ESTOL: a European Specification to Ensure Interoperable Optical Links

Daniel Arapoglou,
Telecom System Section
ESA/ESTEC

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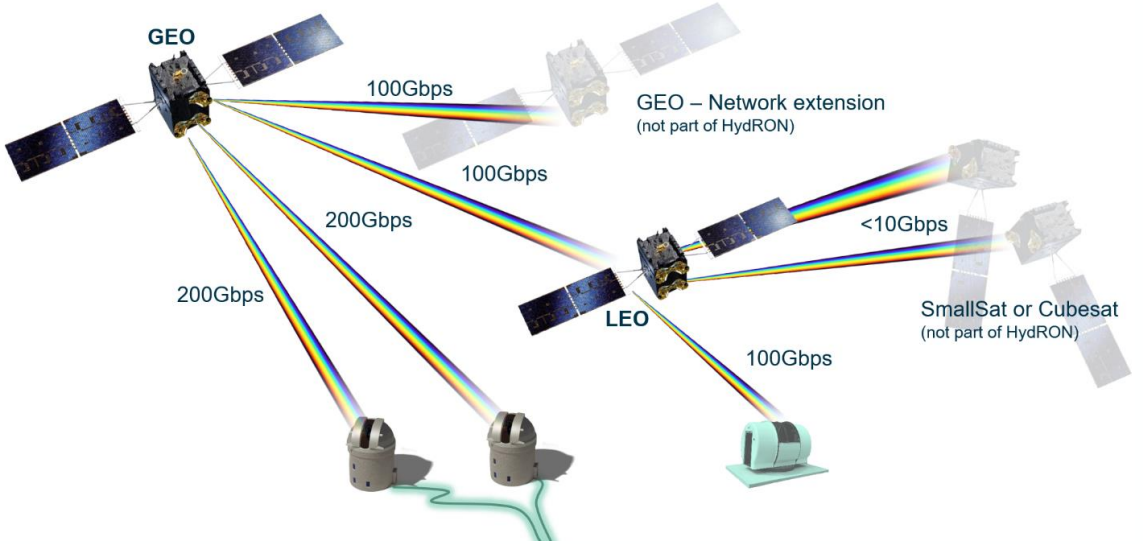
Goal and context

ESTOL: ESA's Specification for Terabit/s Optical Links

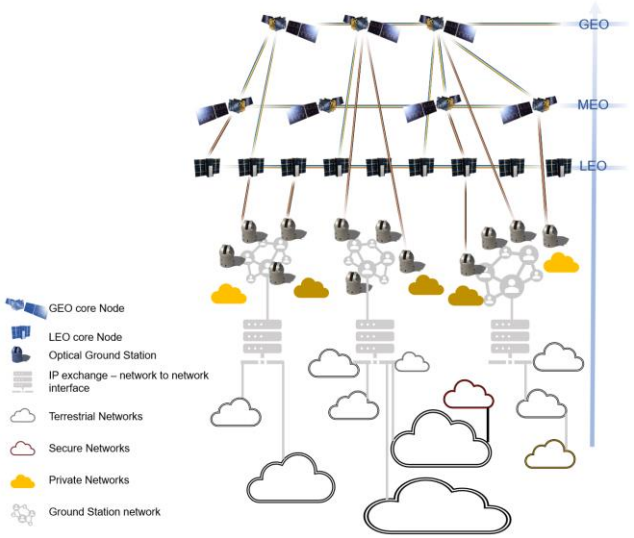
https://connectivity.esa.int/sites/default/files/2024-09/ESTOL_air_interface_v2.2.pdf



GOAL: Interoperability The goal of this specification is to foster the development of interoperable commercial products for space-space and space-ground high data-rate optical links.

Ambition is that any European telecom & EO system employing optical links to implement ESTOL!!!

- Possible candidates are HydRON, IRIS2, Copernicus NG etc.



Status

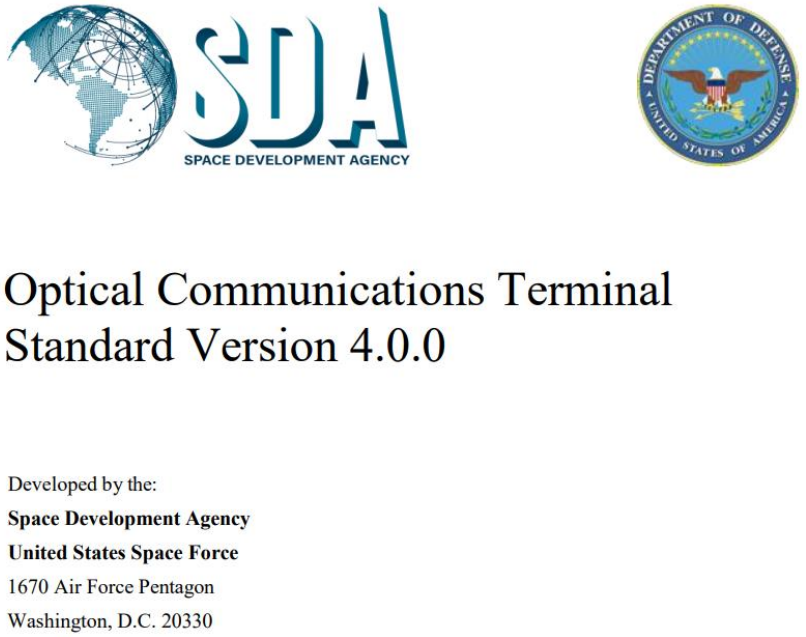
Version*	Reason for change	Date
0.1	New document for discussion (internal)	05/07/2023
1.0	New document on optical intersatellite links	19/07/2023
1.1	PAT update (internal)	31/07/2023
2.0	Satellite-to-ground links included (internal)	17/01/2024
2.1	Wavelength plan and sensitivity values update (internal)	22/03/2024
2.2	PAT and sensitivity values update	01/07/2024

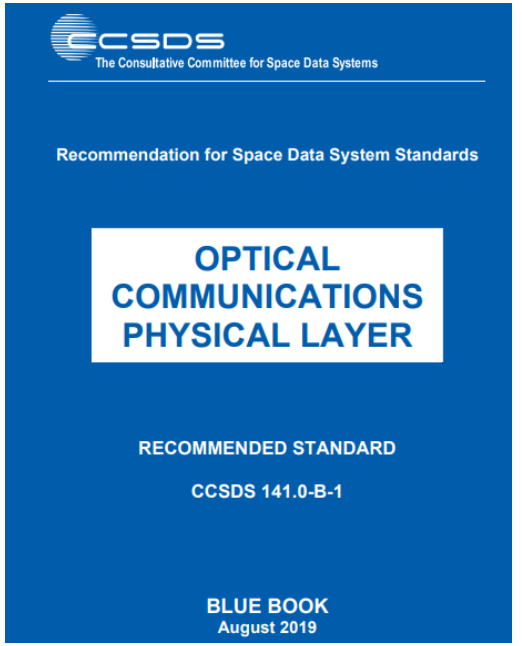
- Included: Optical Inter-Satellite Links (OISLs)
- Planned: Optical Ground-Space Links (OGSLs)

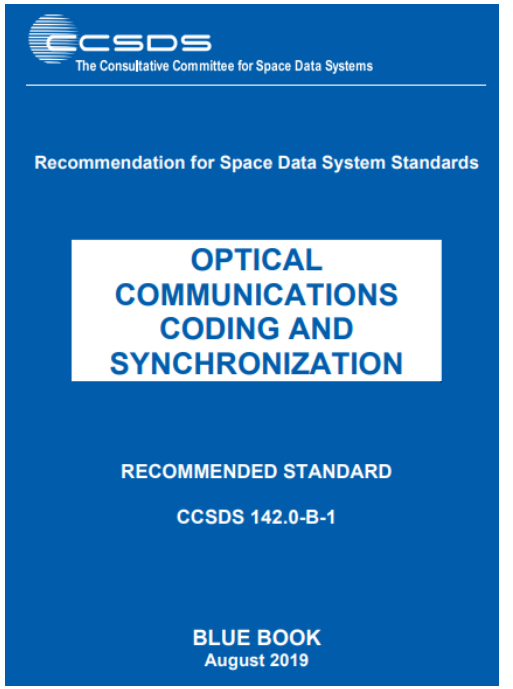
Contributors

- **ESTOL** is a specification document prepared by ESA in joint co-operation with multiple industrial contributors and researchers.
- **MS industries:** ADTRAN (Germany), Aerospacelab (Belgium), Airbus Defence & Space (Germany), Airbus Defence & Space (France), Airbus Defence & Space (Netherlands), Archangel Lightworks (United Kingdom), Celestia (Netherlands), Deutches zentrum für Luft und Raumfahrt (Germany), E-S-TEL (Belgium), Fraunhofer Henrich Hertz Institute (Germany), General Atomics Synopta GmbH (Switzerland), Gooch & Housego (United Kingdom), GMV GmbH (Germany), Honeywell (Canada), Joanneum Research (Austria), mBryonics (Ireland), MPB Communications (Canada), Mynaric (Germany), Officina Stellare (Italy), Rivada Space Networks (Germany), Safran Data Systems (France), Scuola Superiore Sant'Anna (Italy), Spire (United Kingdom), Stellar Project (Italy), Tesat Spacecom (Germany), Thales Alenia Space (Italy), Thales Alenia Space (Switzerland), TNO (Netherlands), Viasat Italy (Italy), WORK Microwave (Germany).
- **International contributors & observers:** JAXA Japanese Aerospace Agency (contributor), Axelspace (observer), Mitsubishi Electric (contributor), NEC (observer), SpaceCompass (contributor).

Optical Standardization Landscape





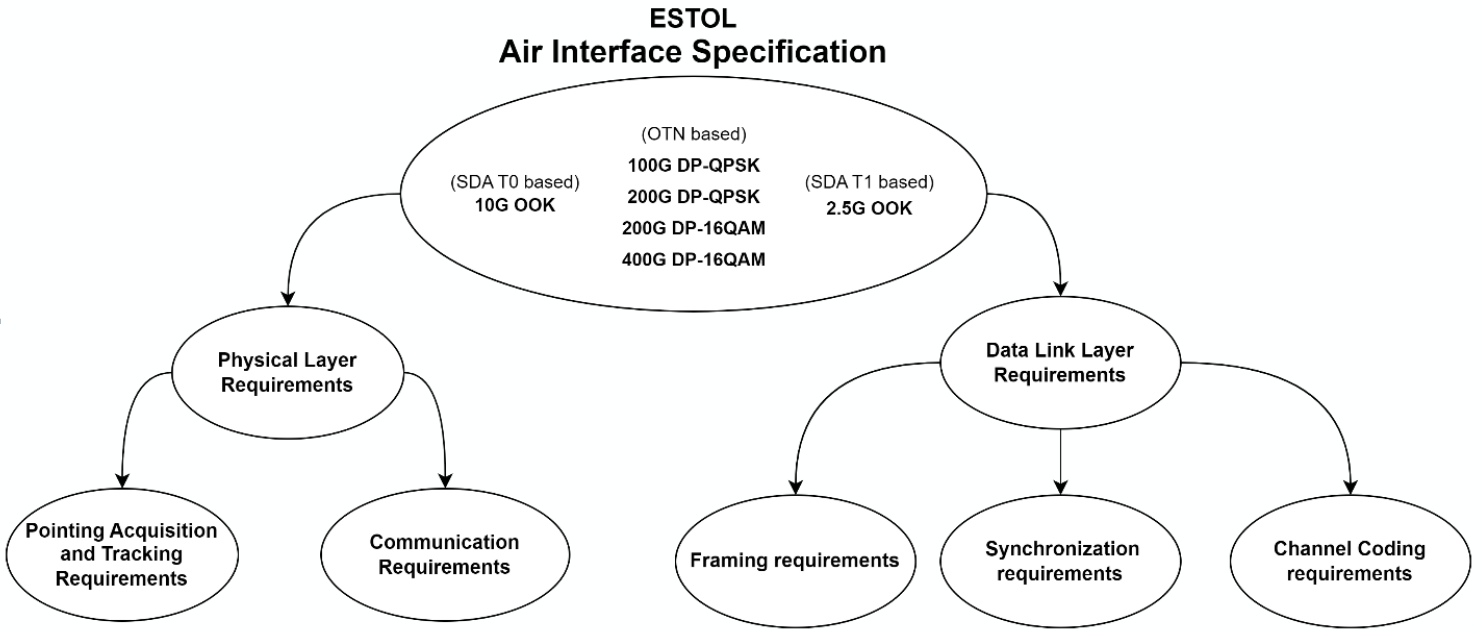


- Applications: Proliferated Warfighter Space Architecture, SDA Transport Layer.
- LEO-LEO, ‘Low’ Data rate.
- Interoperability of OCT manufacturers.

- Applications: Deep space, EO high rate telemetry.
- Space-ground only, typically photon starved.
- Interoperability & cross-support of space agencies.

ESTOL issue 2.2 contents

- Specification for optical inter-satellite and satellite-to ground bidirectional links.
- **Physical layer**
  - The PAT
  - The use of multiple wavelengths (WDM)
  - The transmitted signal properties.
- **Data link layer**
  - Data rates
  - Framing
  - Channel coding FEC



Air interfaces & Motivation

- **3 main air interfaces**
  - 2.5 Gbps OOK
  - 10 Gbps OOK
  - 100+ (100/200/400) Gbps dual pol coherent
- **Motivation**
  - 2.5G: Re-use of popular SDA Tranche1 technology (European suppliers).
  - 100G+: Re-use fiber based COTS transceivers (CFP2 DCO) based on OpenROADM.
  - 10G: Bridge between ‘low’ 2.5G and ‘high’ 100G data rates. Re-use of available products from European suppliers.

Requirement	Air interface
REQ-DLL-010	100G DP-QPSK
REQ-DLL-020	200G DP-16QAM
REQ-DLL-030	200G DP-QPSK
REQ-DLL-040	400G DP-16QAM
REQ-DLL-050	2.5G IM/DD OOK
REQ-DLL-060	10G IM/DD OOK

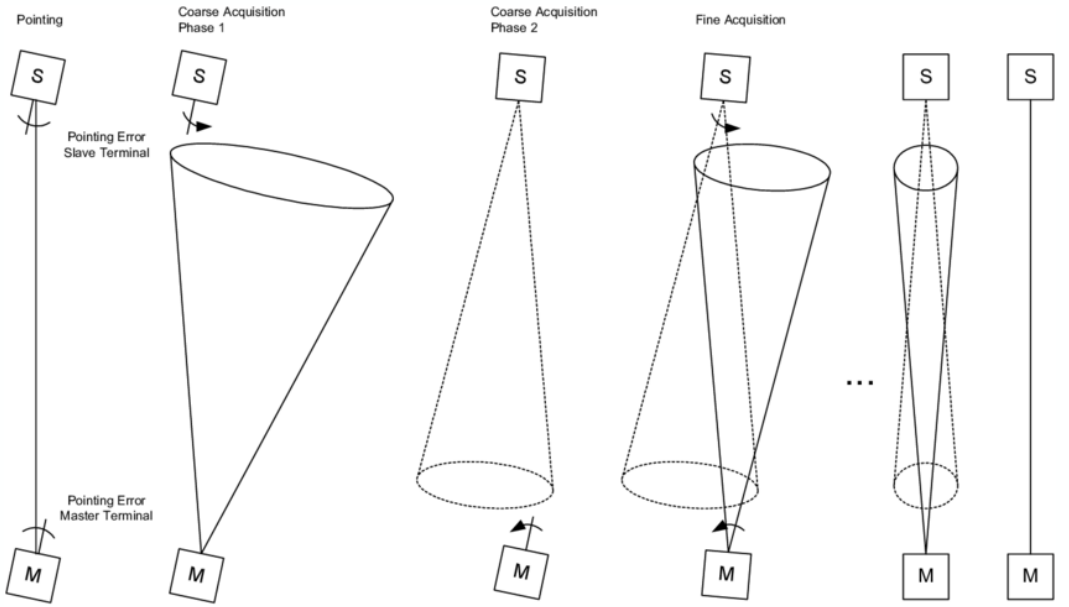
PAT: Pointing, Acquisition & Tracking

- PAT as defined in CCSDS Orange book 141.11-O1 [RD-6] and demonstrated for inter-satellite links and satellite-to-ground links by TerraSar-X, NFIRE, Alphasat and EDRS.
- Same PAT has been described in SDA standard "Optical Communications Terminal (OCT)“.

REQ-PHY-030 The PAT acquisition time (defined as warm start in 2.1.6 of [RD-2]) shall be below 60 s, within the uncertainty cone.

REQ-PHY-040 The PAT acquisition time (defined as warm start in 2.1.6 of [RD-2]) should be below 30 s, within the uncertainty cone.

REQ-PHY-050 The PAT re-acquisition time shall be below 10s.
Note: the re-acquisition time is defined as the time from fine acquisition to tracking.



Wavelength Plan & WDM

Frequency	195,10	195,00	194,90	194,80	194,70	194,60	194,50	194,40	194,30	194,20	194,10	194,00	193,90	193,80	193,70	193,60	193,50	193,40	193,30	193,20	193,10	193,00	192,90	192,80	192,70	192,60	192,50	192,40	192,30	192,20	192,10	192,00	191,90	191,80	191,70	191,60	191,50	191,40	191,30	191,20	191,10	191,00
ITU channel #	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	-1	-2	-3	-4	-5	-6	-7	-8	-9	-10	-11	-12	-13	-14	-15	-16	-17	-18	-19	-20	-21
Wavelength	1536,61	1537,40	1538,19	1538,98	1539,77	1540,56	1541,35	1542,14	1542,94	1543,73	1544,53	1545,32	1546,12	1546,92	1547,72	1548,51	1549,32	1550,12	1550,92	1551,72	1552,52	1553,33	1554,13	1554,94	1555,75	1556,55	1557,36	1558,17	1558,98	1559,79	1560,61	1561,42	1562,23	1563,05	1563,86	1564,68	1565,50	1566,31	1567,13	1567,95	1568,77	1569,59
ESTOL #	U1	U2	U3	U4	U5	U6	U7	U8	U9	U10	U11	U12	U13	U14	U15	U16	U17	U18	U19	U20	U21	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13	L14	L15	L16	L17	L18	L19	L20	L21

Figure 4. ESTOL Wavelength plan

REQ-PHY-190 Channels U1 and L1 (highlighted in Table 1 and Figure 4) shall be reserved for OOK IM/DD.

Note: 2.5Gbps and 10Gbps OOK shall be allocated starting in U1/L1.

REQ-PHY-200 Coherent modulation data channels shall be allocated into the channels U2-21 and L2-L21 starting in U2/L2.

Note: 100Gbps-400Gbps shall be allocated starting in U2/L2.

REQ-PHY-210 Multiple WDM channels shall be allocated in consecutive increasing ESTOL channel numbers.

Note: as matter of example:

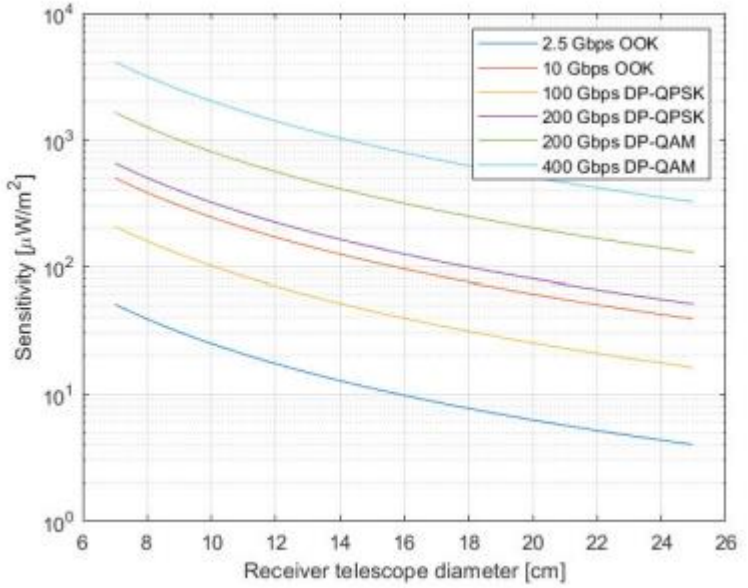
- *4 WDM channels at 100Gbps DP-QPSK will be allocated in channels U2, U3, U4, U5 and channels L2, L3, L4, L5*

REQ-PHY-230: The isolation between Rx and Tx shall be based on spectral separation and split the band into an upper and lower frequency region as seen in Table 1.

Note: the isolation band between both beam directions will limit the maximum number of possible WDM channels that can be implemented. Typically, the isolation band is ~10 nm wide.

Signal power & Link Budget

- PRx is the total power collected at the input of the optical system.
- PRx values include a system margin of 3 dB.
- PRx includes the required signal level for both communications and acquisition and tracking system.



		Space terminal	Ground terminal
	Modulation	P_{RX}	P_{RX}
REQ-PHY-300	DP-QPSK 100 Gbps	-31.7 dBm	-23.7 dBm
REQ-PHY-310	DP-QPSK 200 Gbps	-26.7 dBm	-18.7 dBm
REQ-PHY-320	DP-16QAM 200 Gbps	-23.2 dBm	-15.2 dBm
REQ-PHY-330	DP-16QAM 400 Gbps	-19.7 dBm	-11.7 dBm
REQ-PHY-340	IM/DD-OOK 2.5 Gbps	-37.1 dBm	-29.1 dBm
REQ-PHY-350	IM/DD-OOK 10 Gbps	-27.2 dBm	-19.2 dBm

Requirement	Modulation	Optical S/(N+I)
REQ-PHY-360	DP-QPSK 100 Gbps	20 dB
REQ-PHY-370	DP-QPSK 200 Gbps	25 dB
REQ-PHY-380	DP-16QAM 200 Gbps	28.5 dB
REQ-PHY-390	DP-16QAM 400 Gbps	32 dB
REQ-PHY-400	IM/DD-OOK 2.5G	12 dB
REQ-PHY-410	IM/DD-OOK 10G	15 dB

Framing

- As per SDA, the 2.5G and 10G support both DATA and MGMT type of frames.
- The FlexO (100G) frame structure is defined in G.709.1
- For the 100G, control and management traffic should be multiplexed in the data-plane as packets.

2.5G

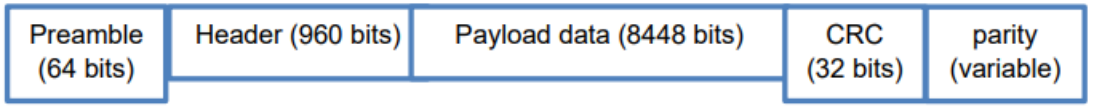


Figure 7. 2.5G OOK frame structure.

10G

Figure 8. 10G OOK frame structure.

100G

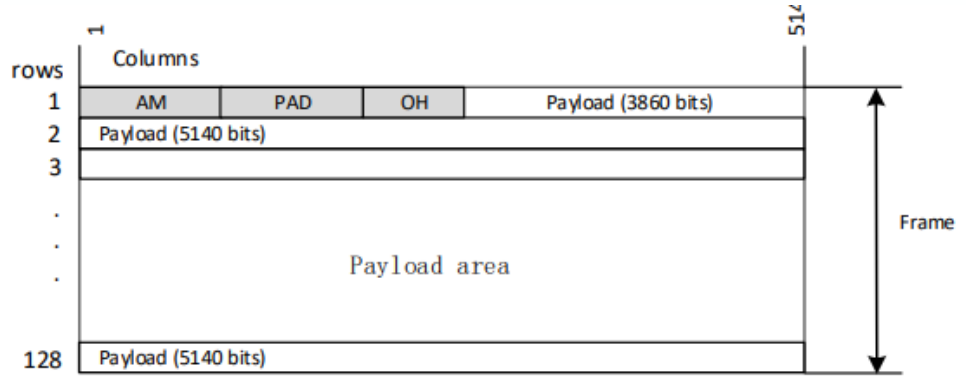


Figure 6. FlexO frame structure.

FEC Coding

2.5G

- Based on 5G NR
- QC-LDPC
- Supports several code rates 1 (no FEC), 0.8462, 0.7586, 0.6667, 0.5000.

10G

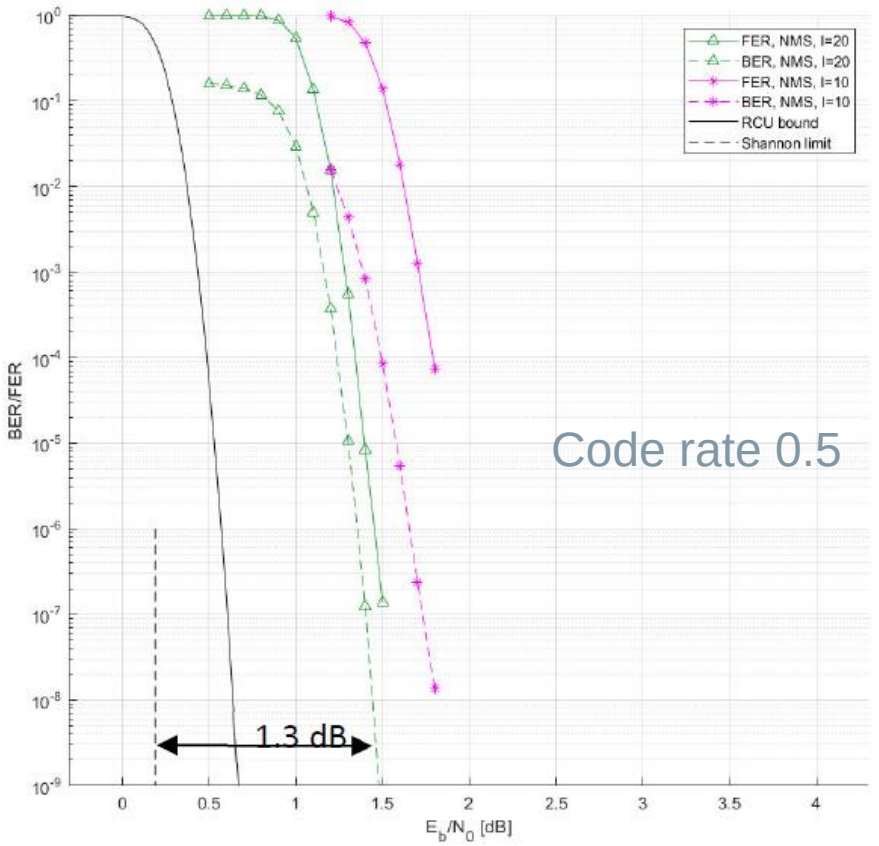
- Based on CCSDS telemetry standard and also SDA Tranche 0.
- RS (255, 239) along with LPC (24,16).
- With a view on ease of implementation

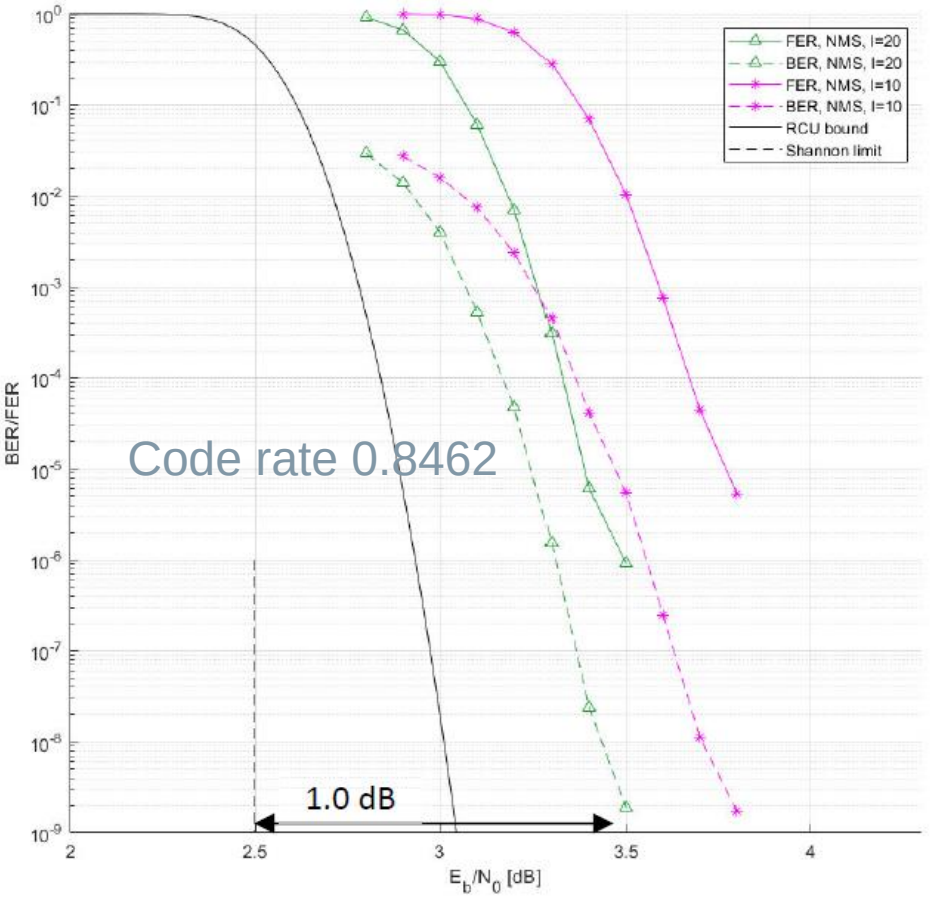
100G

- Based on OTN and OpenROADM
- OpenFEC with Soft decision (SD) decoding
- Code rate 0.867
- With 3 SD iterations the Net Coding Gain (NCG) is 11.1 dB for a BER @ 10-15 (DP-QPSK).

Performance of 2.5G FEC codes (SDA T1, 5G NR LDPC)*

- LDPC codes are known for suffering from ‘error floors.





*Courtesy of DLR in the frame of ESA Contract AO/1-11960/23/NL/FGL LOFEC-HDR

Data Rates

- Net user data rates based on the symbol rates and code rates presented.
- The low user rate of the 10G (6.1 Gbps) has raised request to remove the LPC for reaching ~10Gbps.

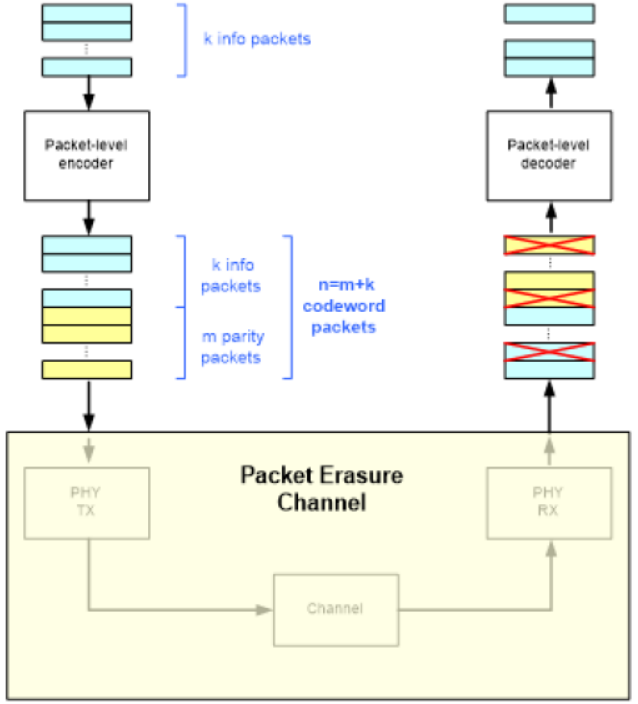
Requirement	User net data rate (upper bound)	Air interface	Symbol rate
REQ-DLL-010	99.5328 Gbps	100G DP-QPSK	31.5 Gbaud
REQ-DLL-020	2 x 99.5328 Gbps	200G DP-16QAM	31.5 Gbaud
REQ-DLL-030	2 x 99.5328 Gbps	200G DP-QPSK	62 Gbaud
REQ-DLL-040	4 x 99.5328 Gbps	400G DP-16QAM	62 Gbaud
REQ-DLL-050	1.174 Gbps - 2.221 Gbps*	2.5G IM/DD OOK	2.5 Gbaud
REQ-DLL-060	6.121 Gbps	10G IM/DD OOK	10 Gbaud

*The user-data depends on the selected code-rates as defined in the next sections

Future Directions

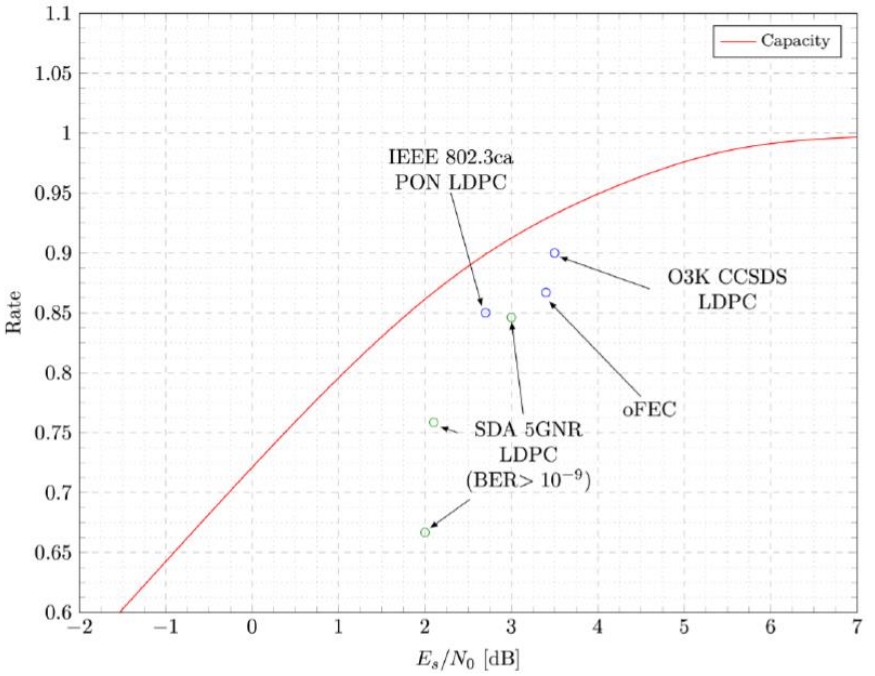
Time Diversity for turbulence mitigation in OGSL

- Options: LDPC Erasure Code (packet level), RS+Long channel interleaver (bit level)



~10Gbps coherent modulation

- Data rates: 2.5-25 Gbps
- Modulation: BPSK, QPSK, dual polarization
- FEC: 5G NR LDPC, oFEC, ITU 25G PON LDPC




HydRON
Vision
HydRON
Demonstration
System
HydRON-DS will be
using ESTOL

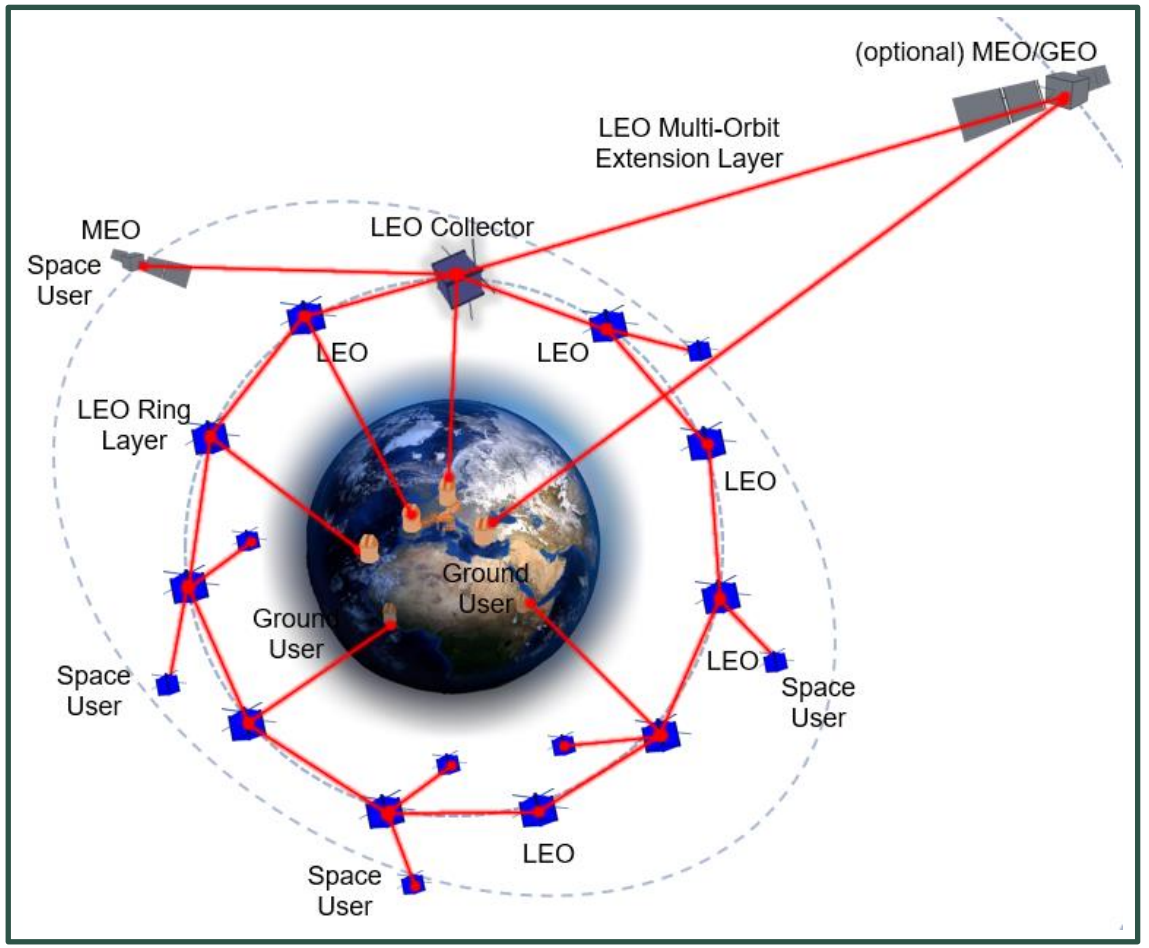
HydRON Demo System – Current Status

- HydRON Project initiated and funded in November 2019 (ESA Council Meeting on ministerial level).
- HydRON Demo System Phase-A/B1 completed in December 2023. Two parallel studies by
  - Airbus Defense and Space (Germany)
  - Thales Alenia Space (Italy)
- Request for Quotation on Element#1 and Element#2 of the HydRON-DS published in Q1 and Q2 2024.
- Evaluations of proposals completed and KO.
- Implementation of HydRON-DS Phase B2/C/D/E Element#1 by Kepler Comms (CA) and Element#2 by TAS-I.

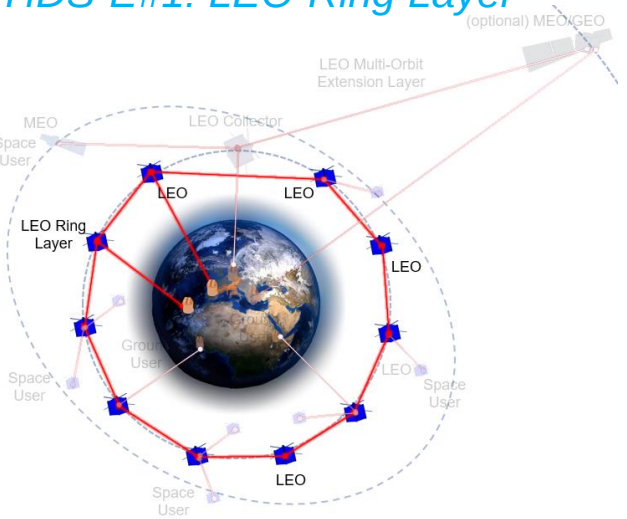
HydRON Demo System

Overview HydRON-DS constituent "Elements"

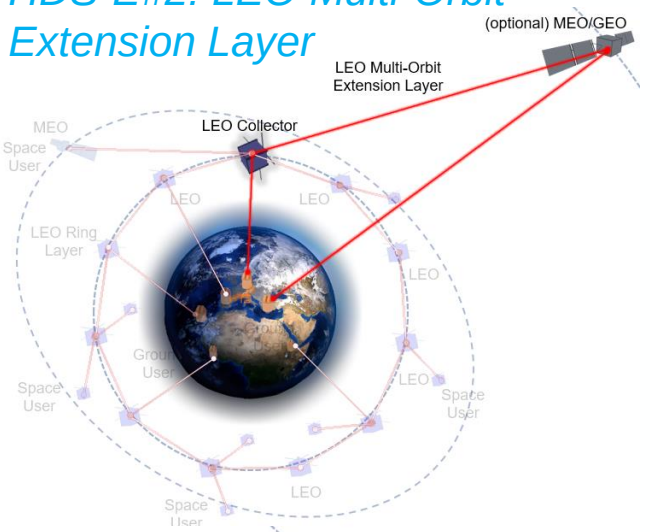
Complete HydRON Demo System



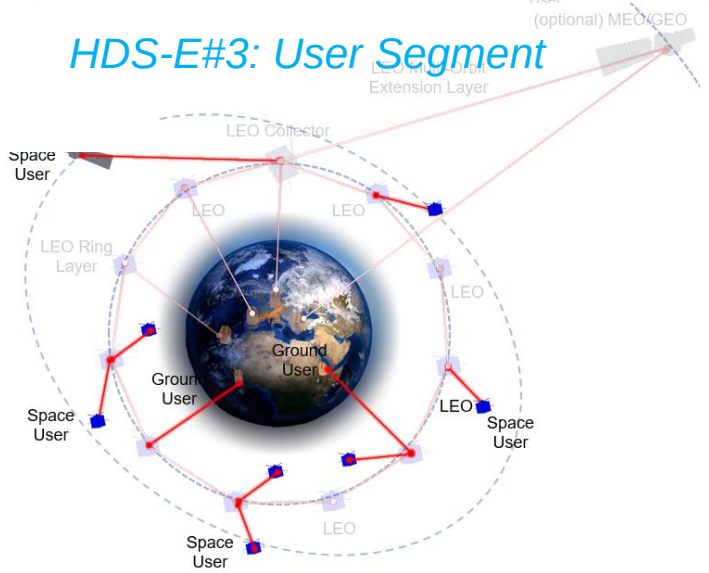
HDS-E#1: LEO-Ring Layer



HDS-E#2: LEO Multi-Orbit Extension Layer



HDS-E#3: User Segment



HydRON Demo System – Technical Baseline

LEO core node (x10)

- 4 LCT (ø~80mm @ 2.5/10/100Gbps) → LEO-ground connectivity
  → LEO-LEO connectivity
- 1 router → packet switching (>100Gbps throughput).

LEO collector (x1)

- 2 LCT (ø~85mm @ 2.5/10/100Gbps) → LEO-ground connectivity
  → LEO-LEO connectivity
- 2 LCT (ø~162mm @ 2.5/10/100Gbps) → LEO-ground connectivity
  → LEO-GEO connectivity
- 1 router → packet switching (>10Gbps throughput).

GEO core node (option)

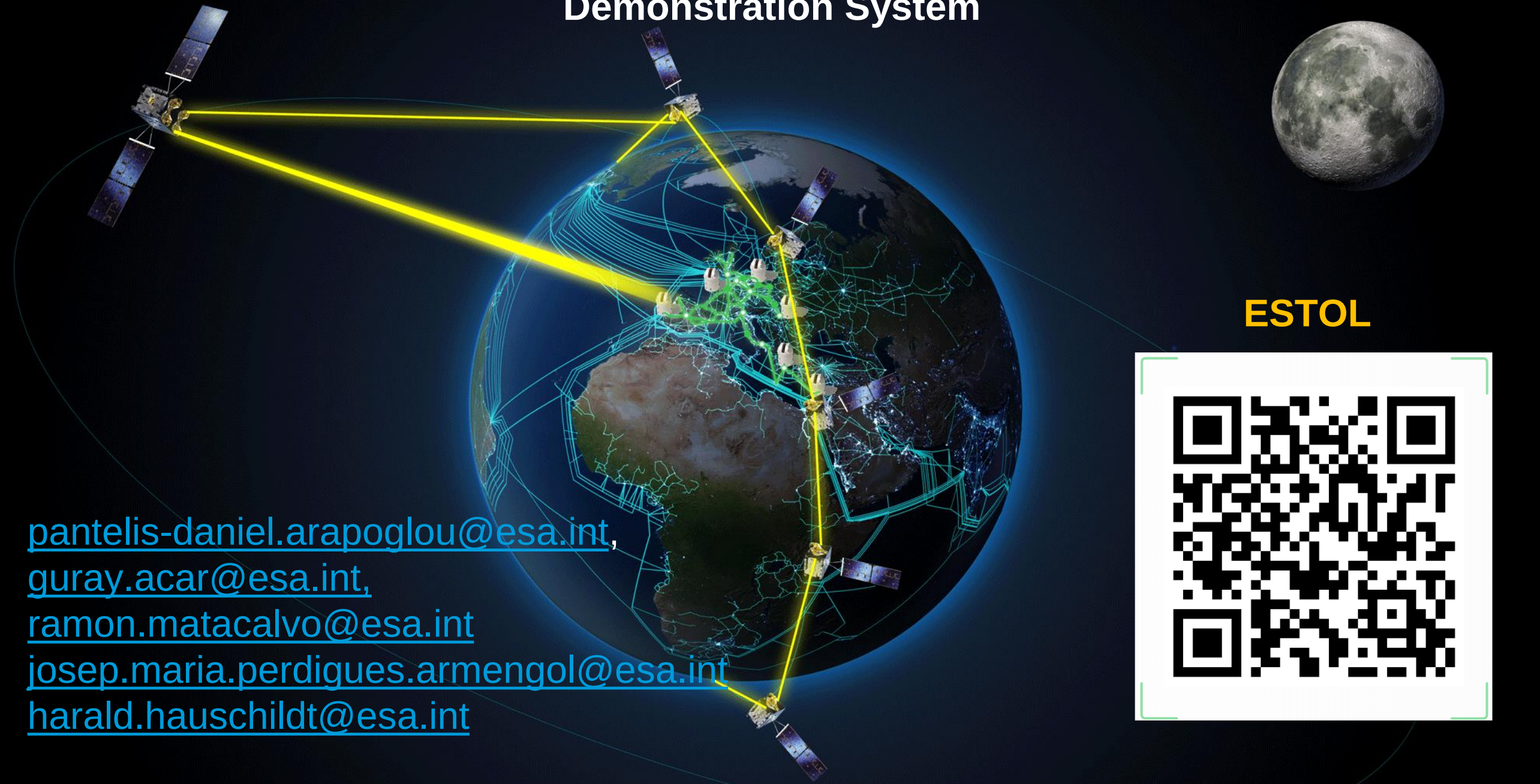
- 2 LCT (ø~135 or 162 or 250 mm) → GEO-ground connectivity (@ 10/100Gbps)
  → space-to-space connectivity **or** network expandability (@100Gbps)
- 1 router → on-board circuit switch

Ground segment

- 2 fixed + 2 transportable optical ground stations all interconnected
- HydRON Control Centre for each element #1 and #2

LEO Launch in Q4/2026
GEO Launch in Q3/2027

High Throughput Optical Network (HydRON) Demonstration System



pantelis-daniel.arapoglou@esa.int,
guray.acar@esa.int,
ramon.matacalvo@esa.int
josep.maria.perdigues.armengol@esa.int
harald.hauschildt@esa.int

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