Optical Satellite Downlinks to Optical Ground Stations and High-Altitude Platforms

Dirk Giggenbach, Joachim Horwath, and Bernhard Epple

Abstract— **Earth-observation (EO) satellite missions using high-resolution optical or radar sensors are producing an immense amount of data which needs to be send down to earth. The fraction of satellite operational time in future missions is therefore clearly limited by the downlink-capability. The current X-Band architecture is facing its technological limitations in terms of data rate while causing increased demand on antenna-sizes and transmit power.**

This bottleneck can be overcome by direct optical downlinks from EO-satellites to the ground with multi-gigabit data rates. According optical satellite terminals will be extremely small and light-weight and will require few transmit power, but one drawback is the link blockage by thick clouds. This can be overcome either by ground station diversity and careful site selection or by using optical terminals onboard high altitude platforms which serve as relays-stations for the satellite.

Here we present feasibility and expected performance of these two optical scenarios and propose according space and ground station architectures.

Index Terms— **high altitude platforms, optical freespace links, optical ground stations, optical satellite downlinks**

I. Introduction

RECENT years have seen an immense increase in the capability of earth observation (EO) sensors flown on satellites. State-of-the-art payloads like high resolution optical or infrared cameras or SAR systems produce data at a speed of gigabits per second. This is why the conventional RF-downlink has become the bottleneck in EO-systems, as it is limited to some hundred megabits per second. The data acquired by the sensor can only be sent to the ground when it is in the reach of an according RF ground station antenna, which happens a few times per day with each downlink session lasting only around 9 minutes at maximum for a LEO (Low Earth Orbit) satellite. This limits the effective operational time fraction of such sensors to only some minutes per day. Due to limitations in the available frequency bands but also in technological feasibility the RF downlink technology is currently reaching its limits.

To solve this communications bottleneck we now have the opportunity of using optical free space high speed links. This technology would instantly multiply the downlink data rate by a factor of ten, while even faster links would be feasible in the near future. At the same time the mass, size, and power consumption of the satellite terminal would be cut to only a fraction of the values of conventional RF-antennas, making high speed downlinks an option even for compact- or micro-satellites (a typical Tx-aperture diameter would be approx. 3 centimeters). Furthermore, also the size of the according Optical Ground receiving Station (OGS) remains quite compact, with only some decimeters of telescope diameter, enabling transportable or even mobile stations. This is an important benefit compared to RF ground stations which have typically antenna diameters of 5 meters and more. The inherent tap-proofness of directed optical beams due to a minimized optical signal spot beam on ground (typically between 10 and 50m) is also very appreciable in security applications.

The Institute of Communications and Navigation of the German Aerospace Center (DLR) has demonstrated together with JAXA the feasibility of direct optical LEO-Downlinks in the Project KIODO (Kirari Optical Downlink to Oberpfaffenhofen). KIODO showed a very good performance with measured bit error rates down to 10^{-6} with a transportable and inexpensive OGS [1].

Solving the Challenge of Cloud-Blockage

Reliable optical downlinks are of course limited to geographical OGS-sites with a minimum fraction of cloud coverage, as the optical signal is blocked by thick water clouds. Therefore, these stations should preferably be situated on mountain tops (like the classical astronomical observation site) or in countries with low cloud probability, like the Mediterranean or sub tropic latitudes. Of course, this practice might not be acceptable for applications like military or other security sensible reconnaissance. Also, for non-EO applications like communications or broadcast, a nearly hundred percent availability is required for the satellite link. Therefore the "ground" station has to be positioned above the clouds. Aircraft or aerostatic High Altitude Platforms (HAPs) provide the suitable bases, with the later having the advantage of stationarity together with lesser vibrations and position uncertainty. The final "last mile" to the ground can then be bridged by standard RF point-to-point links as used today in terrestrial applications. With a buffering strategy onboard the HAP even *optical* downlinks from the HAP to a terrestrial miniature OGS could be used for the HAP-downlink, storing the data during total cloud blockage. This concept here is called *StORe* for *Stratospheric Optical Relays*. In a future scenario - with a network of HAPs in range of sight - linking the data from one HAP to an other without cloud blockage

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underneath would allow a purely optical downlink system [2], [3]. In a future HAP communications network, this networking functionality would be available inherently at no extra expenses.

Other benefits of this concept compared with RF and terrestrial optical ground stations are the extended visibility time of the LEO satellite (the link can already start at negative elevation angles as long as the line-of-sight stays above the maximum cloud altitude of about 13km) and negligible attenuation by the atmosphere. Also the challenge of fading (caused by atmospheric index-of-refraction scintillations) is much reduced or even negligible at stratospheric altitudes.

Further, such HAP-relays could provide downlink capability at any place where a HAP is placed. Even reliable nomadic downlink services can thus be provided to temporary end user sites.

II. System comparison

A. Earth Observation Scenario

The system used for example calculations in this paper consists of a satellite with a mean orbit height of 500 km. The satellite is equipped with a high resolution camera which produces data at a rate of 6.7Gbit/s. This high data rate illustrates that the down link bandwidth is a limiting factor for the operational time of the satellite. For simplicity in calculations, there is only one receiving ground station for the data downlink. Here we use DLR's ground station at Neustrelitz, Germany.

B. State of the Art RF Downlink

Currently used RF downlinks have an effective user data rate of up to 262Mbit/s (e.g. TerraSAR-X). At Neustrelitz it is possible to start data transmission at an elevation angle of 5° of the satellite. This results in a mean daily contact time of 2360s or in a maximum transferable data volume of about 75 GByte per day. Since the ground station can be assumed to be available for downlink 100% of time, the transferable data volume per year is 27 TByte and the camera can be used during 0.1 % of the operational time of the satellite.

C. Proposed Optical Downlink

Due to atmospheric effects, the availability of an optical down link is limited to an elevation angle of 10° and more. This reduced Field-of-View results in a mean daily contact time of 1499s. Nevertheless, using an optical downlink with a data rate of 5Gbit/s, the resulting transferable data volume per day is 936GByte per day when neglecting cloud blockage.

The down link station at Neustrelitz is a rather unfavorable place for an optical ground station because it has a mean availability (limited by cloud cover) between 32% to 45%, depending on the season [4]. But even in worst case, the transferable data volume per year is at least 107 TByte and the camera could be used during 0.4 % of the operational time. The limiting factor in this case is the available data storage on the satellite for cases when no data downlink is possible due to bad weather conditions.

Note that these values are for one OGS at a site with non-optimum cloud cover probability (Neustrelitz). When using four OGSs distributed over Germany (ground station diversity), the combined availability can be boosted to 71% during the winter half year and 91% during the summer half year. Availability approaches 99% when using two or more ground stations in advantageous areas like astronomical observatory sites, where all OGSs should be separated by several hundred km to ensure uncorrelated cloud cover statistics.

D. Proposed Combined RF-Optical Downlink

For overcoming the cases where an optical downlink is not possible due to cloud cover, it is possible to combine an RF downlink terminal with an optical terminal. This approach adds complexity to the data downlink management, e.g. data has to be scheduled for down link via RF or optical channel, but it greatly extends the downlink availability and thus the sensor usage. Using the values from above, the combined downlink volume per year increases to 134 TByte and the camera can be used during 0.5 % of the operational time.

E. Proposed HAP Relay

For the following calculations we assume a HAP placed above the downlink station in Neustrelitz at an altitude of 20 kilometers. For the downlink from HAP to ground station conventional point-to-point RF technology with a steered antenna is used (this "last-mile" link from HAP to ground has 100% availability).

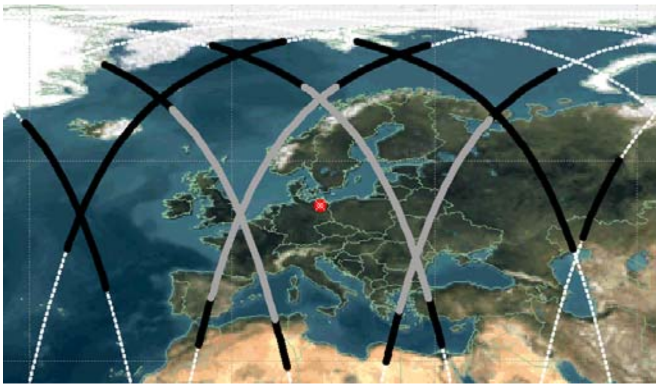

Fig. 1: Example for the improved access by a StORe at 20 km with -2.7° minimum elevation (black+grey lines) over an RF-ground station with +5° minimum elevation (grey lines only), both stations situated at *Neustrelitz, Germany* (red marker). The given orbits are satellite passes of one day.

The HAP holds an optical receiver terminal for data downlinks from EO-satellites. Since the HAP is located above the cloud layer, the data link can be established at an elevation angle of -2.7°. This results in a mean daily contact time of 4759s or in a daily transferable data volume of 2974GByte. The link availability between HAP and satellite is 100%, again because of the HAP position above the cloud layer. With this system the transferable data volume per year can be increased to 1060TByte and the camera can be used during 4.1 % of the time.

The table below compares the different optical technological options with a moderate datarate of 5Gbps with an advanced RF-downlink at 262Mbps.

Table 1: Comparison of LEO-Downlinks to Stratospheric Optical Relays Stations (StORe) with 5Gbps positioned at 20km altitude, terrestrial Optical Ground Stations (OGS) with 5Gbps, and terrestrial RF-Stations (RF) with 262Mbps, for an Earth Observation Satellite in a 500km circular polar orbit (~ 94,7minutes orbit duration). All values for zenith overflights.

	RF	OGS	StORe
start elevation of link	5°	10°	-2.7°
start distance / km	2077	1694	2842
plane view angle (1)	35.1°	28.1°	48.8°
link duration / minutes	9.2	7.4	12.8
average downlink time fraction to *one* station (2)	2.3 %	1.5%	4.5 %
downlink capacity at one zenith contact / Tbit (3)	0.145	2.2	3.8

(1) see fig. 2 for explanation
(2) ratio of the visibility time inside the solid angle Sat-Relais to the complete orbit time; for comparison only, effective values depend on geographical GS-location vs. orbit geometry; no cloud blockage regarded for "OGS"
(3) no cloud blockage regarded for "OGS" for this value

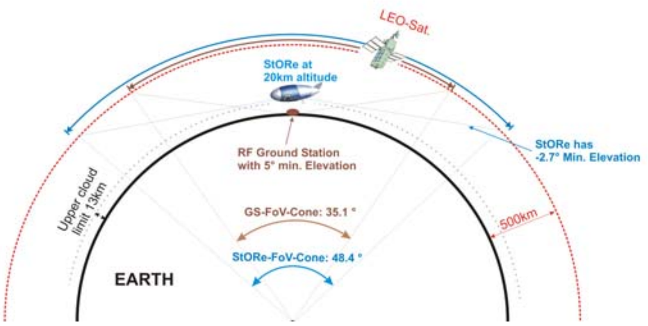

Fig. 2: Geometrical visibility constraints of a StORe with -2.7° minimum elevation and a Ground Station with 5° minimum elevation for a 500km LEO (angles not to scale)

III. Wavelength Selection and Terminal Architecture

Due to the station keeping altitude of HAPs the effects of the atmosphere on optical beams are much smaller compared to scenarios with an OGS. Due to the long horizontal propagation distance especially at low elevation angles, the wavelength has to be selected carefully because of the large variance of the absorption coefficient over the wavelength.

Generally there are three absorption effects. Beside the free-space loss which is determined by the beam divergence angle, two main attenuation effects characterise the propagation in the clear atmosphere: absorption and scattering. These effects lead to specific transmission windows which are suitable for optical communications in the atmosphere. But it is also important that laser sources and detectors are available in the regions with minimal attenuation. The three designated wavelength regions for Free Space Optical (FSO) systems are around 800nm, 1064nm and 1550nm.

800nm technology has some disadvantages: The presence of strong background light and the higher Rayleigh-scattering compared to 1064 and 1550nm. For 1064nm and 1550nm technology one of the clear advantages is the availability of high power optical fibre amplifiers to boost the transmission signal.

The wavelength of 1064nm is used for coherent systems with non-planar Nd:YAG ring oscillators, a laser source with very good coherence and therefore suitable for homodyne systems. This enables the implementation of homodyne binary phase-shift-keying (BPSK) modulation. The advantage of these systems is the high sensitivity which leads to small aperture diameters for the StORe receiver. Due to the homodyne detection scheme the communication signal is recovered at baseband, which considerably simplifies the communications electronics design. The effect of background radiation can be neglected due to the extremely small noise bandwidth of the homodyne receiver which is in the order of the data-bandwidth (e.g. 1GHz signal bandwidth corresponds to only about 3.5pm optical wavelength for 1064nm wavelength).

Optical C-Band technology around 1550nm with on/off-keying and direct detection is widely used in terrestrial fibre-optical transmission systems and has already been tested successfully in a stratospheric test-bed [3]. Current systems are not as sensitive as coherent systems but the use of fast wave front correction systems (adaptive optics) to mitigate atmospheric index of refraction turbulence would allow coupling the received signal into a mono-mode fibre at the receiver. With optical pre-amplification the sensitivity is comparable with current coherent systems [4].

An additional advantage of receiver concepts with mono-mode fiber coupling would also allow the use of Dense Wavelength Division Multiplex (DWDM). The number of channels could be increased considerably and integrated fibre optics off the shelf components can be used. Therefore preference is given to C-Band technology.

The possible architecture of a unidirectional DWDM-FSO system is sketched in Figure 3. Each channel or wavelength is coupled into a single fibre by a multiplexer. When the number of channels for a single booster EDFA (Erbium Doped Fiber Amplifier) reached its maximum, an additional EDFA has to be used for the next set of channels. The outputs of the EDFAs are coupled to a single fibre and delivered to the fine pointing assembly (FPA). This building block removes the high frequency vibrations of the satellite in order to guarantee precise pointing. The coarse pointing assembly enables a wide angular range (e.g. hemispherical).

On the right side of Figure 3 the receiver is outlined. There exist major differences between optical terminals for satellites and optical terminals for the StORe. The spatial orientation of a satellite is usually known very precisely and the attitude changes can be controlled with similar precision (e.g. 300µrad depending on star sensors and reaction wheels). HAPs do not operate in a stable orbit but in the atmosphere. Therefore station keeping manoeuvres are necessary to keep the position against the stratospheric wind. The wind could also lead to oscillating movements of the payload equipment depending on the vehicle's centre of gravity. Also vibrations are much stronger on HAPs compared to satellites' base motion disturbances. The high pointing and tracking requirements for optical terminals require systems that can cope with all these effects on the HAP vehicle. Therefore the control loop bandwidth of the tracking system on the StORe (mainly FPA-performance) needs to be higher compared to the satellite pointing system. At the receiver the FPA compensates the platform vibrations. In addition the FPA also corrects the angle of arrival of the incoming wavefront (tip/tilt correction). Changes in the angle of arrival are caused by atmospheric turbulence. Finally the wavefront correction building block corrects the higher order wavefront distortions in order to reconstruct a plane wave before the signal can be coupled into the mono-mode fibre with the collimation system. In the fibre the DWDM signal is then amplified by a high gain optical pre-amplifier. The variable optical attenuator (VOA) decreases the signal dynamic (fading) of all channels caused by the turbulence before the signal is demultiplexed. With such free-space optical DWDM systems data rates in the order of 10 to 100 Gbit/s would be possible.

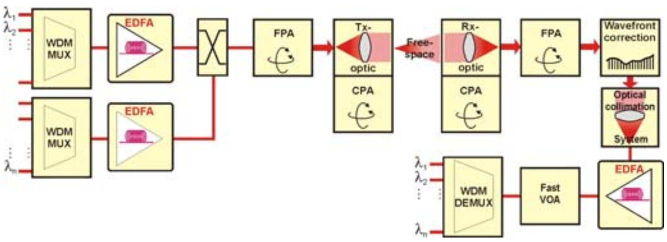

Fig. 3: Potential architecture of a broadband free-space optical DWDM system

IV. Conclusion

We have calculated the practical advantage of optical downlinks from earth observation (EO) satellites over conventional RF-downlinks. The usability of the EO-sensor could be boosted by nearly a factor of forty with a future StORe-System (HAP-Relays) or by a factor six with simple direct downlinks to optical ground stations without RF-backup. This performance is offered by low-power transmit terminals with very small apertures in the range of few centimetres and according low mass.

Optical sample data return channels for LEO satellites using GEO relays satellites (e.g. the SILEX-system) have the advantage of higher link availability as they cover nearly half of the LEO-orbit, but the system-complexity is also high. The terminal size, power consumption, and weight of optical LEO-GEO link terminals is high due to the high free-space loss and therefore this technology offers lower effective datarates and can also not be carried onboard small LEO satellites. Also, the financial effort for setting up a GEO-relays scenario is much higher than for direct LEO downlinks.

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