ONUBLA

Assessment of access availability of space-ground optical links

Executive Summary

ESA Contract

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0 General

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Prepared by:	Christian Fuchs	DLR
Checked by:	Christian Fuchs	DLR
Authorised by:	Christian Fuchs	DLR

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1 Introduction

1.1 Abstract

Optical satellite communications play an increasingly important role in a number of space applications. However, if the system concept includes optical links to the surface of the Earth, the limited availability due to clouds and other atmospheric impacts need to be considered to give a reliable estimate of the system performance. An OGS network is required for increasing the availability to acceptable figures.

In order to realistically estimate the performance and achievable throughput in various scenarios, a simulation tool has been developed under ESA contract. The tool is based on a database of 5 years of cloud data with global coverage and can thus easily simulate different optical ground station network topologies for LEO- and GEO-to-ground links. Further parameters, like e.g. limited availability due to sun blinding and atmospheric turbulence, are considered as well.

Several scenarios have been investigated: LEO-to-ground links, GEO feeder links, and GEO relay links. The key results of the optical ground station network optimization and throughput estimations will be presented. The implications of key technical parameters, as e.g. memory size aboard the satellite, will be discussed. Finally, potential system designs for LEO- and GEO-systems will be presented.

2 Cloud database, OGS-site optimization and simulation software

2.1 Cloud database

Obtaining a spatially and temporally detailed representation of cloud cover is instrumental in evaluating OGS sites and network availability. Although one might ideally want to obtain cloud blockage information at high temporal (~1 min) and spatial (few hundred meters) resolution, this is practically not achievable if one seeks at the same time global coverage so that availability of any arbitrary location on Earth can be evaluated. It is also important that cloud information be provided with an as homogeneous quality as possible globally so that no systematic bias is introduced between candidate OGS sites. Finally, the database shall be covering an extended period so that any annual local anomaly in cloudiness can be smoothed out over the entire simulation period. Candidate sources of observation are therefore naturally satellite observations out of which quantitative information on cloud fraction and cloud properties can be obtained routinely.

The ONUBLA cloud database combines a number of data sources into a single database with global coverage:

- GEO cloud data from SEVIRI/MSG, MTSAT and GOES (15…60min temporal resolution)
- LEO cloud data from MODIS (4 images per day)

Figure 2-1 shows an example image of the ONUBLA cloud database.

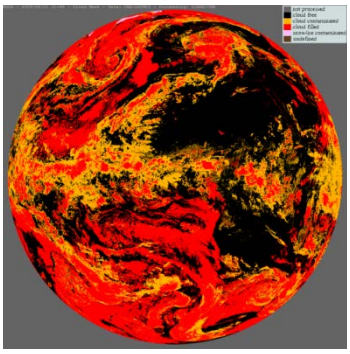


Figure 2-1: Example global cloud image as available in the ONUBLA database

2.2 Optimization of OGS locations

The optimization of the ground station network itself is of course a crucial part for the optimization of the various application scenarios. As first step, a large data base of more than 300 worldwide locations has been created. Subsequently, a ranking of these station locations has been accomplished by using a selection methodology.

2.3 Simulation software tool

The primary purpose of the simulation tool is to deliver availability statistics of optical up-/downlinks. The tool simulates several elements synchronously: an orbiting satellite, a dynamic atmosphere, a ground station network, the Sun position, etc. The atmospheric channel is divided into cloud attenuation and turbulence. Based on cloud measurement data from 5 previous years, the software provides availability statistics of optical up/downlinks for any satellite in the Earth orbit.

Figure 2-2 shows a flow-chart of the simulation software. Based on the list of optical ground stations that was created for the project, the complete cloud data set (hundreds of Gigabytes) can be minimized to a reduced dataset for the stations of interest (tens of Megabytes). This enables an efficient and fast simulation.

Based on the settings for the simulation software, as e.g. ground station locations, satellite orbit, memory size, data rate, etc., simulations can be run for different LEO and GEO scenarios.

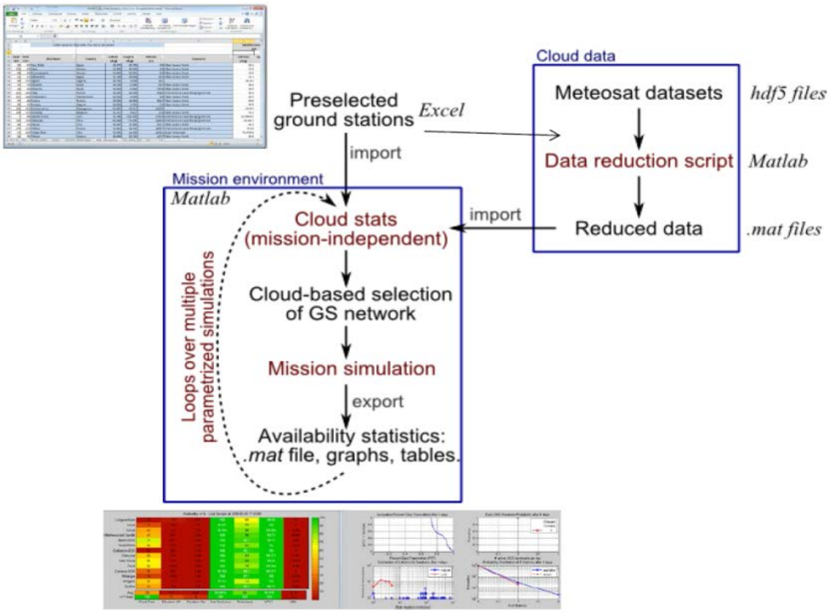


Figure 2-2: Flow-chart of simulation software.

3 Results

3.1 LEO downlink scenarios

Table 3-1 shows the LEO scenarios that were under consideration for the ONUBLA study. They bridged a span from rather small networks with stations in Europe only, to worldwide networks with stations placed around the globe.
Figure 3-1 shows exemplarily the OGS site layout for scenarios LEO 1 and LEO 5, where the difference between a small-scale (Europe only) and large scale (worldwide) network is well visible.

Table 3-1: LEO scenarios under consideration for ONUBLA

Scenario n°	**OGS locations**	**Interest**
Scenario L1	Europe	Optimal OGS network in Europe
Scenario L2	Europe and Africa	Additional stations in Africa improve overall availability, as seasonal effects are balanced
Scenario L3	Europe and selected polar sites	Polar ground stations benefit from more frequent satellite passes (for polar orbits), but usually suffer from worse weather
Scenario L4	Worldwide	OGS network for international cooperation
Scenario L5	Worldwide: ESA, NASA & DLR	Already existing space-communication sites with heritage (e.g. ESTRACK, DSN)

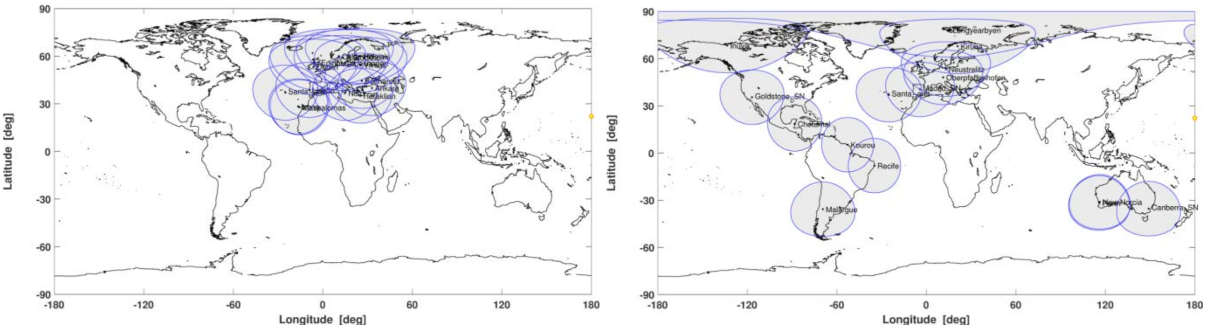


Figure 3-1: Example of OGS layouts for scenarios LEO1 (left) and LEO5 (right)

All LEO scenarios were simulated for OGS network sizes ranging from 1 to 15. The satellite orbit of Sentinel 1 (Altitude: 693 km, LTDN: 6:00) was considered. Furthermore, a large number of simulations were run to identify the impact of different system parameters, as e.g. data rate, sensor acquisition rate, memory size, latency, link planning lead time, etc. Within this paper, only key aspects of the performed evaluations are shown.

Figure 3-2 shows the mean throughput and percentage of data transmitted for a data rate of 8 Gbps, a data volume of 500 Gbit/orbit (i.e. a continuous sensor rate of about 100 Mbps), and a memory size of 1.5 Tbit (i.e. equivalent to 3 full orbits of data acquisition). The results are plotted for increasing number of OGS within the network. Trivially, for larger networks, the mean data throughput is getting larger as well, as OGS contacts are available more frequently to downlink data. The worldwide networks perform best. Also the percentage of data transmitted is increasing for large networks with a better spread of optical ground stations.

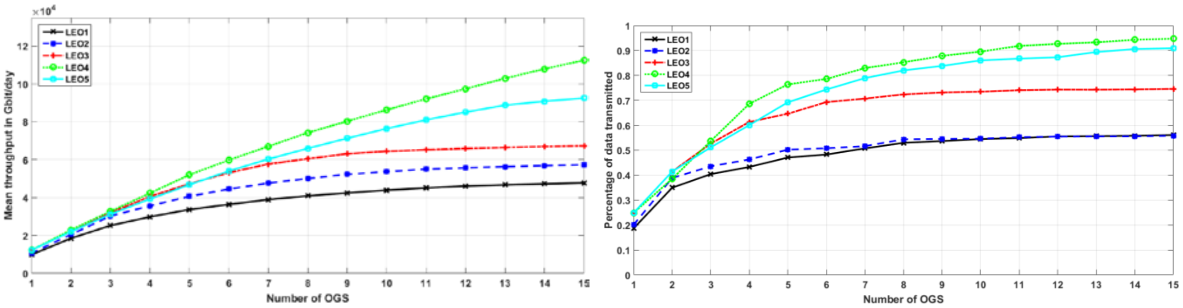


Figure 3-2: Mean throughput (left) and percentage of data transmitted (right) for the 5 LEO scenarios.

Table 3-2 is showing exemplary percentage of data transmitted-results for different numbers of optical ground stations. The simulated equivalent memory size ranges from 0.5 to 3 orbits. Especially for small memory sizes, not the complete amount of data can be transmitted. This means that time-critical data, which e.g. must be transmitted within 1 orbit from image acquisition, might be lost (in case the memory size is as simulated) or delayed (in case a larger memory is available to store the data for later transmission). However, with increasing memory size, almost all acquired data can be transmitted e.g. with an 8 OGS network with station sites around the globe, as e.g. scenario LEO 5.

Table 3-2: Percentage of data transmitted for the 5 LEO scenarios with different memory sizes

Scenario	**Number of OGS**		
	4	**8**	**12**
LEO 1: Data transmitted within 0.5 / 1 / 1.5 / 3 orbits	23% / 42% / 50% / 70%	30% /51% / 60% / 79%	32% / 55% / 61% / 80%
LEO 2: Data transmitted within 0.5 / 1 / 1.5 / 3 orbits	28% / 46% / 52% / 72%	32% / 53% / 60% / 79%	34% / 55% / 61% / 80%
LEO 3: Data transmitted within 0.5 / 1 / 1.5 / 3 orbits	34% / 60% / 68% / 82%	45% / 71% / 78% / 90%	48% / 73% / 80% / 92%
LEO 4: Data transmitted within 0.5 / 1 / 1.5 / 3 orbits	39% / 69% / 78% / 96%	60% / 86% / 93% / 99%	69% / 92% / 98% / 100%
LEO 5: Data transmitted within 0.5 / 1 / 1.5 / 3 orbits	35% / 60% / 68% / 85%	57% / 82% / 90% / 98%	60% / 88% / 92% / 99%

3.2 GEO feeder link scenarios

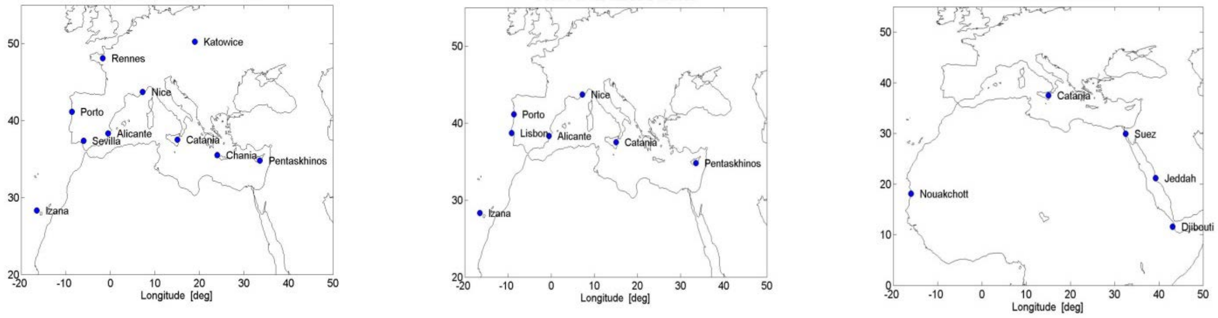
Three scenarios, defined in Table 3-3, have been investigated. GF1 is the baseline scenario. GF2 targets slightly lower feeder availability in order to reduce the size of the OGS network. GF3 targets the same feeder link availability as GF1 but OGS can be installed in Africa or Middle East.

Table 3-3: GEO feeder link scenarios

ID	Description	Comment
GF1	Satellite above Europe with OGS connected to Terabit/s terrestrial fibres in Europe only satisfying 99.9% annual link availability	Baseline scenario
GF2	Satellite above Europe with OGS connected to Terabit/s terrestrial fibres in Europe only satisfying 99.7% annual link availability	Reduced availability to decrease the cost of the ground segment.
GF3	Satellite above Europe with an OGS connected to Terabit/s terrestrial fibres in Europe extended to Africa and Middle East (for example) satisfying 99.9% annual link availability	To reduce the cost of the ground segment thanks to higher spatial diversity

Table 3-5 sums up the performances of the optimized optical ground stations networks. It results that 99.9% annual feeder link availability can be obtained with 10 sites in Europe and with only 5 sites if OGS can be installed in Africa and Middle East.

Table 3-4: Optimized optical ground station networks



The performances of the networks have been derived with the software tool. It can be seen that most of the time half the OGSs in the network are available. Also, seasonal variation at single site availability is retrieved at network level but in a much smaller range due to averaging effects. The number of handovers per year is above 1000 for both scenarios GF1 & GF2 with OGS in Europe only. This number is divided by two for GF3. The maximum number of handovers per day is above 10 for both scenarios GF1 & GF2 with OGS in Europe only. This number is divided by two for GF3. The longest duration of No Link is between 1 and 6 hours.

Table 3-5: Optical ground station network performances

	Feeder link availability		Handovers / year	Longest duration of no link	Max number of handovers / day	Number of sites available at highest probability
	Annual	Seasonal				
GF1	99.88%	99.97% / 99.993% / 99.8% / 99.75%	1314	100 min	~ 10	6 -7 out of 10
GF2	99.61%	99.87% / 99.90% / 99.31% / 99.35%	1180	250 min	~ 15	5 out of 7
GF3	99.89%	99.957% / 99.92% / 99.77% / 99.90%	410	70 min	~ 5	4 out of 5

The targeted link availability can be reached with 5 to 10 OGS. OGS sites in Africa and Middle East present the advantage to reduce the number of OGS in the network by a factor of two, but these sites might have higher turbulence strengths than expected by the used turbulence model, as well as dust/sand storm events may occur that are not yet taken into account for the link availability study.

3.3 GEO relay scenarios

Three scenarios have been investigated for the GEO relay link. GR1 is the baseline scenario of a single GEO DRS above Europe. GR2 reproduces GR1 scenario above Asia and America. GR3 assumed inter-satellite links between 3-4 GEO so that the OGS network is worldwide. The annual feeder link availability target is 99% for every scenario.

Table 3-6: GEO relay link scenarios

ID	Description	Comment
GR1	Single GEO DRS above Europe and optical ground stations in Europe with annual network availability of 99%	Baseline scenario.
GR2	Single GEO DRS above Europe / Asia / America with annual network availability of 99%	Baseline scenario over Asia and America
GR3	3-4 GEO DRS with ISL and a worldwide optical ground station network with annual network availability of 99%	Worldwide cooperation, low number of OGS

Optical ground station networks have been selected according to the method presented in §4.1. It results that 99% annual feeder link availability can be reached with 5 OGS in Europe and America. In Asia, 8 OGS are required. This increase might be due to a smaller number of site candidates in Asia available for the optimization process.

Table 3-7: Optical ground station network performances

		Feeder link availability		Number of sites
		Annual	Seasonal	
GR1		99.88%	99.56% / 99.83% / 98.0% / 97.6%	4-5
GF2	Europe	98.8%	99.56% / 99.83% / 98.0% / 97.6%	4-5
	Asia	98.5%	98% / 98.3% / 98.6% / 99%	8
	America	99.43%	99.69% / 99.60% / 99.52% / 98.9%	5
GF3		99.2%	NA	4

4 System consolidation

4.1 LEO scenarios

Within the system consolidation of the LEO scenarios, a design for fulfilling the requirements has been proposed. It makes use of a simple modulation scheme for moderate data rates (IM/DD for rates up to 10 Gbps), which is in line with the currently ongoing standardization activities at CCSDS. For higher data rates, a scheme based on wavelength division multiplexing is proposed, using multiple 10 Gbps channels, which is still backward compatible with the upcoming standard. Based on DLR's OSIRIS heritage, this resulted in a system design with a weight of 6.5 kg, a power consumption of about 70 W, and a size of 125x125x520 mm^3.

Table 4-1: LEO spacecraft and OGS key technical specifications

Parameter	Value	Comment
Transmit Aperture	30 mm	
Wavelength	1550 nm	C-Band
Optical Tx-Power	1 W	
Modulation & detection scheme	IM/DD (1/10 Gbps) IM/DD + preamp. (50/100 Gbps)	
Receiver sensitivity	900 Photons per bit (IM/DD) 50 Photons per bit (IM/DD + preamp)	
Spacecraft terminal	6.5 kg	

mass	
Spacecraft terminal power consumption	70 W
Spacecraft terminal volume	125x125x520 mm³
OGS Aperture	60 cm
OGS receiver type	Free-space APD (1/10 Gbps with IM/DD) Single-mode fiber coupled (50/100 Gbps with IM/DD + preamp)

4.2 GEO scenarios

Two missions have been investigated.

Transparent 500Gbit/s RF user capacity optical feeder link

Optical ground station networks between 5 to 10 sites (GF1, GF2, GF3) have been optimized in Europe to reach the feeder link availability target. The link availability of these networks has been simulated over 5 years with ONUBLA tool. The results of link availability were derived taking into account the optical link budget assumptions (5dB cloud losses, atmospheric turbulence strength corresponding to 7cm on the LOS). The results are provided Table 4-2.

Table 4-2: GEO Feeder - OGSN results summary

	Annual link availability	Handover / year	Longest duration of no link	Max number of handover /day	Sites available at highest probability
GF1	99.88%	1314	100 min	~ 10	6 -7 over 10
GF2	99.61%	1180	250 min	~ 15	5 over 7
GF3	99.89%	410	70 min	~ 5	4 over 5

Satellite with optical feeder link has been designed to reach the RF capacity of 500Gbits/s.

Two optical transmission formats have been investigated: The first one is called Radio over Fiber; it is based on analog intensity modulation of the optical carrier by the RF signal. The second one is called digital modulation: it is based on digitalization of the RF signal prior to digital modulation of the optical carrier.

Two approaches have been used to derive SWaP:

- First approach is **top-down** by considering the long term 2025 timeline with up to 100 W boosters with 20% WPE and DWDM grid of 25 GHz for 10 Gbps data stream channels. The objective is to challenge optical feeder link system capacity with only one active optical feeder link.
- Second approach is **bottom-up** by considering the short term 2020 timeline with 10 W boosters with 12% WPE and DWDM grid of 50 GHz for 10 Gbps data stream channels. In that option, the purpose is to assess the short term throughput capability of one optical feeder link.

Table 4-3 summarizes the results. All the options are compatible with existing or planned GEO platform.

Table 4-3: GEO Feeder - Satellite system results summary

	Digital – Top Down	Digital – Bottom Up	RoF C band – Bottom Up
Satellite terminal	Φrx = Φtx = 20cm Optical power per 10Gbits/s = 1W		Φrx = Φtx = 60cm Optical power = 1W
OGS	Φrx = 60cm / Φtx = 20cm Optical power / 10Gbits/s channel = 50W		Φrx = 80cm / Φtx = 20cm Optical power / user beam = 100W
Expansion [bit/Hz]	FWD: 12 /// RTN: 18		NA
Sat. capacity	525Gbit/s	525 Gbit/s (3 active optical term.)	525 Gbit/s
Sat. PW	19 331W	19 905 W	14 512 W
Sat. Mass	1987 kg	2211 kg	1513 kg
Optical BW	90 nm	60 nm	60 nm

GEO Transparent DRS optical feeder link

Optical ground station network of 4-5 OGS has been designed over Europe to reach 99% cloud free feeder link availability. The size of the on-board memory has been studied in order to compensation no-link duration for a 24Tbit per orbit mission. It has been shown that a 4Tbit external memory is required to reach 99% service availability. The SWaP of the optical payload is 50kg and 100W power consumption (optical downlink data ate is 20Gbit/s FEC, Framing, synchro included). For 99.98% service availability, the on-board memory shall be increase to 64Tbit. The resulting SWaP of the optical payload is 60kg and 200W.

For both missions, the system proposed (OGS network and space segment) are very positive with limited number of ground sites (less than 10) and compatibility with planned and/or existing GEO platform.

5 Conclusions

A large global cloud data base covering 5 years has been created for realistic system simulations of the access availability of space-ground optical links. The created simulation tool itself is capable of simulating arbitrary OGS networks and satellite orbits including all relevant key parameters, as e.g. data rate of the system, sensor acquisition rate, etc. The tool has been used to simulate and trade-off various LEO- and GEO-scenarios.

In terms of the LEO-downlink scenarios under investigation, 5 different network topologies could be compared against each other. Trivially, larger OGS networks with worldwide topologies behave better than smaller networks. A satellite system making use of optical links to transmit time-critical data, e.g. within 0.5 to 1.5 orbits after image acquisition, requires a large OGS network, or some delays must be accepted. If the memory size can be increased, e.g. to an equivalent of 3 orbits of acquired data, up to 98% of acquired data can be transmitted with a world-wide network and 8 OGS, and up to 99% with 12 OGS.

The investigations concerning the GEO scenarios showed that very high optical feeder link availability, up to 99.9%, can be reached thanks to site diversity techniques with 10 sites or even less. Simulations over 5 years confirmed that handovers between sites occur often. Consequently, the handover process shall be investigated and designed to avoid unavailability of the feeder link.