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# Impact of molecular absorption on the design of free space optical communications

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## ABSTRACT

Free space optical communications systems have to deal with several impairments originating from the interaction of optical signals with the local environment and the atmosphere. These impairments include cloud blockage, aerosols scattering, molecules absorption and turbulence. In this paper, we focus on the impact of molecular absorption bands on the choice of uplink/downlink data wavelength division multiplexing grids (WDM) as well as uplink Pointing/Acquisition and Tracking (PAT) beacon wavelength.

**Keywords:** Molecular absorption, radiative transfer, wavelength multiplexing grids, CCSDS.

## 1. INTRODUCTION

Earth-space free space optical communications are expected to operate in the Short Wave Infra-Red (SWIR) region and more specifically in the C band [1530–1565 nm] and L band [1565–1625 nm]. These wavelengths are unfortunately subject to molecular absorption due to atmospheric gases such as H2O and CO2, etc. The study of the impact of these gases on the radiative forcing and greenhouse effects has been and is still being an area of high interest for communities investigating on climate change. In the case of free space optical communications through the atmosphere, these gases could induce high frequency selectivity depending on the position and width of molecules absorption bands with regard to the transmission wavelengths. The consequence of this frequency selectivity on the selected wavelengths for Pointing/Acquisition and Tracking as well as uplink/downlink data transmission channels needs to be assessed.
In order to evaluate the impact of this C and L intra-band molecular absorption, a representative optical communication chain has been simulated using:

- The 4A/OP (Automatized Atmospheric Absorption Atlas) tool which is a line-by-line radiative transfer model optimized for the infrared region. It allows the simulation of the transmission spectrum for different climates and elevation angles.
- The OpticalSim tool (developed by ISAE-SUPAERO/TeSA in the frame of CNES studies) which simulates and evaluates the performance of end to end optical communication links using different transmission schemes (OOK, DPSK) and receiver architectures (APD, PIN + pre-amplification).

Section 2 of this article presents the atmospheric absorption simulation tool. Section 3 introduces the discussion on band plan selection. In Section 4, the effect of absorption lines on the beacon is presented. In Section 5, the method used for assessing the effect on the communication signal is presented. The optical chain simulation tool is also described and the results of the end to end simulation of BER performance in the presence of atmospheric absorption, for different configurations of channel spacing and wavelength grids are given. Section 6 draws conclusions and future perspectives.

## 2. ATMOSPHERIC ABSORPTION

Infra-Red (IR) signals propagating through the atmosphere are subject to both absorption and scattering from aerosols and molecules. As far as aerosols are concerned, their dominant effect in the SWIR region is scattering rather than absorption (except for soot particles). This scattering impacts the overall transmission continuum in the C band [1530–1565 nm] and L band [1565–1625 nm] resulting in a loss of the received optical power which is independent of the transmission wavelength. Hence, this impairment will not be considered in the article as it does not affect the choice of the wavelength band plan. Atmospheric molecules, on the contrary, have negligible scattering but strong wavelength dependent absorption in the form of deep extinction bands.
In order to characterize the impact of these absorption bands on the eligible transmission wavelength plan, a high spectral resolution simulation of atmospheric molecular transmission is required. To do so, the **A**utomatized **A**tmospheric **A**bsorption **A**tlas (4A)/OP radiative transfer tool has been used in the current study. The 4A/OP simulation tool is a high resolution fast line by line radiative transfer model jointly developed by CNES, LMD/CNRS and NOVELTIS [1]. It allows the computation of radiative transfer using a precompiled optical thickness atlas for various atmospheric molecules and isotopes.

This atlas has been computed using a line by line layer by layer model (STRANSAC [2]) with the up to date GEISA spectroscopic database [3].
Since molecular absorption involves gases such H2O, the overall molecular transmission spectrum can be climate-dependent for some wavelength bands. In order to be representative of different climatic regions of the globe, 5 different climates have been studied. The simulated climates defined in [4] are: tropical, mid-latitude summer, mid-latitude winter, sub-arctic summer, sub-arctic winter.
On the other hand, molecular absorption is also dependent on the propagation path length. Indeed, the lower the elevation, the longer the propagation path in the atmosphere and the stronger the molecular absorption. For GEO optical feeder link, elevations are usually higher than 20°. On the opposite side, link elevations for LEO communications links could go as low as 5°. In order to cover different system needs, the overall transmission spectra have been simulated for 4 different elevation angles: 5°, 10°, 20°, and 40°.

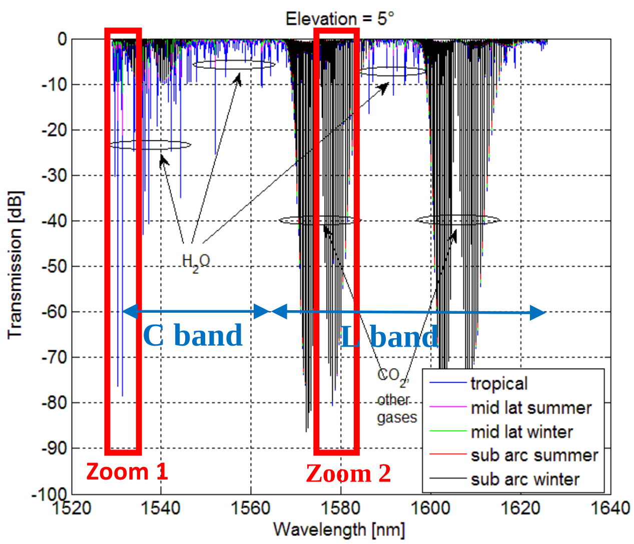


Figure 1: Molecular absorption for elevation = 5°

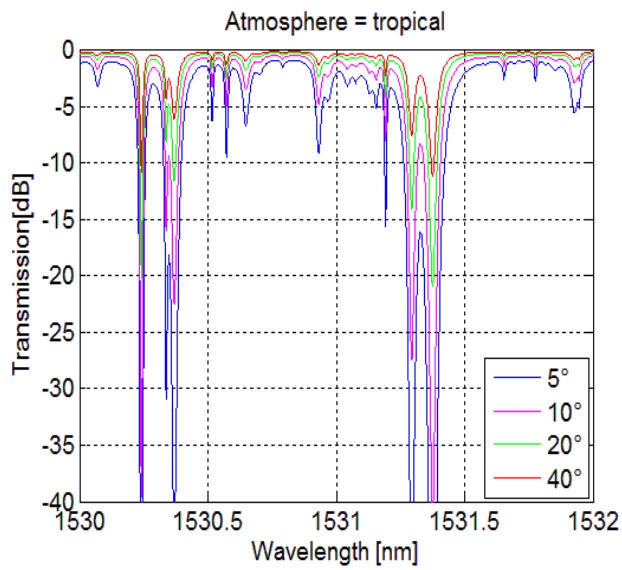


Figure 2: Molecular absorption for tropical climate

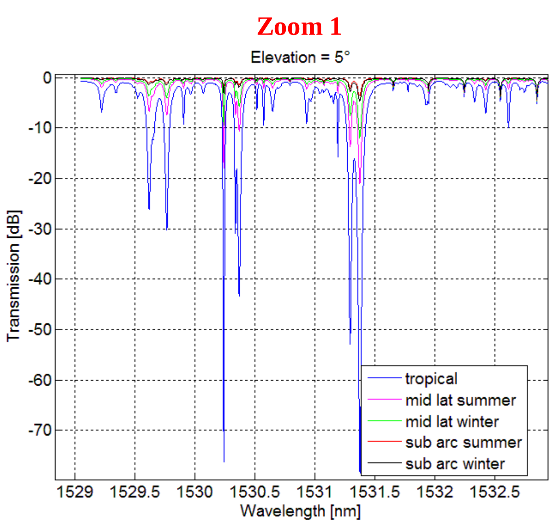


Figure 3: Molecular absorption at 5° elevation: Zoom 1

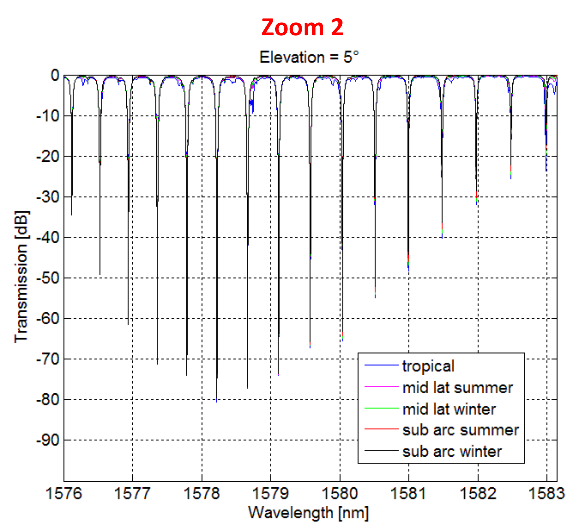


Figure 4: Molecular absorption at 5° elevation: Zoom 2

Figure 1 and Figure 2, present an example of the simulated transmission in the band [1530nm-1532nm] for a fixed elevation (5°) with different atmospheres, and a fixed atmosphere (tropical) with different elevations respectively. On the one hand, a clear dependency of the molecular absorption on the climate can be noticed. However this dependency is not present over the whole C and L band due to the presence of gases other than H2O (CO2, etc.) which are independent of the climate, as it can be seen in Figure 4. On the other hand, a strong dependency on the elevation is noticed which is in line with the dependency of the total absorption on the path length.

## 3. OPTICAL COMMUNICATION BAND PLAN

The purpose of a communications system is to transfer information from one point to another. This transfer is often achieved by imposing a modulation onto a carrier wave, which is then transmitted to its destination. The advantages of using an optical carrier frequency (instead of RF) in space communications are: the possible increase in transmission bandwidth, the ability to achieve significantly higher transmission and reception antenna gains, and the potential reduction of size, mass, and power consumption on a spacecraft.
In order to perform optical space communication, a wavelength band plan is to be defined in order to specify the wavelengths to be used for data transmission and pointing. In the scenarios considered, the optical communications ground terminal is required to transmit a powerful laser beacon as a pointing and tracking aid to allow the space terminal to track the position of the ground terminal with the necessary accuracy.
Discussions on the suitable band plans are conducted in the frame of CCSDS SLS-OPT working group where standards are defined for the use of space optical communications systems. Four agency members of the SLS-OPT working group (NASA, CNES, JAXA, and NICT) have agreed to develop a CCSDS Orange Book for 1550 nm High Data Rate Optical Communications that can support a range of data rates from Mbps to greater than 100 Gbps via Wavelength Division Multiplexing (WDM). The proposed band plan is in the C band (Figure 5): for the uplink beacon the shortest wavelengths are considered, the communication band 2 used for the downlink is located at the longest wavelengths in order to offer sufficient spectral separation with the beacon. The selected center frequencies in the optical C-band are a subset of those defined in the ITU-T G.694.1 frequency grid with 100 GHz channel spacing [6].

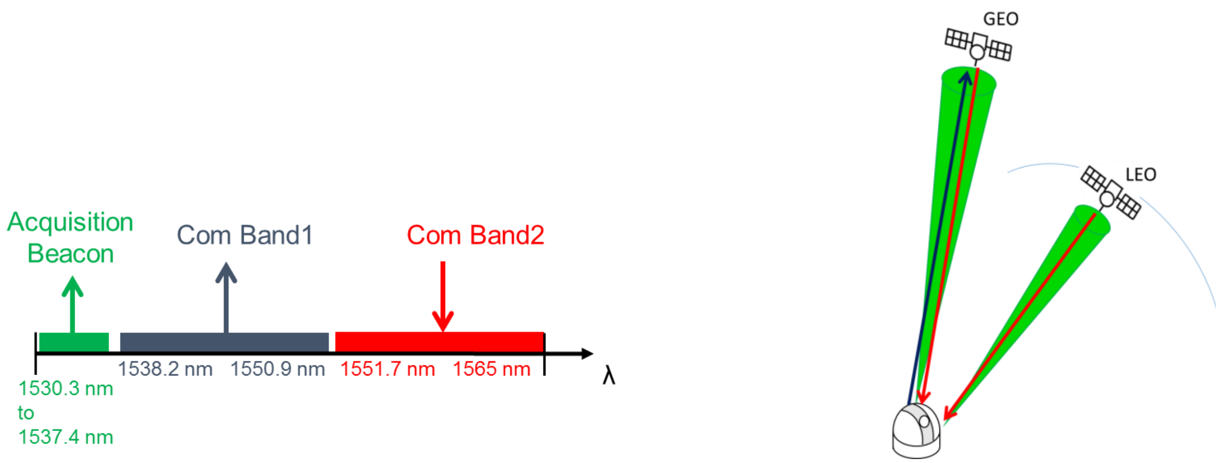


Figure 5: proposed band plan (left), space-to-ground optical communications links: uplink beacon, uplink communication band 1, downlink communication band 2 (right)

The following part of the article evaluates the effect of molecular absorption bands on the choice of uplink/downlink data wavelength division multiplexing grids (WDM) as well as uplink Pointing/Acquisition and Tracking (PAT) beacon wavelengths. It will be done for various climates and also various elevations in order to cope with the current link scenario conditions envisaged for space-to-ground optical communications links.
Transmitting at low elevation increases the contact time, and the quantity of transmitted data. Starting the transmissions at 5° elevation angle, like in the current RF X Band systems, is however challenging for optical links due to penalty at low elevation caused by absorption, aerosols, and stronger turbulences.

## 4. EFFECT OF ABSORPTION LINES ON THE SIGNAL BEACON

The beacon is used to initiate the Pointing Acquisition and Tracking (PAT) sequence: a diverging laser is used to illuminate the target and allow the two optical terminals to point in the same direction. The beacon laser is usually not modulated or modulated at a low data rate (< 100Mbps), its bandwidth is consequently narrow. The central frequency stability of the beacon is dependent of the temperature. In order to assess the degradation caused by the absorption lines on the transmitted beacon, the criteria, proposed by NASA during CCSDS meeting, consists in considering the value of the strongest absorption line inside the selected band.
The width of the band is determined by the stability of the central frequency of the beacon laser, which is directly related to the thermal control. Distributed FeedBack (DFB) laser diode modules usually include an internal temperature control (Thermo Electric Cooler –TEC- and thermistor) in order to operate the laser at a fixed temperature. When the DFB includes a TEC, the variation of the wavelength in function of the temperature is limited. For an operating case temperature [-5°C; +65°C], the wavelength drift in function of the temperature of the case (Tcase) dλ/dTcase varies from 0.5 pm/°C to 5 pm/°C (0.06 GHz/°C to 0.6 GHz/°C).

For a variation of 50°C of the operational ambient temperature, the center frequency may vary from 3 GHz to 31 GHz. It is assumed in this article a variation of the ambient temperature of about 30°C and a drift of 5 pm/°C, which leads to a laser central frequency varying inside a band of ± 9 GHz around the nominal central frequency. The selected central frequencies correspond to the ITU-T G.694.1 frequency grid with 100 GHz channel spacing on the 1530 nm to 1538 nm range. The beacon bands and absorption lines are shown in Figure 6.

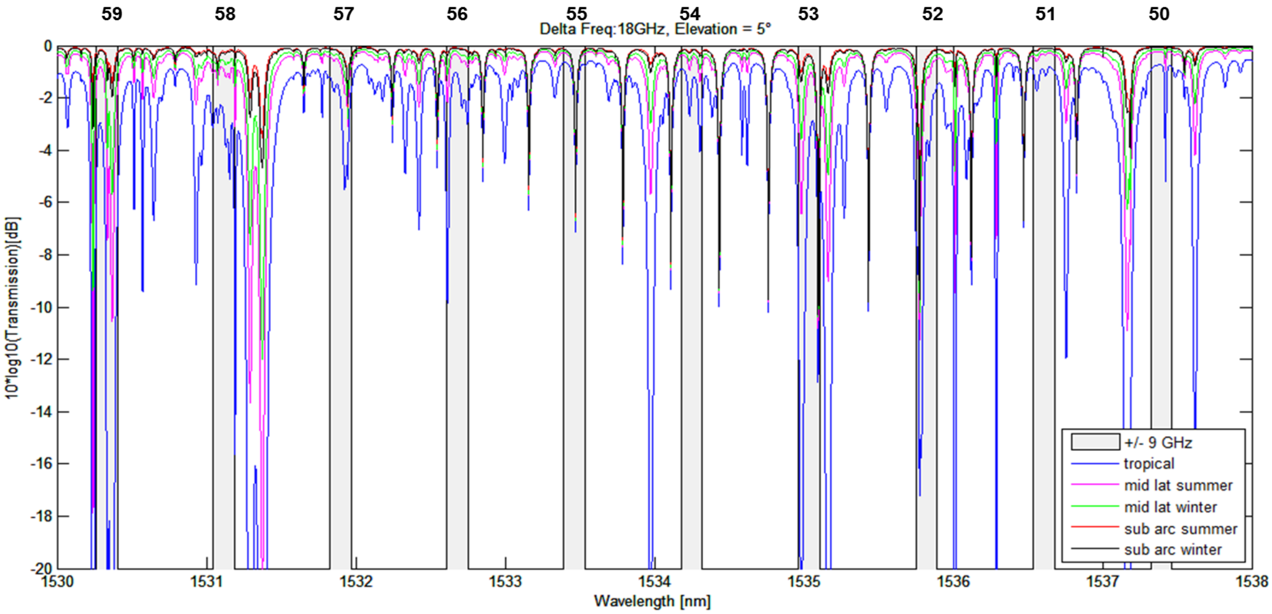


Figure 6: absorption lines at 5° elevation for several climates, for a band of 18 GHz around the ITU WDM 100 GHz grid

The maximum penalty due to absorption lines for various elevations and climates, for a band of 18 GHz around the ITU WDM 100 GHz grid are presented in Figure 7. If a maximal degradation of 3 dB is considered, for the more demanding tropical climate at 5° elevation angle, only one channel is suitable: the channel n° 51. If the considered elevation is 10°, 3 more channels are suitable (57, 54, 50). For other climates, 6 channels are suitable for all elevations. By choosing the ITU grid with a spacing of 50GHz, even more channels are suitable for the beacon as shown in Figure 8. It can be concluded that the band [1530.3 1537.4] nm is appropriate for selecting the beacon wavelength.

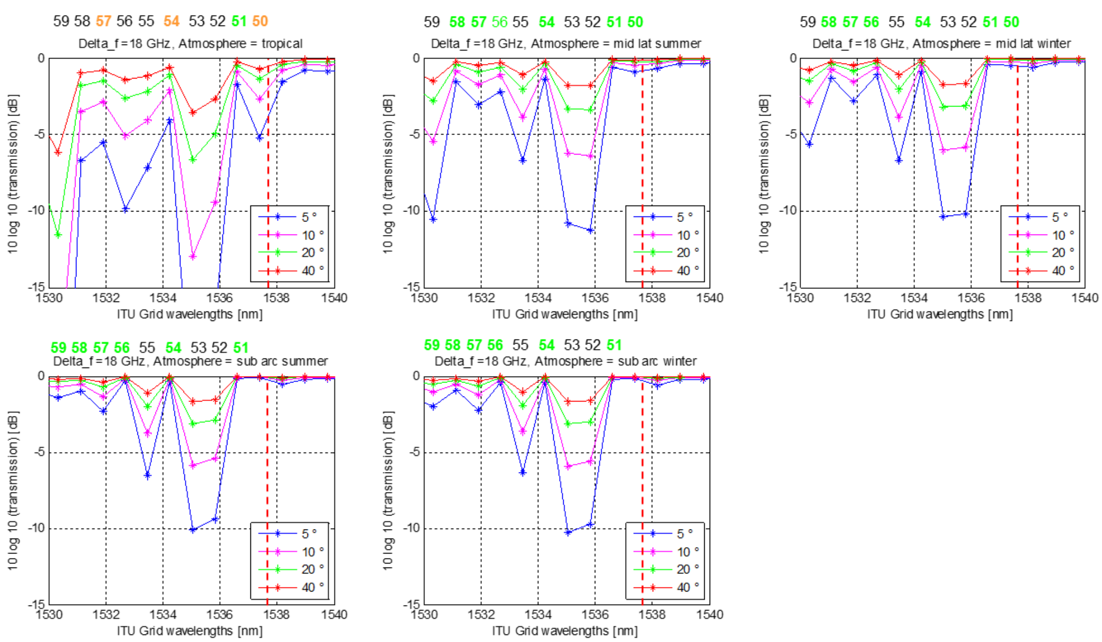


Figure 7: maximum penalty due to absorption lines for various elevation and climate, for a band of 18 GHz around the ITU WDM 100 GHz grid

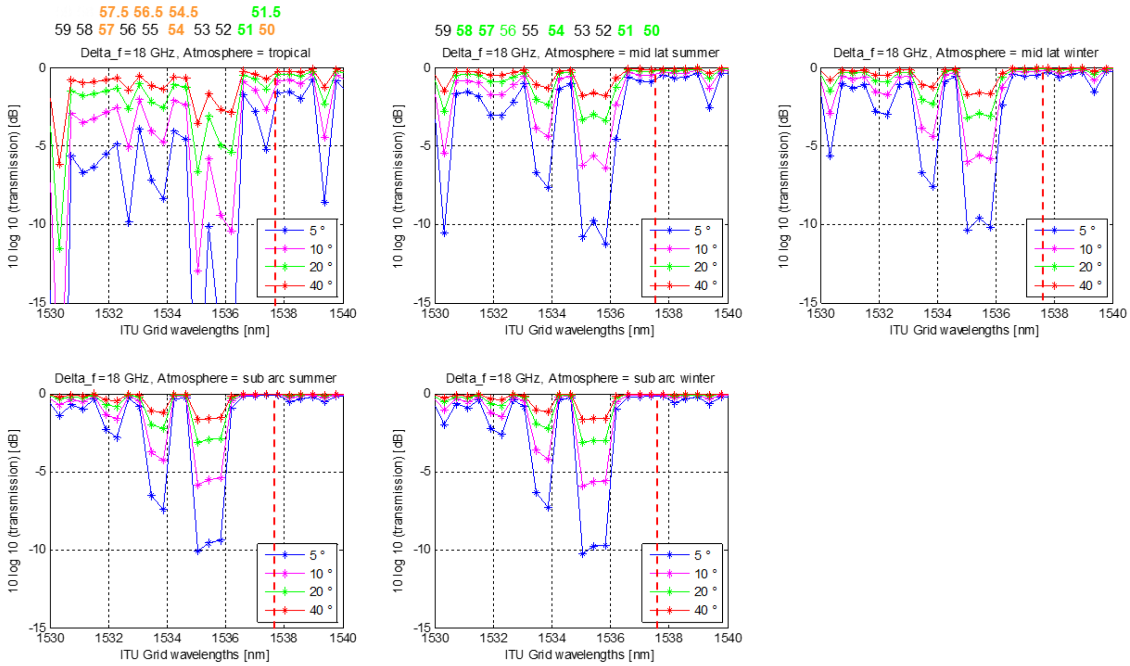


Figure 8: Maximum penalty due to absorption lines for various elevation and climate, for a band of 18 GHz around the ITU WDM 50 GHz grid

## 5. EFFECT OF ABSORPTION LINES ON THE SIGNAL DATA

### 1.1 Principle

In space-to-ground optical communications links, data are transmitted on channels having a bandwidth directly related to the used optical modulation and the data rate. A number of channels can be transmitted in parallel using wavelength division multiplexing, that consists in transporting the channels on different optical carriers which central wavelengths are placed on a predefined grid.

The effect of absorption lines on the signal cannot be estimated by just selecting the strongest line in the useful band, like it was done previously for the beacon. It is needed to take into account the optical modulation and how it is affected by the absorption lines. The followed approach consists in simulating the end to end link, including emission and reception and applying a filter representing the absorption spectrum to the transmitted signal. At the receiver end, the degradation is estimated by computing the difference to a reference case without absorption, in terms of received power and bit error rate. In this article the channel rate of 10 Gbps has been chosen, which corresponds to the maximum data rate considered in the current CCSDS standards.

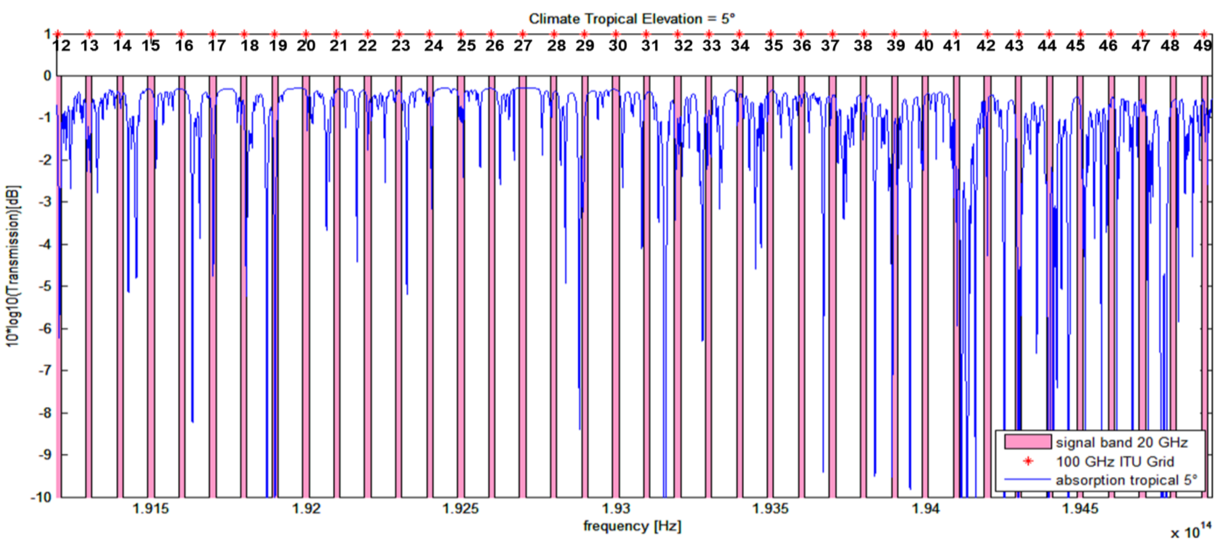


Figure 9: Frequency representation of the absorption lines, and occupied bandwidth of a 10 Gbps signal

## 1.2 Optical communication chain

An end-to-end optical physical layer (PHY) simulator has been developed by ISAE-SUPAERO/TéSA in the frame of CNES studies. It aims at precisely modeling the subsystems of a typical optical transceiver. It accurately takes into account the characteristics of the communication subsystems (link budget, modulation, impact of noises sources at the transmitter and receiver sides, filtering). Therefore, it allows to precisely account for both the effects of inter-symbol interference (ISI) and the exact statistical properties of detection noise. For instance, on the transmitter side, limitations that affect the Continuous Wave (CW) laser source (relative intensity noise, phase noise), the external modulator and pulse carver (extinction ratios) as well as the booster amplifier (amplified spontaneous emission) are precisely modeled.
On the receiver side, depending on the type of architecture considered (pre-amplified balanced or not PIN or APD), similar limitations are specifically modeled. They include photo-detection noises typically characterizing a PIN or APD (shot noise, thermal noise, dark current, bulk and surface leakage currents, finite bandwidth), the amplified spontaneous emission of the EDFA pre-amplifier and a finite bandwidth optical band-pass filter (Lorentzian approximation of a typical Fabry-Perot filter) as well as an electrical low-pass filter (fifth-order Bessel characteristic).
Figure 10 shows the different architectures considered for either OOK or DPSK modulation formats. Using such an end-to-end modeling of optical transceivers, accurate BER estimation can be computed through Monte-Carlo simulation while including the impact of both ISI induced by the limited bandwidth of the photodetectors and filters as well as the exact statistical properties of the most prominent sources of noises. Detailed description of the simulator functionalities can be found in [7].
The FSO channel module is used to apply degradations caused by the atmosphere (absorption lines, turbulences, …). In this article the only propagation degradation that is applied corresponds to the absorption lines. The molecular absorption lines computed by the 4AOP simulator, previously described, were processed in order to obtain equivalent filters that can be applied to the signal. Absorption lines were organized in bands of width 90 GHz around the WDM grid and oversampled to correspond to the sampling frequency of the communication chain simulator. A gate filtering is also applied to avoid discontinuities.

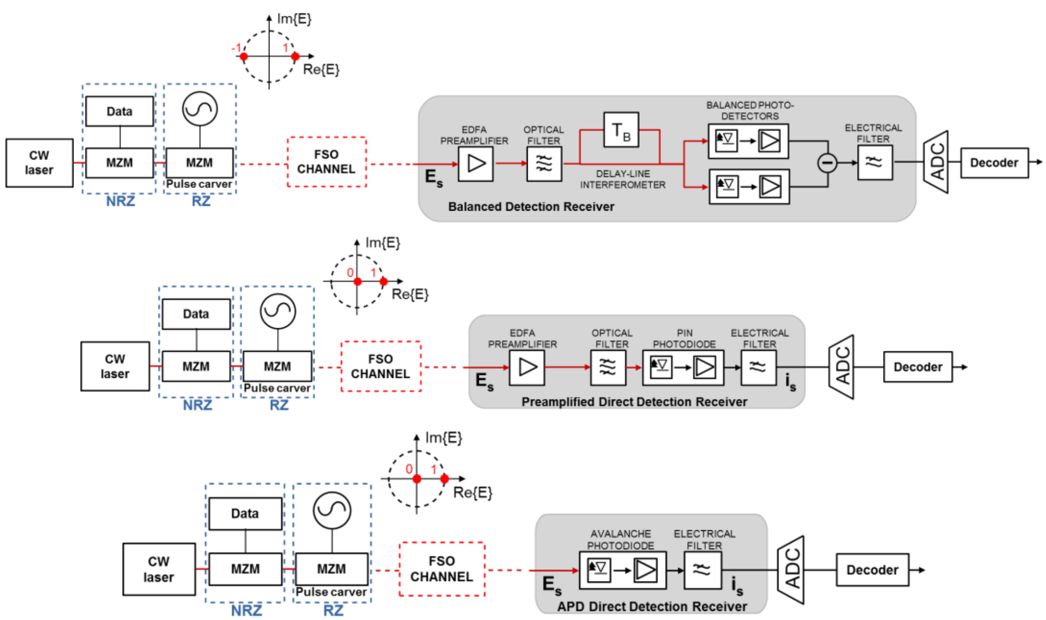


Figure 10: Transceiver designs modeled for NRZ- and RZ- (a) DBPSK (b) pre-amplified OOK (c) APD-based OOK signal generation and detection (constellation diagram shown for normalized to unity average optical power)

An illustration is provided in Figure 11 showing the spectrum of absorption on the left and the spectrum of an NRZ-OOK signal before and after filtering on the right.
The simulator provides bit error rate (BER) curves in function of the received power, which are compared to the reference absorption-free curve. A number of different cases are summarized in Figure 12: if no strong spectral lines affects the main lobe of the signal, the BER curve is not degraded and only the mean received is lower (channel 30); if spectral lines affect the main lobe, the BER curve is degraded (channels 12 and 53), if the absorption lines are too strong, the signal is so degraded that the reception is no longer possible (channel 59).

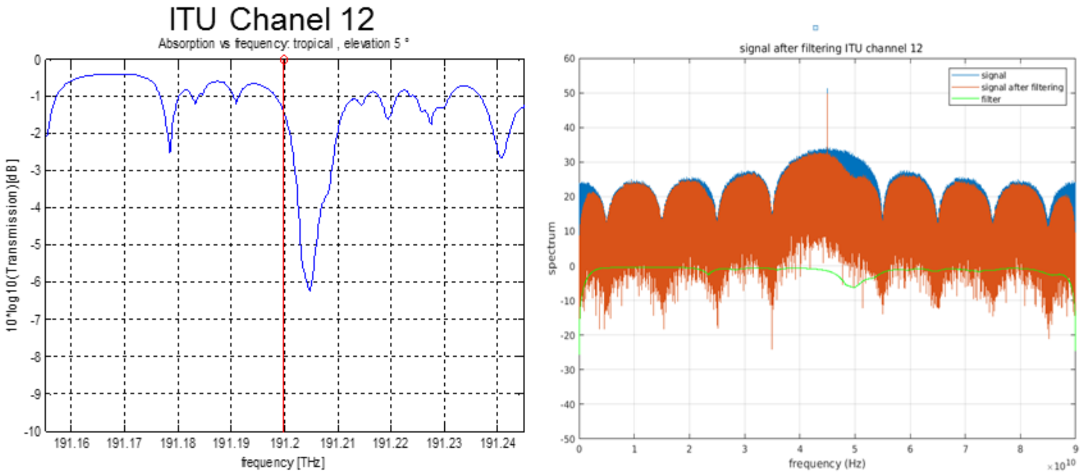


Figure 11: Example of effect of an absorption band on the signal spectrum (NRZ-OOK, 10 Gbps)

The BER performances have been evaluated for all the WDM grid of the C band for a number of climates and elevations, and the degradation on the mean received power and the BER curve are calculated. The case of tropical atmosphere for 5° elevation is presented in Figure 13. The degradation of the BER curve was chosen to be calculated on a non-coded signal and for uncoded bit error rate of $10^{-4}$, which is a good compromise for having representative BER and reasonable simulation duration.

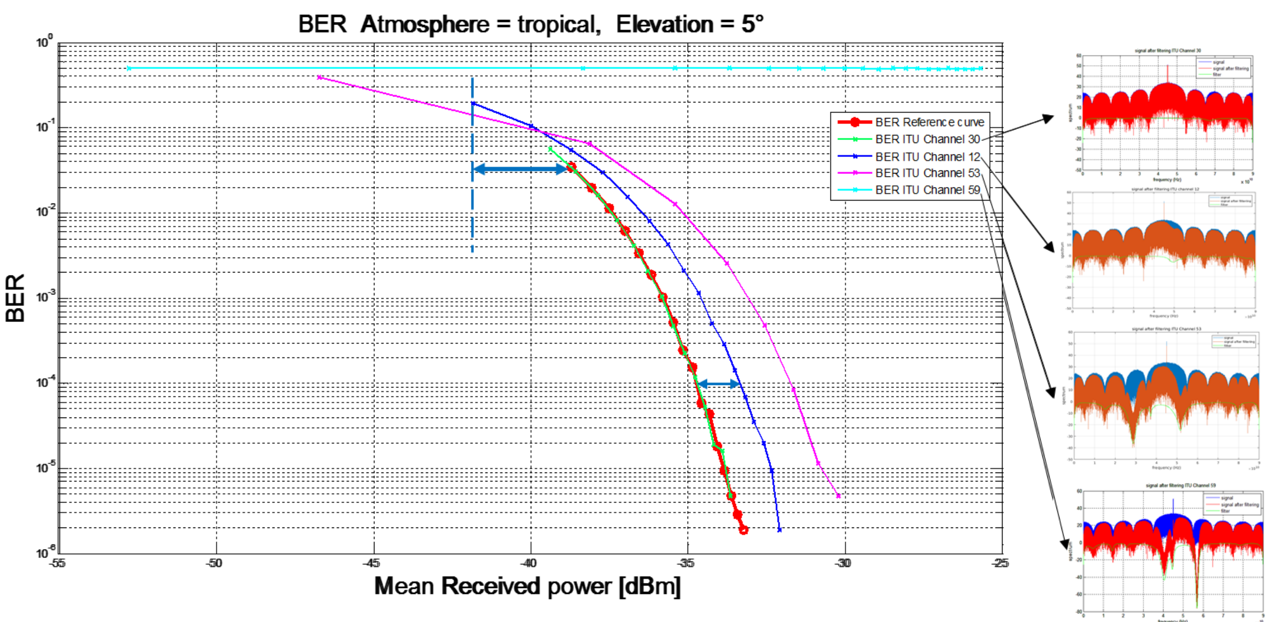


Figure 12: Effect of absorption lines on bit error rate

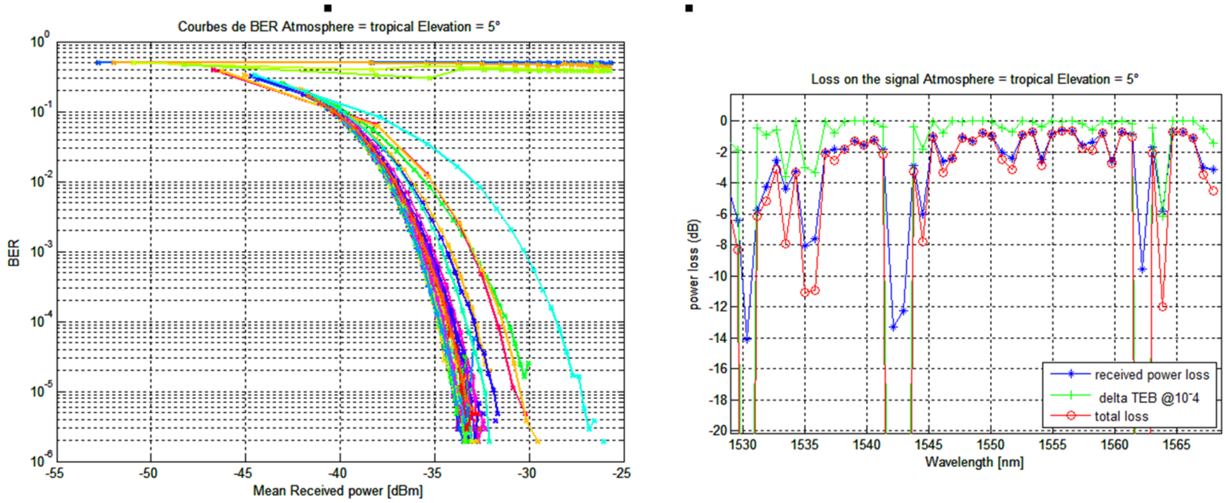


Figure 13: computation of total loss for tropical atmosphere at 5° elevation

## 1.3 Results

The approach presented in the previous chapters has been applied to the two worst case climates: tropical and mid latitude summer, for elevations 5°, 10°, 20°, 40°, and for 2 configurations of communication chains that are described in Table 1.

| | Configuration 1 | Configuration 2 |
|---|---|---|
| Transmitted signal | OOK – NRZ<br>10 Gbps<br>rectangular pulse shape | OOK – NRZ<br>10 Gbps<br>SRRC 0,8 roll-off pulse-shape |
| Receiver | APD based | Pre-amplified ( EDFA + PIN) |

Table 1: configurations of the communication chain

The total degradations on the received signal are presented in Figure 14 and Figure 15. The communication bands 1 and 2 provide 17 channels for WDM each. Table 2 indicates the number of usable channels by considering that the total degradation due to absorption lines is lower than 3dB.

In the worst case scenario: tropical climate at 5° elevation angle, on com band 1: 11 channels over 17 are still usable and on com band 2: 13 channels over 17. The number of usable channels increases with the elevation and a less penalizing climate. It can be concluded that there are sufficient available communication channels in C band that can be used for data communication.

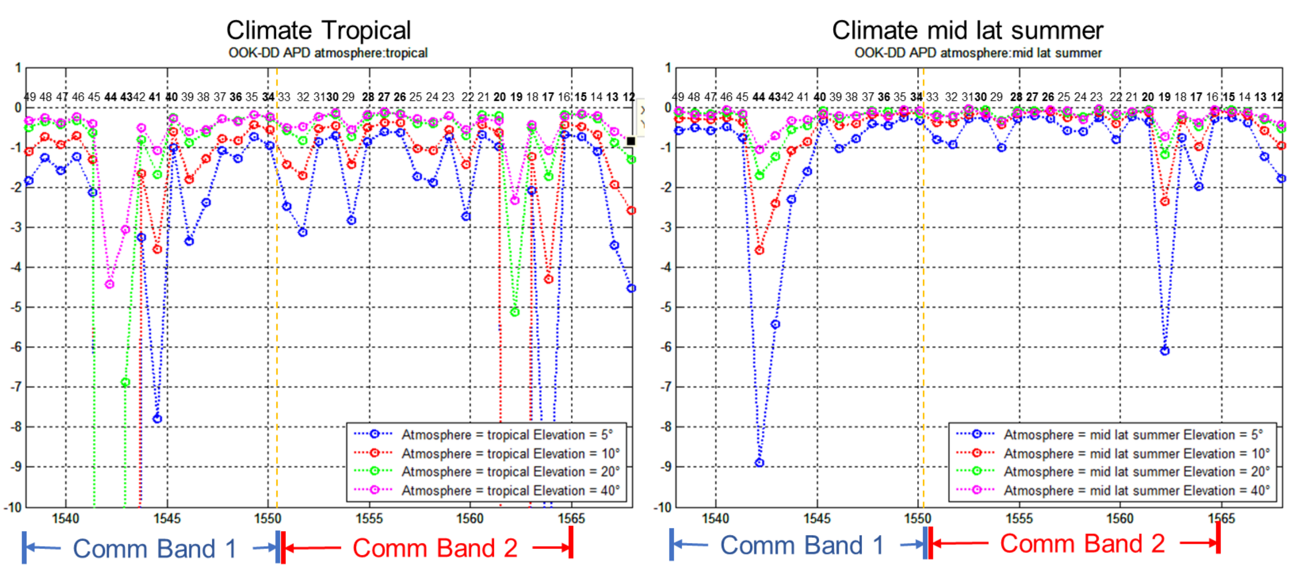


Figure 14: total loss for signal OOK – APD, 10Gbps, rectangular pulse-shape

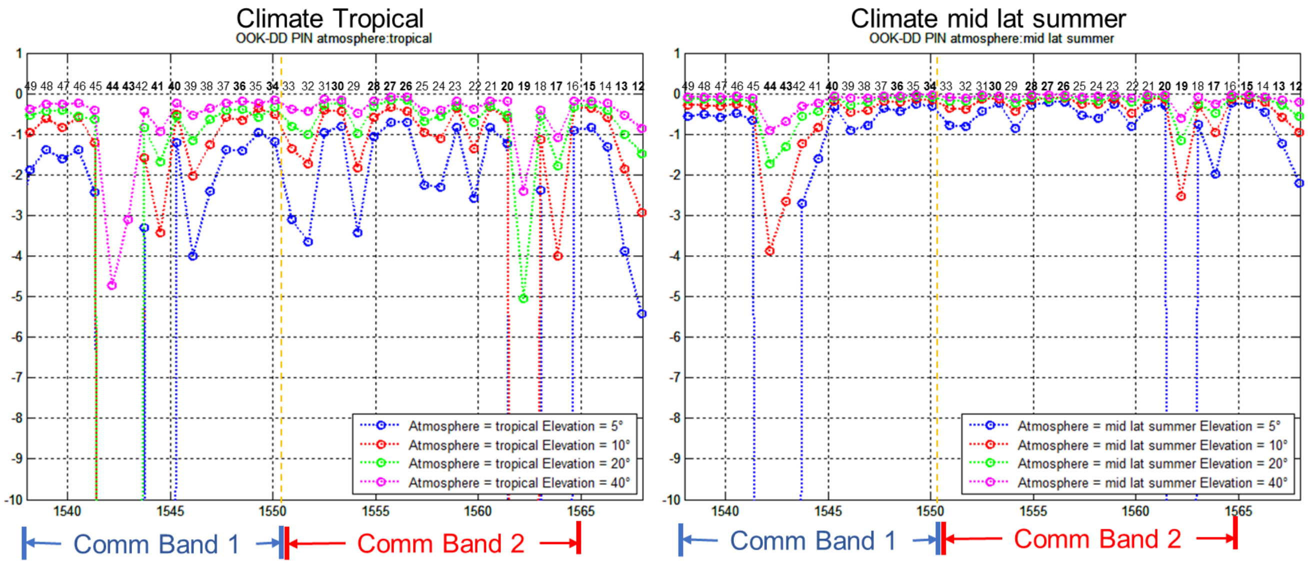


Figure 15: Total loss for signal OOK – preamplified + PIN, 10Gbps, SRRC 0,8 roll-off pulse-shape

| | | 5° | | 10° | | 20° | | 40° | |
|---|---|---|---|---|---|---|---|---|---|
| | | COM 1 | COM 2 | COM 1 | COM 2 | COM 1 | COM 2 | COM 1 | COM 2 |
| conf 1 | tropical | 12 | 14 | 14 | 15 | 15 | 16 | 15 | **17** |
| | mid lat sum | 15 | 16 | 16 | **17** | **17** | **17** | **17** | **17** |
| conf 2 | tropical | 11 | 13 | 14 | 15 | 15 | 16 | 15 | **17** |
| | mid lat sum | 15 | 16 | 16 | **17** | **17** | **17** | **17** | **17** |

Table 2: Summary of the available channels, the maximum being 17

## 6. CONCLUSION

An analysis of end to end performance using WDM ITU wavelength grid spacing in C band has been carried out. Molecular absorption bands have been simulated as frequency selective channels, and impact on the beacon and communication signals has been evaluated. This analysis has allowed to demonstrate that some of the ITU grid wavelengths might be unsuitable for data transfer in some climate/elevation configurations due to high channel selectivity leading to degraded end to end uncoded BER performances. Solutions like flexible wavelengths grids or narrow WDM grids might be thus envisaged to avoid undesired absorption bands. However, there are sufficient available channels in C band that can be used for the beacon and for data communication, proving that the band plan proposed by CCSDS Orange Book for 1550 nm High Data Rate Optical Communications is suitable for space optical communications thought the atmosphere. For systems requiring additional channels, similar study can be performed on the L band. Complementary work will consist in studying the effect of absorption lines on signals with other configuration of modulation, pulse shaping and data rate.

## 7. SPECIAL NOTE

This work has been carried out during L. Canuet PhD when he was affiliated to CNES. At the time of publication of this paper, his new affiliation is Thales Alenia Space.

## REFERENCES

[1] Scott, N.A. and A. Chedin, 1981: A fast line-by-line method for atmospheric absorption computations: The Automatized Atmospheric Absorption Atlas. J. Appl. Meteor., 20,802-812.
[2] Scott, N.A., 1974: A direct method of computation of transmission function of an inhomogeneous gaseous medium: description of the method and influence of various factors. J. Quant. Spectrosc. Radiat. Transfer, 14, 691-707

[3] N. Jacquinet-Husson, R. Armante, N.A. Scott, A. Chedin, L. Crépeau, C. Boutammine, A. Bouhdaoui, C. Crevoisier, V. Capelle, C. Boonne, N. Poulet-Crovisier, A. Barbe, D. Chris Benner, V. Boudon, L.R. Brown, J. Buldyreva, A. Campargue, L.H. Coudert, V.M. Devi, M.J. Down, B.J. Drouin, et al. The 2015 edition of the GEISA spectroscopic database. J. Mol. Spectrosc., 327, 31-72, http://dx.doi.org/10.1016/j.jms.2016.06.007 (2016)
[4] COESA, US. "Standard Atmosphere Supplements, 1966." US Government Printing Office, Washington, DC (1966).
[5] Booth, N. and Smith, A. S., [Infrared Detectors], Goodwin House Publishers, New York & Boston, 241-248 (1997).
[6] Spectral Grids for WDM Applications: DWDM Frequency Grid. ITU-T Recommandation G.694.1. Geneva: ITU, 2012
[7] L. Canuet, PhD thesis "Reliability of satellite-to-ground optical communication" https://www.theses.fr/2018ESAE0005