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DIRECT OPTICAL HIGH SPEED DOWNLINKS AND GROUND STATION NETWORKS FOR SMALL LEO MISSIONS

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Abstract

Direct microwave data downlink capacity of today's earth observation satellites is limited in terms of available spectrum, transmission data rate, and power consumption. One elegant solution is the use of geostationary data relays satellites which connect to the low flying observation satellite by optical or Ka-band links and do the downlink to the ground station by another Ka-band link. This scenario also allows near real-time data access to the EO-sensors for at least half of the LEO's orbit. However it also implies efforts in terms of the number of long-range communication terminals employed by one EO-mission. Compact LEOs often cannot afford such a connection due to financial- but also mass- and power-constraints. To enable also these kinds of missions with high rate downlink capacity, small optical terminals can be used that boost the data rate by orders of magnitude compared to today's RF downlinks. The feasibility of direct optical downlinks from LEO satellites has been demonstrated recently with the laser terminals onboard JAXA's OICETS and onboard the German TerraSAR-X.

As such direct optical downlinks are hindered by cloud cover, a ground station network is required to ensure a certain required average downlink capacity, independent from the cloud situation. For one thing each optical ground station should be situated in a region with low cloud cover in general. But also the different ground stations of one network should be spaced far apart as to avoid correlation of their cloud cover statistics. Furthermore in a global ground station network, sites north and south of the equator are seasonal de-correlated.

DLR's Optical Communications Group is investigating the feasibility of direct optical LEO downlinks theoretically and practically together with partners [1], [2], [3]. The performance of optical downlinks has been evaluated by long-term global cloud statistics with different sets of ground station combinations. Furthermore, downlink campaigns shall be performed in near future with simple optical downlink sources on small LEO missions, verifying the theoretical findings. A Transportable Optical Ground Station (TOGS) will be used to carry out these trial campaigns.

1. Scope and concept of the verification experiments

Access to low earth orbit satellites (LEOs) is limited by available spectrum, data transmission capability, and visibility to ground stations(s). While large-scale missions have the technical and financial resources to implement high-bandwidth transmission systems and can afford to use advanced techniques like GEO data-relays or multiple ground stations, small-scale missions lack these options. However, with the use of small laser transmitters on-board such small LEOs, combined with precise target-pointing ability of the whole satellite bus, a very high data-rate downlink (up to gigabits per second) can be implemented (Optical LEO-to-Ground Links, OLGLs). Such a link is indeed constricted by clouds that may block the line-of-sight to the optical ground receiving station

(OGS), but a certain average throughput can be guaranteed based on a store-and-forward data handling concept. To boost the reliability of the data-downlink, the cloud-blockage problem can be tackled by applying a network of OGSs which are spaced further apart than the local weather correlation distance.

DLR has developed laser transmit sources in different configurations to fly as secondary payloads on diverse compact satellite missions. Besides the benefit of a high data-rate downlink to the satellite user, this laser source can also be used for several scientific purposes. The usage concept for these laser sources in space is summarized as follows:

- Measure the optical downlink statistics and elaborate and improve channel models.
- Scientific measurements of atmospheric data like optical index-of-refraction turbulence, or atmospheric transmissivity. Due to the fast overflight of the LEO over the OGS, a kind of momentary tomographic atmospheric profile can be derived from such measurements.
- Test new technologies for improving the reliability of optical data downlinks like fading mitigation techniques and adaptive optics.
- Test the ground station diversity concept and measure the ground station network throughput.

2. Sources for experimental optical downlinks from compact satellites

On small satellites, the power and space available for a downlink payload is limited. So there is a need for power-saving and lightweight downlink terminals. This can be achieved by using directly modulated semiconductor laser diodes. A fibre-coupled laser diode is driven by an electronic circuit, which connects to the satellite bus and receives TTC data from it, which then is transformed into a current modulating the laser diode. The emitted light is guided in a single-mode fibre and emitted from a collimator with a defined divergence angle. The wavelength used is 1550nm, which allows the use of standard fibre-optic components and ensures eye-safety.

Fig. 1. Space-qualified directly modulated laser diode

This technology allows data rates up to 200Mbit per second and a mean optical output power of approximately 20dBm. The power consumption is typically 8W at an operating Voltage of 5V. The mass of such a device can be as low as 0.2kg.

For applications demanding even higher data rates or transmit powers, a different approach can be targeted. The use of optical amplifiers (erbium-doped fiber amplifiers, EDFAs), as used in commercial fibre optic transmission systems, allows data rates up to 2,5Gbit/s and optical output powers up to 5 W. In this concept, a low-power modulated laser source is used as a transmitter, whose output signal is then amplified by the EDFA and transmitted as described above.

Fig. 2. Laser data source using an optical amplifier

In this concept, the alignment of the collimator towards the ground station is done by the attitude and orbit control system (AOCS) by rotating the body of the satellite. Most modern compact satellites have the capability to do these “target-pointing” maneuvers. The system can easily be adapted to satellites with worse target-pointing capability by enlarging the divergence angle, however this will be to the disadvantage of data rate.

3. Link budgets

For the operation of the laser sources as described in this paper, it is assumed that the emitting laser collimator onboard the satellite is mounted coaligned to the satellite’s reference frame. For an optical downlink, the satellite has to change its attitude during a satellite pass and accomplish a target pointing towards the Optical Ground Station (OGS). Thus the laser beam is continuously illuminating the OGS and a communication link can be set up.

For a high illumination probability of the OGS, the beam divergence must be matched to the pointing accuracy of the satellite. Assuming pointing errors with a Gaussian distribution, the FWHM beam divergence is defined as 6 times the 1δ tracking accuracy of the satellite for a probability of virtually 100%. In other words, the beam divergence emitted from the satellite – and thus also the achievable data rate for a certain link scenario – directly depend on the pointing accuracy of the satellite.

Fig. 3 shows achievable data-rates for different elevation angles of a standard satellite orbit and a transmit power of 1W, as it is feasible for a laser source with integrated optical amplifier. An elevation angle of 2° is used as design point, guaranteeing a non-obscured line-of-sight in most environments.

It is visible that a satellite with a pointing accuracy of some 100µrad, resulting in a beam divergence of 1mrad, allow datarates of several Mbit/s only. Decreasing beam divergences, however, enable much higher data rates up to the Gbit/s range, as it is the case for a beam divergence of 30µrad. This requires a very good pointing accuracy of the satellite bus.

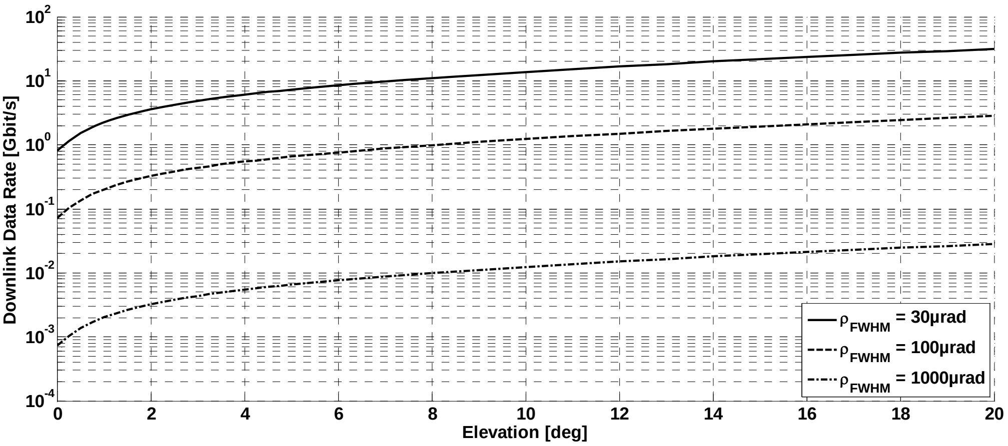

Fig. 3: Link-Budget for a LEO with 545km orbit altitude. Parameters: wavelength: 1550nm, optical sat.-Tx-Power: 1W, OGS-telescope diameter: 40cm, Rx-sensitivity: 1000Photons/bit, optical losses: 3dB, pointing loss: 3dB, atmospheric absorption model: High Volcanic Activity, fade margin: 6dB

As it is unlikely, that a satellite bus can achieve pointing accuracies of only several µrad in open-loop mode, it is possible to use a Four Quadrant Tracking Device onboard the satellite. This enables closed-loop tracking, allowing low tracking errors and thus higher data rates. More information about such a system can be found in [4].

4. Ground station network topologies

When planning for an OGS network, different aspects have to be taken into account. Firstly, the scale of the network has to be clarified in terms of numbers of OGS and area which it spans. It can be limited to a national territory, or span over several neighbouring countries, up to a global network with several international partners and organizations. Then there are several criteria for choosing suitable ground station locations as cloud occurrence, atmospheric turbulence, aerosol scattering, infrastructure, political concerns, etc, whereas the first aspect is the most important.

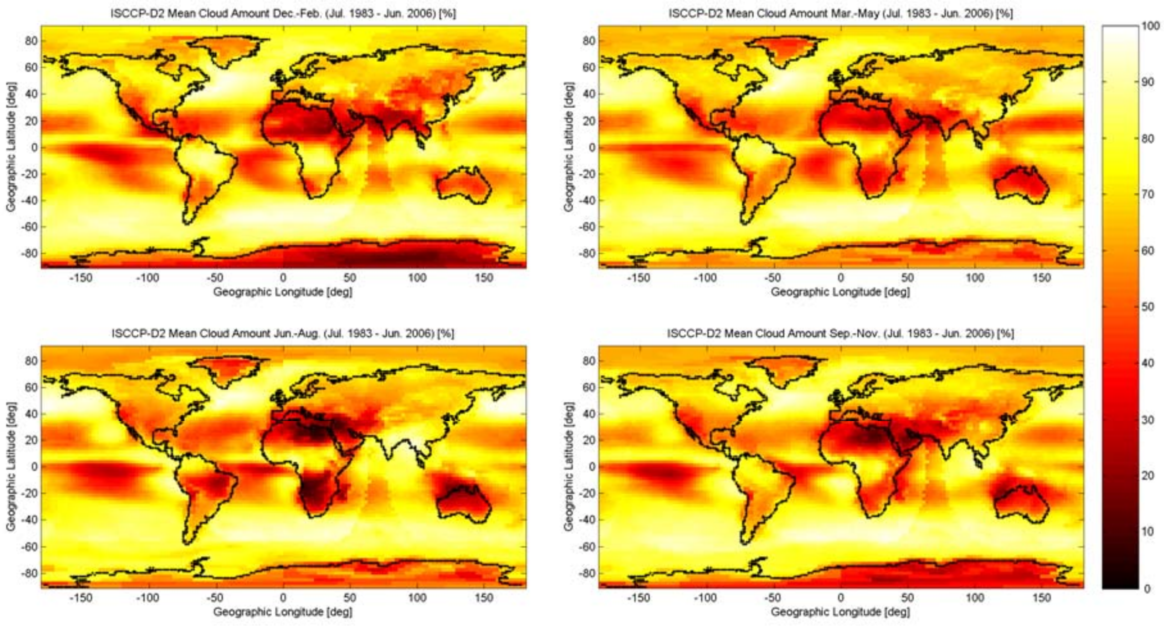

Fig. 4. Global seasonal cloud cover statistics (darker: lower cloud probability) based on data from the International Satellite Cloud Climatology Project (ISCCP) [5].

The four maps in Fig. 4 show the global mean cloud coverage for the four seasons. For some regions it is quite obvious that these are of great interest. These are, amongst others, Australia, Africa, the Arabian Peninsula, Southern Europe, and parts of the Antarctic.

Fortunately, ground stations for LEO-downlinks are not large-scale structures like RF ground station antennas and so can be set-up temporarily or even be implemented transportable (see section 5. below). Thus, they do not imply investments into local permanent infrastructure like buildings or foundations.

In the following, two scenarios are presented that show what can be expected from diversity systems. Like in preceding studies [6] [7] [8], data from ground based weather observations are applied. Since these stations are distributed by the World Meteorological Organisation, certain observation rules ensure the homogeneity of the gathered data which is difficult when using satellite based earth observation data.

4.1 Ground station diversity inside a limited national territory

As an example of a national OGS-network Australia is of interest which as is known features large regions with low cloud probability. Fig. 5 shows the chosen locations that form two different networks: a “convenient” network that comprises stations nearby large cities with good infrastructure and an “optimized” network that consist of locations with better cloud conditions. The joint probability of cloud blockage of both networks is depicted in Fig. 6. The used data base for these statistics are weather observations collected by the World Meteorological Organisation (WMO). Here, the assumptions was made that all stations are visible at the same time and the meteorological conditions are uncorrelated, respectively. Thus, joint probability of cloud cover is a multiplication of the single probabilities.

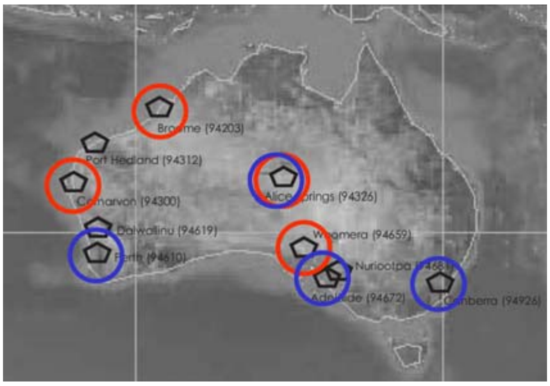

Fig. 5. Two exemplary Australian OGS networks: “convenient” network at large cities (blue circles: Perth, Alice Springs, Adelaide, Canberra) and an “optimized” network at remote sites but with low cloud probability (red circles: Broome, Carnarvon, Alice Springs, Woomera).

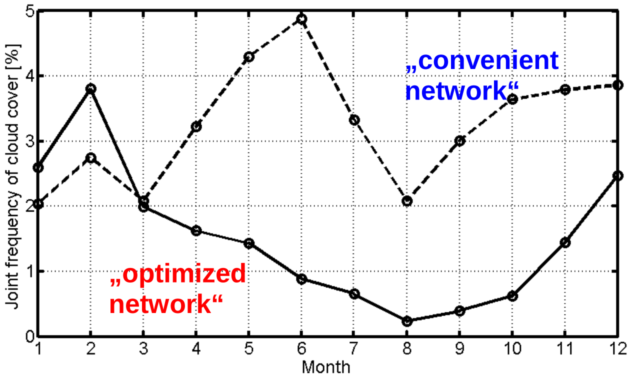

Fig. 6. Monthly combined unavailability rates of the two networks shown in Fig. 5. Obviously an OGS network inside Australia can offer availability rates above 97% over the whole year with just four stations. Values are calculated with synoptic data from meteorological stations.

4.2 Global network considering an inclined satellite orbit

In this chapter, the availability of a dedicated ground station network including an example satellite orbit is investigated. With a maximum number of nine stations, the evolution of availability is shown in three stages.

- A) Oberpfaffenhofen and Neustrelitz as a first experimental stage
- B) Izana on Tenerife (ESA-OGS), Paranal (ESO), Tokyo (NICT-OGS), Adelaide (Uni-SA, planned OGS) plus the sites of A): readily available OGS-sites with existing infrastructure
- C) Perth (ESA/ESTRACK), South African Astronomical Observatory (SAAO), Capella Observatory (CO) on the mountain Skinakas on Crete, plus the sites of B): potential good OGS-sites, but availability of infrastructure and access to be investigated

A satellite orbit with mean altitude of 340km and 52° inclination is used which is quite the one of the International Space Station. The downlink terminal is assumed to transmit with a data rate of 10Gbps and the downlinks are performed with least elevation above 10°. Figure 7 shows the network and the ground tracks of a few orbit revolutions.

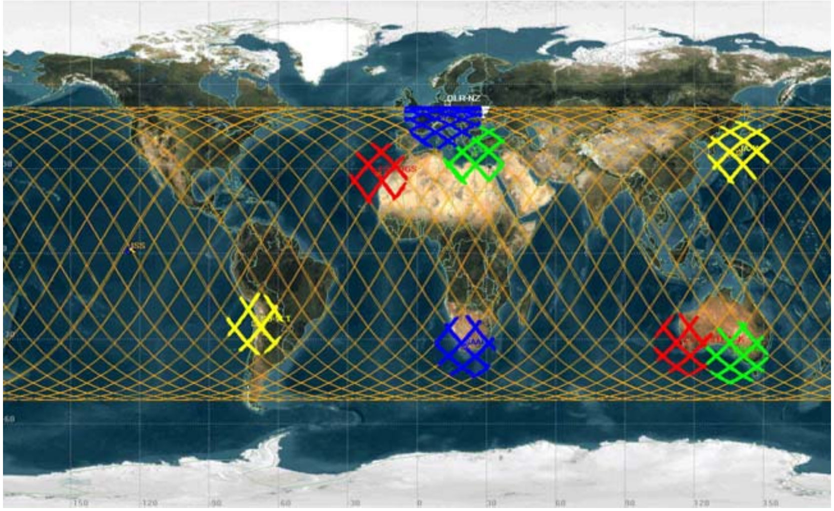

Fig. 7. Geographical locations and visibility areas of the nine proposed OGS sites underneath the satellite orbit according to OGS-network C).

The used data base comprises of ground observation of cloud fraction from weather services all over the globe. Often this kind of data is not available in the very surrounding of the OGS. In that case weather observation stations in some distance are used that are expected to have similar meteorological conditions.

For each station several years of data (in the interval 1990 - 2006) were available. For simplicity the stations in Oberpfaffenhofen and Neustrelitz are assumed to be accessible (regarding geometrical visibility) at the same time and the optical terminal on the ISS can establish a link to one of the two. This results in one double-station with higher link availability. Also the intersections of the geometric visibility between Oberpfaffenhofen and Skinakas and the two OGS in Australia are neglected. These simplifications will be considered in more detail in a pursuing research.

The values of the mean geometrical visibility and the mean cloud free time are listed in Table 1. The visibility per day is a result from simulations with Satellite Tool Kit (STK) for the year 2008. The constraint for every ground station is a minimum elevation of 10°.

OGS site	mean geom. visib. per day / seconds	cloud free in Q1, %	cloud free in Q2, %	cloud free in Q3, %	cloud free in Q4, %	annual mean, %
Oberpfaffenhofen	1227.3	51	57	60	48	54
Neustrelitz						
Izana, Tenerife	809.4	60	75	85	62	71
Tokyo	999.6	49	26	27	45	37
Adelaide	973.9	60	44	44	50	50
Paranal	752.4	74	86	89	86	84
Perth	881.5	71	52	52	63	60
SAAO, S. Africa	907.8	74	65	65	68	68
Crete	983.1	43	70	87	47	62

Table 1. Contact time and mean cloud coverage of the investigated stations. The cloud free time is given for the annual mean and the quarters defined as Q1: January, February, March; Q2: April, May, June; Q3: July, August, September; Q4: October, November, December

It is notable that the geometric visibility of the satellite is maximum at sites near the maximum latitude (more than factor two compared with equatorial sites), but unfortunately cloud probability is also usually higher in these regions.

Table 2 contains the estimated downlink capacity in Tera-Byte per day (based on long term cloud cover statistics) with one 10Gbps-terminal on the satellite with full hemispherical field-of-regard down to earth. With higher number of stations the data volume is heavily increased. It is especially remarkable that in all stages the variance over the year is fairly low.

OGS-stage	TB/day in Q1	TB/day in Q2	TB/day in Q3	TB/day in Q4	TB/day annual mean
A	0.8	0.9	0.9	0.7	0.8
B	3.4	3.3	3.5	3.3	3.4
C	5.6	5.5	5.9	5.4	5.6

Table 2. Data volume transmitted per day for the three OCG-system stages and different periods of the year, with a downlink data-rate of 10Gbps.

5. Transportable Optical Ground Station for verification campaigns

Current Optical Ground Stations, as e.g. the Optical Ground Station Oberpfaffenhofen [9], are typically stationary. Thus the place of the ground-station is fixed and demonstration campaigns are bound to one location. A Transportable Optical Ground Station can be used for optical downlinks around the globe with little effort, resulting in a much higher flexibility regarding the location of operation.

Fig. 8. DLR's Transportable Optical Ground Station (TOGS)

DLR's transportable optical ground station, TOGS, consists of an integrated platform, containing a foldable mast as well as transmitter, receiver and control electronics. The mast is used to deploy a 60 cm Ritchey-Chrétien telescope to a height of 3 m. The telescope mirrors are milled from aluminium and optimized for optical freespace communications. Due to the automatic unfolding mechanism, the station can be set up for operation in very short time. To be able to point to a target precisely, the ground station needs to know its position and attitude. Therefore, GPS and attitude sensors have been implemented to determine the position as well as heading, pitch and roll angles.

By the usage of modern composite materials, a low weight could be achieved, allowing the station to be transported to literally any place in the world in a very short time by means of standard airfreight. It can be operated on both AC and DC power networks supporting common line voltages and frequencies. Autonomous power supply by a generator included in the transport vehicle is also possible.

Optical Ground Stations like DLR's TOGS shall be used for future investigations of optical link technology. Furthermore, DLR intends to use the TOGS for Optical Downlinks from LEO and GEO satellites and other carriers, as e.g. aircraft and UAVs.

6. Conclusions

The use of an optical downlink with one dedicated OGS is limited to certain application areas as a certain throughput can not be guaranteed due to the cloud coverage problem. However, the huge benefits of this technology might compensate this drawback for certain applications; these benefits are mainly the high datarates at very low transmit power and mass requirements and the complete independence from any spectrum regulation issues. Applications that could apply optical downlinks are certain earth observation tasks, precursor payloads, or experimental university satellites with store-and-forward payload handling systems. With the use of a global downlink network (which might be financed on a mutual usage agreement between institutional or university operators) the throughput fluctuations can be smoothed out. Other scientific applications like atmospheric sounding by the laser signal itself have not been investigated here, but are also deemed a promising use of the system.
While for our experiment we use simple transmitter technology without a dedicated pointing unit to enable a robust and low-cost setup, the optical downlink technology in principal leaves much room for improvement. For example on the system sensitivity side, while in this experiment we target at a receiver sensitivity of 1000 Photons per bit, other technologies (e.g. coherent transmission with homodyning reception or pulse position modulation) have shown sensitivity improvements by orders of magnitude compared to this value [11], [12].

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