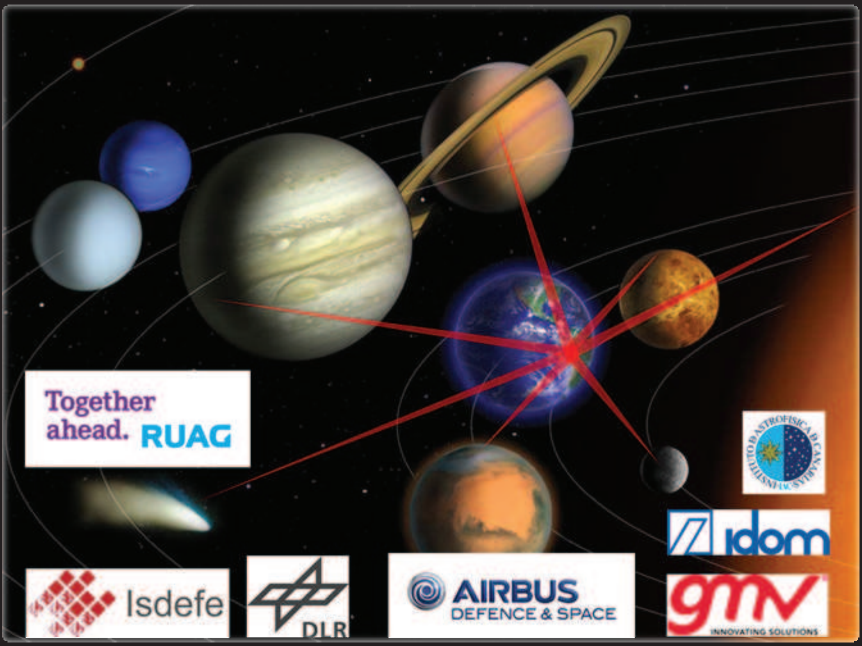
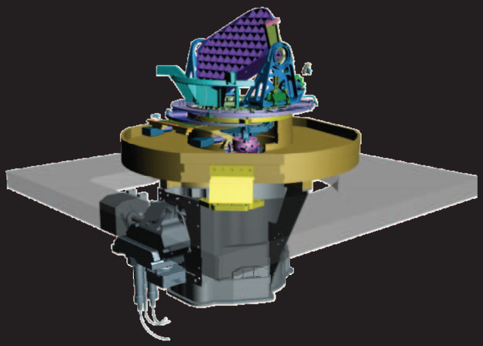
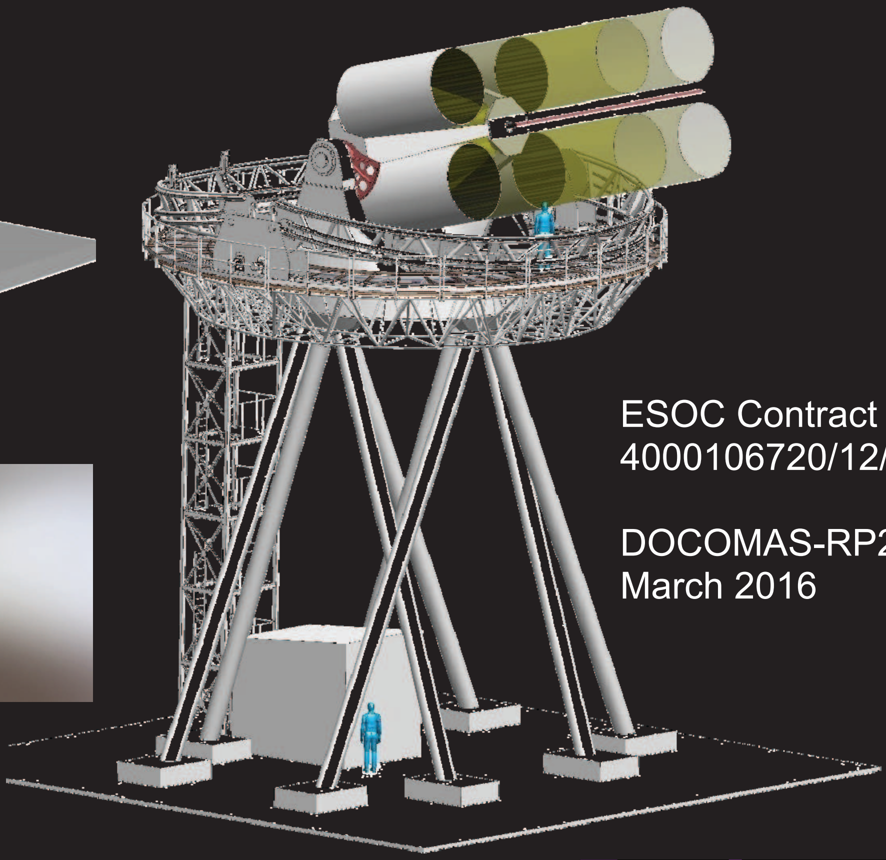
DOCOMAS
Deep Space Optical Communications Architecture Study

Executive Summary







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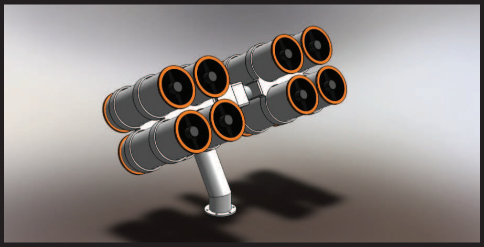


Together ahead. RUAG

1 INTRODUCTION

Satellite based optical communications in space is rapidly progressing, involving an increasing number of flight validations in LEO, GEO and beyond. Various space agencies successfully demonstrated both, optical Inter-Satellite communication Links (ISL's) which have been validated in flight experiments since 2001 and direct-to-Earth (DTE) optical communications.

Most prominently, NASA's lunar lasercom demonstration mission LLCD in 2013 established optical DTE communications at 622 Mbps from the Moon to Earth. European industry developed in short time a PPM modulation receiver that was successfully used during the LLCD demonstration in frame of the Lunar Optical Communications Link cross-support activity between ESA and NASA. This paved the way for inter-operability especially for deep space optical communications.

Europe has been able to maintain a strong position with so far the only commercially available and validated ISL product worldwide: the LCT (Laser Communication Terminal) has reached TRL9 in IOD experiments and in Europe's EDRS program. This provides a sound basis on space qualifications and operations heritage when going for laser communications for deep space.

ESA launched in 2010 the development of a micro-LCT (together with the corresponding ground-station) for high data rate LEO to Earth optical communications (*Optel*-μ) for small Earth observation satellites. The system achieves TRL6 in these days and the development provides interruption-tolerant transmission of on-board user data by a dedicated buffer memory system.

Several inter-island horizontal links (145 km distance through the atmosphere) using PPM modulation successfully demonstrated a simulation of a Deep-Space link from L2 and from Mars.

Given the solidly maturing optical space communication technology and the clearly increasing demand on downlink data rate to increase science return, a technology enhancement in communication technology (particularly from deep space) is called for. The Deep Space Optical Communications Architecture Study (DOCOMAS) focuses on future evolutions of deep space communication architectures for optical downlinks from a deep space probe directly to Earth. The emphasis hereby is on the ground segment, including cloud mitigation strategies.

The key enabling technologies that have been identified are dedicated optical ground antennae, free space coupled single photon counting detectors and a generic design approach to an optical payload terminal that can be applied to more than 3 orders of magnitude in link distance, starting from some ‰ of an A.U. up to several A.U. A genuine example for optical direct-to-Earth communications in a NEO mission context was derived in frame of a CCN to this study. That concept design was tailored for the asteroid investigation mission named "AIM" in frame of the AIDA activity together with NASA.

2 OPTICAL LINK DIMENSIONING

2.1 Dimensioning approach without a given mission

Given the large design parameter space, this allows for a large variation of possible downlink architectures, as indicated for key parameters in Figure 2-1.

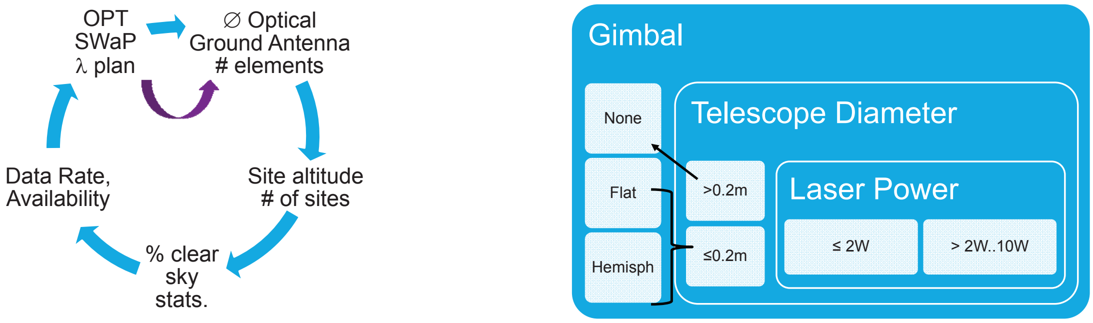


Figure 2-1: Optical link dimensioning loops and OPT scaling options

In order to obtain a clear point for orientation in that backbiting dimensioning circle, it was decided to go first for an extreme dimensioning that favours a minimal OPT versus maximizing the OGA.

OPT mass and power estimates for 4 different mission types are depicted in Figure 2-2. OPT dimensions are minimized and OGA diameter is adapted. Multiple optical channels are assumed for the Lunar downlink case and for downlinks from L1/L2.

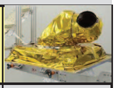
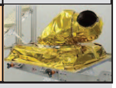
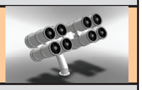
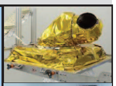
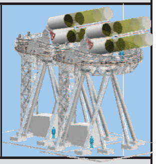
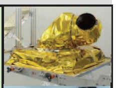
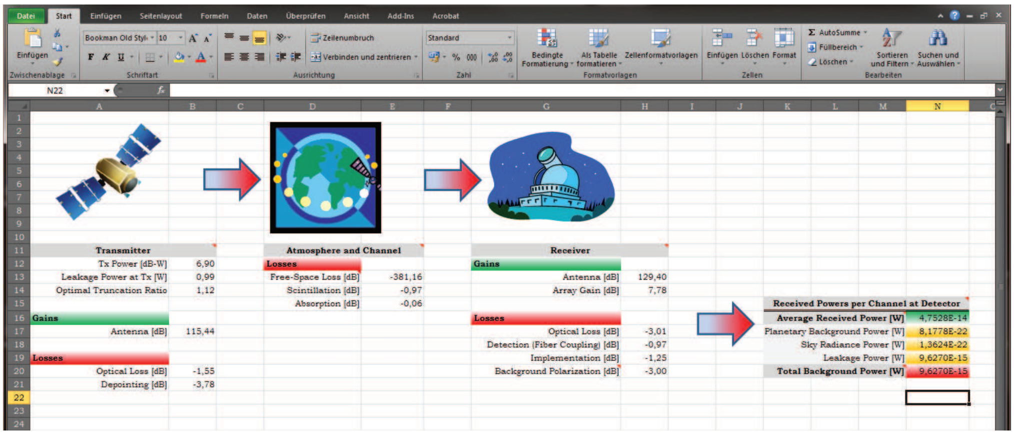
OPT beam agility	Information data rate		OPT Key parameters					OGA Key Parameters	
	60° zenith	norm., 1AU	Telescope ∅	$P_{Tx,optical}$	DC power	Mass	heritage	max. Ant. ∅	
Moon									
gimballed	**1.2Gbps**	**12kbps**	**0.1m**	**<4W**	**≤150W goal: ≤110W**	**≤50kg**		**≤1m**	
L1 & L2									
gimballed	**1.9Gbps**	**124kbps**	**0.1m**	**≤6W**	**≤150W goal: ≤110W**	**≤50kg**		**≤1.5m**	
Mars									
short, gimballed	**135Mbit/s**	**20Mbit/s**	**≤0.16m**	**≤4W**	**≤150W goal: ≤110W**	**goal: ≤50kg**		**≤12m**	
far, gimballed	**3.1Mbit/s**								
short, fixed	**330Mbit/s**	**53Mbit/s**	**≤0.35m**						
far, fixed	**15.7Mbit/s**	**102Mbit/s**							
Jupiter									
short, gimblled	**1.3 Mbit/s**	**20Mbit/s**	**≤0.16m**	**≤4W**	**≤150W goal: ≤110W**	**goal: ≤50kg**		**≤12m**	
far, gimballed	**0.5 Mbit/s**								
short, fixed	**6.3Mbit/s**	**96Mbit/s**	**≤0.35m**						
far, fixed	**2.3Mbit/s**								

Figure 2-2:Extreme scalings for minimum size, weight and power (SWaP) of OPT

That extreme approach increases the ground antenna diameter to a value that leads to non-linear increase of OGA cost. Especially for missions to Mars and Jupiter a moderate increase of the OPT could together contribute significant OGA cost saving over multiple sites.

2.2 ESA Link Budget Tool

DOCOMAS contributed an enhancement of ESA's Optical Communications Link Budget Tool for calculating system level parameters for deep space optical communication links between spacecraft and ground stations. The user is able to configure the system by input key parameters of transmitter, atmospheric channel, receiver and modulation format. As a special feature, this tool allows for calculating probability of symbol error and probability of bit error for different types of (ground) detectors. This tool has been implemented in Microsoft Excel 2007.



Transmitter	
Tx Power [dB-W]	6,90
Leakage Power at Tx [W]	0,99
Optimal Truncation Ratio	1,12
Gains	
Antenna [dB]	115,44
Losses	
Optical Loss [dB]	-1,55
Depointing [dB]	-3,78

Atmosphere and Channel	
Losses	
Free-Space Loss [dB]	-381,16
Scintillation [dB]	-0,97
Absorption [dB]	-0,06

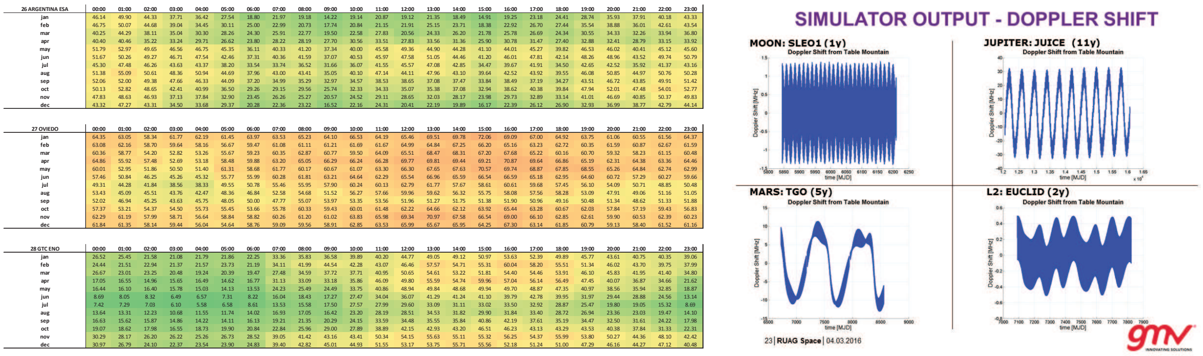
Receiver	
Gains	
Antenna [dB]	129,40
Array Gain [dB]	7,78
Losses	
Optical Loss [dB]	-3,01
Detection (Fiber Coupling) [dB]	-0,97
Implementation [dB]	-1,25
Background Polarization [dB]	-3,00

Received Powers per Channel at Detector	
Average Received Power [W]	4,7528E-14
Planetary Background Power [W]	8,1778E-22
Sky Radiance Power [W]	1,3624E-22
Leakage Power [W]	9,6270E-15
Total Background Power [W]	9,6270E-15

Figure 2-3 - A view of the optical power calculations sheet in the link budget tool

2.3 Cloud statistics and PDT analysis

Initial implementation steps were undertaken in DOCOMAS to establish a generic software tool that allows for calculating percentage of data transmitted (PDT) as a function of link geometry plus site dependent features, such as scattering attenuation and site-specific seeing characteristics based on varying Cn2 index of refraction profile. All parameters are a function of time (season), zenith angle and site altitude. Initial cloud coverage statistics based on the CDFS-II data base are available per pre-selected site. Meta data such as e.g. Doppler shift are generated as well.



26 ARGENTINA ESA	00:00	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00
jan	46.14	49.90	44.33	37.71	36.42	27.54	18.80	21.97	19.18	14.22	19.14	20.87	19.12	21.35	18.49	14.91	19.25	23.18	24.41	28.74	35.93	37.91	40.18	43.33
feb	46.75	50.07	44.68	39.04	34.45	30.11	25.00	22.99	20.73	17.74	20.84	21.15	21.91	25.15	23.71	18.38	22.92	26.70	27.44	35.54	38.88	36.01	42.61	43.54
mar	40.25	44.29	38.11	35.04	30.30	28.26	24.30	25.91	22.77	19.50	22.58	27.83	20.56	24.33	26.20	21.78	25.78	26.69	24.34	30.55	34.33	32.26	33.94	36.80
apr	40.40	40.46	35.22	33.24	29.71	26.62	23.80	28.22	28.19	27.70	30.56	33.51	27.83	33.56	31.36	25.90	30.78	31.47	27.40	32.88	32.41	28.79	33.15	33.92
may	51.79	52.97	49.65	46.56	46.75	45.35	36.11	40.33	41.20	37.34	40.00	45.58	49.36	44.90	44.28	41.10	44.01	45.27	39.82	46.53	46.02	40.41	45.12	45.60
jun	51.67	50.26	49.27	46.71	47.54	42.46	37.31	40.36	41.59	37.07	40.53	45.97	47.58	51.05	44.46	41.20	46.01	47.81	42.14	48.26	48.96	43.52	49.74	50.79
jul	45.30	47.48	46.26	43.63	43.37	38.20	33.54	33.74	36.52	31.66	36.07	41.55	45.57	47.08	42.85	34.47	39.67	41.91	34.50	42.65	42.52	35.92	41.37	43.16
aug	51.38	55.09	50.61	48.36	50.94	44.69	37.96	43.00	43.41	35.05	40.10	47.14	44.11	47.96	43.10	39.64	42.52	43.92	39.55	46.08	50.85	44.97	50.76	50.28
sep	52.06	52.00	49.38	47.66	46.33	44.09	37.20	34.99	35.29	32.97	34.57	38.53	38.65	37.08	37.47	33.84	38.49	37.19	34.27	43.51	46.72	43.85	49.91	51.42
oct	50.13	52.82	48.65	42.41	40.99	36.50	29.26	29.15	29.56	25.74	32.33	34.33	35.07	35.38	37.08	32.94	38.62	40.38	39.84	47.94	52.01	47.48	54.01	52.77
nov	47.83	48.63	46.93	37.13	37.84	32.90	23.45	26.26	25.27	20.57	24.52	29.11	28.65	32.03	28.17	23.98	29.73	32.89	33.14	41.01	46.69	40.85	50.37	49.83
dec	43.32	47.27	43.31	34.50	33.68	29.37	20.28	22.36	23.22	16.52	22.16	24.31	20.41	22.19	19.89	16.17	22.39	26.12	26.90	32.93	36.99	38.77	42.79	44.14

27 OVIEDO	00:00	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00
jan	64.35	63.05	58.34	61.77	62.19	61.45	63.97	63.53	65.23	64.10	66.53	64.19	65.46	69.51	69.78	72.06	69.09	67.00	64.92	63.75	61.06	60.55	61.56	64.37
feb	63.08	62.16	58.70	59.64	58.16	56.67	59.47	61.08	61.11	61.21	61.69	61.67	64.99	64.84	67.25	66.20	65.16	63.23	62.72	60.35	61.59	60.87	62.67	61.59
mar	60.36	58.77	54.20	52.82	53.26	55.67	59.23	60.35	62.87	60.77	59.50	64.09	65.51	68.47	68.31	67.20	67.68	65.22	60.16	60.70	59.32	58.23	61.15	60.48
apr	64.86	55.92	57.48	52.69	53.18	58.48	59.88	63.20	65.05	66.29	66.24	66.28	69.77	69.81	69.44	69.21	70.87	69.64	66.86	65.19	62.31	64.38	63.36	64.46
may	60.01	52.95	51.86	50.50	51.40	61.31	58.68	61.77	60.17	60.67	61.07	63.30	66.30	67.65	67.63	70.57	69.74	68.87	67.85	68.55	65.26	64.84	62.74	62.99
jun	57.46	50.84	46.25	45.26	45.32	55.77	55.99	60.28	61.81	63.21	64.64	62.29	65.54	66.96	65.59	66.54	66.59	65.18	62.95	64.60	60.72	57.29	60.27	59.66
jul	49.31	44.28	41.84	38.56	38.33	49.55	50.78	55.46	55.95	57.90	60.24	60.13	62.79	61.77	57.67	58.61	60.61	59.68	57.45	56.10	54.09	50.71	48.85	50.48
aug	53.43	45.09	45.51	43.76	42.47	48.36	46.84	52.58	54.68	51.52	56.27	57.66	59.96	59.62	56.32	55.75	58.08	57.56	58.28	53.09	47.91	49.06	51.16	51.05
sep	52.02	46.94	45.25	43.63	45.75	48.05	50.00	47.77	55.07	53.97	53.35	53.56	51.96	51.27	51.75	51.38	51.90	50.96	49.16	50.48	51.34	48.62	51.33	51.88
oct	57.37	53.21	54.37	54.50	55.73	55.45	53.66	55.78	60.33	59.43	60.01	61.48	62.22	64.66	62.12	63.92	65.44	63.28	60.67	62.03	57.84	57.19	59.43	56.83
nov	62.29	61.19	57.99	58.71	56.64	58.84	58.82	60.26	61.20	61.02	63.83	65.98	69.34	70.97	67.58	66.54	69.00	66.10	62.85	62.61	59.90	60.53	62.39	60.23
dec	61.84	61.35	58.14	59.44	56.04	54.64	58.76	59.09	59.56	58.91	62.85	63.53	65.99	65.67	65.95	64.25	67.30	63.14	61.85	60.79	59.13	58.40	61.52	61.16

28 GTC ENO	00:00	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00
jan	26.52	25.45	21.58	21.08	21.79	21.86	22.25	33.36	35.83	36.58	39.89	40.20	44.77	49.05	49.12	50.97	53.63	52.39	49.89	45.77	43.61	40.75	40.35	39.06
feb	24.44	21.51	22.94	21.37	21.57	23.73	21.19	34.11	41.99	44.54	42.28	43.07	46.46	57.57	54.71	55.31	60.04	58.20	55.51	51.34	46.02	43.70	39.75	37.99
mar	26.67	23.01	23.25	20.48	19.24	20.39	19.47	27.48	34.59	37.72	37.71	40.95	50.65	54.61	53.22	51.81	54.40	54.46	53.91	46.10	45.83	41.95	41.40	34.80
apr	17.05	16.55	14.96	15.65	16.49	14.62	16.77	31.13	33.09	33.18	35.86	46.09	49.80	55.59	54.74	59.96	57.04	56.14	56.49	47.45	40.07	36.87	34.66	21.62
may	16.44	16.10	16.40	15.78	15.03	14.13	13.53	24.23	25.49	24.49	33.75	40.86	48.94	49.84	48.68	49.94	49.70	48.87	47.35	40.97	38.56	35.94	32.85	18.87
jun	8.69	8.05	8.32	6.49	6.57	7.31	8.22	16.04	18.43	17.27	27.47	34.04	36.07	41.29	41.24	41.10	39.79	42.78	39.95	31.97	29.44	28.88	24.56	13.14
jul	7.42	7.29	7.03	6.10	5.58	6.58	8.61	13.53	15.58	17.50	27.57	27.99	29.60	33.09	31.11	33.02	33.50	32.92	28.87	25.47	19.80	19.05	15.32	8.69
aug	13.64	13.31	12.23	10.68	11.55	11.74	14.02	16.93	17.05	16.42	23.20	28.19	28.51	34.53	31.82	29.90	31.84	33.40	28.72	26.94	23.36	23.03	19.47	14.10
sep	16.63	15.62	15.87	14.86	14.22	14.11	16.13	19.21	21.35	20.29	24.15	33.59	34.48	35.55	35.84	40.86	42.19	37.61	35.19	34.47	32.50	31.61	24.22	17.98
oct	19.07	18.62	17.98	16.55	18.73	19.90	20.84	22.84	25.96	29.00	27.89	38.89	42.15	42.93	43.20	46.51	46.23	43.13	43.29	43.53	40.38	37.84	31.33	22.31
nov	30.29	28.17	26.20	26.22	25.26	26.73	28.52	39.05	41.42	43.16	43.41	50.34	54.15	55.63	55.11	55.32	56.25	54.37	55.99	53.80	50.27	44.36	48.10	42.42
dec	30.97	26.79	24.10	22.37	23.54	23.90	24.83	39.40	42.82	45.01	44.93	51.55	53.17	53.75	55.71	55.56	52.18	51.24	51.00	47.29	46.16	44.27	47.12	40.48

Figure 2-4: Cloud coverage and preliminary PDT analysis based on formula in ESA link budget tool

The design of an operational lasercom system for Direct-to-Earth data transfer addresses short-term and long-term outages. The concept of operations is then tailored to both, physical phenomena related to atmospheric channel statistics and cloud coverage as well as to mission needs such as attitude-constrained periods and occurrence of solar conjunction or –opposition.

3 TECHNOLOGY ROADMAP

3.1 Overview of architectures

The development roadmap in DOCOMAS covers four model scenarios as required by ESA:

- Moon mission,
- L2 mission,
- Mars mission,
- Jupiter mission.

During the development of the communication architecture, two conceptual designs for Optical Payload Terminals (OPT) have been elaborated:

- Optical Payload Terminal with 100 mm telescope aperture. This terminal is suitable for Moon missions and missions to the libration points of the Earth.
- Optical Payload Terminal with 160 mm telescope aperture. This terminal is suitable for Mars missions and Jupiter missions that envisage gimballed pointing actuation of the OPT.

For the Optical Ground Stations also two conceptual designs have been elaborated:

- "Large" optical ground antenna stations suitable for missions in all four scenarios.
- "Small" optical ground antenna stations suitable for Moon missions and missions to the libration points of the Earth but providing a reduced data rate compared the "large" OGS

The model scenarios defined by ESA are covered by the combinations given in Table 3-1.

ESA model scenario **Optical Terminal**	**Moon**	**L2**	**Mars**	**Jupiter**
Optical Payload Terminal				
100 mm OPT	X	X		
160 mm OPT			X	X
Optical Ground Antenna				
"Small" OGA	Alternative	Alternative		
"Large" OGA	Baseline	Baseline	X	X

Table 3-1 Applicability matrix of OPTs and OGAs for the ESA model scenarios

For the OGT architectures a single terminal per mission with appropriate built-in redundancy will be required. For the optical ground architectures also the Optical Ground Station (OGS) network needs consideration. Optical Ground Terminals (OGTs) may be clustered at a ground segment site in order to accomplish a better performance by means of (electrical) arraying. In addition a network of several OGS sites needs to be established in order to achieve a larger coverage of the sky and in order to implement site diversity to minimise link outages due to cloud coverage.

3.2 Optical Payload Terminal

A proven modular design approach is utilized that allows distributing the key functionalities

- Beam control system (Pointing, Acquisition, Tracking “PAT”)
- Pulse Laser system (laser modulation and booster amplifier)
- Electronics S/S (terminal control, data handling, communications, incl. power conversion)

into three physical modules (named “units”), as shown in Figure 3-1. Building blocks of this modular design were already successfully developed and tested to ≥TRL 5 in various payload terminal developments carried out in ESA projects, such as ISLFE, EDRS-LCT and TESLA.

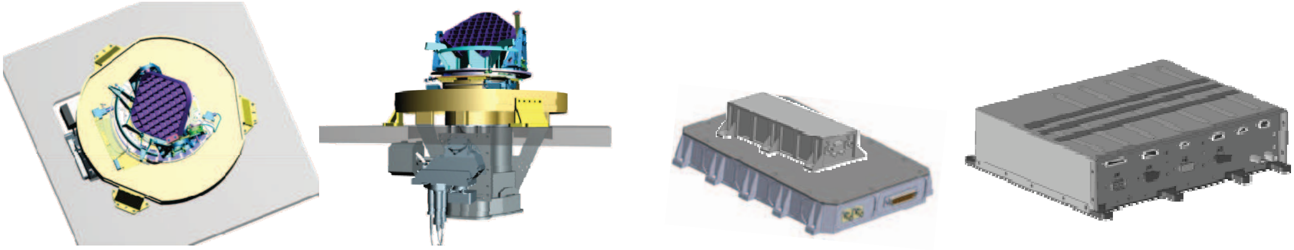


Figure 3-1: OPT decomposition into 3 units, from left: Optical Head, Laser Unit, Electronics Unit

A heritage based design approach, that utilizes technical performance information mainly from past ESA developments is taken as baseline for estimation of the overall development roadmap shown in Figure 3-4, with heritage examples provided Figure 3-2. In contrast to common approaches, a specifically tailored project planning has been developed that is appropriate for both OPTs, as shown in Figure 3-3. While this approach is uncommon for a subsystem development, it has significant advantages. By conducting a study and requirements phase at subsystem level first a set of detailed requirements for the TDAs is established. It enables the TDAs to develop hardware that can actually be integrated at higher level. In this way large parts of the OPT can be built and qualified before the subsystem project for a flight OPT begins. The risk for the space system project stemming from the first utilisation of an OPT is then much reduced because large part , i.e., the main modules of the OPT design, development and qualification will already have been carried out, when the space system project decides to procure an OPT.

Figure 3-2: OPT heritage base (status spring 2016)

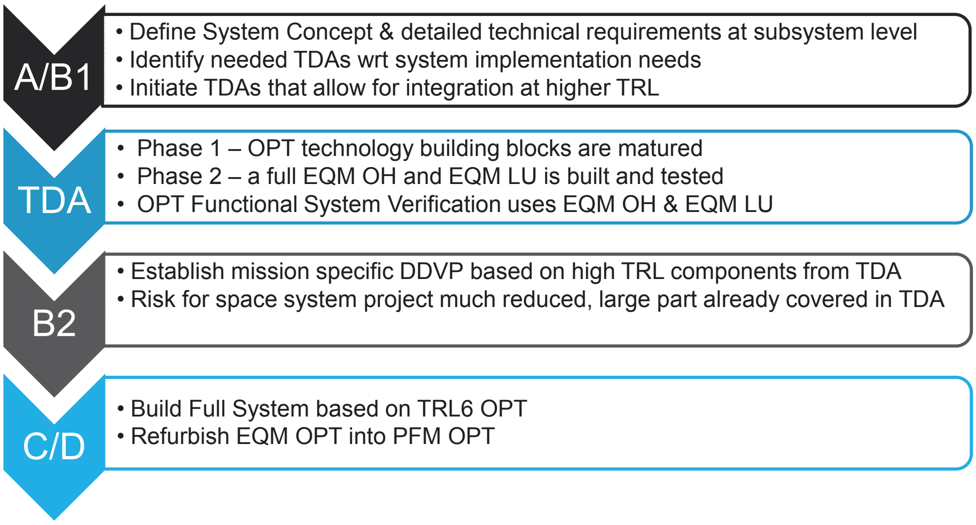


Figure 3-3: Specific tailored project planning for OPT development

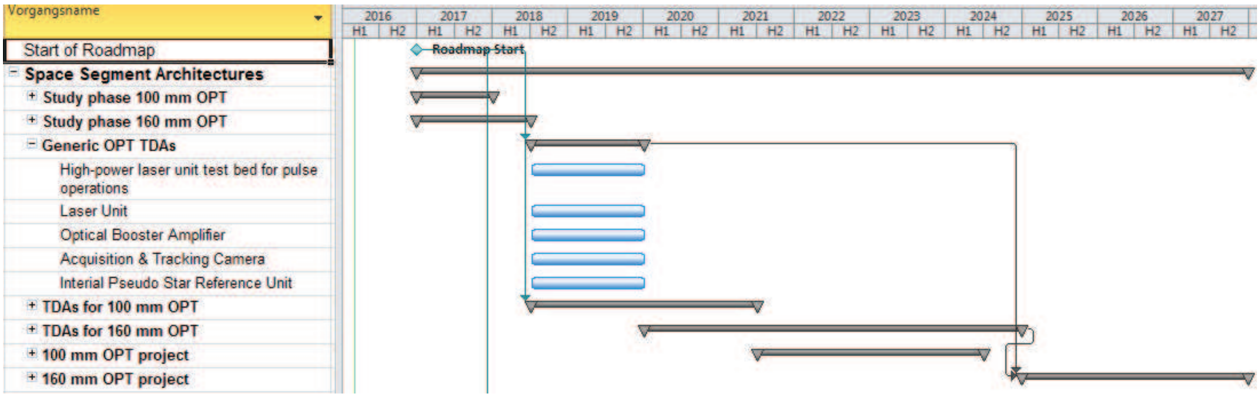


Figure 3-4: Overall development roadmap for 100mm and 160mm OPT, highlighting the generic part

3.3 Large Aperture OGA

In general, an optical ground station (OGS) supports both downlink and uplink (and/or beacon) capabilities. The optical ground station uses of an array configuration consisting of several closely located elements to make up the ground laser receiver (GLR), whereas that the ground laser transmitter (GLT) uses a single uplink telescope unit that is co-aligned in boresight pointing with the GLR. The combination of the GLRs and the GLT forms an optical ground terminal (OGT). Supporting facilities and common infrastructures, together with the OGT, complete the OGS.

The basic building block element of the GLR array, and hence the optical ground station, is a 4×2m multimirror telescope for the proposed design of a large aperture Optical Ground Antenna (OGA). The OGA forms a GLR in combination with an optical receiver system and a PAT assembly. The main characteristics of the OGA are described below.

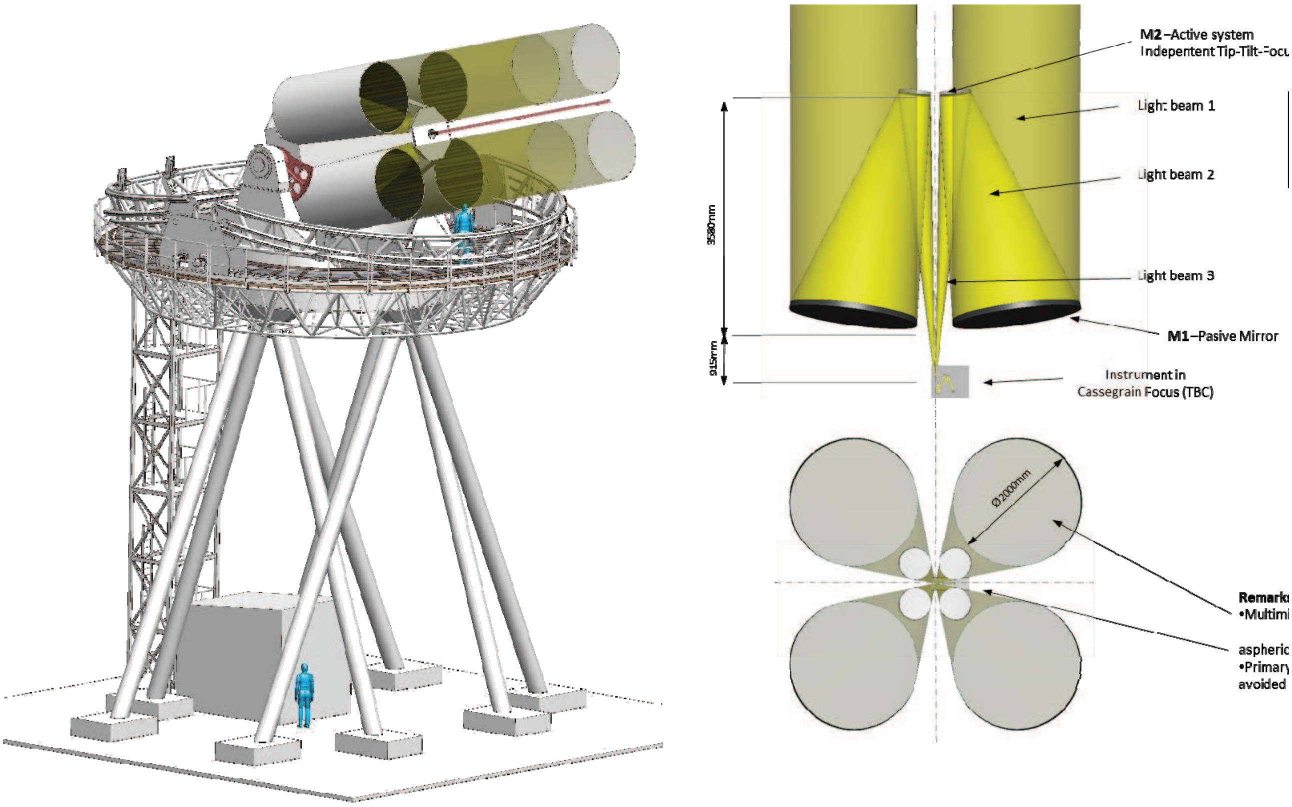


Figure 3-5: Large aperture OGA: realization via multi-mirror telescope example: effective diameter 4m

Engineering activities are initially required to address the overall design, aiming to reduce the development costs and looking for a modular approach. In particular, the cost of optics (mainly referred to the primary mirror) has a high relative weight in the overall cost of the OGT. In DOCOMAS, suppliers have provided costs assuming typical qualities and materials. Due to the large number of OGAs required, a useful next step is then to explore alternative technologies as part of technology development activities.

Due to the significant investment of the full ground segment architecture a qualification model of a receive telescope consisting of 4 x 2m telescopes is developed, built and tested as early as possible. The qualification focus on the thermal control and pointing performance of the telescope which are considered critical technologies and are a prerequisite for successful daylight operations. The QM project is started as soon as the relevant TDAs and engineering studies for these aspects have been completed. A prototype for an operational model (proto-operational model) will be developed before production, since most of the subsystems and assemblies are not commercially available as required.

3.3.1 Receiver system

The receiver architecture proposed as key item for OGA development is shown in Figure 3-6. The critical technologies to be developed are related to the detector assembly, namely the photon-counting detector array and the corresponding readout electronics. The current state-of-the-art suggests the use of superconducting nanowire single-photon-detector arrays based on small superconducting gap materials as detectors. Extremely low-power consumption architectures are then required to implement the readout circuitry. Other elements of the receiver also require engineering activities, mainly related to firmware development. The receiver functions are distributed between the telescope unit and the central processing unit.

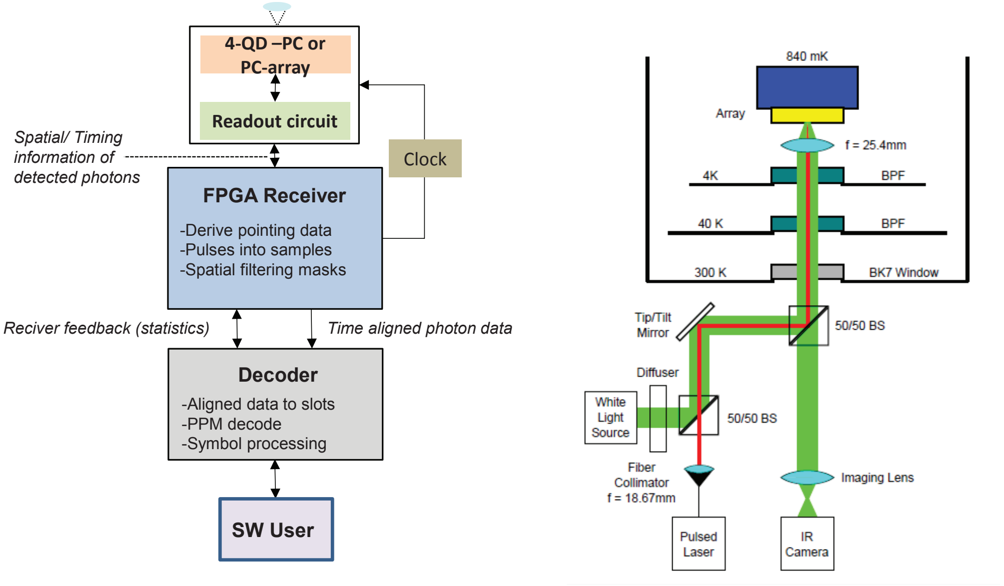


Figure 3-6: Left: Detector & receiver assembly, Right: test setup for SNSPD-type PC array test Fehler! Verweisquelle konnte nicht gefunden werden.

The use of a detector array at the focal plane allows adding tracking capabilities to the communications receiver. This strategy provides two additional advantages: no signal is diverted to the acquisition camera once the link has been established (i.e., optical loss is reduced) and photon-counting sensitivity is available. The spectral acquisition is attained by means of narrow band pass filters in two steps. Especially the corresponding optical bandpass filter with large acceptance angle, large diameter and high throughput is considered a key component of the OGA.

3.3.2 Uplink Beacon System (ULA)

A bi-static approach is the preferred option to develop the uplink. The ground laser transmitter will be located close to the ground laser receiver, still taking into account that the beacon signal backscattered into the receiver is below a certain power threshold. It is necessary to combine several laser beams to form the uplink beacon assembly (ULA), like shown in Figure 3-7. The envisaged configuration uses one ~2m telescope for a Mars scenario and two ~2m telescopes for Jupiter. The ULA system is installed in an independent telescope. This option simplifies the problem of beam expansion. A camera at a focal plane will be used to provide a pointing model reference for the calibration system to ensure laser beam (co-)alignment accuracy.

Early activities on the development roadmap comprise the development and test of an automated ULA multi-beam co-alignment system plus development and testing of high power, high energy optical beam routing optics to prevent (mid-term) damage effects on the ULA telescope.

Another development track for the ULA includes aspects of potential inter-agency cross support requirements, taking into account current CCSDS (draft-) considerations for dee space uplinks.

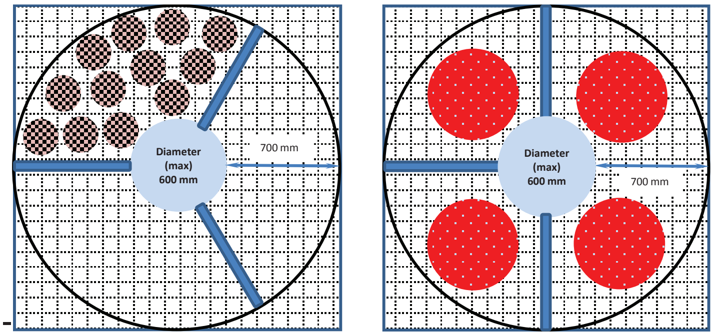


Figure 3-7: Implementation sketches for different types of multi-beam uplink lasers

Milestone Description	Project phase	Relative date from Kick-Off	Absolute Date	Remark
Study Phase Kick-Off		T0	1/2017	
	Phase A			
Customer Requirements Review		T0+12m	1/2018	
	TDA ITTs			ITTs by ESA based on study phase
TDAs Kick-Off		T0+18m	7/2018	
QM Kick-Off		T0+36m	1/2020	
	QM Phase B1			
QM SRR		T0+42m	6/2020	
	QM Phase B2			
QM PDR		T0+54m	6/2021	
	QM Phase C			
QM CDR		T0+66m	6/2022	
	QM Phase D			
Qualification Review		T0+87m	4/2024	
Phase B1 Kick-Off		T0+58m	11/2021	
	Phase B1			
SRR		T0+64m	5/2022	All TDAs finished
	Phase B2			
PDR		T0+82m	11/2023	
	Phase C			
CDR		T0+100m	5/2025	
	Phase D			
ORR		T0+184m	5/2032	3x 9 GS deployed (extreme case, could be just 5 required instead of 9, see § 2.1)

Table 3-2 Schedule for Ground Architecture with “large” Optical Ground Stations

3.4 Small Aperture OGA

The ‘small’ Optical Ground Station is conceptualized as an array of 8 telescopes with a diameter of 50 cm each. This corresponds to a telescope with a single mirror of 1.4 m diameter. Two groups of 4 telescopes are attached on opposite sides of a common altitude-azimuth mount. A dome with a diameter of ~8 m is sufficient to shelter the assembly.

The relatively small diameter of the individual telescopes keeps them in range of the production capability of a large number of manufacturers. Superconducting nanowire single photon detectors (SNSPD) are the recommended detector technology given the success of NASAs Lunar Laser Communications Demonstration (LLCD) with it.

The beacon laser system is conceptualized as a separate telescope to prevent backscatter from optical surfaces or atmospheric backscatter from entering the receiver. Laser safety can be ensured by implementing a 4-tier system as in JPLs Optical Communications Telescope Laboratory (OCTL). Weather monitoring equipment shall consist of an automated weather station, a photometer and an IR whole sky imager to monitor cloud coverage.

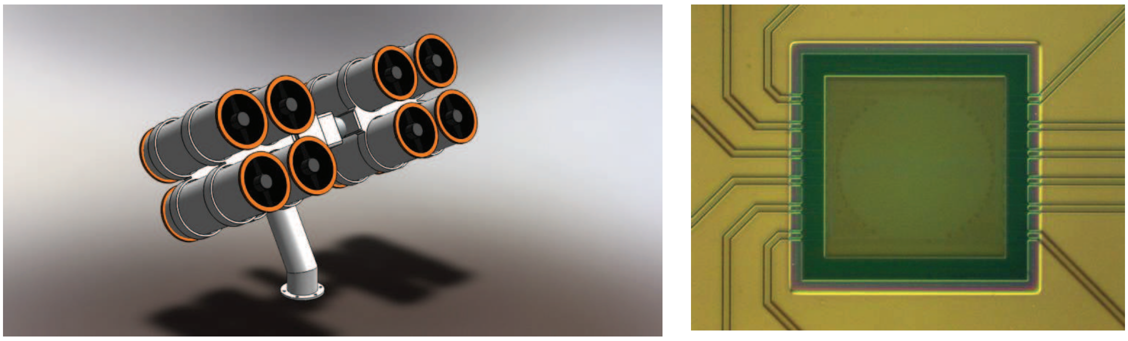


Figure 3-8: Small aperture OGA with 1.4m effective diameter, SNSPD array for 622 Mbps (LLCD)

Milestone Description	Project phase	Relative date from Kick-Off	Absolute Date	Remark
Study Phase Kick-Off		T0	1/2017	
	Phase A			
Customer Requirements Review		T0+6m	7/2017	
	TDA ITTs			ITTs by ESA based on study phase
TDAs Kick-Off		T0+12m	1/2018	
Phase B1 Kick-Off		T0+78m	7/2023	
	Phase B1			
SRR		T0+84m	1/2024	All TDAs finished
	Phase B2			
PDR		T0+96m	1/2025	
	Phase C			
CDR		T0+120m	1/2027	
	Phase D			
ORR		T0+156m	1/2030	Full GS deployed

Table 3-3 Schedule for OGS Architecture with “small” Optical Ground Antenna

3.5 Synthesis schedule

The schedule for the DOCOMAS roadmap is displayed in Figure 3-9. The roadmap is closely related to the extreme scaling described in §2.1. It starts in January 2017 and end in May 2032 with the Operational Readiness Review of the "large telescope" Optical Ground Segment.

Nr.	Vorgangsname	Dauer	Anfang
1	Start of Roadmap	0 Tage	Mo 02.01.17
2	**Space Segment Architectures**	**2870 Tage**	**Mo 02.01.17**
3	**Study phase 100 mm OPT**	**262 Tage**	**Mo 02.01.17**
4	Study Phase Kick-Off	0 Tage	Mo 02.01.17
5	Phase A/B1	262 Tage	Mo 02.01.17
6	System Requirements Review	0 Tage	Di 02.01.18
7	**Study phase 160 mm OPT**	**393 Tage**	**Mo 02.01.17**
8	Study Phase Kick-Off	0 Tage	Mo 02.01.17
9	Phase A/B1	262 Tage	Mo 02.01.17
10	System Requirements Review	0 Tage	Di 02.01.18
11	TDAs ITT Phase OPTs	131 Tage	Mi 03.01.18
12	**Generic OPT TDAs**	391 Tage	Do 05.07.18
13	High-power laser unit test bed for pulse operations	391 Tage	Do 05.07.18
14	Laser Unit	391 Tage	Do 05.07.18
15	Optical Booster Amplifier	391 Tage	Do 05.07.18
16	Acquisition & Tracking Camera	391 Tage	Do 05.07.18
17	Interial Pseudo Star Reference Unit	391 Tage	Do 05.07.18
18	**TDAs for 100 mm OPT**	**782 Tage**	**Do 05.07.18**
19	Coarse Pointing Assembly for 100mm beam	391 Tage	Do 05.07.18
20	100 mm Telescope	391 Tage	Do 05.07.18
21	Optical Head Unit 100 mm	391 Tage	Fr 03.01.20
22	Electronics Unit for 100 mm OPT	391 Tage	Do 05.07.18
23	**TDAs for 160 mm OPT**	**1304 Tage**	**Fr 03.01.20**
24	Coarse Pointing Assembly for 160 mm beam	522 Tage	Fr 03.01.20
25	160 mm Telescope	391 Tage	Fr 03.01.20
26	OH structure and thermal for 160 mm beam	391 Tage	Mo 05.07.21
27	Optical Head Unit 160 mm	522 Tage	Di 03.01.23
28	Electronics Unit for 160 mm OPT	391 Tage	Fr 03.01.20
29	**100 mm OPT project**	**782 Tage**	**Fr 02.07.21**
30	Kick-Off	0 Tage	Fr 02.07.21
31	Phase B2	131 Tage	Mo 05.07.21
32	Preliminary Design Review	0 Tage	Mo 03.01.22
33	Phase C	260 Tage	Di 04.01.22
34	Critical Design Review	0 Tage	Mo 02.01.23
35	Phase D	391 Tage	Di 03.01.23
36	Delivery Review Board	0 Tage	Di 02.07.24
37	**160 mm OPT project**	**782 Tage**	**Mi 01.01.25**
38	Kick-Off	0 Tage	Mi 01.01.25
39	Phase B2	131 Tage	Do 02.01.25
40	Preliminary Design Review	0 Tage	Do 03.07.25
41	Phase C	260 Tage	Fr 04.07.25
42	Critical Design Review	0 Tage	Do 02.07.26
43	Phase D	391 Tage	Fr 03.07.26
44	Delivery Review Board	0 Tage	Fr 31.12.27
45	**Ground Segment Architectures**	**4001 Tage?**	**Mo 02.01.17**
46	**Study phase "small telescope" OGT**	**131 Tage**	**Mo 02.01.17**
47	Study Phase Kick-Off	0 Tage	Mo 02.01.17
48	Phase A	131 Tage	Mo 02.01.17
49	Customer Requirements Review	0 Tage	Mo 03.07.17
50	**TDAs for "small telescope" OGT**	**1695 Tage**	**Mi 03.01.18**
51	TDAs run 1 ITT Phase "small telescope" OGT	131 Tage	Mi 03.01.18
52	SNSPD	782 Tage	Do 05.07.18
53	Beacon telescope	782 Tage	Do 05.07.18
54	Cloud camera	260 Tage	Do 05.07.18
55	Bandpass filter (optional)	782 Tage	Do 05.07.18
56	TDAs run 2 ITT Phase "small telescope" OGT	131 Tage	Fr 01.01.21
57	Synchronization, Demodulation, Decoding	782 Tage	Mo 05.07.21
58	Secondary enclosure	522 Tage	Mo 05.07.21
59	**"Small telescope" OGS project**	**1707 Tage**	**Di 19.12.23**
60	Phase B1	141 Tage	Di 19.12.23
61	System Requirements Review	0 Tage	Di 02.07.24
62	Phase B2	262 Tage	Mi 03.07.24
63	Preliminary Design Review	0 Tage	Do 03.07.25
64	Phase C	522 Tage	Fr 04.07.25
65	Critical Design Review	0 Tage	Mo 05.07.27
66	Phase D	782 Tage	Di 06.07.27
67	Operational Readiness Review	0 Tage	Mi 03.07.30
68	**Study phase "large telescope" OGT**	**262 Tage**	**Mo 02.01.17**
69	Study Phase Kick-Off	0 Tage	Mo 02.01.17
70	Phase A	262 Tage	Mo 02.01.17
71	Customer Requirements Review	0 Tage	Di 02.01.18
72	**TDAs for "large telescope" OGT**	**1130 Tage**	**Mi 03.01.18**
73	TDAs run 1 ITT Phase "large telescope" OGT	130 Tage	Mi 03.01.18
74	Solar Rejection Filter	391 Tage	Mi 04.07.18
75	Thermal Control & Baffling	391 Tage	Mi 04.07.18
76	SNSPD Array (large format)	522 Tage	Mi 04.07.18
77	Readout electronics	478 Tage	Fr 03.07.20
78	Communications/Tracking Filter	262 Tage	Mi 04.07.18
79	Arraying Technology	522 Tage	Mi 04.07.18
80	Beacon Laser (1030 nm)	391 Tage	Mi 04.07.18
81	Acquisition Sensor based on SPD arrays	391 Tage	Mi 04.07.18
82	**"Large telescope" Qualification Model**	**1123 Tage?**	**Do 02.01.20**
83	QM Phase B1	120 Tage	Do 02.01.20
84	QM System Requirements Review	1 Tag?	Do 18.06.20
85	QM Phase B2	262 Tage	Fr 19.06.20
86	QM Preliminary Design Review	0 Tage	Di 22.06.21
87	QM Phase C	262 Tage	Di 22.06.21
88	QM Critical Design Review	0 Tage	Do 23.06.22
89	QM Phase D	478 Tage	Do 23.06.22
90	Qualfication Review	0 Tage	Di 23.04.24
91	**"Large telescope" OGS Project**	**2729 Tage?**	**Mi 17.11.21**
92	Phase B1	120 Tage	Mi 17.11.21
93	System Requirements Review	1 Tag?	Mi 04.05.22
94	Phase B2	391 Tage	Do 05.05.22
95	Preliminary Design Review	0 Tage	Do 02.11.23
96	Phase C	391 Tage	Fr 03.11.23
97	Critical Design Review	0 Tage	Fr 02.05.25
98	Phase D	1826 Tage	Mo 05.05.25
99	Operational Readiness Review	0 Tage	Mo 03.05.32
100	Roadmap competed	0 Tage	Di 04.05.32

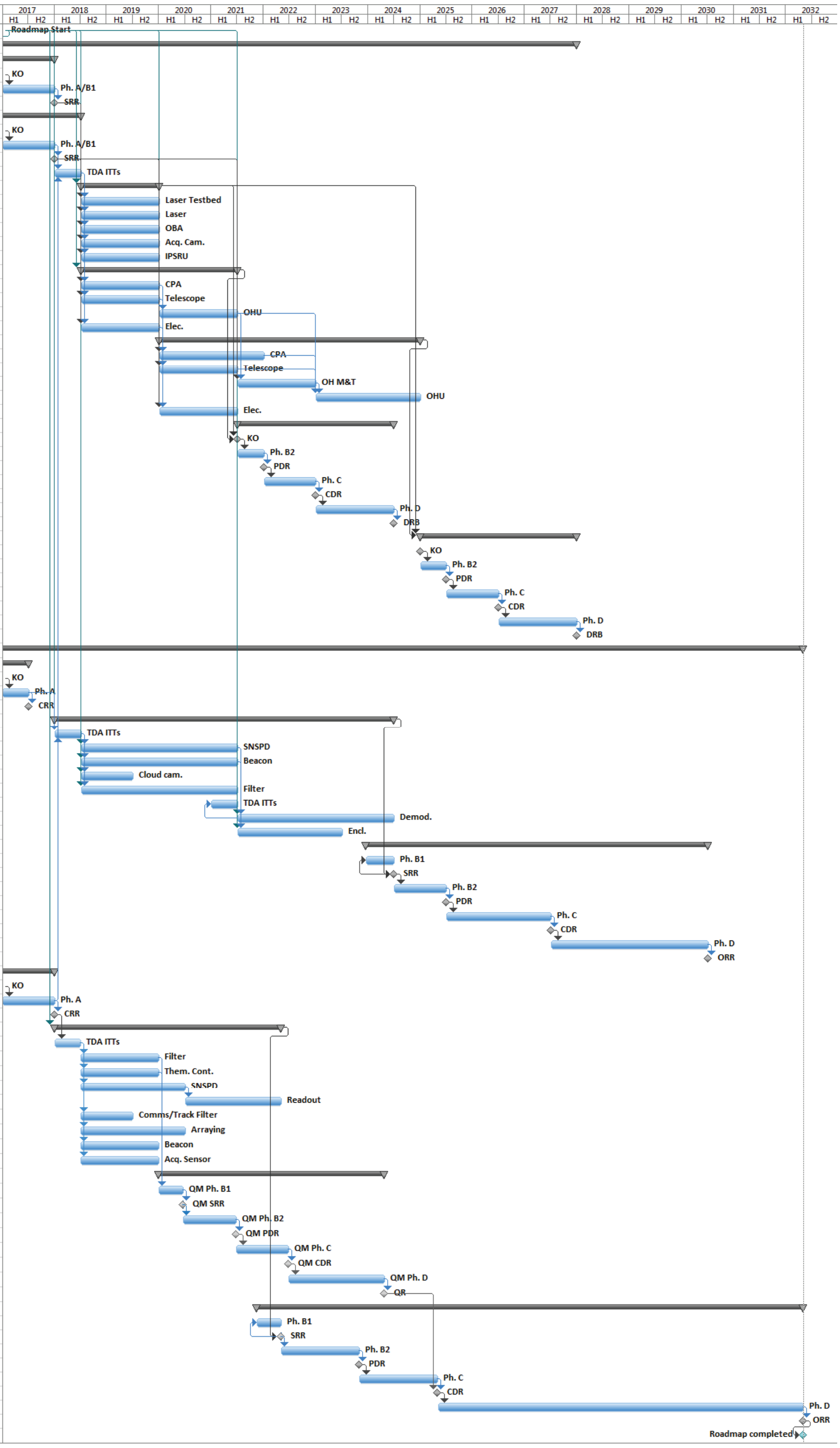


Figure 3-9: Detailed schedule of the DOCOMAS development roadmap