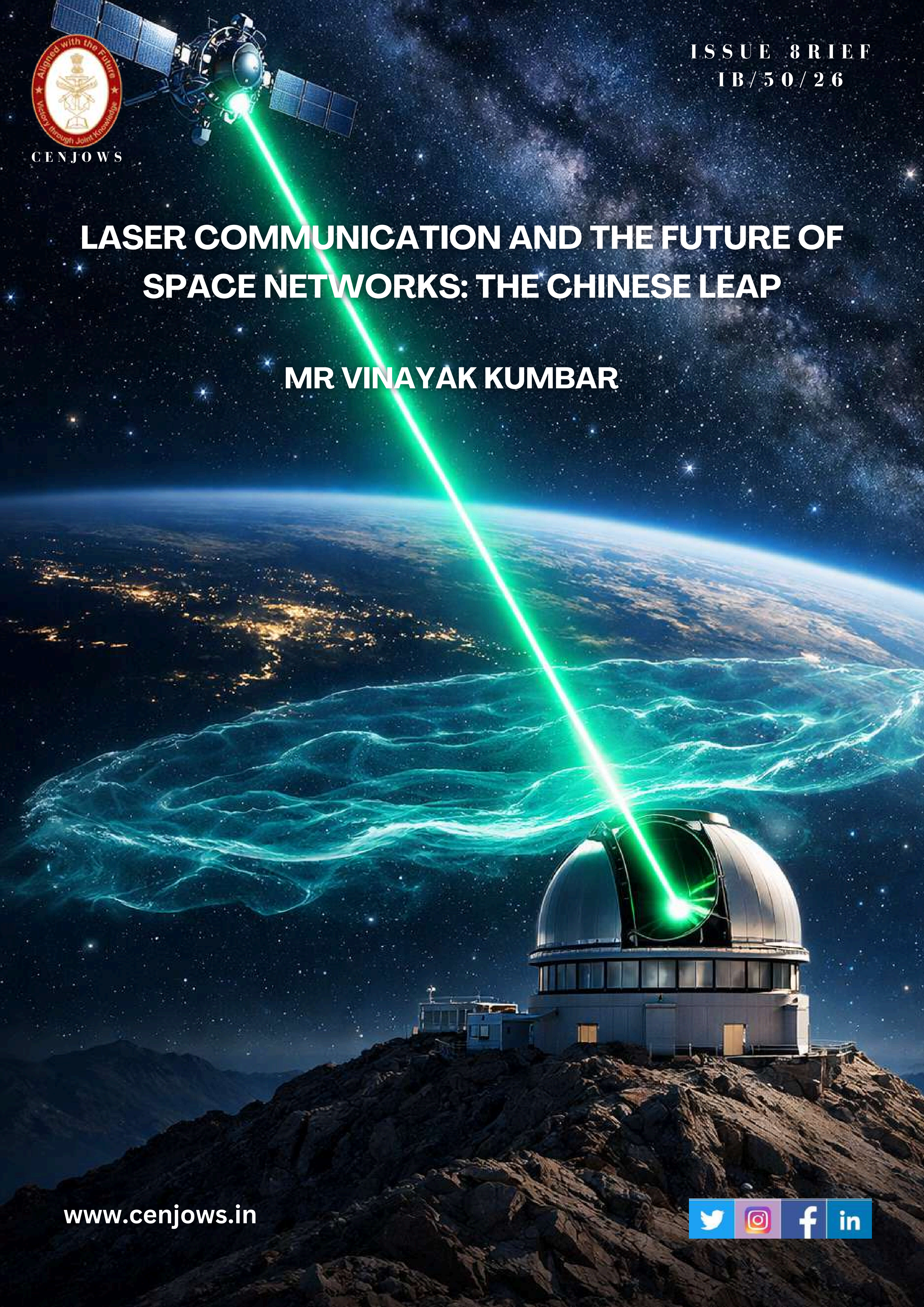

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ISSUE BRIEF
IB/50/26

LASER COMMUNICATION AND THE FUTURE OF SPACE NETWORKS: THE CHINESE LEAP

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Laser Communication and the Future of Space Networks: The Chinese Leap

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Introduction

Satellite communication through laser is a fast-emerging technology for future space information networks. It offers immensely faster data rates, broad bandwidths, enhanced security, and a low size-weight-power terminal when compared with the traditional radio frequency (RF) systems. The high orbit links are of immense value. They offer continuous global coverage, real-time Earth observation data downlink, and deep-space relay, but they remain among the most difficult to implement reliably. The beam must travel very long distances through vacuum and then penetrate the entire atmospheric column during which it experiences strong scintillation, beam wander, and angle fluctuations caused by the atmospheric turbulence. The effect causes power fading and distortions of the wave front. This in turn severely degrades the single-mode fibre coupling efficiency and coherent detection performance.

The laser vs the RFn

Laser communication offers various advantages over the conventional RF systems. It can deliver data ranging from 1 to hundreds of Gbps (with a potential to be expanded to Tbps) in a single beam.[1] Compared to this, the RF has a typical ceiling of a few Gbps. The laser terminals achieve equivalent, if not higher, gain with apertures of only a few centimetres[2] whereas the RF antennas deploy multi-metre ones. This drastically increases the satellite mass, volume, and adds complexities during deployment. Power efficiency is significantly higher (more bits per joule) because of the narrow beams and advanced coherent modulation.[3] The RF maintains better performance in heavy clouds and rain, while the laser links, when equipped with adaptive optics (AO) and mode diversity reception (MDR), achieve availability and reliability approaching RF levels under clear-to-moderate weather.[4] This makes laser communication the clear choice for future high-capacity, secure, and broad-spectrum satellite networks.

GEO Sat Com v/s the LEO Sat Com

Geosynchronous (GEO) satellite communication holds decisive advantages over the low Earth orbit (LEO) constellations. A single GEO satellite provides continuous, fixed-position coverage over roughly 1/3rd of the total Earth's surface.[5] This eliminates the need for a complex inter-satellite handover, moving ground antennas, or the thousands of LEO satellites required. While their latency is higher than the LEO,[6] for the majority of broadband delivery, broadcasting, backbone trunking, and Earth-observation data services, this delay is manageable and acceptable. The simplicity and cost-effective approach to serving millions of users with just one or a few GEO platforms overshadows such drawbacks. The advanced turbulence mitigation techniques, such as the *AO + MDR* approach as demonstrated by Chinese researchers, promises multi-hundred Gbps continuous downlink capacity with far fewer space and ground assets than LEO constellations. Such features make them a preferred architecture for future space communication networks.

The Recent Chinese Advancement

Adaptive optics (AO) is often used to partially correct wave front distortions. But the residual distortions of higher order and the associated intensity fluctuations still limit their efficiency. In order to overcome these challenges, the Chinese researchers have successfully combined the adaptive optics with mode diversity reception (MDR).[7] They have achieved this on an actual high-orbit satellite-to-ground link, achieving a stable coherent transmission. Improved power stability and reduced *bit error rate* performance were also maintained. This paves the way for operational high-speed geostationary laser communication systems. This experiment has achieved a groundbreaking milestone in satellite communication.

Strategic Importance and Technical Significance

High orbit, especially Geo synchronous (GEO) satellite laser communication, is often considered to be one of the most challenging regimes in free space optical communication. This is because the combination of extremely long distance, high propagation loss and the necessity to penetrate the full thickness of the atmosphere adds a multitude of challenges. The high orbit downlinks suffer from heavy power fading and high outage scenarios. The work on which this article centres was conducted by a joint collaboration led by Beijing University of Posts and Telecommunications, the Institute of Optics and Electronics (Chinese Academy of Sciences), and Xi'an Institute of Space Radio Technology.[8] It marks the first time that adaptive optics (AO) combined with mode diversity reception (MDR) have been successfully applied on a high-orbit satellite link.

Experimental Scenario and Link Parameters

Table 1 shows various parameters during the test conducted.

Parameter	**Value**
Telescope diameter	1.8 m
Observatory altitude	3200 m
Satellite type	Geostationary
Slant-range distance	36702 km
Transmit optical power	2 W
Wavelength	1550.52 nm
Atmospheric path length	~20 km
Fried parameter, r_0 (at 550 nm)	7.43 cm
Fried parameter, r_0 (at 1550 nm)	~ 22.5 cm
Turbulence regime at 1550 nm	Moderate-to-strong

(**Table:** Parameters during the test conducted by the Chinese)

(**Source:** Acta Optica Sinica Journal, Vol. 45, Issue 13)[9]

- **The Receiving System Apparatus**[10]

  The ground-receiving system with a 1.8 m Cassegrain telescope employed a high-order adaptive optics chain. It consisted of a 357-actuator deformable mirror and a Hartmann–Shack wavefront sensor with 316 effective sub-apertures. The incoming light was split into a 9:1 ratio by a beam splitter. It directed 10% to the wave front sensor and 90% to the communication path. A fast-steering mirror in a fine-tracking loop was used to remove the residual tip-tilt. The corrected beam was then coupled via focusing optics into a 50/125 µm graded-index multimode fibre (OM2)[1], followed by a Multi-Plane Light Converter (MPLC) that functioned as a programmable photonic lantern and mode demultiplexer. The eight resulting single-mode fibre outputs (SMF-28) were fed into a 3-channel 90° optical hybrid coherent receiver array, with real-time digital signal processing and selection combining performed on an FPGA.

- **Adaptive Optics Performance**[11]

  Closed-loop AO correction reduced wavefront root mean square (RMS) error from 0.82λ to 0.10λ ($\lambda = 1550$ nm). Residual wavefront error was therefore $\lambda/10$, demonstrating near-diffraction-limited correction over most of the 1.8 m aperture. Simultaneously, AO integrated tip-tilt correction reduced tracking error from ~3–5 µrad (open loop) to 0.62–0.69 µrad RMS (closed loop), ensuring stable energy concentration on the multimode fibre core.

- **Mode Diversity Reception Principle and Implementation**[12]

  Even after an excellent AO correction, the higher-order residual aberrations and strong scintillation events still tend to generate speckle. This causes part of the energy to excite the higher-order modes in the fibre. The MPLC then demultiplexes these modes into independent single-mode channels. Upon real-time power monitoring of all eight outputs, it was seen that the fundamental HG_{00} mode carried the highest average power, but during deep

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[i] OM2 - Itis atype of multimode fibre, and its cable jacket colour is orange. It uses LED light source, but with a smaller fibrecore size of 50 µm. It is suitable for Ethernet below 10Gbps, especially in GigabitEthernet.

fades the higher-order modes (LP_{11}, LP_{21}, etc.) temporarily carried significant energy. The 3 strongest channels were selected out of the total of 8 instantaneous channels, and then digital coherent combining was performed. The system harvested the lost energy, eventually converting scintillation-induced fading into a diversity gain.

- **Received Power Statistics and Diversity Gain**[13]

  Power at each MPLC single-mode output was sampled at 10 kHz for 10-second intervals. Probability density functions (PDF) of the eight channels confirmed that AO significantly raised the power floor of all modes, with the largest gain in the fundamental mode. When comparing traditional single-mode reception (using only the strongest channel, equivalent to conventional SMF coupling after AO) against 3-channel selection combining, at 90% availability (CCDF = 0.9), AO + MDR (SC) provided 3.94 dB higher received power than AO-only single-mode reception. This 3.94 dB directly translates to either a doubled link margin or a quadrupled tolerance to additional losses.

- **Complementary Action of AO and MDR**

  The experiment beautifully illustrates that the two techniques are highly synergistic. While the AO concentrates energy into the fibre core, raising the average coupling efficiency, the MDR captures the residual speckle energy that the AO cannot perfectly correct and converts deep fades into moderate fluctuations via selection diversity. Together they work to reduce the turbulence on different physical layers. The AO focuses on wavefront distortion and the MDR on intensity scintillation and mode partitioning.

Geopolitical Implications: The Strategic High Ground

The integration of Adaptive Optics (AO) and Mode Diversity Reception (MDR) and the associated successful trial of the same, signal a significant transformation in the geopolitical "High Ground" in the space domain. The Low Earth Orbit (LEO) constellations, like that of Starlink, have for sure captured public attention through their sheer volume. But the Chinese focus on the Geostationary (GEO) belt could potentially address a broader strategic vacuum.

A GEO that is well linked with laser architecture could provide a nearly hack-resistant (un-hackable), high-bandwidth backbone for the defence communication architecture by offering continuous sovereign surveillance. Radio Frequency (RF) signals spread over vast areas. These are also more susceptible to terrestrial jamming or interception. These narrow laser beams are physically difficult to "listen in" on without being detected. Hence, by mastering the art of overriding or dealing with the atmospheric turbulence which previously made GEO-to-ground laser links unreliable, China is potentially on a journey to position itself to manage global data relays. They can do this with a fraction of the assets that the Western LEO models typically require. This network could offer such a level of data security and throughput that it would redefine how a superpower maintains a constant, consistent, high-speed presence over one-third of the planet using only a single node.

The LEO swarms often require thousands of satellites to maintain coverage. This is because each unit moves across the sky in minutes. Hence, there is a requirement of constant handovers and a massive logistical tail for replacements.

In contrast, the AO+MDR breakthrough discussed earlier in detail suggests that ‘quality can indeed compete with quantity’. By achieving a stable Gigabit-per-second (Gbps) speed from about 36,000 km away, the research has proven that a few high-altitude towers in the sky can do the heavy lifting of a thousand LEO units. This also reduces the risk of space debris significantly and the complexities associated with ground-station tracking. LEO may offer superiority in low-latency gaming or high-frequency trading. But the GEO-laser model could be a more suitable (if not the ultimate) solution for massive backbone trunking and earth-observation (EO) data. It allows a more sustainable and cost-effective expansion of the global internet. This helps nations to move away from the orbital crowding that currently troubles the lower altitudes.

Way Ahead: The Technical Roadmap and Challenges

Looking ahead in the next decade, the roadmap for this revolutionary technology suggests a few points to be noted by the research personnel.

- Firstly, we may be seeing only the baseline of its true potential. The current 1 Gbps success is a proof of concept. The real leap would lie in the scaling up of the same to Terabit-per-second (Tbps) speeds.
- Secondly, with the implementation of Wavelength Division Multiplexing (WDM), which is the same technology that powers transoceanic fibre-optic cables, one can potentially send multiple colours of laser light through the same AO-corrected path. Here, each wavelength could act as an independent data lane. This potentially could help multiply the capacity by a factor of hundreds without having to increase the 1.8m telescope aperture.
- Thirdly, if combined with advanced coherent modulation (ACM), these GEO links could soon act as orbital fibres. They could not only provide the same bandwidth as that of the physical cables but also offer the flexibility of space-based deployment. This kind and level of scalability would ensure that, as global data demands explode with AI and 5G integration, the GEO laser infrastructure can see an evolution via software and frequency upgrades. This can turn out to be better compared to one that needs a complete hardware overhaul.

Despite these revolutionary breakthroughs, the atmospheric wall remains a well-designed and formidable opponent. This for sure requires a shift from laboratory success to a resilient ground infrastructure.

- While AO and MDR can effectively neutralise the effects of turbulence, they unfortunately are not well equipped (in terms of their ability) to penetrate thick, opaque cloud cover or heavy fog. This could be termed as the “Achilles' heel” of optical communication.
- To make this an operational reality, there is a need to develop a diverse Optical Ground Station (OGS) network. This requires placing the telescopes in geographically distinct regions, such as high-altitude deserts like Tibet or arid plains like that of the Gobi. This could ensure that if one station is weathered out partially or completely (in worst-case scenarios), the satellite can hand over the laser link to a clear site.
- The next phase of this "Leap" would likely be less about the physics of the beam. The focus could be laid more on the logistics of the terrestrial network.

Perfecting this handover logic would potentially be the final step in creating a 24/7 laser-based internet. This rivals the reliability of traditional radio waves while offering a thousand times the speed.

Conclusion

The successful demonstration of AO+MDR technology undoubtedly marks a pivotal moment. The "atmospheric wall" has finally yielded (maybe not completely yet!) to high-orbit optical links. By achieving a stable, gigabit-level transmission from geostationary altitudes, China has validated a stepping stone for a leaner, more secure, and highly capable space architecture. By this feat, it challenges the current dominance of LEO constellations. However, the technical hurdles like cloud opacity remain not fully addressed. But the shift from such laboratory theory to operational reality is expected to be a reality sooner, and it sure is undeniable as well. Once this orbital fibre network gets scaled towards terabit speeds, it shall not only redefine sovereign data security but also provide the essential backbone that is a necessity for the next generation of global infrastructure.

Glossary

Laser Satellite Communication / Free space optical communication	A technology that uses laser beams instead of radio waves to transmit data through space or the atmosphere, offering high speeds and bandwidth.
Radio frequency (RF) systems	Communication systems that use radio waves to transmit data. They serve as the conventional baseline compared to laser systems.
Bandwidth	The data transmission capacity of a communication channel.
Data rates / Gbps / Tbps	The speed of data transfer, measured in Gigabits per second (1 billion bits) or Terabits per second (1 trillion bits).
Coherent detection / Coherent transmission	It is an Optical detection method that measures both the amplitude and the phase of the light wave.

Advanced coherent modulation (ACM)	The techniques that are used to encode data onto a laser beam’s phase and amplitude to optimise power and spectral efficiency.
Inter - satellite handover / Link handover	The process of transferring a data connection from one satellite to another.
Broadband delivery	The transmission of high-speed, wide-bandwidth data to users.
Backbone trunking	High-capacity used in core network paths for global data traffic.
Bit error rate	The percentage of bits with errors relative to the total number of bits in a transmission.
High propagation loss / Power fading	The reduction in signal strength as a laser beam travels over long distances.
Outage	Communication signals dropping below the required threshold that causes temporary loss of connection.
Wavelength Division Multiplexing (WDM)	A technology that multiplexes multiple optical carrier signals onto a single optical fibre by using different wavelengths (colours) of laser light.
Space information networks	Interconnected networks composed of space-based assets and ground stations to manage global data.
High orbit links / Geostationary (GEO) / Geosynchronous (GSO)	Satellites positioned at approximately 36,000 km altitude that match Earth's rotation.
Low Earth Orbit (LEO) constellations	Networks of thousands of small satellites operating at low altitudes.
Deep-space relay	Using a satellite link as an intermediary point to transmit data from deep space missions back to Earth.
Real time Earth observation (EO) data downlink	The instantaneous transmission of environmental, geographical, or surveillance data captured by satellites.
Slant - range distance	The line-of-sight distance between a satellite and a ground tracking station.

Space debris	Inactive human-made objects in space posing collision risk in crowded orbits.
Scintillation / Intensity scintillation	Rapid variations in the received intensity of a laser beam caused by density fluctuations.
Beam wander	The physical displacement or shifting of a laser beam's path away from its intended target.
Angle fluctuations	Variations in the arrival angle of the laser wavefront, causing the beam to rapidly shift focus at the receiver.
Atmospheric turbulence	Irregular movements of air and temperature variations in the atmosphere that disrupt and distort light beams.
Wavefront distortions / Wavefront root mean square (RMS) error	Optical aberrations where the phase front of a light beam becomes warped. RMS error is the statistical measure of this distortion.
Single-mode fibre coupling efficiency	The effectiveness of an incoming laser beam injected into a narrow single-mode optical fibre core without losing energy.
Apertures / Telescope diameter	The opening diameter of an optical system through which light is collected.
Adaptive optics (AO)	A technology used to improve the performance of optical systems by using real-time measurements to dynamically deform a mirror and correct wavefront distortions.
Mode diversity reception (MDR)	A reception technique that captures distorted laser light across several spatial modes to prevent signal loss during atmospheric fading.
Fried parameter (r0)	A statistical measure of the quality of optical transmission through the atmosphere, representing the coherent diameter of the atmosphere.
Cassegrain telescope	A type of reflecting telescope that combines a concave primary mirror and a convex secondary mirror.

Actuators	Small mechanical components behind a flexible mirror surface. These push or pull it to warp its shape and correct laser distortions.
Hartmann–Shack wavefront sensor	It is an instrument that is used to measure the exact distortions of an incoming light wave by splitting it into an array of smaller beams.
Sub apertures	The individual, smaller segmented zones within a wavefront sensor that are used to sample different parts of the incoming beam.
Beam splitter	It is an optical device that divides a single beam of light into two or more separate paths.
Fast steering mirror / Fine-tracking loop	A highly responsive mirror and processing loop used to cancel out rapid pointing jitter and tracking errors.
Residual tip-tilt / Tracking error	The alignment errors of the laser beam after the initial tracking corrections have been applied.
Focusing optics	Lenses or mirrors that are designed to concentrate and direct incoming laser light precisely onto a target.
Graded-index multimode fibre (OM2)	An optical fibre with a wider core that isi designed in order to accept multiple modes (paths) of light simultaneously.
Multi-Plane Light Converter (MPLC)	An optical processor that can transform and manipulate light profiles by using multiple spatial reflections.
Programmable photonic lantern	A device that transits light from a multimode path into several independent single - mode fibre paths.
Mode demultiplexer / De-multiplexes	A system that separates different overlapping modes or patterns of light into separate, clean channels.
Single-mode fibre outputs (SMF-28)	Standardised narrow-core optical fibres that only allow a single spatial mode of light to propagate.
90° optical hybrid coherent receiver array	An advanced optical hardware configuration that mixes incoming signal light with a local reference laser.

Selection combining (SC) / 3 - channel selection combining	A diversity combining technique where the receiver dynamically chooses and combines only the strongest signal channels to optimise data recovery.
Field Programmable Gate Array (FPGA)	An integrated circuit designed to be configured by a customer after manufacturing that is used to run fast, hardware-level signal processing.
Closed-loop AO correction / Open loop	A closed-loop system uses real - time sensor feedback to actively adjust its components.
Wavelength (λ)	The physical distance between successive peaks of a light wave that determining its colour and frequency band.
Speckle / Residual speckle energy	A granular, scattered intensity pattern produced when a coherent laser beam undergoes phase distortions.
Fundamental mode (HG00)	The ideal, central, and cleanest spatial profile that a laser beam takes inside an optical fibre.
Higher-order modes (LP11, LP21, etc.)	Complex, wider spatial paths or shapes that light takes inside a fibre when it enters at an angle or with distortions.
Mode partitioning	The distribution or splitting of laser energy into various different spatial modes.
Digital coherent combining	The mathematical process of aligning and merging distinct electronic data channels captured receivers into one stronger signal.
Diversity gain	The signal boost achieved by capturing alternative paths to offset that loss.
Probability density functions (PDF)	The measure of likelihood and distribution of a variable.
Complementary Cumulative Distribution Function (CCDF)	A measure of curve showing how often a signal stays above a specific performance threshold.
Link margin	The safety buffer of extra signal power designed in a communication link to ensure it works during unexpected degradation.

Size - weight - power terminal (SWaP)	Minimising the physical footprint, mass, and energy consumption of aerospace hardware components.
RF antennas	Metal dishes or rods used to transmit and receive radio waves.
Optical Ground Station (OS)	A facility built on Earth with telescopes, sensors, and receivers used to communicate with laser satellites.
Transoceanic fibre - optic cables	High-capacity data cables that are laid along the ocean floor to connect global internet backbones across continents.

Declaration

I declare that this manuscript is being submitted exclusively to CENJOWS for publication consideration, is original, and has not been published or submitted elsewhere. I further certify that it contains no classified, restricted, or sensitive information and is based entirely on open-source material suitable for publication in the public domain.

ENDNOTES

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