CYLAR SPECIFICATIONS

CDT YEBES LASER RANGING

TECHNICAL REPORT 1.2

B. Vaquero Jiménez, J. A. López Fernández

Informe Técnico IT - OAN 2011 - 11

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Abstract

Este informe resume las especificaciones principales que tendrá la futura estación de Satellite Laser Ranging del Observatorio de Yebes y analiza la capacidad de observación que tendrá el sistema. Los parámetros establecidos se basan en los estudios realizados durante los últimos meses en el Observatorio Geodésico de Wettzell (Alemania), es la estación SLR de Graz (Austria) y en las tendencias actuales de estos sistemas. El objetivo de este proyecto es convertir al Observatorio en una estación Geodésica Fundamental.

The present report summarizes the main specifications for the future Satellite Laser Ranging Station at Yebes Observatory and analyzes the tracking capabilities. The parameters are based on studies carried out during the last months at the Geodetic Observatory Wettzell (Germany), the SLR Station at Graz (Austria) and on the current system trends. This project is intended to be one of the key systems of the future Yebes Geodetic Fundamental Station.

1. Introduction

1.1. Satellite Laser Ranging Technique

In Satellite Laser Ranging (SLR) a global network of ground stations measure the instantaneous round trip time of flight (ToF) of ultrashort laser pulses from the stations to satellites equipped with special retro-reflectors. This provides instantaneous range measurements of millimeter level precision which can be accumulated to provide centimeter accurate orbits and host of important science products.

The laser pulse is generated in the ground station, and is transmitted through an optical system (transmitting telescope) to the satellite. Satellites altitudes range from 400 km to 26000 km and the Moon. A small percentage of the outgoing laser pulse is used to start a ToF measurement unit (event timer or interval counter). The reflected pulse is received at the ground station by the receiving telescope, detected, amplified, analyzed, and used to stop the time system.

SLR is one of the fundamental space geodesy techniques and the SLR stations form an important part of the international network of space geodetic observatories, which includes VLBI, GNSS and DORIS.

“The International Laser Ranging Service (ILRS), established in 1998 as a service within the International Association of Geodesy (IAG), coordinates and organizes the SLR activities to support programs in geodetic, geophysical, and lunar research activities and provides important products to the maintenance of the International Terrestrial Reference Frame (ITRF). The ILRS develops the standards and specifications necessary for product consistency and the priorities and tracking strategies required to maximize network efficiency. The Service collect, merges, analyzes, archives and distributes satellite and lunar laser ranging data to satisfy a variety of scientific, engineering, and operational needs and encourages the application of new technologies to enhance the quality, quantity, and cost effectiveness of its data products. The ILRS is composed of the SLR Stations, Operations Centers, Global Data Centers, Analysis Centers, Combination Centers, the Working Groups and the Governing Board”. ILRS web site: http://ilrs.gsfc.nasa.gov/.

1.2. Scientific Applications of Laser Ranging and Data Products

Laser ranging measurements provide a long-term stable time story of station positions and precision orbit determination. The main data products applications are:

- Maintenance of the International Terrestrial Reference Frame, based on contributions from the four different space geodetic techniques (SLR, VLBI, GNSS, and DORIS). The most important contributions of the laser ranging are the fixing of its origin (geocenter) and its scale.
- Precise orbit determination (POD) (sub-centimeter absolute accuracy), verification and calibration of orbit determined with other techniques such as GPS or DORIS and support altimetry missions. More than 60 missions have been tracked by SLR.
- Earth Orientation Parameters: polar motion and length of the day.
- Earth gravity field: static and time-varying gravity field, mass motions within the solid Earth, oceans, and atmosphere.
- Geodynamic: tectonic plate motion and crustal deformation.

- Mass distribution studies.
- General relativity and space science.
- Lunar physics (ephemerides, rotation, tidal displacements, etc.).
- Time transfer.

The ILRS products (official products) are weekly solutions for station coordinates and Earth Orientation Parameters (EOPs) for the derivation of the scale (GM) and time-varying Earth Center of Mass for the ITRF.

1.3. CDT Yebes SLR Construction Motivation

In 2004, the IAG established the Global Geodetic Observatory System (GGOS) project to coordinate geodetic research and integrate different geodetic techniques. The fundamental aspect of GGOS is the upgrading, expansion, and maintenance of a global ground network of co-located Core Site for geodesy to enable the evolution of ITRF. The Yebes Technology Development Center (CDT Yebes) is intended to be one of the Fundamental Stations of this network.

Currently, the main facilities at the CDT Yebes are:

- a 40 m diameter radio telescope carrying out geodetic and astronomical observations. The available bands are: S, CH, C, X, K, W, holography and future K/Q (receiver under construction). All of them developed at the observatory,
- time and frequency system (with 2 H-Maser),
- GNSS receivers,
- absolute (FG5, A10) and relative superconducting gravity meters,
- meteorological and hydrological sensors.

Systems related to some of the requirements of the GGOS project. Furthermore, the observatory has an anechoic chamber for antenna measurements, laboratories for the construction of low noise amplifiers and cryogenic receivers, mechanical workshops, chemistry laboratory, and outreach facilities.

In order to complete the project requirements and turn the observatory into a Core Site, the RAEGE project is being developed. A Spanish-Portuguese Network consisting on four Geodetic Fundamental Stations, two in Spain (in Yebes and Canary Islands), and two in Azores Islands. Each station will be equipped with one VLBI2010 radio telescope. The infrastructure for the new station in Yebes is already available and the construction of the first antenna has started. Also, the establishment of the local tie at Yebes and the design of a Satellite Laser Ranging Station have already started.

Due to the current trends in the new SLR stations and the GGOS project, the future Laser Ranging Station at Yebes (CYLAR, Cdt Yebes LAser Ranging) will fulfill the main characteristics of the Next Generation Systems: low energy laser (taking into account the possibility of participating in one-way ranging and transponder experiments), high repetition rate (1000 to 2000 Hz), few picoseconds (ps) pulse width, pico event timer, single photon detection (CSPAD or APD detector) and high automation. The station will have the capacity to observe all satellites, from 400 to 26000 km (navigation satellites: GPS, Glonass, Compass and Galileo). Other characteristics will be a lightweight biaxial telescope Cassegrain-Coudé for laser pulses transmission and reception (~ 50 cm and 10 cm respectively), Nd:YAG laser (532 nm), night and day operation and air traffic protection compatible with other activities at the observatory (VLBI2010 and 40m radio telescope).

2. SLR Station Main Components

The main components that will be part of Yebes future Station are summarized on this list, without taking into account other alternatives or other elements, just the ones that are complicated to be determined a priori.

2.1. Laser system

- The SLR systems use a **pulsed solid state laser** for pulse generation with one or two colors capacity (to measure the atmospheric refraction). Stations with two color capacity use a Ti:SAP (847 nm) laser, but in principle a **Nd:YAG (532 nm)** laser will be selected for our future system (it could be prepared for two-colour ranging if a suitable detector is available in the future). For ultrashort pulse generation, the systems use to have a SESAM modelocking (Semiconductor Saturable Absorber Mirror), pockels cell and polarizers (electro-optic modulator), control systems (power, phase and polarization), etalon filter, and amplifiers. The laser oscillator also needs a cooling system and to be installed in a clean room.
- **Optical bench**: mirrors, lenses, polarization systems (linear and circular), diaphragms, alignment laser system (2 mirrors), etc.
- **Amplifiers**: depending on the laser type different kinds of amplifiers are required: regenerative amplifier, double-pass or multipass amplifier, post amplification stage.

2.2. Telescope

- **Telescope**:
  - Coaxial (just one telescope for laser pulse transmitting and receiving).
  - Biaxial (one telescope for transmission and the other one for reception).

  Both of them need a Coudé focus, optic observation system (pointing adjustment), dome, telescope control unit, and azimuth and elevation motors.
- External or internal **calibration system** (pre/post observation).

2.3. Detectors and filters

- **Start detector**, photodiode.
- **Stop detectors**:
  - **MPT**, multichannel plate photomultiplier, quantum efficiency, η_q = 10%.
  - **APD**, avalanche photodiode, η_q = 50%, small effective area.
  - **CSPAD**, time walk compensated single photon avalanche diode, η_q = 20%.
- Pulse Distribution Unit, PDU, or **discriminators**.
- Daylight observation filters: **spectral filter**, **spatial filter** or **field of view (FoV)**
- **Temporal filter** or **range gate**.
- **Optical amplitude filtering**.
- Divergence and attenuation control.

2.4. Timing Systems

- **Event timer**, time of flight measurement, few ps resolution.
- **Time and Frequency Standards**: H-maser, GPS receiver, etc.

2.5. Software

- **Optoelectronic control** (detectors, event timer, laser firing…).
- Event timer software, ToF measurement. Time and frequency standard control.
- **User interface**.
  - Telescope control unit. Dome control. Divergence, field of view and attenuation control. Mount model. Laser control unit. Safety system control.
- **Predictions data base**.
- **Observing files generation**. Normal Point calculation. Data delivering.

2.6. Secondary Components

- **Building and foundations**: base foundations, telescope pillar, laser pillar, and control, laser and telescope rooms.
- **Outer security system**: passive or active radars, eye safety laser, cameras, air traffic control data.
- **Inner security system**: glasses, warning signs, secure windows and doors, warning lights, signs with information about the laser characteristics, etc.
- **Security cameras**: laser control and weather observation.
- **Meteorological instrumentation**: temperature, humidity and pressure sensors.

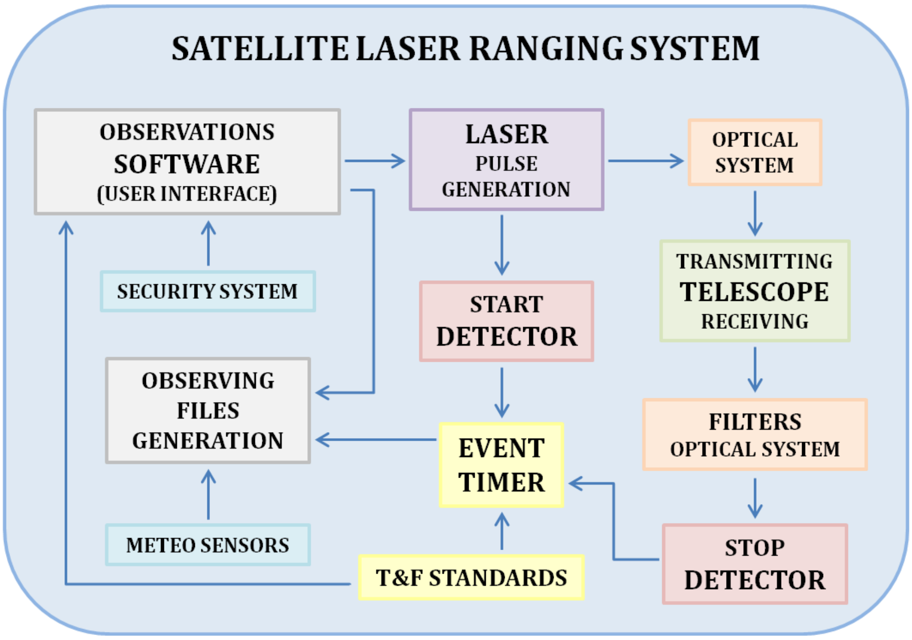


Figure 1. Satellite Laser System diagram.

3. CYLAR Specifications

The first parameters that should be defined are related with the main components (laser, telescope, detection system, etc.) and the radar link equation parameters (receive and transmit optics efficiency, laser wavelength, laser pulse energy, detector quantum efficiency, far field divergence half-angle, beam pointing error, primary and secondary mirror radius). To select the value for these parameters we have to take into account the satellites that are going to be observed, the weather conditions at the station site, the trends in other stations and the available economic budget.

3.1. Tracking Capabilities

Our goal is to develop a SLR station capable of observing all satellites (except the Moon), especially the navigation satellites (an important aim of the GGOS project). The operation schedule depends on the system automation and the number of staff per shift. Our purpose is to observe at least 16 hours per day, observing the same number of hours during night and daytime. The development of a full automated system is under study, with no operator under normal conditions, making possible observations during 24 hours, 365 days/year.

The laser ranging stations will dedicate the 100% of the time to SLR observations.

Parameters	*Characteristics*
Satellites	
Very Low Alt (<400 km)	Yes
Low Altitude (400-2000)	Yes
Lageos	Yes
GLONASS	Yes
Etalon	Yes
GPS	Yes
Moon	No
Operation	
Months per Year	≥ 11 months
Days per Week	≥ 5 days
Hours per Day	≥ 16 hours (night and day)
System Shared With	Nothing
Time Allocated to SLR	100 %
Remotely Controllable	(tbd)
Staff per Shift	≤ 1

(tbd: To Be Determined)

3.2. Laser System and Aircraft Detection

The laser specifications are based mainly on the GGOS requirements (next generation system characteristics: kHz lasers, few ps pulse width, pico event timers, etc.), and the sort of observations that we want the system realizes (to observe high satellite, more power is needed).

The 532 nm lasers (Nd:YAG, Nd:VAN, Nd:YVO), although are more affected by the atmosphere than the 847 nm laser (Ti:SAP), has the advantages of reaching a higher power being more simple (less amplifiers are needed) and with a lower cost. At first, just the 532 nm lengthwave is going to be used at Yebes station.

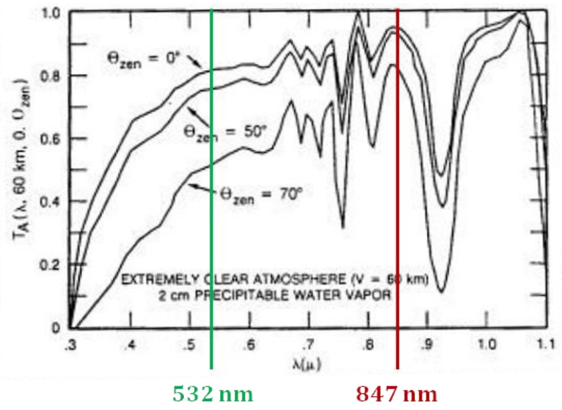


Figure 2. Atmospheric transmission as a function of wavelength [Degnan, 1993].

Typical values for the **far field divergence half-angle** fall between 5” and 15”. In several stations it ranges from 5” to 200” for special observations. The beam divergence uses to be on the order of, or smaller, than the expected system tracking errors. Atmospheric turbulence also sets a lower limit to the minimum beam divergence [Degnan, 1993].

Regarding the security system, we have to take into account the 40 m radio telescope and the future VLBI2010 antenna (RAEGE project) since active radar for aircraft detection, may cause interferences in these systems. We have to study other possibilities, i.e., programs that provide information about the civil and military air traffic. Light aircraft or gliders are often not recorded by these kind of systems so we will need other facilities to complete the safety: security cameras controlled by the operators or eyesafe laser systems to detect the aircraft and stop the observation laser.

Parameters	*Characteristics*
Laser Type	Nd:YAG
Number of Amplifiers	(tbd)
Primary Wavelength	1064 nm
Secondary Wavelength (observations)	532 nm
Secondary Max. Energy	1-4 mJ
Transmit Energy Adjustable	(tbd)
Pulse Width (FWHM)	10-20 ps
Max. Repetition Rate	1000-2000 Hz
Fullwidth Beam Divergence	5-200" (5-20” general observations)
Final Beam Diameter	(tbd) m

3.3. Telescope Information

The system is planning to observe just satellites, not the Moon, so, a big telescope is not needed. Taking into account the better stations around the world, a 50 cm receiving telescope and 10 cm transmitting telescope would be enough.

A **biaxial telescope** has been chosen because almost all kHz systems use that kind of telescope. A coaxial telescope could have problems to transmit and receive the pulses in a high repetition rate system. A biaxial telescope uses whole telescope capacity, the output beam and the incoming returns can have different paths, so most of the noise is avoided into the detectors. The main disadvantage is the pointing error between the two telescopes at every angle (azimuth and elevation), and with temperature changes. A good value for the **beam pointing error** should be around 5” or less. If we have two telescopes, it is the beam pointing error of the complete system. This is one of the most important factors to keep in mind to build a telescope for SLR.

Other telescope parameters: slew rate, tracking rate, azimuth and elevation maximum angles, acceleration, etc., are typical values for a SLR telescope. Other ones will be defined when the construction telescope project will be selected.

The SLR Yebes station is going to be located in a site with good visibility, so we hope to reach a minimum tracking observation of 10-15° (taking into account the radio telescopes).

The foundation dimensions will be determined when specific information about the telescope and the laser is known.

The reference point for the local tie will be the intersection of the azimuth and elevation axes.

Regarding to the **transmit optics efficiency**, η_T = 0,7 (or 70%), can be considered as a conservative value and 0,75 as an optimistic value. It depends on the number of mirrors and their transmit efficiency. A typical value in many stations is 0,7.

The **efficiency of the receiver optics**, η_R, can improve considerably locating the detectors in the telescope mount, reducing the long path and the number of mirrors. It also depends on the different filters that could be used for daylight tracking, like spatial or spectral filter. It could be around 0,7 without any filter, 0,5 with spatial filter and 0,4-0,2 with spectral filter.

Parameters	*Characteristics*
Receiving Telescope Type	Cassegrain-Coudé
Aperture	0,5 m
Mount	AZ-EL
Secondary Mirror	0,1 m
F-number	1,5
Transmitting Telescope Type	Refractor-Coudé
Aperture	0,1 m
Tracking Camera Type	(tbd)
Field of View	(tbd)°
Minimum Magnitude	(tbd)mag
Transmit/Receive Path	Separate
Transmit/Receive Switch	None
Max Slew Rate Azimuth	15-20 °/s
Max Slew Rate Elevation	10-15 °/s
Max Used Tracking Rate Azimuth	10-15 °/s
Max Used Tracking Rate Elevation	5-10 °/s
Azimuth Angle	> 540° (~620°)
Elevation Angle	180°
Azimuth Acceleration	4 $°/s^2$
Elevation Acceleration	$4°/s^2$

Beam Pointing accuracy	≤ 5"
Min. Tracking Elevation	10-15°
Telescope Shelter	Dome
Weight	<1500 kg
Transmit Efficiency	0,7
Receive Efficiency	0,5
Az-El Motors	Servo or stepper motors
Angle Encoder Resolution	(tbd)"
Geologic Characteristic	Bedrock
Foundations	
Depth	3-4 m
Height (above ground)	7-8 m
Dimensions (base)	m
Diameter (telescope)	m
Dimensions (laser)	m
Inner Hole	(tbd)
Reference Point	AZ-EL

3.4. Receiver System, Detectors and Filters

The receiver system mainly consists of the detector, the signal processing and the event timer. Some stations have more than one detector used for different observations or different satellites. Currently, the most widely used detectors are the CSPAD and the APD. In principle, just one detector is going to be used for every observation but it has not chosen yet.

To observe during daytime, several filters are needed. The choice of these filters has direct influence on the receive efficiency; therefore, it is necessary to reach a compromise between the kind of filter and the efficiency.

λ_{BP} or $\delta\lambda$ is the spectral width of the bandpass filter, **spectral filter**. Typical values are:

Spectral filter, λ_{BP}	Transmission
1 nm	0,70
0,3 nm	0,45

Degnan, 1993.

Spectral filter, λ_{BP}	Transmission
1 nm	0,70
0,3 nm	0,53
0,15 nm	0,45-0,3

Tracking Capability Analysis of ARGO-M, 2010.

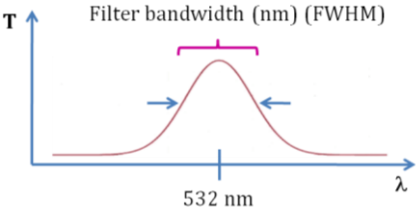


Figure 3. Spectral filter bandwidth.

The receiver **field of view** or **spatial filter** can be in the order of 10”-20” (half-angle) during daytime and 10”-300” at night. For the **range gate**, event timer temporal gate, we are going to consider values between 100 and 400 ns around the estimated time.

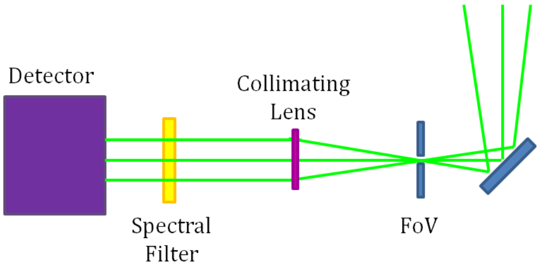


Figure 4. Filters location scheme.

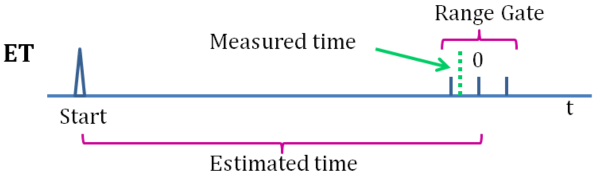


Figure 5. Range gate concept.

Parameters	*Characteristics*
Daylight Filter Type	Spectral Filter (removable)
Daylight Filter Bandwidth	0,15-3 nm
Adjustable Attenuation	(tbd)
Field Of View	10-20"
Receiver system	
Wavelength	532 nm
Detector Type	CSPAD / APD (tbd)
Quantum Efficiency	20 % / 50 %
Signal Processing	(tbd)
Mode of Operation	Single to few photon
Time of Flight Observation	Event Timer
Resolution	~ 1 ps
Precision	< 10 ps
Range Gate Width	100-400 ns

3.5. Calibration

The system calibration will be carried out before and after the observations (every one or two hours), pre/post calibration. It will be external, it still remains to select the final position for the calibration target (in or outside the dome) and its type.

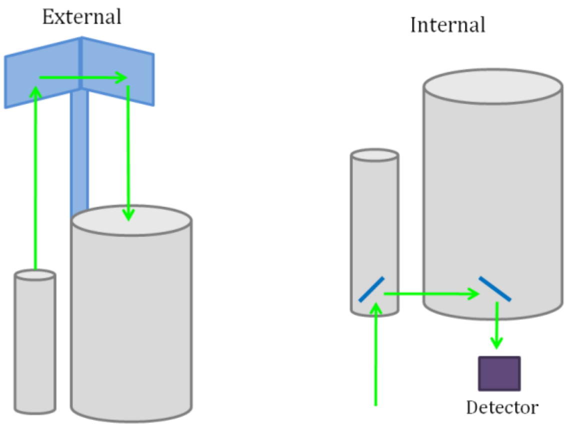


Figure 6. External and internal calibration scheme.

4. Facilities at CDT Yebes

The CDT Yebes has already got several necessary facilities for completing the SLR station.

4.1. Time and Frequency Standards

Parameters	*Characteristics*
Frequency Standard Type	H-Maser
Model	EFOS_C
Manufacturer	T4 Science SA
Short Term Stab.	0,15 e-12 at 1 s
Long Term Stab.	8 e-16/day
Time Reference	GPS (UTC)
Synchronization	GPS
Epoch Accuracy	150 ns
GPS Timing Receiver Model	XL-DC-602
Manufacturer	TrueTime (Symmetricon)

4.2. Meteorological Instrumentation

Parameters	*Characteristics*
Pressure Sensor Model	SP6
Manufacturer	Seac
Measurement range	600 … 1100 hPa
Accuracy	±0,4 hPa mbar
Temp Sensor Model	HMP45A/D - Pt 1000 IEC 751 - Pt 100 IEC 751 1/3 Class B
Manufacturer	Vaisala
Measurement range	-39,2 … +60 °C
Accuracy	±0,2 °C
Humidity Sensor Model	HMP45A/D - HUMICAP 180
Manufacturer	Vaisala
Measurement range	0,8 % ... 100 % (RH)
Accuracy	±1 % (RH)

4.3. Local Ties, Eccentricities, and Collocation Information

The SLR station will be co-located with the 40 m radio telescope, the VLBI2010 radio telescope (RAEGE project), GNSS receivers and the absolute and superconducting gravity meters. Currently, the station local tie is being developed.

5. Radar Link Equation and Daylight Tracking

To complete the report about CYLAR specifications, a basic analysis about the tracking capability of the system and the daylight tracking probability has been carried out.

5.1. Radar Link Equation

The system tracking capability analysis is performed through the radar link equation. With the defined specifications (using a CSPAD detector), for the LAGEOS satellite observation, the following results are obtained:

Radar Link Equation => mean number of photoelectrons:

$$N_{pe} = \eta_q \left(E_T \frac{\lambda}{hc}\right) \eta_T G_T \sigma_S \left(\frac{1}{4\pi R^2}\right)^2 A_R \eta_R T_A^2 T_C^2$$

Transmitter gain for a Gaussian beam:

$$G_T = \frac{8}{\theta_D^2} exp\left[-2\left(\frac{\theta_P}{\theta_D}\right)^2\right]$$

Effective receiver area:

$$A_R = A_P(1-\gamma^2)\eta_D \quad => \quad \eta_D \sim 1 \quad \gamma = \frac{r_{M2}}{r_{M1}} \quad A_P = \pi r_{M1}^2$$

LINK BUDGET		***LAGEOS***		***GPS***		
		Best Case	**Worst Case**	**Best case**	**Worst case**	
Mean number of photoelectrons	**N_{pe}**	**4,769**	**0,004211**	**0,114**	**0,000248**	
Laser pulse energy	E_T	2,5				mJ
Laser wavelength	λ	532				nm
Plank´s constant	h	6,63E-34				Js
Velocity of light in vacuum	c	299.792.458				m/s
$E_T\,\lambda/hc$		**6,70E+15**				
Transmit optics efficiency	η_T	0,7				
Efficiency of the receive optics	η_R	0,5				
Detector quantum efficiency	η_q	0,2				
$\eta_q\eta_T\eta_R$		**0,07**				
Satellite optical cross-section	**σ_S**	**7.000.000**		**40.000.000**		**m^2**
Slant range to the target	R	5.840.000	8.640.000	23.000.000	26.500.000	m
$(1/4\pi R^2)^2$		**5,41E-30**	**1,23E-30**	**2,26E-32**	**1,27E-32**	**m^{-4}**
One-way atmospheric transmission	**T_A**	**0,91**	**0,49**	**0,91**	**0,49**	
One-way transmissivity of cirrus clouds (when present)	**T_C**	**1**	**0,12**	**1**	**0,12**	

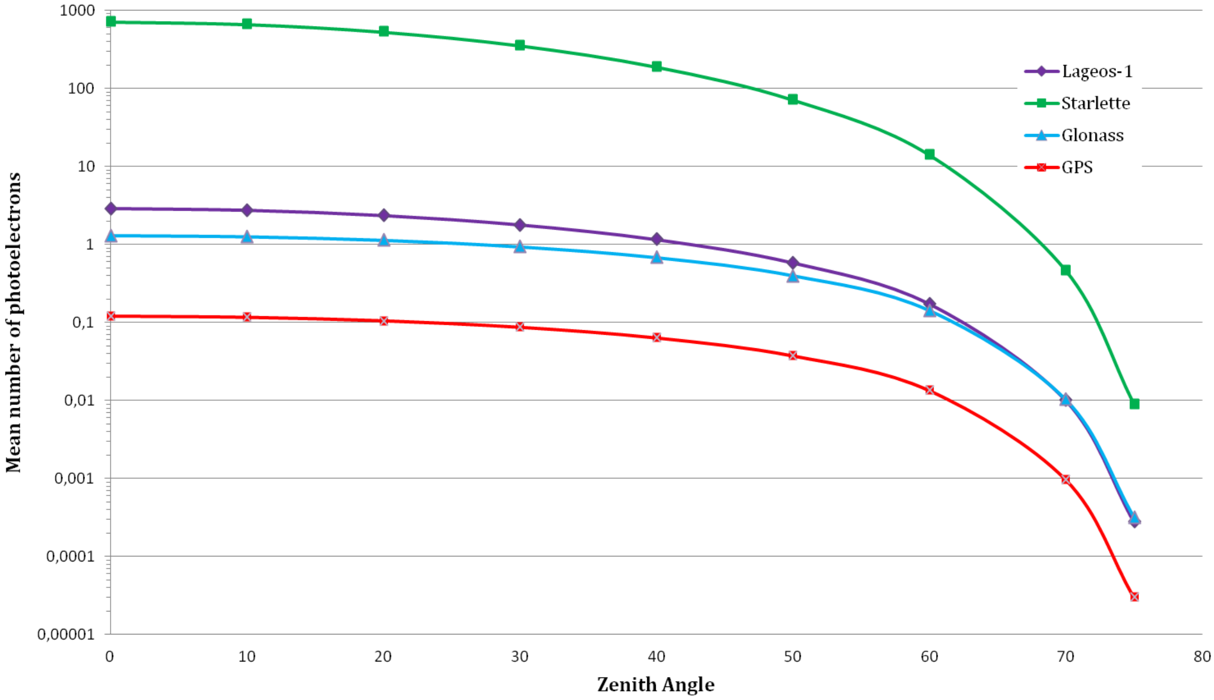
Transmitter gain	**G_T**	**1,84E+09**				
Effective area of the telescope receive aperture	**A_R**	**0,177**				**m^2**
Transmitter gain $8/\theta_D^2\, exp[-2(\theta_P/\theta_D)^2]$	***G_T***	***1,84E+09***				
Far field divergence half-angle	θ_D	2,42E-05				rad
Beam pointing error	θ_P	2,42E-05				rad
Effective area of the telescope receive aperture $A_P(1+\gamma^2)\eta_D$	***A_R***	***0,177***				***m^2***
Receiver obscuration ratio	γ	0,4				
Area of the receiver primary	A_P	0,1967				m^2
Fraction of the incoming light intercepted by a detector	η_D	1				
Receiver obscuration ratio r_{M2}/r_{M1}	***γ***	***0,4***				
Primary mirror radius	r_{M1}	0,25				m
Secondary mirror radius	r_{M2}	0,1				m
Area of the receiver primary πr_{M1}^2	***A_P***	***0,1967***				***m^2***
Primary mirror radius	r_{M1}	0,25				m
Zenith angel	***θ_Z***	***0***	***70***	***0***	***70***	°
One-way atmospheric transmission	***T_A***	***0,91***	***0,49***	***0,91***	***0,49***	
Attenuation coefficient	σ	0,18 (V=60km)	0,46 (V=8km)	0,18 (V=60km)	0,46 (V=8km)	
Scale height	h_{sh}	1,2	1,2	1,2	1,2	km
Cirrus Transmittance	***T_C***	***1 (no cirrus)***	***0,12***	***1 (no cirrus)***	***0,12***	
Mean cirrus cloud thickness	t	1,341				km

Detailed information about the parameters => Appendix

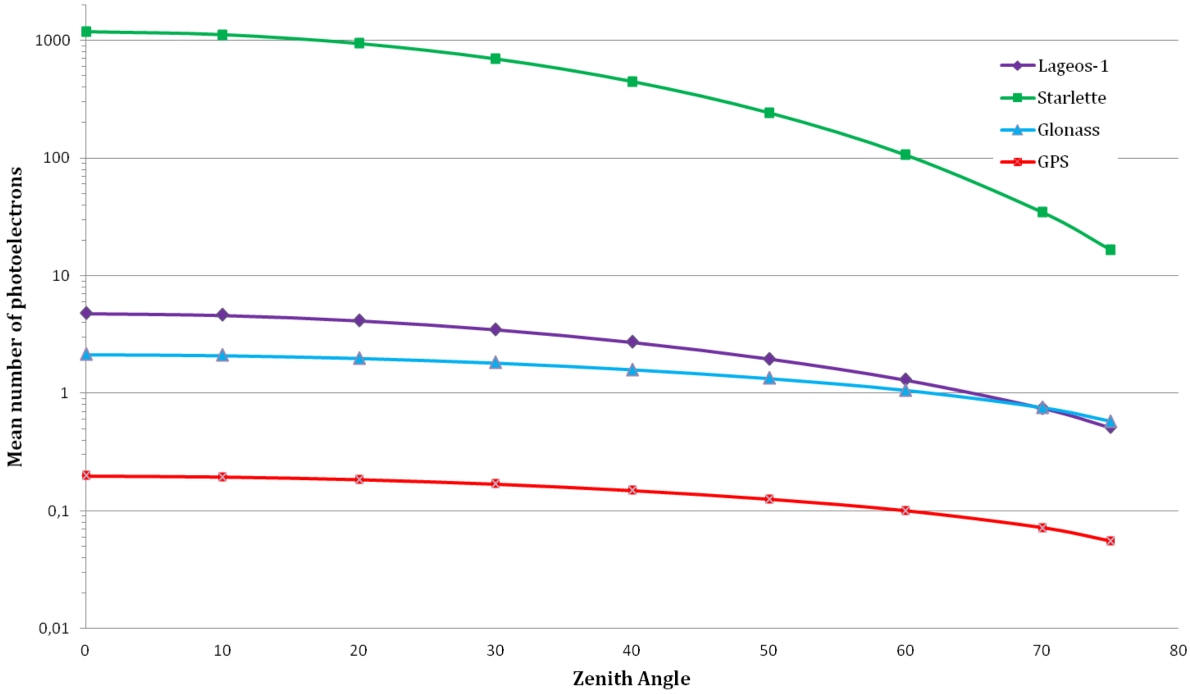
If we consider the best situation (good weather conditions, 60 km visibility, and high elevation, 0°), we would get to observe the Lageos satellite without any problem because the mean number of photoelectrons is greater than 1. Under the worst situation (bad weather conditions, but allowing the observation, and low elevation), with a kHz system, it would be possible to observe, since it must be taken into account the mean number of photoelectron and the number of pulses per second.

A comparison between different satellites under different weather conditions is shown in the following graphs:

- Signal levels: under extremely clear sky with cirrus clouds:



- Signal levels: under extremely clear sky without cirrus clouds:



5.2. Daylight Tracking

The daytime observing probability study is calculated next.

Photoelectron generation rate resulting from background noise:

$$N_B = \frac{\eta_q}{h\nu} N_\lambda \lambda_{BP} \Omega_\mathrm{R} A_R \eta_R \tau_{RG}$$

Probability of detecting one photon from the background noise, false alarm probability:

$$P_{FA} = 1 - e^{-N_B}$$

Photon detection probability, probability of detecting one photon from the background noise and actual signals:

$$P_{PD} = 1 - e^{-N}$$

Signal detection probability, probability of detecting a signal from the background noise:

$$P_{SD} = (1 - P_{FA}) P_{PD}$$

DAYLIGHT TRACKING		***LAGEOS***		***GPS***		
		Best Case	**Worst Case**	**Best Case**	**Worst Case**	
Photoelectron generation rate resulting from background noise	**N_B**	**1,17E+06**				ph/s
Detector quantum efficiency	η_q	0,2				
Effective area of the telescope receive aperture	A_R	0,177				m^2
Efficiency of the receive optics	η_R	0,5				
Laser photon energy	$h\nu$	3,74E-19				J
Background spectral radiance Watt/ster m^2	N_λ	1,40E+08				
Spectral width of the bandpass filter	λ_{bp}	0,3				nm
Receiver field of view in steradians (10”)	Ω_R	5,88E-10				st
Taking into account the range gate	**N_B**	**0,2332**	**0,4664**	**0,2332**	**0,4664**	ph
Range gate width	**τ_{RG}**	***2,00E-07***	***4,00E-07***	***2,00E-07***	***4,00E-07***	nm
Probability of false alarm	**P_{FA}**	**0,21**	**0,37**	**0,21**	**0,37**	
Photoelectron generation rate resulting from background noise	N_B	0,2332	0,4664	0,2332	0,4664	ph
Probability of detection (signal and noise)	**P_{PD}**	**0,99**	**0,38**	**0,29**	**0,37**	
Total number of photon detected	N	5,0023	0,4707	0,3472	0,4667	Ph
Signal detection probability	**P_{SD}**	**0,79**	**0,24**	**0,23**	**0,23**	
Probability of detection (signal and noise)	P_{PD}	0,99	0,38	0,29	0,37	
Probability of false alarm	P_{FA}	0,21	0,37	0,21	0,37	

6. Summary: main parameters

Next, the main parameters or specifications of our future system, on which we are going to base the station development, are presented.

Parameters	*Characteristics*
Receiving Telescope Type	Cassegrain-Coudé
Aperture	0,5 m
Mount	AZ-EL
Secondary Mirror	0,1 m
F-number	1,5
Transmitting Telescope Type	Refractor-Coudé
Aperture	0,1 m
Reference Point	AZ-EL
Max Slew Rate Az	15-20 °/s
Max Slew Rate El	10-15 °/s
Azimuth Angle	~620°
Elevation Angel	180°
Beam Pointing accuracy	≤ 5"
Daylight Filter Type	Spectral Filter
Daylight Filter Bandwidth	0,15-0,3 nm
Transmit Efficiency	0,7
Receive Efficiency	0,5
Field Of View	10-20"
Laser Type	Nd:YAG
Secondary Wavelength	532 nm
Secondary Max. Energy	1-4 mJ
Pulse Width (FWHM)	10-20 ps
Max. Repetition Rate	1000-2000 Hz
Beam Divergence	5-200" (5-15" general observations)
Detector Type	CSPAD / APD
Quantum Efficiency	20 % / 50 %
Time of Flight Observation	Event Timer
Satellites	
Very Low Alt (<400 km)	Yes
Low Altitude (400-2000)	Yes
Lageos	Yes
GLONASS	Yes
Etalon	Yes
GPS	Yes
Moon	No
Range Gate Width	100-400 ns

APPENDIX. Link budget and daylight tracking: detailed information about variable parameters.

Radar Link Equation => mean number of photoelectrons recorded by the ranging detector:

$$N_{pe} = \eta_q \left(E_T \frac{\lambda}{hc}\right) \eta_T G_T \sigma_S \left(\frac{1}{4\pi R^2}\right)^2 A_R \eta_R T_A^2 T_C^2$$

Where $\left(E_T \frac{\lambda}{hc}\right)$ take into account the **laser energy** and **frequency**.

The **detector quantum efficiency**, η_q, range between 10% and 50% according to the used detector => approximately, 10% for MCP, 20% for SPAD and 50% for APD.

For the **transmit optics efficiency**, η_T = 0,7 (or 70%), can be considered as a conservative value and 0,75 as an optimistic value. It depends on the number of mirrors and their transmit efficiency. A typical value in many stations is 0,7.

The **efficiency of the receiver optics**, η_R, can improve considerably locating the detectors in the telescope mount, reducing the long path and the number of mirrors. It also depends on the different filters that could be used for daylight tracking, like spatial or spectral filter. It could be around 0,7 without any filter, 0,5 with spatial filter and 0,4-0,2 with spectral filter.

The **slant range**, R, is given by the equation:

$$R = -(R_E + h_t)cos\theta_z + \sqrt{(R_E + h_t)^2 cos^2\theta_z + 2R_E(h_s - h_t) + h_s^2 - h_t^2}$$

It depends on the station height above the sea level, $h_t = 972\ m$ at Yebes Observatory, the satellite altitude and the **zenith angle**.

Transmitter gain for a gaussian beam is given by the expression:

$$G_T = \frac{8}{\theta_D^2} exp\left[-2\left(\frac{\theta_P}{\theta_D}\right)^2\right]$$

Where θ_D is the **far field divergence half-angle** and θ_P the beam pointing error.

Typical values for θ_D fall between 5” and 15”. In several stations it ranges from 5” to 200” for special observations. In the WLRS station, at Wettzell observatory, is 5” for every satellite except for LRO. The beam divergence uses to be on the order of, or smaller, than the expected system tracking errors. Atmospheric turbulence also sets a lower limit to the minimum beam divergence [Degnan, 1993]. This formula doesn´t take into account that the gaussian profile is usually radially truncated by some limiting aperture and sometimes centrally obscured.

A good value for the **beam pointing error** should be around 5”-7”. If we have two telescopes, it is the beam pointing error of the complete system. This is one of the most important factors to take into account to build a telescope for SLR, the pointing error should be conserved at every elevation and with temperature changes.

NOTE: these calculations assume there is no transmitter pointing error (fixed pointing bias and random pointing error). It could be considered for a more accurate study but it is not necessary in our case. Furthermore, it doesn´t take into account the atmospheric turbulence (long term beam, short term beam and scintillation) that changes the transmitter gain (beam divergence and pointing error) and the gaussian beam.

The **effective receiver area**, A_T, take into account the radiation lost to blockage by a secondary mirror (if any) and spillover at the spatial filter and/or detector (if any) [Degnan, 1993]:

$$A_R = A_P\left(1-\gamma^2\right)\eta_D \quad => \quad \eta_D \sim 1 \quad \gamma = \frac{r_{M2}}{r_{M1}} \quad A_P = \pi r_{M1}^2$$

A_P is the **area of the receiver primary** and γ is the **receiver obscuration ratio**.

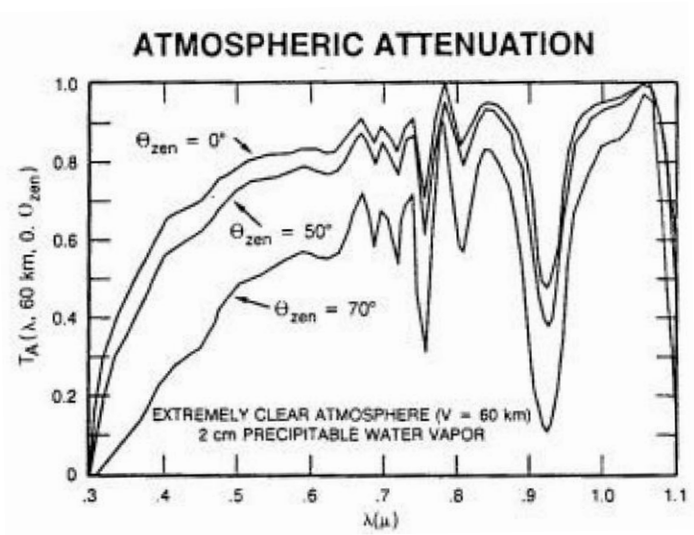
If the detector effective area is enough to detect all the photons (CSPAD or MCP, not APD) then we can consider the fraction of the incoming light intercepted by a detector, $\eta_D \sim 1$.

The **primary mirror ratio**, r_{M1}, is 25 cm for a 50 cm receiving telescope and 10 cm is a standard value for the **ratio of the secondary mirror**, r_{M2}, for this kind of telescope.

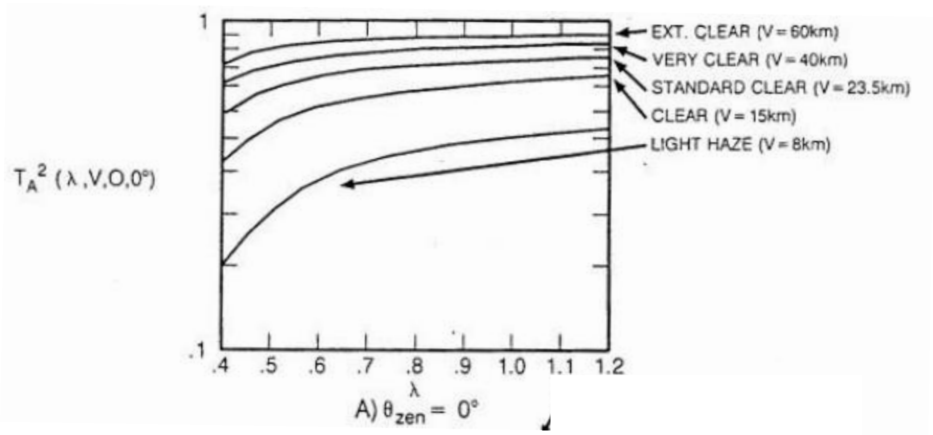
One-way atmospheric transmission:

$$T_A(\lambda, V, h_t) = \exp\left[-\sigma(\lambda, V, 0) h_{SH} \sec(\theta_z) \exp\left(-\frac{h_t}{h_{SH}}\right)\right]$$

Where $\sigma(\lambda, V, 0)$ is the **attenuation coefficient** at wavelength λ for a sea level visibility, V, at the sea level, $h = 0\,m$, and h_{SH} is the scale height, 1,2 km.



Atmospheric transmission as a function of wavelength under extremely clear conditions with 2 cm of precipitable water [Degnan, 1993].



Variation of the two-way atmospheric transmission with sea-level visibility [Degnan, 1993].

According to the figures, we can take these values for Yebes station:

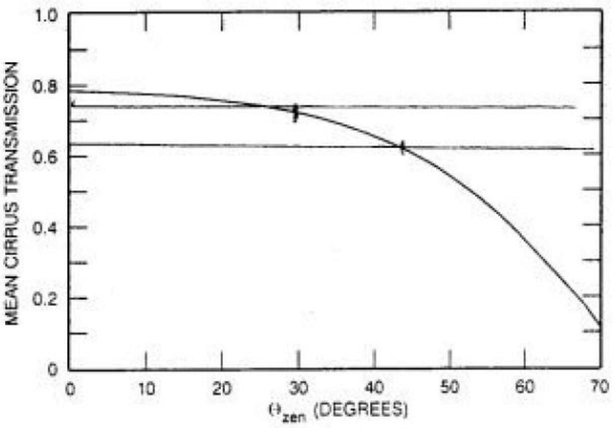
Sky condition	Visibility, V	Attenuation Coefficient, σ	Station height, h_t	Zenith angle, θ_z	**Atmospheric tranmission**, $T_A(\lambda, V, h_t)$
Extremely Clear	60 km	0,18	972 m	0°	**0,91**
				70°	0,75
Clear	15 km	0,25		0°	0,87
				70°	0,67
Light Haze	8 km	0,46		0°	0,78
				70°	**0,49**

Sky condition	Visibility, V	Attenuation Coefficient, σ	Station height, h_t	Zenith angle, θ_z	**Atmospheric tranmission**, $T_A(\lambda, V, h_t)$
Extremely Clear	60 km	0,18	972 m	0°	0,908
				10°	0,907
				20°	0,903
				30°	0,895
				40°	0,882
				50°	0,861
				60°	0,825
				70°	0,755

Cirrus transmittance:

$$T_C = \exp[-0.14(t \sec \theta_z)^2]$$

Cirrus clouds are overheads about 50% of the time at most locations, sometimes they are not visible. The mean cirrus cloud thickness, when present, is $t = 1{,}341$ km [Degnan, 1993]. If we assume this value of the thickness, we obtain the curve below:



Mean cirrus transmission (one-way) as a function of zenith angle [Degnan, 1993].

Although cirrus clouds are not present 50% of the time ($T_C = 1$), and when they are present, their thickness is less than the mean value 50% of the time, we are going to consider cirrus clouds presence and mean thickness value for our link budget.

Zenith angle, θ_z	**Cirrus Transmittance**, T_C
0°	**0,78**
70°	**0,11**
(No cirrus)	**1**

Photoelectron generation rate resulting from background noise:

$$N_B = \frac{\eta_q}{h\nu} N_\lambda \lambda_{BP} \Omega_{\mathrm{R}} A_R \eta_R \tau_{RG}$$

N_λ is the background spectral radiance, sunlit clouds provide a worst case noise background of 1,4x10^8 Watt/ster m^2, $h\nu$ is the laser photon energy, 3,74x10^{-19} J at wavelength of 532 nm.

Ω_{R} is the receiver field of view in steradians or **spatial filter**. It can be in the order of 10”-20” (half-angle) (For example: WLRS Wettzell around 7” high satellites, 15” other satellite).

λ_{BP} or $\delta\lambda$ is the spectral width of the bandpass filter, **spectral filter**. Typical values:

Spectral filter, λ_{BP}	Transmission
1 nm	0,70
0,3 nm	0,45

Degnan, 1993

Spectral filter, λ_{BP}	Transmission
1 nm	0,70
0,3 nm	0,53
0,15 nm	0,45-0,3

Tracking Capability Analysis of ARGO-M, 2010

τ_{RG} is the temporal width of the **range gate**. We are going to consider values between 200 and 400 ns for our study.

Since the photon detection follows the Poisson probability distribution, the probability of detecting m number of photons (where N is the average number of photoelectrons):

$$P(m, N) = \frac{N^m}{m!} e^{-N}$$

Then the probability of detecting one photon from the background noise which is the **false alarm probability** [ARGO-M, 2010]:

$$P_{FA} = 1 - e^{-N_B}$$

The **photon detection probability**, which is the probability of detecting one photon from the background noise and actual signals, is:

$$P_{PD} = 1 - e^{-N}$$

where $N = N_S + N_N \cong N_S = N_{pe}$, is the total photoelectrons from the detector during the response time.

Finally, the **signal detection probability**, probability of detecting a signal from the background noise, is:

$$P_{SD} = (1 - P_{FA})P_{PD}$$

Summary: link budget and daylight tracking general parameters

CYLAR EQUATIONS		
LINK BUDGET		**Possible Values**
Mean number of photoelectrons	$\mathbf{N_{pe}}$	<1 => no detection > 1 => ok
Laser pulse energy	E_T	0,001-0,004 J (1-4 mJ)
Laser wavelength	λ	532 nm => 532x10^{-9} m
Plank´s constant	h	6,62606896x10^{-34} J s
Velocity of light in vacuum	c	299792458 m/s
Transmit optics efficiency	η_T	70-75 % => 0,7-0,75
Efficiency of the receive optics	η_R	50-60% => 0,5-0,6
Detector quantum efficiency	η_q	CSPAD 20% => 0,2
Satellite optical cross-section	σ_S	Satellite
Slant range to the target	R	satellite and elevation
One-way atmospheric transmission	T_A	0,91-0,49 best and worst cases
One-way transmissivity of cirrus clouds (when present)	T_C	0,78-0,12 best and worst cases
Transmitter gain	$\boldsymbol{G_T}$	θ_D, θ_P
Far field divergence half-angle	θ_D	5”-15”
Beam pointing error	θ_P	5”-7”
Effective area of the telescope receive aperture	$\boldsymbol{A_R}$	η_D, γ, A_P
Fraction of the incoming light intercepted by a detector	$\boldsymbol{\eta_D}$	~1

Receiver obscuration ratio	$\boldsymbol{\gamma}$	r_{M1}, r_{M2}
Area of the receiver primary	$\boldsymbol{A_P}$	r_{M1}
Secondary mirror radius	r_{M2}	10 cm
Primary mirror radius	r_{M1}	25 cm
One-way atmospheric transmission	$\boldsymbol{T_A}$	
Attenuation coefficient	σ	0,18-0,46 best and worst cases
Zenith angle	θ_Z	0°-75°
Station height above the sea level	h_t	972 m
Scale height	h_{SH}	1,2-1,5 km
One-way transmissivity of cirrus clouds (when present)	$\boldsymbol{T_C}$	
Zenith angle	θ_Z	0°-75°
Cirrus clouds thickness	Φ (or t)	1,342 km
Slant range	$\boldsymbol{R}$	
Earth radius	R_E	6378 km
Satellite altitude above the sea level	h_s	Satellite
Zenith angle	θ_Z	0°- 75°
Station height above the sea level	h_t	972 m
Satellite optical cross-section	$\boldsymbol{\sigma_S}$	
LAGEOS		$7x10^{6}$ m^{2}
GPS		$40x10^{6}$ m^{2}
GLONASS		$360x10^{6}$ m^{2}
AJISAI		$12x10^{6}$ m^{2}
DAYLIGHT TRACKING		
Photoelectron generation rate resulting from background noise	$\boldsymbol{N_B}$ **(or $\boldsymbol{\Lambda}$)**	
Detector quantum efficiency	η_q	0,2 CSPAD
Effective area of the telescope receive aperture	A_R	r_{M1}=25 cm, r_{M2}=10 cm
Efficiency of the receive optics	η_R	0,5-0,6
Laser photon energy	$h\nu$	$3,74x10^{-19}$ J for 532 nm
Background spectral radiance	N_λ	$1,4x10^{8}$ Watt/ster m^{2}
Spectral width of the bandpass filter	λ_{bp} ($\delta\lambda$)	0,2-1 nm
Receiver field of view in steradians	Ω_R	10”-20”
Gange gate width	τ_{RG}	200-400 nm
Probability of false alarm	$\boldsymbol{P_{FA}}$	N_B
Total number of photon detected	$\boldsymbol{N}$	
Signal photoelectrons	N_S	N_{pe}
Noise photoelectrons	N_N	N_B
Probability of detection (signal and noise)	$\boldsymbol{P_{PD}}$	N
Signal detection probability	$\boldsymbol{P_{SD}}$	P_{PD}, P_{FA}

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