Results of the Interagency Operations Advisory Group (IOAG) Optical Link Study Group (OLSG), ESA's way forward

Klaus-Juergen Schulz
HSO-GS, ESA-ESOC

Zoran Sodnik
TEC-MM, ESA-ESTEC

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Theme 1: Operations Implications with Optical Communications
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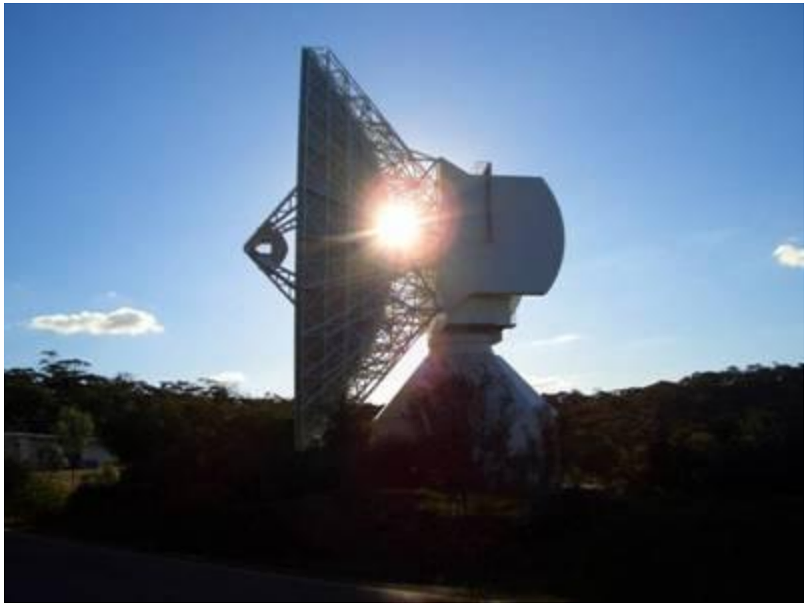

Agenda

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  - Scope
  - Process
  - Results Summary
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    - Eye Safety
    - Scenario Analysis Summary
    - Scenario Ground Segment Cost Summary
    - Standardisation Recommendation
- ESA's potential way forward (Where are the niches ?) – by scenario
  - Inter-Satellite Link (ISL)
  - GEO->Ground
  - LEO->Ground
  - “Deep Space” (Moon, L1, L2, Mars, …)
  - Telecom Uplinks (Tbps satellites)
  - Technology preparation (Technology Harmonisation Dossier)

OLSG Summary: Mandate

- The Optical Link Study Group (OLSG) was established to determine if there is a business case for cross support of optical space communication links, and if so, provide guidance for a set of standards that would foster the advancement of cross support capability among the Agencies.

- The OLSG was formed with seven member Agencies: ASI, CNES, DLR, ESA, JAXA, KARI, and NASA.

- Klaus-Juergen Schulz of ESA and John Rush of NASA co-chaired the study group.

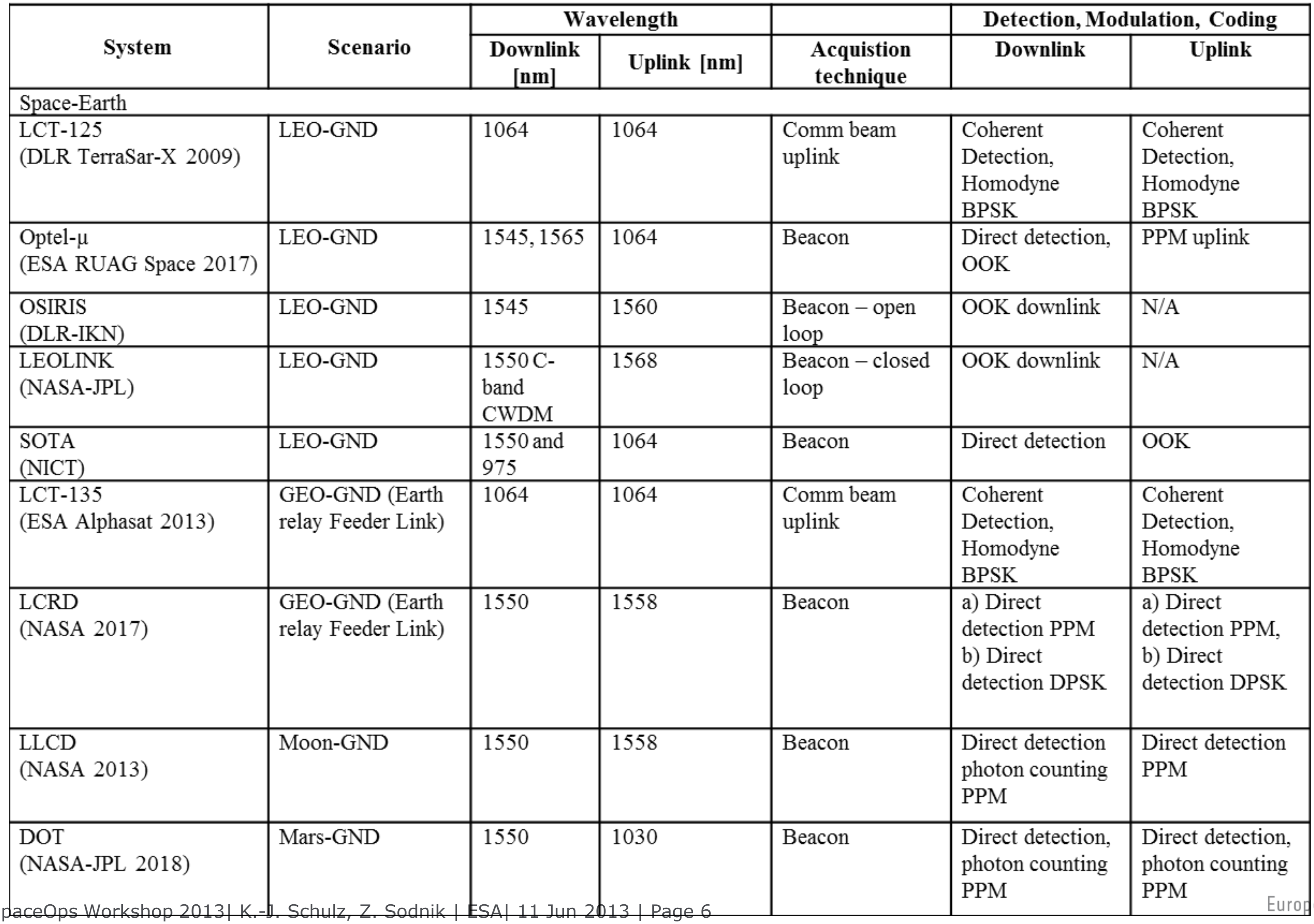
OLSG Summary: Scope

- Scenarios
  - Space-Earth: LEO, GEO, "Deep Space": Moon, L1/L2, Mars
  - Inter-Satellite Links (ISL), around Earth only
  - Telecom Feeder Uplinks were excluded
- Payload data downlinks only
  - assuming an RF based TTC up- and downlink for spacecraft control
  - assuming a beacon uplink for onboard terminal pointing, acquisition and tracking
- Data Uplink was considered an option for later

OLSG Summary: Process

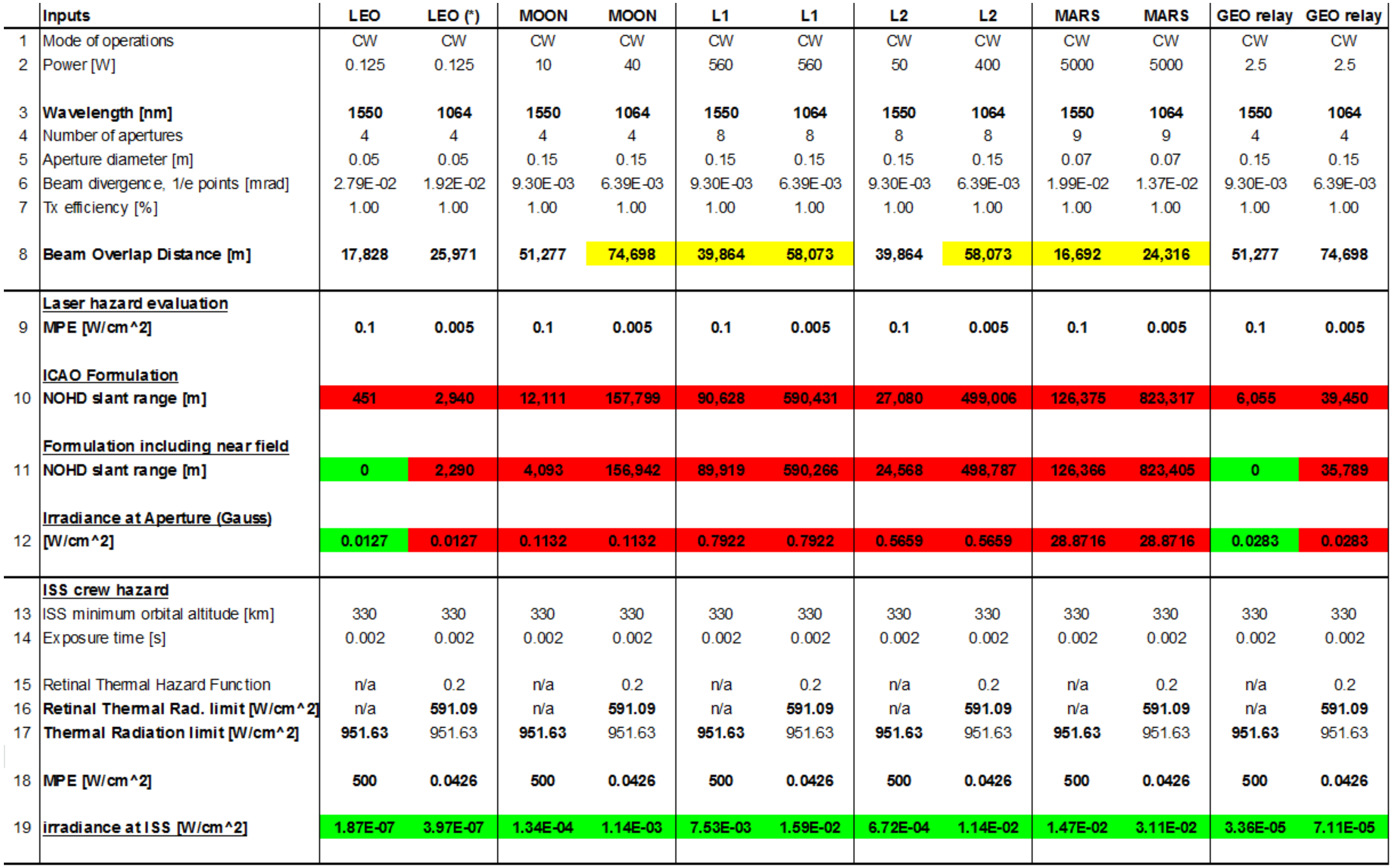
- Surveyed existing optical communications projects among the agencies
- Identified significant issue in dealing with Atmospheric conditions (i.e. clouds, optical turbulence)
- Identify issues and proposed approaches for aviation eye safety concerns for optical communication ground terminals
- Developed scenarios
  - based on Concepts of Operations (ConOps) of known missions
  - in order to prove feasibility based on statistical analysis of cloud data for scenario ground terminal locations
  - assessed feasibility of onboard and ground terminal solutions by mapping to actual projects and verification by associated link budgets
  - assessed feasibility of beacon uplink solution and associated eye safety
  - assessed cost of ground segment solutions (site, terminal, connectivity)
- Identified guidance for the development of cross support standards

OLSG Summary: Results, Diversity of technical solutions



System	Scenario	Wavelength			Detection, Modulation, Coding	
		Downlink [nm]	Uplink [nm]	Acquistion technique	Downlink	Uplink
Space-Earth						
LCT-125 (DLR TerraSar-X 2009)	LEO-GND	1064	1064	Comm beam uplink	Coherent Detection, Homodyne BPSK	Coherent Detection, Homodyne BPSK
Optel-µ (ESA RUAG Space 2017)	LEO-GND	1545, 1565	1064	Beacon	Direct detection, OOK	PPM uplink
OSIRIS (DLR-IKN)	LEO-GND	1545	1560	Beacon – open loop	OOK downlink	N/A
LEOLINK (NASA-JPL)	LEO-GND	1550 C-band CWDM	1568	Beacon – closed loop	OOK downlink	N/A
SOTA (NICT)	LEO-GND	1550 and 975	1064	Beacon	Direct detection	OOK
LCT-135 (ESA Alphasat 2013)	GEO-GND (Earth relay Feeder Link)	1064	1064	Comm beam uplink	Coherent Detection, Homodyne BPSK	Coherent Detection, Homodyne BPSK
LCRD (NASA 2017)	GEO-GND (Earth relay Feeder Link)	1550	1558	Beacon	a) Direct detection PPM b) Direct detection DPSK	a) Direct detection PPM, b) Direct detection DPSK
LLCD (NASA 2013)	Moon-GND	1550	1558	Beacon	Direct detection photon counting PPM	Direct detection PPM
DOT (NASA-JPL 2018)	Mars-GND	1550	1030	Beacon	Direct detection, photon counting PPM	Direct detection, photon counting PPM

OLSG Summary: Results, Eye Safety



	Inputs	LEO	LEO (*)	MOON	MOON	L1	L1	L2	L2	MARS	MARS	GEO relay	GEO relay
1	Mode of operations	CW	CW	CW	CW	CW	CW	CW	CW	CW	CW	CW	CW
2	Power [W]	0.125	0.125	10	40	560	560	50	400	5000	5000	2.5	2.5
3	**Wavelength [nm]**	**1550**	**1064**	**1550**	**1064**	**1550**	**1064**	**1550**	**1064**	**1550**	**1064**	**1550**	**1064**
4	Number of apertures	4	4	4	4	8	8	8	8	9	9	4	4
5	Aperture diameter [m]	0.05	0.05	0.15	0.15	0.15	0.15	0.15	0.15	0.07	0.07	0.15	0.15
6	Beam divergence, 1/e points [mrad]	2.79E-02	1.92E-02	9.30E-03	6.39E-03	9.30E-03	6.39E-03	9.30E-03	6.39E-03	1.99E-02	1.37E-02	9.30E-03	6.39E-03
7	Tx efficiency [%]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
8	**Beam Overlap Distance [m]**	**17,828**	**25,971**	**51,277**	**74,698**	**39,864**	**58,073**	**39,864**	**58,073**	**16,692**	**24,316**	**51,277**	**74,698**
	Laser hazard evaluation												
9	**MPE [W/cm^2]**	**0.1**	**0.005**	**0.1**	**0.005**	**0.1**	**0.005**	**0.1**	**0.005**	**0.1**	**0.005**	**0.1**	**0.005**
	ICAO Formulation												
10	**NOHD slant range [m]**	451	2,940	12,111	157,799	90,628	590,431	27,080	499,006	126,375	823,317	6,055	39,450
	Formulation including near field												
11	**NOHD slant range [m]**	0	2,290	4,093	156,942	89,919	590,266	24,568	498,787	126,366	823,405	0	35,789
	Irradiance at Aperture (Gauss)												
12	**[W/cm^2]**	0.0127	0.0127	0.1132	0.1132	0.7922	0.7922	0.5659	0.5659	28.8716	28.8716	0.0283	0.0283
	ISS crew hazard												
13	ISS minimum orbital altitude [km]	330	330	330	330	330	330	330	330	330	330	330	330
14	Exposure time [s]	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002
15	Retinal Thermal Hazard Function	n/a	0.2	n/a	0.2	n/a	0.2	n/a	0.2	n/a	0.2	n/a	0.2
16	**Retinal Thermal Rad. limit [W/cm^2]**	n/a	**591.09**	n/a	**591.09**	n/a	**591.09**	n/a	**591.09**	n/a	**591.09**	n/a	**591.09**
17	**Thermal Radiation limit [W/cm^2]**	**951.63**	951.63	**951.63**	951.63	**951.63**	951.63	**951.63**	951.63	**951.63**	951.63	**951.63**	951.63
18	**MPE [W/cm^2]**	**500**	**0.0426**	**500**	**0.0426**	**500**	**0.0426**	**500**	**0.0426**	**500**	**0.0426**	**500**	**0.0426**
19	**irradiance at ISS [W/cm^2]**	1.87E-07	3.97E-07	1.34E-04	1.14E-03	7.53E-03	1.59E-02	6.72E-04	1.14E-02	1.47E-02	3.11E-02	3.36E-05	7.11E-05

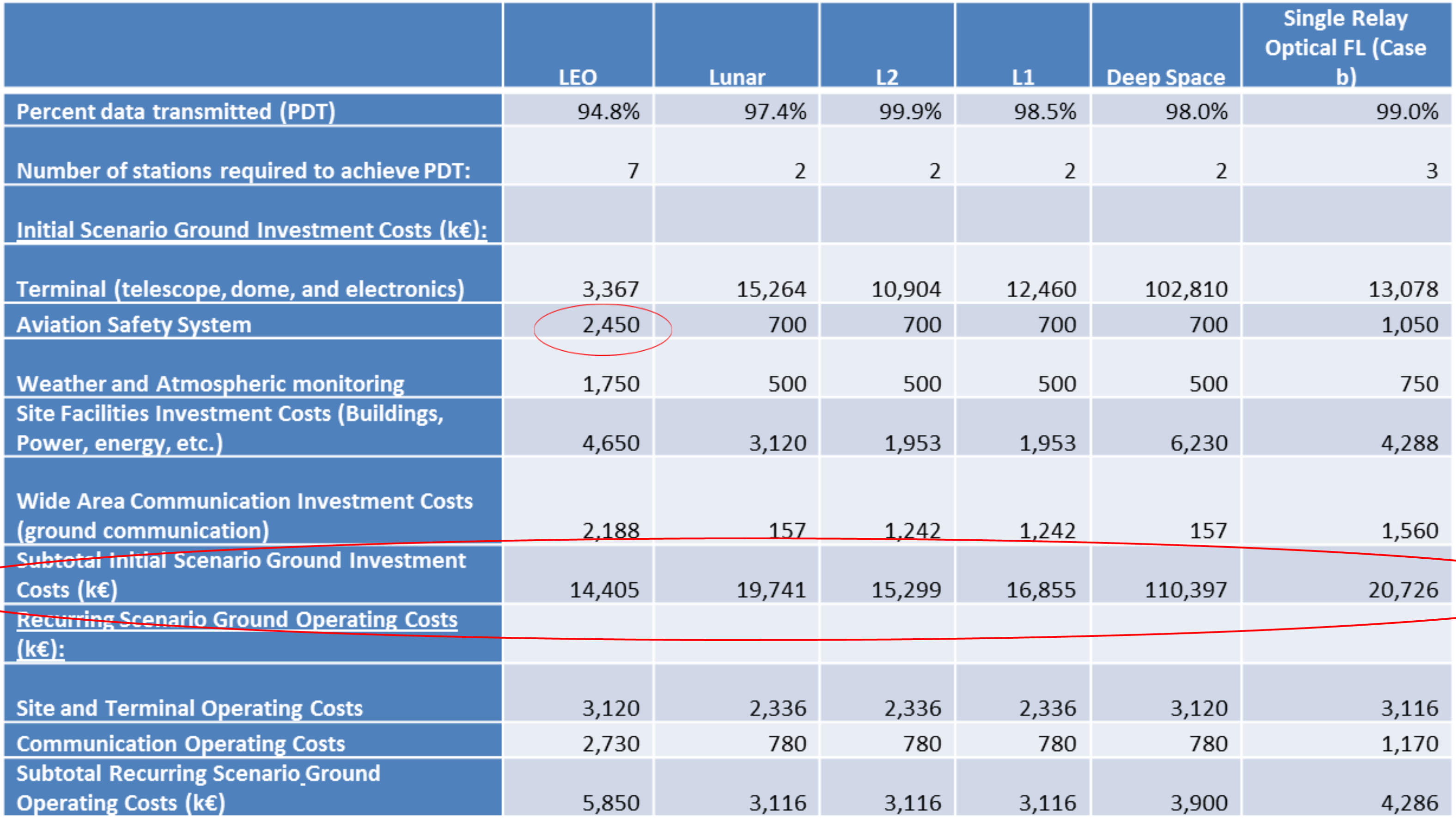
- Values highlighted in red indicate that a scenario is calculated not to be eye safe at the aperture according to a particular formula, and values highlighted in green indicate that a scenario is calculated to be eye safe at the aperture according to a particular formula.
- Eye-safety calculations have been performed on one single radiating sub-aperture for each scenario. The distance at which the individual sub-beams start to overlap is reported in line 8. For the scenarios highlighted in yellow the overlap occurs before the NOHD for a single sub-aperture is reached.
- (*) for the LEO case the design of an eye-safe LEO system operating at 1064 nm is possible.

OLSG Summary: Results, Scenario Analysis Summary

Scenarios	Unit	LEO	Lunar	L2	L1	Deep Space (Mars)	Single Relay Optical FL (Case b)
Scenario ConOps							
Data Volume per day	Tb/d	12	5.72	7.5	7.5	1.1	216
Onboard Storage	Tb	2.3	7.4	22.5	22.5	1.1	10
Data Rate per second	Mb/s	10,000	622	700	700	0.7-260	10,000
CFLOS required per day	h/d	0.33	2.55	3	3	1.2	6
Onboard Terminal							
Aperture	cm	8	10	13.5	13.5	22	13.5
Tx Power	W	0.5	0.5	5	5	4	2.2
Mass	kg	35	30	50	50	< MRO Ka	50
Power Consumption	W	120	140	160	160	< MRO Ka	160
Ground Stations							
Rx Terminal Size diameter	m	0.4	1	1	1	12	1
Tx Apertures and Size		4x 5cm	4x 15cm	8x 15cm	8x 15cm	9x 7cm	4x 15cm
Tx NOHD ICAO (1550nm)	m	451	12,111	27,080	32,042	42,125	6,055
Tx NOHD Near Field (1550nm)	m	0	4,094	24,574	29,957	42,068	0
Number of Terminals		7	2	2	2	2	3
Location of Terminals		Haleakala, TMF, Madrid, Svalbard, La Silla, Tenerife, New Norcia, Hartebeesthoek	Haleakala, Tenerife	Tenerife, Hartebeesthoek	Tenerife, Hartebeesthoek	Haleakala, Tenerife	WSC, Tenerife, La Silla
PDT resulting	%	94.8	97.4	99.9	98.5	99.0	98.0

OLSG Summary: Results, Scenario Analysis Ground Segment Cost

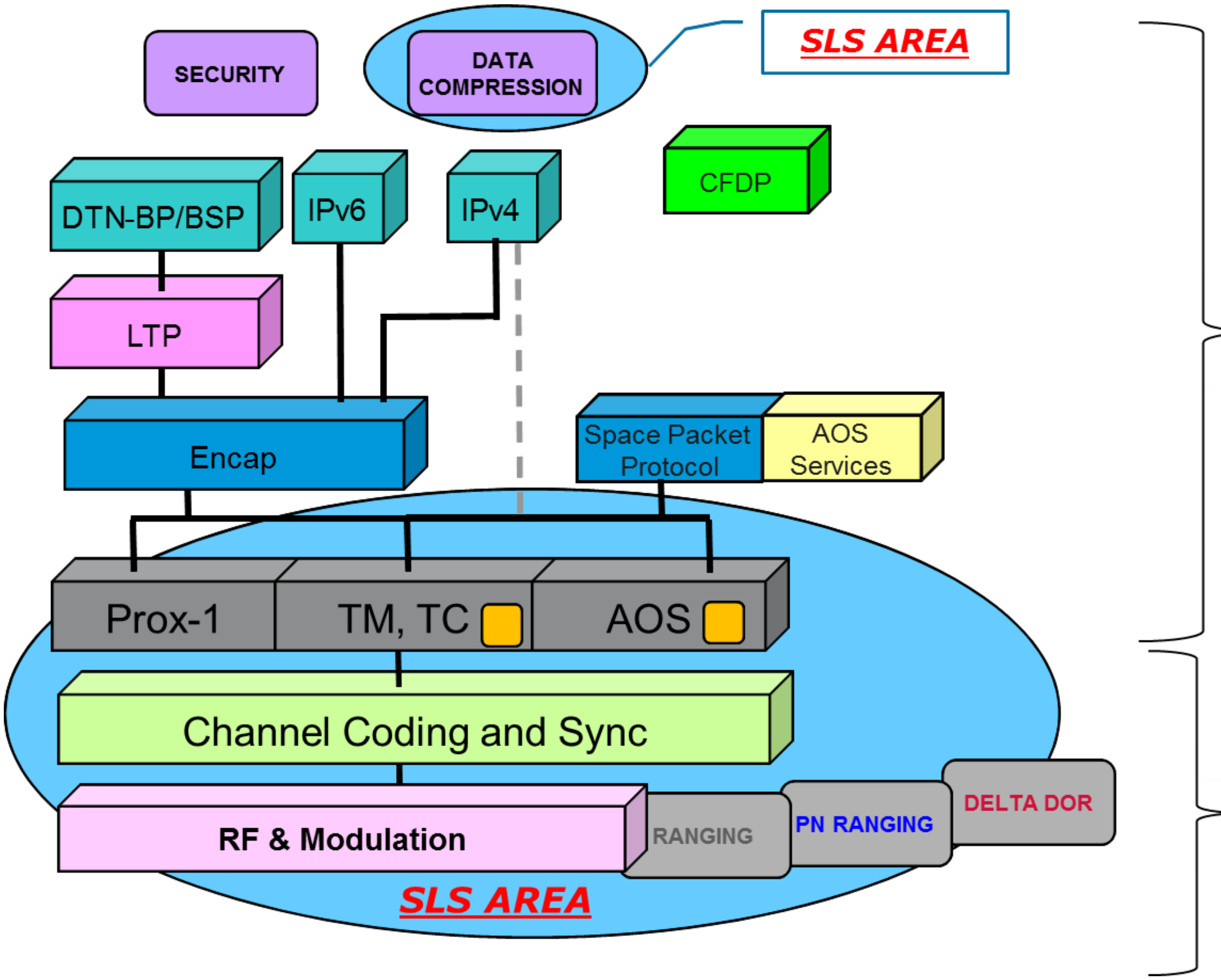
- A cost estimate was developed for each scenario’s ground station compliment and a notional earth relay system optical feeder link (FL)
  - It was assumed that any optical communications flight terminal would be agency-specific mission costs



	LEO	Lunar	L2	L1	Deep Space	Single Relay Optical FL (Case b)
Percent data transmitted (PDT)	94.8%	97.4%	99.9%	98.5%	98.0%	99.0%
Number of stations required to achieve PDT:	7	2	2	2	2	3
Initial Scenario Ground Investment Costs (k€):						
Terminal (telescope, dome, and electronics)	3,367	15,264	10,904	12,460	102,810	13,078
Aviation Safety System	2,450	700	700	700	700	1,050
Weather and Atmospheric monitoring	1,750	500	500	500	500	750
Site Facilities Investment Costs (Buildings, Power, energy, etc.)	4,650	3,120	1,953	1,953	6,230	4,288
Wide Area Communication Investment Costs (ground communication)	2,188	157	1,242	1,242	157	1,560
Subtotal Initial Scenario Ground Investment Costs (k€)	14,405	19,741	15,299	16,855	110,397	20,726
Recurring Scenario Ground Operating Costs (k€):						
Site and Terminal Operating Costs	3,120	2,336	2,336	2,336	3,120	3,116
Communication Operating Costs	2,730	780	780	780	780	1,170
Subtotal Recurring Scenario Ground Operating Costs (k€)	5,850	3,116	3,116	3,116	3,900	4,286

- (*) for the LEO case the design of an eye-safe LEO system operating at 1064 nm is possible., therefore this cost can be saved

OLSG Summary: Results, Standardisation Recommendation



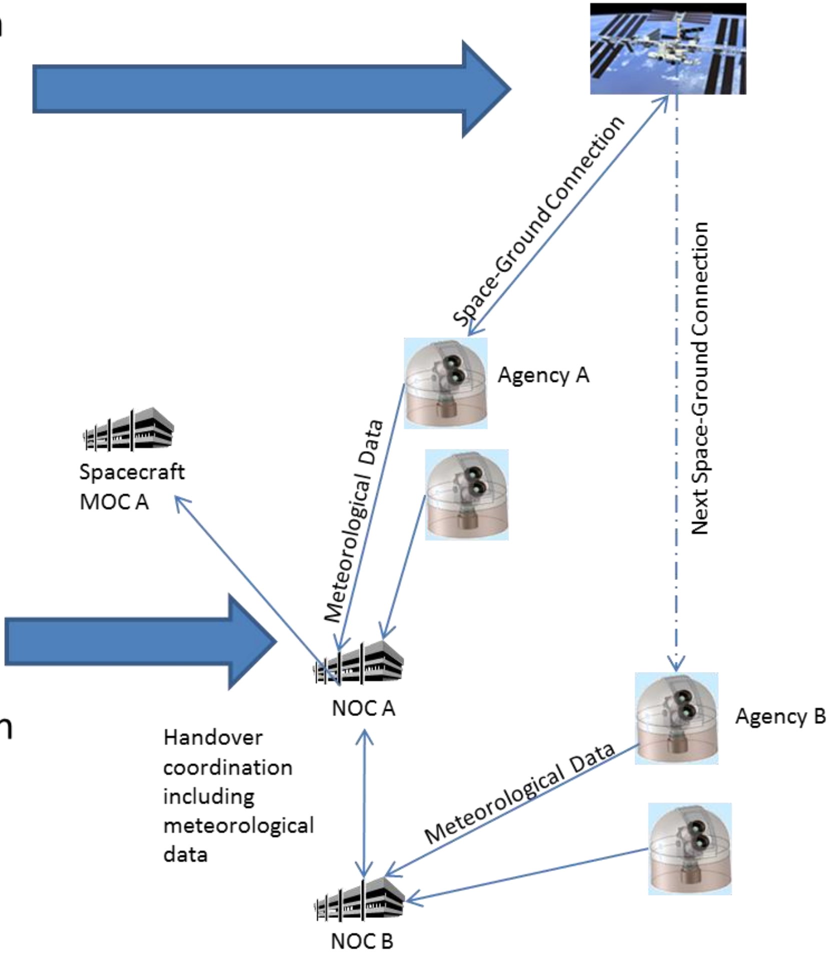
Reuse existing standards for optical communications

Must be developed for optical communications cross support

OLSG Summary: Results, Standardisation Recommendation

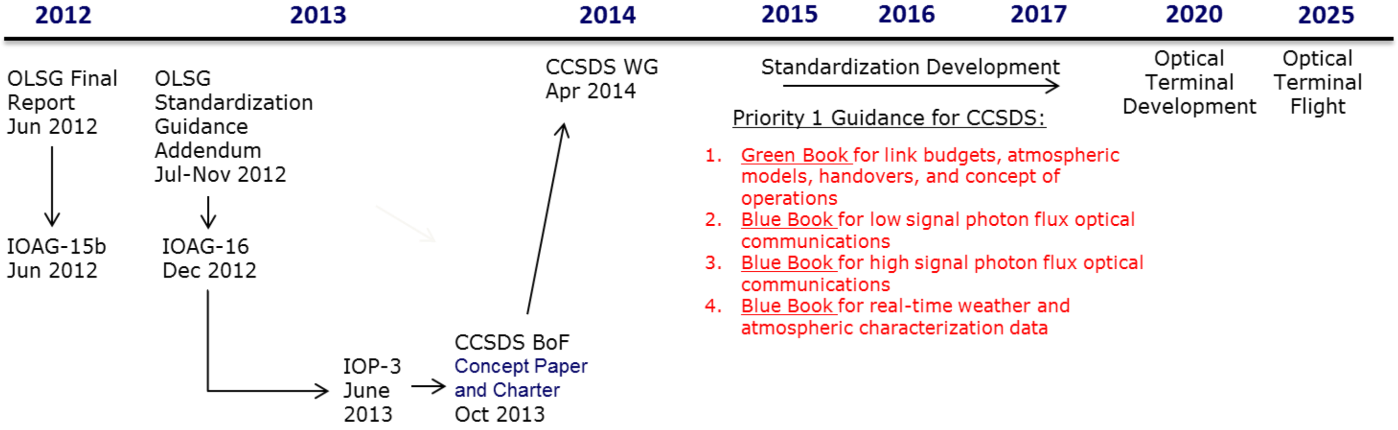
- Optical Communication Space-to-Ground and Space-to-Space Standards

- Ground station coordination requires meteorological forecasts and handover coordination



OLSG Summary: Results, Standardisation Recommendation

OLSG Recommended Standardization Schedule



2012 2013 2014 2015 2016 2017 2020 2025

OLSG Final Report Jun 2012 → IOAG-15b Jun 2012

OLSG Standardization Guidance Addendum Jul-Nov 2012 → IOAG-16 Dec 2012 → IOP-3 June 2013 → CCSDS BoF Concept Paper and Charter Oct 2013 → CCSDS WG Apr 2014

Standardization Development →

Optical Terminal Development

Optical Terminal Flight

Priority 1 Guidance for CCSDS:

1. Green Book for link budgets, atmospheric models, handovers, and concept of operations
2. Blue Book for low signal photon flux optical communications
3. Blue Book for high signal photon flux optical communications
4. Blue Book for real-time weather and atmospheric characterization data

Technology Demonstrations

2012 2013 2014 2015 2016 2017 2020 2025

TerraSar-X (DLR)
- 2009 LEO-ground demo
- 1064 nm, Homodyne BPSK

TerraSar-X to NFIRE (DLR)
- 2008 ISL LEO-LEO demo
- 1064 nm, Homodyne BPSK

OPALS (NASA)
- ISS-ground demo
- 1553 nm, OOK modulation

LLCD (NASA)
- 2013 Moon-Earth demo
- 1550 nm, single photon detection and PPM

LCT-135/Alphasat (DLR)
- 2013 ISL, GEO to Earth demo
- 1064 nm, Homodyne BPSK

SOTA (NICT)
- LEO to ground demo
- 1064 and 1550nm, OOK modulation

Sentinel/EDRS (DLR/ESA)
- 2014 ISL
- 1064 nm, Homodyne BPSK

OSIRIS (DLR-ICAN)
- 2015 LEO-Earth demo
- 1550 nm, IMDD

LCRD (NASA)
- 2017 GEO-Ground and ISL LEO-GEO
- 1550 nm, direct detection PPM, and DTN

Optel-μ (ESA)
- 2017 LEO-Earth demo
- direct detection and PPM

DOT (NASA)
- 2018 Mars-ground
- 1550nm, direct detection PPM

TDRS (NASA)
- 2025 GEO-Ground Operational Relay
- 1550 nm, DPSK and high speed routing

ESA's Potential Way Forward: Where are the Niches ?

- Disclaimer: There is no official ESA position on Optical Communication, however there exists a "European Space Technology Harmonisation Technical Dossier: Optical Communication for Space", Issue 4, Revision 2, 1 April 2014, which is an input to the ESA Technology Harmonisation Advisory Group (THAG), which is a sub-board of the ESA Industrial Policy Committee (ESA delegate body)
- Scenario Inter-Satellite Link (ISL) and associated GEO-Ground link
  - Based on EDRS and Sentinel -> Increase reliability and scale ISL to 10 Gbps and more -> Difficulty seems to be the GEO-Ground link
    - The RF solution based on 26 GHz seems to be limited to 10 Gbps using 1.5 GHz of spectrum and both polarisations
    - Migration to optical GEO-Ground links will be needed -> 2 architectural options possible:
      1. "bent-pipe" attempting high availability 99.9% with ~10 ground stations
      2. with intermediate onboard storage and associated protocols, e.g. DTN, with ~3 ground stations
      - Alphasat (ESA/DLR) will commission LCT-135 and experiment through the atmosphere in a high data rate (1.8 Gbps) scheme and adaptive optics on ground
      - OPHELIE (CNES) will experiment through the atmosphere in a high data rate scheme aiming at 100 Gbps

ESA’s Potential Way Forward: Where are the Niches ?

- Scenario LEO -> Ground
  - Most difficult optical scenario as the orbital geometry favors polar ground sites (e.g. Svalbard), that tend to have “bad” weather
  - The next generation RF solution which uses the 26GHz band with 1.5 GHz of spectrum, max. 2 polarisations, allowing highly reliable up to 10 Gbps downlinks. In order to exploit the low elavations, sophisticated Variable Coding and Modulation (VCM) and Adaptive Coding and Modulation (ACM) are already standardised.
  - A comparable optical solution requires 7 ground sites including Svalbard complemented by 6 mid-latitude sites with good weather conditions

  - => There seems to be a mismatch between the large number of optical demonstrations from LEO (OSIRIS, SOTA, Optel-μ), and the potential for operational use
    - How can this be explained ?
      - Low cost feasibility demonstration ?
      - Miniaturisation and low photon flux demonstration ?
      - This should be a topic for discussion at this workshop

ESA’s Potential Way Forward: Where are the Niches ?

- Scenario “Deep Space” (above GEO: Moon, L1, L2, Mars, …)
  - Typical low signal photon flux scenario
  - High potential if onboard terminals can be built reliably (RF is mature and has proven reliability records, whereas this prove still has to come with optical terminal flight demonstrations) -> ESA R&D focus:
    - Radiation hardened optical 1550 nm pre-amplifier and amplifier
    - Deep Space Pointing, Acquisition and Tracking (PAT)
    - Planetary imaging, LIDAR and communication terminal
    - => the aim should be to build and demonstrate a “deep space” optical terminal
  - While ground optical antenna solutions for Moon and L1/L2 exist today based on 1m class telescopes, ground optical (low cost) antennas of up to 10m do not exist today -> ESA R&D focus:
    - Single Photon Counting Detector
    - Solar baffling for close to sun operation
    - Low cost 2m class optical antenna
    - Low cost 10m class optical antenna
    - Eye-safe and autonomous uplink laser operation
    - => the aim should be to build and demonstrate a “deep space” optical antenna

ESA’s Potential Way Forward: Where are the Niches ?

- Scenario Telecom Uplinks (Tbps satellites) -> ESA R&D focus
  - RF over Optical (while DVB-S2 over RF is the standard solution for Gbps Telecom satellites today)
  - => Concept studies have started that aim at defining a potential R&D roadmap for Telecom Uplinks (Tbps satellites)

ESA’s Potential Way Forward: Where are the Niches ? -> Summary

- Novel optical space communication, although maturing, competes with very mature and well established RF communication systems in all scenarios
- The optical communication systems will not replace RF systems, but the following niche applications have been identified
  - High data volume transfer
  - Spacecraft resource limitations -> miniaturised terminals
  - Interference free operations
  - Spectrum license free operations
  - Covert (un-detectable and secure) communication

ESA’s Potential Way Forward: Where are the Niches ? -> Summary

- Optical space-ground communication solutions (system, onboard, ground) need to mature further and need to be demonstrated in order to be considered as a ready alternative for future missions. The following could be envisaged:
  - High data rates (> 10 Gbps) space-ground scenario not possible with RF, e.g. LEO-to-Ground, GEO-to-Ground
  - Low data rate
    - Deep Space - Ground scenario aiming at onboard terminals for deep space communication with either (10x) higher data rates compared to RF at same mass, or same data rate at lower mass
    - LEO-to-Ground miniaturised onboard terminals for small satellites, and low cost ground terminals

- “Deep Space” demonstration required to prove optical communication capability in order to promote phase-in for future science missions

- Optical ground-space Telecom uplinks could be commercially very attractive