Connectivity Services Based on Optical Ground-to-Space Links

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Abstract

Repeater systems in a geostationary orbit utilizing free-space optical-communication offer great potential to backup, process and archive large amounts of data collected or generated at remote locations. In contrast to existing or upcoming global satellite communication systems, such optical GEO relays are able to provide a huge return-channel data throughput with channel rates in the gigabit-per-second range. One of the most critical aspects of such data uplinks are atmospheric disturbances above the optical ground terminals used to connect to the space segment. In this study, we analyse the design drivers of optical ground stations for land-based applications. In particular, the effects of atmospheric attenuation and atmospheric turbulence are investigated. Moreover, we present implementation ideas of the necessary ground infrastructure and exemplify our results in a case study on the applicability of free-space optical satellite communication to the radio astronomy community. Our survey underpins pre-existing ventures to foster optical relay services like the Space-Data-Highway operating via the European Data Relay System. With well-designed, self-sufficient and small-sized ground terminals new user groups could be attracted, by offering alternatives to the emerging LEO mega-constellations and GEO-satellite communication systems, which operate at low return channel data rates across-the-board.

Keywords: ground data repatriation, EDRS, high-rate free-space optical laser link, optical ground-to-GEO link

Acronyms/Abbreviations

Automated Repeat reQuest (ARQ),
Bit Error Rate (BER),
Devolved Payload Control Center (DPCC),
European Data Relay System (EDRS),
Failure Detection, Isolation & Recovery (FDIR),
Forward Error Correction (FEC),
Free-Space Optical (FSO),
Geostationary Earth Orbit (GEO),
Hufnagel-Valley Model (HVM),
Index-of-Refraction-Turbulence (IRT),
Inter-Satellite Link (ISL),
Low Earth Orbit (LEO),
Mission Operations Center (MOC),
Monitoring & Control (M&C),
Optical-Communication Terminal (OCT),
Optical Ground Station (OGS),
Optical Ground-to-Space Link (OGSL),
Pointing, Acquisition and Tracking (PAT),
Radio-Frequency (RF),
Radio-Frequency Interference (RFI),
Satellite Communication (SATCOM),
Satellite Control Center (SCC)

1. Introduction

Recent advancements in the fields of cyber-physical systems, the internet-of-things, big data analytics and cloud computing have fostered public debates on data sovereignty worldwide. Not only for companies has the lack of data protection carried high risks to suffer from commercial, industrial or personal disadvantages. Therefore, informational self-determination is expected to get lots of exposure in the near term [1]. Ensuring the secure, efficient and sovereign data transfer for commercial enterprises, public authorities and scientific ventures operating at locations remote from their home premises poses a particular challenge at that point.

For that, free-space optical (FSO) communication provides some unique features [2]: (1) communicating at carrier frequencies in the optical bands allows for bitrates several orders of magnitude higher than can be achieved at radio frequencies; (2) the small beam divergence of FSO communication systems favours power efficient, small-sized terminals; moreover, intentional signal interference (jamming) and spoofing attacks are restricted to originate from an area of a few hundred meters around the counterpart stations, i.e. FSO connections show inherent physical security; (3) optical signalling does not create radio noise and is, therefore, not restrained by ITU regulations. By the same token, optical transmission schemes are very well suited to applications heavily sensitive to radio-frequency interference (RFI), particularly to radio astronomy. On the downside, FSO technology can generally not be assumed to be eye-safe and, therefore, requires the introduction of appropriate safety measures and some coordination efforts, for example with authorities (e.g. aviation) and exposed communities (e.g. astronomers).

Where no tethered transmission lines can be employed, satellite communication (SATCOM) has been the connectivity method of choice for decades. By three satellite stations, positioned 120 degrees longitude apart in the geostationary earth orbit (GEO), global coverage can be achieved [3]. To satisfy the upcoming demand for high-bandwidth data links, equipping GEO satellites with optical-communication terminals (OCTs) opens up promising perspectives. The concept was first tested between the SILEx-Terminal on board the Artemis spacecraft and the SPOT4 satellite [4], respectively with the optical ground station (OGS) at Izaña, Tenerife [5]. One current example of this approach is the European Data Relay System (EDRS), which became operational just recently in November 2016 and poses the first commercial endeavour regarding laser communications in space [6]. Catering to low earth orbiting (LEO) spacecraft for the time being, EDRS is focusing on optical inter-satellite links (ISLs). However, possibilities to extend the data-relay service to a broader user community have already been investigated. For example, Seel *et.al.* [7] suggested the utilization of OCTs on airborne reconnaissance platforms and Bobrovskyi *et.al.* [8] investigated the feasibility of optical feeder links to EDRS from ground at low elevation angles. Experimentally, ground to satellite communications is currently performed from the Observatorio del Teide in Tenerife. Tesat Spacecom has reported data rates of 1.8-Gbps with BER of 1e-8 and better employing 50-W transmit power from DLR's Transportable Adaptive Optics Ground Station to Alphasat [9].

Here, we spotlight design criteria for optical earth stations on potentially moving platforms for high-rate data-relay from remote locations via GEO satellites. Owing to the growing user demand for on-the-move global broadband connectivity, mobile ground terminals have occupied an expanding niche in the SATCOM market, however, they exhibit challenging technical and operational characteristics, like the need for a compact layout and a pointing, acquisition and tracking (PAT) system to target the GEO repeater [10]. State-of-the-art earth stations on moving platforms, then, lack a high-bandwidth uplink channel, since small-sized RF antennas can only provide comparably low gain [11]. As of today, no commercially-available optical ground-to-space terminals do exist to the best of our knowledge. Yet, a number of experimental or prototypic optical ground stations have been set up [13, 13]. We assume, that the FSO connection to the GEO satellite only operates in the return direction (uplink), hence, does not allow any in-band control.

Our investigation is supposed to serve as a guideline for hardware manufacturers and emerging service providers, when designing such terminals for operational use. Exemplarily, we focus on compatibility with ERDS, i.e. communication wavelengths in the 1064-nm band, since today the European system is the only readily available GEO relay operating in the optical regime. Moreover, the ongoing expansion of EDRS to GlobeNet, incorporating a repeater station above the Asia-Pacific region at the next level, will attract user communities who operate on global scales [14]. Still, great parts of our analyses hold true for other wavelengths.

The remaining part of the text at hand is organized as follows: In section 2, the design drivers and boundary conditions for ground-to-space OCTs are analysed; in particular, atmospheric effects on the optical transmission channel with respect to. signal obstruction due to clouds, signal attenuation as well as index-of-refraction-turbulence (IRT) induced signal fading are scrutinized and related to the geographical positioning of the ground terminals. Furthermore, we correlate the relevant parameters to the OCTs used by EDRS (with BPSK-homodyne modulation at 1064-nm wavelength) to set a benchmark on the current feasibility of optical ground-to-space links (OGSLs). In section 3, we elaborate different operations concepts of remotely stationed ground-based OCTs. Section 4 exemplifies our results by a case study of a broadband data-relay service for radio astronomers, and section 5 concludes with a summary and outlook.

2. Link Scenario and Performance Assessment

The geometry of the optical uplink from ground to the GEO relay is defined by the link elevation, which is a function of the locations of the OCT on ground versus the orbit position of the GEO relay satellite, as depicted in Fig. 2.1.

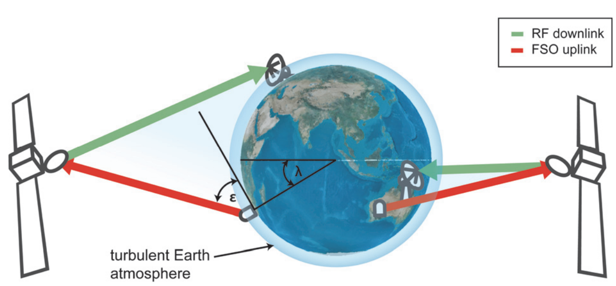

Fig. 2.1: Transmission Scenario of the optical Ground-to-GEO and RF GEO-to-Ground data-relay scenario. With elevation ε of the optical Ground-to-GEO uplink and absolute ground station geographical latitude λ.

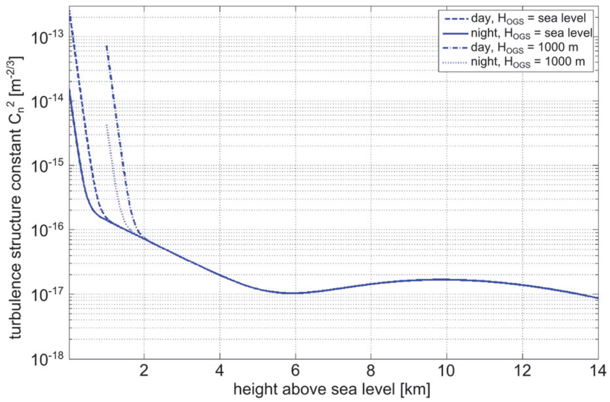

Fig. 2.2: C_n^2 height profiles for OGS at sea level and at 1000 m altitude (H_{OGS} a.s.l.), for night and day situations.

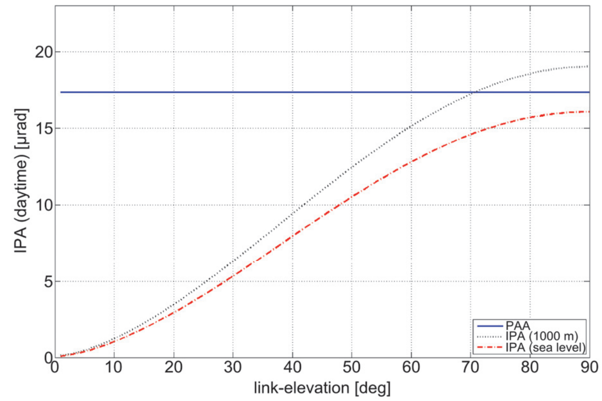

Fig. 2.3: Point-Ahead Angle (PAA) versus Isoplanatic Angle of the Atmosphere (IPA).

By way of illustration of the geometric conditions we simplistically assume satellite and OGS being on the same longitude and the OGS to be stationed at sea level; then the link elevation ε can be calculated from:

$$\varepsilon = 90° - \lambda - \operatorname{acos}\frac{R_E \cdot \sin(\lambda)}{R_{GEO} - R_E \cdot \cos(\lambda)} \qquad (1)$$

With R_E = 6,370-km and R_{GEO} = 42,156-km.

Crucial for OGSLs is the atmospheric index-of-refraction turbulence (IRT) along the first 1-2-km of the optical path close to the origin of the uplink (cf. Fig. 2.2), influencing the beam pointing quality and causing so called *scintillation* of the signal intensity as seen by the satellite's optical receiver terminal. The amount of atmospheric turbulence crossed by the link is influenced by the altitude of the OCT, by the time of the day, plus by temporary meteorological conditions.

Fig. 2.2 presents model height profiles of the parameter defining the IRT strength, C_n^2 (refractive index structure constant), based on a modified Hufnagel-Valley Model (HVM) [15]. Obviously the values of C_n^2 are strongest at lowest OGS locations and at daytime. For further modelling we only use daytime C_n^2 values together with two ground terminal altitudes for comparison. The turbulence path profile must be invoked with this C_n^2-over-height profile from Fig. 2.2 accordingly. This allows deduction of the parameters relevant to assess the reduction in link-budget induced by atmospheric effects. These are: atmospheric attenuation, loss by beam wander plus intensity-scintillation, and loss by the beam divergence being larger than in vacuum. To overcome these effects, widening of the uplink beam is often rendered.

It becomes generally problematic to pre-compensate beam uplink wander from the OGS by tracking the downlink signal, since the point-ahead angle (PAA) - caused by the motion of the satellite and the ground station in a rotating reference frame - is usually larger than the coherence-cone of the atmosphere (IsoPlanatic Angle - IPA). Fig. 2.3 illustrates the theoretical elevation dependent limitations according to Andrews and Phillips [16] for two ground station altitudes under daytime turbulence conditions for the 1064-nm wavelength used by the EDRS OCTs: Only at elevations close to zenith the PAA becomes smaller than the IPA and beam-pointing by tracking the downlink signal would become reliable also in worst IRT situations. In the general cases investigated in this paper, however, we have to make sure that the uplink beam divergence is accordingly increased to cover also the pointing uncertainties (worst-case modelling). In other words, applying pointing-by-tracking will practically still exhibit some gain, which is not yet regarded here.

Under these prerequisites of worst-case modelling, the different losses are calculated, resulting in the losses depending on link elevation as depicted in Figs. 2.4 and 2.5. The outages fraction of 10% accounting for strong fading events can be recovered applying standard coding techniques (*erasure-FEC*), which require only a minor overhead of typically slightly more than the fading loss fraction itself [17, 18]. The independent random processes of IRT-scintillation and beam-wander as derived by Toyoshima [19], Kiasaleh [20] and Giggenbach *et.al.* [21] are combined in one loss parameter ("combined dynamic loss", red dash-dotted curve). As has been mentioned by Andrews and Phillips [16], scintillation-peaking occurs at elevations below 10° (i.e. long atmospheric path suffering from strong turbulence), followed by a decrease of scintillations at higher elevations. Atmospheric attenuation (black dotted curve) is negligible for reasonable elevation ranges and the increased beam divergence angle (blue dashed curve) is optimized (i.e. balanced) with the pointing-loss.

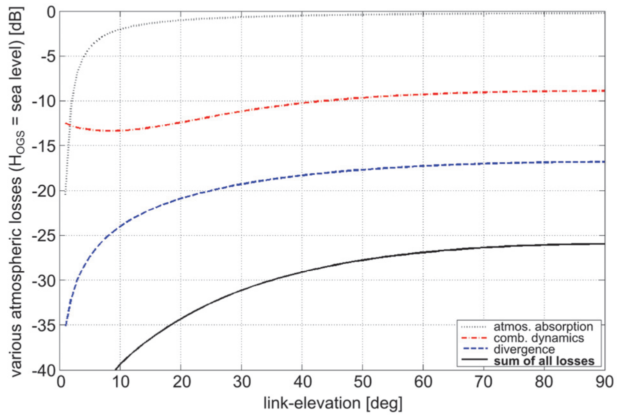

Fig. 2.4: Losses in dB of Ground-Uplink from sea level and at daytime vs. the EDRS-OCT in vacuum. For ground-OCT with optimal beam size and static pointing (no Pointing-by-Tracking).

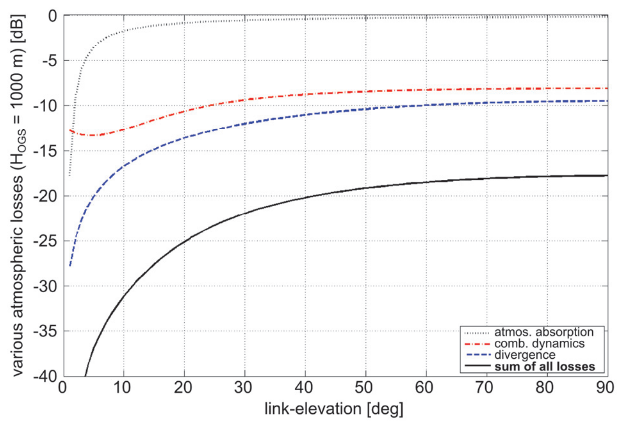

Fig. 2.5: Same as Fig. 2.4 (above), but with OGS at altitude of 1000-m a.s.l.

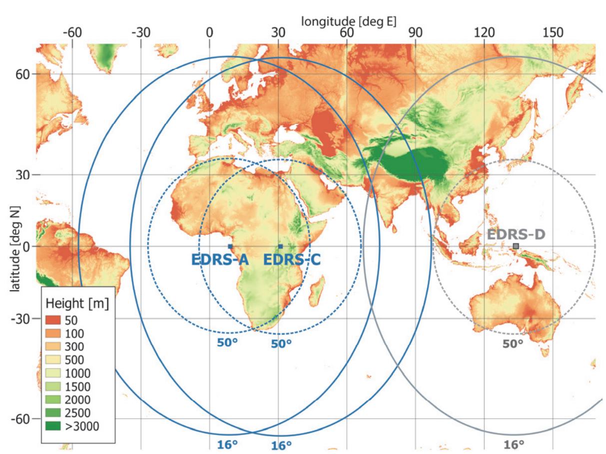

Fig. 2.6: Global areas where the relay service could be provided via EDRS satellites A, C (blue), or the future Asia-Pacific node EDRS-D (grey). Circles indicate visibility of the GEO system at elevations of 50° (dashed) and 16° (solid) from ground.

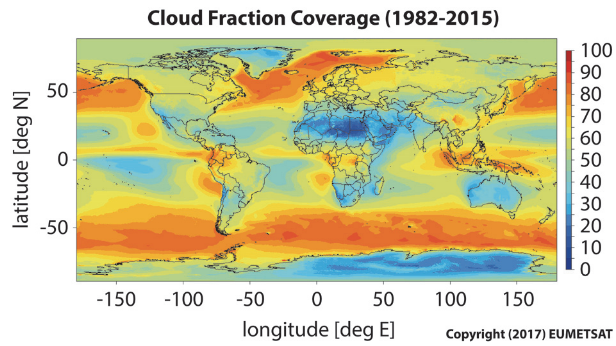

Fig. 2.7: Global map of cloud fraction coverage, averaged over a time period of 33 years (CFC, AVHRR on polar orbiting satellites) [23].

According to Heine *et.al.* [22], in the optical ISL-scenario (optical Inter-Satellite Link LEO to GEO) the OCT of EDRS works with transmit powers down to 180-mW in the 600-Mbps-mode at a Bit Error Rate (BER) of 1e-8 (for the 1.8-Gbps-mode the terminal requires accordingly higher power levels). With current amplifier technology, a margin of 27dB in the ground-uplink versus the ideal (vacuum) ISL can technically be reached employing a 100-W laser transmitter.

For the ground OCT at sea level, this theoretical benchmark on optical link loss implies a minimum elevation of 50°, while at 1000-m a.s.l. the elevation can go down to 16°. Fig. 2.6 depicts the respective areas on the globe where such an uplink would be feasible towards the EDRS-A, -C and -D space segments, respectively. These areas can be compared to global weather data to identify potentially interesting locations of optical ground-to-space terminals. Fig. 2.7 exemplarily shows a map of global cloud fraction coverage. Here, monthly mean values have been averaged over a time period of 33 years (1982-2015), disregarding seasonal variability. When classifying world regions into three domains, (1) CFC: 0-33% (blue/light-blue), (2) CFC: 33-66% (green/yellow), (3) CFC: 66-100% (orange/red), a strong overlap of class 1 and class 2 regions in Africa, Southern Europe, the Middle East and in Australia with the EDRS footprints (cf. Fig. 2.6) can be recognized.

3. Ground Segment Design and Operations

One key factor for a successful service implementation is the operations concept of all transmission terminals involved and their interface to the user. In the following, we detail this by an overall systems architecture aiming at the OGS to be operated very much alike a spacecraft.

3.1 Systems Architecture

The infrastructure of the proposed long range data-relay service is made up of four main elements (see Fig. 3.1): (1) a ground based OCT located at the remote site,

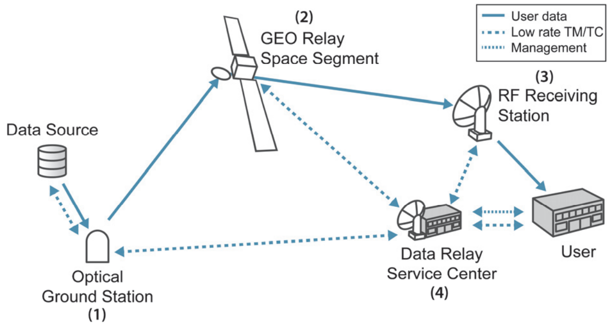

Fig. 3.1: Systems Architecture of a Data Relay Service based on OGSLs.

where user data is collected, (2) a relay satellite in GEO carrying the optical counter terminal and an RF downlink terminal with an appropriate footprint, (3) an RF receiving station within the satellite's footprint and a secure, high-rate connection to the user's home site, as well as (4) a Service Center embodying the interface between the user and the other three elements. Depending on the final implementation of this architecture, a service provider could incorporate all four elements or just parts of the group.

Due to the weather-dependency of the optical uplink, user data are preferably buffered locally at the OGS before they are sent to the spacecraft by modulation of a high-power laser source. On board, the satellite signals are converted and modulated onto an RF carrier for direct-to-Earth downlink. Receiving station(s) could be based directly at the user premises to optimize connectivity. Alternatively, data could be delivered from the ground station to the user via a secure wide area network (WAN) connection.

Lacking in-band control of the FSO uplink, direct low-bandwidth connections between the Service Center and the remaining system elements are used to exchange operational data. For instance, the optical terminals on ground and at the GEO relay need information on the positions of their counterparts (like ephemerides of the spacecraft and geo-coordinates of the OGS, respectively) to orient themselves appropriately before each communication session. Also, the RF ground station needs to be synchronized with the data transfer from the data source. Low rate links could be implemented in different ways. Depending on the actual situation on-site, wired or wireless internet connections could suffice; however, very small aperture terminal (VSAT) linkage (e.g. in C-band) might be necessary at far-off places. The management data flow between the user and the Service Center in Fig. 3.1 represents coordination activities to integrate the transmission scheme into the particular ground network at the user side.

3.1.1 Optical Ground Station

The main constituents of the ground OCT are an optical transceiver-telescope, a fine-pointing mechanism with acquisition and tracking sensors to lock onto the beacon signal from the GEO-OCT, a high-power laser source, optical modulator, optical power amplifier and respective control electronics. Furthermore, a precise coarse-pointing assembly, e.g. motorized azimuth and elevation actuator, is needed to target the space segment from mobile platforms. For that, the position of the terminal needs to be determined, for example by means of GNSS measurements. Finally, besides power supply and low-rate connectivity, the OGS has to be equipped with weather and cloud sensors to ensure free line-of-sight between transmitter and receiver, as well as with a safety system to ensure aviation safety when shining high power laser light up to the sky. For example, air-traffic monitors like ADS-B receivers or RADAR-sensors could be used ancillary to automated notices to Airmen (NOTAMs).

3.1.2 Data Relay Service Center

The relay-service is provided from a joint facility containing user management, network administration and ground control divisions to interface the different system elements. The Service Center could simply be incorporated by the operator of the GEO repeater for obvious reasons, but that is not essential. Here, the scheduling of the links based on the weather forecast for the OGS site and the availability of the GEO-OCT are performed in close coordination with the user, who is in charge of the remote data source. Moreover, the actual execution of the optical and RF link sessions is initiated and feed-through of the user data accomplished.

Though it would seem obvious to integrate the RF receiving station to directly into the user ground network, it could very well be operated (remotely) from the Service Center providing an end-to-end transfer scheme to the user. However, the ideal location of the receiving station needs to be scrutinized as the case arises, since RF transmissions come under ITU regulations and users might be located outside the downlink footprint of the satellite.

3.2 OGS Control Concepts

From an operations point of view, the service proposed here comprises the control of basically the space segment and the two ground stations (OCT and RF receiver). The space segment and RF receiver are to be operated classically from a satellite control center (SCC) and ground station facility, respectively. OGS operations could be implemented in several ways amplified below. Anyway, data is buffered by the OGS on initiative of the user as relay links are requested. The latency between data cache and reception at the user's home premises depends on the cloud cover above the

OCT and the availability of the GEO repeater. Therefore, particular latencies can generally not be guaranteed, narrowing the range of potential users to those, not in need for real-time transmissions. Relay links are to be executed in a five-step approach: (1) Transmissions are requested by the user at the Service Center. (2) In coordination with the space segment and receiving station operators link sessions are scheduled by the Service Center according to the weather forecast at the remote site; a confirmed schedule is sent back to the user. (3) Communication payloads on ground and in space are (pre-) configured in preparation of the link session. (4) The relay link is executed during the planned contact duration; to prevent data losses respective integrity checks are performed and steps 2 to 4 are repeated if necessary. (5) Data consolidation takes place at the receiving ground station and data is disseminated to the user premises.

Concerning the control of the OGS, one can envisage three scenarios:

- On-Site Operations
- Remote Operations
- Autonomous Operations

We presume that the essential actions to acquire, initialize and maintain the FSO link session, such as beacon scan and detection, serial handshake and point-ahead maintenance, are automated processes realized by the optical terminals' control electronics. For that, one needs to initially align the transceiver telescope and has to ensure appropriate coarse-pointing towards the GEO repeater.

3.2.1 On-Site Operations

A large user group will in any case deploy certain infrastructure and personnel at the remote site. For them, it makes good sense to train dedicated operators to manage and control the OGS. Then, low-rate TM/TC connections will mainly serve to exchange the link schedule and position information between the optical counter terminals. Link execution could be started manually or by time-tagged commands. Success approval of the data transmission is given by the user in step 5 (see above) via the low-rate connection before the local buffer is emptied.

3.2.2 Remote Operations

For users, who do not want to train on-site operators or do not deploy permanent staff at their distant site, the ground OCT could be remote-controlled. Low-rate connectivity, then, is essential, since it will serve for the configuration and commanding of the terminal, as well as for the monitoring of the station. Redundant TM/TC communication lines and surplus power supply might be desirable in such a scenario, especially if a high service level is aspired. Additionally, it would seem reasonable for the OGS to be equipped with a fail-safe monitoring and control (M&C) unit. OGS operators should preferably be situated at the Data Relay Service Center to optimize the workflow and system architecture.

3.2.3 Autonomous Operations

When we think of applications, not necessarily in need for a moving earth station at the remote site, fixed optical terminals pose a good option for autonomous operations. Once set-up, aligned and coarse-pointing towards the GEO repeater, those terminals are able to process time-tagged commands and send telemetry to the Service Center without the interference of an operator. In such a scenario, again, low-rate connections to deliver the link schedule and orbit position of the OCT in space (which is constantly drifting) should be redundant. The on-station control system and power supply are essential constituents of an autonomous terminal, which should be properly backed-up. Also, certain failure detection, isolation and recovery (FDIR) mechanisms should ensure fail-safe operations of the ground station. Special attention has to be paid to laser safety here. For example, the control unit needs to be fully aware of the station's environment (weather conditions, air traffic, etc.) and take it into account before initiating a link session, which might complicate the scheduling at the Service Center. Still, autonomously-operating ground OCTs pose an attractive front-end for the data-relay service proposed hitherto.

4. Case Study: Optical Ground-to-Space Data Relay from Radio Astronomy Sites

In this section, we present an example case of broadband data-relay via EDRS for radio astronomers. Highly sensitive to RFI, the radio astronomy community could particularly benefit from OGSLs. The field is characterized by strong team play on international scales. Far-off observatory facilities are preferably established on the southern hemisphere, where observational conditions are superior. Respective data processing and archiving centers, on the other hand, are spread all around the globe. Therefore, SATCOM at high uplink data rates, providing global coverage could embody an advantageous approach to distribute measurements.

4.1 Methods

For our assessment, four prominent astronomy sites in Australia, Africa and South America (see Table 4.1) with ties to the European research community have been selected: (1) in Australia the Australian Square Kilometer Array Pathfinder (ASKAP), (2) in South Africa the MeerKAT radio telescope, (3) in South Africa the Hartebeesthoek Radio Astronomy Observatory (HartRAO), (4) in Chile the Atacama Large Millimeter Array (ALMA). Average elevation

Table 4.1: Availability assessment of selected radio astronomy sites for OGSLs

	ASKAP	MeerKAT	HartRAO	ALMA
Latitude [°N]	-26.70	-30.97	-25.89	-23.02
Longit. [°E]	116.63	21.99	27. 69	-67.75
Altitude [m]	375	1310	1384	5034
Elevation [°]	53**	51 (53)*	53 (60)*	35#
Atmos. Loss [dB]	-24.1	-16.7 (-16.5)	-15.9 (-15.5)	-0
Tx-Power§ [W]	**46.3**	**8.4 (8.0)**	**7.0 (6.4)**	**0.18**
Availability [%]	**74**	**79**	**70**	**76**

* elevation to EDRS-A at 9 °E (to EDRS-C at 31 °E)
** elevation to EDRS-D at 134 °E
# elevation to a hypothetical America-node at 111 °W
§ 600Mbps, BER=1e-8

angles, at which the EDRS satellites are visible, have been determined on grounds of the observatories' geo-coordinates. Orbit positions for EDRS-A and -C are at 9°E and 31°E, respectively; EDRS-D will probably be positioned above the Asia-Pacific region at 134°E (t.b.c.). Above the Americas, a hypothetical EDRS node has been anticipated at 111°W for completion of the satellite system to cover the whole globe [24]. Transmit power requirements of a ground-based OCT have been estimated according to the loss assessment detailed in section 2 (cf. Figs. 2.4 and 2.5). Finally, access availability of OGSLs at the observatories has been evaluated by simulation (ONUBLA software tool) taking into account limitations due to cloud coverage as described in [25]. For that, five-year averages (between 2009 and 2014) have been calculated.

4.2 Results

From MeerKAT and HartRAO both EDRS-A and -C can be accessed at average elevations above 50°; ASKAP could reach out to EDRS-D, also, at a mean elevation above 50°, whereas from ALMA the hypothetical America-node was visible at 35°. Table 4.1 gives a summary of our results.

Transmit powers range from 180-mW (Atacama) to 46-W (Western Australia's Mid-West) depending on OGS altitude and link elevation. The ALMA telescope is situated above 5-km altitude; here, the optical link is hardly affected by the atmosphere, such that seeing conditions allow for transceiver apertures of up to 50-cm. Note, that the transmitter aperture is chosen according to the diffraction limited divergence angle of the telescope. The diameter of this aperture is dimensioned in accordance with the previously determined Fried parameter for the different sites at the varying elevations (cf. section 2 for the details). By comparison against the OCTs on-board EDRS, where aperture size is fixed to 12.5-cm, a 50-cm aperture results in an unfair assessment (theoretically one could "gain" signal strength from ground against the ISL). Hence, we simplistically limit the transmission aperture,

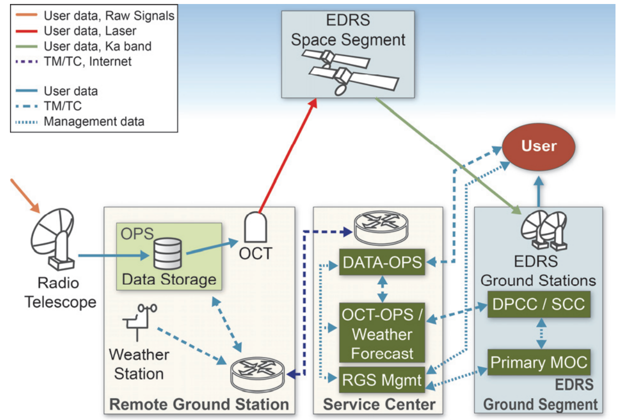

Fig. 4.1: Possible implementation of OGSL-based data-relay from radio astronomy sites utilizing EDRS.

such that no atmospheric losses appear in total, implying a link budget loss of 0-dB in comparison to the vacuum reference. Links from ASKAP, located below 400-m a.s.l., would suffer most from IRT induced losses of -24-dB.

OGSLs turn out to be 70-80% available on average. Highest performance is to be expected at the MeerKAT site, whereas the relay service from Hartebeesthoek would be moderately limited.

4.3 Discussion

All selected sites seem to be promising locations for OGSLs. Transmit-powers range within reasonable means at the different elevations identified. Respective optical terminals could, therefore, most probably be built from mature hardware components. Our survey focused on signal loss due to *power* scintillations, as they empirically pose the main error source for ground-to-space optical-communications. Average availability values compare to what would be expected from astronomical sites. However, seasonal variability has not been considered here, yet, and should be investigated in more detail as the case arises. Still, cloud cover would not form a significant barrier to the relay service, when no real-time processing is required. User data is stored in cache memory by the OGS, anyways, so intrinsic buffering / short-term backup functionality can be provided.

A possible EDRS-centric realization of the system architecture described in section 3 is depicted in Fig.4.1. Raw signals are recorded by the antenna(s) at an observatory and potentially pre-processed before they are cached at the OGS. The Data Relay Service Center is segregated from EDRS ground control offering more flexibility to the users. Operators can connect to the OGS via low-rate internet, as observatory sites are usually online. We suggest that both, OCT and fast-memory, are remote-controlled to simplify coordination at the Service Center and shield the users from the elaboration. The ground OCT acts the part of a usual

LEO spacecraft from the perspective of EDRS operations. Links are requested at the primary mission operations center (MOC) of EDRS, where the link planning for the system is carried out. After sessions have been scheduled, the space and ground OCTs are configured by the corresponding positions at the Service Center and EDRS ground control. EDRS already offers data consolidation at dedicated receiving stations (EDRS Ground Stations) in Weilheim (Germany), Redu (Belgium) and Harwell (UK). Still, users are free to implement their own antennas, if desired.

Looking ahead, there is apparently room to advance the data-relay proposed herein, operating over OGSLs. Disregarded through the main course of the text, higher abstraction layers could help mitigating cloud blockages to enable a fully automated, non-realtime file replication service. Corresponding protocols do exist and could be employed, e.g. CCSDS File Delivery Protocol (CCSDS 727.0-B-4), Disruption Tolerant Networking Bundle Protocol (CCSDS 734.2-B-1) and Licklider Transmission Protocol (CCSDS 734.1-B-1). Beside erasure-FEC, automated repeat request (ARQ) schemes pose viable options for error recovery, however, are probably not the first choice in GEO relay scenarios, since a long overall delay in combination with high-rate signaling then requires large transmission windows. Further on, pre-distortion adaptive optics in the uplink, or tilt-correction mechanisms could relax the link-budget, but come at an increase of complexity and costs. Finally, a broadening of the system architecture by site-diversity could boost availability of the relay service, however, at cost of increased design-intricacy.

5. Summary and Conclusions

On the backdrop of free-space optical data-relay satellite systems currently under construction, we have investigated the main challenges of optical ground-to-space links. Based on a modified Hufnagel-Valley model, signal losses due to atmospheric disturbances have been related to the uplink elevation. Assuming appropriate forward error correction to be applied, we have benchmarked the transceivers of optical ground stations with state-of-the-art space terminals.

Our analyses show that optical ground-to-space links can be readily realized with mature hardware components within a range of minimum uplink elevations between 16° and 50° depending on the altitude of the ground terminal. In combination with long-term cloud cover statistics, possible regions, where optical uplinks to the European Data Relay Satellites could be performed, can now be easily identified (see Figs. 2.6 and 2.7). Moreover, a case study has been presented, substantiating the feasibility and utility of connectivity services with high-rate return channel capacities for processing and archiving of large data volumes gathered or generated at far-off locations. Users are served at best according to their individual needs, as the service proposed allows for a range of operational concepts, including end-to-end data supply.

We conclude that clever utilization of the unique features of free-space optical-communications for the advancement of small, self-sufficient and autonomously operating optical ground terminals could eventually complement existing satellite communication systems obviating the need for high-risk mega-constellations.

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