UNIVERSITÀ DEGLI STUDI DI NAPOLI FEDERICO II

FACOLTÀ DI INGEGNERIA

CORSO DI LAUREA IN
INGEGNERIA AEROSPAZIALE

CLASSE DELLE LAUREE IN INGEGNERIA INDUSTRIALE N. 10

DIPARTIMENTO DI
SCIENZA E INGEGNERIA DELLO SPAZIO

ELABORATO DI LAUREA

LA COMUNICAZIONE OTTICA SATELLITARE: ANALISI DEI REQUISITI DI UNA OPTICAL GROUND STATION RICEVENTE PER LINK IN ORBITA LEO

RELATORE
Ch.mo Prof. Antonio Moccia

Correlatore
Dott. Maria Rosaria Santovito

CANDIDATO
Giuseppe Bove
Matr. 517/114

ANNO ACCADEMICO 2004/2005

INDEX

INTRODUCTION

This study has been developed at laboratories of consortium CO.RI.S.T.A. (Consortium for Research on Advanced Remote Sensing Systems) in Naples in collaboration with Alcatel Alenia Space Italia in Turin and it is part of project that will be funded by ASI (Italian Space Agency). The project is called “OPTICAL TELECOMMUNICATION PAYLOAD” and has the purpose to develop the first Italian optical satellite link.
The project is at phase A2, and the basic reference is the phase A of study performed in 2004 when an overview of the possible applications and technology to be used for the development of an Optical Telecommunication Payload were provided but not finalized to any specific mission.
This thesis develops the mission analysis of phase A2 and particularly the analysis of main characteristics of Optical Ground Stations (OGS) in scenario of LEO-Ground mission.

The study is organized in three chapters.

In chapter 1 are analysed the main differences between optical and radiofrequency satellite communication links pointing out advantages and drawbacks of both systems. Also the principles of operation for an optical satellite communication payload are described. It is performed a study of Direct and Coherent systems for the modulation-demodulation of the optical signal and of the EDFA technology, used to boost the intensity of the optical signals. Finally the SILEX program, developed by ESA (European Space Agency), in which the first-ever transmission of an image by laser link from one satellite to another took place, has been described.

In chapter 2 is reported a preliminary architecture with the key parameters of an Optical Ground Station in scenario of LEO-Ground communication mission. The analysis has been performed studying the characteristics of LEO-Ground link and studying the architecture developed during the phase A of the project for the optical payload to be mounted on board.

In chapter 3 a survey of potential Optical Ground stations in Italy and abroad is performed. We identify the best OGS for the LEO-GND mission carrying out a comparison between the characteristics of the analyzed receiving stations and the key parameters of the preliminary architecture proposed in this study for the OGS.

ABBREVIATIONS AND ACRONYMS

AO	Adaptive Optics
ARTEMIS	Advanced Relay and Technology Mission Satellite
APD	Avalanche Photodiode
AS	Acquisition Sensor
ASI	Italian Space Agency
ATP	Acquisition, Tracking, Pointing
BER	Bit Error Rate
CCD	Charge-Coupled Devices
CNR	National Council of Research
CO.RI.S.T.A.	Consortium for Research on Advanced Remote Sensing Systems
CPA	Coarse Pointing Assembly
CRL	Communications Research Laboratory
CW	Continuous Wave
DE	Directed Energy
DLR	German Aerospace Center
EDFA	Erbium Doped Fiber Amplifier
ESA	European Space Agency
ETS-VI	Engineering Test Satellite
FOV	Field Of View
FPA	Fine Pointing Assembly
FSO	Free Space Optical
GEO	Geostationary Earth Orbit
GND	Ground
GOPEX	Galileo Optical Experiment
IM/DD	Intensity Modulation Direct Detection
IAC	Instituto de Astrofisica de Canarias
ISL	Intersatellite Link
JAXA	Japan Aerospace Exploration Agency
JPL	Jet Propulsion Laboratory
LASER	Light Amplification by Stimulated-Emission Radiation
LCE	Laser Communication Equipment
LCT	Laser Communication Terminal

LCTSX	LCT on TerraSAR-X
LEO	Low Earth Orbit
MGS	Mobile Ground Station
MLRO	Matera Laser Remoting Observatory
NASA	National Aeronautics and Space Administration
OCTL	Optical Communications Telescope Laboratory
OGS	Optical Ground Station
OICETS	Optical Inter-orbit Communications Engineering Test Satellite
PAA	Pointing Ahead Angle
RF	Radio Frequency
SAR	Synthetic Aperture Radar
SILEX	Semiconductor Laser Intersatellite Link Experiment
SOR	Starfire Optical Range
SPOT-4	Satellite Pour l'Observation de la Terre 4
TMF	Table Mountain Facility
TS	Tracking Sensor

1. OPERATION PRINCIPLES FOR AN OPTICAL SATELLITE LINK

Laser have been considered for space communications since their realization in 1960. Advances in system architecture, data formatting, and component technology over the three past decades have made laser communication in space not only a viable but also an attractive approach to intersatellite link applications [1].

The use of Optical Intersatellite Links (ISLs) has some advantages over the use of microwave ISLs : smaller size and weight of the terminal, less transmitter power, higher immunity to interference, larger data rate, and smaller transmitter beam divergence angle [2].

The major disadvantage is related to system technological complexity since the RF (Radio Frequency) communications are consolidated systems while optical space communication is a new application.

The laser communication system is a point to point communication system.

The transmission section consists of simple modulator which drives the elettro-optical device (usually modulates the laser source) and the telescope which function is equivalent to the radiofrequency antenna.

The receiver equipment consists of an optical telescope, an optical sensor device and the demodulator. The described simple scheme is applicable when the line of sight is perfectly aligned between the two terminals. This is the case of Free Space Optical (FSO) link on the Earth with the two terminals fixed on Ground and perfectly aligned, but not in the Space application where the two terminals (one of them could be located on the Earth) are not aligned and furthermore can be subjected to continuous changes during the time.

As showed in Figure 1, laser communication system in Space needs Acquisition, Tracking and Pointing (ATP) subsystems for establishment and maintaining the optical link [3].

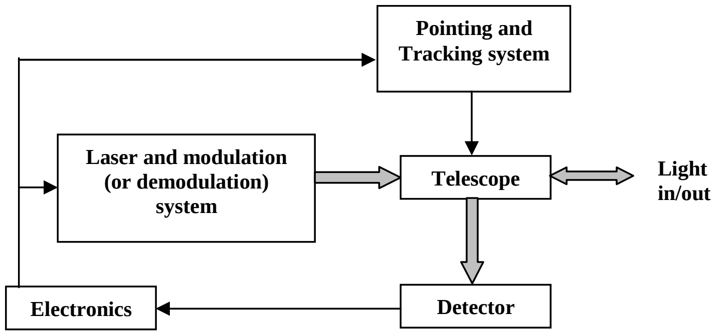

***Figure 1*: High level block diagram of a terminal for optical satellite communication system**

The acquisition is the phase where the two terminals adjust their line-of-sight so exact that they can receive the transmitter beam of the counter terminal. The beginning of acquisition is typically a search or scanning phase.

The tracking phase is subsequent to the acquisition phase. In the tracking phase the line of sight of the two terminals is maintained so exact that both terminals receive the beam of the counter terminal. There is usually a specific Tracking Sensor with a high resolution for the measurement of the tracking error.

During the pointing phase, both satellites point toward the position of their correspondent to begin the transmission of the data.

Of the three phases, acquisition is generally the most difficult, where the tracking is usually the easiest. Acquisition is difficult because laser beams are typically much smaller than the area of uncertainty. Satellites do not know exactly where they are or where the other platform is located, and since everything moves with some degree of uncertainty, they cannot take very long to search or the reference is lost [1].

The complexity of pointing system is another disadvantage of optical ISLs compared with microwave ISLs. This derives from the necessity of satellites to point each other over a distance of tens of thousands of kilometers with a beam divergence angle of microradians and while the satellites move and vibrate [2].

The transmitter typically used in a free-space laser communications system are either semiconductor laser diodes, solid state lasers and recently fiber amplifiers/lasers.

For free space communication system, the dimension of a terminal are driven by the aperture of the telescope required to collect enough photons to achieve a specified Bit Error Rate (BER) at a given data rate, received power and link distance. The sensitivity of the used receiver is, therefore, an essential driven for the telescope size and, hence the terminal dimensions.

Many works [4, 5, 6, 7, 8] demonstrate that for a given link distance the sensitivity of a coherent terminal can be used to reduce the telescope size, the overall dimension and the mass of the terminal. Coherent systems operate with superposition of the electric field of incoming signal with the electric field of a local oscillator at the receiver and detection of the mixed signal by a photodetector, as showed in Figure 2.

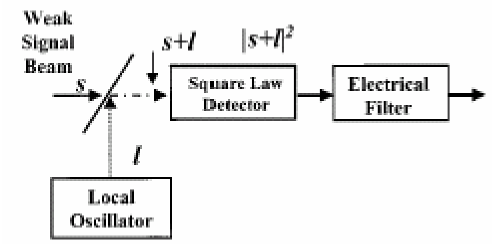

Figure 2**: Coherent receiver [12]**

The optical power at the detector is proportional to the square of the electric field. The photocurrent of the detector, which is proportional to the incident power, contains a mixed term of the local oscillator signal and the received signal. This mixed term represents an intermediate frequency signal and contains the modulation of the received signal. The modulation scheme of the system can be amplitude, frequency or phase modulation. Nevertheless the implementation loss (mechanical/thermal stability requirements) for coherent systems and the higher complexity negates theoretical advantage while direct detection in the space is easier and lower risk based on current technology thanks to terrestrial heritage. In fact Direct systems operate with a laser source which is modulated directly or indirectly (via an external modulator) in intensity or pulse position and use a direct detection receiver (the so-called Intensity Modulation Direct Detection IM/DD). The photodetector converts the received optical signal into a photocurrent proportional to the signal. A direct detection system, showed in Figure 3, simply requires that sufficient optical signal is present to produce a photodetector output that is large enough to be distinguishable from the noise. A local oscillator is not required [1].

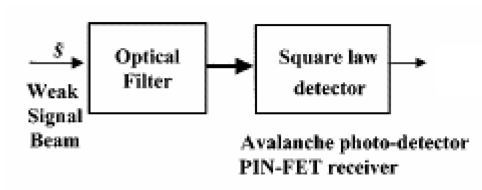

***Figure 3*: Direct detection receiver [1]**

Nevertheless, with a suitable low noise optically preamplified direct detection receiver such as an Erbium Doped Fiber Amplifier (EDFA), many of the lost dBs can be recovered. A basic block diagram of EDFA system is reported in Figure 4.

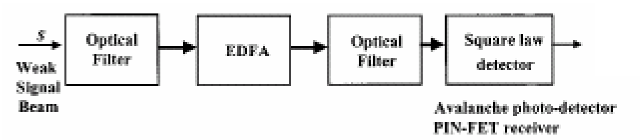

***Figure 4*: Pre-amplifier direct detection receiver (EDFA) [7]**

EDFA is used to boost the intensity of optical signals being carried through the fiber optic communication system. The optical fiber is doped with rare earth element erbium so that the glass fiber can absorb light at one frequency and emit light at another frequency. The external semiconductor laser couples light into the fiber at infrared wavelengths of either 980 or 1480 nm. This action excites the erbium atoms. Additional optical signals at wavelengths between 1530 and 1620 nm enter the fiber and stimulate the excited erbium atoms to emit photons at the same wavelength as the incoming signal. This action amplifies a weak optical signal to higher power.

It has to underlines how though EDFA and coherent detection have similar performance, the EDFA pre-amplified direct detection receiver lends itself to much easier implementation and has to be favourite for optical satellite communication systems [7].

1.1 THE SILEX PROGRAM

The development of satellite optical communication is carried out mostly by Europe, Japan and United States [9, 10, 11].

More than twenty years of technology endeavours, sponsored by ESA (European Space Agency) and other European space agencies, has put Europe in a leading position in the domain of space laser communications. The most visible result of this effort is SILEX (Semiconductor Laser Intersatellite Link Experiment), the world's first launch-ready civilian laser communication system.

On 30 November 2001, by **SILEX**, the first-ever transmission of an image by laser link from one satellite to another took place. The system using a pre-operational link between the French SPOT-4 (Satellite Pour l'Observation de la Terre 4) Low Earth Orbit (LEO) satellite and the ESA Advanced Relay and Technology Mission Satellite (ARTEMIS) in Geostationary Earth Orbit (GEO) [12, 13,14,15] (See Figure 5).

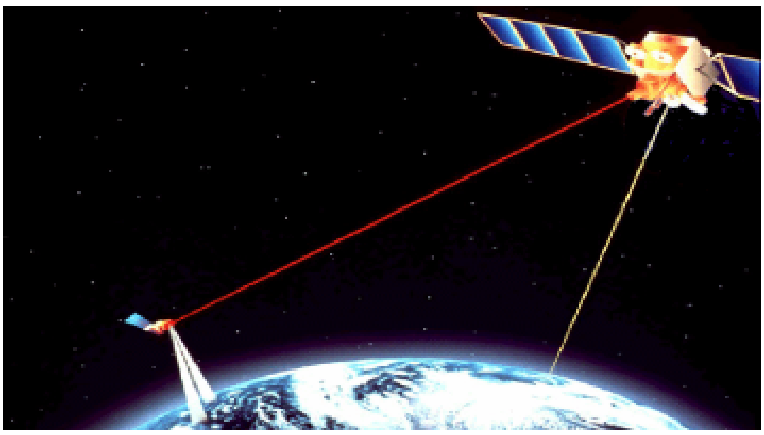

***Figure 5*: Artemis and SPOT 4 communicating via the SILEX system - Artist's impression [13]**

The SILEX design is based on several key component:

- **GaAlAs laser diodes** of two types: single mode laser diodes of 120 mW peak power for communication channel, and a combination of several high-power (500 mW) laser diodes for the bright, divergent, unmodulated beacon used in the link acquisition sequence
- **Silicon Charge-Coupled Devices** (CCDs) are the sensors which detect the optical beam angular incidence and thus maintain submicroradian pointing accuracy. Two types are used: a large field of view (388×388 pixels) sensor is used to detect the partner's position during the acquisition sequence; a smaller matrix (17×17 pixels) with high-frequency read-out (8 kHz) and processing of the centre four pixel output is used for closed-loop tracking process
- **Silicon Avalanche PhotoDiode** (APDs) with highly optimised excess noise factor allow maximum communication performance with the very low-level received signal (135 photons/bit direct detection at 810 nm, BER=10^{-6} and 60 Mbit/s)

The main characteristics of SILEX are reported in Table 1.

SILEX (Semiconductor Laser Intersatellite Link Experiment)		
Satellites	**SPOT-4**	**ARTEMIS**
Mission		
Organization	ESA	
Launch date	1998	2000
Orbit	LEO	GEO
Range	45000 km	
Mission weight	150 kg	
Optical		
Telescope type	Afocal Cassegrain in Zerodur, common to transmission and reception	
Telescope diameter	Transmit: 200 mm Receive: 250 mm	Transmit: 125 mm Receive: 250 mm
FOV	>4000 μrad	
Laser transmitter		
Communication	GaAlAs diodes @847 nm Single mode	GaAlAs diodes @819 nm Single mode
Output power	60 mW (120 mW peak power)	37 mW (120 mW peak power)
Laser beam divergence	6 μrad	8 μrad
Communication		
General scheme	Intensity modulation, direct detection (IM/DD)	
Data rate	50 Mbps	2 Mbps
BER	10^{-9}	
Receiver	None	APD (135 photons/bit)
ATP		
Acquisition sensor	388 x 388 pixels CCD @ 32 Hz	388 x 388 pixels CCD @ 130 Hz
Tracking sensor	17 x 17 pixels CCD @ 1, 4 or 8 kHz	17 x 17 pixels CCD @ 4 or 8 kHz
Point ahead	2 mirrors, piezo actuators, capacitive position sensors	

***Table 1*: Main SILEX characteristics [Adapted from 3 and 8]**

It has to be underlined that SILEX, as reported by Lutz, "*has been dimensioned using the limited laser diode power available at the end of the 1980's, namely 60 mW average power at 830 nm*" [10]. Thus, SILEX appears hardly an attractive alternative to a RF terminal of comparable transmission capability. Nevertheless SILEX programme shows high reliability with a life time higher than 100000 hours [13].

2. KEY PARAMETERS FOR AN OPTICAL GROUND STATION

As mentioned above, this study has been developed at laboratories of CO.RI.S.T.A. (Consortium for Research on Advanced Remote Sensing Systems) in Naples in consequence of a bid invitation asked by Alcatel Alenia Space Italy and financed by ASI (Italian Space Agency). The purpose of the thesis is to perform a study of the Optical Ground Station (OGS) characteristics and perform a survey for the selection of a potential Optical Ground Station in Italy and abroad which will be used during a LEO mission. In this chapter is reported a preliminary architecture with the key parameters of an OGS in scenario of LEO-GND link. The analysis has been performed studying the characteristics of LEO-GND link and studying the preliminary architecture of the optical payload to be mounted on board proposed during the phase A of the project.

2.1 LEO-GND link characteristics

The FSO technology is quite appealing for LEO to Ground communication since the required optical power is achievable with present technology and the data rate is higher than RF communication. The advantages of LEO for communications satellites lie in full global coverage and in ability to provide a greater flux density to a given small area on the ground, allowing use of smaller terminals. This is a very appealing argument for the use of LEO systems in order to communicate with hand-held terminals. In fact the few orbiting platforms with powerful optics sensors have big size and are very expensive. For this reason the market tends to employ microsatellites of small size, light weight and not expensive but where it is not possible to mount on board bulky optical sensors. For these microsatellites usually the insertion in LEO is preferred in order to employ less expensive launchers too.

It cannot be ignored that the main disadvantage of an optical satellite link toward Earth compared to a RF link is the interaction of the laser beam with the atmosphere. A laser beam propagation through the atmosphere can quickly lose energy due to molecular scattering and molecular absorption. Refractive turbulence may also contribute to energy loss, however, it mainly degrades the beam quality, both by distorting the phase front and by randomly modulating the signal power. Moreover the presence of opaque clouds may occlude the signal completely rendering the time-of-sight communication link useless. For this reason the OGS has to be located in specific sites taking into account the weather visibility conditions in order to maximize the light signal and to guarantee continuity in space-ground link with very high probability.

The effect of atmospheric turbulence may be overcome by employing an Adaptive Optics (AO) approach. An AO, as shown in Figure 6, is a "deformable" mirror placed between the telescope, and the detector which compensates the distortions.

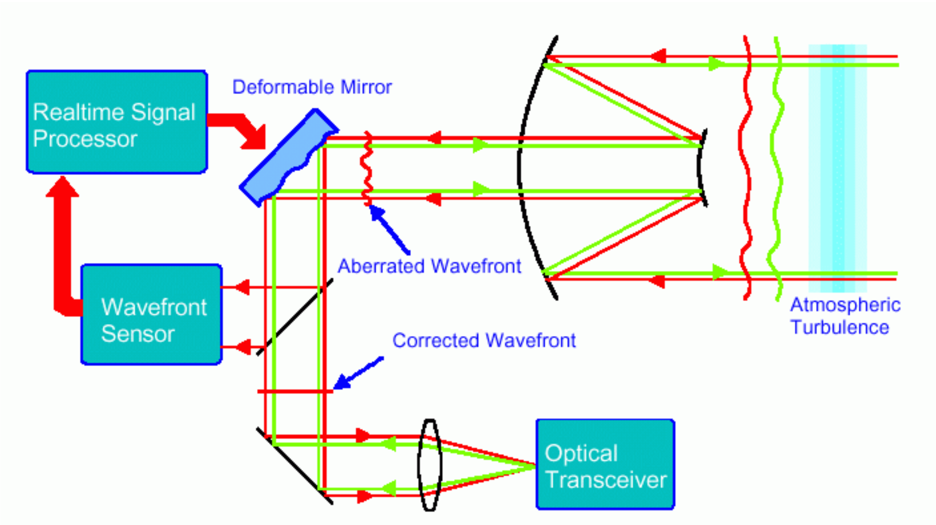

***Figure 6*: Schematic operation system of Adaptive Optics [http://www2.nict.go.jp/mt/b162/ao_sys0-e.html]**

The (red colored) receiving laser beam being incident into the aperture of a ground telescope suffers an aberration due to refractive index turbulence in the atmosphere.

The Adaptive Otics has an ability to correct this aberration or wave front errors by using an realtime feedback control loop and to reconstruct a flat wavefront, after reflecting through a deformable mirror, which is suitable to interconnect with laser communication transciver.

In the (green colored) transmitting laser beam, there is the same wavefront errors as the receiving beam, if we transmit the laser through the same optical path in the telescope. Uplink atmospheric turbulence effect can be also compensated and it results to reduce the pointing error due to atmospheric turbulence.

In our opinion the use of this technology could be too much heavy for the Optical Payload in LEO-GND mission scenario and it could be employed only for the Ground Station receiver subsystem, even if the low level of readiness and the high cost have to be taken in account.

In order to perform laser communication up and downlink, the sky should be perfectly clear, without any clouds, and the path through the atmosphere the shortest possible. It can happen that when the satellite crossing over the GND Station, the link may be lost because of bad atmospheric conditions (e.g. rain, fog): this problem can be solved installing on-board mass memories to store data to be transmitted later with better weather conditions.

Another important issue concerning LEO-to-Ground links is represented by the limits of the optical payload observability and therefore of the light beam signal reception. In fact from a single ground-based receiver station, a LEO spacecraft is typically observable for less than fifteen minutes in a 24-hour period. Studies demonstrate that even sites with favourable atmospheric visibility typically display a 65-70% availability [16].

The most effective strategy to achieve higher than the 90% availability in continuity of space-ground link with the fewest possible stations is a "site diversity" strategy, which consist in redundant sites so that if one is clouded out, another one can be used as a backup. As it was analyzed by R. Link, in his study [17], this availability can be achieved with 4-5 ground stations.

The use of Mobile Ground Station (MGS), may be an interesting alternative respect to OGS, so that when in the area of the fixed ground station the weather conditions are not as permissible for a good propagation, the communication will be transferred to the MGS, showed in Figure 7. Or even the mobile station could be used instead of the fixed OGS [18].

Figure 7 **: Mobile Ground Station of CAPANINA project (Communication from Aerial Platform Networks delivering Broadband Communications for All) [www.capanina.org]**

2.2 Payload preliminary architecture

Technical investigations show that usually for LEO-GND link the laser source employed is a Laser Diode which presents the advantages of less power consumption with respect to the Solid State laser source, only considered for Deep Space missions where a higher power emitted is required.

Concerning the choice of the laser output wavelength, today the diode technology offers three possibility: 800 nm, 1200 nm or 1550 nm.

The approach and choice is not simple and clearly defined in the technical literature.

It must be considered that the attenuation due to the distance is evaluated as:

$$Attenuation = 20 \times Log(4\pi\, distance / \lambda)$$

where λ is the wavelength chosen.

In the Figure 8 are reported the attenuation values obtained for three different laser wavelengths:

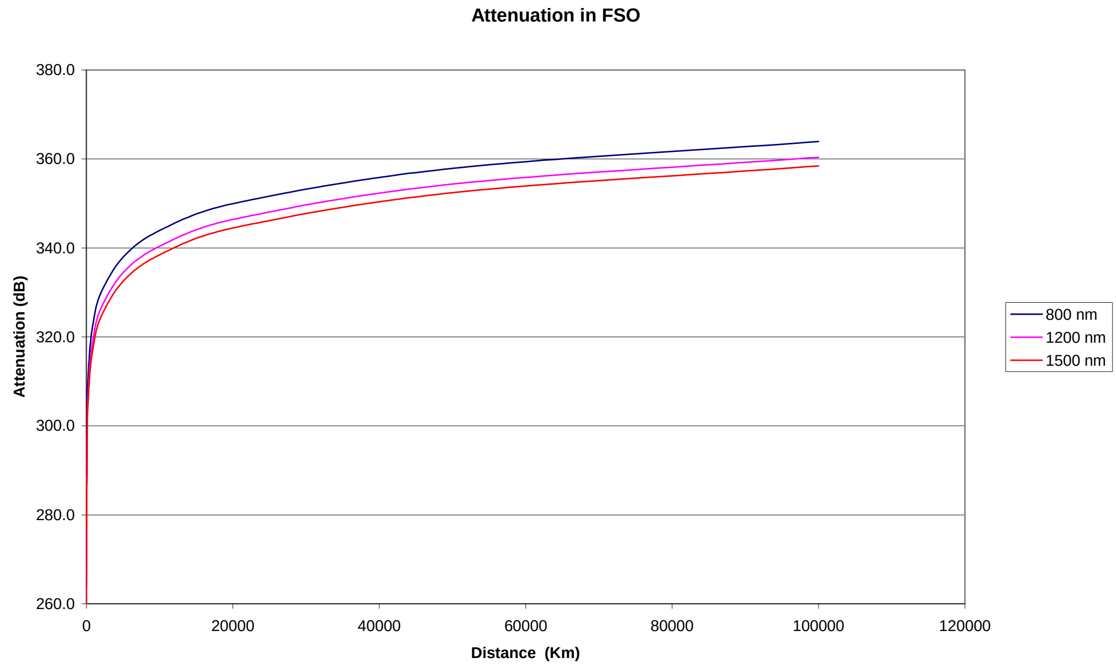

***Figure 8*: Attenuation versus distances at different laser wavelengths**

The graph shows that the output at 1550 nm appears more promising because at this wavelength the attenuation is lower.

Another valid argument to choice this laser wavelength is the possibility to use optical fiber boosters and optical fiber pre-amplifiers, that is the EDFA system described in chapter 1. This possibility allows to increase the optical receiving signal reducing the electrical noise induced by the high gain amplifiers. It must be underlined that the technology related to optical amplifier is already successfully applied on the commercial optical fibre connections but it is relatively new for space applications. Nevertheless many are the advantages of 1550 nm technology:

- high reliability with a life time higher than 10^6 hours
- high data rate capability (several Gbps)
- high output power (up to 5 W)
- simple current modulation up to several Gbps
- compatibility with multiplexing thanks to wavelength selectable by grating modification

Considering the output laser wavelength at 1550 nm the Maximum Permissible Exposure energy parameter (E_{MPE}), that is the level to which the cornea can be exposed without consequential injury immediately or after long time for emission, is [19]

$E_{MPE} = 5600\ t^{0.25}$ J/m^2 for an exposure range time of 0.25-10 s

$E_{MPE} = 10^3$ W/m^2 for an exposure range time of 10-30000 s

To operate in safety condition for ground naked eyes observers the laser has to emit an energy E satisfying the following condition

$$E < E_{MPE} \cdot A = E_{MPE} \cdot \pi (d/2)^2 = E_{MPE} \cdot \frac{\pi}{4} \left(H \cdot \theta_{div}\right)^2$$

where A is the area of the footprint, d is the diameter of the footprint, H is the height of the laser source (H = 350 Km) and θ_{div} the beam divergence (around 10 μrad). It has been estimated that the 1550 nm system, also with a output power of 5 W, is well within safety limits.

In the phase A of the project an evaluation of the link budget for LEO-GND optical communication has been performed; supposing clear sky, a perfect alignment between GROUND and LEO telescopes with null azimuth angle and the effects due to atmospheric losses (absorption and scattering) and scintillation.

For this scenario the following mission parameters have been set :

- Link length: 350 Km
- Bit rate: 2.5 Gbit/s
- BER: 10^{-9}
- Max LEO telescope diameter: 25 cm

With this setting with a connection time of 2-4 min/orbit we obtain 300-600 Gbits of data rate for each orbit.

For the satellite optical transceiver the simplest architecture without any optical preamplificator (Receiver side) and optical booster (Transmitter side) during the transmission has been adopted.

Particularly the Optical Transmitter subsystem preliminary parameters are:

- Optical source: 1550 nm Semiconductor Laser
- Laser type: DFB (Distributed FeedBack)
- Average optical power: 100 mW (Pt = 20 dBm)
- Modulation format: Intensity Modulation
- Modulation bandwidth: Higher than 1.5 Ghz

A block diagram of the Transmitter architecture is shown in Figure 9:

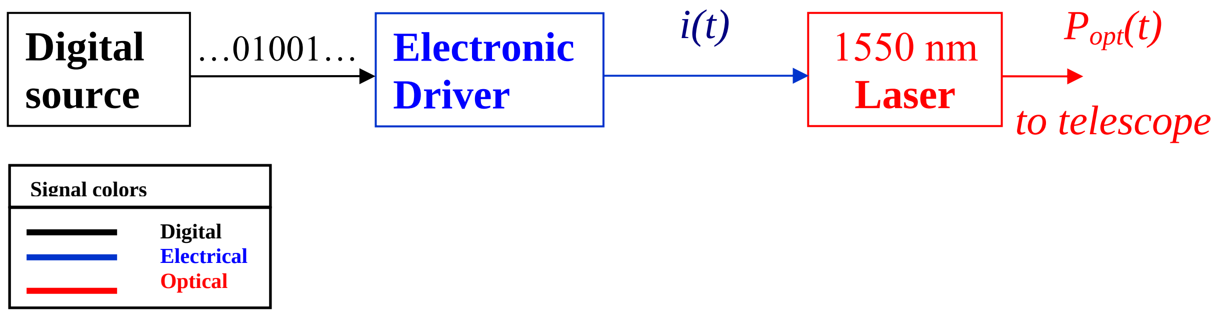

***Figure 9*: LEO Transmitter block diagram**

In order to reduce the use of optical devices and to improve the performances in terms of receiver sensitivity, the Direct Detection technique and an APD detector for satellite optical receiver subsystem has been proposed as result of the phase A of the Alcatel Alenia Space Italia project.

The Optical Receiver preliminary parameters are:

- Photodetector: Semiconductor @ 1550 nm
- Typology: APD
- Responsivity @ 1550nm: 0.69 A/W
- Gain: 20
- Demodulation technique: Direct Detection
- Sensitivity: -35 dBm @ BER = 10^{-9}

Figure 10 shows the satellite receiver.

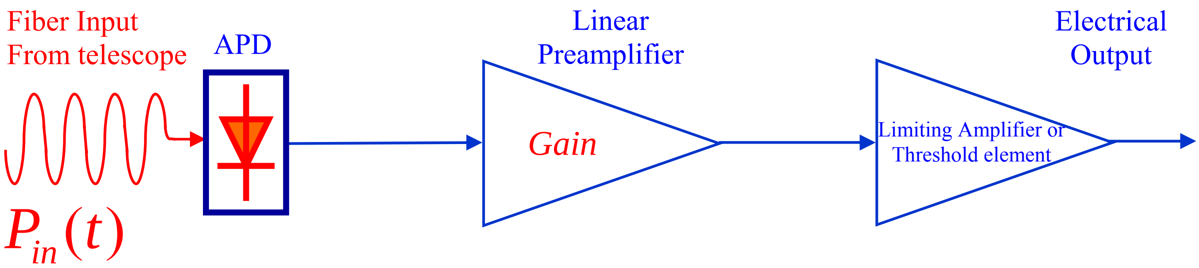

***Figure 10*: LEO Receiver block diagram**

The use of this kind of architecture appears particularly innovative thanks to the use of 1550 nm wavelength on satellite. Moreover during the phase A of the project the satellite terminal with the same wavelength for beacon and signal data transmission has been proposed. This choice appears particularly convenient in order to reduce the weight of the optical payload mounted on board since just one wavelength has to be received and transmitted.

2.3 OGS preliminary architecture

In optical satellite communication system the OGS has three primary functions:

- maintain an illumination on the flight system with the beacon beam
- recover the downlink beam
- facilitate operations and planning

From the optical link point of view, the Ground Station architecture is conceptually similar to the satellite one.

The functional diagram block of the preliminary architecture for the Optical Ground Station proposed in this study is shown in Figure 11.

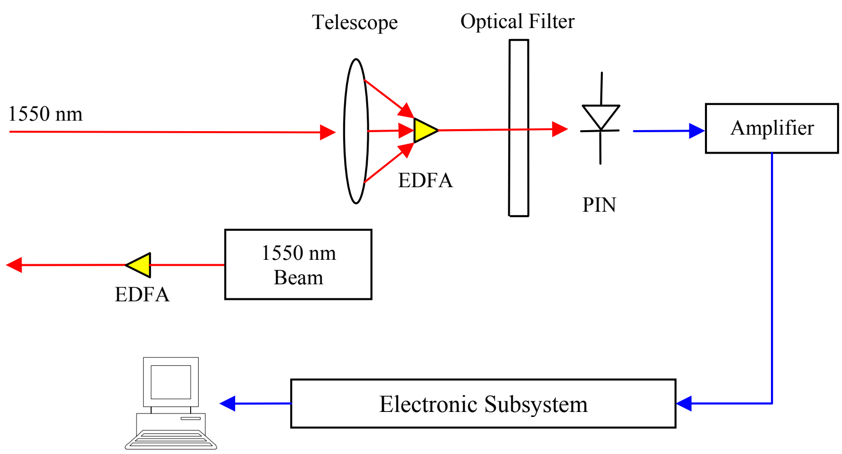

***Figure 11*: Block diagram of the proposed Optical Ground Station**

It is basically made up of:

- the laser beam which transmits at 1550 nm wavelength
- the collector of the satellite transmitted signal, which is a telescope
- the filter to reduce the received signal background noise and to improve the signal to noise ratio
- the modulated signal receiver subsystem
- the electronic subsystem, which include the control of the guidance feedback of the telescope and the signal demodulator.

It must be pointed out that for the designed OGS the use of the laser beam at 1550 nm as beacon function has been considered and that the station only receives at the same wavelength the downlink signal to be demodulated. In our preliminary architecture the OGS is receiving only, and except for the beacon signal there is no bi-directional exchange of optical data signal with satellite.

The transmitter technology at this wavelength is based on a Distributed FeedBack (DFB) laser directly modulated coupled to EDFA, described in chapter 1. At the same wavelength, low noise optical fibre pre-amplifiers are available and therefore Direct Detection is possible [20], reducing the number of the optical components to be used.

On the basis of these considerations, the Optical terminal preliminary architecture of the OGS can be assessed as in Figure 12.

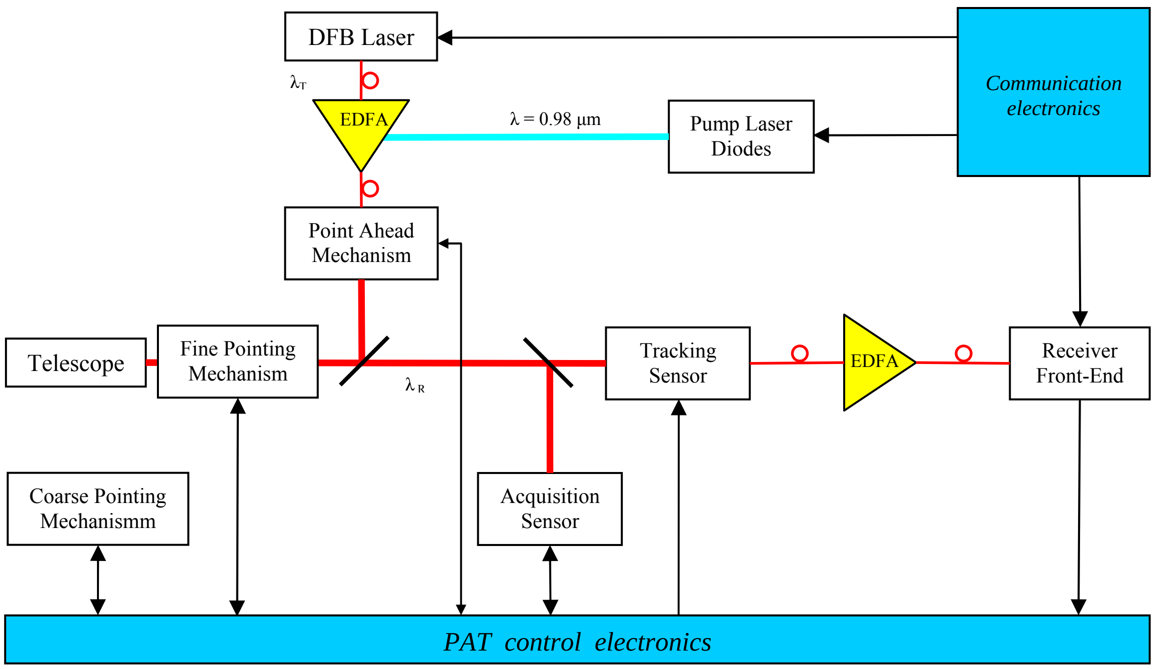

***Figure 12*: Optical terminal preliminary architecture of the OGS**

The Optical Transmitter parameters values proposed for the Ground Station are:

- Optical source: 1550 nm Semiconductor Laser
- Laser type: DFB
- Average optical power: 20 mW (Pt = 13 dBm)
- Modulation format: Intensity Modulation
- Modulation bandwidth: Higher than 1.5 GHz
- EDFA output power: 1 W (Pt = 30 dBm)

The Telescope of OGS has large physical dimensions in order to compensate the small ones at the satellite side. We propose for the Telescope of OGS a diameter of around 1m, following the example of OGS involved in SILEX program.

In order to maintain the simplest layout at the optical transmitter satellite side and to improve link performances, we propose the Direct Detection technique with optical pre-amplification by means EDFA for the OGS receiving subsystem. The whole parameters set is:

- Photodetector: Semiconductor @ 1550 nm
- Typology: PIN
- Responsivity @ 1550m: 0.8
- Demodulation technique: Direct Detection
- BER: 10^{-9}
- Sensitivity: -44 dBm @ BER=10^{-9}

Eventually the PIN photodiode could be cooled in order to have very low electrical noise.

As described in chapter 1 the ATP is the subsystem in charge to acquire and maintain the line of sight between the two terminals. For the proposed LEO-Ground scenario the acquisition phase can be detailed described as follows (TX scanning):

- the ground terminal searches the LEO terminal by scanning with its TX-beam
- the LEO terminal detects the uplink beam and aligns its optical axis with it
- the LEO terminal directs its downlink beam towards the ground terminal
- the ground terminal detects the downlink signal and tracks it, during satellite transmission optical signal

A complete ATP subsystem for OGS should include the following items (see Figure 11), with obvious functionality:

- CPA: Coarse Pointing Assembly (slow mechanism with large angular range)
- PAA: Pointing Ahead Angle (ahead angle motion detector)
- FPA: Fine Pointing Assembly (fast mechanism with small angular range)
- AS: Acquisition Sensor (slow sensor with large area)
- TS: Tracking Sensor (fast sensor with small area)

The detailed characteristics of ATP subsystem strictly depends on link budget analysis of mission scenario, which topic is out of the scope of this thesis.

A schematic general layout of the telescope, dome enclosure, coude and Cassegrain focus, and laser lab area are shown in Figure 13.

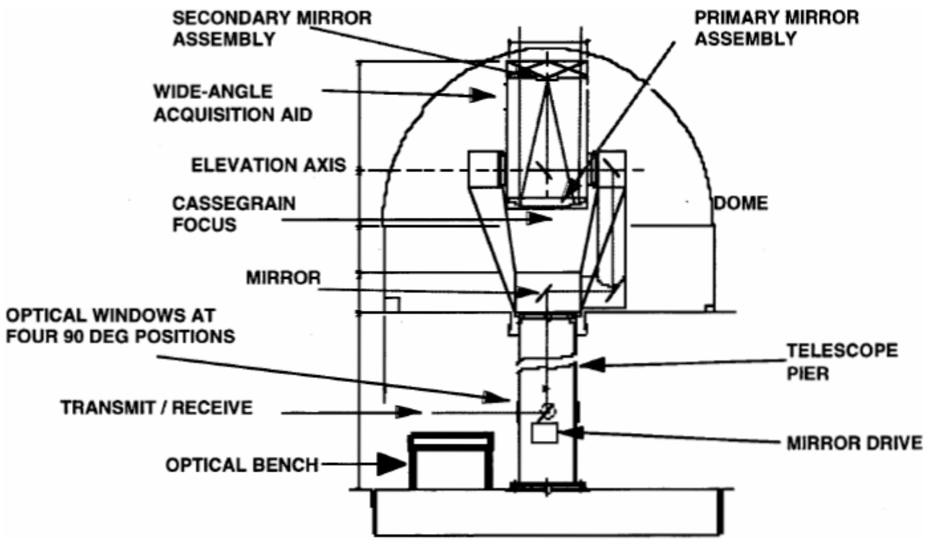

Figure 13**: Schematic diagram of the Optical Ground Station [21]**

2.4 OGS key parameters for LEO-GND scenario

The preliminary characteristics of an OGS for a LEO-GND mission scenario proposed in this study and described in the paragraph 2.3 are summarized in Table 2.

OGS Transmitting subsystem	
Optical source	1550 nm Semiconductor Laser
Laser type	DFB
Average optical power	20 mW
Modulation format	Intensity Modulation
Modulation bandwidth	Higher than 1.5 GHz
EDFA output power	1 W
OGS Receiving subsystem	
Telescope Diameter	1 m
Photodetector	Semiconductor @ 1550 nm
Typology	PIN
Responsivity @ 1550 nm	0.8
Demodulation technique	Direct Detection
BER	10^{-9}
Sensitivity	-44 dBm @ BER=10^{-9}

***Table 2*: Key parameters proposed in this study for the preliminary architecture of the OGS in LEO-GND mission scenario**

These key parameters, as well as the geological characteristics of the location (particularly concerning earthquakes) and the climatic conditions will be compared with the data of the survey of Optical Ground Stations in Italy and abroad performed in the following chapter, in order to identifying the best Optical Ground Station candidates for the LEO to Ground mission.

3. SURVEY OF OGS IN ITALY AND ABROAD

In this chapter, we perform a survey of fixed Optical Ground Stations utilized for satellite optical links. The analysis includes also the study of a mobile OGS that as of this writing is under development at DLR (German Aerospace Center).

Our study shows that data transmission systems based on air laser communications links are now intensively developed. Most of these projects are at their experimentation/testing phase and consequently there is not yet a commercial use of optical satellite links. Nevertheless the results available in literature are not clear even cryptic, and often it is very hard to distinguish among projects realized and projects still at a development phase. For this reasons we have ran into difficulties also to gather information about the OGS's involved in these projects.

The performed bibliographic research permitted us to reconstruct a chronology of optical satellite communication projects all over the world.

In the **U.S.A.**, the National Aeronautics and Space Administration (NASA) free-space laser communications programs are concentrated at the Jet Propulsion Laboratory (JPL). The Galileo Optical Experiment (GOPEX) was conducted on Dec. 9-16, **1992**, during its second Earth flyby. Optical transmitters at the JPL Table Mountain Facility (TMF) in California and at the Starfire Optical Range (SOR) in New Mexico transmitted optical pulses to Galileo satellite, where they were successfully received using the Solid-State Imaging camera as the optical receiver, for ranges from 600,000 to 6,000,000 km [22].

The first bi-directional laser communication experiment between a satellite and a ground station was successfully performed by the Communications Research Laboratory (CRL) in **Japan**, using the Laser Communication Equipment (LCE) on the Engineering Test Satellite (ETS-VI).

The satellite was launched into a high-elliptical orbit in **1994**, and the laser communication experiment was performed using a 35,000 km link between the satellite and the ground stations both at CRL and at JPL, first time in the world. Both up- and down-link transmissions at wavelengths respectively of 0.514 and 0.830 μm at a data rate of 1 Mbps took place successfully [23].
In **Europe**, as described in chapter 1, the ESA developed SILEX, whose laser satellite communication terminals were designed for 50 Mbps LEO-GEO and GEO-GEO inter-satellite link applications. The SILEX laser communication demonstration was performed in November **2001**, which was the first transmission of an image at 50 Mbps via a laser link from SPOT-4 to ARTEMIS [14]. The ground-to-ARTEMIS optical communication experiment was successfully conducted with the OGS in Tenerife, Spain, run by the ESA [15].
In **Japan**, the most important result in the field of satellite optical communication was the successful of the inter-orbit optical communication link experiment between the Optical Inter-orbit Communications Engineering Test Satellite (OICETS) developed by the Japan Aerospace Exploration Agency (JAXA) and the ESA's ARTEMIS satellite in December **2005** [24]. The OICETS was launched into LEO at an altitude of 610 km and an inclination of 97.8° [25]. The employed optical technology was 0.8 μm semiconductor lasers and an avalanche photodiode. In December 2005, the first bi-directional laser communication demonstration between OICETS and ARTEMIS was successfully conducted with a return link of 50 Mbps and a forward link of 2 Mbps.
The basic technology for the inter-orbit optical communication was established.

In the following paragraphs the main characteristics of the OGS involved in some of projects mentioned above will be described.

3.1 SPAIN: Tenerife - La Teide Observatory

As part of the SILEX program, ESA started to construct an OGS in Tenerife, on the Canary Islands in 1993 (see Figure 14).

Figure 14**: ESA's optical ground station at the La Teide Observatory, Tenerife, Spain [26]**

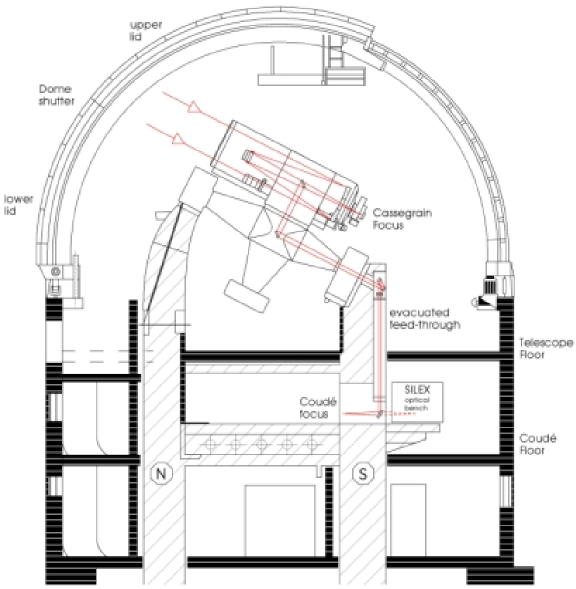

Figure 15**: Schematic layout of the OGS Telescope [26]**

La Teide Observatory, completed at the end of 1997, belongs to the Instituto de Astrofisica de Canarias (IAC) together with the Observatorio del Roque de los Muchachos, located on the island of La Palma.

La Teide Observatory rises on a 50 hectares surface area at 2,400 m above the sea level; it is at latitude 28^o 18’ 00” N, longitude 16^o 30’ 35” W.

The main features of this OGS are [26]:

- high pointing velocity (of up to two degrees per second, with maximum acceleration of 0.5 degrees/s^2)
- high pointing precision (the average error in all possible telescope orientations is less than 10 arcseconds)
- high tracking precision (average error of 2.5 arcseconds per hour)
- possibility of external control, for example by means of a workstation, that provides a pointing position to the telescope every 100 milliseconds. In this way it is possible to track an artificial satellite or a fragment of space debris, whose apparent motion is very different to that of a star

It is also important to emphasize the precise location of the telescope. As described in chapter 2, to perform a laser communication from ground to space the sky must be perfectly clear and the path through the atmosphere must be as short as possible. Both conditions are satisfied at the Observatorio La Teide which is situated on the crest of the mountain, permitting an excellent seeing due to the normal circulation of the wind and moreover is the closest point to the equator in an ESA member state. For this reason the Spanish OGS is considered a privileged sites.

The OGS telescope installed in La Teide Observatory has been built by Carl Zeiss laboratories. The telescope is a 1 m Ritchey-Chretien/Coudé telescope inside a dome of 12.5 m in diameter. Its main purposes are:

- to be the optical ground station of the Artemis telecommunications satellite (the project from which the telescope takes its name)
- to make surveys of space debris in different orbits around the Earth
- to make scientific astronomical night observations

The technical instrumentation for optical satellite communications are:

- Spectrometer: spectral range between 750 and 900 nm; resolution better than 0.1 nm
- Polarimeter
- Astrocam CCD camera. Format: 1152x1242 pixels
- Tunable laser between 750 and 900 nm, with up to 5 W of power
- Acquisition and tracking sensors
- Image motion correcting mirror

3.2 ITALY: Matera - Matera Laser Ranging Observatory

The Space Geodesy and Geodynamics Center of Matera is operative since 1983 supported by National Council of Research (CNR) , Regione Basilicata and NASA. The Center is one of the most important technology research institutes of South Italy. In the Center is installed the sophisticated Matera Laser Ranging Observatory (MLRO), shown in Figure 16, the most advanced Satellite and Lunar Laser Ranging facility in the world, since the end of 1999 [27].

***Figure 16*: Matera Laser Ranging Observatory [28]**

The MLRO building has been realized by Salento Impianti on behalf of the Regione Basilicata government and it has been conceived to be a multipurpose state-of-the-art observatory capable of supporting a variety of experiments. Its main mission is both one- and two-color laser ranging to artificial satellites and Moon.

MLRO system specification and major performance features are [28]:

- 1.5 meter astronomical quality telescope (in Figure 17) with a high resolution imaging system
- multipurpose observatory (in Figure 18) with
    - Laser room
    - Transmit/Receive optics room
    - Operation control/Instrumentation room
- day and night ranging capabilities from satellites in orbits of 400 km to the moon
- ranging system designed to accomodate multi-color ranging
- calibration capability with internal and external targets
- 10 Hz operation
- man machine interface through graphical user interface
- computer assisted maintenance procedures
- high level of automated and computer assisted functions
- computerized documentation with access to database information structure using an expert system

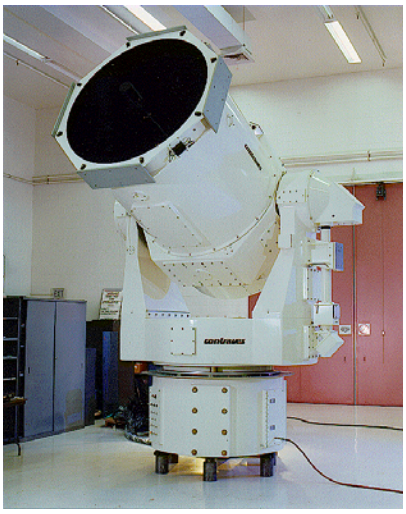

Figure 17**: MRLO 1.5 m telescope [28]**

Laser ranging instrumentation are distributed in three rooms (see figure 18):

- *Laser room*: in this room is located the MRLO laser, an active hybrid ND:YAG configured to emit 40 ps long pulses; the wavelength of the laser is 532 nm in one-color mode, and 532/355 nm in two-color mode. The pulse energy is 100 mJ in one-color, 50/30 mJ in two-color mode. The beam divergence is diffraction limited and can be tuned in a continuous way from 1 to 20 arcsec
- *Transmit/Receive optics room*: the T/R optics in this room support the transfer of the laser beam from the laser to the telescope for transmission to the target. The T/R optics also couple the retroreflected signal from the target through the telescope to the detectors in the receiver system. The T/R electronics perform the opto-electronic detection and time measurements associated with each event
- *Operation control/instrumentation room*: from this site it's possible to have control of the following subsystems
    - Telescope subsystem and Dome
    - Timing subsystem
    - Meteorological subsystem
    - Safety subsystem
    - Software subsystem

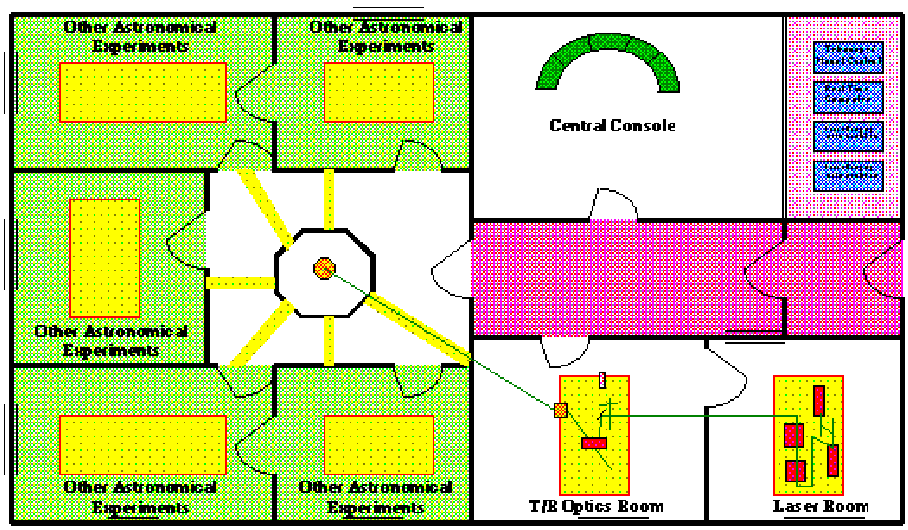

Figure 18: **Schematic layout of the MLRO [28]**

3.3 U.S.A.: San Gabriel Mountains - Optical Communications Telescope Laboratory

The JPL-Table Mountain Facility is a 37 acre research center located just west of the town of Wrightwood, in the San Gabriel Mountains overlooking the Mojave Desert about 60 miles northeast of JPL's main facility in Pasadena, CA. TMF is at latitude 34^{o} 22.9' N, longitude 117^{o} 40.8' W and at an elevation of 2290 m. Since 1962 TMF has been developed and supported by JPL. The site viewing conditions are excellent since owing to the altitude of the site and to the blocking of the mountains to the south, TMF is relatively unaffected by air pollution from the Los Angeles basin [29]. Within this complex, NASA completed in November 1999 the construction of the 1-m Optical Communications Telescope Laboratory (OCTL), shown in Figure 19, and the telescope was installed by Brashear-LP of Pittsburgh during the summer of 2001.

Figure 19**: OCTL building [http://lasers.jpl.nasa.gov/PAGES/ground.html]**

The telescope, designed as a multipurpose instrument, has the following main goals [30]:

- conduct daytime and nighttime communication experiments and demonstrations with laser-bearing spacecraft from LEO to deep space, with emphasis on deep space telemetry
- develop optical spacecraft communications technologies, with emphasis on deep space applications, by conducting ground-to-ground, ground-to-LEO, and ground-to-deep space experiments

The telescope main features are:

- 1-m clear aperture primary mirror
- an optical throughput
  - $> 67\%$ if $500 \text{ nm} < \lambda < 600 \text{ nm}$
  - $> 72\%$ if $\lambda > 600 \text{ nm}$
- ability to track targets with less than 2 arcsec line-of-sight RMS jitter at frequencies below 20 Hz

Moreover the OCTL telescope is coupled with a daytime Adaptive Optics system.

3.4 U.S.A.: Manzano Mountains - Starfire Optical Range

The Air Force Research Laboratory, based in New Mexico's Kirtland Airforce Base, discovers, develops and integrates affordable war-fighting technologies for U.S. aerospace forces. Its wide area includes the Directed Energy Directorate (DE), the Department of Defense's research center for lasers, high-power microwaves, and other directed energy technologies. The DE houses several research divisions, including Advanced Optics and Imaging, High-Power Microwave, Laser, Optical Surveillance, the new Beam Control, and the Starfire Optical Range Division (SOR). The SOR is a military observatory and space research laboratory in the Manzano Mountains, east of Kirtland Air Force Base, near Albuquerque. The SOR, as shown in Figure 20, uses lasers to track and monitor satellites and includes a 3.5 m telescope, one of the largest in the world, which is able to image satellites passing quickly overhead. The facility also uses lasers and Adaptive Optics as part of its research for obtaining high-resolution images of objects in space [31].

***Figure 20*: SOR laser link [www.ashdome.com/ page5.html]**

3.5 U.S.A.: Maui - Air Force Maui Optical and Supercomputing

The Air Force Research Laboratory (AFRL) operating location on Maui has a double mission purpose:

- conducts the research and development mission on the Maui Space Surveillance System (MSSS) at the Maui Space Surveillance Complex (MSSC)
- oversees operation of the Maui High Performance Computing Center (MHPCC)

AFRL's research and development mission on Maui was formally called AMOS (Air Force Maui Optical and Supercomputing); the use of the term AMOS has been widespread throughout the technical community for over thirty years and is still used today by the scientific community. The accessibility and capability of the Maui Space Surveillance System provides an unequaled opportunity to the scientific community by combining state-of-the-art satellite tracking with a facility supporting research and development.

The AMOS, shown in Figure 21, is routinely involved in numerous observing programs and has the capability of projecting lasers into the atmosphere, which is unusual at astronomical sites. Situated at the crest of the dormant volcano Haleakala on the island of Maui, Hawaii, the observatory stands at an altitude of 3058 meters, latitude 20.7 degrees N, and longitude 156.3 degrees W. Virtually year-round viewing conditions are possible due to the relatively stable climate. Dry, clean air and minimal scattered light from surface sources enable visibility exceeding 150 km. Based on double star observations, seeing is typically on the order of 1 arcsec.

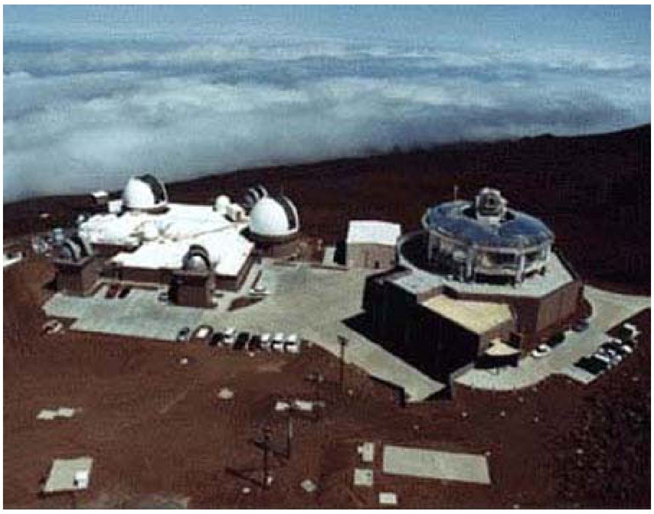

***Figure 21*: Maui Space Surveillance System (known as AMOS) [www.afosr.af.mil/ pages/aeos_tele.htm]**

Currently, through its primary mission for Air Force Command, the Maui Space Surveillance System combines large-aperture tracking optics with visible and infrared sensors to collect data on near Earth and deep-space objects. The 3.67 m telescope, known as the Advanced Electro-Optical System (AEOS), owned by the Department of Defense, is the nation's largest optical telescope designed for tracking satellites. The AEOS telescope points and tracks very accurately, yet is fast enough to track both low-Earth satellites and missiles. AEOS can be used simultaneously by many groups or institutions because its light can be channeled through a series of mirrors to seven independent coudé rooms below the telescope. Employing sophisticated sensors that include an adaptive optics system, radiometer, spectrograph, and long-wave infrared imager, the telescope tracks man-made objects in deep space and performs space object identification data collection.

AEOS is equipped with an adaptive optics system, the heart of which is a 941-actuator deformable mirror that can change its shape to remove the atmosphere's distorting effects. Other equipment at AMOS includes a 1.6 m telescope, two 1.2 m telescopes on a common mount, a 0.8 m beam director/tracker, and a 0.6 m laser beam director. The telescopes accommodate a wide variety of sensor systems, including imaging systems, conventional and contrast mode photometers, infrared radiometers, low light level video systems, and acquisition telescopes [32].

3.6 JAPAN: Konagei - Communications Research Laboratory

Communications Research Laboratory (CRL) is recognized in Japan as the center of excellence in advanced technologies for optical communications and remote sensing. Its primary focus is on mobile and high data rate multimedia satellites, optical communications technology, and satellite/terrestrial communications systems experiments. To support this effort, the staff is studying “light wavefront control technologies”, which include lasers, detectors, high speed modulation/demodulation, propagation, superconductivity for optical devices, and lightwave/radiowave conversion [33].

CRL planned to perform basic optical communication experiments using the Japanese ETS-VI, launched in 1994. The optical payload for the ETS-VI, named Laser Communication Equipment (LCE), was manufactured in 1992. The ETS-VI Laser Communications Equipment uplink operated at 0.51 μm and the downlink at 0.83 μm. The LCE included a 7.5 cm diameter telescope, a Si APD receiver, and a 13.8 mW transmitter incorporating two AlGaAs laser diodes. The data rate was 1.024 Mbps. The downlink could be used to retransmit uplink data or transmit telemetry or test data generated onboard the spacecraft. The dual link optical communications experiment was performed between the ETS-VI and the OGS located at the Space Optical Communication Research Center of CRL, Koganei, Tokyo [34].

The main instrumentations of OGS at Koganei are:

- a transmitting telescope (20 cm diameter) with a fine pointing mechanism
- a main 1.5 m diameter telescope with an image intensifier tube camera
- optics to modulate an argon laser beam intensity
- a communication signal detector (APD)

- a protitype Adaptive Optics system dedicated for the 1.5 µm laser communication [35]
- other additional optical systems such as a 50 cm diameter Cassegrain telescope

3.7 GERMANY: a project for a mobile OGS

The next space demonstration after the described OICETS will be the TerraSAR-X project. TerraSAR-X is a new German radar satellite that will be launched in 2007 into LEO at an altitude of 514 km with an inclination of 97.44° (Figure 22).

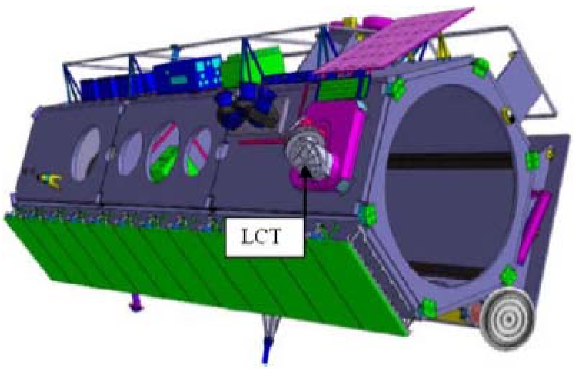

***Figure 22*: Laser Communication Terminal (LCT) mounted on TerraSAR-X satellite, LCTSX [36]**

The scheduled lifetime is 5 years. It carries a high frequency X-band Synthetic Aperture Radar (SAR) sensor developed by the German Aerospace Center, and the data measured will be downloaded to the OGS via a 5.5 Gbps optical link. The in-orbit verification program is called LCTSX (LCT on TerraSAR-X). The onboard optical terminal for LCTSX is being developed by Tesat Spacecomm. Bi-directional communication with a BER of 10^{-9} can be performed at 8 Gbps across 6,000 km and 1 Gbps across 20,000 km with an optical transmit power of 0.7 W, and 500 Mbps across 72,000 km with a high power laser (typically 5-7 W) using a 125 mm diameter telescope. The terminal mass is less than 30 kg, and the power consumption is below 130 W [36].

Related to the TerraSAR-X project, DLR is also developing a Transportable Optical Ground Station for broadband optical communications and atmospheric-turbulence measurements. The ground station, shown in Figure 23, is designed for a wide range of application scenarios, including satellite links, balloon links, and ground-to-ground links. The system is optimized for communication wavelengths in the range from 700 to 1600 nm. The station is designed to be deployed anywhere in the world due to its light-weight construction and highly flexible software for calibration. The system includes a 40 cm Cassegrain telescope, several cameras for the tracking system and measurement instruments, and a data processing system [37]. The Transportable Optical Ground Station successfully received data at rates of up to 1.25 Gbit/s and performed extensive atmospheric measurements to test optical transmission in a turbulent atmosphere [38].

***Figure 23*: Transportable Optical Ground Station during balloon trial in Kiruna, Sweden (August 2005) [37]**

3.8 Identification of the best OGS for the LEO-GND mission

In this paragraph we identify the best OGS for the LEO-GND mission carrying out a comparison between the characteristics of the receiving stations described in the previous paragraphs and the key parameters of the preliminary architecture proposed in this study for the OGS (see paragraphs 2.3 and 2.4).

Analyzing the features of the six Optical Ground Stations, no one seems to fulfill the characteristics of the OGS proposed in this study and summarized in table 2 of paragraph 2.4.

All the receiving stations have both good geological characteristics and excellent viewing conditions due to their locations. Moreover the analyzed OGS's have been already employed for successful optical link experiments.

La Teide* (Spain)**, has been dimensioned to perform an optical link at a wavelength about 800 nm. Therefore in order to employ this station for Alcatel Alenia Space Italia optical communication project, a new optical transmitter/receiver subsystem at 1550 nm should be installed. Also the ***MLRO* (Italy)** has not been dimensioned for an optical link at 1550 nm, but it has the advantage to be a sophisticated Italian multipurpose observatory capable of supporting a variety of experiments. We have gathered few information about the optical wavelength employed at the ***OCTL* (USA)**, even if the building has been realized to conduct optical GND-LEO link experiments. Moreover the OCTL telescope is coupled with a daytime Adaptive Optics system. For the ***SOR* (USA)** it has been possible to gather information just about the telescope diameter (3.5 m). Besides the station is an Air Force research Laboratory and it could be difficult to conduct civil experimentation. The accessibility and capability of the ***AMOS* (USA)** provides an unequaled opportunity to the scientific community by combining state-of-the-art satellite tracking with a facility supporting research and development. Nevertheless at the moment we have no information about the laser sources employed. We know the telescopes diameters (in a range from 0.6 to 3.67 m) and that among the facility there is an Adaptive Optics system. At ***CRL **(Japan)** are operative optics to modulate the intensity of an argon laser beam (wavelength about 480 nm), but there are no TX/RX susystem at 1550 nm. In this station is installed a main 1.5 m diameter telescope, a communication signal detector (APD) and a protitype of Adaptive Optics system is under development to perform an innovative project of laser communication at 1550 nm. Finally, concerning the ***Transportable Optical Ground Station*** **(Germany)**, it is optimized for communication wavelengths in the range from 700 to 1600 nm.

According to the performed comparative analysis we propose the Matera Laser Ranging Observatory in Italy as the best OGS candidate to perform the first-ever Italian optical link between a LEO satellite and a GND station, but with few and appropriate modifications of the optic subsystems. To make the MLRO in a position to perform an optical link with the payload proposed by Alcatel Alenia Space Italia (see paragraph 2.2) mounted on board a LEO orbit satellite, the main modifications to realize are:

- install a DFB laser (wavelength of 1550 nm) with an optical booster system
- install a PIN detector with an optical preamplificator

In this way, a totally Italian optical satellite communication project could be realized.

Alternatively to the MLRO, to perform a LEO-GND optical link, the Transportable Optical Ground Station in development at DLR could be employed. The system is already optimized for communication wavelengths in the range from 700 to 1600 nm and therefore it requires no modifications about laser subsystem. At our best knowledge the mobile station is at moment equipped with 40 cm Cassegrain telescope, instead of a 1 m telescope proposed in our preliminary architecture for the OGS.

CONCLUSIONS

The purpose of this thesis is to perform the analysis of main characteristics of an Optical Ground Station (OGS) in LEO-Ground optical link mission scenario.
The study has been developed at laboratories of consortium CO.RI.S.T.A. (Consortium for Research on Advanced Remote Sensing Systems) in Naples in collaboration with Alcatel Alenia Space Italia in Turin and it is part of project that will be funded by ASI (Italian Space Agency). The project is called "Optical telecommunication payload" and has the purpose to develop the first Italian optical satellite link. The project is at phase A2, and the basic reference is the phase A of study performed in 2004 when an overview of the possible applications and technology to be used for the development of an Optical Telecommunication Payload were provided but not finalized to any specific mission.

A comparison between a radiofrequency communication system and an equivalent optical communication system, both thought for space applications, reveals the following advantages of the laser communication over the radiofrequency one:

- Smaller antenna size
- Lower weight
- Lower power consumption
- Immunity from intercept of data communication due to the small Field Of View
- Larger bandwidth (and consequently higher bit rates) with respect to the radiofrequency systems
- Immunity to Electromagnetic Interferences

The major disadvantage is related to system technological complexity since the RF communications are consolidated systems while the satellite optical communication is a new application.
The expected bit rate for a typical optical link is in the range between some tenth of Gbps to some Gbps depending on the distance and the laser output power.
These advantages and in particular the possibility to obtain more bandwidth with smaller antenna size and radiated electromagnetic power are the main reasons to investigate in this new technical field of space communication.
The increase in high-speed data link and data handling capability of satellites and planned satellite clusters has reached a level that needs for the wide implementation of free-space laser communications links.
The Free Space Optical communication (FSO) is based on laser technology and optical telescope with the aim to obtain the same performances obtained with the optical fibers.
Worldwide Space Agencies have developed programs to increase the satellite links data rates and, as shown in a study performed by NASA, the current X-band links are almost saturated and the plan is to use the Ka band and optical links.

In optical satellite communication system the OGS has three primary functions:

- maintain an illumination on the flight system with the beacon beam
- recover the downlink beam
- facilitate operations and planning

The analysis of the OGS appears a critical issue. It cannot be ignored that the main disadvantage of the optical satellite link compared to the RF link is the interaction of the laser beam with the atmosphere. A laser beam propagating through the atmosphere can quickly lose energy due to molecular scattering, molecular absorption, and particulate scattering.

Refractive turbulence may also contribute to energy loss, however, it mainly degrades the beam quality, both by distorting the phase front and by randomly modulating the signal power. The presence of opaque clouds may occlude the signal completely rendering the time-of-sight communication link useless. For this reason the OGS has to be located in specific sites taken into account of the weather visibility conditions in order to maximize the light signal and to guarantee continuity in space-ground link with very high probability.

The optical communication technology is quite appealing for LEO to Ground communication since the required optical power is achievable with present technology and the data rate is by far higher than Radio Frequency communication; the disadvantage is that the link performance is strongly dependent on the atmospheric condition (e.g. rain, fog) and therefore during the satellite crossing over the ground station some links may be lost. This drawback can be solved imposing on-board mass memories to store data to be transmitted later with better weather conditions.

The architecture for the payload developed during phase A of the project consider the use of the innovative technology at 1550nm. Particularly the Optical Transmitter subsystem preliminary parameters are:

- Optical source: 1550 nm Semiconductor Laser
- Laser type: DFB (Distributed FeedBack)
- Average optical power: 100 mW (Pt = 20 dBm)
- Modulation format: Intensity Modulation
- Modulation bandwidth: Higher than 1.5 Ghz

In order to reduce the use of optical devices and to improve the performances in terms of receiver sensitivity, the Direct Detection technique and an APD detector for satellite optical receiver subsystem have been proposed.

The Optical Receiver preliminary parameters are:

- Photodetector: Semiconductor @ 1550 nm
- Typology: APD
- Responsivity @ 1550nm: 0.69 A/W
- Gain: 20
- Demodulation technique: Direct Detection
- Sensitivity: -35 dBm @ BER = 10-9

Moreover during the phase A of the project the satellite terminal with the same wavelength for beacon and signal data transmission has been proposed. This choice appears particularly convenient in order to reduce the weight of the optical payload mounted on board since just one wavelength has to be received and transmitted.

The preliminary architecture for the OGS appears innovative too. From the optical link point of view, the Ground Station architecture is conceptually similar to the satellite one. The OGS is made up of the laser beam which transmits at 1550 nm wavelength, the collector of the satellite transmitted signal (which is a telescope), the filter to reduce the received signal background noise and to improve the signal to noise ratio, the modulated signal receiver subsystem, the electronic subsystem (which include the control of the guidance feedback of the telescope and the signal demodulator).

The preliminary characteristics of an OGS for a LEO-GND mission scenario proposed in this study are summarized in the following table:

OGS Transmitting subsystem	
Optical source	1550 nm Semiconductor Laser
Laser type	DFB
Average optical power	20 mW
Modulation format	Intensity Modulation
Modulation bandwidth	Higher than 1.5 GHz
EDFA output power	1 W
OGS Receiving subsystem	
Telescope Diameter	1 m
Photodetector	Semiconductor @ 1550 nm
Typology	PIN
Responsivity @ 1550 nm	0.8
Demodulation technique	Direct Detection
BER	10^{-9}
Sensitivity	-44 dBm @ BER=10^{-9}

In this thesis a survey of potential Optical Ground stations in Italy and abroad In order to identify the best OGS for the LEO-GND mission a comparative analysis has been carried out between the characteristics of the receiving stations studied and the key parameters of the preliminary architecture proposed in this study for the OGS (see paragraphs 2.3 and 2.4).

According to the performed comparative analysis we propose the Matera Laser Ranging Observatory (MLRO) in Italy as the best OGS candidate to perform the first-ever Italian optical link between a LEO satellite and a GND station, but with few and appropriate modifications of the optic subsystems. To make the MLRO in a position to perform an optical link with the payload proposed by Alcatel Alenia Space Italia (see paragraph 2.2) mounted on board a LEO orbit satellite, the main modifications to realize are:

- install a DFB laser (wavelength of 1550 nm) with an optical booster system
- install a PIN detector with an optical preamplificator

In this way, a completely Italian optical satellite communication project could be realized.

Alternatively to the MLRO, to perform a LEO-GND optical link, the Transportable Optical Ground Station in development at DLR could be employed. The system is already optimized for communication wavelengths in the range from 700 to 1600 nm and therefore it requires no modifications about laser subsystem. At our best knowledge the mobile station is at moment equipped with 40 cm Cassegrain telescope, instead of a 1 m telescope proposed in our preliminary architecture for the OGS.

REFERENCES

[1] D.L. Begley, "Laser cross-link system and technology", IEEE Communication Magazine, vol. 38, n. 8, August 2000, pp. 126-132.

[2] S. Arnon, N.S. Kopeika, "Laser satellite communication network - Vibration effect and possible solutions", Proceedings of the IEEE, vol. 85, n. 10, October 1997, pp. 1646-1661.

[3] K. Araki, Y. Suzuki, "Inter-Satellite link by lightwave", Technical Digest of International Topical Meeting on Microwave Photonics, 3-5 December 1996, pp. 221-224.

[4] R.S. Bondurant, "High rate space laser communication", LEOS '99, San Francisco, CA.

[5] E. Rochat et al., "Fiber amplifiers for coherent space communication", IEEE Journal on selected topics in quantum electronics, vol.7, no.1, January/February 2001.

[6] S. Shimer et al., "High bandwidth optical intersatellite link technologies", International topical meeting on Microwave photonics 1999, vol.1, pp.101-104.

[7] V.W.S. Chan, "Optical space communication", IEEE Journal on selected topics in quantum electronics, vol.6, no.6, Nov/Dec 2000, pp. 959-975.

[8] R.A. Cryan, “Space communications employing optical pulse position modulation”, ECSC, 3rd European Conference on Satellite Communications, November 2-4 1993, pp. 192-195.

[9] Edelson et al., “Laser satellite communications. Program, technology and applications”, IEEE-USA Aerospace policy committee rep., Apr. 1996.

[10] H.P. Lutz, “Optical Communications in Space – Twenty Years of ESA Effort,” ESA Bulletin 91, 1997, pp. 25-31.

[11] Y. Suzuki, “Recent R&D activities for optical data link in NASDA”, CRL Int. Topical Workshop on Space Laser Communication-Current Status and future perspectives, Tokio, Japan, March 10-11 1997, pp. 29-33.

[12] G.D. Fletcher et al., “The SILEX optical interorbit link experiment”, Electronics & Communication Engineering Journal, vol. 3, no.6, Dec. 1991, pp.273-279.

[13] G. Planche et al., “SILEX in-orbit performances”, Proceedings of the 5th International Conference on Space Optics, 30 March- 2 April 2004, Toulouse, France.

[14] T. T. Nielsen, G. Oppenhaeuser, B. Laurent, and G. Planche, “In-orbit test results of the optical intersatellire link, SILEX. A milestone in satellite communication”, 53rd International Astronautical Congress, IAC-02-M.2.01, Huston, Oct, 2002.

[15] M. Reyes, S. Chueca, A. Alonso, T. Viera, and Z. Sodnik, “Analysis of the preliminary optical links between ARTEMIS and the Optical Ground Station,” in Proc. SPIE Free-Space Laser Communication and Laser Imaging II, vol. 4821, 2003, pp. 33–43.

[16] H. Hemmati et al., “Multi-gigabit data-rate optical communication depicting LEO-to-GEO and GEO-to-Ground links”, Earth Science Technology Conference, August 27-30, 2001, Greenbelt, MD (USA). Available at: http://techreports.jpl.nasa.gov/2001/01-1834.pdf

[17] R. Link, M. E. Craddock, R. J. Alliss, “Mitigating the Impact of Clouds on Optical Communications”, IEEE Aerospace Conference, 05-12 March 2005, pp. 1-8.

[18] Information and scientific publications on project are available at: http://www.capanina.org/news.php

[19] B. A. Tozer, “The Calculation of Maximum Permissible Exposure Levels for Laser Radiation”, J. Phys. E : Sci. Instrum., vol. 12, 1979, pp. 922-924.

[20] B. Laurent, G. Planche, C. Michel, “Inter-Satellite Optical Communications: from SILEX to next Generation Systems”, 5th International Conference on Space Optics, 30 March - 2 April 2004, Toulose, France, pp. 1-8.

[21] K. E. Wilson, M. Britcliffe, N. Golshan, “Progress in Design and Construction of the Optical Communications Laser Laboratory”, SPIE, Free Space Laser Communications, 26 Jan. 1999, San Jose, California, USA. Available at: http://trs-new.jpl.nasa.gov/dspace/bitstream/2014/17067/1/99-0489.pdf

[22] K. E. Wilson ane J. R. Lesh, "An Overview of the Galileo Optical Experiment (GOPEX)", The Telecommunications and Data Acquisition Progress Report 42-114, Jet Propulsion Laboratory, 192-204 (1993). Available at: http://tmo.jpl.nasa.gov/tmo/progress_report/42-114/114Q.pdf

[23] Y. Arimoto, M. Toyoshima, M. Toyoda, T. Takahashi, M. Shikatani, and K. Araki, "Preliminary result on laser communication experiment using Engineering Test Satellite-VI (ETS-VI)", Proc. SPIE 2381, pp. 151-158 (1995).

[24] Available at: http://www.jaxa.jp/press/2005/12/20051209_oicets_j.html

[25] Available at: http://www.jaxa.jp/press/2005/08/20050824_oicets_index_j.html

[26] Available at: http://www.iac.es/telescopes/ogs/OGSE.html

[27] Available at: http://www.ricercaitaliana.it/lab_asi.htm

[28] Available at: http://www.asi.it/html/eng/asicgs/geodynamics/mlro.html

[29] Available at: http://tmf-web.jpl.nasa.gov/index.html

[30] K. E. Wilson, M. Britcliffe, and N. Golshan, "Progress in Design and Construction of the Optical Communications Laser Laboratory", SPIE, Free Space Laser Communications, San Josè, California,U.S.A., 26 - Jan – 1999. Available at: http://trs-new.jpl.nasa.gov/dspace/bitstream/2014/17067/1/99-0489.pdf

[31] Available at: http://www.adic.com/us/collateral/storageGov.pdf

[32] Available at: http://www.maui.afmc.af.mil/about.html

[33] Available at: http://www.wtec.org/loyola/satcom2/c_01.htm

[34] Available at: http://www.wtec.org/loyola/satcom/ac_kashi.htm

[35] Available at: http://www2.nict.go.jp/mt/b162/index-e.html

[36] R. Lange and B. Smutny, "In-Orbit Verification of Laser Communication Terminals", 23rd ICSSC of AIAA, No. I000280, Rome, September (2005).

[37] D. Giggenbach and J. Horwath, "Optical Free-Space Communications Downlinks from Stratospheric Platforms – Overview on STROPEX, the Optical Communications Experiment of CAPANINA", IST Mobile Summit 2005, Dresden, 19-22 June (2005).

[38] Available at: http://www.capanina.org/