

The Challenges of Free-Space Optical Communication Miniaturization - Future in-orbit demonstration of the 2U PUCHACZ nanosatellite

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ABSTRACT

This paper addresses the principal hardware challenges of miniaturizing Free-Space Optical (FSO) communication payloads for nanosatellites. This work offers a systematic description of the DZIDA module, analyzing the fundamental hardware limitations and engineering compromises associated with compact FSO payload design. The challenges are presented through the design and development of an optical downlink module scheduled for in-orbit demonstration aboard the 2U PUCHACZ CubeSat in 2027. The signal will be received by the Optical Ground Station (OGS) equipped with an InGaAs avalanche detector. DZIDA is among the first laser communication modules of its kind developed in Poland. The size of the system, approximately 0.2U, is smaller than that of most commercially available CubeSat laser terminals. A deliberately wide-beam optical design relaxes the pointing from the traditionally required sub-milliradian level. The aggressive miniaturization of the optical system reveals many fundamental hardware issues. The high peak power of the light source requires the highest optics cleaning standards. The emission area of commercial off-the-shelf (COTS) pulsed high-power SWIR lasers is a long rectangle. To achieve a desired power intensity distribution on the Earth's surface, the illuminated area must form an elliptical shape. The other limitation is the maximum acceptable diameter of the optical elements. The major challenge is to manufacture an optical system's package. Resolving the presented issues might pave the way for cost-effective miniaturized laser communication payloads, especially those equipped with low-accuracy Attitude Determination and Control Subsystems (ADCSs). A successful demonstration will validate wide-beam FSO as a practical downlink option for nanosatellites.

Keywords: FSO, OGS, SWIR, ADCS, CubeSat, downlink, miniaturization

1. INTRODUCTION

The data volumes generated by Earth-observation and remote-sensing payloads on small satellites continue to grow, while the S- and X-band spectrum allocated to their RF downlinks is increasingly congested and licensed; a CubeSat-class RF link rarely exceeds tens of Mbit/s without an antenna mass and power budget a nanosatellite bus cannot support.¹ Free-space optical (FSO) communication addresses this bottleneck directly, concentrating transmit energy into a narrow, licence-free optical beam to offer data rates one to three orders of magnitude higher per watt of transmit power and per unit of receive aperture than an equivalent RF link.

Several CubeSat-class laser terminals have already flown or reached advanced development,² and their published parameters set the scale a new payload must beat. OSIRIS4CubeSat, DLR's compact downlink terminal, occupies 0.3U and 350 g, draws under 8.5 W, and delivers 100 Mbit/s, but only by pairing $\pm 1^\circ$ coarse body-pointing with a dedicated fast-steering mirror (FSM) for fine pointing.^{3,4} CubeCAT reaches 1 Gbit/s from a 1U, 1.0 kg, 10.8 W terminal, at the cost of a shared-aperture optical architecture requiring 0.3 μ m lateral co-alignment stability.⁵ NASA's OCSD terminal dispenses with an FSM and points the whole 1.5U, 2.3 kg spacecraft body, but only because its star-tracker ADCS holds 0.024° (3σ), letting a $\sim 0.06^\circ$ FWHM beam deliver up to 200 Mbit/s on 10–20 W.⁶ CLICK B/C and its predecessor NODE/CLICK-A occupy 1.2–1.7U and 15–20 W and combine

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0.15° (3σ) coarse ADCS pointing with a 16 μrad (1σ) MEMS FSM to close a 71 μrad beam.^{7–9} None of these terminals is smaller than 0.3U, and every one below 1.5U carries a dedicated fine-pointing mechanism.

What these figures show is that terminal volume tracks pointing strategy, not laser power. A beam narrower than the host ADCS accuracy cannot close a link without some element to correct residual pointing error in real time – an FSM servo, a beacon detector, tracking optics, or all three – and that element, not the transmitter itself, dominates the mass, volume and non-recurring cost of the terminals above. This is precisely the cost/volume overhead that keeps FSO downlinks out of low-budget CubeSat missions: a fine-pointing chain is difficult to justify on a bus whose ADCS, power and integration budget were sized for a single, modest optical payload rather than a dedicated pointing subsystem.

This paper takes the opposite starting point. Rather than shrinking a fine-pointing system to fit a sub-U volume, the DZIDA (Demonstrator of Zapping Infrared Downlink Apparatus) module trades transmit gain for pointing tolerance, widening the beam until it matches the accuracy already available from the host platform’s own reaction-wheel ADCS, and removing the FSM, the beacon chain and the associated alignment budget entirely. That trade is what allows DZIDA to occupy approximately 0.2U – smaller than any COTS terminal reviewed above – but it does not eliminate hardware difficulty so much as relocate it: an elongated, high-peak-power COTS diode emitter, a single-lens collimator with essentially no margin for adaptive correction, and a fixed aperture that must be shared between beam-shaping and packaging constraints together produce a distinct set of optical and optomechanical problems, which are the subject of this paper.

The remainder of the paper is organized as follows. Section 2 describes the PUCHACZ platform and the DZIDA transmit chain. Section 3 derives the beam divergence and describes the resulting source and collimating-optics design. Section 4 presents the optomechanical, alignment and contamination-control problems that miniaturization of that design creates, and the compromises adopted to resolve them. Section 5 describes the ground segment and the resulting link budget.

2. MISSION AND PAYLOAD OVERVIEW

PUCHACZ (Polish for *Eurasian eagle-owl*) is the second flight mission of SatLab AGH, a student research group operating under the Faculty of Space Technologies and the Space Technology Centre of the AGH University of Krakow.¹⁰ The mission follows HYPE, a $5 \times 5 \times 5$ cm PocketQube and the smallest satellite built in Poland, which was launched on 14 January 2025 aboard the SpaceX Transporter-12 rideshare from Vandenberg Space Force Base into a low Earth orbit and returned its first images shortly afterwards.¹¹ HYPE was developed entirely in-house, including custom printed circuit boards, flight software and final assembly, and the resulting design, qualification and operations experience forms the heritage baseline for the present mission. PUCHACZ increases the envelope volume by roughly a factor of sixteen relative to its predecessor, which is what makes a dedicated optical communication payload feasible.

The spacecraft conforms to the 2U CubeSat standard, with external interface dimensions of $10 \times 10 \times 22.7$ cm and a launch mass below 4 kg.¹² Launch is currently manifested for 2027 into a low Earth orbit; the reference orbit assumed throughout this paper is a Sun-synchronous orbit at 500–550 km altitude, which bounds the slant range and the ground-station pass geometry used in the link budget of Sec. 5.

Three payloads share the available volume: the Earth-observation payload, the BEAR experiment, and the DZIDA demonstration.

BEAR evaluates the shielding performance of bio-composite materials in LEO using dosimeters beneath bacterial cellulose composites doped with tungsten and MXene, plus uncovered and reference dosimeters as controls.

The third payload is DZIDA (Demonstrator of Zapping Infrared Downlink Apparatus), the subject of this paper. DZIDA occupies approximately 0.2U and transmits by means of a directly driven high-peak-power pulsed SWIR laser diode, controlled by a radiation-tolerant automotive-grade COTS FPGA.^{13,14} The architecture is chosen to deliver adequate peak irradiance at the receiver while keeping the average electrical power within what a 2U bus can supply.¹² The module is deliberately designed around a wide transmit beam so that the pointing requirement falls within the capability of the low-cost attitude determination and control subsystem carried by the platform, rather than demanding a dedicated fine-steering mechanism.

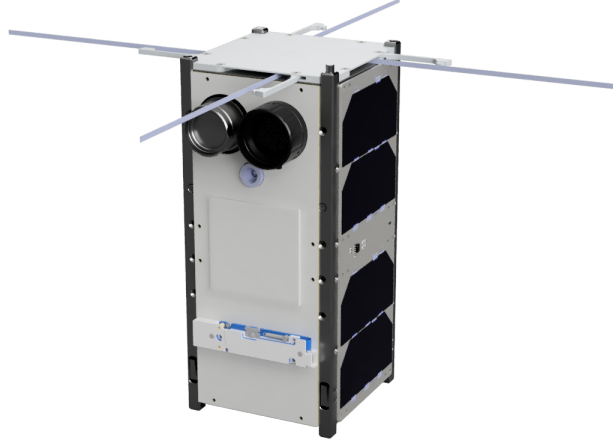


Figure 1. Satellite render prepared for digital preliminary fit-checks.

The relevant platform characteristic for the optical design is consequently the achievable pointing performance. No optical beacon is transmitted from the ground and no closed-loop tracking is implemented on board; the downlink is strictly one-way and open-loop, pointed solely on the basis of the on-board orbit propagation and attitude solution. This constraint, more than the volume limit itself, dictates the minimum admissible beam divergence derived in Sec. 3. Table 1 summarizes the platform parameters that propagate into optical and link analyzes.

Table 1. PUCHACZ platform and mission parameters relevant to the DZIDA optical downlink.

Parameter	Value
Form factor	2U CubeSat, $10 \times 10 \times 22.7$ cm
Launch mass	< 4 kg
Reference orbit	SSO, 500-550 km
ADCS control accuracy	$\pm 0.1^\circ$ (3σ)
Launch window	2027
Payloads	RGB and multispectral imagers, DZIDA, BEAR
DZIDA volume	$\approx 0.2U$
Peak power available to DZIDA	≤ 25 W (duty cycle $\approx 0.07\%$)
RF TMTC link	UHF band

2.1 DZIDA Downlink Concept

DZIDA carries no optical receive path, no acquisition sensor and no optical feedback of any kind, so the beam width alone must absorb the residual attitude error. Among the terminals reviewed in Sec. 1, only OCSD dispenses with a fine-pointing mechanism in the same way, and it does so behind a far more accurate star-tracker ADCS.

The signal chain comprises five blocks, shown in Fig. 2. Control and configuration are handled by an STM32 microcontroller on the platform’s baseline board, which takes commands and payload data from the spacecraft bus and configures the FPGA. A Lattice CrossLink-NX LIFCL-40 FPGA, built on the 28 nm FD-SOI Nexus platform, implements the pulse-position modulator and the coding and synchronization layer described in Sec. 2.2. Its timing output drives a spike-forming circuit and power driver, which exposes a dynamically settable pulse length, so the slot width of the modulation is a reconfigurable parameter rather than a fixed one. That stage supplies the drive current to the laser diode, and a single collimating lens reduces the diode’s raw emission to the system beam divergence.

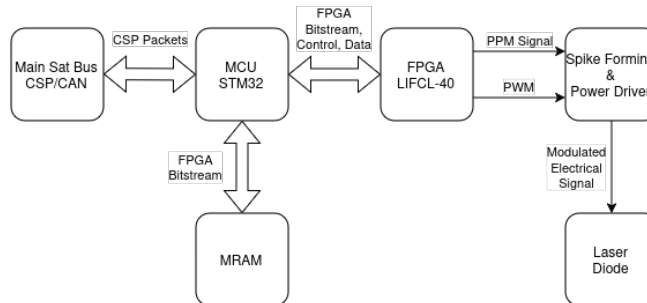


Figure 2. Data flow through the DZIDA transmitter, from the satellite bus to the laser diode. The collimating optics are omitted.

Two architectural choices define the module. The first is that the transmitter generates its output directly from the pulsed laser diode, with no optical amplifier and no pump, and the driver switches the diode in a purely binary fashion with no analogue level control. Omitting the amplifier is what makes the volume and power budgets of Table 1 attainable at all, a route already taken successfully by OSIRIS4CubeSat.³ Because a pulsed diode draws far more current during a pulse than the bus can supply, the driver carries local energy storage sized to deliver that current and recharge between pulses within the bus limit; this, rather than the optical design, is the principal constraint on the driver.

The second is that thermal control is passive. The module operates across the host platform’s thermal environment without active wavelength stabilization, so its emission wavelength moves with temperature at 0.55 nm per °C. The consequence falls on the ground segment, which must accommodate that excursion rather than filter it, as discussed in Sec. 5.1.

2.2 Modulation

The channel code is 1024-ary pulse-position modulation. Each symbol carries $\log_2 M = 10$ bits in the position of a single pulse among $M = 1024$ slots, followed by 16 guard slots that bound the duty cycle and allow the driver stage to recover before the next symbol. For M -ary PPM at slot rate R_s , the information rate and duty cycle are

$$R_b = \frac{\log_2 M}{M} R_s, \quad D = \frac{1}{M}, \quad (1)$$

for the ideal scheme; the 16 guard slots make the realized symbol 1040 slots long, and the duty-cycle and peak-to-average figures quoted below follow from that rather than from M alone. Either way the slot rate, not the modulation order, sets the achievable throughput, and the receiver decides the slot rate: detector noise and the optical power of Sec. 5.2 confine the usable electrical bandwidth to roughly 30 MHz, which corresponds to a slot width near 30 ns and, over the 1040-slot symbol, to a data rate of approximately 300 kbit/s.

The choice of $M = 1024$ rests on two reasons rather than the usual one. The first is the photon efficiency for which PPM is normally selected in power-starved links. The second, and equally decisive here, is the peak-to-average power ratio, which for M -ary PPM is exactly $\text{PAPR} = M$. It is this property that allows the transmitter to exploit the diode’s full 25 W rated peak while keeping the average optical and electrical power inside what a 2U bus can supply, and it is the reason a high-peak-power, low-duty-cycle COTS source is a viable basis for the module at all. PPM itself is well established in optical communication; what is untried is the order. $M = 1024$

exceeds by a factor of four the $M = 256$ ceiling that the CCSDS high-photon-efficiency coding standard specifies, and it is chosen to match a directly modulated diode’s duty-cycle limit rather than an amplifier’s average-power limit.

Forward error correction is provided by a Reed–Solomon RS(221,205) code over $\text{GF}(2^{10})$: 205 message symbols, 16 parity symbols, 10-bit symbols. The symbol width is a deliberate match to the modulation order, since $M = 2^{10}$ means one Reed–Solomon symbol maps onto exactly one PPM symbol with no bit repacking between the coding and modulation layers. The (n, k) pair is that of the inner code of the CCSDS Reed–Solomon product code for optical communication, which specifies it natively over 8-bit bytes; the present implementation uses a single RS(221,205) layer over 10-bit symbols rather than the standard’s full two-layer structure, reflecting the current state of the implementation rather than a decision to exclude the outer code.

The resulting transmitted duty cycle satisfies the platform constraint. The raw figure of $1/1040 = 0.096\%$ is reduced further by the end-of-frame field, which occupies 25% of the frame and contains no pulses, giving approximately 0.072% measured on a frame basis, within the 0.1% budgeted for the module. One consequence of the scheme is worth stating explicitly, because it drives the digital design: PPM places the entire payload in the timing of a pulse, so slot-clock stability is not a peripheral quality of the implementation but the mechanism by which data is carried. The requirement is symmetric, since the ground station reconstructs the same slot grid, and short-term jitter matters more than long-term accuracy because slow drift is absorbed by the periodic synchronization field while jitter between synchronization opportunities is not.

Fig. 3 shows a composed frame produced by this chain, with the individual 1024-PPM pulses and the boundaries of the synchronization, metadata, data and parity fields marked.

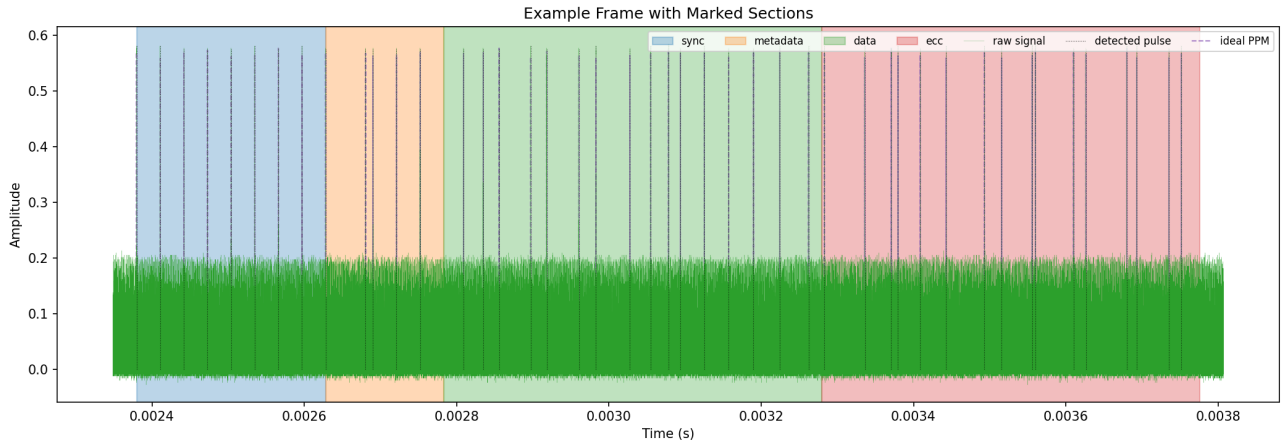


Figure 3. Example of a composed DZIDA frame. Each spike is one 1024-PPM symbol, positioned within its 1040-slot window; the shaded regions mark the synchronization, metadata, data and Reed–Solomon parity fields.

Framed against the terminals of Sec. 1, DZIDA is a demonstration of link closure at minimum SWaP rather than a rate contender. The throughput is set by what the receiver can extract from the available optical power, not by the modulator, and the result being sought in orbit is that a 0.2U transmitter with no fine-pointing chain, no optical amplifier and no beacon closes a link at all.

3. OPTICAL SYSTEM DESIGN

3.1 Wide-Beam Trade-Off

The beam divergence of DZIDA is not an independent optical choice. It is derived from the platform’s attitude control, and it is the parameter through which every other optical and link quantity follows. Among the body-pointed terminals flown to date, OCSD established the sizing heuristic that transfers most directly to a module of this class: with no fine-steering element, the beam should be at least twice the ADCS 3σ pointing error, so

that the residual attitude excursion stays inside the illuminated cone. Applied to the $\pm 0.1^\circ$ (3σ) control accuracy of the PUCHACZ platform, this fixes a minimum full-angle divergence of

$$\theta_{\text{div}} \geq 2\theta_{\text{err}} = 0.2^\circ = 3.491 \text{ mrad}, \quad (2)$$

the value adopted throughout this paper, stated as the 3σ full width of the beam's Gaussian intensity profile. Any improvement or degradation in the attitude budget propagates straight into it. The beacon-aided terminals of Sec. 1 take the opposite posture, buying a beam an order of magnitude narrower at the cost of a beacon detector, an FSM servo, stray-light baffling and a cooperative source at the far end. DZIDA carries none of those.

The illuminated footprint on the ground follows from the divergence and the slant range. Table 2 evaluates it at the two geometries that bound a pass.

Table 2. Beam geometry at the two limiting pass geometries, for a 550 km Sun-synchronous orbit and a 0.2° full-angle beam. The corresponding collimation gain, $G_{tg} = 10 \log_{10}(4\pi/\theta_{\text{div}}^2) = 60.13$ dB, is set by the divergence alone and does not vary with geometry.

Quantity	Nadir	25° elevation
Slant range	550 km	1123 km
Footprint diameter	1.92 km	3.92 km

The cost of the trade is transmit gain, and it is substantial. The 10.0 mm aspheric lens of Sec. 3.3 would, at 1550 nm, support an aperture-limited full-angle divergence of approximately $378 \mu\text{rad}$, corresponding to a collimation gain of 79.4 dB. Operating at 0.2° instead surrenders roughly 19 dB of transmit gain relative to what the same aperture could deliver. That deficit is what the link budget of Sec. 5.2 must absorb, and it is why the design depends on a high peak power rather than on optical gain.

What the trade buys is optomechanical. A narrow beam is paid for in alignment tolerance: CubeCAT's shared aperture demands lateral transmit/receive co-alignment within $0.3 \mu\text{m}$, and OSIRIS4CubeSat holds angular co-alignment below $3 \mu\text{rad}$. A milliradian-class beam relaxes both by two to three orders of magnitude, which is the single most consequential simplification available to a miniaturized design, and it is what permits the single-lens collimation of Sec. 3.2 in place of an adaptive or multi-element system.

3.2 Source Characteristics and Beam Shaping

The light source is a modulated COTS high-power (25 W) pulsed 1550 nm laser diode. The emitting surface is a 350×1 micrometer rectangle with FWHM divergence of $24^\circ \times 10^\circ$. The emitter spectral width is 15 nm and the temperature shift coefficient is equal to 0.55 nm per 1°C . The size of the laser diode is standardized at 9 mm. Significant asymmetric divergence requires highly collimating optics. The desired beam shape is an ellipse with an RMS divergence angle close to 0.2° in the fast axis (3σ 99.7 percent of energy). The required collimation is achieved by only one special aspheric lens. Due to the pointing relaxation, the adaptive or more complicated optical systems are not necessary.

3.3 Optical components limitations

The miniaturization of the FSO downlink module imposes the optics envelope limits. The COTS special high-precision aspheric lens has only a 10.0 mm diameter with an effective focal length equal to 8.0 mm. The Numerical Aperture (NA) of the lens is 0.55. The lens glass material is S-LAH64 with an antireflective coating from 1050 - 1700 nm. The impact of radiation-induced glass degradation is insignificant for this mission because of its limited duration.

4. MINIATURIZATION CHALLENGES

4.1 Optomechanical Packaging and Thermal Stability

The DZIDA optical system uses a custom mechanical mount designed for harsh space conditions. The aspheric lens sits in a precisely machined slot and is bonded radially to the mount with a space-rated, low-outgassing epoxy, preventing contamination and angular misalignment. Orbital instruments experience large thermal gradients between sunlit and shadowed regions, causing metallic structures to expand and affecting performance. Because thermal distortion and thermoelastic stress are hard to model precisely, exact parameter calculation is impossible, but careful engineering reduces thermal-failure risk. To limit thermal gradients, the lens is placed inside the satellite body, with only an aperture cut in the front panel.

4.2 Alignment Tolerances and Error Budget

The dimensional tolerances of the DZIDA optical assembly have a key influence on the divergence of the downlink laser beam. The field of uncertainty has to ensure that the beam is broad enough for pointing requirements and narrow enough to avoid excessive dispersion of the optical power. The divergence angle is determined primarily by a distance between the lens and the laser diode, however a significant optical path distortion might appear due to positioning error in a radial direction. The use of COTS elements and standard machining tools introduce dimensional uncertainties large enough to impair the performance of a long range system for space applications. The diameter of the lens has a manufacturing uncertainty of $50\mu\text{m}$. Additional dimensional errors due to mount machining and misalignment between the optical and mechanical axis of the lens might cause an unacceptable deviation exceeding $150\mu\text{m}$. A biaxial adjustment screw mechanism is being developed to ensure precise axial alignment. Fine-thread screws allow pre-launch compensation for manufacturing tolerances, achieving centering accuracy within $30\mu\text{m}$.

4.3 Contamination Control at High Peak Power

Even minor contamination on a lens surface may disperse the signal path due to the high optical power. The optical tests and module integration are performed in a certified ISO7 cleanroom. The interior contamination-avoidance procedures include a separate zone with an anti-vibration, ESD-protected optical bench. Optical elements are cleaned using a special ecological liquid with dust-free tissues on an advanced holder. Cleaned elements are stored in pouches. Every element is inspected using a digital microscope. The ESD protective suit provides full head and body coverage, including a headcup, beard cover, mask, and gloves.

5. GROUND SEGMENT AND LINK BUDGET

5.1 Optical Ground Station

The receiving infrastructure is an optical ground station planned for the summit of Suchora in southern Poland. As the station is still under development, the following describes required capabilities rather than an as-built configuration.

The station must provide a receive aperture of at least 50 cm. Two candidate apertures, 80 cm and 50 cm, are assessed in parallel in the link budget of Sec. 5.2, since the telescope design is not fixed; both are Cassegrain instruments with a secondary obscuring 20% of the primary area. Because DZIDA transmits no beacon and expects none from the ground, the station must acquire and track the spacecraft open-loop from orbital elements alone, and maintain lock over the full visibility window down to the 25° minimum elevation used in the link budget. No adaptive optics is required: the wide transmit beam and direct-detection receiver impose no wavefront-quality constraints on the receive path, unlike the coherent high-rate case of TBIRD.

The key spectral requirement follows from the transmitter architecture. DZIDA is passively controlled and its emission wavelength shifts with temperature (Sec. 2.1), so the receive path must be wide enough to pass this excursion around 1550 nm. This rules out the usual daylight strategy: a filter narrow enough to reject solar background would also reject signal at the thermal-drift extremes.

The detector has not been selected. Two candidates are carried: a bare InGaAs PIN photodiode, offering high responsivity uniformity and wide bandwidth but requiring an external transimpedance amplifier whose noise

the detector specification cannot account for; and an InGaAs avalanche photodiode module with an integrated transimpedance amplifier and adjustable multiplication, whose specified noise figures are already end-to-end. The choice between them follows from the receiver noise budget rather than from the optical link budget, and is therefore left open here. Either way the outcome for the waveform is the same: receiver noise confines the usable electrical bandwidth to roughly 30 MHz, so the detector choice sets the available margin rather than the achievable data rate. Finally, although DZIDA claims no conformance to optical communication standards, the station is required not to preclude it later, since Suchora is expected to outlive PUCHACZ.

5.2 Link Budget

Table 3 gives the optical power delivered to the receiver photodiode for both candidate apertures, evaluated at the worst-case geometry of the pass: the top of the 500–550 km reference range seen at 25° elevation, giving a 1123 km slant range. The budget is deliberately scoped to power at the photodiode. Detector sensitivity, and therefore link margin, depend on the receiver noise budget and on a detector choice that Sec. 5.1 leaves open, and are being established by a separate link-closure simulation; quoting a margin here would require fixing both prematurely.

Table 3. DZIDA optical downlink budget, power delivered to the receiver photodiode. Conditions: 550 km Sun-synchronous orbit, 25° elevation, 1123 km slant range, 0.2° full-angle beam, $\pm 0.1^\circ$ (3σ) pointing error, 20% secondary-mirror obstruction, 0.9 aperture efficiency.

Parameter	80 cm aperture	50 cm aperture
Tx optical power (25 W peak)	+43.98 dBm	
Tx optics loss ^a	−0.30 dB	
Tx collimation gain	+60.13 dB	
Tx pointing loss (mean) ^b	−0.51 dB	
Range loss (FSPL)	−259.19 dB	
Atmospheric loss ^a	−0.60 dB	
Rx aperture gain	+122.77 dB	+118.69 dB
Power at photodiode	−33.72 dBm	−37.80 dBm

^a Adopted from TBIRD’s published budget.¹⁵

^b Mean loss under Rayleigh-distributed beam wander,¹⁶ not a static boresight offset.

The pointing loss needs a word of explanation. Treating it as a fixed offset from boresight assumes the spacecraft holds one attitude, when in practice it wanders throughout a pass, so Giggenbach et al. model the error as Rayleigh-distributed jitter about boresight and give the resulting *mean* loss for a Gaussian beam,¹⁶

$$\beta = \frac{\theta_{\text{FWHM}}^2}{4 \ln 2 \sigma_{\text{BW}}^2}, \quad a_{\text{BW}}[\text{dB}] = 10 \log_{10} \left(\frac{\beta}{\beta + 1} \right), \quad (3)$$

where θ_{FWHM} is the beam’s full-width half-maximum divergence and σ_{BW} the standard deviation of the wander angle. For the 0.2° beam against the platform’s $\pm 0.1^\circ$ (3σ) pointing, this gives $\beta = 8.0$ and a mean loss of 0.51 dB. Half a decibel for a tenth of a degree of attitude error is what the wide beam buys, and it should be read against the 19 dB of transmit gain given up to obtain it (Sec. 3.1).

The transmit optics and atmospheric loss terms are taken from TBIRD’s published budget for a comparable 1550 nm direct-detection downlink.¹⁵

6. CONCLUSIONS

Miniaturization of free-space optical communication poses many technical impediments, and the DZIDA design meets them by sizing the transmit beam to the platform’s attitude control rather than to its optics: a 0.2° beam

matched to $\pm 0.1^\circ$ (3σ) pointing removes the fine-steering mechanism, the beacon chain and their alignment budget outright. What that removes in pointing hardware it relocates into the optics, where an elongated high-peak-power emitter, single-lens collimation with no adaptive margin and contamination control at high peak irradiance – not the transmitter electronics – set the achievable performance. The result is a downlink to a 50–80 cm ground aperture from a 0.2U amplifier-free, beacon-free transmitter, at a rate set by what the receiver can extract from the available optical power rather than by the modulator. Qualification and the 2027 in-orbit demonstration remain to be completed, and it is that demonstration which would establish wide-beam FSO as a practical downlink option for low-cost CubeSat missions.

ACKNOWLEDGMENTS

This work was supported by the Initiative of Excellence – Research University.
This work utilized AI for language and grammar clean-up.

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