International Conference on Space Optics—ICSO 2018

Chania, Greece

9–12 October 2018

Edited by Zoran Sodnik, Nikos Karafolas, and Bruno Cugny

Optical feeder link architectures for very HTS: ground segment

Nicolas Girault

Pantelis-Daniel Arapoglou

International Conference on Space Optics — ICSO 2018, edited by Zoran Sodnik, Nikos Karafolas, Bruno Cugny, Proc. of SPIE Vol. 11180, 111805M · © 2018 ESA and CNES · CCC code: 0277-786X/18/$18 · doi: 10.1117/12.2536121

Optical Feeder Link Architectures for Very High Throughput Satellites: Ground Segment

Nicolas Girault[a], Pantelis-Daniel Arapoglou[a]

[a] Radio Frequency Systems Division, European Space Agency, European Space Research & Technology Centre (ESA/ESTEC), Keplerlaan 1, Noordwijk, The Netherlands

ABSTRACT

The paper deals with an analysis of Very High Throughput Satellite (VHTS) systems employing optical feeder links. As the capacities of newly announced next generation VHTS systems are exceeding the Terabit/s barrier, a large amount of investment needs to be directed not only to the space segment (as was the case traditionally), but also to the ground segment in support of the feeder links. To reduce this investment, satellite operators are reviewing various options and technologies for the feeder links, among which optical feeder links [1]. In this paper, different approaches are analysed for ground segment networks relying on Optical Ground Stations (OGS), exploring the concept of smart gateway diversity with N active OGS and P redundant ones, like is currently done in VHTS systems with RF feeder links. OGS locations are assessed in terms of aggregate availability and total cost for the satellite operator, which is an essential element for the viability of the VHTS system. Different options are assessed for the distribution of OGS gateway processing functions (local at OGS or centralised), and for their interconnection. The main technical challenges are discussed, identifying which technologies will be required for an operational VHTS system with OGS.

Keywords: Optical feeder links, Very High Throughput Satellite, Optical Ground Stations, Smart gateway diversity, Cloud Free Line of Sight, Optical fiber, Multi-feed optical terminal

1. INTRODUCTION

While there is clear interest to use optical communications in VHTS feeder links ([1],[2],[3]), thanks to their very large capacity, several challenges need to be resolved before they can be adopted by satellite operators. A companion paper in the same conference [4] investigates different options for the feeder link technologies and presents several solutions for the satellite payload. The present paper focuses on the ground segment aspects. Even if technology is becoming mature for optical ground segment, with performance reaching tens of Gbit/s, one of the main issues that arises when choosing an optical feeder link instead of RF is the need for a large number of OGS sites in order to achieve an aggregated link availability of typically 99.9% or 99.99% against cloud blockage. This implies replicating OGS functions on many sites, with only one site active at a time, while the others are in stand-by. In addition, the high-speed connectivity between OGS sites and Internet eXchange Points (IXP) has a high cost, even if used for a fraction of the time. All these add to the total cost of ownership for the satellite operator, which represents hundreds of M€ over the lifetime of the satellite.

In this context, the paper investigates different solutions to make the ground segment costs affordable. A first possible improvement consists of using multiple small active OGS, compared to conventional systems, to benefit from statistical de-correlation between OGS sites, as well as reducing the technical constraints on data rates and adaptive optics. Another axis of improvement is to reduce the capital and operational costs per OGS by means of miniaturisation, by moving certain functions to a central computing place, and by automating OGS operations.

2. OPTICAL GROUND STATIONS NETWORK

2.1 OGS Site Diversity

A typical ground segment network with optical ground stations is depicted in Figure 1. As discussed in [2], the overall traffic can be divided between (N) active OGS, using smart gateway diversity techniques. A number of redundant OGS

(P) is needed in order to achieve the required aggregate feeder link availability. The ground segment therefore consist of N (active) + P (redundant) optical ground stations. The feeder link is considered fully operational when at least N out of N+P sites are under Cloud Free Line of Sight (CFLOS) conditions. To handle atmospheric blockage events, it is assumed that the network has the capability to switch traffic dynamically to redundant OGS when active OGS are no longer in CFLOS conditions, without any loss of data. The particular case of N=1 active OGS means that the full traffic of the feeder link goes through a single OGS, while other OGS are in standby.

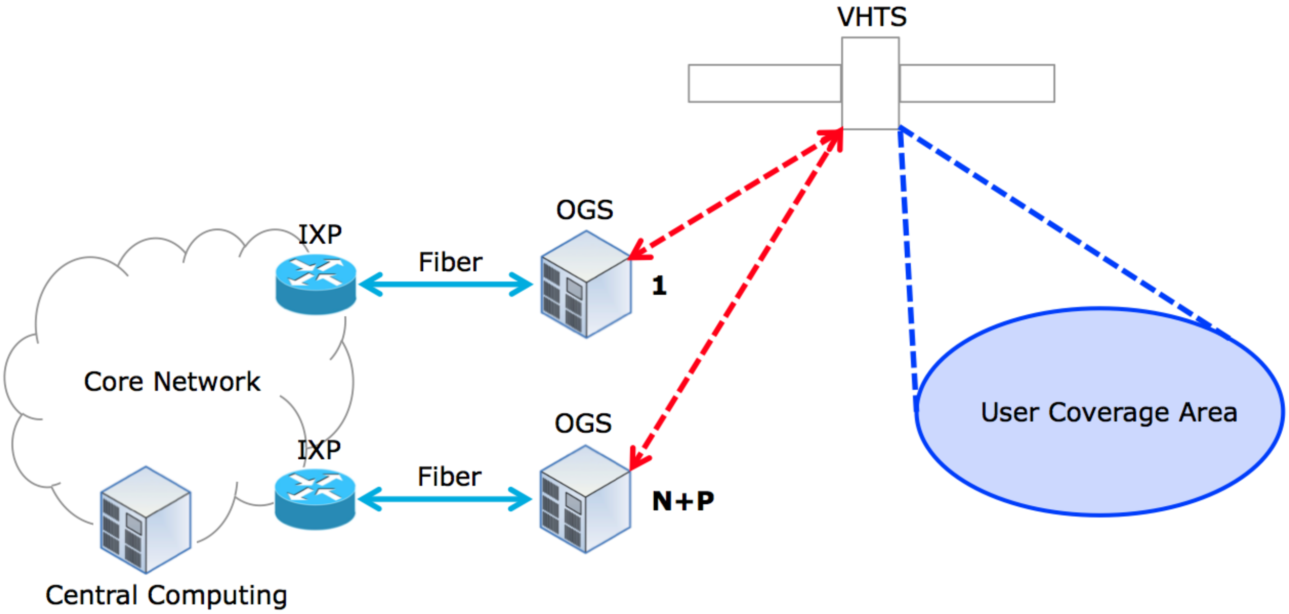

Figure 1. A VHTS system with a network of N+P OGS, connected to the core network with dedicated optical fiber, together with a central computing facility.

When sizing the network of N+P OGS, it is expected that:

- P increases as a function of the target availability of the feeder link, because a higher level of protection requires more redundancy.
- P increases as a function of N, with statistical gains as N increases. In other words, splitting the traffic between more active sites (N) requires more redundancy (P), but the relative overhead (P/N) should diminish as N increases.

2.2 OGS Sizing

Table 1 presents different optical terminal sizes ranging from 100 cm down to 20 cm, that would be required for different values of N.

Table 1. Scaling OGS for different values of N.

Number of active OGS sites (N)	1	3	6	12	25
Throughput per OGS (forward uplink)	492 Gbit/s	164 Gbit/s	82 Gbit/s	41 Gbit/s	20 Gbit/s
OGS telescope diameter	100 cm	60 cm	40 cm	30 cm	20 cm
Cost per OGS (analogue part only)	3050 k€	1300 k€	820 k€	640 k€	465 k€
Cost per Gbit/s (analogue part only)	6 k€	8 k€	10 k€	16 k€	23 k€

For simplicity, it is assumed that the throughput per terminal (calculated based on the user requirements described in [4]) is proportional to its effective area (so to the square of the diameter), with a transmit power of a few hundred Watts. In practice noise floors may limit the efficiency of the telescope and lead to different values. Uplink disturbances such as index of refraction fading and beam wander must be pre-compensated in the OGS transmitter with adaptive optics techniques, which should be easier to achieve when the terminal is smaller. The cost of the analogue part of the terminal, including the telescope, has been estimated for different OGS sizes and calculated relative to the throughput.

2.3 Selection of OGS Sites

Next, the selection of the OGS sites is carried out to form the feeder network. In doing so, it is important to keep OGS locations sufficiently separated in order to avoid correlated cloud blockage events, as clouds usually extend over tens of kilometres. In practice, the separation should be typically larger than 300 to 1000 km, which effectively limits the number of OGS that can be instantiated on a given geographical area. Another important aspect is the distance between the OGS site and the IXP, which heavily impacts the cost of interconnection by optical fiber cable.

Considering a VHTS satellite positioned between 5°W and 30°E of longitude on the GEO arc, two scenarios are envisaged for the OGS sites: Europe only, and EMEA (Europe, Middle East and Africa).

An example network with 18 OGS sites in the EMEA region is illustrated by Figure 2. Most OGS sites are located close to optical fiber cables or to undersea cables landing sites to lower the cost of connectivity. The average annual CFLOS for these OGS sites is shown in Table 2.

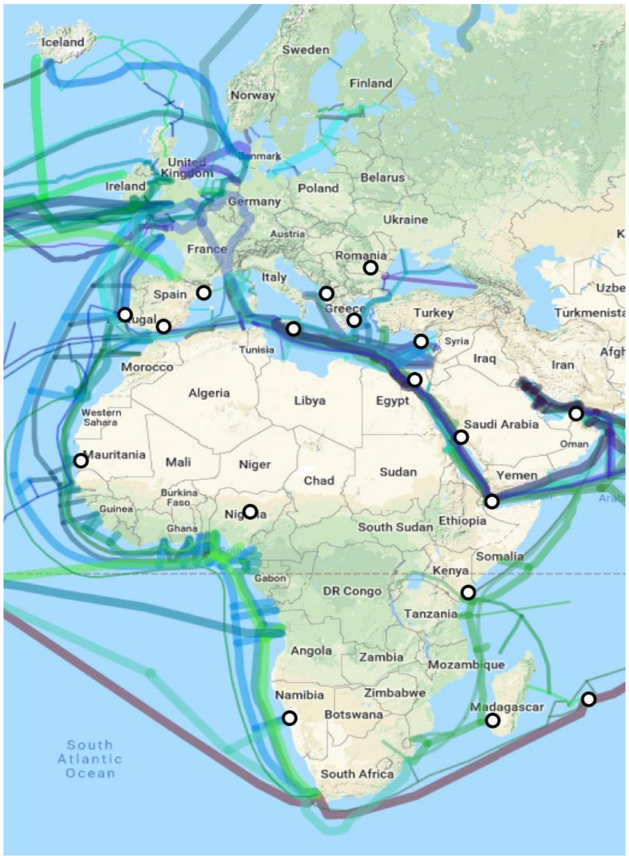

Figure 2. Example network of OGS locations in Europe, Middle East and Africa.

Site	Location	Average annual CFLOS
1	Dubai	88,48%
2	Suez	86,95%
3	Jeddah	85,41%
4	Toliara	81,98%
5	Walvis Bay	83,25%
6	Nouakchott	80,19%
7	Jos	50,21%
8	Malindi	54,80%
9	Granada	68,08%
10	Athens	66,72%
11	Noto	72,52%
12	Djibouti	77,39%
13	Mauritius	60,75%
14	Tirana	60,71%
15	Lisbon	60,84%
16	Nicosia	80,72%
17	Bucharest	53,43%
18	Barcelona	64,42%

Table 2. Average Annual CFLOS for OGS locations from Figure 2.

In the study, an initial list of OGS sites in the European scenario has been chosen from previous publications and ESA studies. When extending to Africa and Middle East for the second scenario, the candidate sites were chosen considering favourable atmospheric conditions, proximity to fiber points, and existing ground stations facilities (e.g. for earth observation satellites).

A sophisticated cloud blockage time series generator developed by ONERA, that makes use of meteorological databases of past years [5], has been used as a reference to select the OGS sites giving the best CFLOS performance. Feeder link CFLOS availability was calculated not only per OGS site (the time period considered was 2005-2006), but most importantly the aggregated availability was computed for a combination of OGS sites at different geographical locations, taking into account the actual correlation of their respective CFLOS in time. In other words the time series have been used to assess the complementarity between N+P OGS to satisfy the required availability over time for at least N OGS. It should be noted that the feeder network availability has been estimated assuming ideal and instantaneous switching between OGS, assuming perfect knowledge of the channel conditions. Hence, results do not account for operational constraints of a large optical ground network.

The problem to be solved for selecting the best sites from the initial list is the following: amongst the M candidate OGS sites of the initial list, how many redundant sites (P) are required in order to achieve CFLOS conditions for at least N active sites within the target availability (for instance 99.9% of the time)?

The algorithm to select OGS consists of the following steps:

1. Select the first site with highest CFLOS availability over the selected period of time.
2. Amongst the remaining sites, select the site that, combined with the other sites selected so far, gives the higher aggregate CFLOS availability.
3. Repeat step 2 until all M sites have been passed.

This incremental algorithm gives a list of OGS sites sorted by CFLOS performance. The notion of aggregated CFLOS actually depends on the number of active (N) and redundant (P) OGS for the required availability. For this purpose the incremental algorithm uses weighting factors on the cloud blockage time series when calculating the performance gain brought by an additional OGS. The advantage of this simple algorithm is to provide a quick answer to the problem for all values of N, without requiring exhaustive calculations involving large combinatorial, which are computer intensive. In Table 2, the 18 OGS sites listed are actually ordered according the incremental algorithm: from an initial list of M=40 OGS, site 1 (Dubai) corresponds to the highest CFLOS, and other sites have been added 1 by 1 with the objective to maximise the combined CFLOS. Interestingly, even OGS sites with relatively low individual availability like site 7 (Jos, Nigeria, with 50.21% average CFLOS) appear to provide a high aggregated CFLOS when combined with previously selected OGS.

2.4 Simulation Results

Tables 3 & 4 present the results of simulation for sizing the number of redundant OGS (P) for a certain number of active OGS (N values from Table 1), for availability targets of 99%, 99.9% and 99.99%, based on the time series from 2005 and 2006. The initial number of OGS sites was M=27 in the European scenario, and M=40 in the EMEA scenario.

Table 3. N+P results for OGS sites in Europe.

	CFLOS availability target		
N	**99%**	**99.9%**	**99.99%**
1	1+4	1+7	1+11
3	3+8	3+14	3+22
6	6+18	No solution	No solution
12	No solution	No solution	No solution
25	No solution	No solution	No solution

Table 4. N+P results for OGS sites in EMEA.

	CFLOS availability target		
N	**99%**	**99.9%**	**99.99%**
1	1+2	1+3	1+5
3	3+4	3+7	3+9
6	6+8	6+12	6+18
12	12+21	12+28	No solution
25	No solution	No solution	No solution

The results can be analysed as follows:

- In certain cases, no solution could be found to meet the target availability. For instance, in the European scenario, the combined CFLOS availability of N=12 OGS sites out of M=27 (so P=15) is always below 99%.

- Expanding candidate sites from Europe to EMEA always gives better results. For instance, with N=3 and for a 99.9% availability, the required number of sites N+P diminishes from 3+14=17 to 3+7=10, which is a significant gain. In the latter case, the first 8 sites are actually located in Africa and Middle East, the last 2 sites being in Europe. The benefits of expanding to EMEA can also be expressed in terms of CFLOS availability: for the same number of sites N+P=6+18, availability increases from 99% to 99.99%, reducing the number of unavailability events by a factor 100. This is the consequence of better atmospheric conditions of individual sites (higher CFLOS), but also of the geographical de-correlation and seasonal de-correlation between sites (diversity of climates and seasons between North and South).
- When comparing results between 99%, 99.9% and 99.99% availability targets, it is observed that the relative increase of P is moderate. For instance, for N=6 active OGS in the EMEA scenario, the total number of OGS required (N+P) is 14, 18 and 24 for the 3 respective availability targets. This means availability targets of 99.9% or 99.99% usually considered for the feeder link in RF case can also be achieved with a reasonable number of sites in the optical case.

The relative overhead of redundant sites (P) compared to active sites (N) can be expressed as P/N, to reflect the additional resources needed to be deployed to accommodate for redundancy. P/N ratio is plotted in Figure 3 for values of N ranging from 1 to 12, for the 3 availability targets, and considering 3 different cases: the European and EMEA scenario (using the time series), and a binomial model. The binomial model corresponds to the case where all OGS sites are assumed to be independent from each other, and where the probability of CFLOS per site is 80% at any time, reflecting typical CFLOS performance from Table 2. The aggregated CFLOS availability follows a binomial distribution as a function of N and P. This model was analysed in [2] and the results have been extended in Figure 3 for higher availabilities and for higher values of N, where the probability distribution tends to become Gaussian.

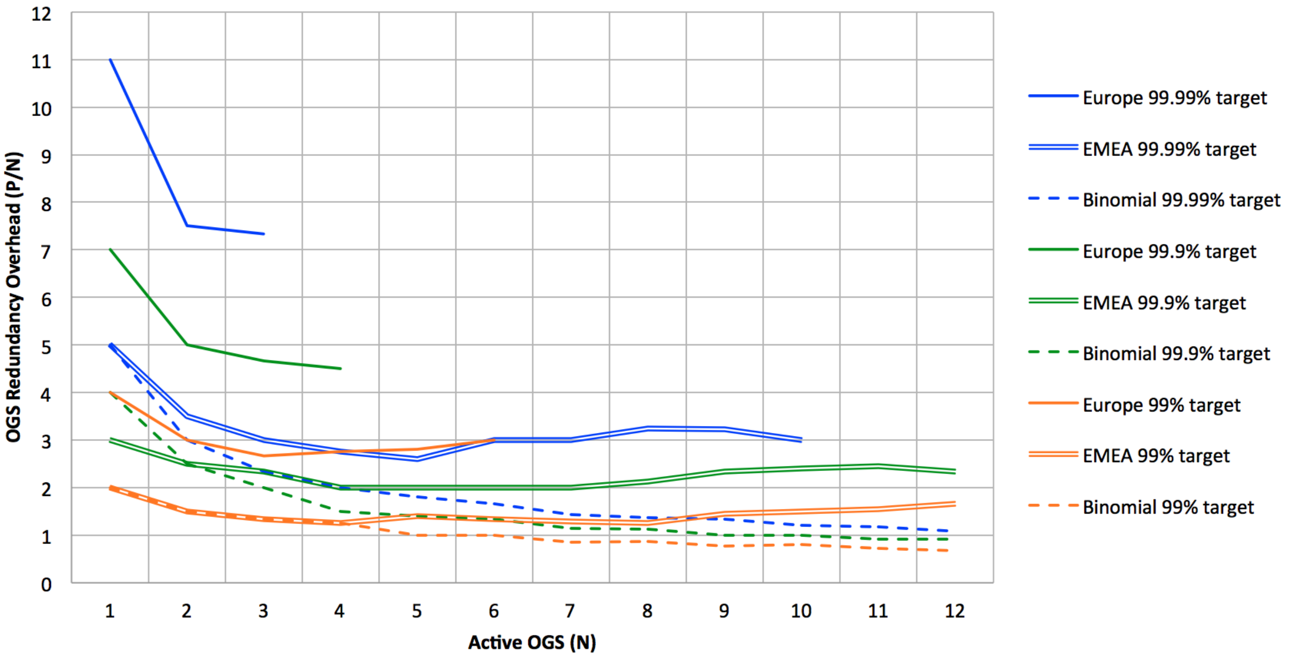

Figure 3. Relative overhead for OGS redundancy P/N.

The expected statistical gain, corresponding to a decrease of P/N as N increases, can be seen especially for the first values of N and for the binomial distribution. However there appears to be some asymptotic effect for the two scenarios based on the time series when N is larger than 4. This behaviour could indicate some correlation of time series between adjacent sites. Another reason could be the limited number of candidate sites as N increases, reducing the benefits of site diversity. For instance, in the European scenario targeting 99.9% availability, N+P=12+28 case makes use of all the M=40 candidate sites from the initial list. If such results were encountered also for higher values of M, considering more candidate sites, it would mean that the geographical de-correlation hits a limit, and it would be more efficient in that case to deploy a limited number of active sites and instantiate multiple OGS per site.

3. TECHNOLOGY

3.1 Ground Segment

Technologies for optical reception and transmission on ground continue to progress, notably in Europe. The main challenges concern the transmit part (forward uplink), which has to achieve a higher throughput than the return link. One advantage of splitting the feeder link traffic between multiple smaller optical terminals is to reduce the requirements in terms of aperture and throughput, as shown in Table 1, without having to wait for the most demanding technology (1 m, 492 Gbit/s transmit) to be available. Another benefit is to relax the requirements for adaptive optics on the uplink transmission, which are less stringent for smaller size terminals. Other technical challenges in the optical domain could be the output power levels that can be achieved with High Power Optical Amplifiers (HPOA) and bulk multiplexers following the HPOA bank to collect all sub-channels into a single optical beam.

For the digital part of the OGS, most functions are already available off-the-shelf for RF VHTS systems: modulators & demodulators, digital processing (network control, traffic classification, data compression…). The amount of redundancy needed, both at system level (N+P dimensioning of OGS network) and inside the OGS gateway, reduces in a distributed approach (N>1). Further savings can be envisaged in the digital part, for instance by moving digital processing functions (N+P elements) to a central place where only N active elements are needed, but requiring dedicated connectivity between all OGS, as discussed in [2]. Section 4 presents the economical aspects of these different options.

Connection between the OGS and the core network requires optical fiber cables. Two cases are distinguished:

- **Local computing:** if all the processing functions are performed at each OGS site, the traffic only needs to be transported to the nearest IXP for interconnectivity and peering.
- **Central computing:** if processing is performed remotely in a central place, for instance in a commercial cloud computing facility or in a private computing cluster, the OGS should be interconnected by a dedicated ring of optical fiber to guarantee processing in real time. An interesting scheme consists of transporting the feeder link optical signals directly over the fiber, exploiting the synergies between the two technologies: both can rely on optical standard (D)WDM at 1550 nm wavelength. Frequency conversion for the user link (typically RF Ka-band) can be performed at the central location. In that case, the main functions left to the OGS are to amplify the signal and track the satellite.

Different fiber solutions can be envisaged: owning a fiber network, long term rental of dark fibers (IRU scheme), rental of wavelengths (shared fiber). Whatever the scheme, the fiber needs to be available at all times because switching between OGS occurs dynamically. Fiber costs very much depends on two factors:

- **Distance**:
    - Local computing: for small values of N, an average distance of 100 km can be typically assumed between the OGS and the IXP; for large values of N, where the terminal is miniaturised and is compatible with populated areas, the distance can be much shorter. For instance, the optical terminal could be located at a data center with large IXP connectivity, provided that safety regulations for population and aircrafts are satisfied.
    - Central computing: the average distance between OGS becomes much larger. For the European scenario, the average distance between OGS on the ring is of the order of 500 to 1000 km. For the EMEA scenario, it increases well above 1000 km, which makes it too expensive in the short/medium term, considering the fact that there is only a limited offer of sea cables around Africa.
- **Bandwidth**:
    - Local computing: IP data is transported over fiber with existing solutions. For instance, N=6 requires 82 Gbit/s on the forward link, which can be served by 100 Gigabit Ethernet (IEEE 802.3ba) technology over a single strand of fiber.
    - Central computing can be more demanding in terms of bandwidth: in the extreme case where the feeder link signals are digitised at OGS and samples are transported over fiber, with modem functions performed remotely, the bandwidth typically expands by a factor 5 to 10 compared to local computing. Other functions like network management or data processing (routing, compression…) could be performed remotely without impacting the bandwidth.

3.2 Space Segment

While the space segment characteristics for a VHTS system are discussed in detail in companion paper [4], the present section addresses the specific needs of the satellite optical terminal in the case of multiple OGS.

The approach of having as many dedicated on-board telescopes as OGS, which can be several tens, appears to be too demanding to be accommodated on a single satellite platform, whether N active OGS are tracked (requiring at least N telescopes), or N+P fixed OGS sites. An alternative approach is a single multi-feed optical terminal on-board the satellite, as illustrated in Figure 4. Such concept was presented by RUAG in [6]. Assuming the OGS locations are known and fixed during the lifetime of the satellite, a single coarse pointing assembly can be designed, integrating both receiving and transmitting functions. Provided that the satellite position is kept in a small box on the GEO arc, the multi-feed telescope can track all OGS at the same time, in particular for pointing ahead angle (PAA) and to compensate for residual satellite rotation.

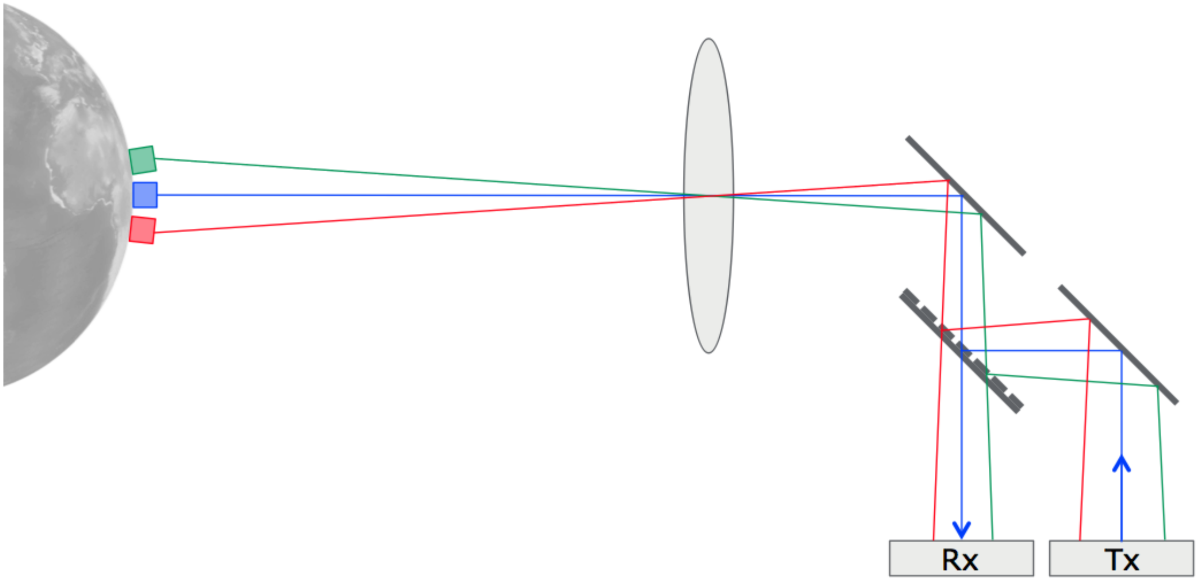

Figure 4. Multi-feed optical terminal. Each colour corresponds to a different OGS.

4. COST ANALYSIS

An overall cost assessment for the ground segment was performed. Figure 5 shows the results of this assessment for different scenarios discussed in the previous sections, projected from 2022 to 2036, assuming 15 years of operations. The cost elements of the ground segment consist of:

- **Capital Expenditure** (CAPEX): analogue part (including telescope) and digital part (including modem, network control and management centers, etc)
- **Operational Expenditure** (OPEX): OGS operating costs (including supplies, space rental, maintenance), connectivity costs (fiber, transit), and central computing costs when relevant.

The costs assessment excludes the space segment, as well as the non-recurring expenditure to bring the technology maturity to a level where is can be used operationally. There are several unknowns regarding the cost of technology when it becomes available, as well as how the costs of computing and transporting data will evolve in the long term (up to 2036). The exercise remains relevant though for identifying the most important parameters, and for quantifying and benchmarking different options.

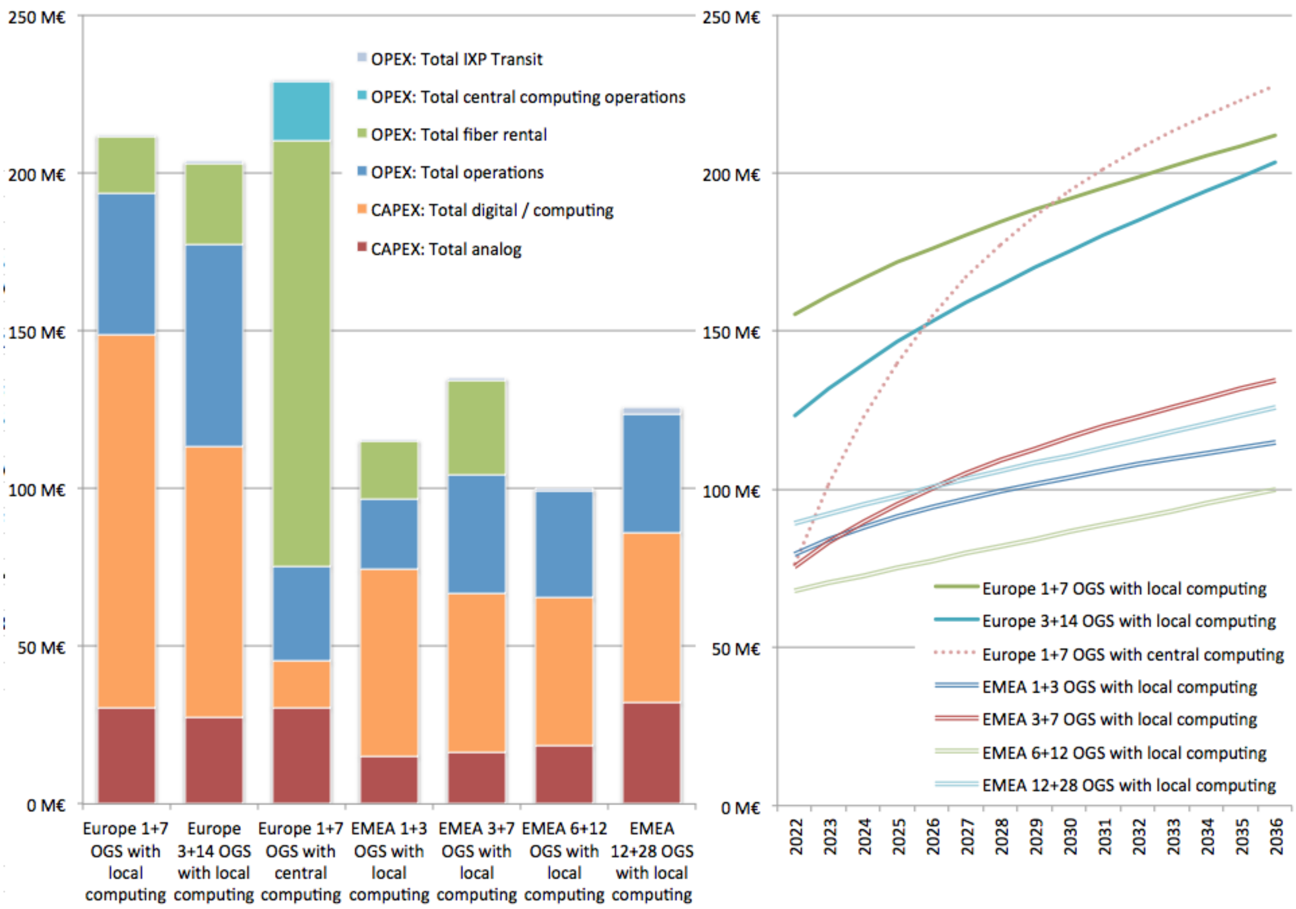

Figure 5. Cost projections for the ground segment for different OGS scenario, for a 99.9% feeder link availability target. Left: breakdown per cost element (CAPEX and OPEX) after 15 years of operations. Right: timeline of the total costs.

The following observations are made:

- For a given number of active OGS (N), the cumulative costs are always lower in the EMEA scenario compared to the European scenario, because the amount of redundant OGS (P) is less, as seen in section 2.4. This confirms the interest of expanding OGS sites to Africa and Middle East.
- The total costs for the EMEA scenario with local computing are quite similar for all N+P cases analysed. Only small differences can be observed. While there is a reduction of CAPEX when moving from 1+3 to 3+7 OGS, these are compensated by higher OPEX (mainly operations and fiber costs). N=6 appears to be the most attractive configuration of all. It is assumed here that the telescope is small enough (40 cm diameter) such that it can be located in a data centre very close to an IXP, avoiding the need to rent a fiber. The real differentiator may actually be the availability of optical ground terminals, which is expected to start from small dimension telescopes, so more favourable to a large N+P networks. Variants like clusters of small optical terminals discussed in [3] may be equally attractive.
- The CAPEX digital part (essentially modem and CPUs) is the most expensive element in all cases with local computing. It is minimum in the central computing case (because the functionality is not replicated in every OGS site), but the interconnect costs make it too expensive.
- OPEX operations is the second element of cost in most cases. Improvements could be achieved by means of automation, virtualisation and remote operations, which are beneficial especially for large number of OGS.

- In the European 1+7 OGS central computing scenario, nearly 60% of the costs are dedicated to renting optical fiber, which makes the total costs more expensive than any local computing scenario, and all other central computing scenario (not represented in Figure 5) are even more expensive. This is due to the large distances required for a ring network (about 12,000 km in the European scenario) and of the wide bandwidth (typically 10 strands of fiber for each OGS). There are several ways to mitigate these costs, which may invert the trade-off in the long term and make central computing more attractive than local computing:
    - Assuming the cost per bit/s continues to decrease exponentially in time as optical fiber technologies become more efficient (explaining the curvature of the timelines in Figure 5), delaying the start of operations by a few years will allow to benefit from reduced prices and avoid a high investment at the beginning.
    - As the traffic demand for VHTS is expected to ramp up gradually, the full capacity will only be required after a few years, and therefore the OGS capabilities and their interconnections can be scaled accordingly.
- In general, a progressive deployment of the ground segment over several years can be advantageous as the technology will continue to evolve in the terrestrial domain (CPUs, fiber, operational software, etc) and in satellite communications (modem, optical communications), and amortisation and economies of scale will make these technologies more affordable.
- The overall costs of the ground segment with optical feeder links are comparable to those of RF based feeder links. In fact, the number of RF gateways to be deployed in the most recent VHTS systems is approaching or even above 100, because of the limited amount of spectrum available in RF.

5. CONCLUSIONS

Choosing an optical solution for the feeder link of future VHTS system appears to be an attractive option, which can compete with RF solutions. Optical has a higher potential in the long term as it offers a very large bandwidth and does not require any licensing, while RF spectrum is limited and will encounter similar atmospheric impairments if expanding at high frequencies above several tens of GHz.

The ground segment network architecture can be optimised to reduce significantly the total cost of the ground segment, for instance by deploying multiple small OGS terminals in sites over Europe, Middle-East and Africa to benefit from site diversity, by automating operations, and by deploying the OGS capacity progressively as VHTS traffic demand ramps up. To complete the picture, the business case of the satellite operator should include a full system analysis as well as other costs of ownership (satellite, launcher, insurance, operations…), which are beyond the scope of this paper.

A number of technologies need to be developed, both on ground (small OGS telescope with high power optics and high throughput) and in space (multi-feed telescope). Synergies between optical feeder link and optical fiber cables can be exploited to miniaturise the OGS.

ACKNOWLEDGMENTS

The authors would like to acknowledge the inputs and contributions from all their colleagues participating in this Feeder Link study and particularly their colleagues from the optoelectronics section in ESTEC.

REFERENCES

[1] Mody, A., Gonzalez, E., "An Operator's View: The Medium-Term Feasibility of an Optical Feeder Link for VHTS", IEEE Int. Conf. on Space Optical Systems and Applications (2017).

[2] Gharanjik, A., Liolis, K., Shankar M. R., B., Ottersten, B., "Spatial Multiplexing in Optical Feeder Links for High Throughput Satellites", IEEE Global Conference on Signal and Information Processing (2014).
[3] Roy, B., Poulenard, S., Dimitrov, S., Barrios, R., Giggenbach, D., Le Kernec, A., Sotom, M., "Optical Feeder links for High Throughput Satellites", IEEE Int. Conf. on Space Optical Systems and Applications (2015).
[4] Arapoglou, P.-D., Girault, N., "Optical Feeder Link Architectures for very HTS: Issues and Possibilities," in Int. Conf. on Space Optics (2018).
[5] Jeannin, N., "RFOGSO Optimization software- TN 3-4 User Manual of RF/Optical Ground Segment Optimization Software", June 2015.
[6] Weigel, T., Dreischer, T., "Wide Angle Cross-Folded Telescope for Multiple Feeder Links", Proc. Int. Conf. on Space Optical Systems and Applications (2012).