IEEE ICSOS™

IEEE ComSoc®

IEEE INTERNATIONAL CONFERENCE ON SPACE OPTICAL SYSTEMS AND APPLICATIONS

29–31 March 2022

Virtual Conference

Final Program

icsos2022.ieee-icsos.org

Platinum Patron

NICT National Institute of Information and Communications Technology

Technical Program Supporter

esa European Space Agency

Welcome Message

Recently, the field of space laser communications is gaining astonishing popularity with the introduction of multiple satellite mega constellations and high-throughput satellites. Among them, the Starlink provided by SpaceX has been becoming so famous as to get a lot of attention in Ukraine war. More over, extremely small payloads for Cubesats, adaptive optics technologies for geostationary-to-ground optical feederlink implementations, and last but not least, satellite quantum key distribution technologies show fast growth.

The International Conference on Space Optical Systems and Applications (ICSOS) began in 2009 in Asia with the idea to provide a stage for the young field of free-space optical systems. The venue is constantly rotated between USA and Asia in every one or two years. Since 2015 ICSOS has become a part from the IEEE society and shows steady growth in papers from a number of countries worldwide.

Aiming to give the stage to the researchers, we planned a hybrid event in Kyoto that will allow the exchange of latest achievements in the field regardless of the pandemic travel restrictions that constantly change. Unfortunately, the global pandemic situation did not improve significantly and in 2022, IEEE ICSOS will be held entirely online.

I wish all the participants of ICSOS get the most benefit from this opportunity.

Shigeru Shimamoto
General Chairperson of IEEE ICSOS 2022
Organizing Committee
Professor, Waseda University, Japan

IEEE ICSOS 2022 PROGRAM-AT-A-GLANCE

Day 1		29 March 2022	Location: Virtual Hall
		Opening Session • Chair: Kolev Dimitar	
9:30	9:35	Opening address	Shigeru Shimamoto (Waseda University, Japan)
9:35	9:40	Welcome address	Naoto Kadowaki (National Institute of Information and Communications Technology, Japan)
9:40	9:45	Guest speech	Masato Ota (MIC, Japan)
		Plenary Session • Chair: Hamid Hemmati	
9:45	10:05	(Invited) Latest Status of the CCSDS Optical Communications Working Group	Bernard Edwards (NASA Goddard Space Flight Center, USA)
10:05	10:25	(Invited) Optical Communications for Human Space Exploration-Status of Space Terminal Development for the Artemis II Crewed Mission to the Moon	Bryan Robinson, Farzana Khatri and Mark Padula (MIT Lincoln Laboratory, USA); Steven Horowitz (NASA Goddard Space Flight Center, USA); Michael Bay (Bay Engineering Innovations, USA); Jonathon King (NASA Johnson Space Center, USA)
10:25	10:45	(Invited) Optical high-speed data network in space - an update on HydRON's System Concept	Christopher A Vasko (European Space Agency & Aurora Technology B. V., The Netherlands); Pantelis-Daniel Arapoglou (European Space Agency, The Netherlands); Josep Maria Perdigues Armengol (ESA, The Netherlands); Guray Acar (European Space Agency - ESTEC, The Netherlands); Monica Politano (European Space Agency, The Netherlands); Wael El-Dali, Harald Hauschildt and Carlo Elia (ESA, The Netherlands)
10:45	11:05	(Invited) LUCAS : The second-generation GEO satellite-based space data-relay system using optical links	Shiro Yamakawa, Yohei Satoh, Takamasa Itahashi, Yutaka Takano, Shintaroh Hoshi, Yuko Miyamoto, and Hiroki Kohata (Japan Aerospace Exploration Agency (JAXA), Japan)
11:05	11:25	(Invited) Space Development Agency Optical Communications: Progress Update and OCT Standard v3.0	Michael Butterfield (Space Development Agency, USA)
11:25	11:45	(Invited) DSTG Laser Satellite Communications - Current Activities and Future Outlook	Kerry Mudge and Bradley Clare (Defence Science Technology Group); Elisa Jager (Defence Science Technology Group, Australia); Vladimir Devrelis (Defence Science Technology Group); Francis Bennet, Michael Copeland, Nick Herrald and Ian Price (Australian National University, Australia); Gottfried Lechner (University of South Australia, Australia); Jeewani Kodithuwakkuge, Joseph Magarelli, Dharmapriya Bandara, Christopher Peck, Monique Hollick, Paul Alvino, Peter Camp-Smith, Barbara Szumylo and Agam Raj (Defence Science Technology Group, Australia); Kenneth Grant (Defence Science & Technology Group, Australia)
11:45	13:00	Lunch	
		Technical Session: Mission and Demonstration Status Updates • Chair: Bernard Edwards	
13:00	13:15	Challenges and Methodologies of LCRD Optical Payload Assembly, Integration, and Test Campaign	Glenn B Jackson (NASA Goddard Space Flight Center, USA); Patricia Randazzo (Integrity Applications Inc, USA)
13:15	13:30	Recent R&D activities of the Lunar - the Earth optical communication system in Japan	Tomohiro Araki (JAXA, Japan); Hideaki Kotake (National Institute of Information and Communication Technology (NICT), Japan); Yoshihiko Saito, Hiroyuki Tsuji and Morio Toyoshima (National Institute of Information and Communications Technology, Japan); Katsumi Makino, Masaru Koga and Naoki Sato (Japan Aerospace Exploration Agency (JAXA), Japan)

IEEE ICSOS 2022 PROGRAM-AT-A-GLANCE *Continued*

Day 1		29 March 2022	Location: Virtual Hall
13:30	13:45	Status Update on Laser Communication Activities in NICT	Dimitar R. Kolev (National Institute of Information and Communications Technology (NICT), Japan); Koichi Shiratama, Alberto Carrasco-Casado and Yoshihiko Saito (National Institute of Information and Communications Technology, Japan); Yasushi Munemasa (National Institute of Information and Communications Thechnology, Japan); Junichi Nakazono and Phuc V. Trinh (National Institute of Information and Communications Technology, Japan); Hideaki Kotake (National Institute of Information and Communications Technology & The University of Electro-Communications, Japan); Hiroo Kunimori and Toshihiro Kubo-oka (National Institute of Information and Communications Technology, Japan); Tetsuharu Fuse (National Institute of Information and Communications Technology & University of Electro-Communications, Japan); Morio Toyoshima (National Institute of Information and Communications Technology, Japan)
13:45	14:00	The communication experiment result of Small Optical Link for ISS (SOLISS) to the first commercial optical ground station in Greece	Hiroaki Yamazoe (Sony Computer Science Laboratories, Japan); Kyohei Iwamoto (Sony Computer Science Laboratories & Japan Aerospace Exploration Agency, Japan); Hennes Henniger (German Aerospace Center (DLR), Germany)
14:00	14:10	Coffee Break	
		Technical Session: Satellite QKD missions I • Chair: Florian Moll	
14:10	14:30	(Invited) Satellite-based QKD for Global Quantum Cryptographic Network Construction	Atsushi Mamiya, Kentaro Tanaka and Saori Yokote (SKY Perfect JSAT Corporation, Japan); Masahide Sasaki and Mikio Fujiwara (NICT, Japan); Masaki Tanaka (NEC Corporation, Japan); Hideaki Sato (Toshiba Corporation Corporate Research&Development Center, Japan)
14:30	14:45	QKD and optical terminals for Canada's Quantum Encryption and Science Satellite (QEYSSat)	Hugh Podmore (Honeywell Aerospace, Canada)
14:45	15:00	A CubeSat platform for space-based quantum key distribution	Srihari Sivasankaran, Clarence Liu, Moritz Mihm, Ali Anwar, Riadh Rebhi and Alexander Ling (Centre for Quantum Technologies, Singapore)
15:00	15:15	CARAMUEL: The future of Space Quantum Key Distribution in GEO	Antonio Abad (C/Anabel Segura 11 - Edificio Albatros 4 floor & Hispasat, Spain)
15:15	15:25	Coffee Break	
		Technical Session: Atmospheric Turbulence - Measurements and Demonstrations Chair: Phuc V. Trinh	
15:25	15:45	(Invited) Design and validation of a new coding and synchronization layer for space optical communications	Géraldine Artaud (CNES, France); Alain Thomas (Safran Data Systems, France); Jean-Frederic Chouteau (Airbus Defense & Space, France); Lyonel Barthe (Airbus Defence & Space, France); Benjamin Gadat (Airbus Defense & Space, France); Thomas Anfray (Airbus Defence and Space, France); Alain Quentel (SAFRAN Electronics & Defence, France)
15:45	16:00	Bit Error Rate Performance of a Laser Ground-to-Satellite Uplink Communications Systems in the Presence of Atmospheric Turbulence and Loss	Larry B Stotts (Science and Technology Associates & Stotts Consulting, USA)
16:00	16:15	Optical Transmitter Diversity with Phase-Division in Bit-Time	Christian Fuchs (German Aerospace Center (DLR), Germany); Dirk Giggenbach and Ramon Mata Calvo (German Aerospace Center, Germany); Werner Rosenkranz (University of Kiel, Germany)
16:15	16:30	Experimental Setup for Single Pixel Imaging of Turbulent Wavefronts and Speckle-Based Phase Retrieval	Oliver J Pitts (National Research Council Canada, Canada); Michael Taylor (Honeywell International Inc Ottawa, ON, Canada); Mohamadreza Pashazanoosi and Steve Hranilovic (McMaster University, Canada); Costel Flueraru (National Research Council of Canada, Canada); Antony Orth (National Research Council Canada, Canada)
16:30	16:45	Photonic Lantern Based Wavefront Sensing for Daytime High Photon Efficiency Communications and Astronomy	Martijn Dresscher (TNO, The Netherlands)
16:45	17:00	Turbulence mitigation via Multi-Plane Light Conversion and coherent optical combination on a 200 m and a 10 km link	Antonin Billaud (Cailabs, France); Andrew Reeves (German Aerospace Center (DLR), Germany); Adeline Orieux (Cailabs, France); Helawae Friew Kelemu (German Aerospace Center (DLR), Germany); Fausto Gomez-Agis, Stephane Bernard, Thibault Michel and David Allioux (Cailabs, France); Juraj Poliak (German Aerospace Center (DLR) & Institut für Kommunikation und Navigation, Germany); Ramon Mata Calvo (German Aerospace Center, Germany); Olivier Pinel (Cailabs, France)

IEEE ICSOS 2022 PROGRAM-AT-A-GLANCE *Continued*

Day 2		30 March 2022	Location: Virtual Hall
		Workshop • Chair: Dimitar Kolev	
10:30	10:45	Recent research and development of space communications at NICT	Hiroyuki Tsuji, NICT, Japan
10:45	11:00	Modelling of optical refractive index structure parameter using radiosonde data	Florian Quatresooz, Danielle Vanhoenacker-Janvier, Claude Oestges (Université catholique de Louvain, Belgium)
11:00	11:15	SGL Activities with Uplink Communication from Switzerland with the enhanced T-AOGS	Robert Mahn, Julian Woicke, Karen Saucke, Thomas Marynowski, Patricia Martin-Pimentel and Frank F Heine (Tesat Spacecom, Germany)
11:15	11:30	C-DIMM: an autonomous, outdoor seeing monitor for astronomy, atmospheric studies and free space optical communications	Frederic Jabet (MIRATLAS & AIRYLAB, France)
11:30	11:45	Improving LEO Downlink Laser Communications through Predictive Adaptive Optics	Pablo Robles (ONERA & LAM, France); Cyril Petit and Jean-Marc Conan (ONERA, France); Bouchra Benammar (Centre National d'Etudes Spatiales (CNES), France); Benoit Neichel (LAM, France)
11:45	12:00	Estimates for IM/DD key distribution over an optical LEO-to-ground link	Michał Jachura, Konrad Banaszek, (University of Warsaw, Warsaw, Poland); Mikołaj Lasota, Piotr Kolenderski (Nicolaus Copernicus University, Torun, Poland)
12:00	13:00	Lunch	
		Technical Session: Space Optical Communication Systems I • Chair: Tomohiro Araki	
13:00	13:20	(Invited) RF and Optical Hybrid LEO Communication System for Non-Terrestrial Network	Takashi Eishima, Soichiro Inoue, Akihiro Yonemoto and Jumpei Sudo (Axelspace Corporation, Japan); Takayuki Hosonuma and Shinichi Nakasuka (The University of Tokyo, Japan); Atsushi Shirane, Takashi Tomura and Kenichi Okada (Tokyo Institute of Technology, Japan); Kosuke Kiyohara (KIYOHARA OPTICS, Inc., Japan)
13:20	13:35	Multi-layer Constellation based Is-OWC employing NOMA	Wataru Tachikawa, Swarali Ajgaonkar, Kazutoshi Yoshii and Jiang Liu (Waseda University, Japan); Shigeru Shimamoto (Waseda University & Graduate School of Global Information and Telecommunication Studies, Japan)
13:35	13:50	Analysis of Tracking Gimbal Angles for Inter-Satellite Optical Communication System Between Two Orbits	Ryuichi Hirayama and Shinichi Nakasuka (The University of Tokyo, Japan)
13:50	14:05	Pulse positioned differential phase shift keying for high data rate satellite optical communications	Won-Ho Shin (YONSEI, Korea (South); Sang-Kook Han (Yonsei University, Korea (South)
14:05	14:20	4-Level Optical Modulation Formats for LISLs in a Satellite Broadband Constellation Network	Amrita Gill (University of Nottingham Malaysia Campus, Malaysia); Gnanam Gnanagurunathan (The University of Nottingham Malaysia Campus, Malaysia); Nafizah Khan (University of Nottingham Malaysia Campus, Malaysia); Amin MalekMohammadi (California State University, USA)
14:20	14:30	Coffee Break	

Day 2		30 March 2022	Location: Virtual Hall
		Technical Session: OGS and Site Diversity • Technologies Chair: Wim Korevaar	
14:30	14:45	A study of cloud cover over multiple sites within Australia for satellite/ground atmospheric optical communication	Brett Nener (The University of Western Australia, Australia); Helen Chedzey and Mervyn Lynch (Curtin University, Australia); Vladimir Devrelis (DSTG, Edinburgh, Australia); Kerry Mudge (Defence Science Technology Organisation, Australia); Kenneth Grant (Defence Science & Technology Group, Australia)
14:45	15:00	Greek Helmos Observatory readies for Optical and Quantum Communication	Zoran Sodnik (European Space Agency (ESA), The Netherlands); Harald Hauschildt (ESA, The Netherlands); Hans Smit (European Space Agency, The Netherlands); Donatas Miklusis (ESA, The Netherlands); Emmanuel Xilouris, Spyros Basilakos, Panayotis Hantzios and Alex Gourzelas (National Observatory of Athens (NOA), Greece); Athanasios Marousis (University of Piraeus, Greece & National Observatory of Athens, Greece); John Alikakos (National Observatory of Athens (NOA), Greece)
15:00	15:15	The Mount Stromlo Optical Communication Ground Station	Marcus Birch, Noelia Martinez, Francis Bennet, Michael Copeland and Doris Grosse (Australian National University, Australia)
15:15	15:30	Beacon system for ESA IZN-1 Optical Ground Station	Jason Singleton (NKT Photonics, United Kingdom (Great Britain); Shaif-ul Alam (SP Photonics Ltd, United Kingdom (Great Britain) & University of Southampton, United Kingdom (Great Britain); Mike Yarrow (NKT Photonics, United Kingdom (Great Britain); Richard Schafers (NKT Photonics Ltd., United Kingdom (Great Britain); Andrea Di Mira (Serco@ ESA, ESOC, Germany); John Clowes (NKT Photonics, United Kingdom (Great Britain); Clemens Heese (European Space Agency, Germany)
15:30	15:45	BER Performance Improvement using Spatial Diversity Combining in an Atmospheric Turbulent Channel with Satellite Vibration-Induced Fading	Charleston Dale M. Ambatali (University of Tokyo, Japan); Vinicius Ferreira Nery and Shinichi Nakasuka (The University of Tokyo, Japan)
15:45	15:55	Coffee Break	
		Technical Session: Space Optical Communication Systems II • Chair: Curt Schieler	
15:55	16:10	Low power-consumption coherent receiver architecture for satellite optical links	Alexis W Bernini and Martyn Fice (University College London, United Kingdom (Great Britain); Katarzyna Balakier (University College London (UCL) & Airbus Defence & Space, United Kingdom (Great Britain)
16:10	16:25	Focal Plane Assembly demonstrator for two-way Laser communication link	Jean-Baptiste Haumonte and Nathalie Gimbert (Bertin Technologies, France)
16:25	16:40	PhLEXSAT - A Very High Throughput Photo-Digital Communication Satellite Payload	Madhubrata Chatterjee (MDA, United Kingdom (Great Britain); Chiara Palla and Edem Fiamanya (MDA Space and Robotics, United Kingdom (Great Britain); Marta Beltran (DAS Photonics S. L., Spain); Miguel Àngel Piqueras (Das Photonics S. L, Spain); Antoni Castells Cervello and Laurent Roux (Eutelsat, France); Patrick Runge (Fraunhofer Heinrich-Hertz-Institut, Germany); Nigel Cameron (Axenic, United Kingdom (Great Britain); Jakub Zverina (Argotech, Czech Republic)
16:40	16:55	Compact radiation resistant, high-gain optical fiber pre-amplifier for small 1.55 um laser-com terminals	Leontios Stampoulidis and Ahmed Osman (LEO Space Photonics, Greece); James Edmunds, Clive Palmer and Keith Simpson (Gooch & Housego, United Kingdom (Great Britain); Anaelle Maho (Thales Alenia Space, Toulouse, France); Michael Sotom (Thales Alenia Space, France)
16:55	17:10	Robust atmospheric FSO communication receiver based on the coherent combination of spatial modes: an experimental evaluation	Anaelle Maho (Thales Alenia Space, Toulouse, France); Vincent Billault (Thales Research & Technology, France); Jerome Bourderionnet (Theales Research and Technology, France); Luc Levandier, Patrick Feneyrou and Arnaud Brignon (Thales Research & Technology, France); Michael Sotom (Thales Alenia Space, France)
17:10	17:25	Capacity Analysis of a MIMO Laser Link from Lunar Surface to Earth	Hung Le Son and Robert T. Schwarz (Bundeswehr University Munich, Germany); Marcus Knopp (DLR, Germany); Dirk Giggenbach (German Aerospace Center, Germany); Andreas Knopp (Bundeswehr University Munich, Germany)

IEEE ICSOS 2022 PROGRAM-AT-A-GLANCE *Continued*

Day 3		31 March 2022	Location: Virtual Hall
		Technical Session: Optical Communications for Cubesats I • Chair: Bryan Robinson	
9:30	9:50	(Invited) DLR's Optical Communication Terminals for CubeSats	Christopher Schmidt, Benjamin Roediger and Jorge Rosano Nonay (German Aerospace Center (DLR), Germany); Christos Papadopoulos (DLR IKN, Germany); Marie-Theres Hahn, Florian Moll and Christian Fuchs (German Aerospace Center (DLR), Germany)
9:50	10:05	TBIRD 200 Gbps CubeSat Downlink: System Architecture and Mission Plan	Curt Schieler, Kathleen Riesing, Bryan Bilyeu, Bryan Robinson and Jade Wang (MIT Lincoln Laboratory, USA); William Thomas Roberts (Jet Propulsion Laboratory (JPL), USA); Sabino Piazzolla (NASA Jet Propulsion Laboratory, USA)
10:05	10:20	SelenIRIS: a Moon-Earth Optical Communication Terminal for CubeSats	Jorge Rosano Nonay, Christian Fuchs, Davide Orsucci and Christopher Schmidt (German Aerospace Center (DLR), Germany); Dirk Giggenbach (German Aerospace Center, Germany)
10:20	10:35	On-Orbit Risk Mitigation for a ½-U Orbital Laser Guidestar Link	Albert Q Thieu (Massachusetts Institute of Technology & MIT Lincoln Laboratory, USA); Lulu Liu (MIT Lincoln Laboratory, USA)
10:35	10:45	Coffee Break	
		Technical Session: Optical Communications for Cubesats II • Chair: Christopher Schmidt	
10:45	11:05	(Invited) Architecture for Reconfigurable Next-Gen Lasercom Terminals	Robert Carlson (The Aerospace Corp, USA)
11:05	11:20	NICT's versatile miniaturized lasercom terminals for moving platforms	Alberto Carrasco-Casado, Koichi Shiratama and Phuc V. Trinh (National Institute of Information and Communications Technology, Japan); Dimitar R. Kolev (National Institute of Information and Communications Technology (NICT), Japan); Tetsuharu Fuse (National Institute of Information and Communications Technology & University of Electro-Communications, Japan); Hiroyuki Tsuji and Morio Toyoshima (National Institute of Information and Communications Technology, Japan)
11:20	11:35	Agile Beaconless Laser Beam Alignment with Adaptive Mm-Wave Beamforming for Inter CubeSat Communication	Chengtao M Xu and Eduardo Rojas (Embry-Riddle Aeronautical University, USA); Thomas Yang (Embry Riddle Aeronautical University, USA)
11:35	11:50	Development and Testing of the Laser Transmitter and Pointing, Acquisition, and Tracking (PAT) System for the CubeSat Laser Infrared CrosslinK (CLICK) B/C Mission	Hannah Tomio (Massachusetts Institute of Technology, USA); William Kammerer III (MIT, USA); Peter Grenfell (Massachusetts Institute of Technology, USA); Ondrej Cierny, Charles Lindsay, Maddie Garcia and Paul C Serra (MIT, USA); Kerri Cahoy (Massachusetts Institute of Technology, USA); Myles Clark, Danielle Coogan and John Conklin (University of Florida, USA); David Mayer and Jan Stupl (NASA Ames Research Center, USA)
11:50	13:00	Lunch	
		Technical Session: Space Optical Communication Systems III • Chair: Dimitar Kolev	
13:00	13:15	Telesat LightspeedTM - Enabling Mesh Network Solutions for Managed Data Service Flexibility Across the Globe	Gerry Jansson (Telesat & Intelsat General, USA)
13:15	13:30	An investigation into the technical and system operational impacts of applying FSO point to multipoint communications technology	Barry A Matsumori and Paul Searcy (BridgeComm, Inc., USA)
13:30	13:45	Multi-aperture Transmission and DSP Techniques for Beyond-10 Tb/s FSO Networks	Keisuke Matsuda, Hayato Sano, Yukari Takada, Masashi Binkai, Shota Koshikawa, Yuta Yokomura, Tsuyoshi Yoshida, Yoshiaki Konishi and Naoki Suzuki (Mitsubishi Electric Corporation, Japan)
13:45	14:00	Link Budget Design of Adaptive Optical Satellite Network for Integrated Non-Terrestrial Network	Hideaki Kotake (National Institute of Information and Communications Technology & The University of Electro-Communications, Japan); Yuma Abe and Mariko Sekiguchi (National Institute of Information and Communications Technology, Japan); Tetsuharu Fuse (National Institute of Information and Communications Technology & University of Electro-Communications, Japan); Hiroyuki Tsuji and Morio Toyoshima (National Institute of Information and Communications Technology, Japan)
14:00	14:10	Coffee Break	

IEEE ICSOS 2022 PROGRAM-AT-A-GLANCE *Continued*

Day 3		31 March 2022	Location: Virtual Hall
		Technical Session: Optical Feederlink Technologies • Chair: Zoran Sodnik	
14:10	14:25	FEELINGS: the Onera's optical ground station for Geo Feeder links demonstration	Cyril Petit and Aurélie Bonnefois (ONERA, France); Jean Baptiste Volatier (Office National d'Etudes et de Recherches Aérospatiales, France); Caroline B. Lim (ONERA, France); Francois Gustave (Office National d'Etudes et de Recherches Aérospatiales, France); Joseph Montri, Philippe Perrault, Laurie Paillier, Marie-Therese Velluet and Jean-Marc Conan (ONERA, France); Anne Durecu (Office National d'Etudes et de Recherches Aérospatiales, France); Nicolas Vedrenne (ONERA, France)
14:25	14:40	ALASCA: the ESA Laser Guide Star Adaptive Optics Optical Feeder Link demonstrator facility	Roberto Biasi (Microgate, Italy); Domenico Bonaccini Calia (European Southern Observatory, Germany); Noelia Martinez (Australian National University, Australia); David Jenkins (ESO, Germany); Ollie Farley (Durham University, United Kingdom (Great Britain); Martin Enderlein (Toptica Projects, Germany); Petr Janout (ESO, Germany); Filippo Ambrosino (INAF-OAR, Italy); Hira Virdee (Lumi Space, United Kingdom (Great Britain); Matthew Townson (Durham University, United Kingdom (Great Britain); Mauro Centrone and Marco Faccini (INAF-OAR, Italy); Pierre Haguenauer (ESO, Germany); Marcos Reyes Garcia-Talavera (Instituto de Astrofisica de Canarias, Spain); Enrico Pinna (INAF-OAA, Italy); James Osborn (Durham University, United Kingdom (Great Britain); Guido Agapito (INAF-OAA, Italy); Daniele Gallieni (A. D. S. International, Italy); Frank Lison (Toptica Projects, Germany); Laura Salvi (Microgate, Italy); David Gooding (Lumi, Germany); Zoran Sodnik (European Space Agency (ESA), The Netherlands)
14:40	14:55	New results from the 2021 FEEDELIO experiment - a focus on reciprocity	Perrine Lognoné (ONERA & Telecom Paris, France); Aurélie Bonnefois, Jean-Marc Conan, Laurie Paillier, Cyril Petit, Caroline B. Lim, Serge Meimon, Joseph Montri, Jean-Francois Sauvage and Nicolas Vedrenne (ONERA, France)
14:55	15:10	End-to-End Performance Analysis of Analog Coherent Optical Satellite Feeder Links	Cornelis Willem Korevaar and Jeroen J. Boschma (TNO, The Netherlands); Remco den Breeje (TNO / OC Engineering, The Netherlands); Johannes Ebert (Joanneum Research, Austria)
15:10	15:20	Coffee Break	
		Technical Session: Satellite QKD Missions II • Chair: Alberto Carrasco-Casado	
15:20	15:35	High-level concepts and design of commercial satellite-based QKD networks	Manuel Erhard, Armin Hochrainer, Johannes Handsteiner, Matthias Fink, Philipp Sohr, Thomas Herbst and Thomas Scheidl (Quantum Technology Laboratories GmbH, Austria)
15:35	15:50	Link technology for all-optical satellite based quantum key distribution system	Florian Moll, Eltimir Peev, Andrew Reeves, René Rüddenklau, Agnes Ferenczi, Luca Macri and Stefanie Häusler (German Aerospace Center (DLR), Germany); Jorge Pacheco-Labrador (German Aerospace Center, Germany); Davide Orsucci and Marie-Theres Hahn (German Aerospace Center (DLR), Germany); Juraj Poliak (German Aerospace Center (DLR) & Institut für Kommunikation und Navigation, Germany); Nino Walenta and Jan Krause (Fraunhofer Institute for Telecommunications Heinrich Hertz Institute, Germany); Friederike Fohlmeister (German Aerospace Center, Germany)
15:50	16:05	Design considerations for a Transportable Optical Ground Station for QKD	Luis Fernando Rodríguez Ramos (Institute of Astrophysics of the Canary Islands, Spain); Jorge Socas Negrín (Instituto de Astrofísica de Canarias IAC, Spain); Marcos Reyes Garcia-Talavera (Instituto de Astrofisica de Canarias, Spain)
16:05	16:20	Entangled photon sources for space applications	Armin Hochrainer, Manuel Erhard, Matthias Fink, Johannes Handsteiner, Thomas Herbst, Thomas Scheidl, Philipp Sohr and Rupert Ursin (Quantum Technology Laboratories GmbH, Austria)
16:20	16:35	Large - Scale LEO Satellite Constellation to Ground QKD links: Feasibility Analysis	Argiris Ntanos and Nikolaos Lyras (National Technical University of Athens, Greece); Saif Anwar (University of Warwick, United Kingdom (Great Britain); Obada Alia (University of Bristol, United Kingdom (Great Britain); Dimitris Zavitsanos, Giannis Giannoulis and Athanasios D. Panagopoulos (National Technical University of Athens, Greece); George Kanellos (University of Bristol, United Kingdom (Great Britain); Hercules Avramopoulos (National Technical University of Athens, Greece)
16:35	16:45	Coffee Break	
		Closing Session • Chair: Kolev Dimitar	
16:45	17:00	TPC report and Award Ceremony	Morio Toyoshima (NICT, Japan)
17:00	17:05	IEEE ICSOS 2023	Hamid Hemmati (Viasat, USA)
17:05	17:10	Closing remarks	Hiroaki Harai (NICT, Japan)

Atmospheric Turbulence - Measurement and Demonstrations

WITHDRAWN Photonic Lantern Based Wavefront Sensing for Daytime High Photon Efficiency Communications and Astronomy

Martijn Dresscher (TNO, The Netherlands)

Light being received on the Earth surface from space travels through the atmosphere. The local differences in atmospheric composition and pressure affect the propagating light, resulting in spatial variations in phase, intensity and angle of incidence across the pupil of the receiving telescope. Particularly the angle and phase perturbations make focusing on a small fiber core cumbersome, resulting in losses. This problem is typically addressed by implementing adaptive optics, providing high spatial and temporal resolution corrections through a deformable mirror in feedback configuration with a wave front sensor (WFS). Implementations with (typically) a Shack-Hartman WFS work very well when sufficient photons and signal-to-noise ratio is available, but problems arise when noise levels increase, the required bandwidth becomes higher (during daytime) and when signal levels decrease. In this work we investigate alternative wavefront sensing solutions that may provide better performance under these circumstances. Situations where such solutions are needed include High Photon Efficiency or deep-space communications, where only a few photons are available, and daytime astronomy, which suffers from higher noise and bandwidth requirements than nighttime astronomy. A potential solution which we study in greater detail features the use of a Photonic Lantern WFS (PLWFS), with three distinct advantages over traditional methods: i) in-fiber spectral filtering before detection, ii) use of fiber coupled detectors and iii) potentially fewer detector pixels required for detection. This approach relies on a neural network model to characterize the nonlinear transformation between input and outputs. The PLWFS softens requirements on the optical signal, while burdening the digital signal processing. We carried out a breadboard study to investigate some of the major risks, including the device's stability and its ability to deal with realistic perturbations. The first promising results indicate that the device can address the above-mentioned problems, but further development and investigation is needed.

Bit Error Rate Performance of a Laser Ground-to-Satellite Uplink Communications Systems in the Presence of Atmospheric Turbulence and Loss

Larry B Stotts (Science and Technology Associates & Stotts Consulting, USA)

The Bit Error Rate (BER) performance of a ground-to-space laser uplink communications systems subject to atmospheric turbulence and loss is analyzed. Beam wander-induced effects like scintillation and receiver noise variance have a greater effect on communications system performance than has previously been assessed. A new model for the signal-to-noise ratio is presented that includes atmospheric loss, intensity fluctuations, beam wander, and intensity noise variance. This model easily can be modified to other communications systems, e.g., Differential Phase Shift Key. The scintillation index and the BER are readily evaluated with Forward Error Coding (FEC) to compensate for atmospheric turbulence effects. Specifically, comparisons in 10^(-12) BER performance for 10 Gigabit per second, Non-Return to Zero On-Off Key, Erbium-Doped-Fiber Amplifier communications systems as a function of link zenith angle are given for the Hufnagel-Valley 5/7 and Hufnagel-Andrews-Phillips refractive index structure parameter models under two specifics benchmarks. These models were evaluated using a round-earth model. These models essentially are commensurate with the multiplicative version of the Hufnagel-Valley 5/7 model, which appears to the more realistic way of model comparison. Results show that in this last situation, BER performance has an asymptotic limit for high zenith angles. The conclusion is that other means in addition to a FEC are needed to achieve a 10^(-12) BER for high zenith angle. Example is given that shows an approach for augmenting a FEC in mitigating turbulence

Optical Transmitter Diversity with Phase-Division in Bit-Time

Christian Fuchs (German Aerospace Center (DLR), Germany); Dirk Giggenbach and Ramon Mata Calvo (German Aerospace Center, Germany)

The application of free-space optical communication systems in satellite applications has gained increasing attention in recent years. Their high data rates and comparably low size, weight and power requirements make them an attractive solution to increase data throughput in a number of applications, such as for optical GEO feeder links with throughputs beyond 1 Tbit/s.

In order to use free-space optical links in such application scenarios, a number of challenges must be overcome, such as link-blockage by clouds and, most importantly, impairments due to atmospheric turbulence.

Transmitter diversity makes use of the fact that a spatial separation of about 1 m between two transmitters is sufficient to achieve decorrelated channels.

When the transmitted signals are combined on receiver side, a diversity gain can be observed. However, typical transmitter diversity systems make use of different wavelengths to separate the diversity channels in order to avoid interference among those channels. This leads to increased system complexity and is bandwidth inefficient.

The transmitter diversity scheme Phase-Division in Bit-Time is a novel concept to avoid interference among multiple channels by adding an additional phase modulation on transmitter side in a free-space optical communication system with intensity modulation and direct detection (IM/DD). It enables using the same wavelength and even the same laser source for multiple transmitters.

WITHDRAWN (Invited) Design and validation of a new coding and synchronization layer for space optical communications

Géraldine Artaud (CNES, France); Alain Thomas (Safran Data Systems, France); Jean-Frederic Chouteau (Airbus Defense & Space, France); Lyonel Barthe (Airbus Defence & Space, France); Benjamin Gadat (Airbus Defense & Space, France); Thomas Anfray (Airbus Defence and Space, France); Mathieu Llauro (SAFRAN Electronics & Defence, France)

The paper will first present an overview of the planned earth-space optical communications demonstrations in which CNES is involved. It concerns a LEO direct to earth demonstration and a bidirectional GEO demonstration.

The second part of the paper will focus on the communication chain, and especially the techniques developed at the coding and synchronization layer, in order to mitigate the propagation channel impairments on the space to ground link.

We address the design of a cost-efficient and flexible modem technology for multi-gigabit per second optical communication downlinks. To tackle this challenge, we investigate a new flexible and high-performance coding and synchronization layer that takes into account hardware constraints of state-of-the art on-board and ground hardware data processing technologies. In particular, we introduce the code design of a new Forward Error Correction (FEC) based on LDPC codes combined with a flexible interleaver. It provides a competitive trade-off between coding performance and implementation complexity. We also present a robust framing structure of the coding and synchronization layer that enables, during a pass, variable coding rate, and in addition variable data rate, based on spread spectrum technique, for use in LEO satellite optical downlinks with strong signal power fading.

The performances of the proposed solution have been assessed in simulation against various propagation channel fading vectors. This led to its recent adoption by CCSDS as one of the two new schemes of the optical communications coding and synchronization recommended standard CCSDS 142.0-B-1.

The performances are currently confirmed in laboratory on an end to end optical bench running at 10Gbps, that includes representative satellite emitter, propagation emulator applying to the optical signal fading vector, optical front-end, and a modem that performs, in real-time, time synchronization, frame synchronization, de-interleaving and soft LDPC decoding.

The comparison between the simulated and measured performances will be presented, in particular synchronization robustness, and bit error rate in the presence of fading.

Turbulence mitigation via Multi-Plane Light Conversion and coherent optical combination on a 200 m and a 10 km link

Antonin Billaud (Cailabs, France); Andrew Reeves (German Aerospace Center (DLR), Germany); Adeline Orieux (Cailabs, France); Helawae Friew Kelemu (German Aerospace Center (DLR), Germany); Fausto Gomez-Agis, Stephane Bernard, Thibault Michel and David Allioux (Cailabs, France); Juraj Poliak (German Aerospace Center (DLR) & Institut für Kommunikation und Navigation, Germany); Ramon Mata Calvo (German Aerospace Center, Germany); Olivier Pinel (Cailabs, France)

Current satellites are generating more and more data which needs to be brought back to Earth for processing and analysis. Robust optical communications links are compulsory to follow this growing demand for high-speed ground-to-space links with targets of several Gbps. Atmospheric turbulences compensation is a key element to enable such throughput.

Here we investigate the capacity of turbulence mitigation via the use of a Multi-Plane Light Conversion (MPLC) followed by a coherent optical combiner, also called TILBA-ATMO. The MPLC demultiplexes the incoming turbulent beam into a set of Gaussians beams whose relative energy distribution and phase evolve according to turbulence fluctuations. These Gaussians are then sent into an active system based on a photonic integrated chip where the channels are optically combined two-by-two in separate Mach-Zehnder interferometers.

An 8-HG mode MPLC was placed at the reception end of a free-space optical link in C or L-band, depending on the link used. Different configurations where tried such as different levels of turbulence. Two different link lengths were tested; a 200 m link with a 20 cm telescope at Cailabs and a 10 km link at the DLR Weilheim with a 10 cm telescope which is normally used for testing and developing adaptive optics solutions. The first link showed high level of phase degradation on the received beam whilst on the second link the main effect of atmospheric turbulence was scintillation inside the pupil. In both cases tip-tilt was compensated via an auxiliary system and was not implemented inside the TILBA-ATMO component.

The results are focused on fading in free-space channel relative to the TILBA-ATMO output. A numerical sum of the demultiplexed modes is also performed to determine the upper limits of such a system.

Experimental Setup for Single Pixel Imaging of Turbulent Wavefronts and Speckle-Based Phase Retrieval

Oliver J Pitts (National Research Council Canada, Canada); Michael Taylor (Formerly McMaster University); Mohamadreza Pashazanoosi and Steve Hranilovic (McMaster University, Canada); Antony Orth (National Research Council Canada, Canada); Costel Flueraru (National Research Council of Canada, Canada)

Free-space optical receivers operating over atmospheric channels suffer from phase distortions due to turbulence. These phase distortions are the dominant contribution to coupling loss in sensitive single-mode fiber-based fully coherent or optically pre-amplified direct detection receivers. Many optical ground stations and terminals with high-speed receivers employ some form of adaptive optics to restore the wavefront phase and improve coupling efficiency, which requires a wavefront sensor to estimate the phase distortions and drive the correction control loop.

We apply compressive sensing techniques and single-pixel imaging to turbulent wavefront estimation by capturing images of the speckle pattern from a simulated turbulence-corrupted wavefront using sequential patterns displayed on a digital micromirror device (DMD). We show that the single-pixel image of the turbulent speckle pattern can be used as an input to a phase-retrieval algorithm to estimate the wavefront phase that produced the speckle. We present the concepts of single-pixel turbulent speckle imaging along with an experimental setup to demonstrate the technique. A spatial light modulator (SLM) is used to simulate turbulence-degraded wavefronts that are imaged onto a single-pixel camera implemented with a DMD. The experimental setup is described along with the single-pixel imaging algorithm. Preliminary single-pixel speckle images are presented and compared with the predicted measurement decomposition from numerical simulation results.

Recent R&D activities of the Lunar - the Earth optical communication system in Japan

Tomohiro Araki (JAXA, Japan); Hideaki Kotake (National Institute of Information and Communications Technology & The University of Electro-Communications, Japan); Yoshihiko Saito, Hiroyuki Tsuji and Morio Toyoshima (National Institute of Information and Communications Technology, Japan); Katsumi Makino, Masaru Koga and Naoki Sato (Japan Aerospace Exploration Agency (JAXA), Japan)

"ARTEMIS program, that is targeting Mars and Lunar human exploration by international cooperation, has started.

As a part of Lunar manned exploration, JAXA Space Exploration Center (JSEC), where is conducting Japanese activity for ARMEMIS program, requesting over than 1Gbps data transmission from Lunar to the Earth, as to transmit huge amount of 8K HDTV data and scientific data in 2030 decade, that difficult to realize using RF technology. Moreover, in 2040 decade, it is estimated that both directional several G bps data transmissions will be needed

For the user requirement and technical target indicating above, JAXA and NICT has just started joint research activity under the publicly offered research funds of Ministry of Education, Culture, Sports, Science and Technology Japan (MEXT).

In this presentation, preliminary and conceptual study results of Lunar - the Earth high seed optical communication system, which will be expanded and established in step-by-step development, will be described. Moreover, several technical issues and our R&D plan will be discussed.

Also, our request to international partners will be indicated, that to discuss applied standard and international interface discussion on Lunar - the Earth optical link and relay."

Status Update on Laser Communication Activities in NICT

Dimitar R. Kolev (National Institute of Information and Communications Technology (NICT), Japan); Koichi Shiratama, Alberto Carrasco-Casado and Yoshihiko Saito (National Institute of Information and Communications Technology, Japan); Yasushi Munemasa (National Institute of Information and Communications Thechnology, Japan); Junichi Nakazono and Phuc V. Trinh (National Institute of Information and Communications Technology, Japan); Hideaki Kotake (National Institute of Information and Communications Technology & The University of Electro-Communications, Japan); Hiroo Kunimori and Toshihiro Kubo-oka (National Institute of Information and Communications Technology, Japan); Tetsuharu Fuse (National Institute of Information and Communications Technology & University of Electro-Communications, Japan); Morio Toyoshima (National Institute of Information and Communications Technology, Japan)

We will introduce the current status of HICALI (High Speed Communication with Advanced Laser Instrument) payload development planned to be mounted on the Engineering Test Satellite-9 (ETS-9) which will be launched in 2023 [1]. HICALI mission aims for a 10Gbps class optical feederlink between geostationary orbit and the ground. We will also show and discuss the optical ground station preparation and initial tests with celestial bodies and a low-earth orbit satellite to ground links.

Furthermore, we will present two main fields for future research - deep learning implementation for cloud recognition for site-diversity technology based on our Observation system of the patch of Blue Sky for Optical Communication (OBSOC) [2], and space optical communications with Cubesats.

The communication experiment result of Small Optical Link for ISS (SOLISS) to the first commercial optical ground station in Greece

Hiroaki Yamazoe (Sony Computer Science Laboratories, Japan); Kyohei Iwamoto (Sony Computer Science Laboratories & Japan Aerospace Exploration Agency, Japan); Hennes Henniger (KSAT, Norway)

Free-space optical communication (FSOC) in low-Earth orbit (LEO) is one of the most active areas of research and development in space communication technology. Since LEO has narrower coverage than higher orbits, optical communication terminals need to support multiple optical ground stations (OGSs) for sufficient link opportunities. In addition, considering that optical lasers are more susceptible to bad weather than radio waves, supporting multiple stations is also effective in terms of site diversity.

Recently, Sony Computer Science Laboratories (Sony CSL) and Kongsberg Satellite Services (KSAT) conducted a successful experiment to downlink data from an optical communication terminal attached to the International Space Station (ISS) to an OGS in Nemea, Greece. In this paper, we report the results of the demonstration.

The space terminal used in the experiment is the same individual used in a previous demonstration of Sony CSL that achieved optical communication with an OGS in Japan, indicating that our space terminal is compatible with independently designed multiple OGSs. More to the point, KSAT designed their OGS for commercial use, with low complexity and cost-competitive to radio ground stations. Our terminal is compatible not only with OGSs established for specific missions but also with such small and generic commercial OGSs, which could contribute to the widespread use of our optical communication terminals in orbit.

In the future, the OGS used in this study will be connected to the Optical Nucleus Network, which is a network of OGSs. Since it is significant to be able to utilize such terrestrial resources, we plan to continue our development while maintaining compatibility with various OGSs.

Challenges, Lessons Learned, and Methodologies from the LCRD Optical Communication System AI&T

Bernard Edwards (NASA Goddard Space Flight Center, USA); Patricia Randazzo (Integrity Applications Inc, USA); Nidhin Babu (NASA Goddard Space Flight Center, USA); Kendall Murphy (ASRC Federal, USA); Shane Albright (NASA - THE HAMMERS COMPANY INC., USA); Nick Cummings (NASA - Arctic Slope Technical Services, Inc., USA); Javier Ocasio-Perez, William Potter and Russell Roder (NASA Goddard Space Flight Center, USA); Sharon Zehner (NASA - ASRC FEDERAL SYSTEM SOLUTIONS, USA); Ricardo Salah (NASA - Alcyon Technical Services (JV), LLC, USA); Jonathan Woodward (NASA - Arctic Slope Technical Services, Inc., USA)

The Laser Communications Relay Demonstration (LCRD) is a technology demonstration mission, managed and integrated by the National Aeronautics and Space Administration's (NASA) Goddard Space Flight Center (GSFC) in Greenbelt, Maryland. It is a payload hosted on the Department of Defense STPSat-6 space vehicle operating in near-geostationary orbit and providing optical communication from GEO through Earth's atmosphere into Optical Ground Stations (OGSs). STPSat-6 launched 7-Dec-2021 aboard an Atlas V launch vehicle. The LCRD payload is conducting a minimum of two years of experiments with OGS-1 at NASA's Jet Propulsion Laboratory (JPL), OGS-2 in Hawaii, and the International Space Station in Low Earth Orbit (LEO) to further the scientific and engineering knowledge of optical communications.

This paper describes the LCRD assembly, integration, and test activities from pre-flight AI&T through SV AI&T and provides the latest LCRD flight status. The pre-flight AI&T campaign lasted more than 4 years, spanned multiple test facilities, collaborated with several partners (NG, MIT LL, JPL, GRC, WSC, GSFC, Space Force, ACCESS) and posed unique challenges as it space qualified the LCRD optical systems with the GEO space vehicle.

AI&T activities described in this paper include: LCRD assembly, integration, test, and verification of the LCRD payload with a radio frequency high bandwidth communication system, testing the LCRD payload after delivery to space vehicle factory, Mission Readiness Tests, Ground Readiness Tests, and Interface Compatibility Tests. Recommendations to the next optical communication missions are detailed.

Latest flight payload status is discussed as LCRD launched on 7-Dec-2021.

OGS and Site Diversity Technologies

A study of cloud cover over multiple sites within Australia for satellite/ground atmospheric optical communication

Brett Nener (The University of Western Australia, Australia); Helen Chedzey and Mervyn Lynch (Curtin University, Australia); Vladimir Devrelis (DSTG, Edinburgh, Australia); Kerry Mudge (Defence Science Technology Organisation, Australia); Kenneth Grant (Defence Science & Technology Group, Australia)

Australia is known to be the most arid continent on Planet Earth. Given the link between aridity and the lack of clouds, Australia should be well placed to have favourable conditions for space related optical communications. There are many investigations in the literature that focus on identification of the preferred site(s) in those countries for siting of satellite-to-ground optical communications infrastructure. On this matter there are several observations about Australia that are of relevance. Firstly, the country is large and very geologically old and has been subjected over time to significant erosion. Apart from the high terrain in the SE of the continent the country is relatively flat, which implies the selection of sites with low atmospheric scintillation may be a limiting factor. Change in cloud cover due to climate change appears to be regional but variable on the decadal scale. Finally, much of the interior is inhospitable rangeland and desert with low population density and consequently little in the way of high bandwidth communications infrastructure. We reported previously on an analysis of a 40-year data set of satellite-derived cloud cover statistics to assess cloud cover change. In this study we investigate, using the most recent decade of that data set, the ranking of six of 19 widely distributed sites across the Australian continent. Additionally, we explore multi-site selections to provide a statistically-based ranking of combinations of sites: any combination of 3 sites of the 6 sites analysed will achieve an average clear sky probability greater than 0.90 with some combinations as high as 0.98. The large distances between sites (~500 - 2,000 km) supports the assumption of statistically independent cloud cover.

The Mount Stromlo Optical Communication Ground Station

Marcus Birch, Francis Bennet, Michael Copeland and Doris Grosse (Australian National University, Australia)

We present a description and plan for the Optical Communication Ground Station (OCGS), which will be a facility for free space optical communication at Mount Stromlo Observatory, Australia. The OCGS, to be commissioned in 2022, will allow Australia to engage with the existing global network of ground stations, and laser communication terminals in-orbit. The OCGS will be a two level structure with a 0.7m Ritchey-Chrétien telescope in an upper dome and a large laboratory in the lower level which receives the beam through a hollow central pier. The OCGS will be equipped with numerous detection capabilities, including superconducting nanowire single photon detectors for lunar communication with the Artemis program and room for visitor instruments from industry and research partners. The facility will also be equipped with adaptive optics, and quantum communication capability. Adapting ANU's research into continuous-variable quantum key distribution over horizontal links to establish quantum communication with a satellite is a primary goal of the OCGS. Engaging with partner countries in high-bitrate relay demonstrations will be another goal of the OCGS.

Three other optical ground stations in Australia/New Zealand, becoming operational in a similar timeframe, will join the OCGS to form a regional network and take part in link relay and handover tests. Remote sensing satellites were also used to understand cloud coverage at the relevant sites, finding them to generally have low cloud coverage. High site availability for this proposed network and the intrinsic site diversity of a regional network will make Australia/New Zealand an ideal location for optical communication.

Greek Helmos Observatory readies for Optical and Quantum Communication

Zoran Sodnik (European Space Agency (ESA), The Netherlands); Harald Hauschildt (ESA, The Netherlands); Hans Smit (European Space Agency, The Netherlands); Donatas Miklusis (ESA, The Netherlands); Emmanuel Xilouris, Spyros Basilakos, Panayotis Hantzios and Alex Gourzelas (National Observatory of Athens (NOA), Greece); Athanasios Marousis (University of Piraeus, Greece & National Observatory of Athens, Greece); John Alikakos (National Observatory of Athens (NOA), Greece)

The Institute for Astronomy, Astrophysics, Space Applications and Remote Sensing, which is part of the National Observatory of Athens (NOA), joined ESA's ScyLight program and made its 2.3m Aristarchos telescope of the Helmos observatory available for Quantum, Lunar and Deep-Space Communication experiments. The Aristarchos telescope operates in the Cassegrain configuration, where a main field-corrected focus and four side foci are available for instrumentation. For ultimate isolation between transmit laser and data receiver, the transmitter is attached to the side of the main telescope assembly. The accuracies of Tx/Rx coalignment and pointing, acquisition and tracking (PAT) performance of such a bi-static implementation were successfully tested in July and November 2021 in links with the optical communication payload onboard the Alphasat satellite in GEO (orbital location 25º East).

This paper will describe the tests performed with Alphasat and will outline the proposed equipment design to implement optical communication and quantum key reception from satellites in LEO. This is performed in preparation of ESA's High thRoughput Optical Network (HydRON) project and of the European Quantum Communication Initiative (EuroQCI), in which two more Greek observatories (Skinakas in Crete and Holomondas near Thessaloniki) will participate.

The paper will also cover the proposed design and implementation of equipment for optical communications with satellites in lunar and deep-space orbits.

BER Performance Improvement using Spatial Diversity Combining in an Atmospheric Turbulent Channel with Satellite Vibration-Induced Fading

Charleston Dale M. Ambatali, Vinicius Ferreira Nery and Shinichi Nakasuka (The University of Tokyo, Japan)

Atmospheric turbulence is a major impediment in the successful establishment of wireless optical communication from satellite to the ground. Due to the refraction index inhomogeneities of the atmosphere, the received optical signal power at a point on the ground fluctuates. To mitigate its effects, spatial diversity is considered as a solution wherein receivers are placed far enough such that atmospheric turbulence influence is uncorrelated between them.

Most studies treat the effect of atmospheric turbulence and internal satellite vibrations separately. In the latter's case, a random pointing error is present during transmission, and this induces additional fluctuation to the received beam. As such, the communication link's performance is expected to decrease even further than previously investigated in existing literature. Moreover, the effect of internal satellite vibration is not uncorrelated on a spatial diversity scenario. Since uncorrelated assumption is not valid anymore, it is necessary to re-evaluate system performance. In the paper, we assess multiple diversity combining techniques in satellite-to-ground optical communications where atmospheric turbulence and satellite-induced pointing errors are present. A model encompassing the influence of aforementioned error sources to the bit error rate (BER) is proposed. Furthermore, the performance is evaluated in different atmospheric turbulence conditions to examine the robustness of spatial diverse systems compared to the no diversity case.

Beacon system for ESA IZN-1 Optical Ground Station

Jason Singleton (NKT Photonics, United Kingdom (Great Britain); Shaif-ul Alam (SP Photonics Ltd, United Kingdom (Great Britain) & University of Southampton, United Kingdom (Great Britain); Mike Yarrow (NKT Photonics, United Kingdom (Great Britain); Richard Schafers (NKT Photonics Ltd., United Kingdom (Great Britain); Andrea Di Mira (Serco@ESA, ESOC, Germany); John Clowes (NKT Photonics, United Kingdom (Great Britain); Clemens Heese (European Space Agency, Germany)

This poster describes a beacon system for satellite optical communications developed for IZN - the optical ground station of the European Space Agency deployed in Tenerife.

The system provides a CCSDS standard compatible 1590 nm signal at two selectable modulation frequencies (10 and 100 kHz) to support optical acquisition of two cubesat missions in low Earth orbits.

The system architecture is based on a multistage optical amplifiers seeded by a directly modulated DFB laser diode. The average optical power generated by the system is >6 W with diffraction limited beam quality and the beacon signal will be transmitted via the station telescope.

The beacon will be installed at IZN-1 and first support to LEO Direct-to-Earth optical communications will start at the beginning of 2022.

Concept Development of a Moon-Earth Optical Communication Terminal for CubeSats

Jorge Rosano Nonay, Christian Fuchs, Davide Orsucci and Christopher Schmidt (German Aerospace Center (DLR), Germany); Dirk Giggenbach (German Aerospace Center, Germany)

Miniaturization and sinking costs of satellites are shifting the focus of many space companies and agencies back to the Moon. However, achieving the desired data rates on CubeSats over long ranges is proving increasingly challenging with traditional radio-frequency communication systems. Free-Space Optical (FSO) communication offers a compact, light, and low-power alternative with higher data throughput and fewer limitations (e.g. fewer governmental regulations, channel interference, eavesdropping…).

Based on its long heritage of laser communications and new-space technology the German Aerospace Center (DLR) is investigating "SelenIRIS" - a miniaturized terminal for Moon-Earth optical data transmissions. This paper will analyze the necessary adaptations that are required to transfer the technology from the flight-proven Low-Earth Orbit (LEO) terminals like "OSIRIS4CubeSat" to a Lunar Orbit (LO) concept. First-order limitations have been assessed via a detailed performance link budget between a lunar satellite and a terrestrial ground station. To overcome these limitations and enhance the transmission performance, this paper will describe the necessary subsystem improvements that have to be met. We propose multiple concepts with 2, 4, and 8 Units (U) to achieve user-specific Size, Weight, and Power (SWaP) limitations and the required data rates. Finally, this paper will show an environmental radiation analysis for the most relevant lunar transfers and mission durations. In a worst-case scenario with a slow-thrust maneuver and 1-year mission duration, the total radiation dose still meets the acceptable levels tested on most Commercial Off-The-Shelf (COTS) components used in previous missions.

(Invited) DLR's Optical Communication Terminals for CubeSats

Christopher Schmidt, Benjamin Roediger and Jorge Rosano Nonay (German Aerospace Center (DLR), Germany); Christos Papadopoulos (DLR IKN, Germany); Marie-Theres Hahn and Florian Moll (German Aerospace Center (DLR), Germany)

Free space optical communication (FSO) overcomes the challenges of traditional RF-communication in space. With its high data-rates, robustness against electromagnetic influences and being free from organizational regulations, FSO provides solutions for high-rated Direct to Earth (DTE) and Intersatellite (ISL) communication.

With the raising CubeSat market and the increasing number of satellite constellations, the request for compact and efficient designs increases as well. Thus, German Aerospace Center (DLR) developed the world's smallest laser communication terminal for CubeSats (OSIRIS4CubeSat, O4C). O4C is flying on the CubeL satellite in the PIXL-1 mission. The payload itself has a modular design which allows to transfer the technology into other fields of satellite communication. The basic payload can be adapted and/or extended by different subsystems to provide solutions for intersatellite communication or Quantum Key Distribution (QKD).

This paper gives an overview of the first results of the PIXL-1 mission. After the Launch and Early Orbit Phase (LEOP) the first contact between the laser terminal and DLR's Transportable Optical Ground Station (TOGS) could be established. Afterwards, further experiments were done to demonstrate the performance of the O4C terminal. Furthermore, this paper shows the ongoing and upcoming developments. Based in the O4C dedicated terminals towards higher data rates, optical intersatellite links and QKD on CubeSats are and will be developed.

On-Orbit Risk Mitigation for a ½-U Orbital Laser Guidestar Link

Albert Q Thieu (Massachusetts Institute of Technology & MIT Lincoln Laboratory, USA); Lulu Liu (MIT Lincoln Laboratory, USA)

The AMS Beacon is a ½-U laser guidestar payload, scheduled to launch in March 2022 aboard the Agile MicroSat (AMS) 6-U CubeSat. This payload, carrying a 500 mW, 976 nm laser, will be the first to provide an active lasing low Earth orbit reference for high-angle rate adaptive optics (AO). During the science phase of the mission, it will establish a space-to-ground link with an AO-equipped ground station. Due to budget constraints and size, weight, and power limitations, AMS Beacon was designed without gimbals or fast-steering mirrors, to utilize only open-loop body-pointing and generic CubeSat attitude control software. To mitigate the risk of pointing error, a relatively wide 1.3° 1/e2 full-width beam divergence was chosen and a precise pointing calibration campaign undertaken prior to launch. This paper presents the radiometric link analysis that informed our selection of compatible ground station components and fed into the development of an on-orbit search scan pointing recalibration procedure. Within the limits of our ADCS, our search mode can accommodate up to 1.75 deg of pointing error during a single pass, and has the capability to potentially search larger areas by concatenating data from multiple successive passes. As our expected pointing error is approximately 0.1 degrees, this search mode is a fail-safe in case of larger than expected pointing shifts during launch and deployment. Our scheme utilizes AMS's body-pointing capability, AMS telemetry, and ground-based radiometric readings to re-characterize beam alignment on-orbit. Because this procedure relies on standard CubeSat pointing capabilities and telemetry, we believe that our procedure could be used for future laser guidestar CubeSat payloads.

This material is based upon work supported by the Under Secretary of Defense for Research and Engineering under Air Force Contract No. FA8702-15-D-0001. Any opinions, findings, conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the Under Secretary of Defense for Research and Engineering.

Optical Communications for Cubesats/Small Sats I *Continued*

TBIRD 200 Gbps CubeSat Downlink: System Architecture and Mission Plan

Curt Schieler, Kathleen Riesing, Bryan Bilyeu, Bryan Robinson and Jade Wang (MIT Lincoln Laboratory, USA); William Thomas Roberts (Jet Propulsion Laboratory (JPL), USA); Sabino Piazzolla (NASA Jet Propulsion Laboratory, USA)

The Terabyte Infrared Delivery (TBIRD) program will establish an optical communication link from a 6U CubeSat in low-Earth orbit (LEO) to a ground station at burst rates up to 200 Gbps, resulting in data volumes that can exceed 1 Terabyte in a single pass. The space and ground terminals utilize commercially available 1550-nm coherent transceivers in conjunction with an automatic repeat request (ARQ) system to guarantee robust communication in the presence of an atmospheric fading channel. This allows the system to perform a reliable end-to-end transfer of data from the payload's 2-TB storage buffer to the ground terminal. In this work, we describe the system architecture, link analysis, and concept of operations for the upcoming TBIRD flight demonstration in 2022. We also provide an update on the development of the 3U terminal payload and the ground terminal at JPL's Optical Communications Telescope Laboratory (OCTL).

Optical Communications for Cubesats/Small Sats II

(Invited) Architecture for Reconfigurable Next-Gen Lasercom Terminals

Robert Carlson (The Aerospace Corp, USA)

Intersatellite laser communications (lasercom) offers very high data rates (1 to 100+ Gbps), and unequaled transmission security due to a laser beamwidth 100 to 1000 times narrower than an RF crosslink. As more high-value satellites are equipped with lasercom terminals, the space network lasercom architecture becomes more important. We propose a space lasercom architecture and wavelength/polarization plan for high-rel, high-value satellites that facilitates lasercom terminal reconfigurability for network robustness, evolution, and longevity. We also present a corresponding on-orbit reconfigurable optical bench design for maximum flexibility for intra or inter-network connectivity, with multiple features for rapid establishment of a crosslink and resilience to potential hostile interference. Such reconfigurable terminals not only enhance network robustness, but also improve network cost-effectiveness because of the connectivity flexibility. A prototype reconfigurable optical bench is being designed for future build at The Aerospace Corporation. Our intent is that the design details will be made available as a reference design for adoption or adaptation, and the prototype performance test results will be made available on a non-proprietary basis, to encourage network adoption and interoperability and space qualification activities.

Agile Beaconless Laser Beam Alignment with Adaptive Mm-Wave Beamforming for Inter CubeSat Communication

Chengtao M Xu and Eduardo Rojas (Embry-Riddle Aeronautical University, USA); Thomas Yang (Embry Riddle Aeronautical University, USA)

Inter small satellite/CubeSat communication (C2C) plays a key role in configuring mega low earth orbit satellite constellation, which provides wider network coverage globally and better resolution of spatial and temporal geo-sensing. A highly direct laser link for C2C allows high-data-rate communication to enable massive data transmission with low delay and power consumption. However, the pointing loss from imperfect acquisition and tracking between satellites with different relative velocities impedes the optical links to achieve the desired ultra-reliable link capacity. In this paper, we proposed an agile beaconless laser beam alignment (ABLBA) method that realizes a low cost of scanning for pre-alignment between CubeSat, which is essential to small satellites with a limited power budget. The mmWave radios with highly directional antennas are used to find the best alignment direction between transmitter and receivers based on the omnidirectional optical communicator with lasers telescopes and detectors fitted inside a truncated dodecahedron geometry, which provides full space coverage. Adaptive pencil-beams width with various transmitter configurations is considered for a more power-efficient free space scanning scheme. Given all possible directions of setting the optical beam width, ABLBA is capable mitigates the effects of laser beam misalignment brought by the CubeSat perturbation and different relative velocities within a closed coarse pointing loop. Accuracies of mutual alignment are evaluated based on the model of rating intersection surface in a geometric coverage model, which provides a direct mapping between platform dynamics and optical link alignment performance. Link budget of accurate laser beam pointing system and the mmWave scanning scheme is simulated with considering the adaptive power consumption on a 2U CubeSat platform.

NICT's versatile miniaturized lasercom terminals for moving platforms

Alberto Carrasco-Casado, Koichi Shiratama and Phuc V. Trinh (National Institute of Information and Communications Technology, Japan); Dimitar R. Kolev and Femi Ishola (National Institute of Information and Communications Technology (NICT), Japan); Tetsuharu Fuse (National Institute of Information and Communications Technology & University of Electro-Communications, Japan); Hiroyuki Tsuji and Morio Toyoshima (National Institute of Information and Communications Technology, Japan)

With the goal of meeting the diverse requirements of many different types of platforms, ranging from small drones to big satellites, and being applied in a variety of diverse scenarios, ranging from fixed terrestrial links to moving platforms in general, and operating within a wide range of conditions and distances, the Japanese National Institute of Information and Communications Technology (NICT) is currently working towards the development of a series of versatile miniaturized free-space laser-communication terminals. By choosing the appropriate terminal configuration for any given scenario, the basic conditions of operations can be satisfied without the need of customization, and the adaptive design of the terminals can close the gap to achieve an optimum solution that meets the communication requirements. This paper presents NICT`s current efforts regarding the development of this series of lasercom terminals and introduces the first prototypes developed for validation and test purposes.

Development and Testing of the Laser Transmitter and Pointing, Acquisition, and Tracking (PAT) System for the CubeSat Laser Infrared CrosslinK (CLICK) B/C Mission

Hannah Tomio (Massachusetts Institute of Technology, USA); William Kammerer III (MIT, USA); Peter Grenfell (Massachusetts Institute of Technology, USA); Ondrej Cierny, Charles Lindsay, Maddie Garcia and Paul C Serra (MIT, USA); Kerri Cahoy (Massachusetts Institute of Technology, USA); Myles Clark, Danielle Coogan and John Conklin (University of Florida, USA); David Mayer and Jan Stupl (NASA Ames Research Center, USA)

Laser crosslinks can provide high data rate communications and precision time transfer and ranging, using low size, weight, and power (SWaP) terminals to enable constellations of small satellites. The CubeSat Laser Infrared CrosslinK (CLICK) mission will demonstrate terminals capable of conducting full-duplex, high data rate crosslinks and enabling high precision ranging on 3U CubeSats in low Earth orbit (LEO). An initial risk-reduction mission, CLICK-A, will demonstrate a downlink of at least 10 Mbps to a 28 cm aperture optical ground station. CLICK-B and CLICK-C will follow to demonstrate a laser crosslink with a data rate of at least 20 Mbps over separation distances ranging from 25 km to 580 km. The CLICK-B/C mission will also demonstrate precision ranging better than 50 cm. Key to achieving these capabilities is the performance of the transmitter and fine pointing, acquisition, and tracking (PAT) system. We present results from recent testing and characterization of the transmitter and PAT subsystems, which were shown to meet their requirements for operation on orbit. For the transmitter subsystem, the mission requirements necessitate operating using M-ary pulse position modulation (PPM) with orders ranging from 2 to 128. The 1550 nm transmitter must be capable of outputting 200 mW average power with a pulse width of less than 10 ns. To meet the requirements of the PAT subsystem, the transmitter full width at half maximum (FWHM) beam divergence must be less than 71 urad. For the PAT system, testing focuses on the demonstration of the beam detection, sub-modulation filtering and fine steering mirror (FSM) actuation. The testing of the transmitter includes confirming the output power and modulation of the seed laser and semiconductor optical amplifier (SOA) and characterizing the output pulse shape at the output of the Erbium Doped Fiber Amplifier (EDFA), at the end of the transmit fiber train. This testing was conducted using a dedicated hardware-in-the-loop testbed with an optical test setup. CLICK A is expected to launch no earlier than May 2022 for deployment from the International Space Station (ISS) in June 2022, while CLICK B/C is anticipated to launch in late 2022.

Optical Feederlink Technologies

FEELINGS: the Onera's optical ground station for Geo Feeder links demonstration

Cyril Petit and Aurélie Bonnefois (ONERA, France); Jean Baptiste Volatier (Office National d'Etudes et de Recherches Aérospatiales, France); Caroline B. Lim (ONERA, France); Francois Gustave (Office National d'Etudes et de Recherches Aérospatiales, France); Joseph Montri, Philippe Perrault, Laurie Paillier, Marie-Therese Velluet and Jean-Marc Conan (ONERA, France); Anne Durecu (Office National d'Etudes et de Recherches Aérospatiales, France); Nicolas Vedrenne (ONERA, France)

The future of ground-space communications will rely on high capacity optical links between the ground and GEO satellites, the so-called GEO-feeder links. Still, it implies, among others, development of performant, cost effective and highly operational optical ground stations.

In that respect, some critical scientific and technological issues need to be addressed, such as fine calibration and optimization of the point-ahead angle, mitigation of turbulence effects, both downlink and uplink. Adaptive Optics is potentially a game changer, in particular for uplinks through precompensation, ensuring additional link margin and increased operability. These entails however handling of point-ahead induced anisoplanatism.

Development and design of OGS also means a precise understanding and estimation of link budget on sky down to detection, including atmospheric transmission, actual pointing errors, turbulence conditions and AO performance, considering that these effects are coupled. All these elements shall thus be evaluated and compared to models to refine systems design.

It also means developing high power amplifiers compatible with multi-channel operation, very high rate phase or amplitude modulation (>10 Gb/s per channel), but also integrating them within the OGS, ensuring shape of the beam, isolation of up and downlinks, diffusion on optics.

Finally, operability of such OGS will closely depend on instrument stability, and if needed control and identification of instrument evolution, robustness to turbulence and weather conditions.

To address these challenging issues, ONERA is currently developing an experimental optical ground station (OGS), FEELINGS, dedicated firstly to GEO feeder links to investigate GEO feeder link optimization and related scientific and experimental issues, to pave the way of future OGS, with high capacity and operability. Extension to LEO links is already included. We present the FEELINGS OGS design and current status. We also discuss how critical scientific issues related to GEO Feeder links will be addressed through it.

End-to-End Performance Analysis of Analog Transparent PM and DSB-SC Coherent Optical Feeder Links

Cornelis Willem Korevaar and Jeroen J. Boschma (TNO, The Netherlands); Remco den Breeje (TNO / OC Engineering, The Netherlands); Johannes Ebert (Joanneum Research, Austria)

To enable the next generation of high-throughput satellites, optical feeder links (OFLs) may play a major role due to the abundance of license-free bandwidth in the near-infrared spectrum. There is ongoing debate which architecture - analog, digital or regenerative - is best suited for OFLs [1, 2, 3]. In contrast to digital transparent architectures, which include analog-digital conversion, the analog transparent architecture directly modulates the RF signals onto the optical carrier.

Key advantage of the analog transparent architecture is the simplicity of the satellite payload, as the analog transparent is alike current RF based feeder links. In terms of performance, it helps to avoid bandwidth expansion associated with analog-to-digital conversion and minimization of on-board power and satellite processing [3]. However, there are key questions about the degradation of the Es/N0 due to the OFL, and its ability to cope with turbulence- and pointing-induced fading. These questions form the rationale for the presented study.

In contrast to previous studies of analog transparent OFLs employing direct detection [4, 5], this study assesses the performance of digital video broadcasting (DVB) signals transported by a coherent analog OFL, using phase modulation (PM) or double-sideband suppressed-carrier (DSB-SC) modulation. Advantage of DSB-SC is that the optical modulation index can be reduced such that the modulator is operated in the linear regime, and the subsequent booster Erbium-Doped Fiber Amplifier (EDFA) compensates for the loss in power. As a result, the non-linear distortion of the optical modulator becomes negligible.

Using end-to-end simulations of a GEO feeder link, as depicted in Figure 1, we have analyzed the Es/N0 penalty due to the OFL. In the paper, we will present a detailed insight in the impairments due to the optical as well as the RF link. With typical dimensioning, the required optical transmit power is derived for several DVB modulation and coding schemes. In general, the Es/N0 penalty stays below 1 dB such that the RF traveling-wave tube amplifier (TWTA) and the RF user channel remain the key limiting factors for the end-to-end performance.

A link-layer interleaver and forward error correction (FEC) scheme has been considered to mitigate fading, and unlock coding and diversity gain. However, it increases latency and we show that lowering the DVB modulation and coding scheme can lead to a similar gain, at the cost of a comparable reduction in throughput.

The results as presented in the paper - in combination with the reduction in on-board power, complexity, latency and overhead in comparison to digital transparent architectures - makes the analog transparent architecture a promising candidate to feed the next generation of very high-throughput DVB satellites.

New results from the 2021 FEEDELIO experiment - a focus on reciprocity

Perrine Lognoné (ONERA & Telecom Paris, France); Aurélie Bonnefois, Jean-Marc Conan, Cyril Petit, Caroline B. Lim, Jean-Francois Sauvage, Serge Meimon, Joseph Montri and Nicolas Vedrenne (ONERA, France)

In order to address the increasing need for very high throughput data links between ground and geostationary satellites, optical technologies are a very competitive candidate. However, their future depends on the ability to overcome channel disruptions and large link budget losses caused by the optical propagation through the turbulent atmosphere.

In 2019, the first FEEDELIO experiment, which consisted in a 13 km slant path optical link in Tenerife, proved the feasibility of Adaptive Optics (AO) pre-compensation of optical links in an environment whose properties are similar to a GEO feeder link. It also showed an order of magnitude gain in the link budget, as well as significant signal fluctuation reductions, compared to an uncompensated or a tip-tilt only corrected beam [1].

We performed in October 2021 a second FEEDELIO experiment, with the aim of acquiring new time series with improved calibration procedures. We will present the first results obtained during this campaign with a particular focus on the signal reciprocity experiment. Quasi-reciprocal time-series have been obtained with a co-axial bi-directional link corrected/pre-compensated of tip-tilt with a correlation coefficient up to 95%. We show that the remaining 5% are in accordance with the decorrelation induced by the residual non-common path aberrations (NCPAs) measured on the bench. The impact of these NCPAs is evaluated through numerical simulations thanks to in house pseudo-analytical models [2].

We will then discuss how this reciprocity experiment can be used for calibration purpose.

[1] A. Montmerle-Bonnefois, J. M. Conan, C. Petit, C. B. Lim, V. Michau, S. Meimon, P. Perrault, F. Mendez, B. Fleury, J. Montri, and N. Védrenne, "Adaptive optics pre-compensation for GEO feeder links: the FEEDELIO experiment, in International Conference on Space Optics - ICSO 2018, (2019), p. 83

[2] J.-M. Conan, A. Montmerle-Bonnefois, N. Védrenne, C. Lim, C. Petit, V. Michau, M.-T. Velluet, J.-F. Sauvage, S. Meimon, C. Robert et al., "Adaptive optics for geo-feeder links: from performance analysis via reciprocity based models to experimental demonstration," in COAT-2019-workshop (Communications and Observations through Atmospheric Turbulence: characterization and mitigation), (2019).

ALASCA: the ESA Laser Guide Star Adaptive Optics Optical Feeder Link demonstrator facility

Roberto Biasi (Microgate, Italy); Domenico Bonaccini Calia (European Southern Observatory, Germany); Noelia Martinez (Australian National University, Australia); David Jenkins (ESO, Germany); Ollie Farley (Durham University, United Kingdom (Great Britain); Martin Enderlein (TOPTICA Projects GmbH, Germany); Petr Janout (ESO, Germany); Filippo Ambrosino (INAF-OAR, Italy); Hira Virdee (Lumi Space, United Kingdom (Great Britain); Matthew Townson (Durham University, United Kingdom (Great Britain); Mauro Centrone and Marco Faccini (INAF-OAR, Italy); Pierre Haguenauer (ESO, Germany); Marcos Reyes Garcia-Talavera (Instituto de Astrofisica de Canarias, Spain); Enrico Pinna (INAF-OAA, Italy); James Osborn (Durham University, United Kingdom (Great Britain); Guido Agapito (INAF - Osservatorio Astrofisico di Arcetri, Italy); Daniele Gallieni (A. D. S. International, Italy); Frank Lison (Toptica Projects, Germany); Laura Salvi (Microgate, Italy); David Gooding (Lumi, Germany); Zoran Sodnik (European Space Agency (ESA), The Netherlands)

We report on the novel ALASCA facility being built for ESA by a consortium of industry and national research institutes under the ScyLight program.

The aim of ALASCA is to create a facility for Optical Feeder Links (OFL) field tests, as well as to demonstrate at the ESA Optical Ground Station in Tenerife, starting in 2023, 24/7 reliable operation of optimal Optical Feeder Links based on Laser Guide Star Adaptive Optics (LGS-AO) to solve the point-ahead problem on ground for space laser communications.

Optical Feederlink Technologies *Continued*

Space optical communication represents a technological challenge due to its specific requirements, and parameters of merit; the consortium's extensive experience in LGS-AO in the astronomical field allows an expert technology transfer to earth-space communication. This will enhance the review of the ALASCA main requirements, their implementation by a proper tailoring of the modular solutions that will be adopted by the design, facing the new challenges at system level posed by the OFL applications compared to astronomical solutions. The ALASCA project will, last but not least, provide a technology assessment and a development roadmap towards the industrial exploitation of a 24/7 operational OGS.

We will present the overall ALASCA project, its goals, phases and planned timeline up to the field experiments; the presentation will then focus on the simulations results of LGS-AO assisted OFL and the comparisons with OFL systems which are not using LGS-AO technologies.

Plenary Sessions

(Invited) Latest Status of the CCSDS Optical Communications Working Group

Bernard Edwards (NASA Goddard Space Flight Center, USA)

International civil space agencies around the world are working together in the Interagency Operation Advisory Group (IOAG) and the Consultative Committee for Space Data Systems (CCSDS) to develop interoperability architectures and standards for space communications. Within CCSDS, there is a working group dedicated on developing recommendations and standards for optical communications. These standards include recommendations for the physical layer, coding and synchronization layer, and best practices for measuring and monitoring atmospheric conditions and operating optical links. The working group has developed standards for both Near Earth and Deep Space robotic and hum exploration missions. The standards generally address both free space links between spacecraft and free space links between spacecraft and ground. This paper will provide an overview and update on the set of standards the CCSDS Optical Communications Working Group has developed.

(Invited) Optical Communications for Human Space Exploration-Status of Space Terminal Development for the Artemis II Crewed Mission to the Moon

Bryan Robinson, Farzana Khatri and Mark Padula (MIT Lincoln Laboratory, USA); Steven Horowitz (NASA Goddard Space Flight Center, USA); Michael Bay (Bay Engineering Innovations, USA); Jonathon King (NASA Johnson Space Center, USA)

NASA is currently developing optical communications technologies to support a variety of future missions, including its human exploration efforts. The Artemis II mission, which will return humans to the Moon for the first time since the Apollo missions, will include an optical communication payload for the Orion Artemis II Optical Communications (O2O) demonstration. We describe the O2O demonstration plans and objectives. We also provide a description and status of the Orion communications terminal, which includes a 10-cm gimballed optical telescope fiber-coupled to a pulse-position-modulation optical modem capable of supporting forward links up to 20 Mbps and return links up to 250 Mbp

(Invited) Optical high-speed data network in space - an update on HydRON's System Concept

Christopher A Vasko (European Space Agency & Aurora Technology B. V., The Netherlands); Pantelis-Daniel Arapoglou (European Space Agency, The Netherlands); Josep Maria Perdigues Armengol (ESA, The Netherlands); Guray Acar (European Space Agency - ESTEC, The Netherlands); Monica Politano (European Space Agency, The Netherlands); Wael El-Dali, Harald Hauschildt and Carlo Elia (ESA, The Netherlands)

The ambition of the High thRoughput Optical Network (HydRON) vision of the European Space Agency (ESA) is to seamlessly extend terrestrial high-capacity networks into space. The concept aims to empower satellite networks by developing terrestrial optical networking capabilities, in order to interconnect a variety of space and ground assets by an "Internet backbone beyond the cloud(s).

Different to earlier publications on HydRON [1], [2] focused on the vision and the mission concept, this paper will present an update on the overall HydRON-S system concept. This will include a summary of the trade-offs for the overall system architecture, the space segment (including the HydRON payload) and the ground segment. This update follows the successful conclusion of internal assessments addressing various mission- and first system implementation aspects, as well as the conclusion of external studies completed in 2021. The objective of these industrial studies was to further consolidate the mission requirements of the HydRON-S, derive a preliminary list of the system requirements and elaborate the system and sub-system definition to achieve those. The paper will present the latest iterations of the overall system concept, including the definitions of ground- and space segments, as well as preliminary network architectures. Furthermore, it will overview the outcome of key system trade-offs, referring to fundamental characteristics of HydRON, such as the choice of wavelength, the satellite orbit, the number of satellites in the constellation, the type of switching and the interfaces between the HydRON payload and the Customer (RF) payload.

The implementation of the full HydRON-S is considered beyond the scope of the HydRON project, taking into account estimated financial envelope and effort. However, it allows for definition, development and validation of a representative demonstration system, HydRON-DS.

Plenary Sessions *Continued*

(Invited) DSTG Laser Satellite Communications - Current Activities and Future Outlook

Kerry Mudge and Bradley Clare (Defence Science Technology Group); Elisa Jager (Defence Science Technology Group, Australia); Vladimir Devrelis (Defence Science Technology Group); Francis Bennet, Michael Copeland, Nick Herrald and Ian Price (Australian National University, Australia); Gottfried Lechner (University of South Australia, Australia); Jeewani Kodithuwakkuge, Joseph Magarelli, Dharmapriya Bandara, Christopher Peck, Monique Hollick, Paul Alvino, Peter Camp-Smith, Barbara Szumylo and Agam Raj (Defence Science Technology Group, Australia); Kenneth Grant (Defence Science & Technology Group, Australia)

This paper is an overview of the activities in laser satellite communications at the Defence Science and Technology Group (DSTG), Australia. In particular, it provides a status update on the development of the DSTG optical ground station (OGS), which is located at a near sea level site in Adelaide, South Australia. This is in contrast to astronomical observatory sites, which are typically chosen for their favourable atmospheric characteristics including low turbulence. We present the results of local site characterisation demonstrating that the optical turbulence can be significantly greater at low altitudes. To combat the effects of turbulence, the OGS will be augmented with a low-cost adaptive optics system developed by the Australian National University. An update will also be given on the optical communications payload for the Buccaneer Main Mission CubeSat. Finally, our future outlook will be presented.

(Invited) LUCAS: The second-generation GEO satellite-based space data-relay system using optical links

Shiro Yamakawa and Yohei Satoh (Japan Aerospace Exploration Agency, Japan)

LUCAS introduction

(Invited) Space Development Agency Optical Communications: Progress Update and OCT Standard v3.0

Michael Butterfield (Space Development Agency, Japan)

Space Development Agency Optical Communications: Progress Update and OCT Standard v3.0

Satellite QKD missions I

A CubeSat platform for space-based quantum key distribution

Srihari Sivasankaran, Clarence Liu, Moritz Mihm, Ali Anwar, Riadh Rebhi and Alexander Ling (Centre for Quantum Technologies, Singapore)

Satellite nodes are an enabler of global quantum networks by overcoming the distance limitations of fiber and free-space links on ground. The design of quantum sources and receivers for satellites, however, is challenging in terms of size, weight, and power consumption, as well as mechanical and thermal stability. This is all the more true for cost-efficient nanosatellites such as the popular CubeSat platform standard.

Here we report on the follow-up mission of SpooQy-1, a 3U CubeSat that successfully demonstrated the generation of polarization-entangled photons in orbit. The next iteration of the quantum payload will showcase satellite-to-ground quantum key distribution based on a compact source of polarization-entangled photon-pairs. The launch is scheduled for late 2023 and we have recently completed the integration of a fully functional demonstrator (engineering model) as a milestone towards the flight model.

We also briefly describe the design of the optical ground station that we are currently building in Singapore for receiving the quantum signal. We present the most important subsystems and illustrate the concept of operation.”

QKD and optical terminals for Canada’s Quantum Encryption and Science Satellite (QEYSSat)

Hugh Podmore (Honeywell Aerospace, Canada)

Honeywell Aerospace is implementing on behalf of the Canadian Space Agency the Quantum Encryption and Science Satellite (QEYSSat), a Canadian owned and operated scientific and technology demonstration mission aimed at developing the next generation of secure communications infrastructure backed by quantum physics. The mission management is led by the Canadian Space Agency and the science is led by the Institute for Quantum Computing at the University of Waterloo. Quantum key distribution (QKD) is a method that uses single photon quantum states to generate verifiably secure encryption keys between two parties. This capability solves the fundamental problem of symmetric key encryption; how to guarantee the security during the transfer of encryption keys. However, current and foreseeable terrestrial QKD networks are limited to a few hundred kilometers due to attenuation of single photons in fiber, and several tens of kilometers for free space lines-of-sight due to the curvature of the earth, and other geographic constraints. QEYSSat will use a satellite receiver as a trusted node to demonstrate the distribution of secure keys to ground stations separated by at least 400 km. Honeywell will also fly an optical intersatellite link (OISL) terminal as a hosted payload on this mission.

The QEYSSat mission will utilize both weak coherent pulse (WCP) sources and entangled photon sources in an uplink configuration to study the performance of QKD, and to perform Bell tests of long-range quantum entanglement. The mission will also incorporate an onboard WCP source as a downlink demonstration. Honeywell is building the QKD terminal consisting of a front-end telescope, a precision pointing and tracking system and single-photon detectors. Major technical challenges include throughput and polarization management throughout the optical chain, accurate pointing and tracking, and suppression of background and stray light sources.

To address these challenges, Honeywell will leverage its commercial optical communications solutions to meet the stringent performance requirements for space-based QKD. The QKD terminal consists of an afocal front-end telescope; a wide FOV high-precision pointing and tracking assembly; a polarization analyzer; and a single-photon detector system. A 25 cm diameter, on-axis telescope forms the basis for the terminal's front-end optics, and Honeywell's commercial Optical Pointing and Tracking Relay Assembly for intersatellite Communications (OPTRAC) has been adapted as a quantum-ready pointing and tracking unit (QTRAC). Customized coatings and high-fidelity, polarization-preserving optics have been developed for the large number of surfaces in the optical chain.

This paper will highlight the recent development and testing of the qualification unit for the QKD terminal and the secondary OISL payload.

CARAMUEL: The future of Space Quantum Key Distribution in GEO

Antonio Abad (C/Anabel Segura 11 - Edificio Albatros 4 floor & Hispasat, Spain); Angel Alvaro Sanchez (Thales Alenia Space, Spain)

The usage of QKD protocols through the current terrestrial infrastructure is limited to a hundred kilometers due to attenuation problems with fiber. This implies that the satellite will be necessary for the transmission of quantum keys in order to avoid these terrestrial limitations. Therefore, the current debate does not lie in the need for the satellite but rather in what type of infrastructure will be best suited, and specifically the usage of GEO vs LEO satellites. This analysis is not trivial and should not consider only the link budgets and the physical layer as it has been done up to date. It should also consider even more important factors, as the service KPIs that the end user will request such as key rate, availability, security of the keys and their maintenance, etc, as well as the possible communications architectures to provide the service. Therefore, the analysis should introduce the market oriented component, and provide the optimal solutions based on the scenarios and requirements requested by the customer. In this frame, and under ESA ARTES funding, a Spanish consortium led by Hispasat is defining an operational GEO QKD mission that shall fly as hosted payload in 2025. Details of the challenges and approach of this mission shall be presented.

Using Adaptive Optics to Improve Long Distance Free Space Continuous Variable Quantum Key Distribution

Ciaron Quinlivan (Australian National University, Australia); Oliver Thearle (DSTG, Australia); Ozlem Erkilic (Australian National University, Australia); Syed Assad (ANU, Australia); Marcus Birch, Michael Copeland, Doris Grosse, Francis Bennet and Ping Koy Lam (Australian National University, Australia)

Realising long-distance, free-space quantum key distribution (QKD) is an important step for the future of QKD in encryption. Key to this is successfully performing QKD over free-space channels, which have the potential for lower loss and suffer less from dispersion than fibre-optic channels. Additionally, free space QKD is essential in situations where a fibre-optic link is either impractical or impossible, such as between a ground station and a satellite. Significant progress has been made and a combination of discrete variable (DV) QKD technologies has been used to create a quantum network [1] but continuous variable (CV) QKD technology has lagged DV and only achieved shorter distances so far [2]. However, CV remains a promising alternative to DV based on its use of cheaper, commercially available optical communications devices rather than expensive single photon sources and detectors as well as the greater potential to make use of multiplexing [3,4].

A key difficulty to overcome for free-space QKD is atmospheric scintillation which affects the optical channel and causes effects such as beam wander, broadening and deformation as well as aberrations in the phase of the beam wavefront. In the CV regime these aberrations manifest as deep fades in the channel or as increased excess noise which decreases the signal-to-noise ratio of the detected signal [3]. This greatly affects the security of the protocol and reduces the secure key rate.

In this work, we investigate the use of adaptive optics as a method to reduce the excess noise in the channel by correcting phase aberrations in the wavefront. Our experiments make concurrent measurements of the phase and amplitude quadrature noise and the scintillation index with and without adaptive optics. By using these measurements to calculate theoretical secure key rates, the impact of scintillation is quantified to allow any improvement from adaptive optics to be determined. In this talk I present an overview and the latest designs, simulations, and results based on our instrument to achieve free-space QKD.

References

[1] Y.A. Chen et al., Nature 589, 214 (2021).

[2] S.Y. Shen et al., Phys. Rev. A 100, 012325 (2019).

[3] E. Villaseñor et al., arXiv:2005.10465v1 (2020)

[4] D. Dequal et al., npj Quantum Information 7:3 (2021)

(Invited) Satellite-based QKD for Global Quantum Cryptographic Network Construction

Atsushi Mamiya, Kentaro Tanaka and Saori Yokote (SKY Perfect JSAT Corporation, Japan); Masahide Sasaki and Mikio Fujiwara (NICT, Japan); Masaki Tanaka (NEC Corporation, Japan); Hideaki Sato (Toshiba Corporation Corporate Research&Development Center, Japan); Yusuke Katagiri (The Japan Research Institute, Limited. (JRI), Japan)

Recently, Quantum Key Distribution (QKD) and Cryptographic Technology development are in progress all over the world. In Japan as well, a wide range of QKD study and development is being conducted, including public offerings of research and development from the Ministry of Internal Affairs and Communications (MIC). SKY Perfect JSAT Corporation (SJC), which has been engaged for more than 30 years in space industry, has been selected as the representative company of the consortium for executing the public offering from MIC in 2021, "Study and Development of Satellite-based QKD and Cryptographic Technology for Global Quantum Cryptographic Network Construction", and plans to actively engage in research and development, especially for satellite-based QKD. The consortium to execute the project consists of National Institute of Information and Communications Technology (NICT), NEC Corporation, TOSHIBA CORPORATION and SJC, and they are actively engaged in many other projects related to QKD and Cryptographic Technology and have been contributing on Japanese QKD and Cryptographic Technology development.

This paper introduces recent QKD development situation of several countries all over the world and of Japan. Then this paper describes the concepts and the requirements of MIC public offering, "Study and Development of Satellite-based QKD and Cryptographic Technology for Global Quantum Cryptographic Network Construction", the role of the consortium to work on the project and their progress so far.

In addition, this paper describes about the prospects for future business development of SJC, associated with satellite-based QKD.

Satellite QKD Missions II

WITHDRAWN Entangled photon sources for space applications

Armin Hochrainer, Manuel Erhard, Matthias Fink, Johannes Handsteiner, Thomas Herbst, Thomas Scheidl, Philipp Sohr and Rupert Ursin (Quantum Technology Laboratories GmbH, Austria)

Entangled photon sources today are on the verge of reaching very high TRLs. High performance in terms of photon pair rate and entanglement quality are routinely achieved in scientific laboratories. Some demonstrators have even been tested in orbit, albeit with limited performance. We are now at a position to manufacture compact, stable, and space qualifiable sources with a performance that enables a wide range of applications. Most importantly, the achievable secure key rates in satellite based QKD applications are sufficiently high to be commercially exploited.

At qtlabs, we are working on the design and optimization of entangled photon sources for space, ranging from fundamental tests of innovative operating principles to the transfer of laboratory build and alignment procedures to an industry grade reliable manufacturing process.

We present our current design approaches and capabilities regarding this development. Our vision is that within the coming year, space qualified high performance entangled photon sources become a commercially available tool that enables customers to perform competitive space-based quantum key distribution, develop space-based quantum sensing applications as well as fundamental quantum science experiments.

High-level concepts and design of commercial satellite-based QKD networks

Manuel Erhard, Armin Hochrainer, Thomas Herbst, Matthias Fink, Philipp Sohr, Johannes Handsteiner, Thomas Scheidl and Rupert Ursin (Quantum Technology Laboratories GmbH, Austria)

Quantum Key Distribution (QKD) is a fast-growing scientific but today primarily commercial field. Governments and private businesses seek enhanced security solutions that can withstand future hacking attacks directed against public key encryption systems. Today, many different QKD protocols claim to offer "unconditional" security. However, looking in more detail, many subtleties lead to different security levels, or in worst-case scenarios, to no security at all. Thus, it is essential to appropriately select and design QKD protocols and networks suitable for intercontinental long-distance satellite-based QKD networks. This talk presents and compares different QKD protocols concerning their security, key-rate performance, and applicability, especially for satellite-based QKD networks. Our focus lies in high-level mission planning parameters, such as orbital height, number of satellites per orbit, and realistically achievable secret key rates with various QKD protocols and technologies. Finally, we present simulation results of various case studies ranging from European to intercontinental use-cases.

Design considerations for a Transportable Optical Ground Station for QKD

Luis Fernando Rodríguez Ramos (Institute of Astrophysics of the Canary Islands, Spain); Jorge Socas Negrín (Instituto de Astrofísica de Canarias IAC, Spain); Marcos Reyes Garcia-Talavera (Instituto de Astrofisica de Canarias, Spain); Noelia Martinez (Australian National University, Australia); Álex Oscoz and Pablo González de Chaves Fernández (Institute of Astrophysics of the Canary Island, Spain); Joan Torras Estruch (Institute of Astrophysics of the Canary Islands, Spain); Ángel Alonso Sánchez (Institute of Astrophysics of the Canary Island, Spain); Iciar Montilla (Instituto de Astrofisica de Canarias (IAC), Spain)

IACTEC, as the technology transfer division of the Institute of Astrophysics of the Canary Islands, is starting a program towards practical applications of optical communications and specifically quantum key distribution, leveraging its facilities and experience in free-space optical communications and its "know-how" in Adaptive Optics.

The main objective of this group is related with the use of the compensation of the atmospheric turbulence to improve the performance of a Transportable Optical Ground Station (TOGS). This compensation is specially challenging when day-time operations are considered and also if the TOGS is expected to work in virtually any location, including common city buildings, where the atmosphere turbulence is much worse than the one found in astrophysical observatories.

The role of the Adaptive Optics could be especially relevant when superconducting nanowires detectors are being used, which can achieve very low dark counts when fed by a single mode fiber [1]. In this situation, the coupling capability of the light received at the telescope to the fiber is vital, and if the wavefront aberration caused by the atmospheric turbulence is corrected before the coupling to the fiber, the overall quantum channel loss will be lowered and the key rate improved [2]. This improvement will be estimated using simulations regarding the atmospheric turbulence characteristics of the different scenarios.

References

[1] Brian E. Vyhnalek et al. "Few-mode fiber coupled superconducting nanowire single-photon detectors for photon efficient optical communications"

[2] C B Lim et al. "Single-Mode Fiber Coupling with Adaptive Optics for Free-Space Optical Communication under Strong Scintillation"

Link technology for all-optical satellite based quantum key distribution system

Florian Moll, Eltimir Peev, Andrew Reeves, René Rüddenklau, Agnes Ferenczi, Luca Macri and Stefanie Häusler (German Aerospace Center (DLR), Germany); Jorge Pacheco-Labrador (German Aerospace Center, Germany); Davide Orsucci and Marie-Theres Hahn (German Aerospace Center (DLR), Germany); Juraj Poliak (German Aerospace Center (DLR) & Institut für Kommunikation und Navigation, Germany); Nino Walenta (Fraunhofer Institute for Telecommunications Heinrich Hertz Institute, Germany); Friederike Fohlmeister (German Aerospace Center, Germany); Jan Krause (Fraunhofer Institute for Telecommunications, Heinrich Hertz Institute, Germany)

Satellite based quantum key distribution (QKD) enables the delivery of keys for quantum secure communications over long distances. Maturity of the technology as well as industrial interest are ever increasing. Same is true for satellite free-space optical communications (FSOC). A satellite QKD system actually comprises a quantum communication subsystem and a classical communication subsystem (public channel). Both are implemented with free-space optics. Thus, in satellite QKD system design, there are strong synergies that should be exploited as much as possible and lead to an all-optical satellite QKD system. In this paper, we present a system like this locating all optical channels in ITU DWDM c-band. We focus on the overall conceptual design and the setup of the optical channel for quantum and classical signal transmission. The system description addresses the breadboards of a transmitter laser terminal (Alice terminal), a receiver laser terminal, (Bob terminal), the public channel implementation, the interfaced QKD system and the deployed crypto system. The design basis for the Alice terminal is the laser terminal development OSIRISv3. The design basis for the Bob terminal is the ground station development THRUST. The later contains an adaptive optics correction to enable single mode fiber coupling. This enables the interfacing to almost arbitrary quantum receivers such as the Bob modules used in the described experiment. The public channel is composed of a bi-directional 1 Gbps IM/DD system and a MODEM that implements a proprietary waveform optimized for free-space channels.

The system was experimentally analyzed in a field test in the framework of the German initiative QuNET which addresses the use case of quantum secure communication for authorities. The results of the experiment are used to model a feasible LEO satellite-ground link. Performance indicators such as quantum bit error rate and secure key rate of a potential mission are estimated analytically."

Large - Scale LEO Satellite Constellation to Ground QKD links: Feasibility Analysis

Argiris Ntanos and Nikolaos Lyras (National Technical University of Athens, Greece); Saif Anwar (University of Warwick, United Kingdom (Great Britain); Obada Alia (University of Bristol, United Kingdom (Great Britain); Dimitris Zavitsanos, Giannis Giannoulis and Athanasios D. Panagopoulos (National Technical University of Athens, Greece); George Kanellos (University of Bristol, United Kingdom (Great Britain); Hercules Avramopoulos (National Technical University of Athens, Greece)

Nowadays, Quantum Key Distribution (QKD) is gaining a lot of interest. Towards global scale quantum secured networks, satellite communications can play vital role to successfully support the terrestrial Quantum Communication Infrastructure (QCI) by delivering quantum keys to optical ground terminals. To this end, several studies regarding the applicability and feasibility of the QKD over satellite optical links and especially LEO satellite to ground links under different atmospheric conditions during nighttime have been published, while already some first experimental demonstrations have been successfully performed. However, in the majority of these studies either a single LEO satellite or a small size LEO satellite constellation is investigated, resulting on a reduced visibility of order of few minutes during each day for a given area.

In this paper, a feasibility analysis of large-scale LEO satellite constellations supporting LEO satellite to ground QKD links is performed. A software tool to simulate the physical properties of a large-scale satellite constellation has been developed. The constellation can be parameterized with the number of orbital planes and the LEO satellites per orbital plane; the orbital inclination and the altitude of satellites. The tool is employed to record the dynamic physical attributes of satellites e.g., their geographical coordinates and velocities and determine the satellites line of sight area at any given time. This information provides feedback to a link budget calculator tailored for LEO satellite to ground QKD links. The developed link budget calculator tool considers the diverse atmospheric phenomena that degrade the performance of the link and emulates QKD physical layer protocols for the estimation of network figures of merit, like availability and secure key rate among others.

Assuming a given Optical Ground Station (OGS) network, the performance of large-scale satellite constellations with different satellite densities and altitudes will be evaluated in terms of availability and secure key rate, during nighttime, under different atmospheric conditions including turbulence effects. For this analysis, the decoy-state BB84 QKD protocol will be employed and two different wavelengths (i.e., 800nm and 1550nm) will be examined. The given OGS network will include 3 observatories (Helmos, Skinakas, Cholomondas) located in Greece. European Space Agency has selected these 3 observatories to be used under the ARTES Scylight/Hydron/SAGA program while will also be utilized as OGS network under the Euro-QCI.

To conclude, in this paper a unified software tool for the performance evaluation of a QKD-downlink LEO large-scale satellite constellation to ground system will be presented. Considering realistic atmospheric conditions and system considerations, feasibility studies of diverse LEO constellations and an OGS network will be presented.

Space Optical Communication Systems I

Analysis of Tracking Gimbal Angles for Inter-Satellite Optical Communication System Between Two Orbits

Ryuichi Hirayama and Shinichi Nakasuka (The University of Tokyo, Japan)

This study focuses on the maximum angular velocity of the tracking gimbal, which can be one of the constraints for inter-satellite optical communication crosslinks between two intersecting orbits in a constellation. This is because there are limits to the tracking gimbal movement and the establishment of laser links. In the previous research, the crosslink angular velocity of the tracking gimbal was calculated in the constellation that was composed of multiple polar orbits. However, this result was not for more general cases.

Under each condition, the operation of the azimuth and elevation angles of the tracking gimbal in the body coordinate system of two satellites passing each other is calculated. Sensitivity analysis of the maximum angular velocity of the tracking gimbal to the relative position of the two satellites is performed for the difference in inclination angle, phase, and altitude of the two orbits. The result shows that how long time the maximum angular velocity rapidly exceeds the tracking accuracy constraint. Depending on the moment of inertia design of the tracking gimbal, the effect of the torque at the maximum angular acceleration on the attitude control of the entire satellite is discussed. The relation of the torque in azimuth and elevation angles for each parameter and the reaction wheel in a satellite is considered. The amount of attenuation in optical communication can be estimated from the tracking accuracy, beamwidth, aberration of light, and relative distance between satellites. These constraints on the satellite's orbit crossing can be taken into account in the optimization conditions for the design and autonomous operation of the optical communication constellation in general cases to avoid the maximum angular velocity exceeding the design constraints.

Pulse positioned differential phase shift keying for high data rate satellite optical communications

Won-Ho Shin, Young-Jin Hyun and Sang-Kook Han (Yonsei University, Korea (South)

We propose a pulse positioned-differential phase shift keying (PP-DPSK) technique that can provide both high data rate and multi-rate for satellite optical communications. Polarization-rotation based DPSK is employed to avoid the use of delay-line interferometers, which is a major impairment for multi-rate DPSK. Furthermore, a novel modulation format suitable for polarization-rotation based DPSK is proposed for higher data rates. The signal is modulated at the pulse position and the phase of optical carrier in this modulation format. Because of the use of average power limited amplifiers such as EDFA in the TX, the proposed technique produces large peak signal power as in PPM. Unlike fiber optical communications, the dominant factor determining the data rate in satellite optical communications is not the bandwidth but the received power. If the received power to satisfy a specific BER is reduced, higher data rates can be achieved when a specific power is received. In other words, the high data rate can be achieved with improved photons-per-bit performance. Therefore, higher data rates can be obtained with large peak signal power. The performance enhancement of the proposed technique was theoretically demonstrated compared to conventional pulse position modulation and differential phase shift keying. In addition, the proof of concept of the proposed technique was experimentally demonstrated. The simulation and experimental results show that a high data rate could be obtained with the proposed technique. Although 2-pulse, 4-pulse and 8-pulse positions are presented in experiments, higher-order extensibility is possible with enhanced average power limited amplifier. Therefore, high data rate and multi-rate differential phase shift keying can be realized using the proposed technique for next-generation satellite optical communication.

4-Level Optical Modulation Formats for LISLs in a Satellite Broadband Constellation Network

Amrita Gill (University of Nottingham Malaysia Campus, Malaysia); Gnanam Gnanagurunathan (The University of Nottingham Malaysia Campus, Malaysia); Nafizah Khan (University of Nottingham Malaysia Campus, Malaysia); Amin MalekMohammadi (California State University, USA)

Summary
Satellite broadband constellation networks such as Starlink and Telesat LEO plan to incorporate laser inter-satellite links (LISLs) in its respective networks. The inclusion of these links would reduce the number of ground stations and better aid the network with providing coverage to the Polar Regions. By managing on-orbit traffic, the LISLs ensures the continuity of the networks' services when faced with high user traffic. These links could then benefit from adopting spectral-efficient modulation formats. Past space programs have demonstrated LISLs using variations of the binary intensity modulation and direct-detection (IM/DD) modulation format [1][2].

Due to its inherently low spectral-efficiency, coherent modulation formats, such as the quadrature phase shift keying (QPSK), were investigated for high-capacity LISLs [3][4]. These modulated links, however, are complex and costly. An alternative to binary IM/DD and coherent modulation formats, multilevel intensity signaling formats such as the 4-pulse amplitude modulation (4-PAM), improves the spectral-efficiency of the former modulation type and reduces the cost and complexity of the latter. Its multilevel nature, however, introduces a power-penalty in its receiver-sensitivity. Using partial response signaling, the absolute added correlative coding (AACC) is a 4-level intensity modulation format that improves power-penalty of the 4-PAM [5].

This paper presents the AACC in a LISL operating in a LEO satellite broadband constellation network. The link is evaluated for its receiver-sensitivity, link-extendibility, power and spectral-efficiency against two other LISLs adopting the 4-PAM and QPSK modulation formats, respectively. Both the AACC and QPSK required a transmitter laser power of 27 dBm to support a bit rate of 20 Gbps over the maximum LEO ISL distance of 6000 km. The 4-PAM needed 32 dBm and all three modelled links shared identical spectral-widths. The AACC modulated LISL further observes an enhancement of ~7 dBm in receiver-sensitivity, in addition to an improvement in terms of power-efficiency and link-extendibility over the 4-PAM modulated LISL.

The Modulated LISLs

Using the parameters under consideration by Telesat LEO for its LISLs [6], the OptiSystem simulation software is used to model the 4-PAM, AACC and QPSK modulated LISLs. Figures 1, 2 and 3 shows the modelled optical transmitters of the links, respectively. The 4-PAM transmitter comprises two NRZ pulse sequences of unequal amplitudes. The two sequences are combined to form a 4-level signal with each level carrying two binary notations of either {00, 01, 11, 10}. The signal then undergoes optical modulation using a Mach-Zehnder Modulator (MZM), forming a single 4-level intensity modulated optical signal.

The AACC transmitter comprises two duobinary (DB) pulse sequences, of unequal amplitudes, combined to form a 4-level signal. The signal undergoes optical modulation to form the 4-intensity level AACC modulated optical signal. The QPSK transmitter comprises several sequence generators to form the in-phase (I) and quadrature (Q) components of the signal. Both components are then used to map 2 bits/symbol onto one of four distinct phases of an optical carrier. Each component is then optically modulated and combined to form the QPSK modulated optical signal.

Figures 4 and 5 shows the modelled direct-detection (DD) and the coherent homodyne detection optical receivers, respectively. The 4-PAM and AACC modulated optical signals are detected using the DD receiver which comprises an optical bandpass filter (OBF), a PIN photodetector, a low pass filter (LPF) and a decoder and data recovery unit. The QPSK modulated optical signal is detected by the coherent homodyne optical receiver which comprises a local oscillator (LO), several PIN photodetectors and a digital signal processing (DSP) unit.

Results

Figures 6, 7 and 8 observes the performance of all three modulated LISLs against varying transmitter laser powers, LEO ISL distances and receiver-sensitivities, respectively. To meet the bit-error rate (BER) requirement of 10-9, which corresponds to a quality (Q)-factor of 6, Figure 6 notes that both the AACC and QPSK modulated links require a transmitter power of 27 dBm to support a bit rate of 20 Gbps over the maximum LEO ISL distance of 6000 km. The 4-PAM needed 32 dBm. At a constant transmitter power of 30 dBm, the 4-PAM link sustains up to a distance of 4000 km whereas both the AACC and QPSK supports the maximum LEO ISL distance. From Figure 8, the AACC further observes an improvement of ~7 dBm over the 4-PAM in receiver sensitivity. The QPSK, however, outperforms the two modulated links due to its coherent nature. Nevertheless, all three modulation formats share a spectral-efficiency of 1 bits/s/Hz as shown in Figure 9.

Conclusion

At a transmitter power of 27 dBm, the modelled AACC modulated LISL supports a bit rate 20 Gbps over the maximum ISL distance of 6000 whilst keeping to a BER of 10-9. Its performance is then compared to the 4-PAM and QPSK and while its performance is similar to the latter, the AACC observes an improved power-efficiency, receiver-sensitivity and link-extendibility over the 4-PAM.

References

[1] T. Tolker-Nielsen and G. Oppenhauser, "In-orbit test result of an Operational Optical Intersatellite Link between ARTEMIS and SPOT-4," in Free-Space Laser Communication Technologies XIV, vol. 4635, Apr. 2002.

[2] T. Jono et al., "OICETS on-orbit laser communication experiments," in Free-Space Laser Communication Technologies XVIII, vol. 6105, Feb. 2006.

[3] B. Patnaik and P. K. Sahu, "Inter-satellite optical wireless communication system design and simulation," IET Communications, vol. 6, Nov. 2012.

[4] J. B. Padhy and B. Patnaik, "100 Gbps multiplexed inter-satellite optical wireless communication system," Optical and Quantum Electronics, vol. 51, Jul. 2019.

[5] N. Dong-Nhat and A. Malekmohammadi, "Absolute added correlative coding: an enhanced M-PAM modulation format," Electronics Letters, vol. 51, Oct. 2015.

[6] E. Neasmith, "Telesat Canada, Petition for Declaratory Ruling Requesting Access to the U.S. Market for Its Non-Geostationary Orbit Constellation," Washington, D.C., 2017."

Multi-layer Constellation based Is-OWC employing NOMA

Wataru Tachikawa, Swarali Ajgaonkar, Kazutoshi Yoshii and Jiang Liu (Waseda University, Japan); Shigeru Shimamoto (Waseda University & Graduate School of Global Information and Telecommunication Studies, Japan)

Satellite communication, especially Low Earth Orbit (LEO) network, is attracting attention because of its global connectivity, the flexibility of network design and availability in the event of a disaster. In addition, Inter-Satellite Optical Wireless Communication (Is-OWC) is regarded as the best choice because of its large throughput, low transmission power and high immunity to interference. In order to increase the availability of Is-OWC, it is required to implement a communication scheme that realizes lower latency and handles more traffic. In this paper, we propose a new Is-OWC system that uses multi-layer satellite constellation and applies uplink Non-Orthogonal Multiple Access (NOMA) to achieve delay suppression and increased throughput. In our proposed scheme, to distribute packets and reduce queue delay in each satellite, each communication path is adapted to the distance between terrestrial transmitter and receiver. If the distance between them is long, LEO and Medium Earth Orbit (MEO) links are selected as the communication path. In contrast, in the short case, only LEO links are selected as the communication path. Furthermore, uplink NOMA is applied to communication from multiple LEO satellites to an MEO satellite to achieve large throughput.

Simulation results validate the performance of our NOMA model is better than that of the conventional OMA model. Furthermore, they show the BER of our model is improved by introducing the original algorithm to optimize the transmission power and the allocated sub-band of each satellite for the NOMA transmission. As a result of comparing the latency between the proposed model using LEO and MEO satellites and the conventional model using only LEO satellites, the proposed model realizes delay suppression and the difference between the two models becomes more significant as the number of sessions in the entire network increases.

(Invited) RF and Optical Hybrid LEO Communication System for Non-Terrestrial Network

Takashi Eishima, Soichiro Inoue, Akihiro Yonemoto and Jumpei Sudo (Axelspace Corporation, Japan); Takayuki Hosonuma and Shinichi Nakasuka (The University of Tokyo, Japan); Atsushi Shirane, Takashi Tomura and Kenichi Okada (Tokyo Institute of Technology, Japan); Kosuke Kiyohara (KIYOHARA OPTICS, Inc., Japan)

Small satellite LEO constellations are expected to play an important role in NTN (Non-Terrestrial Network) which expands communication service areas in three-dimensions (from sea to sky and space) in the age of Beyond 5G / 6G.

To build fast and stable communication infrastructure for NTN over LEO constellations, hybrid operation of RF and optical communications is important. The team of Axelspace Corporation, the University of Tokyo, Tokyo Institute of Technology and Kiyohara Optics has identified the following key technologies to be developed in NICT Beyond 5G R&D promotion project.

- Low-cost and small SWaP (Size, Weight and Power) OCT (optical communication terminal) for inter-satellite and satellite-to-ground communications that can be installed onto micro-satellites.
- Precise laser beam pointing for optical communications by coordinated control between satellite bus and OCTs
- Ka-band transceiver with beam forming capability
- RF/optical hybrid low-latency routing control
- Low-cost mobile optical ground station
- Automated constellation operation for stable and robust communication service

Through this R&D project, we aim to develop RF/optical hybrid communication payload system that can be installed onto 100kg-class micro-satellites."

Space Optical Communication Systems II

Compact radiation resistant, high-gain optical fiber pre-amplifier for small 1.55 um laser-com terminals

Leontios Stampoulidis and Ahmed Osman (LEO Space Photonics, Greece); James Edmunds, Clive Palmer and Keith Simpson (Gooch & Housego, United Kingdom (Great Britain); Anaelle Maho (Thales Alenia Space, Toulouse, France); Michael Sotom (Thales Alenia Space, France)

We present the development of a radiation resistant erbium doped fiber (EDF) pre-amplifier suitable for compact laser communication terminals carried out within the framework of the ORIONAS H2020-SPACE project [1]. The primary application target is 1.55 um optical inter-satellite links and as such the device design was driven by size, weight and power (SWaP) reduction. The device weighs approximately 100 grams, has a footprint of 45 cm2 and delivers up to 57 dB of optical gain at 1550 nm. The module features RS-232 controllability through an embedded micro-controller, includes optical power and pump laser diode bias monitors and can be switched between constant current and constant power modes. It can operate at hot temperatures of 60oC and it has a typical electrical power consumption of < 4 W. The device compactness is assisted by the use of a reduced clad (RC) EDF that has been selected following gamma radiation testing of COTS RC-EDFs. By selecting a radiation resistant RC-EDF and optimizing the optical circuit topology, we demonstrate a radiation induced gain drop (RIGD) of 2 dB and 6.5 dB at 40 krad and 100 krad respectively. Finally, we report the functional testing of a bread-board model of the pre-amplifier in optical transmission experiments with 25 Gb/s OOK and DPSK signals. Results show that the high optical gain and low noise figure of the pre-amplifier enable to achieve a receiver sensitivity as low as -42.5 dBm at 10-3 BER for 25 Gb/s DPSK modulation which corresponds to 17 photons per bit.

Robust atmospheric FSO communication receiver based on the coherent combination of spatial modes: an experimental evaluation

Anaelle Maho (Thales Alenia Space, Toulouse, France); Vincent Billault (Thales Research & Technology, France); Jerome Bourderionnet (Theales Research and Technology, France); Luc Levandier, Patrick Feneyrou and Arnaud Brignon (Thales Research & Technology, France); Michael Sotom (Thales Alenia Space, France)

Free-space optical (FSO) communications are an enabling technology to meet the increasing demand of capacity in satellite applications, whether for broadband telecommunications or Earth observation. Nevertheless, turbulence can seriously impair communication through the atmosphere by altering the spatial coherence of the laser beam and ultimately degrading coupling into the input single mode fiber (SMF) of high-sensitivity optical receivers. Efficient mitigation of turbulence effects is thus a prerequisite to the deployment of FSO communications through the atmosphere. Approaches to increase the collection area and efficiency of the ground terminal include adaptive optics assemblies compensating the wavefront distortions with fast deformable micromirror array . However, the complexity of the control algorithm limits in practice the compensation loop speed. Another technique based on spatial mode diversity and digital recombining [1, 2] has been demonstrated with convincing improvements [3-5] but this solution becomes complex as the number of modes increases.

In this paper, we report on the experimental assessment of an all-optical FSO communication receiver device based on a spatial mode demultiplexer and a photonic integrated coherent combiner [6]. This device collects light from a large number of high-order spatial modes and coherently recombines these modes into an output single-mode fiber via a binary-tree integrated photonic circuit. It was evaluated in high-speed FSO transmission laboratory experiments, which included an atmospheric propagation channel emulator using two spatial light modulators to produce representative phase and amplitude distortions.

The bit error rate (BER) performance of a pre-amplified, OOK direct-detection receiver were measured at 10 Gbps, under various disturbance conditions and strengths. Efficient coupling at the proposed device output into the SMF input of the OOK receiver was shown to be maintained resulting in almost constant BER. Limited detection sensitivity penalties and acceptable BER floors were observed. The device efficiency was also shown to increase with the number of spatial modes handled. Not only was the feasibility of the proposed FSO receiver proven, but also its ability to provide higher collection efficiency and greater robustness to phase and intensity disturbances than standard SMF receivers.

Low power-consumption coherent receiver architecture for satellite optical links

Alexis W Bernini and Martyn Fice (University College London, United Kingdom (Great Britain); Katarzyna Balakier (University College London (UCL) & Airbus Defence & Space, United Kingdom (Great Britain)

As the demand for satellite data transmission increases, higher capacity optical links need to be developed to allow satellites to be connected directly to ground stations (GST). The advantages of Low Earth Orbit (LEO) direct-to-Earth links are smaller latency when compared to relay systems using Geostationary Orbit (GEO) satellites, i.e. LEO-to-GEO and GEO-to-GST, and an increased available bandwidth offered by the optical spectrum with respect to radiofrequency (RF) which allows for much higher link capacity. However, the increase in data rate of optical satellite to ground links towards 100 Gbps will require implementing optical coherent transceivers with capability to compensate for Doppler shift and atmospheric channel impairments. An important figure of merit which needs to be carefully considered in a satellite system is the equipment power consumption. The power consumption of coherent receivers used for terrestrial applications is closely related to the bit rate, with a receiver back-end digital signal processing being responsible for the vast majority of the power consumed [1]. The power levels of coherent receivers are in the range of 420mW/Gbps for a homodyne receiver chipset [2]; such power consumption will create a challenge, particularly for smaller satellite platforms.

In this paper we propose a hybrid approach to signal processing consisting of simplified digital and analogue elements [3] allowing for significant power reduction, already at baud rates around 10 Gbaud. Moreover, one of the attractive aspects of the proposed approach is that it does not require an increased complexity for an increase in baud rate as long as a reference tone is detectable by the locking mechanism. An overview of the major power consuming elements in an optical coherent receiver will be given; this will then be compared against the proposed analogue equivalent. Analogue systems, such as a Costas Loop, or Optical Injected Phase Lock Loop (OIPLL), have been reported to consume around 1W and 3W [4] depending on the design. It will be discussed that the analogue approach to the frequency and phase recovery would allow to save approximately 40% to 50% of power on the overall DSP block at baud rates between 10GBaud and 100Gbaud.

PhLEXSAT - A Very High Throughput Photo-Digital Communication Satellite Payload

Madhubrata Chatterjee (MDA, United Kingdom (Great Britain); Chiara Palla and Edem Fiamanya (MDA Space and Robotics, United Kingdom (Great Britain); Marta Beltran (DAS Photonics S. L., Spain); Miguel Àngel Piqueras (Das Photonics S. L, Spain); Antoni Castells Cervello and Laurent Roux (Eutelsat, France); Patrick Runge (Fraunhofer Heinrich-Hertz-Institut, Germany); Nigel Cameron (Axenic, United Kingdom (Great Britain); Jakub Zverina (Argotech, Czech Republic)

Photonic components offer the advantage of minimizing the size, weight and power consumption (SWaP) of a satellite communication payload. This benefit can be leveraged to increase the capacity of Very High Throughput Satellites (VHTS) while reducing the in-orbit cost.

Photonics is capable of offering limitless bandwidth in the THz range at the band around 1550 nm while offering high data rates and frequencies with almost lossless propagation in an optical fibre. However, at present only a few demonstrations of photonic devices in non-critical equipment with a limited degree of integration can be found in the satcom industry as well as in literature. With the advancement of the photonic technology, it is now possible to develop Tbps range software defined photonic payloads.

This paper presents a space-based photo-digital communication payload called PhLEXSAT. PhLEXSAT is a THz range communication system that will use novel optical devices for space-based systems which are currently under design and in the development stage.

The architecture presented incorporates advanced broadband photonic ADC and photonic DAC with digital processing firmware along with a high degree of miniaturization and power-consumption efficiency. This system design is suitable for future Terabit per second communication satellites. The two main components of the photonic sampler architecture presented are the Mach-Zehnder interferometer (MZI) modulators PIC and high-linear photodetector (HL-PD) PIC. The frequency clock used for the photonic sampler is a space-grade pulsed laser. The target maturity level of these key photonic components which are under development, as well as the photo-digital payload is up to TRL5.

PhLEXSAT project, funded under the European Union H2020, is led by DAS Photonics in co-operation with MDA UK, Eutelsat, Axenic, HHI Fraunhofer and Argotech.

WITHDRAWN Focal Plane Assembly demonstrator for two-way Laser communication link

Jean-Baptiste Haumonte and Nathalie Gimbert (Bertin Technologies, France)

In the framework of the TELEO project, BERTIN has manufactured a focal plane assembly (FPA) to be used for the laser communications instrument of the TELEO demonstrator, precursor for future feeder laser links applications.

The FPA demonstrator model (DM) has an optical, mechanical and thermal design largely derived from a Bread-Board (BB) already developed in the previous project (FOLC2).

This demonstrator is intended to be mounted on a telecommunications satellite scheduled for launch in early 2023 and it should have a minimum lifetime of 2 years on a GEO spacecraft, in addition to a several month-orbit rising.

Its objective is to establish and maintain a two-way laser communication link with an optical ground station (OGS), for a full-scale proof of concept.

The function of the Focal plane Assembly is to route in free space the laser beam issued from Booster Amplifier of the terminal to the telescope assembly (via the Fine Pointing Mechanism) and the laser beam collected by the telescope assembly to the Rx part of the terminal (via the Fiber Injection Mechanism) and to the Acquisition and Tracking Sensor.

The Focal Plane Assembly allows bi-directional management of laser beams (Tx and Rx channels) that are split in polarization, separated in wavelength and in space.The wavelengths are in the C-band (1530 / 1565 nm).

3 Channels with 200 GHz (or 1.6 nm)-spacing WDM are transmitted, and 4 channels with 200 GHz (or 1.6 nm)-spacing WDM are received. The booster output optical power baseline is 5 W and the focal plane has been designed and manufactured according to this baseline.

Main challenges are the following:

- Compactness, obliging to look for solutions of mass lightening (by integration of functions within the same component for example),
- In a long-term perspective of lowering production costs (exploration of manufacturing processes by additive technologies),
- While guaranteeing the dimensioning performance of this device achieving the functionalities of multiplexing / demultiplexing space (between a high power transmission channel and a reception channel to detect low power signals; the transmitted and received signals are conveyed by single-mode optical fibers, integral parts of the focal plane) and ground and flight calibration based on spectral filtering: thermomechanical stability and high rejection rate (from transmission to reception).

In addition, a new program is starting in Q4 2021 with the CNES in order to design and prototype an upgraded version able to manage power of 50W. The goal is to be able to operate industrial optical GEO communications in 2025 with commercial products

This presentation will present the technical concept and first results obtained during the project.

Capacity Analysis of a MIMO Laser Link from Lunar Surface to Earth

Hung Le Son and Robert T. Schwarz (Bundeswehr University Munich, Germany); Marcus Knopp (DLR, Germany); Dirk Giggenbach (German Aerospace Center, Germany); Andreas Knopp (Bundeswehr University Munich, Germany)

Moon explorations are expected to develop over the next decades. National space agencies around the world are considering the Moon as a Gateway for space missions in general, and in a first attempt towards the goal of an astronautical mission to Mars. Moreover, the Moon's natural resources might enable lunar habitation and could be exploited in the future. Realizing these ambitions necessitates a stable broadband communications link for data transmission between Moon and Earth. Free-space optical (FSO) laser communications is a promising candidate solution as FSO links promise much higher data rates than can be achieved with conventional radio frequency (RF) systems. However, a huge amount of data is expected in the future that must be transferred between the Gateway on the Moon and Earth.

The multiple-input multiple-output (MIMO) technology is a well-known approach in terrestrial communication systems that linearly increases the data rate with the number of transmitting and receiving elements. We propose the application of MIMO to FSO laser communication to further increase the capacity of Moon-Earth connections. In order to take full advantage of the MIMO capacity gain, the transmitting and receiving elements must be properly arranged. In fact, the MIMO capacity of FSO links depends on the geometrical arrangement of the lasers and optical receivers. Assuming uniform linear arrays (ULAs) on both link ends, a minimum spacing between the elements is necessary for maximum MIMO capacity gains. Since the Moon is orbiting around the Earth, the transmitter-receiver geometry is constantly changing with time. A variation of this geometrical arrangement results in an accordingly varying capacity and, thus, data rate. The MIMO capacity degrades, and the maximum data rate cannot be durably obtained.

In this paper, we analyze these capacity variations in relation to the Moon orbit. We propose an adaptive array geometry on Earth to control the array orientation of the receiving telescopes. In particular, we show that the rotation of the ULA on Earth according to the passage of the Moon maintains the capacity gain over time. We analytically derive the optimal orientation of the ULA on Earth as a function of time, i.e. the motion of the Moon. Simulation results show that - applying this analytical approach - the maximum MIMO channel capacity can be constantly obtained.

An investigation into the technical and system operational impacts of applying FSO point to multipoint communications technology

Barry A Matsumori and Paul Searcy (BridgeComm, Inc., USA)

The capability of FSO point to multipoint communications using BridgeComm's Managed Optical Communications Array (MOCA) technology has been presented including a general architecture of the terminal. What is worthy of further investigation are the technical and system operational impacts of a MOCA technology based design for a specific application, namely for Low Earth Orbit (LEO) satellite constellations. Some of the benefits of MOCA technology have been cited including providing size, weight, operational volume and power advantages relative to a mechanical gimbal for beam steering. However, there are capabilities extend beyond these parameters. This presentation will investigate the affect of MOCA technology on network management, network routing, and other aspects of the network as well as the satellite itself.

Telesat LightspeedTM - Enabling Mesh Network Solutions for Managed Data Service Flexibility Across the Globe

Gerry Jansson (Telesat, USA)

Rapid advances in global broadband requirements are driving advanced commercial Low Earth Orbit (LEO) satellite communications systems that can deliver global broadband capacity at terrestrial level costs and performance. Flight demonstration programs such as the Defense Advanced Research Projects Agency (DARPA) "Blackjack" program are exploring the utility of Optical Inter-Satellite Links (OISLs) for these new LEO systems. For global communications, LEO systems, such as that being developed by Telesat, provide unprecedented broadband capabilities. In addition, Telesat's new LEO system, LightspeedTM represents very low latency communications, fiber-like mesh connectivity via OISLs increasing the capabilities for data dissemination and delivery across the globe. The ability for a User Terminal (UT) to reach back without the need for anchor relay stations through multiple OISL hops between communication satellites, provides secure and resilient connectivity. Unilateral global (including the polar) connectivity, at fiber like speeds, provides a dramatic change to high capacity data distribution and dissemination while delivering robust reliable and trusted information. The purpose of this paper is to provide an architectural overview of the Lightspeed mesh network interfaces as spacecraft-to-spacecraft (via OISL) relay data between spacecraft, ground stations, satellite operations center, and network operations center concepts. The mesh connectivity created by Telesat's Lightspeed network enables managed data service flexibility and should be considered as an important step in interleaving optical communication space systems within the Lightspeed commercial constellation. Additionally, Lightspeed introduces an incremental constellation construct of polar and inclined shells that can integrate and manage various capabilities to deliver key network metrics, prioritizations, performance, at Gbps data rates. We identify and address challenges associated with operating OISLs within Lightspeed's mesh network, to include acquisition, tracking, tasking, efficient data routing, and managing network data. Lastly, we present enabling standards and technologies that enhance network flexibility, inter-operability and identify areas of future capability development.

Multi-aperture Transmission and DSP Techniques for Beyond-10 Tb/s FSO Networks

Keisuke Matsuda, Hayato Sano, Yukari Takada, Masashi Binkai, Shota Koshikawa, Yuta Yokomura, Tsuyoshi Yoshida, Yoshiaki Konishi and Naoki Suzuki (Mitsubishi Electric Corporation, Japan)

"For beyond fifth-generation (B5G) mobile services, high-capacity free-space optical communications (FSO) is expected to be utilized for expanding the service area beyond terrestrial. For fiber communications, digital signal processing (DSP) large scale integrated circuits (LSIs) having high speed digital-to-analog and analog-to-digital converters, and supporting advanced coding, modulation and equalization, have been developed, while expanding the bandwidth of the optical devices is ongoing. With these DSP-LSIs and very high bandwidth optical devices, the transceivers can support signals at beyond 60 Gbaud and capacities beyond 400 Gb/s [1 - 3], whence the capacity of a single wavelength channel and the capacity of a single fiber have been increasing while the power consumption is reduced. By adopting these technologies along with multi-aperture transmission [4, 5], which reduces the per-aperture transmit power, we demonstrated a high capacity 14 Tb/s FSO system while keeping the transmitter output within the Class 1 eye-safe criteria [6]. In the forthcoming B5G era, greater capacity extension with even higher baud rates and higher order quadrature amplitude modulation (QAM) is expected to be achieved [7]. High-bandwidth transceivers will enable more efficient optical networks, since a single transceiver will be able to accommodate the signals of multiple users.

In this paper, a real-time demonstration of 14 Tb/s high transmission capacity in 220 m outdoor FSO experiments with a 9-aperture transmit and single-aperture receive FSO system transmitting 35 wavelength division multiplexed 400 Gb/s dual polarization probabilistically shaped 16QAM signals is presented. In addition, we propose a virtual optical channel DSP which enables one transceiver to support multiple users. We implemented the virtual optical channel DSP on a field programmable gate array and evaluated its performance. The virtual optical channel DSP is beneficial for constructing efficient networks based on FSO.

[1] OIF implementation agreement, "Implementation Agreement 400ZR," OIF-400ZR-01.0, Mar. 2020.

[2] Open ROADM white paper "Open ROADM MSA Device White Paper," release 7 v1.2, Nov. 2020.

[3] M. Binkai, S. Chikamori, T. Yoshida, K. Matsuda, K. Ishii, Y. Konishi, S. Hirano, N. Suzuki, "Demonstration of shallow probabilistic shaping for low-power transmissions at 400 Gb/s and beyond", IEICE Communications Express, vol. 10, no.3, pp. 117-123, Mar. 2021.

[4] F. Silvestri, F. Pettazzi, M. Eschen, J. J. Boschma, J. B. Lutgerink, G. F. I. J. Kramer, W. C. Korevaar, R. den Breeje, C. M. Duque, and N. J. Doelman, "Beam multiplexing for satellite communication optical feeder links," in Proc. SPIE 11272, Free-Space Laser Communications XXXII, San Francisco, CA, USA, Mar. 2020, Paper 1127213.

[5] K. Matsuda, S. Koshikawa, T. Suzuki, S. Chikamori, H. Goto, M. Binkai, T. Yamauchi, J. Nishioka, T. Akamatsu, T. Yoshida, and N. Suzuki, "Parallel optical amplification and multi-aperture transmission with digital coherent reception for wavelength division multiplexed high capacity FSO and its real-time evaluation," in Proc. SPIE 11678, Free-Space Laser Communications XXXIII, San Francisco, CA, USA, Mar. 2021, Paper 116780N.

[6] K. Matsuda, M. Binkai, S. Koshikawa, T. Yoshida, H. Sano, Y. Konishi, and N. Suzuki, "Field demonstration of real-time 14 Tb/s 220 m FSO transmission with Class 1 Eye-safe 9-aperture transmitter," in Proc. Opt. Fib. Commun. Conf. (OFC), Jun. 2021, Paper F3C.2.

[7] https://acacia-inc.com/blog/acacia-unveils-industrys-first-single-carrier-1-2t-multi-haul-pluggable-module/"

Link Budget Design of Adaptive Optical Satellite Network for Integrated Non-Terrestrial Network

Hideaki Kotake (National Institute of Information and Communications Technology & The University of Electro-Communications, Japan); Yuma Abe and Mariko Sekiguchi (National Institute of Information and Communications Technology, Japan); Tetsuharu Fuse (National Institute of Information and Communications Technology & University of Electro-Communications, Japan); Hiroyuki Tsuji and Morio Toyoshima (National Institute of Information and Communications Technology, Japan)

"In our previous work, the Adaptive Optical Satellite Networks (AOSN) has been proposed to support the operational management for the Non-Terrestrial Network (NTN). The AOSN is a concept of optical satellite network which enables the automatic operations. System architecture of the AOSN using the totally integrated management function has also been proposed to handle various terrestrial communication services for the Beyond5G/6G networks.

In this paper, we describe the link budget design of the AOSN for the integrated NTN. Our target optical links include the inter-satellite links and the ground-to-satellite links using relay Geostationary Earth Orbit (GEO) satellites, relay Low Earth Orbit (LEO) satellites and relay High Altitude Platform Stations (HAPSs). We also utilize the experimental results of the receiver sensitivity using the terrestrial optical and RF devices, considering that Commercial-Off-The-Shelf (COTS) devices will be generally utilized in the future integrated NTN. Furthermore, we will also investigate the link budget design considering various use cases such as communication services. In our analysis, optical transmitters and receivers employ Wavelength Division Multiplexing (WDM) technology, various multi-level modulation methods, variable symbol rates (the maximum is 10 Gbaud) and digital coherent detection.

icsos2022.ieee-icsos.org

Platinum Patron

National Institute of Information and Communications Technology

Technical Program Supporter

European Space Agency