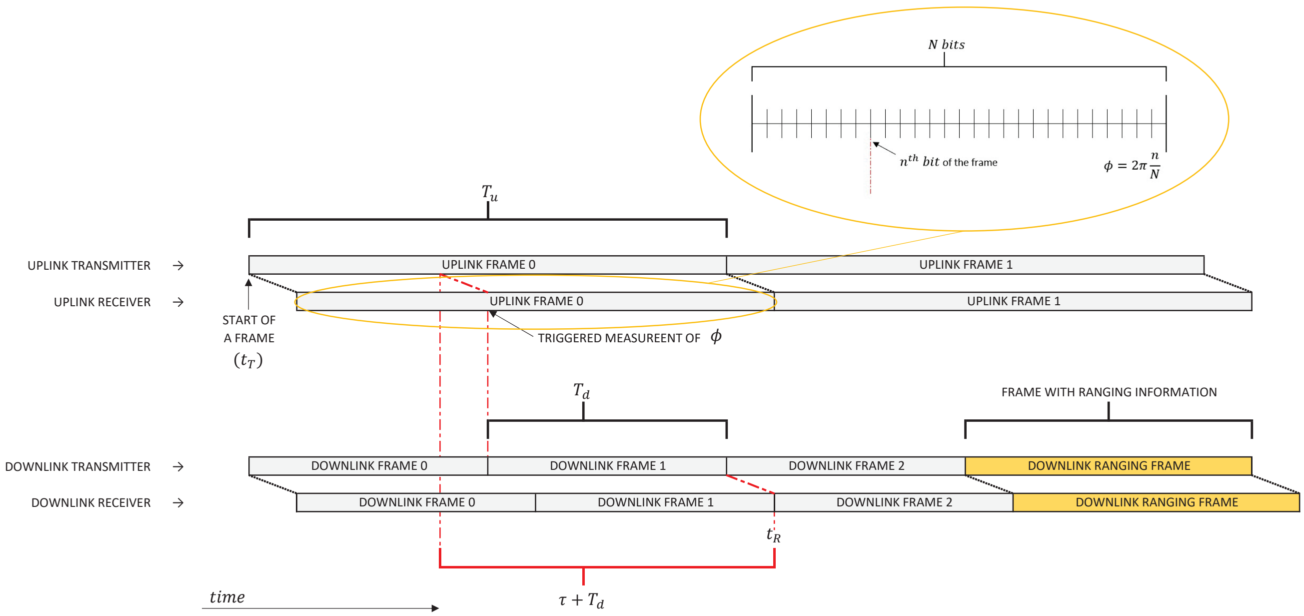

Figure 1. Telemetry ranging system concept

their travel time. Depending on the specific protocol it can be either one-way, ground station to satellite and vice versa, or two-way measurement, round trip from ground station to satellite and back, with some variations in details. The optical pulses generated by the ground station's transmitter are either detected by the satellite or reflected towards the ground station, where they are measured by the receiver. In the former (latter) of these cases the distance d between the ground station and the spacecraft can be calculated as $d = c\tau$ ($d = c\tau/2$), where τ is the measured travel time of the signal.

There exist various ranging methods designed for optical frequencies, including satellite laser ranging in one- and two-way synchronous and asynchronous variants, interferometry laser ranging and the techniques based on bit clock or carrier phase measurements[13–19]. In this work we focus on the optical telemetry ranging[5] in two-way synchronous and asynchronous variants. Telemetry ranging is the technique in which electromagnetic signals are used for simultaneous optical ranging measurement and data sharing. In it's basic asynchronous variant, illustrated in Figure 1, the ground station sends to the satellite a stream of data and registers the time t_T at the ground station's clock at which a particular uplink frame was initiated. Simultaneously, the satellite sends to the ground station a separate stream of data, which is not synchronized with the uplink transmission. Whenever a new downlink frame begins, the satellite's receiver measures the current phase of the uplink signal. For example if the measured bit is the n-th bit belonging to the current uplink frame and there are N bits in each frame, then the current phase of the uplink signal, measured with the accuracy of $2\pi/N$, is $\phi = 2\pi n/N$. The information on ϕ is included in the downlink telemetry data, typically in the subsequent frame after the one that initiated the particular measurement. Then, when the first bit of a new downlink frame is detected by the ground station's receiver, the information of the current local time t_R at the ground station's clock is taken and the information included in the downlink data stream is used to calculate the round-trip time of the signal τ. If T_u (T_d) is the time duration of a single (uplink) downlink frame, then τ can be calculated as

$$\tau = t_R - \left[t_T + \frac{\phi}{2\pi}T_u\right] - T_d, \tag{1}$$

where the third term is due to the assumed one-frame delay in relaying of the ranging data at the satellite. In the synchronous version of the protocol uplink and downlink telemetry signals are synchronized with each other, making the phase ,ϕ, measurement unnecessary. However, such synchronization may be difficult to obtain, especially if the distance between the spacecraft and the ground station changes rapidly *e.g.* in the case of LEO satellites.

3. PARAMETERS OF OPTICAL LINK

Over the years, there have been different studies on modelling and simulation of atmospheric turbulence[20–23]. The references[20, 22] uses Kolmogorov atmospheric turbulence model for simulation while the reference[23] uses the von Karmann model as basis for modelling of time-varying turbulence signal as a function of receiver aperture diameter and rms wind speed. In our case, we focus mainly on optical scintillation effect observed on ranging signal due to atmospheric turbulence. The optical communication link is affected by the atmospheric turbulence as well as the motion of satellite leading to fluctuations in optical frequency and signal strength over the duration of communication. Optical scintillation originates from temperature and pressure variations in the atmosphere, causing continuous fluctuations in the value of refraction index along the propagation path. It leads to the time varying fluctuations in the intensity of the optical signal and variation in propagation time of the signal. The fluctuations of refractive index are quantified with the scintillation index, σ_I^2. Statistical models such as Kolmogorov turbulence model for weak turbulence, non-Kolmogorov and von-Karmann model for moderate to strong turbulence, describe the power spectral density of refractive index fluctuations. They are characterized by the refractive/turbulence structure parameter C_n^2. The scintillation index, σ_I^2, quantifies the normalized intensity variance caused by atmospheric turbulence.For a plane wave it is given by Rytov variance based on Kolmogorov model as:

$$\sigma_I^2 = 1.23 k^{7/6} {C_n}^2 L^{11/6}, \tag{2}$$

where, $k = 2\pi/\lambda$ is the wavenumber, L is the path length between transmitter and receiver. The Rytov variance represents scintillation index of an unbounded plane wave in weak fluctuations based on Kolmogorov spectrum[5, 8]. The wavelengths considered in this project are $\lambda = 1530$ nm for uplink and 1550 nm for downlink. For the vertical and slant optical path between satellite and ground stations, the equation of scintillation index is further modified with respect to the satellite's co-ordinates with respect to ground station[8]. The scintillation index is form of log-irradiance, N (Np^2) function[24]:

$$\sigma_{lnN}^2 = 2.253 k^{7/6} (\sec\Phi)^{11/6} \int_{h_0}^{H} {C_n}^2(z)(H - h_0)^{5/6}\, dz, \tag{3}$$

where, Φ is zenith angle, h_0 is the height of the ground station measured from sea level, H is the effective height of optical turbulence path, z is height above ground level.

According to the ITU recommendations ITU-R P1621-2 and ITU-R P1622-0[24, 25], for frequencies between 20 THz and 375 THz (0.799 μm and 14.98 μm), the Huffnagel-Valley 5/7 model equation can be used to estimate the value of C_n^2:

$$C_n^2(h) = 8.148 \times 10^{-56} v_{\text{rms}}^2 h^{10} e^{-h/1000} + 2.7 \times 10^{-16} e^{-h/1500} + C_0 e^{-h/100}, \tag{4}$$

where h is the height above the ground level, C_0 stands for nominal value of C_n^2 at the ground level, typically $1.7{\times}10^{-14}\text{m}^{-2/3}$, and v_{rms} is a speed along vertical path calculated using Bufton wind model[8, 24] and it is given by:

$$v_{rms} = \sqrt{v_g^2 + 3.11 v_g + 360.31}. \tag{5}$$

Here, if the ground wind speed, v_g, is unknown, then $v_g = 2.3$m/s can be taken as an approximation, thus giving v_{rms} value to be 21m/s[8, 24]. The duration of time for which satellite is visible to ground station depends on the orbit height and its velocity. The characteristic time scale for continuous fluctuations due to scintillation is of the order of milliseconds. They are caused by the pockets,eddies, of varying refractive index formed in atmosphere due to varying temperature and pressure. As the satellite passes over the ground station, the propagation path of optical signal varies continuously, so does the thickness of atmospheric layers. This systematic variation in optical path length and constitution results in a overall 'slow fading' of the signal. On the other hand, with respect to the former effect, scintillation is 'fast-fading' effect. The time-varying optical turbulence effect is simulated based on combination of these two effects and additionally Doppler effect due to satellite's relative motion.

4. SATELLITE ORBITING AND ATMOSPHERE EFFECTS SIMULATOR

The schematic diagram of the breadboard implementation is presented in Figure 2. Free space link between the ground station and the spacecraft will be implemented by SERDES transceivers connected to the optical system through SFP+ optical modules. The Ground station and the spacecraft FPGA along with the atmospheric turbulence simulator are interfaced by the Windows OS personal computer with restful API server. The breadboard is fiber based with no free space links.

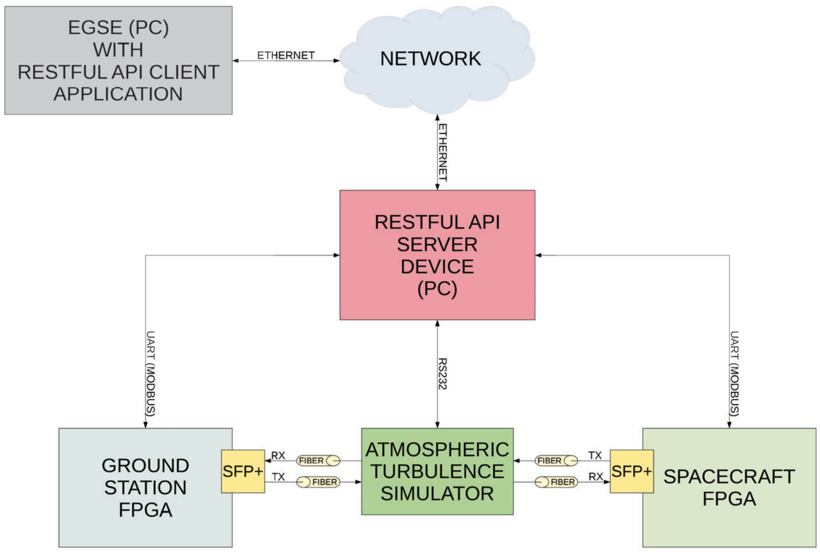

Figure 2. Test Setup Design

The atmosphere simulator, implemented in fiber optic technology, emulates the optical turbulence effects such as optical scintillation experienced by optical ranging signal while propagation.

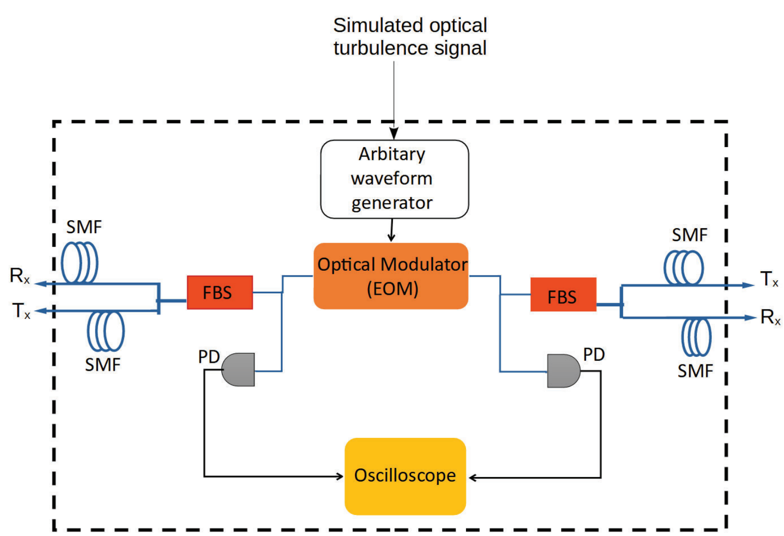

Figure 3. Optical turbulence simulator: 'T_x/R_x' module controlled by FPGA for optical signal/ranging, electro-optic modulator (EOM) (part. no: JDSU 10020425 OC-192, 10Gbps), FBS: Fiber beam splitters, SMF: Single mode fibers, PD: Fast photodiode.

In atmospheric turbulence simulator,the transmitter, receiver and the network PC for turbulence simulation are interfaced using Python platform. The time-varying turbulence simulation code based on scintillation will be developed using Python. An arbitary waveform generator (SDG 2042X, 40MHz max bandwidth and 1.2 G sampling rate, 20V pp output) with python interfacing compatibility is used to generate the turbulence signal which is then supplied to the fiber based electro-optical modulator. The experimental design is presended in Figure 3. This modulator (JDSU, 10020425 OC-192, with operational wavelength 1530-1605 nm) is used for varying the intensity of the optical signal. A fraction of the transmitted signal, directed to a photodiode and observed on oscilloscope, is used to monitor and verification of the performance of the simulator. This signal is stored and can be used for comparison with the modulated signal observed at the receiver end after successful optical ranging measurement. The specifications of both waveform generator and optical modulator is sufficient for the required operating specification as the time scale of optical scintillation is of the order of milliseconds.

5. SUMMARY

In this paper we have presented the preliminary design of the test setup for the new variant of satellite optical telemetry ranging protocol. It is being developed under the contract *ARTES 4.0 SPL Optical Communication – CCSDS standardized ranging for optical communication terminals* with European Space Agency. The setup is currently in the detailed design phase.

As the result of detail design phase the Ground Station IP Core for O3K RS ranging implementation will be prepared. Ranging IP Core will be used in M3O optical modem, which is under preparation in Work Microwave GmbH company as a part of *4000135208/21/NL/FGL/fm - M3O optical receive only modem* project from ESA.

We have also presented the design of the turbulence simulator that will be used to emulate the Earth-to-satellite free space optical link implemented in fiber-optic technology. The simulator can be used to test any satellite laser communication protocol. The tests results of the developed hardware setup will be the inputs to Consultative Committee for Space Data Systems (CCSDS) working group standardization process.

Acknowledgements

The project is a part of European Space Agency contract "ARTES 4.0 SPL Optical Communication – CCSDS standardized ranging for optical communication terminals" led by Nicolaus Copernicus University in Torun in collaboration with Syderal Polska and Work Microwave GmbH. AA, ML and PK acknowledge financial support by the Foundation for Polish Science (FNP) (project First Team co-financed by the European Union under the European Regional Development Fund, POIR.04.04.00-00-3FD9/17).

REFERENCES

[1] Hamkins, J., Kinman, P., Xie, H., Vilnrotter, V., and Dolinar, S., "Telemetry ranging: Concepts (ipn progress report 42-203)," (2015).

[2] Kinman, P., [*DSN Telecommunications Design Handbook: 203 Rev.C Sequential Ranging*], DSN Telecommunications, NASA, California Institute of Technology (2009).

[3] Kinman, P., Chang, C., and Pham, T., [*214 Pseudo-noise and Regenerative ranging handbook*], DSN Handbook, California (2015).

[4] Heckler, G. W., andLuke B. Winternitz, A. L., Donaldson, J., and Yang, G., "Metric tracking services in the era of optical communications," *International Aeronautical Congress* , International Aeronautical Federation (IAF) (2019).

[5] Andrews, L. C., Phillips, R. L., Hopen, C. Y., and Al-Habash, M. A., "Theory of optical scintillation," *JOSA* **16**, 1417–1429 (June 1999).

[6] Net, M. S. and Hamkins, J., "Optical telemetry ranging: Concepts (ipn progress report 42-221)," (2015).

[7] NASA, G. s. f. c., "The doppler equation in range and range rate measurement," (1965).

[8] Andrews, L., Phillips, R., and Hopen, C., [*Laser beam scintillations with Applications*], SPIE Press (2001).

[9] Stevens, M. L., Parenti, R. R., Willis, M. M., Greco, J. A., Khatri, F. I., Robinson, B. S., and Boroson, D. M., "The lunar laser communication demonstration time-of-flight measurement system: overview, on-orbit performance, and ranging analysis," in [*Free-Space Laser Communication and Atmospheric Propagation XXVIII*], Hemmati, H. and Boroson, D. M., eds., **9739**, 973908, International Society for Optics and Photonics, SPIE (2016).

[10] Oaida, B., Abrahamson, M., Witoff, R., Martinez, J., and Zayas, D., "Opals: An optical communications technology demonstration from the international space station," *IEEE Aerospace Conference* , 1–20 (03 2013).

[11] Team, N., "Messenger media resources."

[12] Agency, E. S., "European data relay system (edrs) applications."

[13] Reynolds, M., Reinhart, M., Bokulic, R., and Bryant, S., "A two-way noncoherent ranging technique for deep space missions," *Proceedings, IEEE Aerospace Conference* **3**, 3–3 (2002).

[14] Degnan, J. J., "Asynchronous laser transponders for precise interplanetary ranging and time transfer," *Geodynamics Journal* **34**(3), 551–594 (2002).

[15] Birnbaum, K. M., Chen, Y., and Hemmati, H., "Precision optical ranging by paired one-way time of flight," *Free-Space Laser Communication Technologies XXII* **7587**, 86–93 (February 2010).

[16] Dirkx, D., Prochazka, I., Bauer, S., Visser, P., Noomen, R., Gurvits, L. I., and Vermeersen, B., "Laser and radio tracking for planetary science missions—a comparison," *Journal of Geodesy* **93**, 2405–2420 (2019).

[17] Sheard, B. S.and Heinzel, G. D. K., Shaddock, D. A., Klipstein, W. M., and Folkner, W. M., "Intersatellite laser ranging instrument for the grace follow-on mission," *Journal of Geodesy* **86**, 1083–1095 (2012).

[18] Abich, K., Abramovici, A., Amparan, B., Baatzsch, A., Okihiro, B. B., Barr, D. C., Bize, M. P., Bogan, C., Braxmaier, C., Burke, M. J., Clark, K. C., Dahl, C., Dahl, K., Danzmann, K., Davis, M. A., de Vine, G., Dickson, J. A., Dubovitsky, S., Eckardt, A., Ester, T., Barranco, G. F., Flatscher, R., Flechtner, F., Folkner, W. M., Francis, S., Gilbert, M. S., Gilles, F., Gohlke, M., Grossard, N., Guenther, B., Hager, P., Hauden, J., Heine, F., Heinzel, G., Herding, M., Hinz, M., Howell, J., Katsumura, M., Kaufer, M., Klipstein, W., Koch, A., Kruger, M., Larsen, K., Lebeda, A., Lebeda, A., Leikert, T., Liebe, C. C., Liu, J., Lobmeyer, L., Mahrdt, C., Mangoldt, T., McKenzie, K., Misfeldt, M., Morton, P. R., Muller, V., Murray, A. T., Nguyen, D. J., Nicklaus, K., Pierce, R., Ravich, J. A., Reavis, G., Reiche, J., Sanjuan, J., Schütze, D., Seiter, C., Shaddock, D., Sheard, B., Sileo, M., Spero, R., Spiers, G., Stede, G., Stephens, M., Sutton, A., Trinh, J., Voss, K., Wang, D., Wang, R. T., Ware, B., Wegener, H., Windisch, S., Woodruff, C., Zender, B., and Zimmermann, M., "In-orbit performance of the grace follow-on laser ranging interferometer," *Phys. Rev. Lett.* **123**, 031101 (Jul 2019).

[19] Vilnrotter, V. and Cheung, K.-M., "Carrier-phase aided pseudo-noise range estimation at rf frequencies," in [*2020 IEEE Aerospace Conference*], 1–12 (2020).

[20] Toselli, I., Andrews, L., Phillips, R., and Ferrero, V., "Scintillation index of optical plane wave propagating through non-kolmogorov moderate-strong turbulence," *Proceedings of SPIE - The International Society for Optical Engineering* (10 2007).

[21] Jurado-Navas, A., Garrido-Balsells, J., del Castillo Vázquez, M., and Puerta-Notario, A., [*A Computationally Efficient Numerical Simulation for Generating Atmospheric Optical Scintillations*] (09 2011).

[22] Shrestha, A., Giggenbach, D., Mustafa, A., Pacheco-Labrador, J., Ramirez, J., and Rein, F., "Fading testbed for free space optical communications," 999105, SPIE (10 2016).

[23] Toyoshima, M., Takenaka, H., and Takayama, Y., "Atmospheric turbulence-induced fading channel model for space-to-ground laser communications links," *Optics express* **19**, 15965–75 (08 2011).

[24] of ITU, R. S., "Prediction methods required for the design of earth-space systems operating between 20 thz and 375 thz (in force)- itu-r p.1622-0," (2003).

[25] of ITU, R. S., "Propagation data required for the design of earth-space systems operating between 20 thz and 375 thz (in force)- itu-r p.1621-2," (2015).