

BOREALIS -- A Canadian Facility for Lasercomm Interoperability Testing

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ABSTRACT

Optical inter-satellite link (OISL) technology is emerging as a critical enabler for next-generation low Earth orbit (LEO) constellations, offering high-throughput, low-latency connectivity with inherent immunity to radio-frequency interference and congestion. This paper presents the results of a laboratory demonstration in which two optical communications terminals were operated in a closed-loop free-space optical link within a controlled indoor environment. To replicate realistic on-orbit conditions, the testbed incorporated hardware-in-the-loop simulation of platform motion dynamics, including attitude perturbations and vibration profiles representative of LEO spacecraft, as well as emulation of the narrow angular selectivity characteristic of diffraction-limited inter-satellite optical links. Successful pointing, acquisition, and tracking (PAT) performance was demonstrated across a range of simulated dynamic conditions, and key link metrics including received optical power, and PAT residual error were characterized throughout.

Building on this demonstration, this paper further describes the architecture and development of a multi-vendor optical communications interoperability testbed. The facility is designed to accommodate terminals from any vendor or supplier, providing a standardized interface environment including simulated orbital dynamics, calibrated optical channel emulation, and physical-layer test instrumentation. The testbed is intended to support the validation and qualification of OISL terminals destined for planned LEO constellations, providing a vendor-neutral platform for confirming adherence to emerging OISL standards and interface control specifications. A roadmap for the facility's continued development in support of Canada's growing role in the global optical satellite communications ecosystem is presented.

Keywords: Optical Intersatellite Links, Interoperability Testing, Optical Communication Terminals, Laser Communication, LCT100, LEO Constellations, Optical Crosslinks

1. INTRODUCTION

Optical intersatellite links (OISLs) are an increasingly important technology for next-generation space communication architectures. By enabling interference-free direct communication between satellites, OISLs can reduce reliance on ground infrastructure, improve network resilience, and support global data transport with lower latency [1][2]. Several commercial and government organizations have announced or deployed constellations that rely on intersatellite connectivity as a key component of their network architecture, including SpaceX's Starlink [3], Telesat's Lightspeed [4], Amazon's Kuiper, the SDA's Transport Layer [5], ESA's HyDRON initiative [6], the Rassvet network[7], the Thousand Sails Constellation[8], and many more. As these constellations continue to grow in number and complexity, reliable optical networking between spacecraft is expected to play a critical role in delivering high-capacity communications services worldwide.

The primary advantage of OISL systems is the extremely large communication bandwidth that can be achieved using optical carrier wavelengths. Compared with conventional radio frequency systems, optical links can support substantially higher data rates while avoiding spectrum congestion and reducing size weight and power (SWaP). These benefits, however, come at the cost of significantly tighter pointing requirements. Because optical beams are highly directional, a successful link requires both terminals to establish and maintain precise angular alignment in the presence of continuous spacecraft motion, location uncertainty, and jitter.

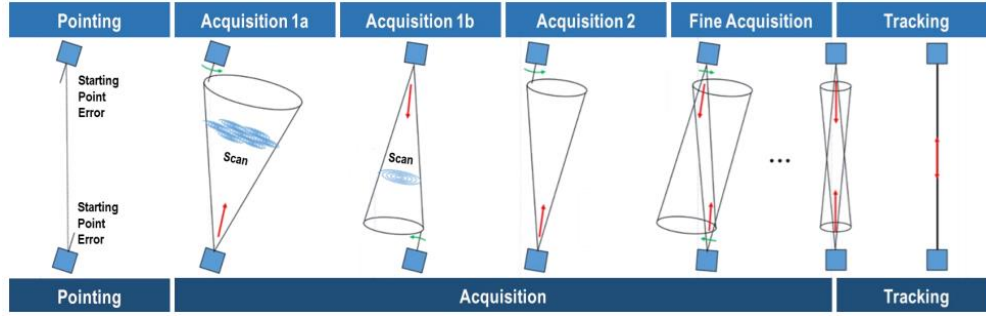


Figure 1. Optical terminal acquisition sequence reproduced from the SDA OCT Standard [5].

As a result, acquisition and tracking remain among the most challenging aspects of OISL system design. Acquisition is the process by which two optical communication terminals (OCTs) initially locate one another and establish sufficient location knowledge to enable signal transfer. Tracking refers to a steady-state of operation in which both terminals are illuminated and each terminal has firmly established a control loop to stabilize the angle of the incoming and outgoing beams, thereby enabling high-speed communication between the OCTs. This functionality has received considerable attention within efforts to develop industry standards, including those authored by the Space Development Agency (SDA) and the European Space Agency [9]. These standards recognize acquisition performance as a fundamental requirement for achieving reliable interoperability between independently developed terminals. The typical sequence of acquisition stages for SDA and ESTOL-compliant OCTs is shown in Figure 1.

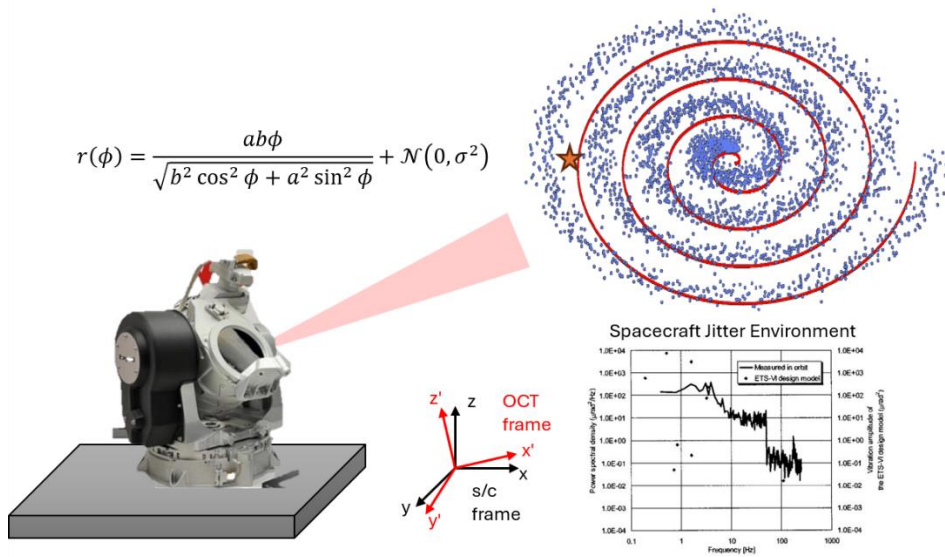


Figure 2 Diagram of an OCT tracing out an Archimedean spiral scan in the far field, while subject to errors caused by spacecraft-to-OCT frame rotation, mechanism drift, and line-of-sight jitter. Spacecraft jitter is the observed microvibration spectrum from the ETS-VI mission[10].

Several factors can adversely affect acquisition and tracking performance in an operational environment, and these factors are shown diagrammatically in Figure 2. An OCT attempting to perform the first-stage of acquisition must trace out a spiral scan in the far-field until it illuminates the partner terminal (represented by a star). Generally, the terminal attempts to trace an Archimedean spiral with radius given by $r = a\theta$, however a variety of effects will conspire to create deviations from this ideal case. One important consideration is the long-term stability of the alignment between the optical terminal and the spacecraft reference frame. Mechanical loads experienced during launch, thermal distortion throughout the mission lifetime, and changes in structural configuration can all contribute to pointing offsets that accumulate over time and will cause the origin of the OCT spiral scan to deviate from the planned origin of the scan. Mechanism drift in the OCT itself may also cause elongation or contraction of the spiral along a particular axis, changing the relationship between r and θ as seen in Figure 2. Finally, the optical terminal must also operate while mounted on a spacecraft platform that is itself

subject to disturbances, vibration, and attitude control errors. These effects introduce pointing uncertainty and jitter that can reduce acquisition probability, increase acquisition time, or degrade tracking performance after link establishment. While these microvibrations may be compensated by the OCT during fine-tracking, this is not the case during acquisition, and spacecraft jitter will add a noise term, $\mathcal{N}(0, \sigma^2)$, to the initial spiral scan – increasing the probability of missing the partner terminal.

To assess these challenges and validate OCT PAT performance, Honeywell has developed a hardware-in-the-loop testing approach that enables optical communication terminals to be evaluated under representative orbital conditions within a laboratory environment. Rather than testing individual subsystems in isolation, this approach exercises the terminal using realistic dynamic inputs that replicate the geometry, pointing uncertainties, and disturbance environment expected during on-orbit operation. The resulting test capability allows acquisition and tracking performance to be assessed early in the development cycle and provides a mechanism for validating system-level behavior prior to flight.

2. EXPERIMENT

The hardware-in-the-loop experiments were conducted using two optical terminal systems configured to emulate an on-orbit optical link. The two ends of the experiment are shown in Figure 3 and Figure 4, each end comprises a 100 mm OCT which is attempting to communicate by acquiring and tracking on a signal delivered by GSE optical partner terminals. The GSE partner terminals are connected via a single-mode optical fiber which conveys the signals back and forth between the two terminals. The GSE partner terminals on either end of the fiber channel provide beam launch, jitter injection, and beam expansion before delivery to the OCTs. The OCTs are initially mis-aligned and are run through their acquisition sequences before eventually transitioning into fine-tracking, and the time-to-acquire and PAT performance data is assessed throughout.

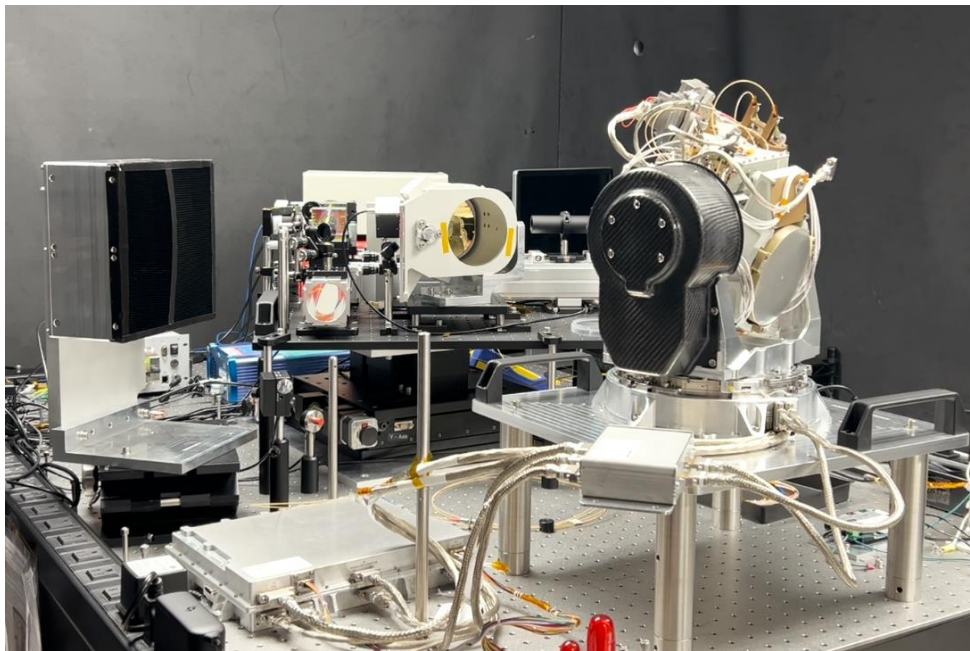


Figure 3. Honeywell's 100 mm Laser Communication Terminal (LCT100Y) in a static configuration conducting an acquisition sequence with a reference partner satellite simulator.

Particular emphasis was placed on understanding the sensitivity of the acquisition process to uncertainties in spacecraft attitude and terminal alignment. These parameters directly influence the initial search region that must be explored before a partner terminal can be detected. By varying these conditions within the laboratory environment, it was possible to assess acquisition robustness and identify operating regimes that could significantly affect link establishment performance.

Additional testing was performed to evaluate the impact of platform-induced disturbances during both acquisition and closed-loop tracking. Representative spacecraft jitter profiles can be introduced into the test environment to emulate the dynamic disturbances expected from reaction wheels, attitude control systems, and structural vibrations. This enables the

response of the terminal tracking system to be characterized under realistic conditions and provides insight into the margins available for maintaining a stable optical link.

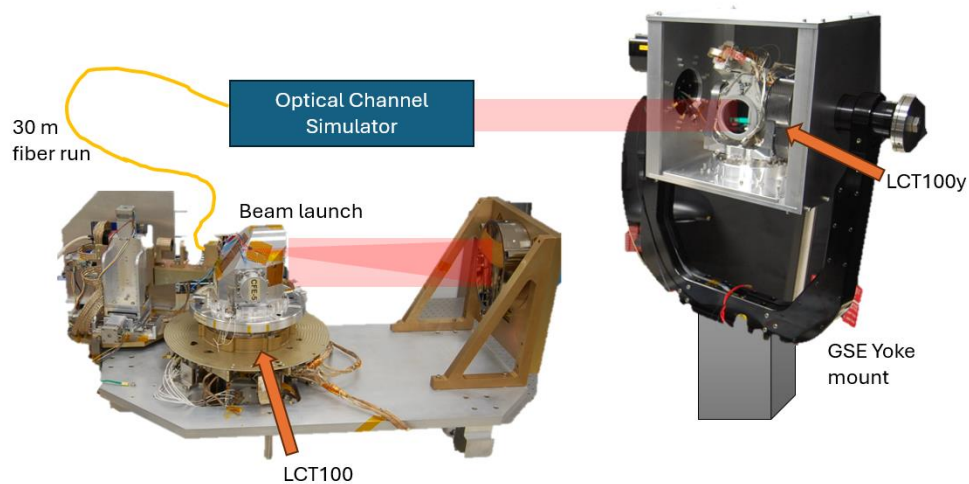


Figure 4. Simplified setup for a dual-ended configuration in which an LCT100Y system (leader) performs an acquisition sequence with a previous-generation LCT100 (follower) under simulated satellite drift and jitter conditions.

Using this configuration, representative acquisition sequences were successfully reproduced in the laboratory environment. The testbed enabled controlled investigation of the interactions between spacecraft pointing performance, terminal alignment accuracy, disturbance rejection capability, and acquisition success probability. Results of this testing across the FOV and in a representative acquisition point are shown in Figure 5.

Figure 5 shows the results of characterizing the pull-in time -- the time to transition from search into fine-track following initial detection of the leader terminal. The results show very little variation in pull-in time across the initial uncertainty cone, indicating that the time-to-acquire the partner terminal is ultimately limited by the time taken to sweep out the initial spiral scan. Within the tested line-of-sight (LOS) errors, the spiral scan portion of the acquisition (Acquisition 1a from Figure 2) was usually completed in <10.0 s, and the terminals transitioned to Acquisition 2 and into fine tracking in <0.5 s. Variation in pull-in times observable across the FOV is largely dependent on the initial detection position on the fine-tracking sensor and the number of pull-in steps that are required to move from initial detection into stable fine-track.

A detailed view of the transition to fine-tracking mode is also shown in Figure 5 for an example acquisition run. The plot shows the final stages of the spiral scan during which a detection is registered on the tracking sensor, and the system transitions to fine-tracking. The plots may be separated into three sections, the first from 10.0s to 10.7s shows the system in search mode in which the detector power is zero and the leader terminal has not registered a "hit" on the follower. At 10.7s a hit is registered and the fine steering mirror (FSM) immediately responds to drive down the LOS error on the tracking sensor. The system rapidly runs through its acquisition modes, and reaches a steady-state at 11s before engaging the gimbal unit to offload the fine-steering mechanism at 11.8s. From 11.8s onwards, steady-state pointing has been established, and the residual LOS error stabilizes at 0.36 μ rad RMS.

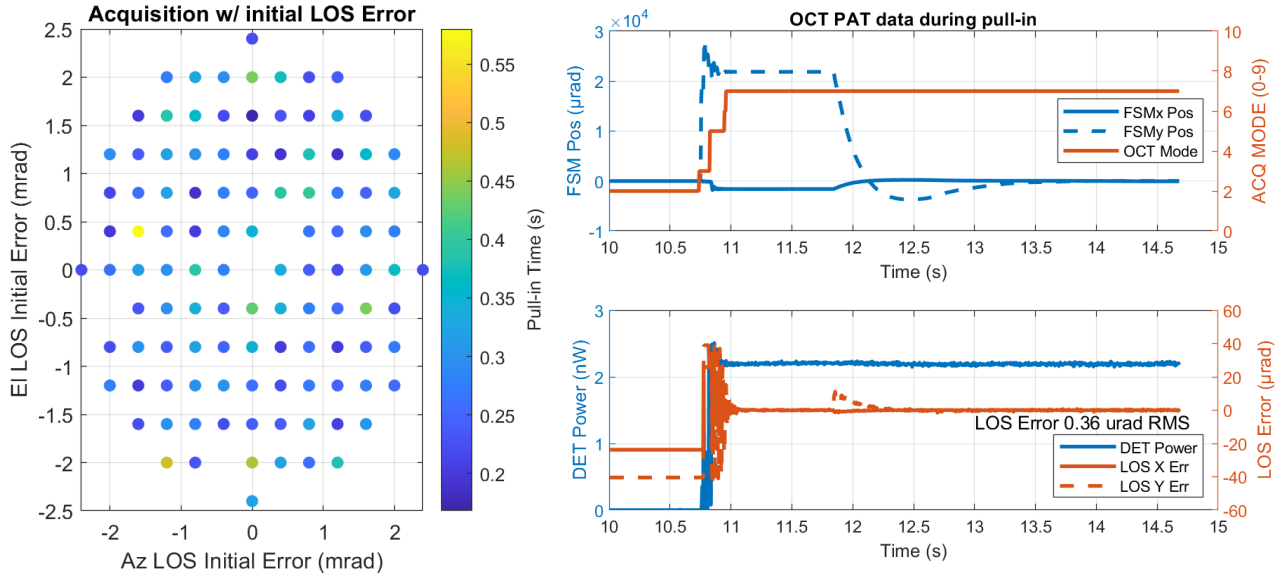


Figure 5. Bubble plot of time to transition to fine-track after completion of spiral search, as a function of initial off-pointing error (left), detailed view of “follower” OCT transitioning to fine-track immediately following detection of “leader” OCT (right).5.

3. INTEROPERABILITY TESTBED

The LCT100 testing system presented in Figure 3 represents an initial breadboard of a more advanced interoperability testbed system, which Honeywell Aerospace will deliver to Defense Research and Development Canada. Leveraging the experience from the LCT100 testing system, Honeywell Aerospace is building the Bidirectional Orbit and Range Emulation Apparatus for Lasercomm Interoperability Studies (BOREALIS), a vendor-agnostic terminal testbed facility in Canada for interoperability testing. The facility replicates the functionality of the dual-ended test, but provides the following expanded capabilities

1. Enhanced user-selectable far-field angular selectivity to match arbitrary OCT far-field beam divergence
2. Independent channel emulators to provide non-symmetric link losses
3. Independent motion control and jitter-injection for each OCT with near 2π addressable field-of-regard
4. Variable channel attenuation at high-speeds for simulation of atmospheric fading
5. Far-field beam profile characterization

The architecture of the interoperability testbed is shown in Figure 6. The testbed facility comprises two optical tables each of which contains an optical assembly for beam launch, jitter injection, and expansion of the OCT Rx signal via a large off-axis parabolic mirror (OAP). At the same time, the bench also provides for compression, far-field measurement and characterization of the OCT Tx signal, before the Tx signal is coupled into an optical fiber channel which passes the beam to the opposing identical optical table.

As the beams transfer between optical tables, and the Tx beam from one OCT becomes the Rx beam for the other OCT, the beams are attenuated by means of a digital variable optical attenuator (VOA). The attenuation profile of the link in each direction is managed by the control computer which combines the loss terms due to beam far-field profile, pointing error, and the specified link range. A second high-speed attenuator is also incorporated to enable the simulation of atmospheric fading profiles.

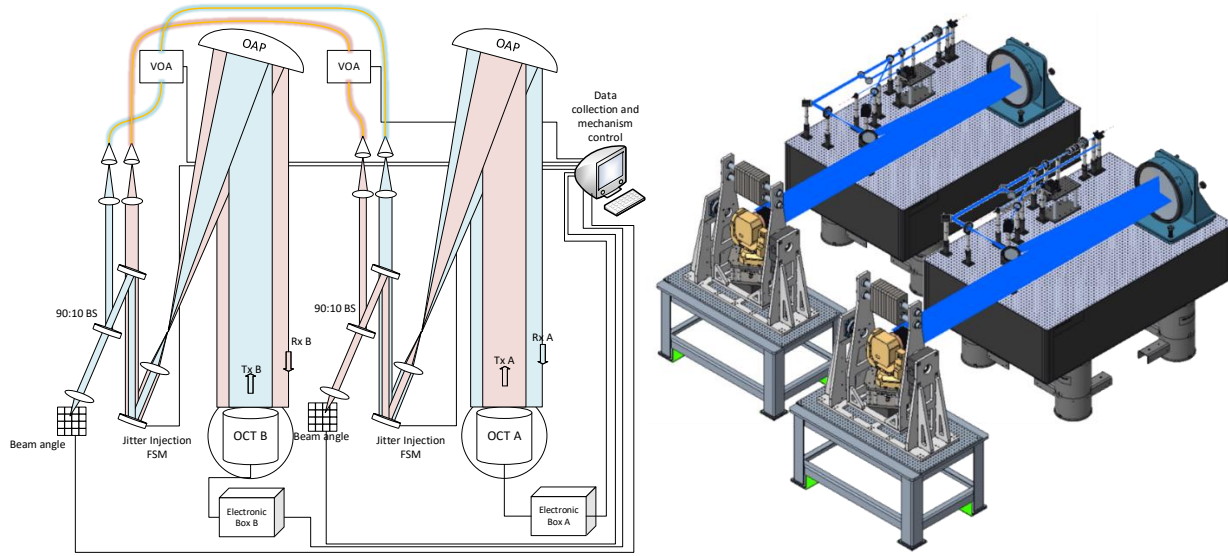


Figure 6. BOREALIS interoperability testbed architecture (left) and mechanical layout (right)

As the facility is intended to be vendor-agnostic, the motion control platform for the interoperability testbed is designed to accommodate a wide variety of optical terminals; the opto-mechanical interface details for the interoperability testbed are presented in Table 1. The terminal is nominally configured to address LEO-to-LEO and LEO-to-Ground link ranges, however LEO-to-MEO and GEO-to-GEO ranges are also achievable with the use of additional attenuators.

Table 1 BOREALIS OCT Interface Capabilities

OCT Parameter	Value
Terminal Volume	60 cm x 60 cm x 30 cm
Terminal Head Unit Mass	20 kg
Azimuth travel range	360° continuous
Elevation travel range	+70°/-50°
Terminal output power	2.5W
Terminal aperture	120 mm
Wavelengths	1550 nm $\pm$ 30 nm

The BOREALIS facility is currently undergoing build and commissioning in Cambridge, Ontario, and is expected to be operational and delivered to DRDC by Q2 2027. Initial demonstrations with the facility will focus on interoperability testing between SDA-compliant OISL terminals, but it is envisaged that future updates to the facility may incorporate testing of ESTOL-compliant terminals. The facility is intended to support constellation network operators and regulators in assessing the end-to-end performance and limitations of OCTs under simulated conditions, as well as evaluating interoperability between different OCT products (e.g. for inter-network connection).

4. SUMMARY AND CONCLUSIONS

Pointing acquisition and tracking is a critical functionality for enabling optical intersatellite links. Pointing acquisition and tracking approaches have been broadly standardized but may still be subject to vendor-specific and satellite-specific implementations which hamper interoperability between OCTs. Robust end-to-end acquisition and tracking testing of OCTs under simulated orbit conditions is critical to ensure operational success on day one of deployment. To address the critical need for realistic on-orbit testing required by DRDC Honeywell Aerospace has developed BOREALIS, a vendor-

agnostic interoperability testbed for assessing OCT performance under simulated orbit conditions. The architecture for the BOREALIS interoperability testing facility is also presented as well as the generic interface information for user OCTs. In addition, initial results from dual-ended acquisition and tracking testing of Honeywell Aerospace's LCT100Y OISL terminal have been presented under simulated jitter environments using a precursor setup. The results show that the terminal is capable of acquiring a partner terminal in < 30s, and typically much faster provided low initial uncertainty between the spacecraft body frame and the OCT frame. Residual pointing accuracy is typically less than 1 urad RMS under simulated spacecraft jitter conditions, which is sufficient to maintain low link loss considering the divergence of the 100 mm terminal aperture. These results anticipate the future utility of the BOREALIS facility and highlight the criticality of pointing and tracking testing for OCTs.

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AI TRANSPARENCY STATEMENT

The authors used GPT5.6 to assist in the drafting of parts of the introduction and experiment sections based on an outline from the authors. The authors have reviewed and edited the content and take full responsibility for the final publication.

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