raymetrics lidar systems

**USER MANUAL**


# LR101-ESS-D200

## Depolarization Scanning LIDAR

DOC 0602

August 2017

# PREFACE

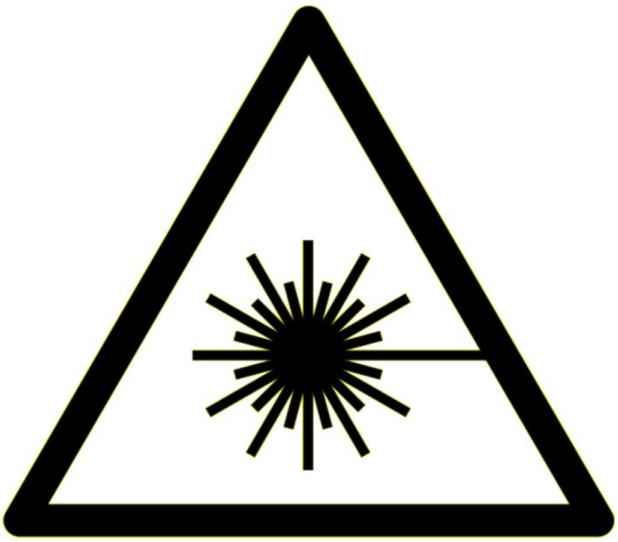
This User Manual contains the technical information needed to properly operate and maintain RAYMETRICS' Depolarization Scanning LIDAR system. It comprises a set of instructions for operation, servicing and preventive maintenance, as well as a troubleshooting (fault-isolation) guide.

For a quick reference use the contents table or document map. The manual is separated in three major chapters; the hardware description, the lidar's operation and the post analysis. At the last chapters, the user can find the technical details, the maintenance and the trouble shooting guide. Finally, at the last chapters is a summary of the methods and theory that is used for the lidar analysis software.

**Please read the manual before attempting to use the lidar.**

Caution and warning labels, in accordance with CDRH and CE requirements, are prominently displayed on the Laserhead and power supply of the laser unit, as well as in the front and rear panels of the Lidar telescope. For safety, the maximum ratings indicated on the system labels are more than the normal operating parameters.

The laser system produces laser radiation, which is hazardous to eyes and skin, can cause burning and fires and can vaporize substances. The laser safety chapter in the User Manual contains essential information and user guidance about these hazards.



# QUALITY CONTROL

FINAL TEST DATA SHEET

Model: LR101-ESS-D200

S/N: 200-02-17

Test Date: 18/12/2017

| | | |
|---|---|---|
| | Telescope Calibration: | ✓ |
| | Laser Beam Calibration: | ✓ |
| | Lidar Alignment : | ✓ |
| Lidar signals | 355 nm P : | ✓ |
| | 355 nm S : | ✓ |
| | Polarization Calibration: | ✓ |
| | Laser Safety Interlocks: | ✓ |
| | Laser Energy Measurement: | ✓ |
| | Electrical Connections: | ✓ |
| | Internal –External connections: | ✓ |
| | Rain Sensor | ✓ |
| | LPC | ✓ |
| | PDU | ✓ |
| | AZP | ✓ |

Any suggestions to be returned to:

**Raymetrics S.A.**
32 Spartis str., Metamorfosi
GR-144 52 Attiki - GREECE

Tel: +30 210 6655860
Fax: +30 210 2827217
info@raymetrics.com

For technical queries and support:
support@raymetrics.com

**Visit www.raymetrics.com for more info**

# TABLE OF ABBREVIATIONS

| ABREVIATION | EXPLANATION |
|---|---|
| A/D ADC | Analogue to Digital Conversion |
| AN | Analogue |
| APD | Avalanche PhotoDiode |
| AR | Anti-Reflection |
| ASCII | American Standard Code for Information Interchange |
| AZP | Altazimuth Positioner |
| BG | Background |
| CGU | Coolant Group Unit |
| CNC | Computer Numerical Control |
| DAQ | Data Acquisition System |
| DB | Database |
| EARLINET | European Aerosol Research Lidar Network |
| EXT | External |
| FOV | Field Of View |
| GL | Glued |
| HR | High Reflectivity |
| HT | High Transmitting |
| HV | High Voltage |
| HVAC | Heating Ventilation and Air Cooling |
| IFF | Interference Filter |
| INT | Internal |
| IP | Internet Protocol |
| LAN | Local Area Network |
| LCD | Liquid Crystal Display |
| LED | Light Emitting Diode |
| LIDAR | Light Detection and Ranging |
| LMC | Lidar Measurement Controller |
| LPC | Lidar Peripheral Controller |
| LR | Lidar Ratio |
| LSB | Least Significant Bit |
| ND | Neutral Density |

| | |
|---|---|
| OU | Optical Unit |
| PBC | Polarizing Beam Splitter Cube |
| PC | Photon Counting |
| PCC | Power Supply Cooling Unit Cabinet |
| PDU | Power Distribution Unit |
| PMT | Photo Multiplier Tube |
| PSU | Power Supply Unit |
| QS | Q-Switch |
| RAM | Random Access Memory |
| RCS | Range Corrected Signal |
| RDP | Remote Desktop |
| SAU | Signal Acquisition Unit |
| SHG | Second Harmonic Generator |
| SNR | Signal To Noise Ratio |
| TEC | Thermo-Electric Cooler |
| TED | Thermo-Electric Dehumidifier |
| TCP | Transmission Control Protocol |
| THG | Third Harmonic Generator |
| TR | Transient Recorder |
| TTL | Transistor–Transistor Logic |
| WOL | Wake On LAN |
| WSU | Wavelength Separation Unit |

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# 1 LIDAR SAFETY

## *DANGER*

**VISIBLE AND/OR INVISIBLE LASER RADIATION**

The Model LR101-ESS-D200 Lidar System contains a Class IV laser. Its output beam is, by definition, a safety and fire hazard. Precautions must be taken to prevent accidental exposure to both direct and reflected beams. Safety information provided in this manual, the laser manual and on training courses must be adhered to always. Raymetrics S.A. shall not be held responsible for accidents to the user or to third parties caused by improper use of the equipment.

The warning symbols below are used throughout this document and on the Lidar equipment itself to highlight potential hazards.

| | |
|---|---|
| DANGER | Imminent hazards which, if not avoided, will result in serious injury or death. |
| WARNING | Potential hazards which, if not avoided, could result in serious injury or death. |
| CAUTION | Potential hazards which, if not avoided, could result in minor or moderate injury. |
| CAUTION | Potential hazards which, if not avoided, could result in product damage. |
| NOTE | Points of interest for more efficient or convenient equipment operation; additional information or explanation. |
| WARNING LASER RADIATION | Avoid exposure of eyes or skin to direct or diffused laser radiation. Permanent eye damage or blindness may occur. |
| WARNING HIGH VOLTAGE | Electric shocks and burns from capacitor discharge or power circuits could lead to serious injury or even death. |

Class IV laser systems may produce lesions from the direct beam, its spectacular reflections and its diffuse reflections. The laser must only be accessed within the enclosure by personnel with sufficient experience with their operation; these personnel must be qualified and approved by the Laser Safety Officer. The safety rules explained below must be read and followed by everyone who accesses or attends the laser. Access to the laser should be limited to required personnel only.

1. Never look at the direct or scattered beam of the laser.
2. Avoid exposing any part of the body to the beam.
3. Remove all objects with a reflecting or shiny surface from the work area prior to work commencing, as well as all inflammable materials. Do not wear reflective jewelry while using the laser, as it might cause inadvertent hazardous reflections.
4. Ensure that the laser beam emission area is well lit, to limit the amount of light which enters the eyes of workers.
5. When not in use, it must be made impossible for unauthorized people to operate them, for example, by removing the door key or the laser key.
6. Using laser radiation to aim at individuals, vehicles, aircraft or any other flying object is formally prohibited.
7. Laser radiation must never be aimed at individuals, vehicles, aircraft or any other flying object.
8. Due to the risk of electric shock, the laser power supply must be switched off and disconnected from the flashlamp prior to any maintenance operation. Electric shocks or burns resulting from the power supply of the network or from condenser discharges may cause serious wounds and traumas and may even be fatal.

**Precautions for Safe Operation of Class IV Lasers**

9. Do not operate the laser with the covers removed for any reason.
10. Use protective eyewear always
11. Operate the laser at the lowest possible beam intensity, given the requirements of the intended application.
12. Increase the beam diameter wherever possible to reduce beam intensity and thus reduce the hazard.
13. Avoid blocking the laser beam with any part of the body.
14. Establish a controlled access area for laser operation. Limit access to those trained in the principles of laser safety.
15. Post prominent warning signs near the laser operation area.

16. Drain the laser power supply and cover the Lidar if you intend not to use it for more than a month.
17. Operate the laser power supply every day for at least 30 minutes to circulate the coolant fluid.
18. In low ambient temperatures (below zero Celsius) it is necessary to use ethylene glycol with water mixture and leave the laser power supply on.
19. After continuous operation for more than an hour, leave the laser power supply on for at least 10 minutes to cool down the head.

**Precautions for Safe Operation of LIDAR**

1. Always leave the HVAC on to control temperature and humidity inside the cabin.
2. Do not cover the inlet and outlet of the air-conditioning unit.
3. Check frequently the number of flashlamp shots and replace after 50million shots.
4. Never allow direct sunlight to reach the telescope's FOV.
5. Do not direct the laser beam inside the telescope.
6. Do not place any additional force on the telescope.
7. Do not alter the height of the primary and secondary mirrors of the telescope.
8. Always wear clean surgical gloves when handling optical parts.
9. Keep the protective windows clean.
10. Avoid any action which may scratch the protective windows.

**WARNING:** Only operations or procedures which have been described in this User Manual should be undertaken. Any procedures undertaken which have not been described in this manual may result in hazardous radiation exposure.

# 2 INTRODUCTION TO THE LIDAR TECHNIQUE

Atmospheric laser remote sensing employs the so-called Light Detection And Ranging (LIDAR) technique, to probe the atmosphere up to altitudes as high as ~120 km. The development of matured pulsed laser sources has enabled the range-resolved measurements of the principal atmospheric gases[1] and atmospheric/meteorological parameters, in a manner somewhat analogous to the radar technique. For the Lidar technique, a short laser light pulse is emitted into the atmosphere in one or more wavelengths (Fig. 2.1).

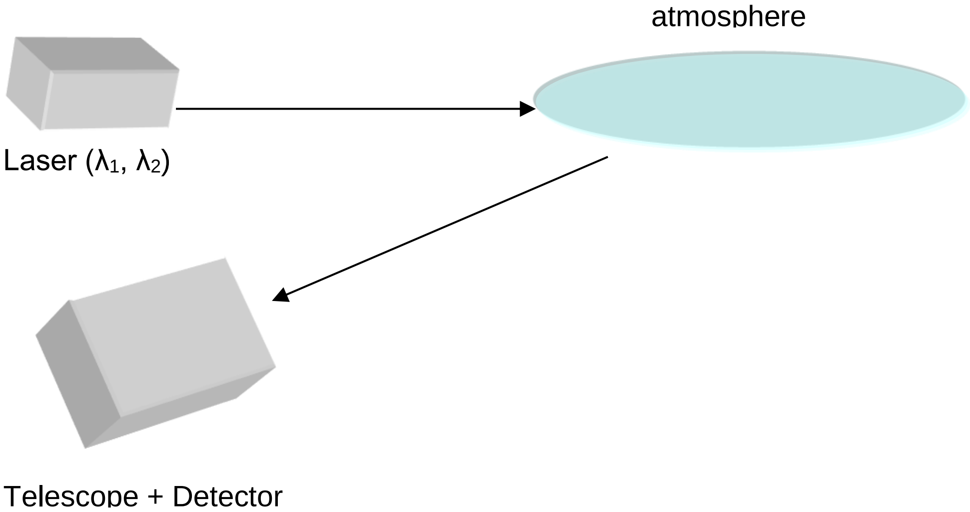



**Fig. 2.1**: The principle of operation of the Lidar technique.

The atmospheric volume being probed 'backscatters' the laser radiation. A receiving telescope is used to collect the backscattered laser light which occurs through elastic and inelastic processes. A Wavelength Separation Unit (WSU) is used to spectrally separate the Lidar signals at various wavelengths and to reject the atmospheric background radiation. The Lidar signals are then fed to fast detectors (photomultiplier tubes or PMTs). After amplification and digitization, the PMT output signals are sent to a central computer for further processing and storage.

The time between the emission of the laser pulse and the arrival of the returned backscattered signal is directly related to the range at which the scattering occurred. The most common processes related to laser pulse scattering by the suspended aerosol particles include the elastic Mie and Rayleigh scattering and the inelastic Raman scattering[2].

Observations of suspended aerosol particles can be made remotely, with high spatial and temporal resolution using the Lidar technique. Lidar systems can be operated from ground or mobile platforms, such as planes, helicopters or satellites.

The basic Lidar equation is given below:

$$P(z) = P_o \frac{c\tau}{2} \beta(z) A_{tel} O(z) \frac{1}{z^2} \exp\left[-2\int_0^z a(z^*)dz^*\right] \qquad (1)$$

where P(z) is the power incident on the receiving optics from distance z, $P_o$ is the laser output power, τ is the duration of the laser pulse, c is the velocity of light, $\beta(z)$ is the volume backscattering coefficient, $a(z)$ is the extinction coefficient of the atmosphere and $A_{tel}$ is the receiving telescope aperture. $O(z)$ is the so-called geometrical form factor (or overlap factor). This factor represents the probability of radiation in the target plane at range z reaching the detector, based on geometrical considerations. The $1/z^2$ dependence leads in many applications to a signal-amplitude dynamic range that extends over several tens of kilometers. Therefore, two detection modes are used: the analogue detection mode and the photon counting operation mode (section 3.3.2 Detection Electronics).

The detection of the suspended aerosol particles can be performed by an elastic Lidar system (one to three wavelengths) or by an inelastic (Raman) Lidar system. The elastic backscattered Lidar signals can be inverted using the Klett's inversion algorithm[3], while the inelastically backscattered Lidar signals can be inverted using the Raman inversion technique, as presented by Ansmann et al. (1992)[4].

# 3 LIDAR SYSTEM HARDWARE COMPONENTS

A typical LIDAR contains an emitter, a receiver, a Data Acquisition System (DAQ) as well as a computer that controls the transmitter and receiver and stores the acquired data. A power distribution unit is used to protect and power the various systems. The unit that contains the transmitter and receiver is called Lidarhead. The Lidarhead is enclosed in a climate controlled enclosure and mounted on a positioner that can turn the head in any direction of a hemisphere. The computer along with the DAQ and the Laser's power supply form the control unit which is also enclosed and climate controlled.

The image below shows a typical Lidar with its main components illustrated.


**Fig. 3.1:** Scanning Lidar Overview

All its components are described in detail below.

## 3.1 Emitter

The Lidar emitter consists of four sub-units: a laser, a High Reflectivity mirror, a Beam Expander, and a motorized High Reflectivity mirror.

The emitter and the light path are enclosed in a case that protects the user from direct contact with the laser beam and prevents light to enter the receiver.

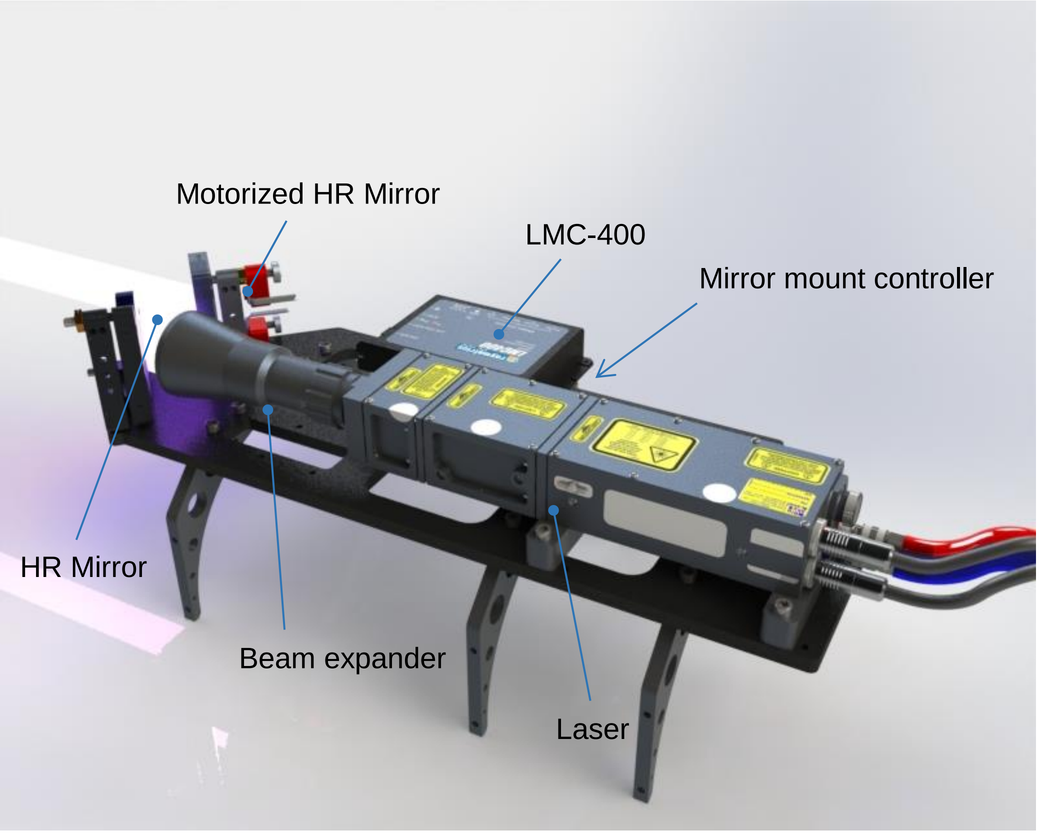



**Fig. 3.2:** Lidar Emitter Layout

### 3.1.1 Laser

The laser source is a water cooled pulsed Nd: YAG laser emitting short pulses at 1064nm. The pulse repetition rate is 20Hz. The pulse duration is of the order of 6-9 ns. Through the Second Harmonic Generation (SHG) the 532nm wavelength is produced and through the Third Harmonic Generation (THG) the 355nm wavelength is produced. This specific laser is optimized for maximum energy at 355nm. Note: the user should not change, remove or alter any of the laser components or sub-units. The laser consists of two major sub-components: the Laserhead and the power supply unit (PSU). These are connected by power and signal cables and water hoses for cooling the head. The laser model is a ULTRA100 manufactured by Quantel, including the PSU model ICE450 standard version.

A detailed description of the characteristics, specifications and operation mode of the laser source is given in the laser's instruction manual DOC00040.pdf.

**Safety Instructions**

- The user is requested to wear laser protective eyewear during the laser operation whenever close to the Lidar. Even when using laser protective eyewear goggles, the beam must not be stared at directly.
- Do not place any obstruction or reflective object in the emitted laser beam. Primary or secondary reflections may damage eyes or be reflected back into the laser causing damage.
- Before you turn off the laser the water circulation pump (ICE450) should be left in the ON position for at least 10-15 minutes to cool down the Laserhead.
- Always adhere to the instructions of the laser manufacturer regarding the maximum number of laser shots before replacement of the flashlamp is undertaken. (See laser instruction manual DOC00040.pdf).
- Always adhere to the instructions of the laser manufacturer regarding the replacement of the de-ionizing filter unit of the laser system (see laser instruction manual DOC00040.pdf).

**Fig. 3.3:** The Laserhead

***Attention!***

- Do not touch the optical components of the Lidar system (laser mirrors, laser windows, protective windows, etc.). This may lead to a complete destruction of their optical coatings and/or to a misalignment of the Lidar optics.
- Before undertaking any laser maintenance, consult the laser manual and follow all instructions exactly. Failure to comply with instructions may result in destruction of the Laserhead, requiring complete laser replacement which would not be covered under warranty.

### 3.1.3 Beam Expander

The beam expander serves two main purposes; it reduces the energy concentration and adjusts the light's divergence. This means that it adjusts the beam angle and eventually it improves the maximum range and the precision of the system. The beam's diameter is expanded by 10 times.

**Fig. 3.4:** Beam expander

### 3.1.4 Motorized HR Mirror

A crucial component for remotely operated systems is the motorized High Reflectivity mirror. The High Reflectivity mirrors (HR mirrors) in Raymetrics Lidars provide a high reflection >98% at 355nm wavelength and high transmission at 532nm and 1064nm due to the special coating on the front side which is designed for high laser energy. On the back side, there is a special anti-reflection coating to ensure that no back reflections will be emitted. The beam must be aligned to the telescope to achieve the best possible data. A piezoelectric motorized mirror mount manufactured by New Focus is used for this purpose. The main advantage of a motorized mirror mount in comparison to a manual mirror mount is that the user can align the LIDAR remotely. In addition, there is no need to remove any covers or use any tools which makes the process safe and easy.

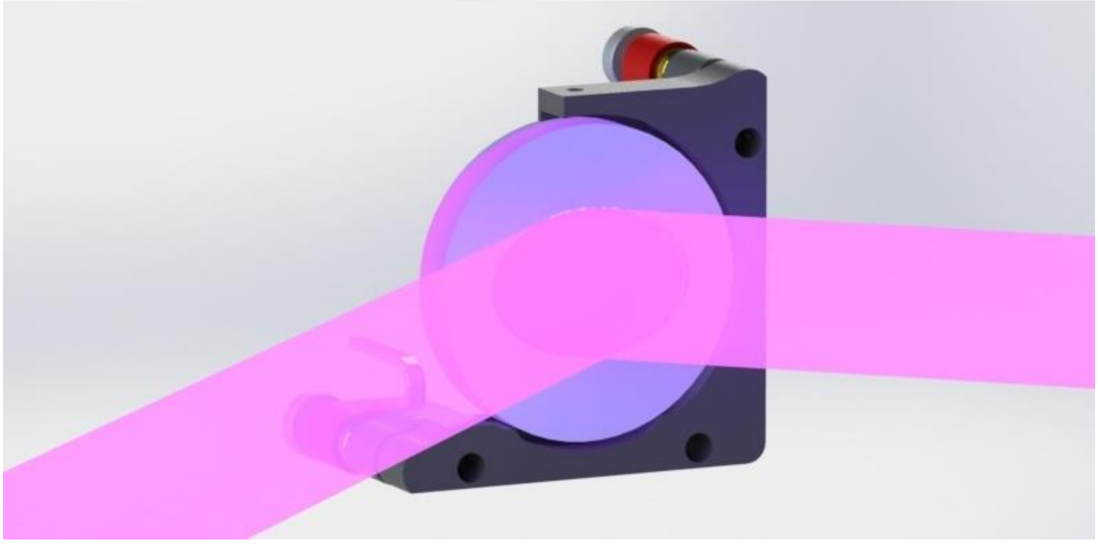


**Fig. 3.5:** Motorized HR Mirror

### 3.1.5 Photo Diode

The user can monitor laser power using a photo diode installed inside the emitter. The photo diode is located close to the motorized HR mirror and receives residual light from the transmission of the mirror. The photo diode is factory calibrated to match its return signal to the laser's power.

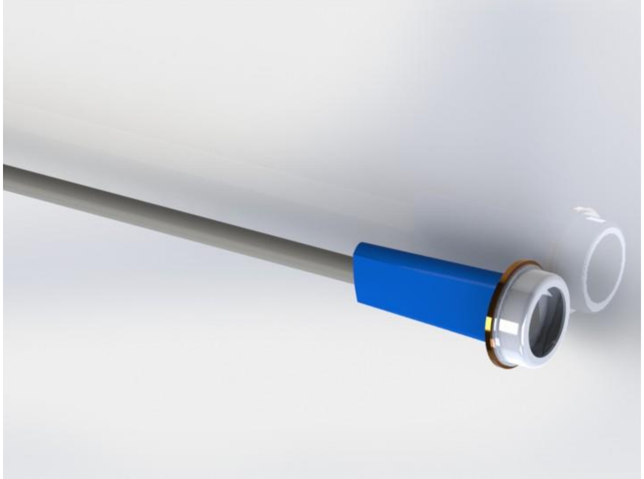


**Fig. 3.6:** Photo diode

## 3.2 Receiving System

The receiving system consists of two sub-units: a receiving telescope and a Wavelength Separation Unit (WSU) (Fig. 3.6).

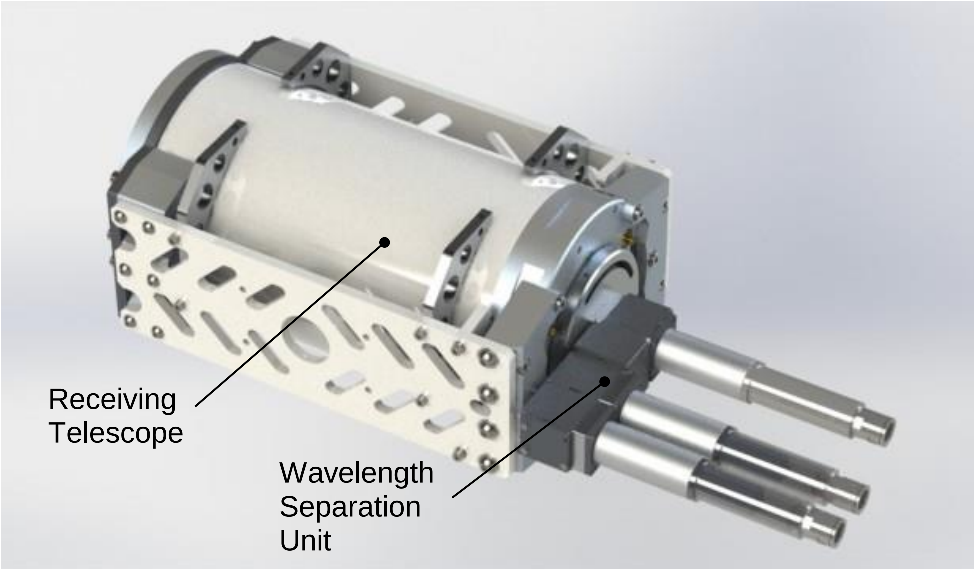



**Fig. 3.7:** Receiver Components

### 3.2.1 Telescope

The backscattered light is relatively weak. It is therefore essential to collect as much light as possible with the telescope. In this Lidar, a powerful 200mm diameter Cassegrain telescope is used. The primary reflective mirror has a diameter of 200mm and is coated with a durable High Reflectivity coating designed for the 350-1100 nm spectral region. The optical material selected displays a very low thermal expansion coefficient, like that of Zerodur® optical properties. The secondary reflective mirror has a diameter of 48mm and is coated similarly to the primary mirror.

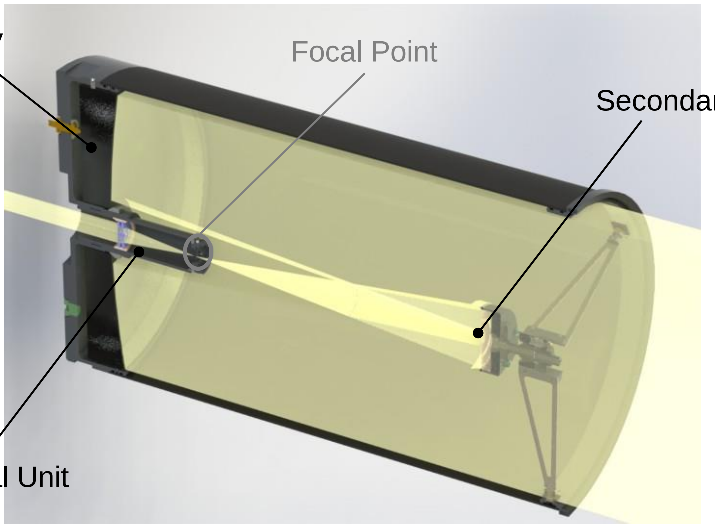
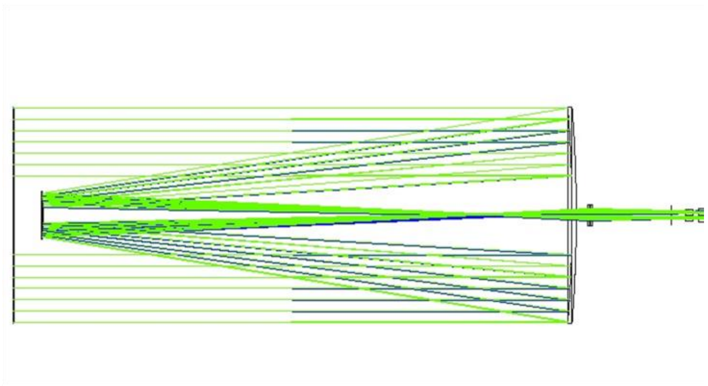



**Fig. 3. 8** Telescope Main Components

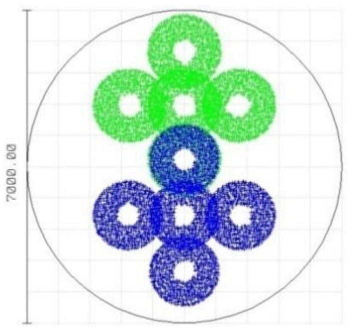
The received Lidar beams are collected and focused on an Optical Unit (OU) placed at the telescope's focal point. At the exit of the OU the Lidar beams are then collimated using an achromat technique.

Each telescope designed and built by Raymetrics has been designed using advanced raytracing techniques in Zemax software. As with all optical instruments, each distance is critical. Even a fractional error can alter the focus of the telescope, resulting in drastically inferior performance.



- Telescope
  - Type: Cassegrain
  - F4
  - Focal Length: 800mm
- **Primary**
  - Diam.: 200mm
- **Secondary:**
  - Diam.: 48mm

**Fig. 3.9:** Telescope Characteristics



- Green : Far Field (25 Km),
- Blue : Near Field (0.5 Km)

**Fig. 3.10:** Typical Light simulation from far and near field at the field stop

### 3.2.2 Wavelength Separation Unit

At the entrance of the Wavelength Separation Unit (WSU), the received light is collimated into one parallel beam. A series of factory preset custom-made dichroic reflective mirrors and one polarizing beam splitting cube perform the wavelength separation at the required wavelength and polarizations [355P, 355S].

At each wavelength exit specially designed interference filters (IFF) are used to select the required wavelengths and to reject the atmospheric background radiation.

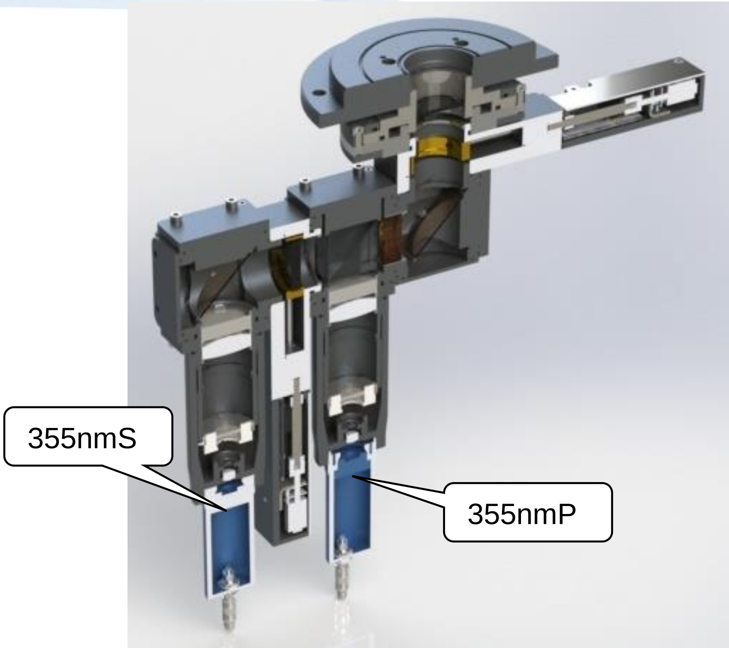



**Fig. 3.11:** WSU

### 3.2.3 Depolarization Technique

The laser emits a narrow, fully polarized beam of light in which light waves oscillate in the same plane. The receiver measures the polarization of light scattered in the backward direction. For a cloud of spherical water droplets, the backscattered light is fully polarized in the same direction as the emitted beam; i.e. it has only a 'co-polarized' or parallel component. However, for a cloud composed of non-spherical ice crystals, the backscattered light can be partially depolarized; i.e., it can have a 'cross-polarized' component which oscillates perpendicularly to the emitted polarization.

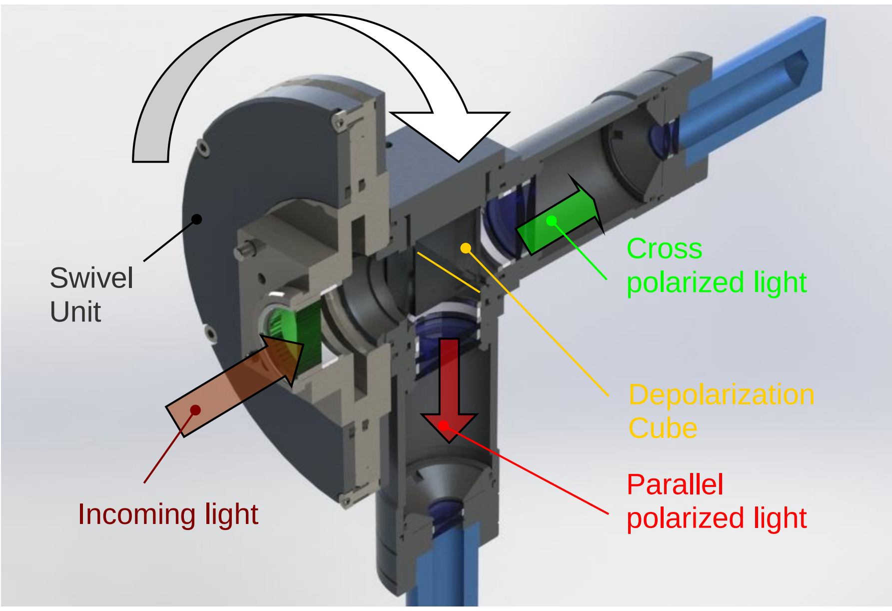



**Fig. 3.12:** Depolarization Module

This system can measure simultaneously both the parallel (denoted as ‘P’ for Primary) and the cross-polarized (denoted as ‘S’ for Secondary) component of the backscatter wavelength which is at 355nm. This is achieved by separating the parallel and the cross-polarized components, with a polarizing beam splitting cube. Each component is then measured using a PMT. From the combination of these two signals the user can extract the depolarization ratio. The depolarization ratio can therefore reveal the presence of non-spherical particles. To reduce the contamination of the different polarized light, additional linear polarizers are placed between the two collimating lenses of each eyepiece. These are calibrated during the WSU assembly to reject any unwanted polarization. Therefore, the eyepiece must be mounted correctly relatively to the polarizer; if for example the eyepiece is turned 90 degrees the resulting signal will be very weak because the useful polarized light is rejected.

To calculate the depolarization ratio, the user must calculate the depolarization calibration constant. This constant depends on various parameters of the system itself and is calculated analytically. This is done by comparing measurements taken with the depolarization module turned at ±45° degrees from the normal position. When the depolarization module is turned the parallel signal is decreased and the cross-polar signal is increased. It is important during the ±45° Test to keep all parameters regarding the electronics the same. Using the same high voltage for the cross polarized PMT will increase the range and insert an error to the calibration constant. To avoid this, an extra neutral density filter is inserted in front of the cross polarized eyepiece. The design makes this procedure precise and as easy as possible. The procedure can be outlined in three steps.

1. Pull the plungers illustrated below.
2. Turn the depolarization module slightly, release the pins and turn at 45 degrees until a clicking sound is heard from the pin.
3. Now the measurement can be started.

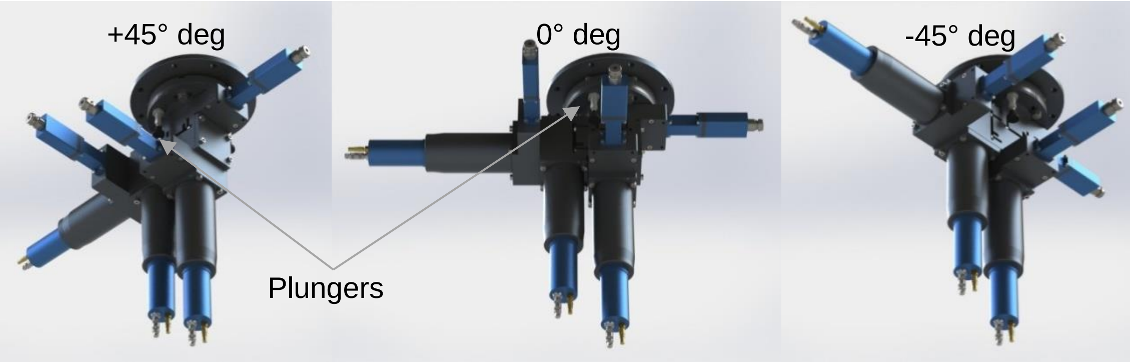



**Fig. 3.13:** WSU ±45° polarization calibration procedure

### 3.2.4 Light Detectors

Light is detected by the photomultiplier tubes (PMT) and converted into a signal that is passed to the detection electronics. The electronics are synchronized with the laser control and the signal is recorded in relation to the time. The electronics communicate via Ethernet with the PC where the data is saved. The detection electronics are discussed in section 3.3.2. The detectors along with the electronics are called Signal Acquisition Unit (SAU).

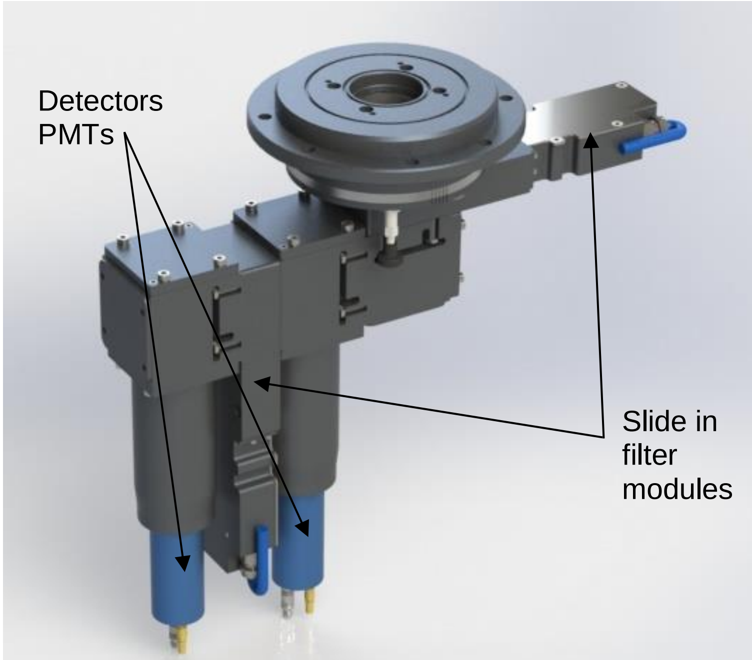



**Fig. 3.14:** WSU and PhotoMultiplier Tubes (PMT).

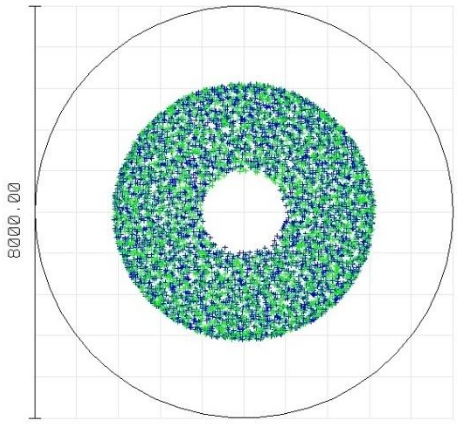



**Fig. 3.15:** Image of the Cathode for 355 nm

The spectrally resolved Lidar signals inside the WSU are detected by photomultiplier tubes (PMTs) directly mounted at the respective exits of the WSU. The PMTs used are selected to be compact and to provide optimum operation in the spectral range 355-532 nm.

The PMTs work in the pulse mode regime and are characterized by a short rise time constant.

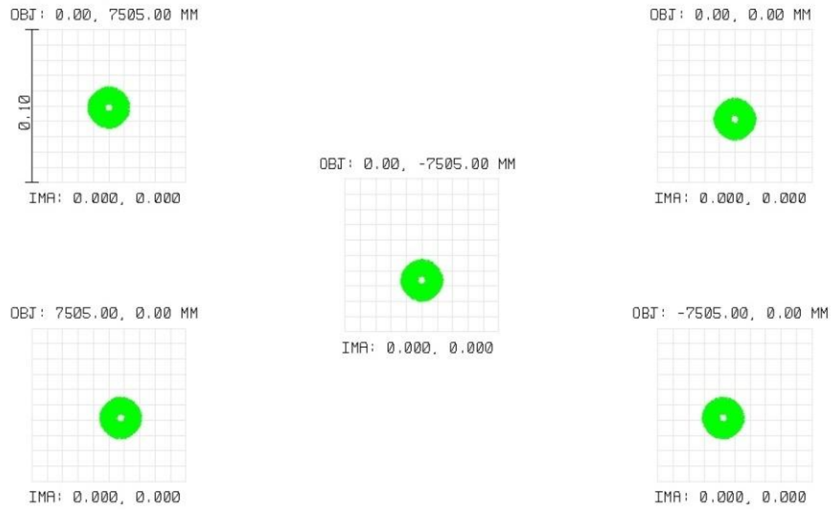



**Fig. 3. 16:** Max Angle for IFF 355: typ 1.54 degrees

The PMTs have been tested prior to shipment. Their optimum working voltage (for linear operation) is between 800-950V, depending on the amplitude of the received signal and the atmospheric conditions (background skylight conditions during daytime or nighttime conditions and/or cloud presence). During daytime conditions, the PMT working voltage should be slightly lower than during nighttime operation.

**Technical Specs**

| | | |
|---|---|---|
| Part Number | R9880U-11x |  |
| PM Type | Hamamatsu | |
| PM High Voltage (V) | 0-1000 | |
| Supply Voltages (V) | +15 | |
| Current Limit (mA) | 200 | |
| Resistance Anode-GND (Mohm) | 1.0 | |
| Output Connector | BNC (50 Ohm) | |

Detailed technical specifications for the PMTs are included in Licel's printed manual.

***Attention!***

- For optimum operation the temperature and humidity conditions should remain unchanged during field operation.

- Operation at HV higher than maximum of the range, may lead to PMT saturation, thus to a *nonlinear* operation and/or possibly to PMT permanent failure.
- Environmental conditions of the PMTs have been provided below (noting that they are included in a climate controlled enclosure).

**Humidity:** Operation in a very damp atmosphere may lead to insulation problems, because of the high voltages (HV) used. Condensation gives rise to leakage currents which in turn increase the PMTs dark current. Therefore, the PMTs should be operated only under the environmental conditions given in Licel's user manual.

**Light conditions:** The PMTs are highly sensitive to ambient light conditions. They must never be exposed to ambient light, even when no HV is applied. If high voltage is applied to the PMTs which are exposed to ambient light, the PMTs will be permanently destroyed.

**Mechanical stress:** Like all electronic devices, PMTs should be protected against mechanical and thermal stress. Vibration or shock applied to the PMT dynodes can modulate the PMTs gain.

**Magnetic fields:** Never expose the PMTs to magnetic fields. Even magnetic fields as weak as the Earth's may affect the PMT performance. Strong fields may permanently magnetize some parts, thus damaging the PMT.

### 3.2.5 Slide-in Filters

For some measurements, the user is required to cover the telescope or add an extra filter. To simplify the process, slide-in filter modules have been supplied within the WSU by using the same modular design. As seen below in Fig. 3.17 there are an actuator and a filter case that slides in and out the light path. Instead a thick rubber gasket can be used to block the light.

**Fig. 3.17:** Slide in filter module

These are typically used for three purposes:

a. As a shutter to block all incoming light for a dark current measurement.

b. As a shutter to block the light at the Raman channels during daytime to increase its lifetime (N/A).

c. As a Neutral Density (ND) filter for the cross-polarization channel during the depolarization calibration procedure.

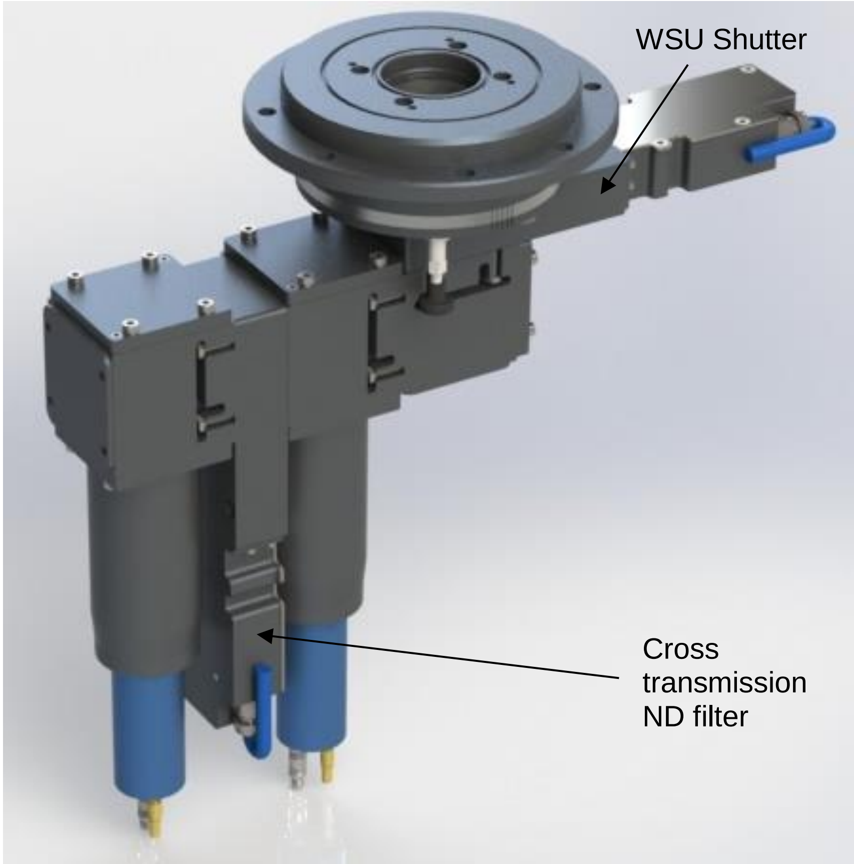



**Fig. 3. 18:** Slide in filter modules

The modules are operated by a dedicated controller called the LMC. More information in paragraph *'3.3.5 Lidar Measurement controller'*.

## 3.3 Control Unit

The control unit consists of four main components; the laser control and power supply (ICE450 standard version), the Transient Recorders and PMT power supply, the PC and the electrical cabinet.

### 3.3.1 Laser Control and Power Supply

This device controls all the functions of the laser and supplies the Laserhead with power and deionized water as a coolant.

**Fig. 3.19:** Laser power supply and controller

#### *3.3.1.1 Control*

The user can operate the laser and check its status through the laser Control Box. The main operation performed this way is the flashlamp/Q-switch start and stop and the Q-switch delay (that reduces the laser beam energy). The user can also obtain various information about the status of the Laserhead, such as the counted number of shots, the temperature, the flow of the pump etc. All interlocks appear on the control with a short explanation.

The device has two interfaces; one remote control box and a RS232 that is connected to the PC. This means that the laser can be controlled either from the Lidar itself via the PC or through the Control Box.


**Fig. 3.20:** Control Box

**NOTE:** By default, the laser is set to be controlled by the PC. However, if a button on the Control Box is pressed, the communication is automatically set to the control box. To set back to the PC, the user must manually configure the laser from the Control Box. This can be done by navigating using the ▽ △ buttons to select 'System Info' and confirm with the ENTER button. Serial link can be selected and changed from 'off' to 'on' with the ▷ button.

#### 3.3.1.2 Power and Water Supply

The laser requires a water supply since the head is water cooled. This is achieved via an individual sub-unit inside the ICE450 called the Coolant Group Unit (CGU). The CGU cools the flashlamp(s) and the laser rod with a closed loop of de-ionized coolant. This temperature regulated coolant also provides thermal stabilization of the oscillator's structure.

A thermostatic electronic circuit, which regulates the fan's speed and airflow rate through the exchanger, provides thermal stabilization of the coolant. The temperature stabilization is within ± 1 °C. The ambient air temperature within the enclosure can range from 15 °C to 28 °C with no effect on laser operation.

The CGU includes a de-ionizing system that, with proper maintenance, can maintain the conductivity of the coolant at less than 1.0 μS · cm-1 (resistivity ≥ 1.0 MΩ · cm). The CGU has coolant level, flow, and heat-sensing switches to interlock with the Power Supply Unit to prevent damage to the Laserhead in the event of a cooling system failure.

The CGU requires approximately 1.5 liters (0.4 US gal.) of coolant for standard systems incorporating three-meter coolant lines. **Use only distilled water with 1MΩ-cm to 5MΩ-cm resistivity.** The water is transferred to the Laserhead though two hoses. In one of the hoses a deionizing cartridge is interfered that deionizes the water.  Even though the CGU has a powerful pump, if the umbilical cord is bend too much, an interlock will occur and the laser will stop. For further information refer to the laser manual.

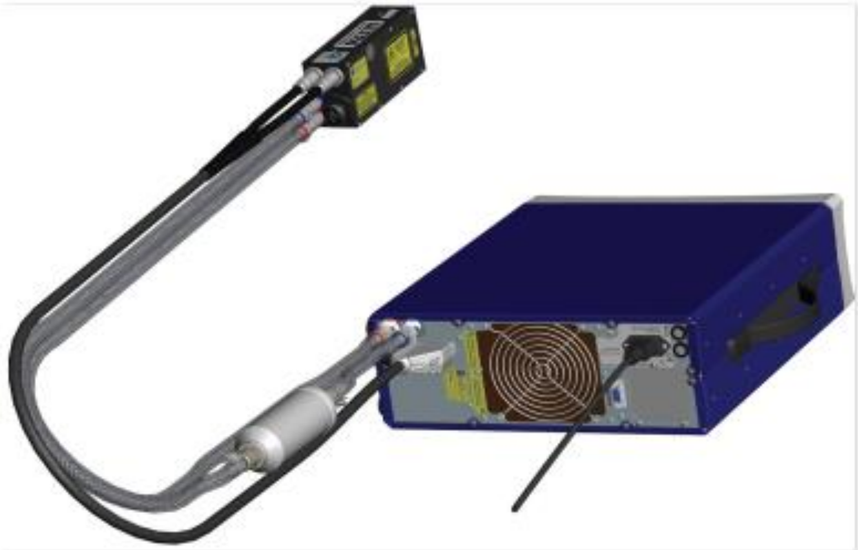
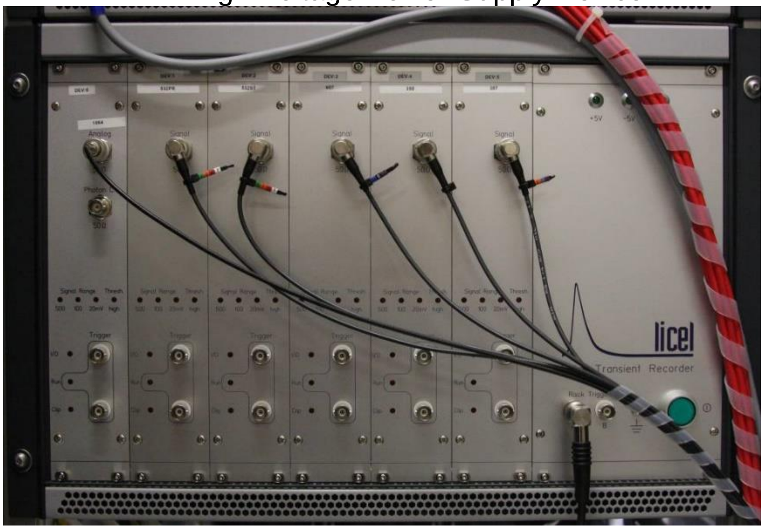


**Fig. 3.21:** Laser System with coolant hoses, power and signals cables.

### 3.3.2 Detection Electronics

The detection electronics receive an analogue signal from the PMTs and transform it into a Lidar signal. This device is designed to work in two modes: analog detection mode and photon counting detection mode.

PMT High Voltage Power Supply Device




Transient Recorder Device

**Fig. 3.22:** TR and HV devices of the PMTs.

#### *3.3.2.1 Concept*

The Licel Transient Recorder is a powerful Data Acquisition System, especially designed for remote sensing applications. To meet the demanding requirements of optical signal detection, a new concept was developed to reach the best dynamic range together with high temporal resolution at fast signal repetition rates.

Analogue detection of the photomultiplier current and single photon counting are combined in one acquisition system. The combination of a powerful A/D converter (12 Bit at 20 or 40 MHz) with a 250 MHz fast photon counting system increases the dynamic range of the acquired signal substantially compared to conventional systems. Signal averaging is performed by specially designed ASIC's which outperform any CISC- or RISC-processor based solution. A highspeed data interface to the host computer allows readout of the acquired signal even between two laser shots. Fig. 3.23 shows the connectivity of the

Transient Recorder. The implementation of this concept makes the Licel Transient Recorder a state of the art solution for all applications where fast and accurate detection of photomultiplier, photodiode or other electrical signals is required at high repetition rates.

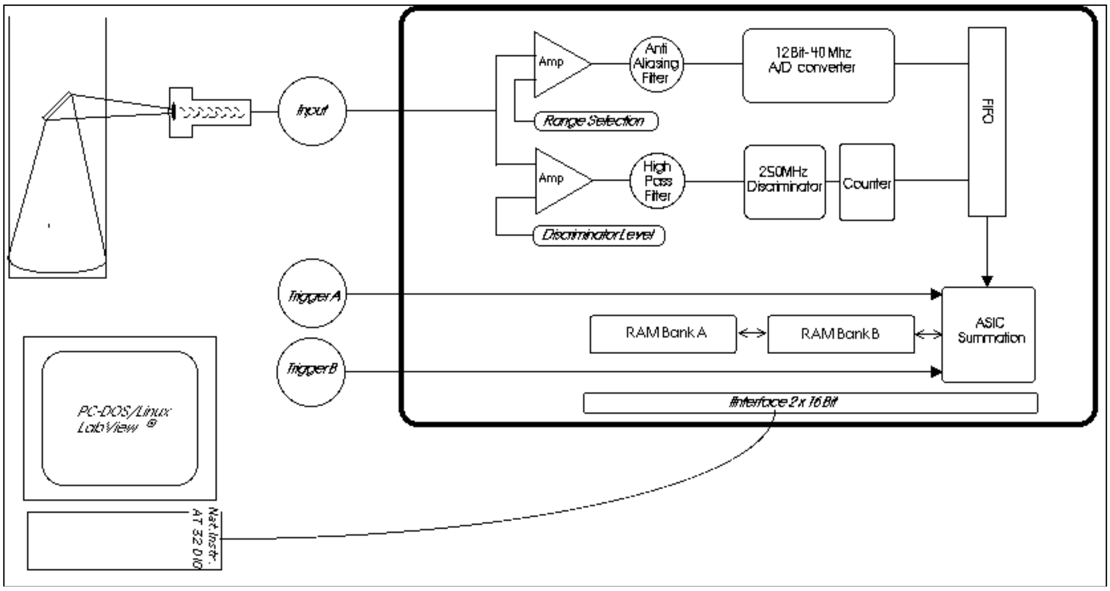



**Fig. 3.23:** Electronics concept

### 3.3.2.2 Principle of Operation

The Licel Transient Recorder is comprised of a fast-transient digitizer with on board signal averaging, a discriminator for single photon detection and a multichannel scaler combined with preamplifiers for both systems. For analogue detection, the signal is amplified according to the input range selected and digitized by a 12-Bit-20/40 MHz A/D converter. A hardware adder is used to write the summed signal into a 24-Bit wide RAM. Depending on whether trigger A or B is used, the signal is added to RAM A or B, which allows acquisitions of two repetitive channels if these signals can be measured sequentially.

At the same time, part of the signal which resides in the high frequency domain is amplified and a 250 MHz fast discriminator detects single photon events above the selected threshold voltage. 64 different discriminator levels and two different settings of the preamplifier can be selected by using the acquisition software supplied. The photon counting signal is written to a 16-Bit wide summation RAM which allows averaging of up to 4094 acquisition cycles.

### 3.3.2.3 Analogue Detection

The analogue detection mode is used to detect intense Lidar signals coming from relatively short distances (typically less than 8-10 km). A Transient Recorder operating in the analogue detection mode is based on an analogue-to-digital converter (ADC), which samples and digitizes the Lidar signals with a sampling rate of 20-40 MHz (depending on the type of the Transient Recorder used) with a 12-bit resolution. A memory length up to 8192 or 16000 time-bins (Tr-xx-80 or Tr-xx-160) depending on the Transient Recorder type) can be selected. Each time bin corresponds to a spatial resolution of 3.75 or 7.5 m (depending on the sampling rate of the Transient Recorder used, Tr-20-yy or Tr-40-yy). For instance, the 20 MHz sampling rate corresponds to a 7.5 m spatial resolution.

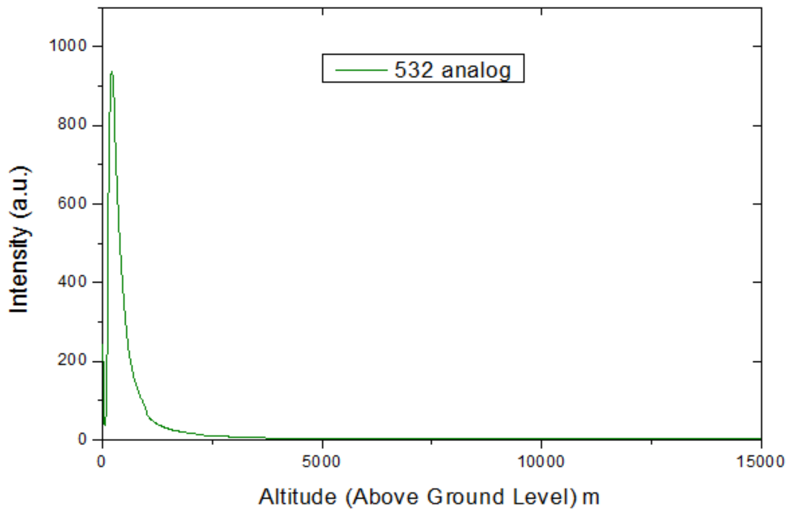



**Fig. 3.24:** Typical Lidar signal acquired in the analogue mode.

#### *3.3.2.4 Photon Counting Detection*

The photon counting detection mode is used to detect very low intensity Lidar signals coming from relatively large distances (typically higher than 8-10 km). Thus, the PMT is operated under single electron conditions. Flux levels as low as a few tens of photons per second can be measured. In the photon counting mode the level of the incident flux is such that the cathode transmits only single electrons. The individual anode charges due to single photons are integrated to produce proportional voltage pulses, which are passed by a discriminator to a pulse counter, whose output over a pre-set period is a measure of the incident flux.

Because of statistical fluctuations in the electron multiplication, the amplitude of the single-electron pulses is distributed according to the Poisson statistics. To obtain a satisfactory signal-to-noise ratio (SNR) of the Lidar signal in the photon counting mode, a sufficiently large number of laser shots should be obtained (normally more than 1000). If the received Lidar signal is higher than 60-100 MHz the PMT output signal should be corrected to consider the dead-time effect. If the dead-time of the counter ($\tau_d$) is comparable to the mean interval separating two successive pulses, the counting error may be appreciable. If a dead-time correction should be applied, then if the $N_{obs}$ is the observed count rate, then the true count rate ($N_{true}$) corrected for the dead-time effect is given by:

$$N_{true} = \frac{N_{obs}}{1 - N_{obs} \times \tau_d} \quad (2)$$

**NOTE**: The value of $\tau_d$ depends on the type of the PMT module used (i.e. $\tau_d = 4$ ns).

Specific environmental effects may increase or decrease the count rate. For instance, background radioactivity increases it.

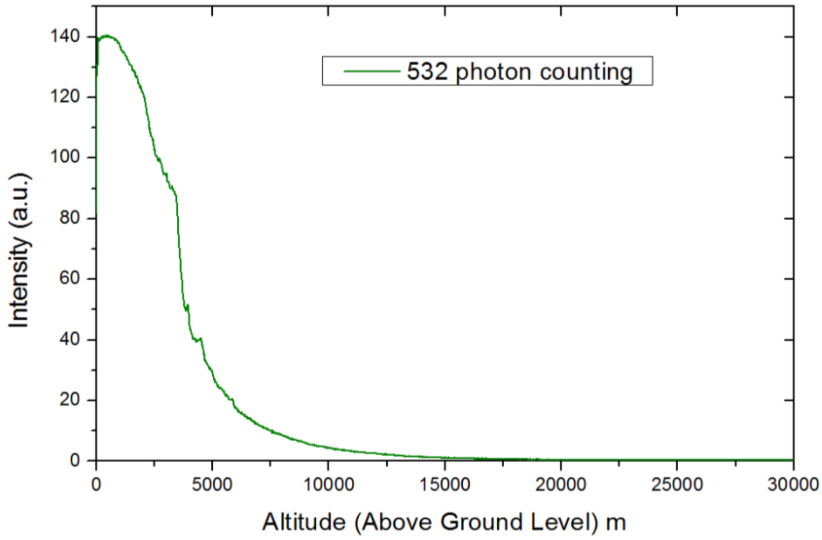



**Fig. 3.25:** Typical Lidar signal acquired in the photon counting mode.

### 3.3.2.5 Signal Processing

The Lidar data processing is fulfilled in two steps: (i) Lidar data pre-processing and (ii) Lidar inversion algorithm, which are explained hereafter.

*Step I- Lidar Data Pre-processing*

The Lidar data pre-processing is performed on the raw Lidar signals. Each Lidar data file (containing the average of a certain number of backscattered Lidar signals S(z) coming from a range z) is corrected for the background noise contribution (BG) due to atmospheric skylight and electronic noise of the instrumentation used. A distance square-law correction ($z^2$) is applied to each data point (time bin) to compensate for range-related attenuation from the atmosphere. Then, the natural logarithm of the resulting quantity is calculated. On the resulting *log range-corrected* signal SLOG where $\mathrm{SLOG} = \ln\left[(\mathrm{S}(z) - \mathrm{BG})z^2\right]$, a running low-pass derivative digital filter, with variable path is applied. The smoothing method is a running least-square fit of the dataset to the second-order polynomial, which represents a good fit for the vertically decreasing atmospheric scale height (Ancellet al., 1989)[1]. The spatial resolution of the measurement is related to the number 2n+1 of data points fitted to the second-order polynomial.

*Step II- Lidar Inversion Algorithm*

To retrieve the vertical profile of the aerosol backscatter coefficient ($b_{aer}$) at 532 nm the improved Klett inversion technique is used. This technique is based on a far-end backward iterative technique, considering also the atmospheric molecular contribution as described by Klett (1985)[3]. The uncertainties associated with this technique have been discussed in detail by Chazette et al.(1995)[5] and by Boesenberg et al. (1997)[6], while the limitations of this technique arise from an ill-posed mathematical problem (one set of signals measured with two sets of parameters to be retrieved: the aerosol extinction and backscatter coefficients) in conjunction with the a priori assumptions made for the Lidar inversion, such as the selection of the 'reference height' (a height where the atmosphere is considered to be purely molecular), and of the so called aerosol '*Lidar ratio' LR where* $LR(sr) = \frac{a_{aer}(km^{-1})}{\beta_{aer}(km^{-1}sr^{-1})}$ .

At 355 nm, the inelastically backscattered Lidar signals can be inverted using the Raman inversion technique, as presented by Ansmann et al. (1992)[4]. This technique is applicable mostly under low light conditions (during late evening to early morning) since the Raman Lidar signal is sensitive to the presence of daytime background skylight.

### 3.3.3 Lidar Peripheral Controller & Industrial Computer – LPC[2]

Raymetrics offers highly customizable solutions on all its LIDAR products. Depending on the customer's requirements, a LIDAR system can contain the bare minimum components required to carry out the necessary measurements or it can be equipped with a full set of automation components. These peripheral components are controlled and managed by a LIDAR Peripheral Controller (LPC).

Furthermore, an custom-made industrial computer is used as a Controlling Unit, which features industrial grade robust mechanical design and reliability. All LIDAR subcomponents (LASER, DAQ, LMC, and LPC) can be controlled from this Unit. The computer also acts as a storage unit and as a communication interface.

These two units share the same case to form the brain of the LIDAR. A touch screen is used as an interface to give the user information from the sensors (such as temperature and relative humidity) and to control some of the peripherals. The LEDs indicate the status of the unit and two USB3 ports are located on the front where the user can connect a hard disc or any USB device.


**Fig. 3.26:** LPC$^2$

### 3.3.3.1 Computer Specifications

The Commell LS-576 industrial motherboards are state-of-the-art Human Machine Interfaces with 3rd Generation Intel® Core™ i3 and i5 CPU options and 4GB of RAM will make sure that the computing needs are over fulfilled. Several serial ports ensure that there is always a free port to connect any additional hardware, but the key feature is the 6 separate LAN interfaces that can communicate with another device or connect on a network without going through an external Ethernet switch.

| | |
|---|---|
| **Motherboard** | Commell LS-576 |
| **Chipset** | Intel QM77 Express chipset |
| **CPU** | 3rd Generation Intel® Core™ i3 2.4GHz / i5 2.7GHz |
| **Memory** | DDRIII SO-DIMM 1066 MHz 4GB |
| **Hard Disk** | 500GB |
| **Integrated Graphics** | Intel® HD Graphics 4000/2500 Technology |
| **External Ports** | 4 x RS232, 6 x LAN, 1 x VGA, 4 x USB3.0, 3 x USB2.0 |
| **Internal Ports** | 1 x PS/2, 1 x RS232, 1 x Parallel, 1 x Parallel, 1 x SMBUS, 1 x GPIO, 1 x IrDA, 1 x DVI, 1 x LVDS, 4 x Serial ATAII, 2 x Serial ATAIII, 1 x Front Panel Audio and 1 x CDIN |
| **LAN Interface** | 1 x Intel 82579LM Gigabit LAN (Support iAMT8.0)<br>5 x Intel 82574L Gigabit LAN |
| **Audio Interface** | Realtek ALC888 HD Audio |

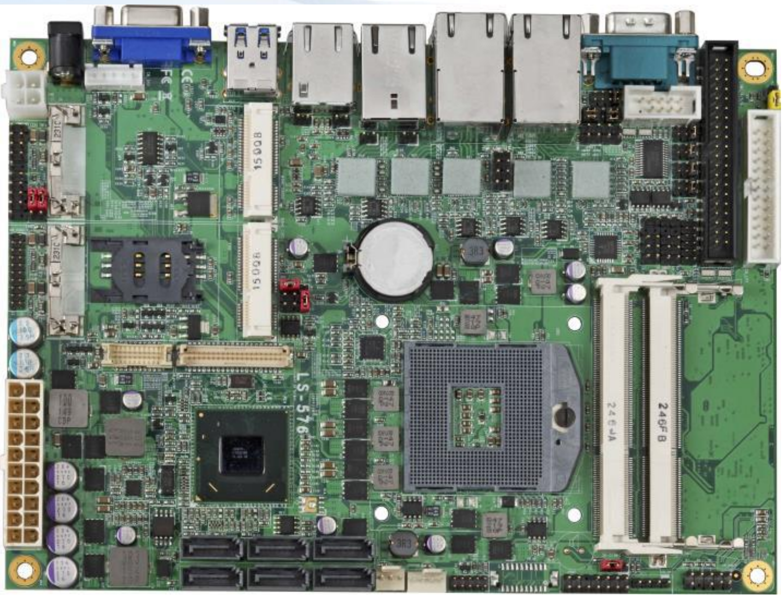


**Fig. 3.27:** Commell Industrial Motherboard

### 3.3.3.2 LIDAR Peripheral Controller LPC

Depending on the LIDAR type and the customer's needs the LPC is capable to control any automation that a LIDAR needs. All the peripheral sensors and interface components which plug onto the LPC can be classified into categories based on the type of the LIDAR (scanning or vertical) and the environmental conditions. The contents of the categories are listed below:

| | Scanning | Vertical | |
|---|---|---|---|
| **Features** | **Outdoor** | **Indoor** | **Outdoor** |
| External Laser Interlock Emergency Stop Button [(1)] | ● | ● | ● |
| 2 x External Laser Interlock Auxiliary Connectors [(2)] | ● | ● | ● |
| Power Fail Management [(3)] | ● | ● | ● |
| LCD Touch Panel | ● | ● | ● |
| Automated Hatch for window protection | | | ● |
| Hatch Proximity Sensor for Laser Interlock | | | ● |
| Rain Sensor | ● | | ● |
| Humidity/Temperature Sensors [(4)] | x2 | x1 | x2 |
| Pressure/Temperature Sensors | | | x1 |
| Sun Detection Sensor | | | ○ |
| Anti-Dew Window Blower | | | ○ |
| PID Ventilation Blower | | ● | |
| Dehumidifier | ● | ○ | ○ |

● Standard features ○ Optional features

Remarks:

1) Emergency button box is supplied and connected to a chassis IP68 connector.
2) Used for doors, IR traps and radar. One IP68 connector supplied.
3) Works in combination with a UPS and the PDU.
4) Up to 4 Humidity/Temperature Sensors upon request.

**NOTE:** that the actual laser interlock is not controlled by the LPC. Each Interlock is isolated through a double throw relay and are all connected in series to a final relay that is hardwired to the Laser Control Unit, which is responsible for turning off the laser in case of any interlock. The second contact of the relays is used as an input signal for the LPC.

At the heart of the LPC an Atmel ATmega2560 processes the signals and acts accordingly. The LPC works in combination with the Power Distribution Unit (PDU) whose main function is to detect a power failure event and to control the 12VDC, 24VDC and 230VAC lines. For example, the LPC reads the humidity inside the LIDAR and if it exceeds 40% it will send a command to the PDU to turn on the dehumidifier. At the diagram below is shown how the LPC communicates with other hardware.

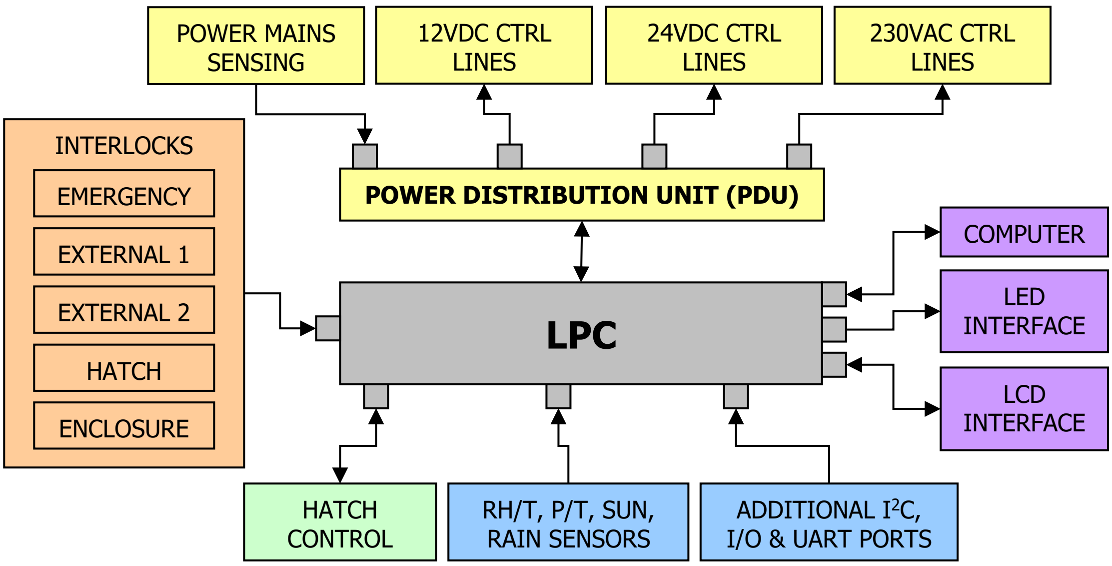



**Fig. 3.28:** LPC Control Diagram

One of the main functions of the LPC is the power fail management. In case of a power failure the PDU will inform the LPC, the LPC will close the hatch or park the positioner and send a signal to the computer. The computer will stop any measurement that is underway, wait for the laser to cool down and shutdown itself. Then the LPC commands the PDU to turn off all lines to preserve the UPS batteries. Once the power is back the PDU turns on all lines and the computer starts automatically resuming the measurement or schedule.

Another function is to close the hatch in case it rains to protect the windows or if the sun is above the telescope to prevent any damage to the PMTs. Once the event passes the hatch will open unless it is commanded to remain closed. It also controls a ventilation blower via PID to regulate the enclosure's temperature and, using a unique detection algorithm, forecasts dew formation on the instrument's windows and turns on the anti-dew blowers (N/A on a scanning lidar). Finally, the combination of the PDU, the LPC and the additional ports makes a very flexible system that can accommodate a tailor-made automation solution.

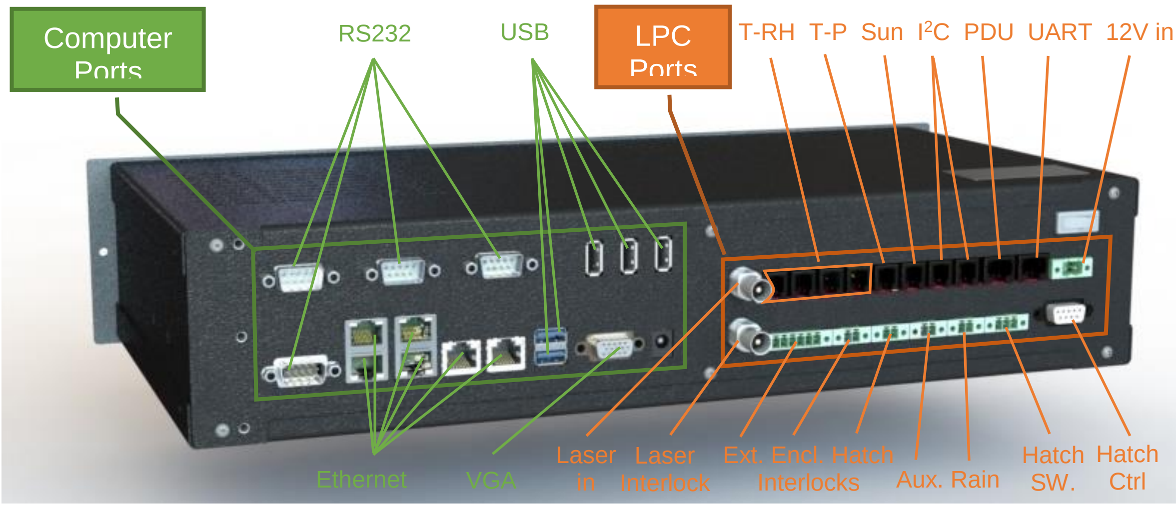



**Fig. 3.29:** LPC$^2$ Back Connections

**<u>Connectors LPC</u>**

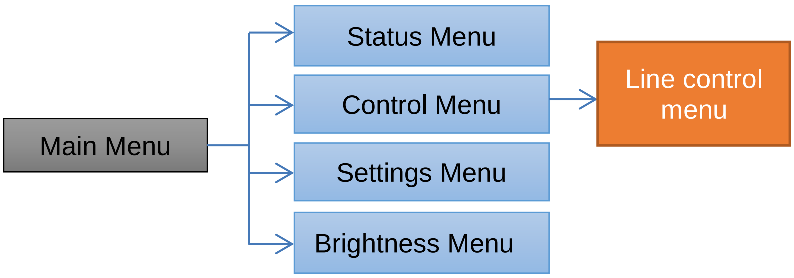
| # | Connector Label | Type | Pins | Description |
|---|---|---|---|---|
| 1 | Laser in | BNC | 1 | Input that the laser when it is on |
| 2 | T- RH Sensor #1-4 | RJ-11 | 4 | I$^2$C temperature and relative humidity sensor |
| 3 | T- P Sensor | RJ-11 | 4 | I$^2$C temperature and pressure sensor |
| 4 | Sun Sensor | RJ-11 | 4 | I$^2$C Photodiode for sun sensing |
| 5 | Auxiliary I$^2$C #1-2 | RJ-11 | 4 | Any I$^2$C device can be connected |
| 6 | PDU | RJ-45 | 8 | Communication UART port for the PDU |
| 7 | UART | RJ-45 | 8 | Auxiliary UART port |
| 8 | 12V in | Phoenix | 2 | Power input for LPC and computer. |
| 9 | Laser interlock | BNC | 1 | Interlock output to stop the laser |
| 10 | External Interlock | Phoenix | 6 | Interlocks connected to the external panel |
| 9 | Enclosure Interlock | Phoenix | 2 | Interlock when the Lidar's door is open |
| 10 | Hatch Interlock | Phoenix | 2 | Interlock when the hatch is closed |
| 11 | Auxiliary I/O | Phoenix | 2 | Can be a relay from a device |
| 12 | Rain Detector | Phoenix | 2 | Input signal when raining |
| 13 | Hatch Control | DSUB-9 | 9 | I/O for controlling the hatch |
| 14 | Hatch Switch | Phoenix | 3 | N/A |

**LEDs on LPC (Front Panel)**

| # | Indicator Label | Color | Description |
|---|---|---|---|
| L1 | LPC Status | Blue | Blinks when the controller is working normally |
| L2 | LASER On | Yellow | On when the laser is emitting |
| L3 | Rain Detected | Yellow | On when it is raining |
| L4 | Sun Detected | Yellow | On when the sun is in the FOV of the telescope |
| L5 | Power Fail Detected | Yellow | On when there is no power |
| L6 | Hatch Manual Mode | Yellow | On when the hatch is manually operated |
| L7 | Auxiliary Input | Yellow | On when the pin is high |
| R1 | LPC Power | Green | The controller board has power. |
| R2 | Hard disk | Orange | On when the hard disk is accessed |
| R3 | Hatch INTLK | Red | On when the hatch is closed. Interlock active |
| R4 | Door INTLK | Red | On when the enclosure is open. Interlock active |
| R5 | Emergency INTLK | Red | On when the emergency is pressed. Interlock active |
| R6 | External INTLK 1 | Red | External interlock activated |
| R7 | External INTLK 2 | Red | External interlock activated |

### 3.3.3.3 LPC Touch Screen

The LPC is equipped with a touch screen that acts as a quick interface with the LIDAR. This interface permits the control of some of the instrument's hardware by turning power lines on or off and displays information about the lidar's current status. The menu navigation is presented below.

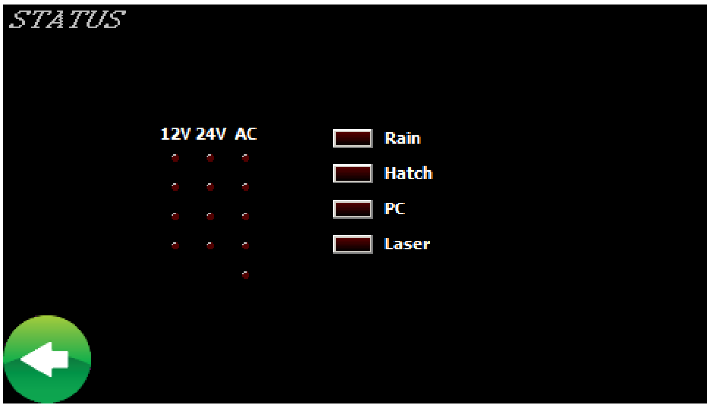



The main menu provides live information about the temperatures and relative humidity from the sensors and will display a message in case of power failure or rain.

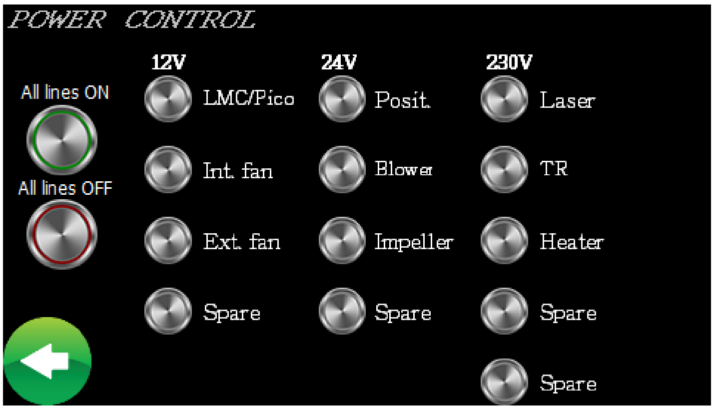
By default, the system has two sensors connected.

| *Sensor* | *Location* |
|---|---|
| **Sensor 1** | Lidarhead enclosure |
| **Sensor 2** | N/A |
| **Sensor 3** | Lidar Cabin |
| **Sensor 4** | N/A |

Under the status menu the user can see information such as which lines are on for the 12VDC, 24VDC and 230VAC and whether the rain sensor, hatch, PC and laser are on.



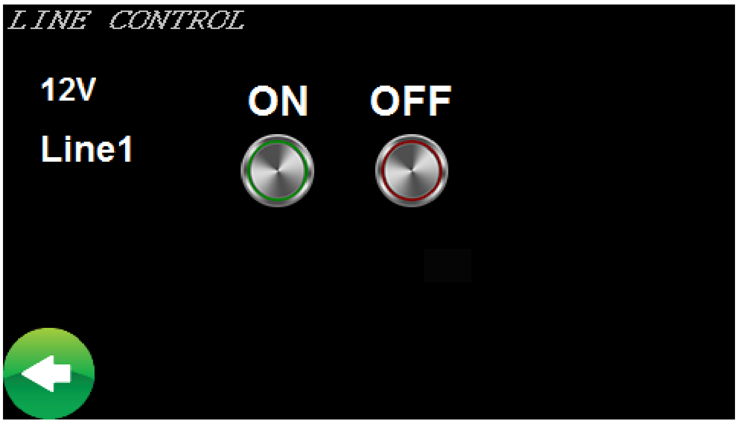

Under the control menu at the power control screen the user can turn on and off any line. These are normally controlled automatically but the option can be used for testing purposes. The 'All lines ON' turns all line ON and the OFF button the opposite.




Depending on the systems features each line powers a device. A general description is shown below. Some of these features may not apply in your system.

| *Input* | *Function 12 VDC* | *Function 24 VDC* | *Function 230 VAC* |
|---|---|---|---|
| **Line 1** | LMC, Picomotor | Positioner/Hatch | Laser |
| **Line 2** | Internal fan (if applicable) | Thermo-electric Dehumidifier | TR1, TR2 |
| **Line 3** | External fan (if applicable) | Impeller (if applicable) | Heater (if applicable) |
| **Line 4** | Spare | Spare | Spare |
| **Line 5** | - | - | Spare |

By pressing the button corresponding to each line, a sub menu appears where the user can turn ON-OFF the specific line or set a PWM value if the line supports the PWM feature.




Finally, on the settings menu the user can select if the screen will turn off after 30 seconds, return to the main menu after 10 idle seconds or adjust the brightness.

### 3.3.4 Power Distribution Unit (PDU)

As mentioned above the LPC works in combination with the PDU to allow for flexibility in automating the system. It provides remote hard reset for all components and can generate PWM pulses for most of its DC outputs. While the front of the device looks like a typical power distribution panel, inside an Atmel ATmega32u4 processes commands sent by the LPC and monitors the controlled lines. Each AC line has its own circuit breaker that provides safety to the devices and the grid and a 30mA residual current circuit breaker protects the user in case of a voltage leak. As an optional feature, a series of lightning surge protection devices ensures that the electronic parts will remain unharmed during a thunderstorm.

**Note:** a surge protection does not replace the grounding antennas and rods.


**Fig. 3.30:** PDU-544

On the back side of the PDU the user has access to each device power connection. The whole unit can be easily disconnected from the lidar for servicing purposes. All the DC lines are equipped with a cartridge fuse next to the connector. Two of the AC sockets are not supported from the UPS and these are used for the HVAC. Finally, the USB port is mainly used for programming the PDU and the UART port is the interface with the LPC.

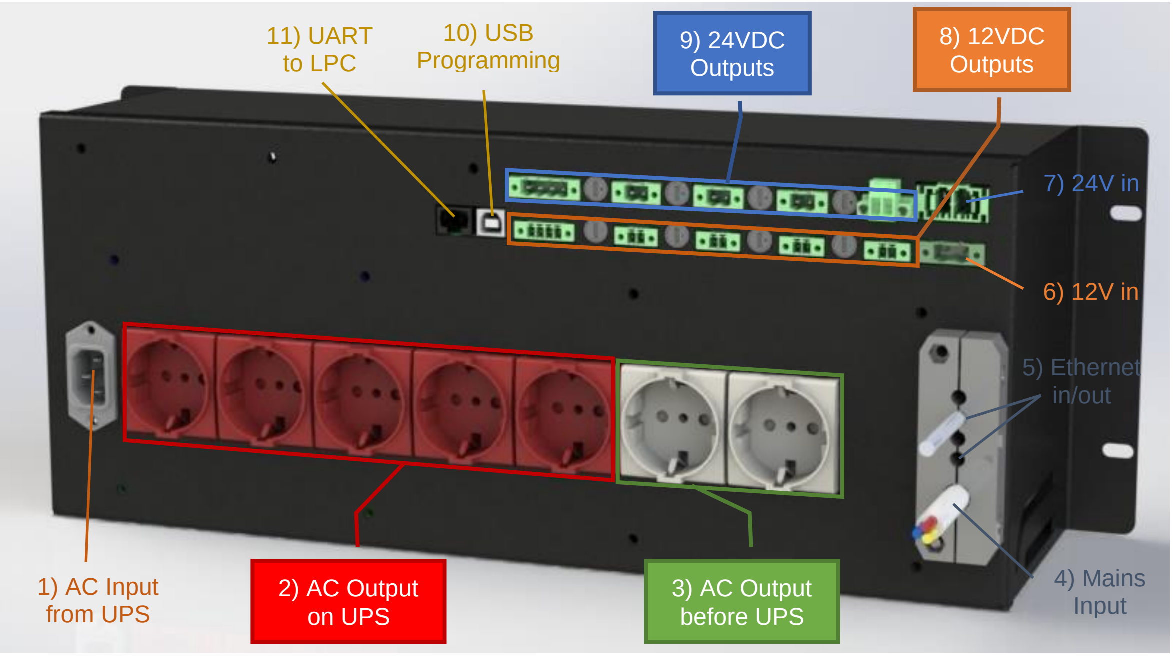



**Fig. 3.31:** PDU Back Connections

Each LIDAR has a different configuration according to the automation level required. Below is a general description of the connectors and the actual connections are noted with a label on the cable and a sign on the PDU case. See also *'3.3.7.3 Electrical Drawing'*.

**Connectors on PDU (Rear Panel)**

| # | Connector Label | Type | Description |
|---|---|---|---|
| 1 | AC Input from UPS | IEC C14 | Main power line coming from the UPS |
| 2 | AC Output on UPS | CEE 7/3 | Controlled lines that powers the TR, Laser etc. |
| 3 | AC Output before UPS | CEE 7/3 | Direct lines to power the HVAC |
| 4 | Mains Power (Input) | Through | Main power line coming from the grid |
| 5 | Ethernet in/out | Through | For Ethernet surge protection (if applicable) |
| 6 | 12VDC in | Phoenix | 12 VDC power input |
| 7 | 24VDC in | Phoenix | 24 VDC power input |
| 8 | 12 VDC outputs | Phoenix | Controlled lines for the LMC, ATC, and picomotors |
| 9 | 24 VDC outputs | Phoenix | Controlled lines for the hatch, AZP, blower and TED |
| 10 | Computer | USB - B | Programming port |
| 11 | UART Host | RJ45 | Serial communication with LPC |

### 3.3.5 Lidar Measurement controller (LMC)

The Lidar Measurement Controller (LMC) module is responsible for selecting the best Lidar configuration of each measurement for optimal results. Optical filters and apertures are used to alter the Lidar measurement parameters to ensure the optimum performance of the device. The LMC-400 is the small version of the LMC and can control shutters and filters that slide in and out of the light path in the WSU.


**Fig. 3.32:** LMC-400

The LMC firmware is dedicated to receiving commands through the serial port from the Lidar PC and to moving the appropriate optical components. Four channels can incorporate up to 14 linear actuators (using an add-on module), with the ability to have all four channels active simultaneously.

Upon starting the LMC establishes communication with the PC via the serial port. Next it identifies the connected actuators in each channel and their position. After initialization, the module waits for a command from the PC. The acquisition software is responsible for handling the state of each module according to the type of measurement. For example, when acquiring a dark current file, the software sends a command to the LMC to close the WSU shutter. The user can control the actuators from the Live display software.

| # | Connector Label | Type | Description |
|---|---|---|---|
| 1 | Shutter Actuator | RJ-45 | Controls the main shutter used for dark current measurements. |
| 2 | RAMAN Actuator | RJ-45 | Controls the shutter used for Raman channel (PMT protection). Not Available |
| 3 | ND Filter Actuator | RJ-45 | Controls the sliding ND filter for the cross channel. |
| 4 | AUX Actuator | RJ-45 | Can control either a shutter or a filter. |

## 3.3.7 Control Cabinet

The control cabinet provides protection for the electronics. It contains the laser power supply unit, the Licel electronics, the UPS, the PDU and the LPC$^2$.

Having two doors and sliding trays, enables easy access to every component. The cabinet is made from aluminum alloy sheet steel which is robust and lightweight.

**Fig. 3.33:** Control Cabinet

### *3.3.7.1 Features*

- Robust and lightweight double walled outdoor aluminum enclosure.
- Light indicator and rain sensor
- Industrial outdoor thermoelectric air conditioning
- Castors and feet
- Door locks
- Weatherproof connectors and plugs for quick connection
- Circuit protection breakers
- Power supply box
- Service ladder (if applicable)

### *3.3.7.2 Connections*

By default, the network IP is set as shown in the figure below. As illustrated below the internal computer has six Ethernet ports. Three of these are used by the Licel electronics whilst another one is connected to the external Ethernet socket. This gives the option to connect to a Local Area Network (LAN) or directly to another computer with a cross link cable. If the local network allows access to this computer through the firewall, then it can be reached and the lidar can be operated from anywhere in the world by using Windows remote desktop. The unconnected ports can be used locally for servicing purposes.

The image below shows the connections between all components.

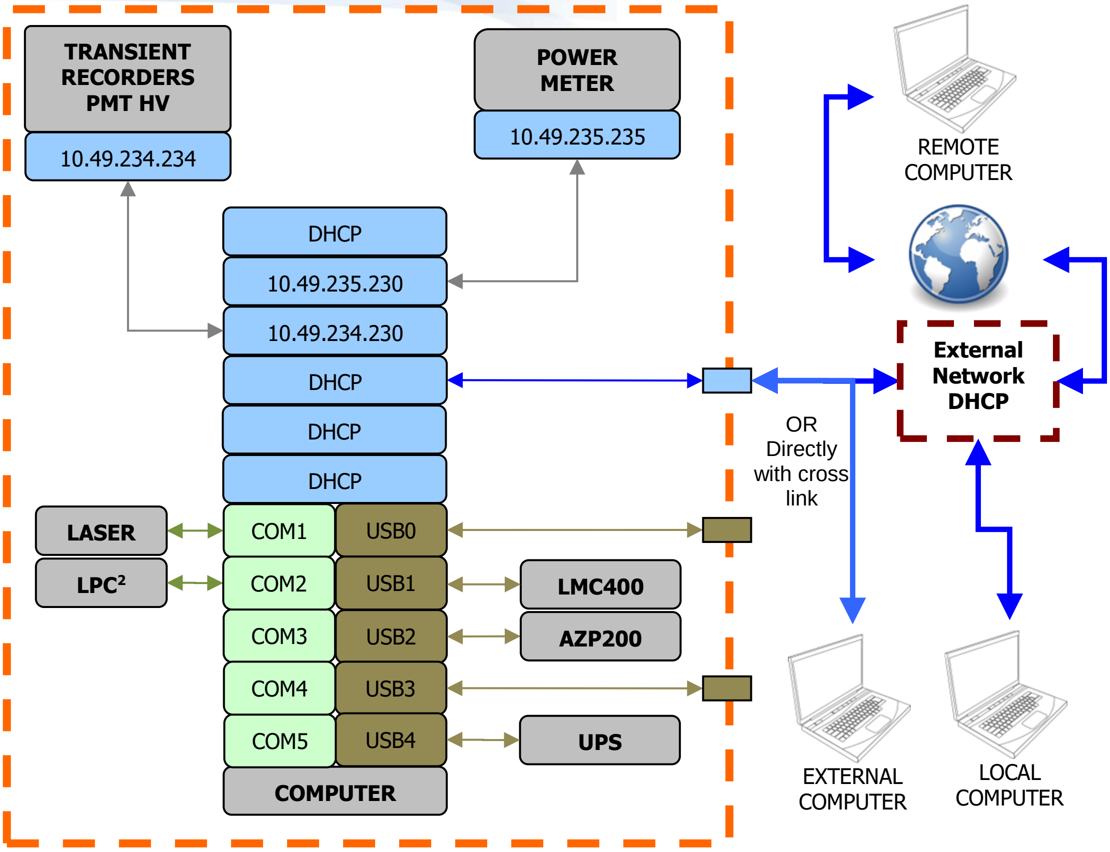



**Fig. 3.34:** LIDAR Local Network

The Transient Recorders are externally triggered from the ICE450 through a BNC cable. The laser creates a TTL pulse to trigger the flashlamp for every shot. ICE450 features a Q-switch whose function is to create a short delay before allowing the outgoing laser pulse to leave the instrument, producing, in this way, laser pulses of optimum energy. The user can increase the delay to reduce the energy. For this reason, another TTL pulse is produced to trigger the Q-Switch with the required delay. The Transient Recorders are triggered by the Q-Switch TTL pulse, so that the laser emission is synchronized with the acquisition start time.

As shown in the image below, the default connection is at memory A on the Transient Recorder and at 'QS OUT' on the laser.

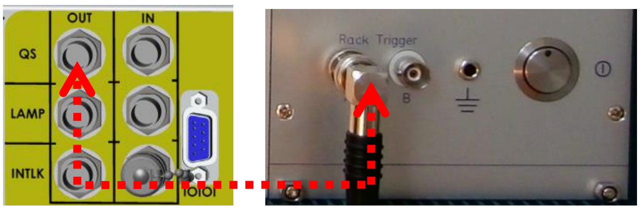



**Fig. 3.35:** Trigger Connection

For advanced measurements, the TR can be triggered by the flashlamp and the laser's flashlamp and Q-Switch can be triggered using an external trigger device. To use these features, refer to appendix section A1 How To Control The Laser. Furthermore, the laser's "interlock in" is connected to the LPC for the external interlocks and the "interlock out" creates a signal when the laser is emitting and is used primarily for the beacon.

### 3.3.7.3 Electrical Drawing

The electrical cabinet has a power distribution unit which contains the switches for the components of the control unit. The power is distributed in such a way that the LPC can switch two different lines whilst still having a safety switch for these lines.

1. Lightning surge protection T2+T1 9200kA (optional)
2. Lightning surge protection T3 10kA (optional)
3. Lightning surge protection T1 N+PE (optional)
4. Lightning surge protection T3 N+PE SPD (optional)
5. 'Main' Switch. This gives power to the all components.
6. 'RCD 30mA' Circuit protection breaker 30mA. In case of a short circuit this automatically shuts down the mains power.
7. 'UPS' Circuit breaker for the UPS which powers everything except for the TEC or AC.
8. 'TEC'. Circuit breaker for the 24VDC PSUs of the air condition unit.
9. 'SOCKET' Circuit breaker for the socket.
10. 'SOCKET' A free socket to power external equipment while one site.
11. 'LASER'. Circuit breaker for the laser
12. 'TR' Circuit breaker for the Licel Electronics
13. 'LN3' Circuit breaker for auxiliary device.
14. 'LN4' Circuit breaker for auxiliary device.
15. 'LN5' Circuit breaker for auxiliary device.

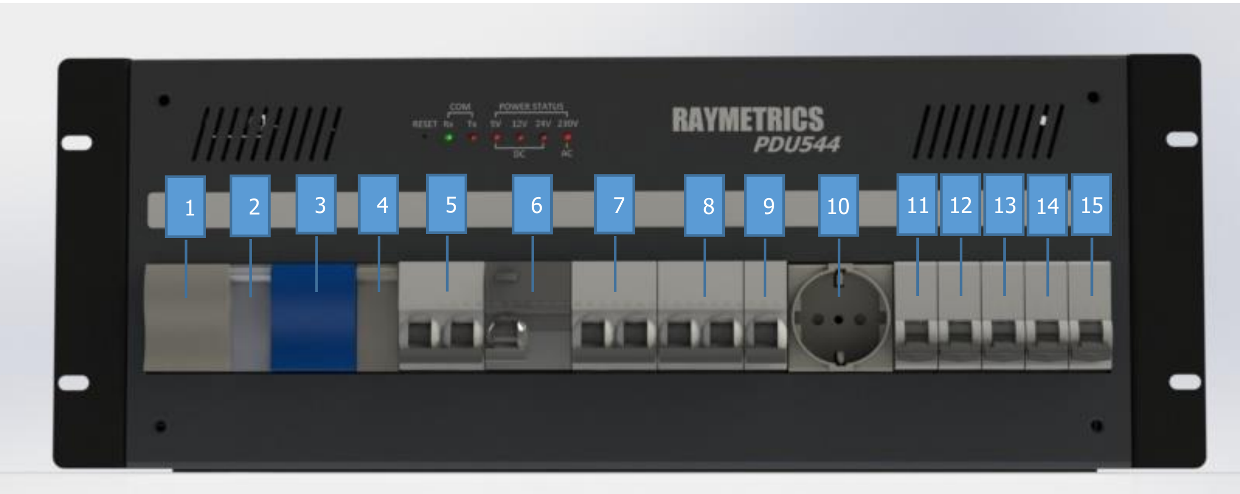
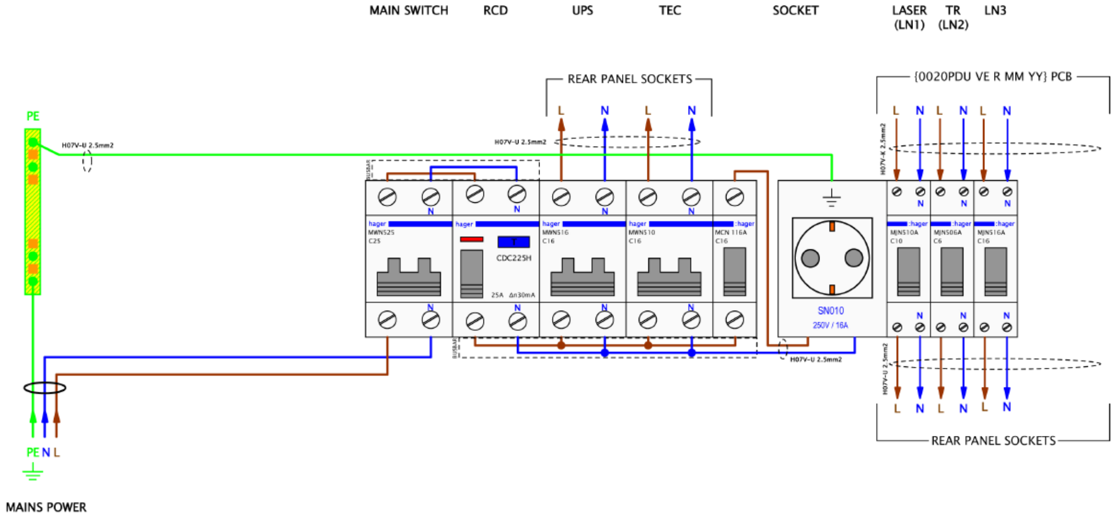



**Fig. 3.36:** Energy box

**WARNING – HIGH VOLTAGE:** Do not operate the Lidar without the protective cover. Keep away from liquids. Electric shocks could lead to serious injury or even death.

The figure below shows the electrical drawing of the power distribution unit. Note that this is for reference only. Changes must not be applied without first consulting Raymetrics.

<u>Front Side of PDU</u>




<u>Back Side of PDU</u>

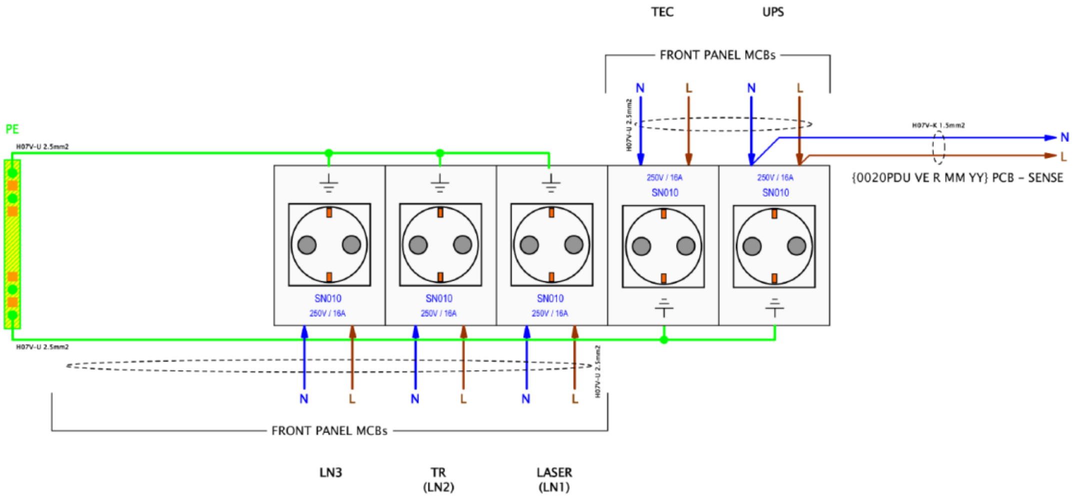



**Fig. 3.37:** Wiring Diagram

## 3.4 Positioner (AZP200)

The altazimuth positioner is used to move the LIDAR head in any direction of a hemisphere. It is specially designed by Raymetrics and used for scanning LIDARs applications. The design allows the head to be mounted on its mass center and rotated at altitude direction leaving enough clearance for the umbilical. The “200” stands for the telescope size.

**CAUTION:** MOVING PARTS. OPERATION OF THE AZP WITHOUT THE COVERS MAY LEAD TO SERIOUS INJURY.

**Fig. 3.38:** AZP200

### 3.4.1 AZP Operation

The positioner moves by a stepper motor and a belt drive that transits to a worm gear. The power is transmitted to the rotating shaft by a coupler. To achieve the highest position repeatability the drive has an anti-backlash mechanism. The mechanics and electronics are protected with covers and a system of fans and blower is used to extract the built-up heat. A flush connector on the bottom of the device is used to power and communicate with the device, which if unplugged the positioner can sit on its base and transported easily. The image below illustrates the main components of the positioner.

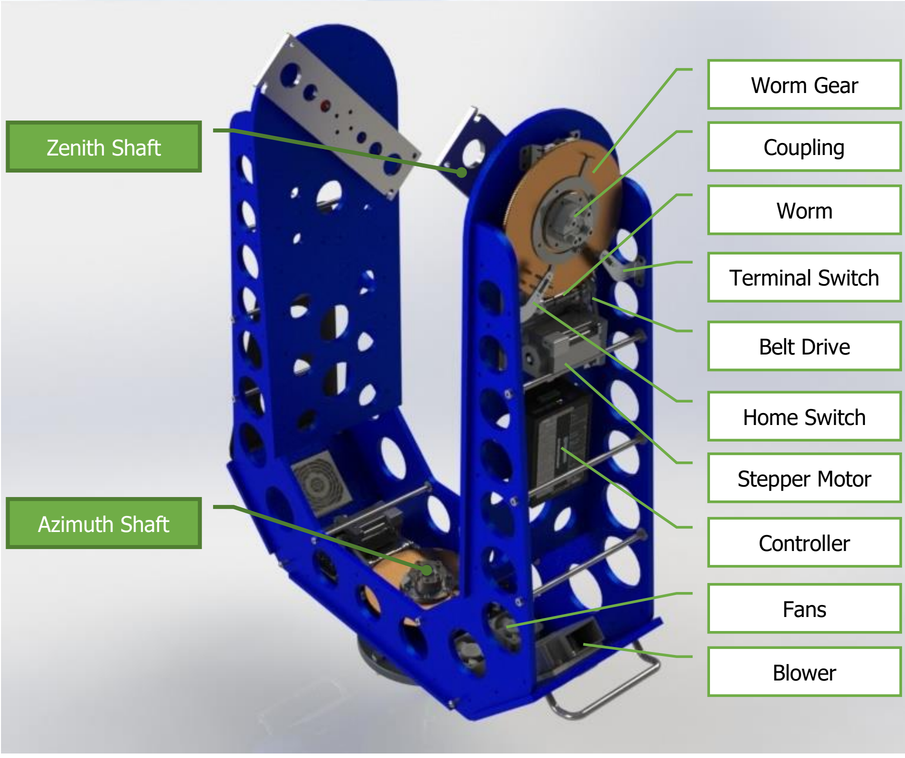



**Fig. 3.39:** AZP200 Main Components

Each motor is driven with a state of the art bridge that is controlled with a dedicated processor. The bridge sends pulses to the motor while the controller reads the position from the encoder and verifies in each step the correct position to achieve the highest possible accuracy. One of the two controllers, is used as a master controller that communicates with the computer and commands the slave controller. A pair of switches ensures the correct limits will be kept and provides an accurate home position.

**Fig. 3.40:** AZP200 Controller

Finally, separate temperature set points activate the appropriate fan to cooldown the motor and electronics. The blower on the side diverts the intake air upwards to cooldown the controller, therefore the side cover is necessary for proper cooling.

### 3.4.2 AZP Specifications

All materials are carefully chosen to reduce the weight but to also keep a robust overall structure. The welded frame is made from aluminum and along with the robust ball bearing base, ensure the high rigidness of the positioner. The covers are made from gel coated fiberglass and carbon fiber to withstand all weather conditions. At the table below are listed the technical specifications of the positioner.

| TECHNICAL DATA | |
|---|---|
| **Power Input** | 24VDC / 10A |
| **Power Consumption** | 80Watt |
| **Motor** | Stepping motor |
| **Resolution** | 0.002° |
| **Repeatability** | ±0.0078° |
| **Range** | Zenith: 6° to -90°<br>Azimuth: 0° to 360° |
| **Communication** | RS232, baud rate: 9600, data bits: 8, Stop bit: 1 |
| **Torque** | 40 Nm |
| **Speed** | 3.9 deg/s |
| **Acceleration** | 5.9 deg/$s^2$ |
| **Transmission rate** | 1 step is 0.002 degrees |
| **Environmental conditions** | -20°C to 40°C |

# 4 LIDAR SYSTEM SOFTWARE

The Lidar comes with a suite of software. Programs can be grouped into three main categories; System Operation, Post Processing and Tools. Operational software programs are used to acquire the Lidar raw data. Post processing software is used to analyze the raw data. Tools are used for maintaining the Lidar at peak performance, for customization and for system diagnostics.

Below is a diagram showing some of the basic software modules.

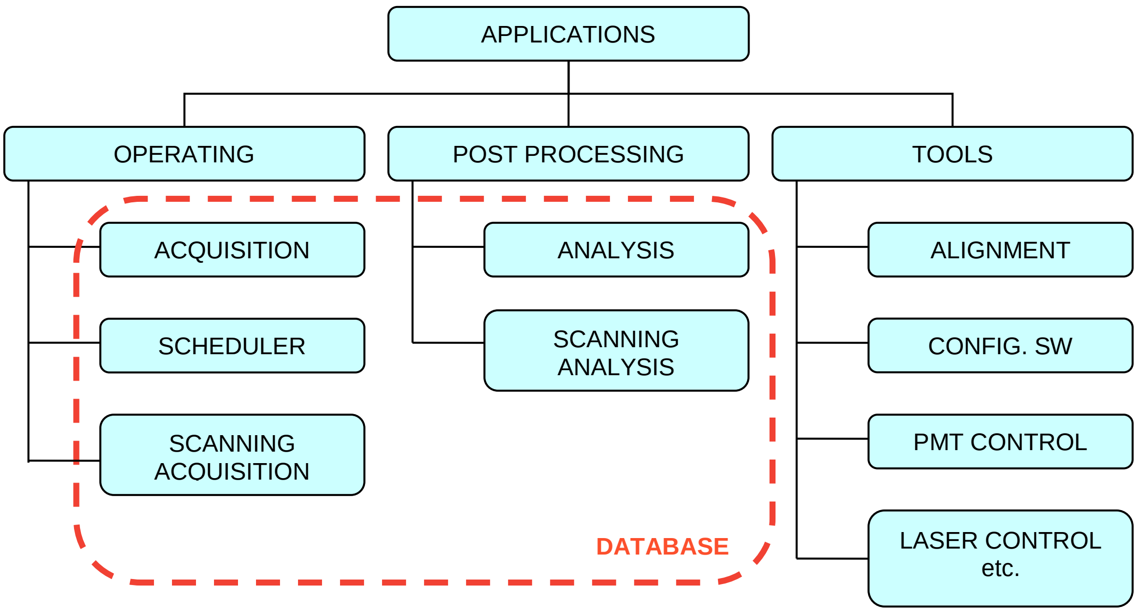



**Fig. 4.1:** Software Modules

Data acquired from measurements (raw data) is saved in a database. This database is accessed by the analysis software which has the capability of editing it. It is important to understand how this database works so that the measurements are stored and indexed properly. Users can create more than one database but it should be kept in mind that the raw data can be bulky and not easy to handle. All raw data in each database is saved in a single folder with a unique datalog file which contains all information for the records (measurements).

The following sections present the main software modules as a reference guide only. Some features may not be available in every system. Refer to chapters *'6 LIDAR OPERATION'*, *'7 LIDAR DATA PROCESSING'* and *'8.1 Lidar Alignment'* for further information on how to use the software.

## 4.1 System Operation Software

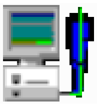
As previously noted, acquisition software is used to acquire the Lidar data. This program can start and finishing a complete lidar measurement, saving the data acquired. To do so, the software has control over the devices that are used for the measurement and logs the output of the measurement. Raymetrics has combined into a single program all hardware controlling software required, to make the process of measurement as easy as possible.

The acquisition software performs the following tasks simultaneously:

- Controls the Transient Recorders, PMTs, Laser, LMC, LPC and Positioner
- Records the Raw data and saves quick look images
- Data logging

The program can also repeat a measurement with a time delay.

### 4.1.1 Acquisition



The acquisition program is the most important program for the Lidar. Knowing how to acquire good Lidar data is effectively more important than analyzing the data, as good post-processing can only be done if there is good data to begin with. Below is the interface of 'Lidar Acquisition.exe'.

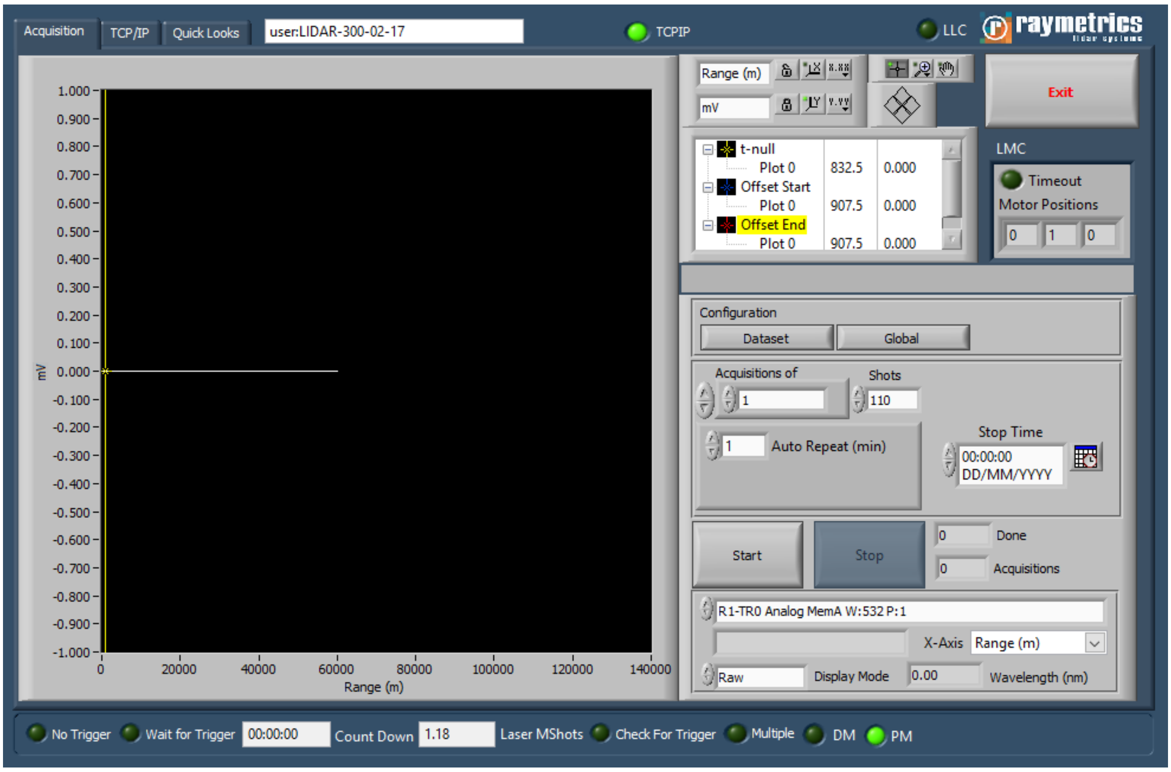



**Fig. 4.2:** Lidar Acquisition.exe

The GUI contains three main tabs. The Acquisition tab, the TCP/IP tab and the 2D Tab. Here only the Acquisition tab is presented since this is the most important. The TPC/IP is used only for the configuration of the connection with the Transient Recorder whilst the 2D tab shows a 2D graph of the time evolution of the acquired measurements.

The main features in the Acquisition tab are:

- a graph that displays the acquired profiles in real time
- various controls for the graph display features
- two configuration buttons 'Dataset' and 'Global'
- a Start/Stop button

The 'Dataset' button opens a new window which allows the user to set the parameters for each channel. The interface and the main parameters have been shown below.

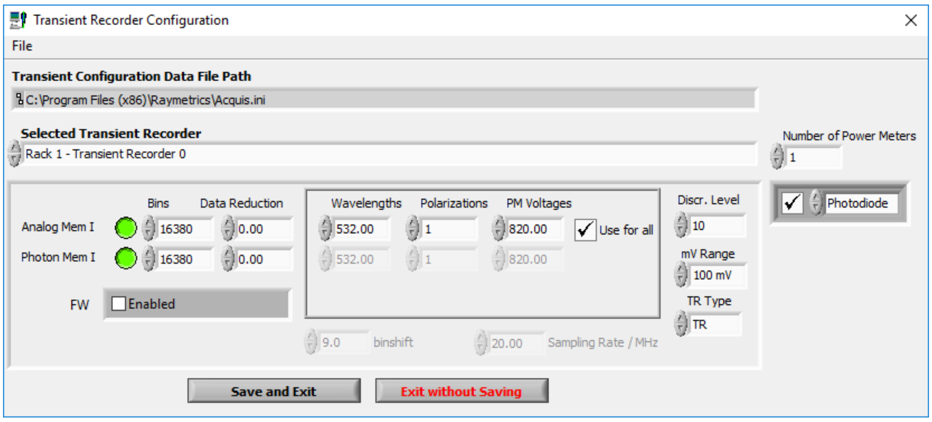



**Fig. 4.3:** Dataset window

On the menu under 'File' is the option to load and save a configuration file. The selected file is shown at the text box under 'Transient Recorder Data File Path'. Next to the Transient Data frame there is a numeric control that indicates the selected device

The parameters and settings here are:

- Memory selection and measurement size for Analog and Photon counting.
- TR parameters such as mV range, TR type and sampling rate.
- PMT high voltage setting.

The 'Global' button opens a dialogue to set general settings regarding the measurement. As shown below the user can set:

- the location parameters (Name, Altitude, Longitude and Latitude)
- The ambient temperature and pressure
- The laser's information (wavelengths and frequency)
- And the position of the head for a scanning Lidar.

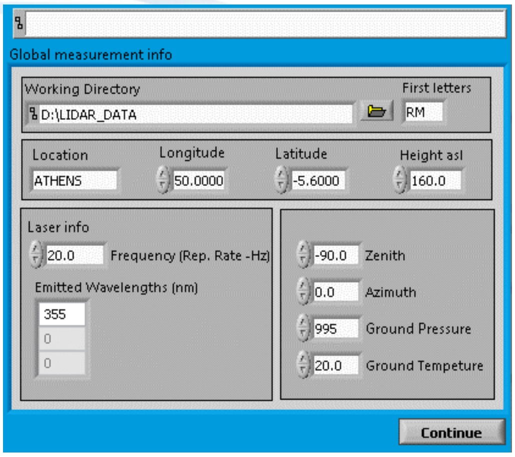



**Fig. 4.4:** Global settings dialog

## 4.1.2 Scheduler

The 'Time scheduler' program allows the user to create an automated series of Lidar measurements. This is invaluable, especially in the case where the instrument is stationed in a remote location without a reliable internet connection. The user can set a daily plan of measurements and may select which days of the week will use this schedule.

The purpose of this software is to offer the user the ability to control the Lidar in a fully automated way. The need for user supervision is eliminated, as this program has complete control over the measurement, the storing of the data acquired and the control of all the instrument's peripherals. Furthermore, if a mail account is connected, the software can prompt the user in case of an emergency or a failure. Only the main interface of the program is shown here. For more information please refer to *'6.4 Measurement Scheduling'.*

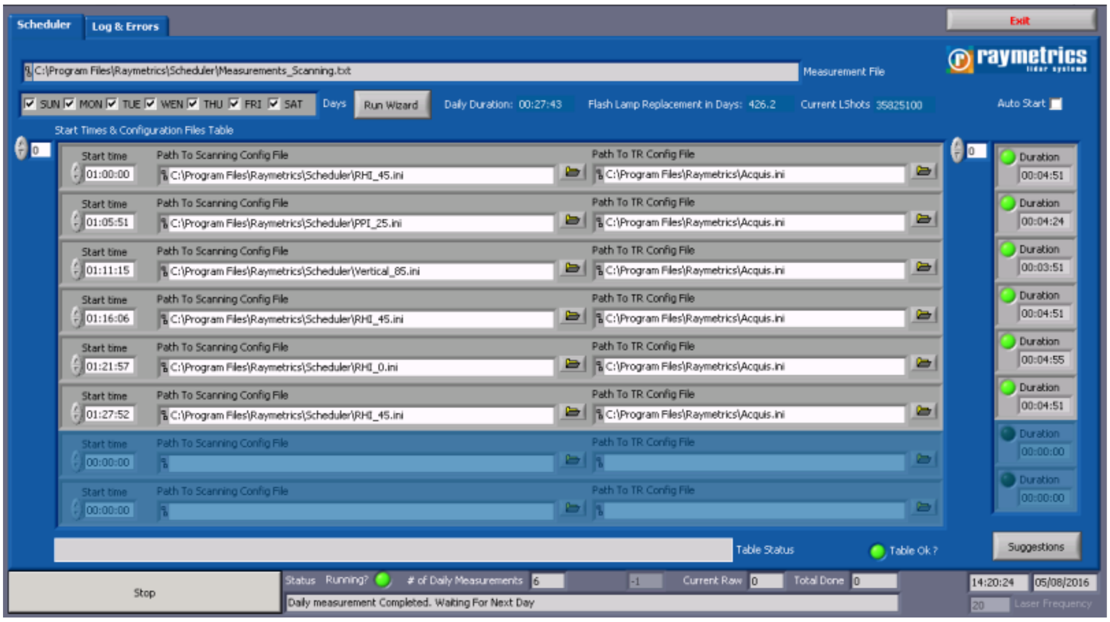



**Fig. 4.5:** Time scheduler main interface

### 4.1.3 Scanning Acquisition

For a scanning lidar there is the ability to scan an area or even schedule to scan multiple areas. From this program, the user can create files used in the time scheduler which contain geometrical information regarding the scan. To create such a file there is an extra tool called acquisition configurator.

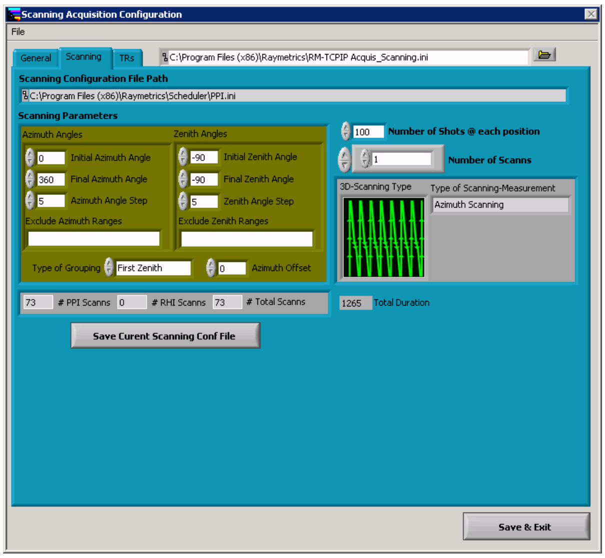



**Fig. 4.6:** Scanning Configurator main interface

To make this software complete there is the equivalent data processing program for scanning measurements. This is totally necessary while the volume of data when scanning is vast. Here are only presented the main interfaces of the configurator and the scanning acquisition. You can find more information in paragraph *'6.3 Scanning Acquisition'*

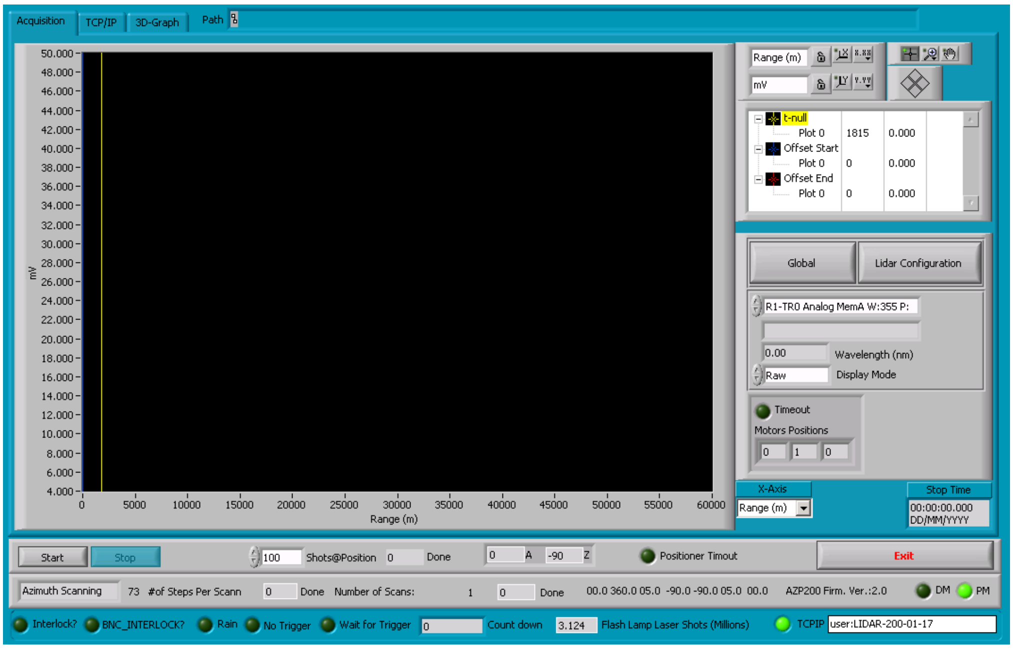



**Fig. 4.7:** Scanning Acquisition main interface

## 4.2 Post Processing Software

There is an obvious need to use a program which can organize the database and at the same time process and plot the data. The Lidar computer has a powerful program preinstalled, named 'Data Preview and Analysis', used for post processing raw data. Raymetrics software license comes with the Lidar and can be installed on any other computer, in case a computer other than the Lidar's is used for the analysis. If another data post-processing software is used, we provide a software tool which translates the data from binary to ASCII format, as well as the decoding method to read directly the binary files.

The 'Data Preview and Analysis' program was created based on the needs of Lidar users. In this section, the program is only briefly presented, please refer to section *'7.2 Data Preview'* for more information on using the database and for analyzing acquired data. With the 'Data Preview and Analysis ' program the user can:

- Preview and edit a database
- Analyze the raw data and extract various information such as the Range Corrected Signal the backscatter coefficient the beta molecular and the telecover, among other.
- Use a worksheet to perform additional calculations.
- Use advanced Lidar techniques such as data Gluing
- Present the data in 2D, surface (time evolution) and 3D plots.
- Use this software as a health diagnostic tool for the system.
- Convert data to ASCII from binary files
- import radiosonde data or background noise files to improve the data quality

### 4.2.1 Database and Working Directory

Each measurement produces a series of binary files which contain the raw data. The volume of data is normally large, which makes it necessary to use a program which can arrange the data in databases.

The raw data is saved in one working directory (single folder) which forms along with the datalog file one unique database. At first glance, this appears unwieldy since one folder can contain thousands of data files. However, these files are not relevant for the user since they are in a binary form. There is no actual need to ever use this folder directly. Files are instead organized automatically in the database. It is important not to alter the folder and keep a regular backup of your data. A new database can be created by changing the working directory. Users may make as many databases as desired, but should be kept in mind that it will not be possible to have an overview of the measurements with multiple databases.

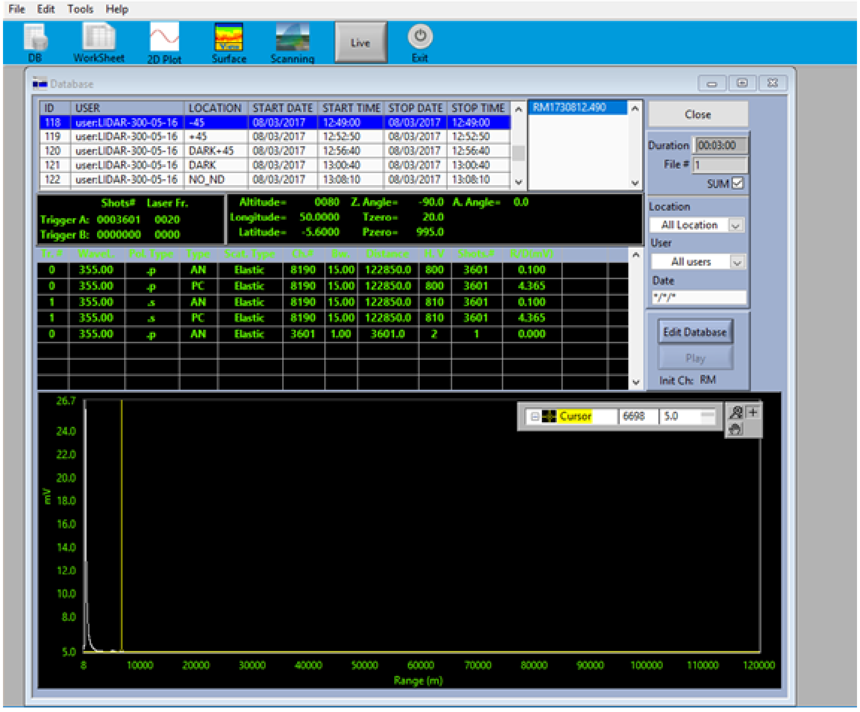


**Fig. 4.8:** Data Preview Interface

### 4.2.2 Analysis Software

This software has been developed over the past 14 years so that today the user can find many features embedded. Raymetrics also provides the methods used by the software for the analysis, so that the user can be aware of the theory which underpins the result. The software has a core part called basic analysis which produces results for all classical Lidar parameters such as the alpha, beta, RCS, etc. In addition to that there are other tools such as depolarization analysis, telecover, water vapor and many other.

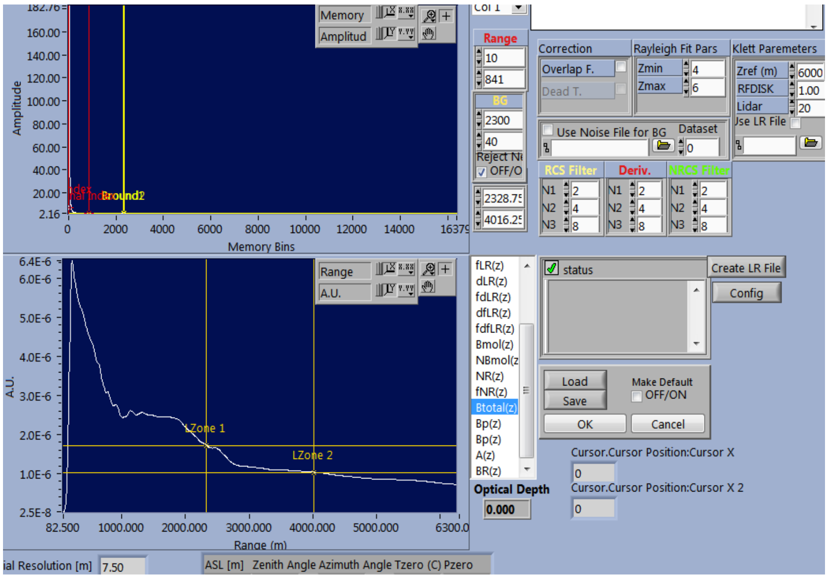


**Fig. 4.9:** Data Analysis Interface

Another useful tool is the scanning analysis which is specially designed to handle scanning data. With this program, the user can group scanning data analyses plot save and many more.

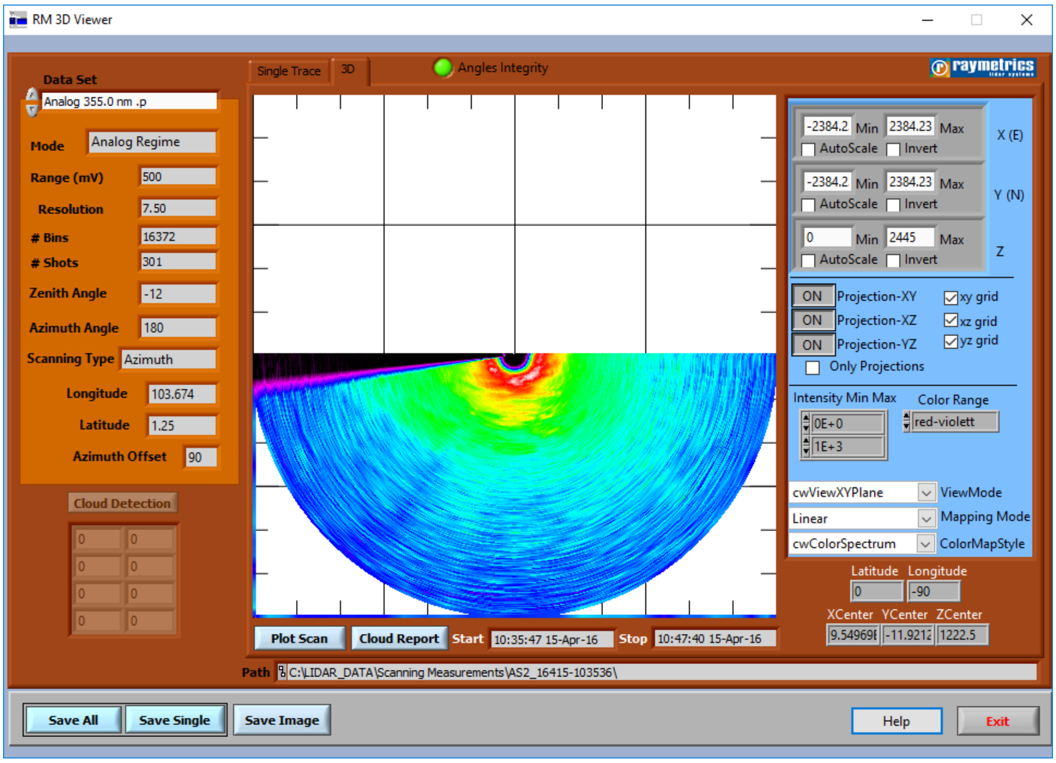



**Fig. 4.10:** Scanning Analysis

This software also cooperates with Google SketchUp to create 3D representations of scanning data in Google Earth. You can read more in Lidar analysis software manual.

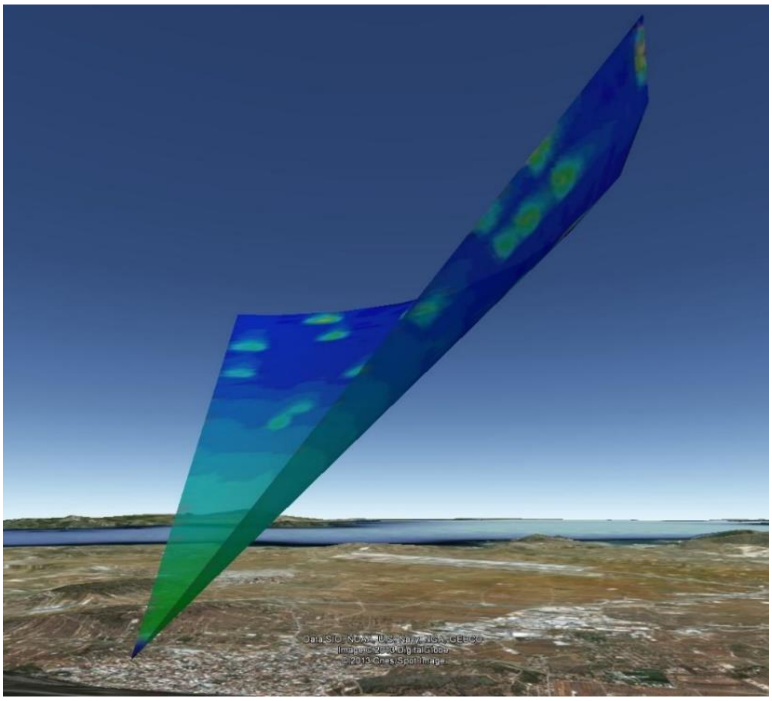
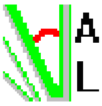


**Fig. 4.11:** Google Earth representation

## 4.3 Software Tools

There are some software tools which are very useful to the Lidar operator. To begin with a very useful tool is the 'Lidar Alignment' program, which is used to align the Lidar. In addition, a series of software modules have been provided to control different devices individually. Finally, there is software used for diagnostics and for the configuration of the Lidar's components.

### 4.3.1 Lidar Alignment Program




This program is a real-time acquisition software which allows the user to preview the signal without storing any raw data files. To ensure the quality of the acquired data, it is suggested to check the signal and align the lidar regularly. For this, the user can control the motorized mirror mount to steer the laser beam. Further information concerning the alignment has been included in section *'8.1 Lidar Alignment'.*

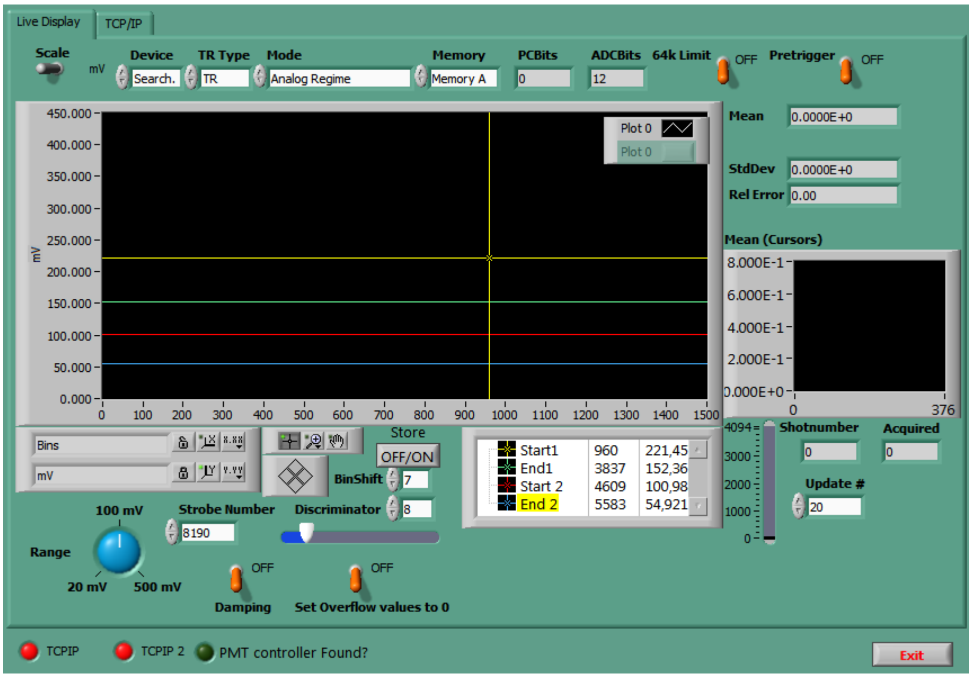



**Fig. 4.12:** Lidar Data alignment Interface

The interface appears like the 'Lidar Acquisition' program. Apart from the common features such as a graph with the control buttons for the axes and four cursors, there are some important additions which make this alignment tool unique. Firstly, there are several inputs such as the shot number, memory bins, bin shift, discriminator, range, TR Type, mode and device. Another addition is a small graph on the right side of the window with a series of numeric outputs above, used for alignment the process. On the bottom of this interface, is embedded the control of the motorized mirror mount. Finally, on the last tab the user can set the control the PMT High Voltage, start and stop the laser, control the AZP and LMC.

### 4.3.2 Laser Control Interface


This software module is provided in case the user may need to control just the laser. Furthermore, it provides information about the laser state (flashlamp shots, water level and flow etc.). The user can change and save the laser's parameters.

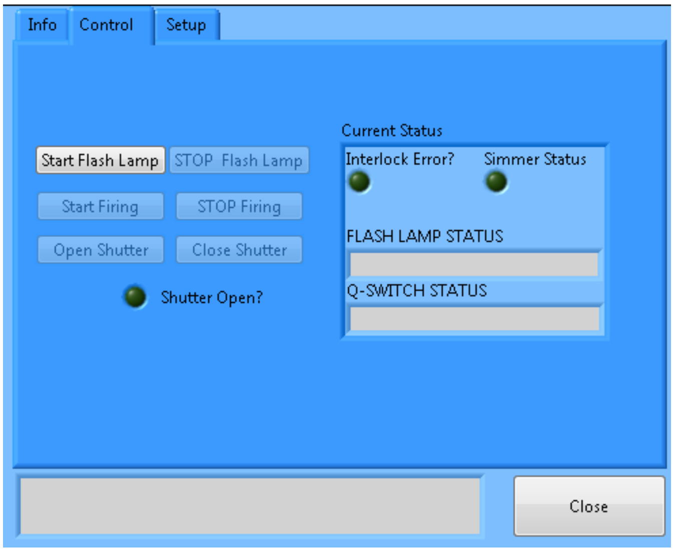


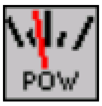

**Fig. 4.13:** Laser Control Interface

### 4.3.3 Licel Software

Along with Raymetrics' software, Licel's software has also been installed. This can be used as an alternative means of controlling the Transient Recorder the PMT HV device and some additional devices such as the trigger generator. It also provides diagnostic tools such as the 'Track' or 'search controllers' programs.

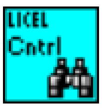
With this set of programs an experienced Lidar user can separately control the devices and can also perform advanced Lidar measurements manually. Since these programs have their own documentation, only the most commonly used are presented here.

- Power meter program



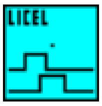

A very useful tool to monitor the laser's energy for every pulse. This information can instantly indicate the health of the laser. However, the program is only for viewing the live readings therefore it is used by the Acquisition program that saves the info.

- Search Controllers program




This tool is useful when the user has a communication issue. If for example, the computer is not communicating with the Transient Recorder or the PMT's HV device, then by running the Acquisition or the Alignment software, an error message will appear and the TCP/IP LED will turn red. This may be caused by a faulty cable or by an Ethernet card overflow. The 'Search Controllers' program searches for Licel devices in the same network and provides information about their status and their IP address, confirming that the issue is of a hardware nature or not.

- Control Timing program




The Lidar is equipped with a trigger generator which is used to trigger the laser and the electronics individually. This option is useful when a special study needs to be performed where there must be a time delay in between the laser pulse and the recorder. When using this option, the acquisition becomes a non-automated procedure and the user should use all control programs separately.

- TCPIP Set Fixed IP Address program


Users with advanced network knowledge may at some stage need to change the IP addresses of the Licel devices. In this case the 'TCPIP Set Fixed IP Address' program may be used to set a new fixed IP address for each device. Note here that the external trigger is a different device and has a unique IP address.

### 4.3.4 LPC Interface


This software module is the user interface for the LPC. It communicates with the device, updates the status whenever there is a change, controls the various hardware connected to the LPC and sets the parameters of the controller. This software also keeps a log file with every critical event such as a power failure.

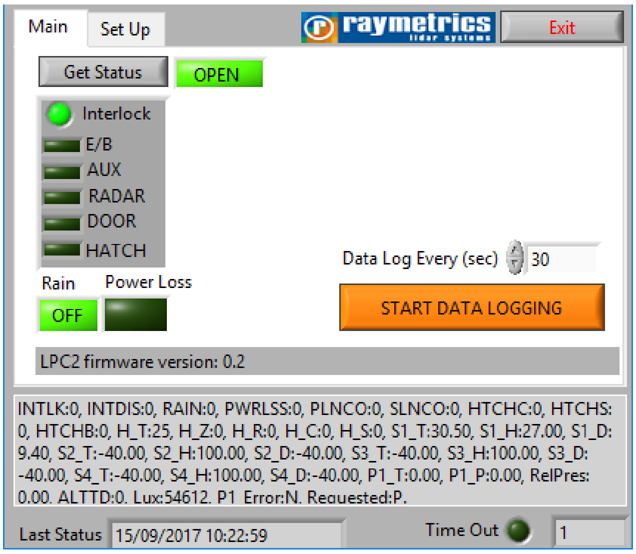



**Fig. 4.14:** LPC Interface

On the left side of the interface all interlocks are presented. An interlock is a situation which prevents the laser from operating. Underneath it, the status of the rain sensor can be found. In the case where there is a power loss, the LED next to the rain sensor indicator will turn on.

On the top left side there is the 'Get Status' button which queries the LPC for its status. Next to this is an LED that indicates whether the hatch is closed or open. The 'Open-Close' button opens and closes the hatch (if any).

On the right are the controls for the data logging. To start datalogging, the user must select the frequency of the data logging and press the start button. Additional information will also be saved, such as temperature, humidity, etc. To stop data logging, the user must press the 'Stop' button.

Bellow the data logging button, is a text box used to display messages from the software. At the bottom of the window is a text box used to display the last status received from the LPC. At the setup tab, the user can select the cooldown time in case of a power failure.

Whenever the program starts it establishes the serial communication with the LPC and opens the hatch (if not open already). Always press the exit button to quit the program. When exiting the program, the hatch will close automatically.

### 4.3.5 AZP Interface

This program is used whenever the user wants to test the Lidarhead positioner and should not be running if an acquisition is to take place. On the setup tab, the user can select the appropriate communication port and send a direct command to the positioner. When connected the positioner sends a message with the firmware version which verifies that the connection is established. On the control tab, the user can select the desired position and perform a homing procedure.

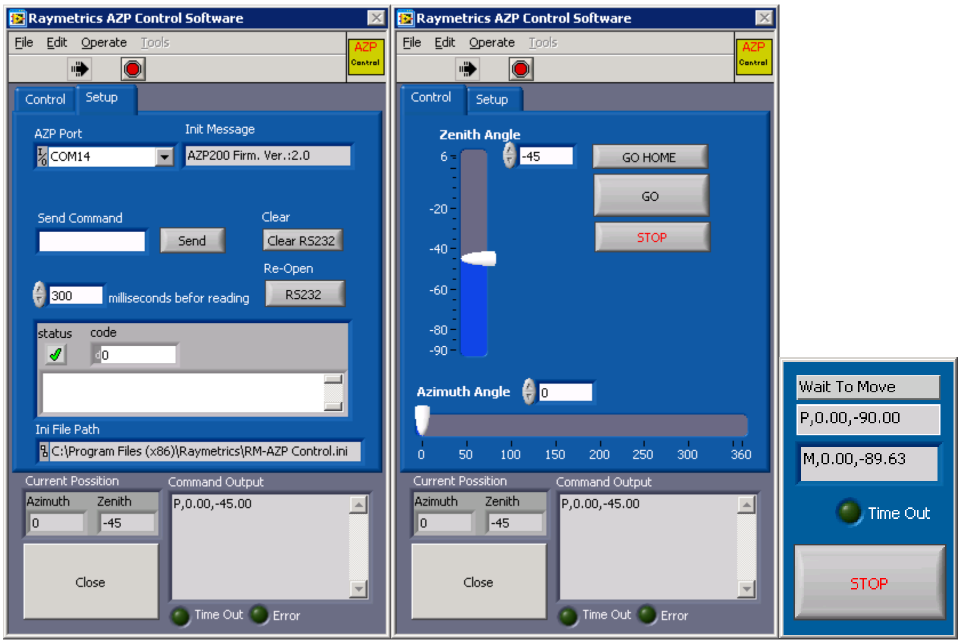
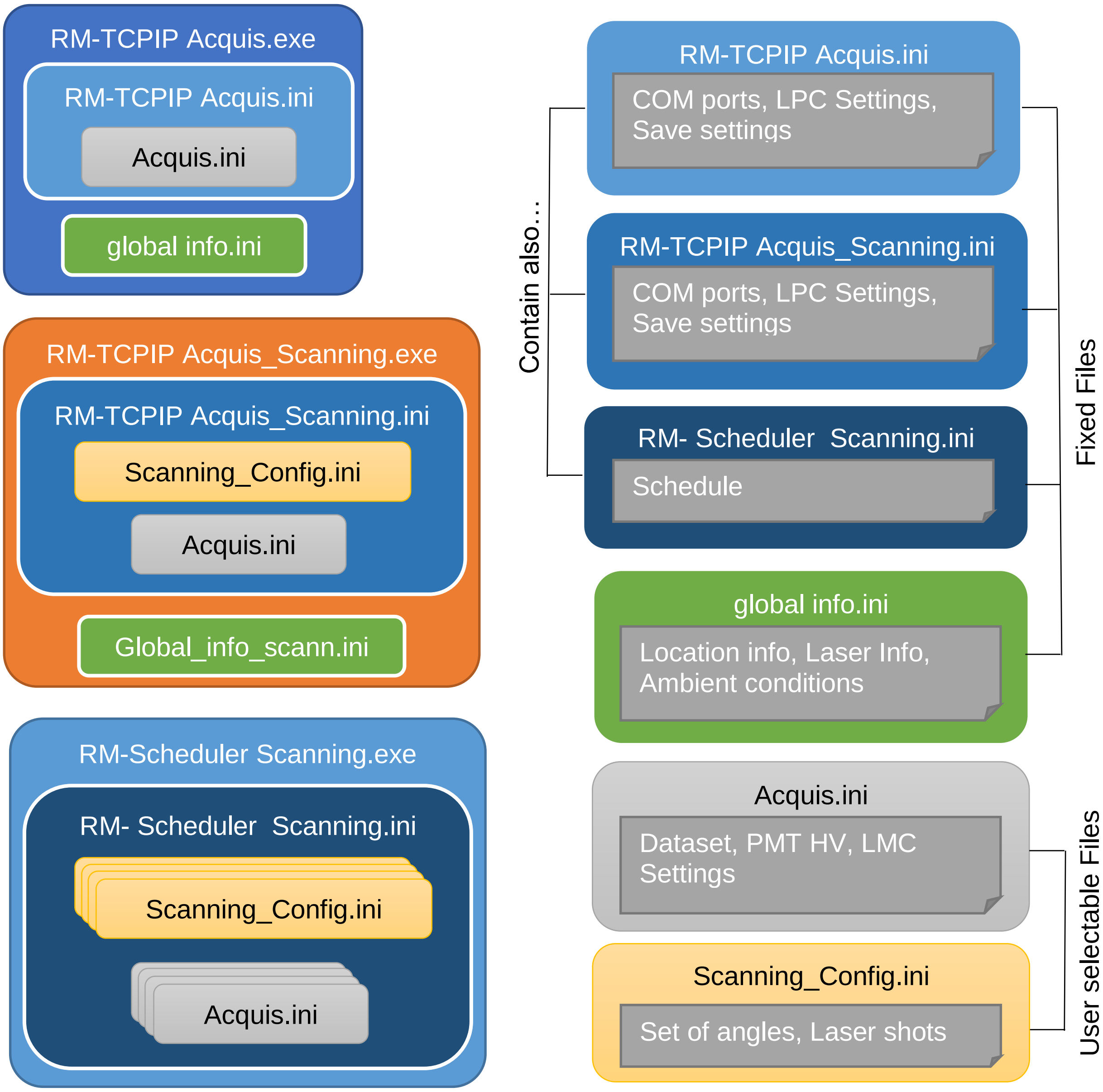



**Fig. 4.15:** LPC Interface

The small window on the right appears when the positioner is moving and indicates the current position. This window also appears in the acquisition and alignment programs.

## 4.4 Configuration Files

It may be confusing for a beginner to setup a measurement, not only because of the multitude of the parameters one must set, but also because of the different configuration (.ini) files that must be created. Some of these files are commonly used. The diagram below visualizes the necessary file used for each program.




As illustrated above, each program has a configuration file with the same name. These files contain general information about the program and paths and names for other files such as the Acquis.ini. These and the global info are fixed files, meaning that their name must never be changed, whereas the scanning configuration and acquis files are user selectable, can have any name and can be as many as the user needs.

# 5 UNPACKING AND INSTALLATION

## 5.1 Unpacking the Lidar System

The Lidar system has been carefully packaged to ensure its secure delivery to the customer.

*Inspection after shipment*

Inspect carefully the crate for damage before uncrating the Lidar system. Take notes and photographs if any external damage is visible. **If you notice any damage caused during the transportation please advise Raymetrics before signing the delivery note.**

*Unpacking*

**DANGER:** Serious injury or even death may be caused during unpacking. The Lidar system should be unpacked only by the authorized personnel of Raymetrics S.A. during the Lidar installation on site. Raymetrics S.A. will not be held responsible for any damage caused to the Lidar or for any injuries sustained by personnel who improperly handle or attempt to open the crate. Any attempt to unpack and install the Lidar without prior written authorization from Raymetrics or without an authorized member of Raymetrics staff present may result in damage which is not covered by the warranty. The Lidar must be kept safe from falling due to tilting and protected from impacts or sudden movements, at all times.

**NOTE:** The following instructions must only be applied if Raymetrics has granted the user permission in writing to unpack the Lidar system.

1. First remove the external film covering the crate.
2. Then, open the crate by removing all screws (being careful to ensure the lid or sides of the crate do not fall once they have been unscrewed).
3. Once the crate is open, loosen and carefully remove the straps holding the lidar in place.
4. With the use of the car jack lift the lidar and place the wooden planks beneath the wheels.
5. Fix the ramps on the end of the planks using screws. Make sure the ramps are aligned with the wheels.
6. Lift the lidar’s leveling feet, lower the lidar back on its wheels and remove the car jack.
7. Gently push the lidar so that its wheels enter the metal ramps you placed earlier and use those to roll the instrument out of the box. At this point, make sure that at least three persons are present, so that you can prevent the lidar from gaining too much speed while rolling down the metal ramps.
8. Once the Lidar is onto solid ground, lower the leveling feet to hold it steadily in position.

## 5.2 Installation of The Lidar System

*Site:*

For proper operation of the Lidar system the ambient temperature should range between 18 and 28˚C, unless otherwise specified in *‘10. LIDAR TECHNICAL SPECIFICATIONS’*. It is preferable that the Lidar system is positioned and secured on a solid horizontal surface. When choosing an indoor location for your Lidar system, make sure that the housing has an opening (hatch) over the Lidar with an area 15-20% larger than the total area of the emitting/receiving windows of the Lidar system. The housing/room must have an air conditioning and heating unit. If the lidar is intended for outdoor use it should be placed on solid ground and be leveled by the feet. The maximum allowable tilting angle is 5 degrees. You may also secure the feet using the holes. If the location suffers from intense wind gusts it is better to place the lidar on a concrete platform and replace the feet with metal expansion anchors with an M12 bolt.

**Always keep in mind:**

- Access should be available from all sides of the Lidar system, especially in the front where the control unit is located,
- Each side of the cabinet should be at least 25-30 cm away from a wall or obstacle. For efficient cooling of the instrument of the instrument it should be at least 50 cm away from a wall or other obstacle.

*Power:*

Power range should be from 220 to 240V or 110 V (50/60 Hz) with available average current up to 10A or 20A, respectively. The power must be stable with no large motors using the same power line. If for any reason the power has large peaks the laser will not function. The lidar is equipped with an on-line UPS that stabilizes the power and safely shuts down the instrument. **For the installation, the user must ensure the availability of a socket rated for at least 25A and must supply an appropriate plug to fit this socket and the power cable (Fig. 5.1). The power cable type is 3x2,5mm$^2$.**

*Water Coolant:*

The laser cooling unit is a water/air heat exchanger which does not require any external water supply. However, the user must make sure that there is distilled water with 1MΩ-cm to 5MΩ-cm resistivity always available at any time and especially during the installation.

The on-site installation and Lidar system alignment will be undertaken by Raymetrics S.A. personnel.

**CAUTION:** No attempt should be made by the user to install the Lidar system. Any damage which may occur due to the non-respect of the previously mentioned instructions will not be covered by the warranty.

### 5.2.1 Assembly

This specific outdoor lidar is shipped as one unit. No special assembly is required. Only the power cable has a free end which needs a suitable plug which will fit the socket on site.

**NOTE:** The polarity is not critical for the lidar operation, however due to the laser's capacitor discharge sometimes there may be a residual current which may escape through the neutral wire causing the buildings protection breaker to switch off. Therefore, it is always better to keep the polarity as suggested below.

The cable colors are explained below:

- Brown cable goes to 'L' (Live)
- Blue cable goes to 'N' (Neutral)
- Yellow-Green cable goes to '⏚' or 'G' or 'E' (Ground or Earth)

A plug which fits the socket at the installation site can be attached to the power cable (Fig. 5.1) The plug and socket must meet the requirements of the Lidar's power consumption. The power cable is a 3 x 2,5$mm^2$ 10 meters long.

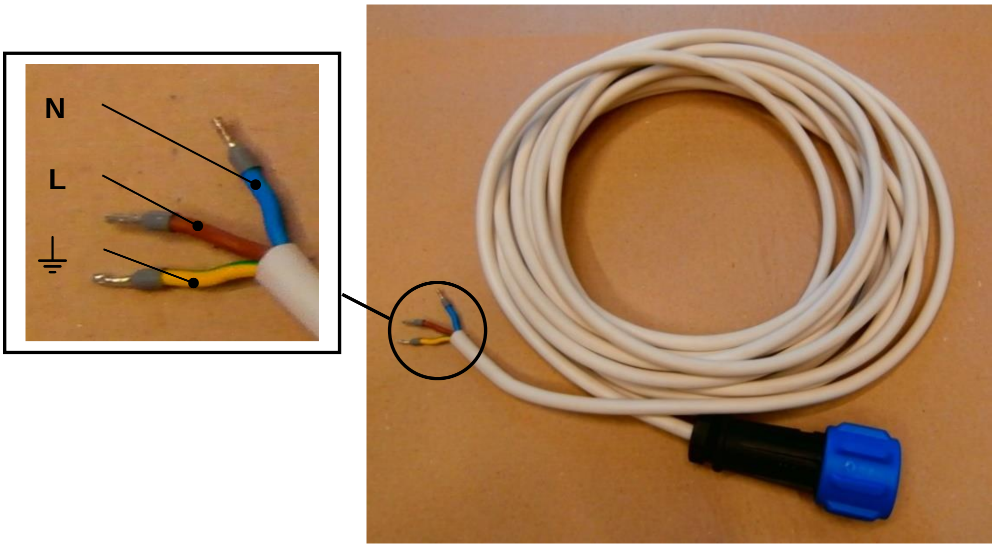



**Fig. 5.1:** Plug Assembly

### 5.2.2 External Connections

Additional connectors are located on the enclosure. The Ethernet port may be used to connect the Lidar with a network. The USB port may be used to connect a USB device. An additional USB or Ethernet port is available on request.

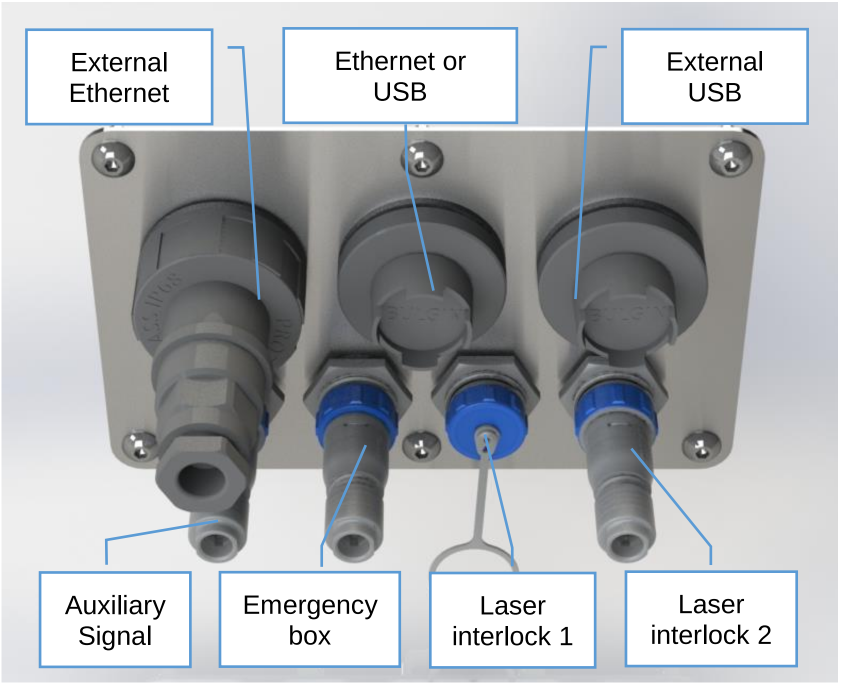



**Fig. 5.2:** External Connections

The lidar is equipped with three interlock inputs. These are all connected in series and keep the circuit closed. In case of an interlock the circuit opens and the laser stops the emission. The second connector from the left 'Emerg Intlk' as indicated in **Fig. 5.2** is permanently connected to the emergency push button box, which should be connected at all times The two on the right 'Laser Intlk 1 & 2' are used as auxiliary. The user can connect on these a switch activated by a door, a hatch, an infrared trap or a radar. Since both are short-circuited the switch must be normally closed. To connect the switch to the auxiliary input, remove the cover and the pin and plug in the switch using the supplied connector.

### 5.2.3 Water Filling

Before shipping out the Lidar from the factory, the laser coolant has been drained from the laser's reservoir. Before use, the customer must fill the coolant reservoir with approximately **1 liter of distilled water with 1MΩ-cm to 5MΩ-cm resistivity**. The instructions below should be followed to prepare for water filling. After this, the laser manual supplied by Quantel should be followed. The laser manual is located on the USB stick supplied by Quantel, in the Raymetrics binder, or on the Lidar computer in the following folder

'C:\Users\user\My LIDAR\Documentation\LASER\DOC00040.pdf'

1. Turn on the red main switch which can be found on the rear side of the cabinet.

**Fig. 5.3:** Main Switch

2. Open the front door of the cabinet.
3. Switch on all the switches on the front of the energy box.

**Fig. 5.4:** Energy Box Switches

4. Press the first button on the left of the UPS. The UPS should go to bypass mode. The UPS display will read 'BASS'.

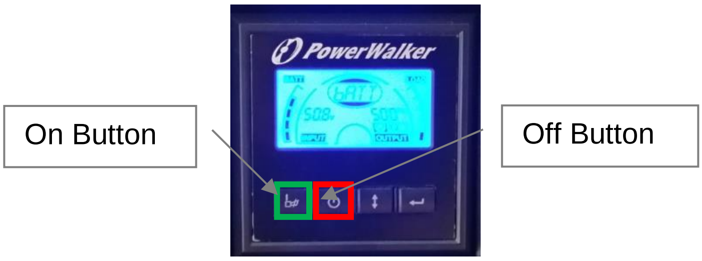



**Fig. 5.5:** UPS Control Panel

5. Wait until the UPS goes into online mode. UPS display will read 'LINE'.
6. After this has been completed, follow the instructions on how to fill the laser on page 11 of Quantel User's Manual DOC00040.pdf. (Quantel's USB stick is in Raymetrics' binder)

**CAUTION:** Each time the Lidar is transported by plane the coolant **must** be drained from the reservoir and especially from the Laserhead to avoid freezing which will destroy the Laser and will not be covered under warranty.

## 5.2.4 Software Installation

Raymetrics Lidar systems are supplied with a computer system which has all the necessary software for apparatus alignment, data acquisition and data preview and analysis pre-installed. The executable files which come with the instrument may be installed at any time on any number of computers. The Lidar analysis software can be installed in any computer simply by copying the software and installing the appropriate Labview runtime engine which is supplied free of charge from the National Instruments website.

### *5.2.4.1 Configuration Utility*

To manually configure the software, run the 'Configuration Utility' which can be found at: <installation path\Registry Tools\Config Application.vi>

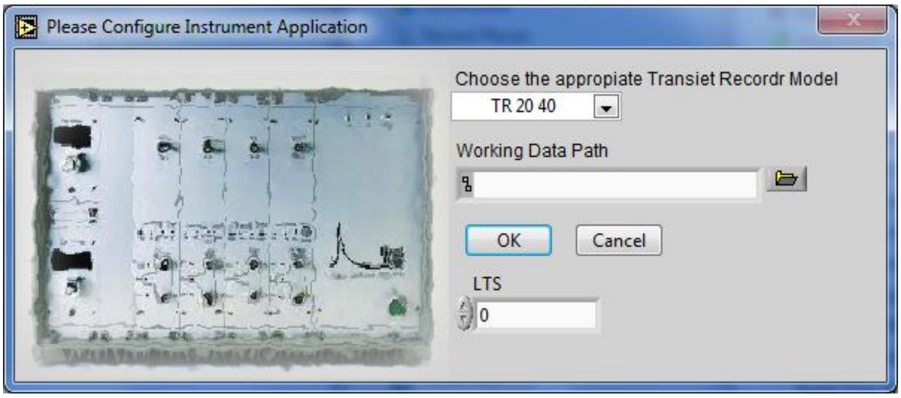



**Fig. 5.6:** Software Configuration

Select type of Transient Recorder Tr-xx-yy

xx: Sample rate: 20 MHz (7.5m range resolution) or 40 MHz (3.75m range resolution)

yy: FIFO memory Length: 160 (16384 databins) or 80 (8192 databins)

Select default location (folder) for saving raw data during data acquisition

Select default location (folder) for ASCII data when converting raw files to ASCII format

Select default location (folder) for backup raw data.

Press Ok to confirm or cancel to quit.

## 5.3 Storage and Service

**Storage**

- Shut down the computer
- Turn all the electrical units OFF.
- Hold the UPS Off button until it turns off.
- Turn the main switch off
- Disconnect the power cord from the Lidar system.
- **In freezing temperatures remove the laser's water or replace with ethylene glycol – water mixture.**
- Even if the Lidar is not used, the laser's ICE450 should be turned on every month for 30minutes.
- If the Lidar is to be stored for an extended period, it must be protected against intense rain and humidity. It should be brought indoors or covered up with a waterproof material.

**Service**

If the Lidar is to be returned to Raymetrics, it must be carefully packed in the original package material that came with the unit.

**NOTE:** The packing material must therefore be retained.

**WARNING:** The instructions in the manuals must be followed for every instrument. Any actions undertaken which have not been fully described in this manual or in a component's manual may result in serious injury or system damage which is not covered by the warranty.

# 6 LIDAR OPERATION

## 6.1 Start-Up

There are two ways to use the Lidar; manually or automatically through the software. The user can choose which is more convenient to use. Both methods are described below. The next steps will guide you through the operation safely. The first steps are common for either manual or automated operation.

1. Plug in the power cord (**Fig. 5.2**) and follow the first 5 steps of the procedure described in section 5.2.3 Water Filling.
2. Turn the '**Power Key Switch**' on the front panel of the PCC to the ON ('I') position. The 'power' and the 'interlock' indicators on the Remote Box will illuminate. If this does not happen, check for interlock fault messages on the Remote-Control Box LCD Display (**Fig. 6.5**).

**Fig. 6.1:** Laser Power Up

3. Wait approximately 10-15 minutes, depending on the environmental conditions and amount of coolant in the system (coolant line length), until the coolant temperature reaches the preset value for flashlamp operation.
4. Check the status LED of the LPC and power up if needed. By default, the computer on start-up will send a command to the LPC to open the hatch, if any. If the hatch does not open automatically, use the software interface of the LPC to open the hatch.
5. Power up the Licel electronics (TR, PMT).



**Fig. 6.2:** Electronics Power Up

6. For each PMT High Voltage device, select the desired control mode. Lift the switch first and push it up or down. Set to manual for manual operation or remote for automated operation.

**Fig. 6.3:** Control Mode Selection

### 6.1.1 Manual Operation

7. Turn on the HV by switching the HV switch to the manual position for each HV power supply to be used. Turn the HV potentiometer counter clockwise up to the desired value. (High Voltage values should be 800-950V for linear range of operation)

**Fig. 6.4:** PMT High Voltage Adjustment

8. Press the '**Flashlamp Ready**' button on the Remote-Control Box. The corresponding 'ready' LED and 'LASER ON' indicators should illuminate. Wait for a couple of seconds and if no interlock appears on the remote box's display, press the '**Flashlamp Start**' button. The corresponding flashlamp 'start' LED will blink and the flashlamp will begin flashing.
9. After the flashlamp has started firing, the PCC requires a warmup time of up to 8 seconds before it enables Q-Switch operation. This is the same for both Internal and External Q-Switch operation modes.

**WARNING:** The following steps result in laser light emission from the output aperture of the Laserhead. Do NOT look directly the laser beam. Before pressing the Q-Switch it should be ensured that nothing is blocking the light coming out of the aperture.

10. On the remote control, press the 'Q-Switch Start' button to activate the Q-Switch. Verify that the corresponding Q-Switch 'start' LED blinks and the 'Laser ON' sign illuminates.

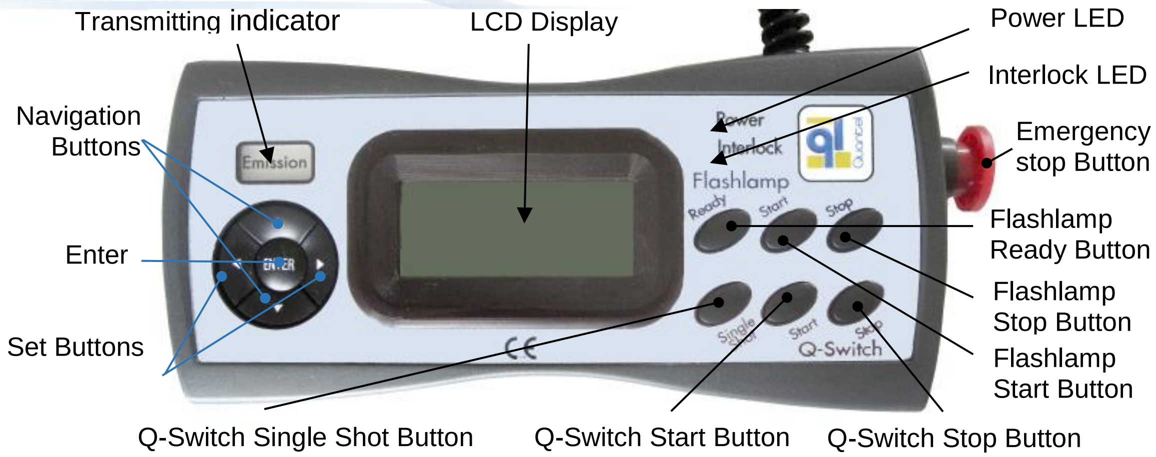



**Fig. 6.5:** Remote Control Box Indications

11. Run the 'Lidar Alignment' program . Check the signal and fine align if necessary (see section *'8.1 Lidar Alignment'*)
12. Exit the 'Lidar Alignment' program and run the 'Lidar Acquisition' program
13. To stop laser emission, press the 'Q-Switch Stop' button. Verify that the Q-Switch 'start' LED turns off. To stop the flashlamp, press the 'Flashlamp Stop' button. Verify that the flashlamp 'start' and 'ready' LEDs turn off. The laser is now on standby.

### 6.1.2 Remote Operation

7. Set the switch on each PMT HV to remote.
8. **Whenever the user presses any button on the remote control of the laser the serial communication with the computer is set to the remote control**. To set the serial communication back to the computer, navigate through the menu using the buttons, choose 'System Info' and validate with the ENTER button. Go to serial link and with the button change the status from 'off' to 'on'.

**WARNING:** The following steps result in laser light emission from the output aperture of the Laserhead. Do NOT look directly the laser beam. Before pressing the Q-Switch it should be ensured that nothing is blocking the light path.

9. Run the 'Lidar Alignment' program to make sure that the signal is okay and align if necessary. Otherwise, directly run the
10. 'Acquisition' program to perform a single measurement or the 'Scheduler' program to set a series of daily measurements. To stop the measurement, press the 'stop' button to stop the laser and PMTs.

## 6.2 Data Acquisition

### 6.2.1 Introduction to the Acquisition Interface

To use the ‘Lidar Acquisition’ program, first exit any Lidar program that is running and click on ‘Lidar Acquisition’ icon. Keep in mind that:

- This interface is intended for multiple fixed-point measurements.
- Before starting a measurement, all parameters must be configured (see below).
- **Once the ‘Start’ button has been pressed the laser will start firing without any notice. Follow the safety rules.**
- **Exiting program while running a multiple acquisition measurement, may add unpredictable entries to the main database.**

Below the main features of the ‘Lidar Acquisition’ interface is presented.

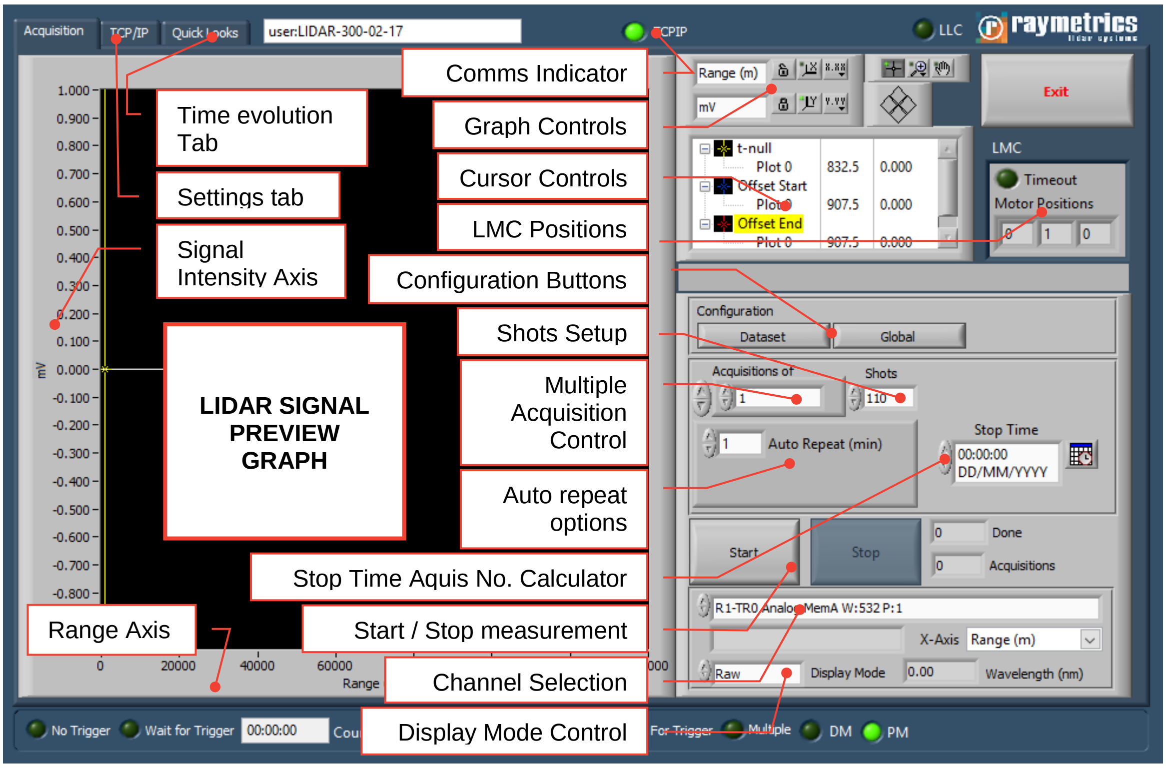



**Fig. 6.6:** Lidar Acquisition Interface

### 6.2.2 Configuring Measurements

The required parameters can be set using the ‘Dataset’ and ‘Global’ buttons. The dataset parameters are those related to the channels to be used. The global parameters are more general and usually do not require changing often. The global parameters are saved by default whereas the dataset can be saved as a configuration file which can be reloaded for future use. Most operators tend to make several different dataset configurations (i.e. different configurations during day time and night time) which can be re-used to save time and avoid mistakes.

### 6.2.2.1 Configuring the Transient Recorder

To configure the TR, start by determining the dataset. Click the ‘Dataset’ button, which will make a new window to appear. At the top of the window is a file menu which contains four options. To edit an existing file, select ‘Load transient information’ and select a file. After the data has been edited, the information can be saved by selecting ‘Save transient information as...’ and you can either choose the same file name, which overwrites the old file, or type a new name. If a mistake is made when editing the data, the original file can be reloaded by pressing ‘Reset Information’. The current configuration file is shown in the display below the menu. If ‘Exit without saving’ is selected, the original dataset will be used.

Below the ‘Transient Configuration Data File Path’ is a numeric control. 0 This selects the device (Transient Recorder). Pressing the up and down arrow will navigate through the devices. For instance, here device 0 is selected.

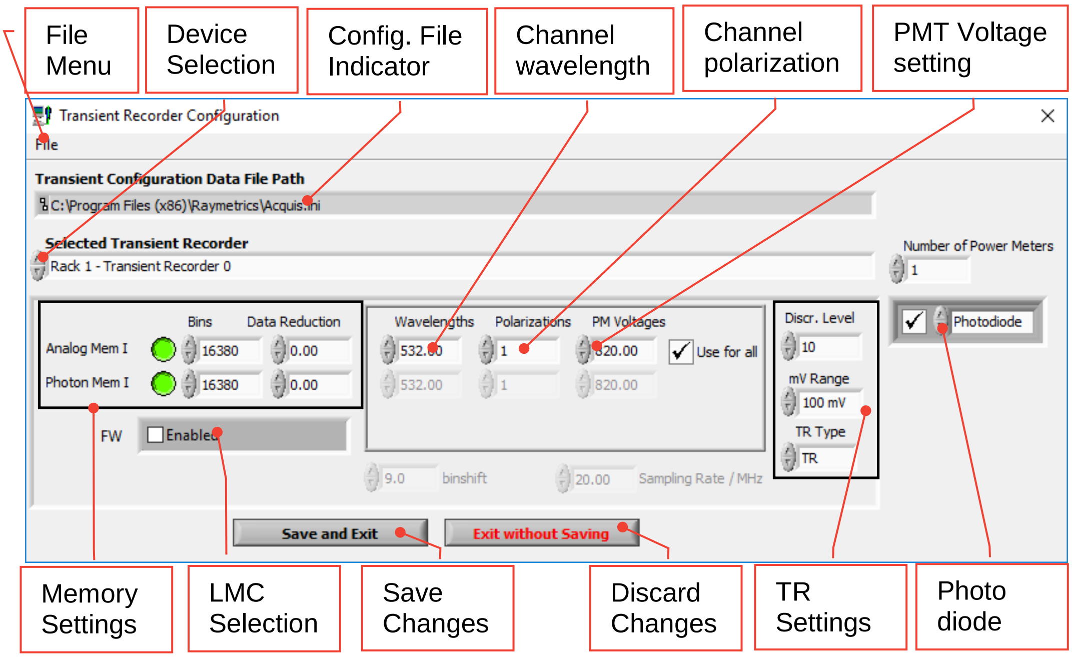



**Fig. 6.7:** Transient Recorder Configuration

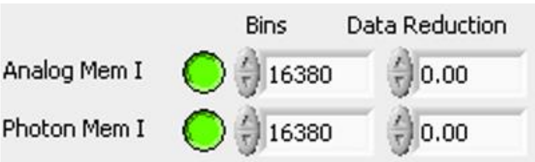
Beneath the ‘Selected Transient Recorder’, several inputs and controls can be found. The values set here must be different for each device, as each device measures a unique wavelength.

With the memory settings the user can select the data to be recorded. When the button is green the memory is activated and when grey it is deactivated. Here the user can independently select the memory required: ‘Photon’ or ‘Analogue’. For the elastic backscatter channels, both are required. For Raman only photon may be needed if the signal is weak. If a certain channel is not required uncheck (gray) both buttons. This may be useful for a Raman channel during day time to save data space, for example. Space may also be saved by reducing the memory bins. As already explained the memory bins are related to the range of the received signal. The spatial resolution of the recorder depends on the sampling rate or in other words the recoding frequency. This system has a 20MHz recorder which means that every 0.050μs writes a memory bin. When a laser pulse is emitted the recorder starts the time counter. The first photons that arrive back are recorded after 0.050μs. However, this time includes both the time spent for the photon to reach the target and the time for the return journey. So, the time that the photon needed to reach the target was 0.0250μs. The speed of light on the other hand is approximately $3x10^8$ m/s so the distance is 300 x 0.0250 = **7.50m**. This is the minimum distance that the recorder can record, known as the spatial resolution. The memory limit of the 12bit TR is 64336bins. This gives a total of 64336 x 7.50 = **482520m**. For most applications, such high data range is not needed.

Another way to reduce the data size is by using the data reduction function. This function groups bins together to make a superbin. One level of data reduction, groups bins by two, effectively reducing the spatial resolution in half. A data reduction level of 0, 1 and 2 corresponds to 1, 2, and 4 bins being grouped together, respectively. In this way, the spatial resolution is increased but the maximum range remains the same. This also means that the maximum number of bins is reduced.

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 0 Data reduction | Bins | 1 | 2 | 3 | 4 | … | 64333 | 64334 | 64335 | 64336 |
| | meters | 7.50 | 7.50 | 7.50 | 7.50 | … | | | | 7.50 |
| 1 Data reduction | Bins | 1 | | 2 | | … | 32167 | | 32168 | |
| | meters | 15.00 | | 15.00 | | … | 15.00 | | 15.00 | |
| 2 Data reduction | Bins | 1 | | | | … | 16084 | | | |
| | meters | 30.00 | | | | … | 30.00 | | | |

The data reduction and the Bins number can be set to read from the memory bank. It must however be kept in mind that the maximum number of bins is given by 64336 / (2^data reduction).

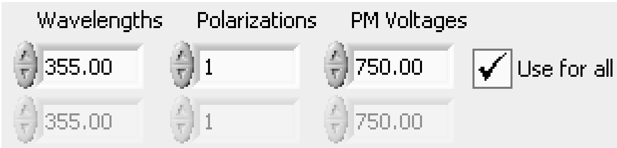


Next to the memory setting is the channel's information. Here the user must specify the detected wavelength and the polarization type. The polarization types are:

0 ........ No Polarization

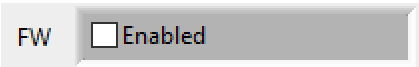
1 ........ Parallel Polarization

2 ........ Cross Polarization




Next to the polarization the user can set the voltage to be applied to the PMT during the measurement. The allowable range for linear behavior is 800-950V. Similarly, to the range, this is set based on the signal intensity observed using the 'Lidar Alignment' program. Therefore, it is important to know the correct value.

Below the memory settings is the setting for the LMC. There are two types of Lidar Measurement Controllers; LMC400 which controls the sliding filters and shutters and the LMC300 which controls the filter wheels. Depending on the type of Lidar the WSU is equipped with either slide filters or filter wheels but the setting is done from the same control.




For the LMC300 a numeric value is required that describes the position of the filter used for the specific channel. Each channel is equipped with a filter wheel. For instance, in transient recorder 0 it is selected FW No. 3. Upon save and exit the program will turn the filter wheel of the channel in TR0 (in the image above is 532nm P) to the slot No. 3 of the filter wheel.

For the LMC400 the setting is just a tick box because the slide filter has either a retracted or extended position. However not all channels have a slide filter, instead a there is a slide filter with a blank used as a main shutter (block the light for all WSU) another shutter for the Raman channels and a ND filter for the cross transmission of the depolarization channel. As a rule, the first device TR0, which is also the main channel, controls the main shutter, TR1 is usually the cross transmission that controls the ND filter and TR2 is usually the Raman channel that controls the shutter for the Raman. In this case if for example, the user ticks the box for TR0 the main shutter will be activated and a dark current measurement can start (external light is blocked); if it is checked for TR1 then the ND filter will be activated and can perform the ±45° calibration test; and if it is checked for TR2 then the shutter for Raman channel will activate and this can be used as a day time measurement.

When the user presses the save and exit button the filter wheels or slide filters will move to the requested position. This is shown in the main interface of the acquisition program. Note that there is a different connection for the LMC300 and 400, shown in the next image.

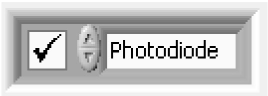

**Fig. 6.8:** LMC400 and LMC300 corresponding channels

In the Transient Recorder settings, the range values of the Transient Recorder, the discriminator level, the TR type and the sampling rate should be set. The ranges values are 0-20mV, 0-100mV and 0-500mV. These are selected based on the signal intensity observed when using the 'Lidar Alignment' program. According to EARLINET the range should be twice the signal peak. For example, if the signal peak is close to 50mV, 0-100nV should be used; or if close to 250mV select 0-500mV. **Setting the wrong range may result in signal saturation and eventually PMT damage.**

There are 64 discriminator levels (values 0-63) which correspond to either a range of 0-24mV without gain reduction or 0-96mV with gain reduction.

Transient Recorder devices may be of different types depending on the Lidar model. Each device must be set to the correct type TR (analogue and photon) or PR (only Photon).

The final parameter refers to all channels and is the photodiode. Select this (if it is available in your system) to monitor the laser's energy. The information will be recorded and appended as the last set of data of each measurement file.




After the Transient Recorder units have been configured, the configuration window may be exited by either pressing the 'Save and Exit' button (to save the information to the file path shown), or, alternatively, by selecting 'Exit without Saving' to exit without saving changes. Please note that when exiting the program without saving, any unsaved data is lost! Thus, if the dataset has been configured and may be of future use, the 'Save and Exit' button should be used. Alternatively, the 'File->Save Transient information as...' option from file menu may be used before exiting the program. In this way, the user can create as many different configurations as files required. It is also possible to load a file from the menu, which is useful when working with the 'Scheduler' program where a different configuration file can be used for each set of measurements. To use the current Transient Recorder configuration as the default option the data must be saved as Acquis.ini in the installation path.

### 6.2.2.2 Configuring Global Parameters

The global parameters are more general settings. Here the user can set:

- The working directory which is where the measurement data will be saved.
- The location information of the measurement site (8 characters length), longitude, latitude and altitude (in meters)
- The emitted wavelengths and frequency from laser source
- The ground temperature (in Celsius) and ground pressure (in mPa)
- The direction is an indicator of the angle of the Lidar (azimuth and zenith angle). For a scanning Lidar, the program gets the current direction from the positioner; if the user changes the values the positioner will move to the specified direction.

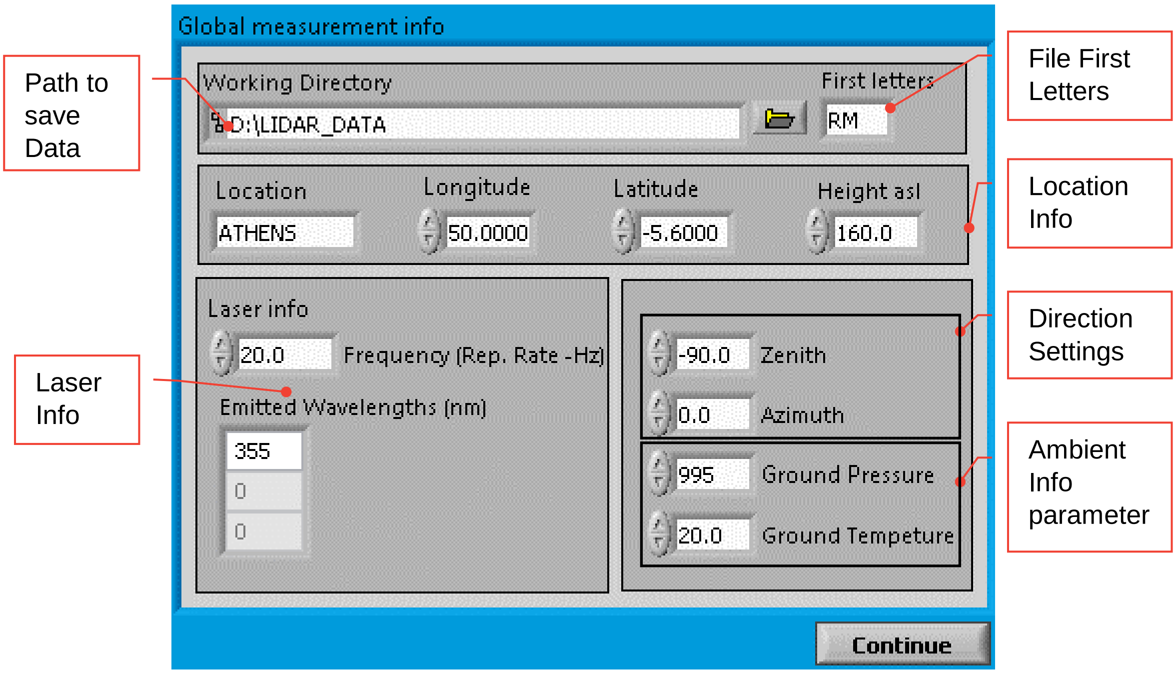



**Fig. 6.9:** Global Settings

After each of the above steps has been completed, every parameter has been set. Note there two types of parameters; those for information purposes and those which configure the measurement. All informational parameters are stored in a header in the data files, so that the user can see what parameters were used for each measurement. The information entered in these fields has no effect whatsoever upon the data acquisition. It is used purely to help the user categorize the measurement files. For example, the location field could be used during a telecover test to state the different parts of the telescope used ('East', 'West' etc.) or ‘Dark’ may be entered during a dark current measurement. This makes it easier when viewing data in the ‘Lidar Analysis’ program.

### 6.2.2.3 Configuring General Parameters

The TCP/IP tab contains the setup options. At the top is the option for whether the measurement will automatically start when the program starts. The measurement parameters (i.e. type of acquisition, number of shots, configuration file, etc.) are saved in the program initialization file ‘RM-TCPIP Acquis.ini’. This file is saved when the exit button is pressed. This means that if the ‘Auto Start Measuring’ option is selected, the measurement parameters used are those that were saved the last time the program was used.

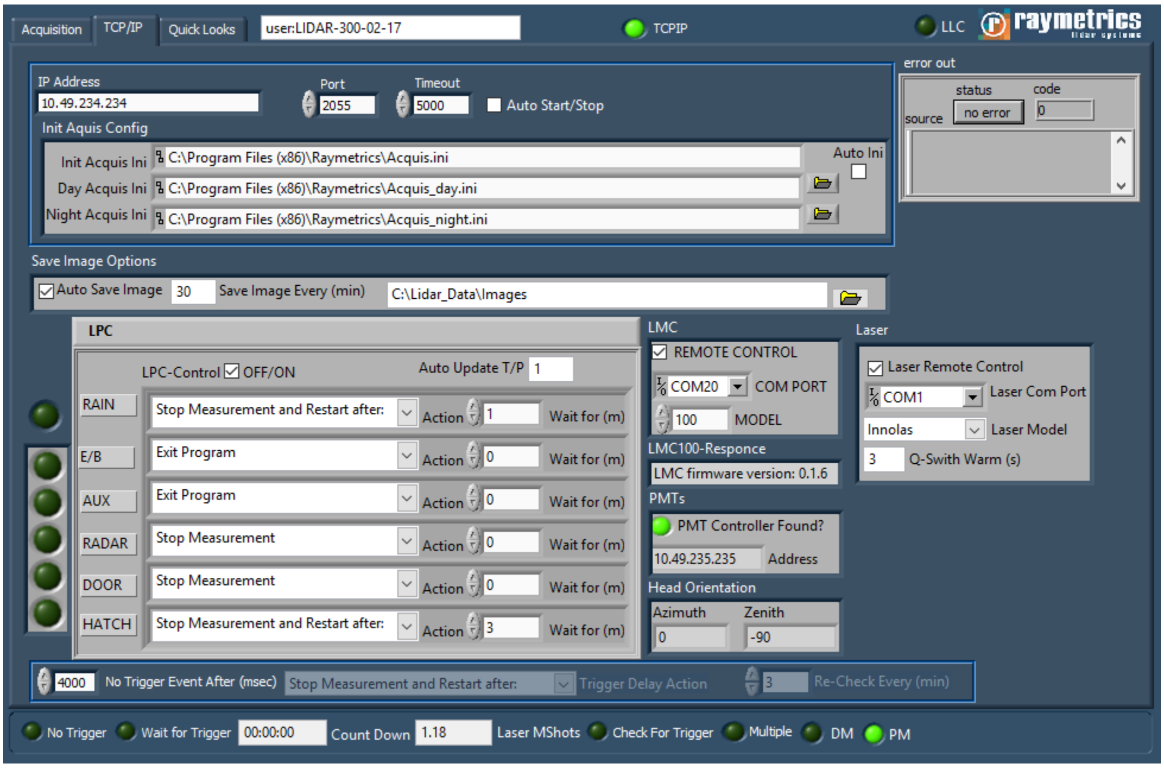



**Fig. 6.10:** Setup Tab Interface

Next are the settings for the TR and the PMT HV device. The IP address and port of the TR are by default 10.49.234.234 and 2055 respectively. If for any reason the TR has another IP address the user has to enter it in the box. The timeout refers to the time that the system will wait to establish the communication; if no communication is established by that time a dialog appears then the user can retry or cancel and change the TR’s IP address. The initialization file contains all the information regarding the dataset. The user may create from the dataset many different files and can select here the path of the one to be used during day time and night time. If the ‘Auto ini’ box is checked then the dataset will automatically change based on the time and the coordinates.

The option ‘Auto Save Image’ refers to the 2D plots from the third tab of the program. Here the user can set if the images displayed there will be saved or not, how often these will be saved and the folder where they will be stored.

The program constantly checks if the number of shots increase. If the shot number remains the same for a short period of time (which is set in milliseconds in the ‘NoTriggerTimeout_ms’ text box) the program automatically gets the status of the laser. If the laser has an interlock (other than an external one), it stops and writes the cause on the log file. It also sends an e-mail to the user if it is running from the scheduler. If the interlock is an external one[1], the system will perform the action which is set in the corresponding control. There are four ways that the software can deal with external interlocks:

a. Ignore: The program does nothing; it pauses the measurement. If the laser restarts the emission it continues writing to the same data file.

b. Stop Measurement: The program stops the current measurement, rejects the last profile and updates the log file, as if the user had pressed the stop button. To restart it requires the user's intervention.

c. Stop Measurement and Restart After: The program stops the measurement as in the previous option but it will try to restart after the time delay specified in the box at the right has elapsed. The measurement then starts in a new record.

d. Exit Program: The program stops the measurement as in the previous options and exits completely.

Furthermore, if there is an LPC device included in the Lidar, the program establishes the type of the external interlock and handles each case individually. The user should set the action for each case. If for example the door opens the user may decide that the measurement must stop and the system should wait for the user's action to restart. But if it is raining the user may require that the program restarts automatically when the rain stops.

Finally, the program will establish the communication with the PMT HV controller, the laser, the positioner and the LMC. Here the IP address of the PMT HV appears in the text box and the current position of the positioner. There is, also the option to set individually, the LMC and the laser type and communication port and whether there are to be controlled by the program or not.

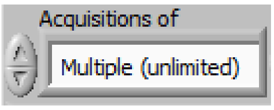
[1] An external interlock is an interlock that is connected to the laser's BNC input connector. For example, if there is a switch on the Lidar enclosure door connected to the BNC interlock, the laser emission will be stopped when the door opens.

### 6.2.3 Lidar Measurements

There are two different ways to acquire Lidar measurements. Each one results in the same lidar data being acquired; what differs is the number of files created and the total time of the measurement. These are described below.

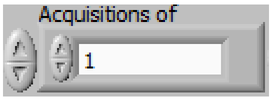
a. Multiple unlimited Acquisition

With an unlimited measurement, the lidar will start measuring when the user presses the start button and will stop when the stop button is pressed or an event such as an interlock occurs. To select this, press the up arrow so that the 'Multiple' appears on the box.



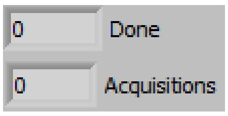

b. Multiple finite Acquisition

This of measurement, will perform a predefined number of acquisitions. To do so, press the arrow pointing upwards on the left of "Acquisitions of" and a smaller numerical input box will appear in place of "Multiple (unlimited)", allowing you to specify the number of required measurements to be acquired. In this case, the measurement is stopped when the desired number of profiles has been reached.

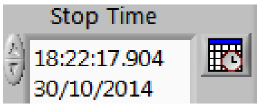



In either case the file is saved as one record containing many profiles. Each profile is the average of single profiles which correspond to single laser shots. The number of shots can be set in the 'Shots' box. This setting determines how many profiles will be averaged to create a single averaged profile. The higher the value, the smoother the Lidar data you get, but higher values also mean longer times between profiles. As a general guideline, a fast acquisition is 200 shots and a detailed one is 1200 shots. If for example the repetition rate is 20Hz the 200shots acquisition will take 10seconds and the 1200shots one minute. The maximum allowable value is 4094, due to Transient Recorder RAM limitations.

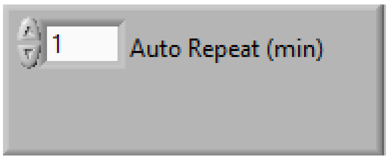

The 'Done' box indicates the current shot number. Right below this is the 'Acquisition' indicator which shows the current number of acquisitions taken.



Since users usually need to measure for a specific time duration there is a tool to calculate the number of profiles that fit in this time frame. To do this, the user has to set a stop time in the 'Time' box and press the button to calculate, based on the number of shots for each profile and the repetition rate, how many acquisitions are required. This is shown in the 'Acquisitions of' box which is automatically updated.




Another way of measuring is also on a repeating pattern. For example, one may need to take one hour of measurement wait for 5 hours and repeat this until the stop button is pressed. The user can set the wait time on the Auto Repeat box. If this value is set to 0 then it will run the measurement only once. If the lidar has a hatch or it is a scanning lidar, the user has the option to close the hatch or park the lidar head, respectively.




Once the settings are all set the user must press the Start button.


**WARNING:** When the Start button is pressed it automatically starts the laser light emission from the output aperture of the Laserhead. Follow the safety instructions carefully. Do NOT look directly the laser beam.

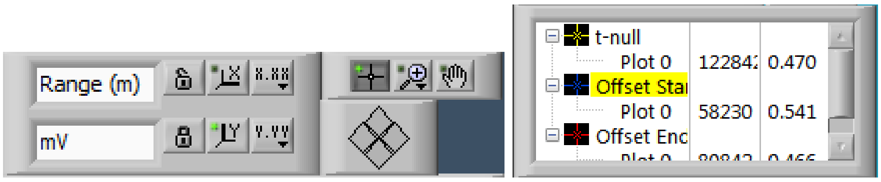
The Transient Recorders, which were activated at the datasets configuration stage, should be now acquiring data. If the acquisition has started successfully, the number of shots completed in the 'Shots' indicator box should start increasing. When this number reaches the number set by the user, the graph area will display the measurement taken and a new unique file is saved containing the raw data. A new record is simultaneously created in the datalog file with the current start and stop time. When the next profile is acquired a new data file is created and the datalog is updated with the new stop time. If the stop button is pressed the running acquisition is rejected but all profiles before that are saved and registered in the datalog file. If it is the first acquisition then no file will be saved and no record will be registered in the datalog. When using the single acquisition mode press the 'Save' button to save acquired data to a unique file and register the record in the data log file.

The naming convention is explained in section *'7.1 Data File Handling'*. The waveform graph is refreshed with the newly saved data and a new measurement is begun.

The desired dataset to be displayed can then be selected from the drop-down list. Note that in the description 'P' stands for the polarization type.


The display mode can also be changed using the drop-down box to see the raw signal (raw), the offset corrected signal or the Range Corrected Signal (Pr2).


Underneath the graph are controls to customize its view; the user can change the scale of the axes, the units, lock the axes or set to auto-scale, zoom in on a selected area or pan the graph. Also, the user can place cursors on the graph by using the controls below. Each cursor has its properties like colors name behavior etc. The user can access the properties by clicking on the cursor sign.




In the bottom-left corner are two indicators. The left one ('No Trigger') lights up when the transient recorders are not triggered; either because the laser is not emitting or the trigger cable is not connected. There are several reasons that may prevent the laser from emitting. The most common is an interlock which comes from the various interlock sources connected to the BNC input of the laser. The second indicator ('Wait for Trigger'), lights up when the program is waiting for the trigger to start again to continue with the measurement. Next to that the countdown indicator shows the time required to check again for the laser. Next to the counter is an indicator showing the flashlamp's shots in millions. If this number reaches 50 the flashlamp needs replacement.


The third tab titled 'Quick Looks' provides an overview of the data acquired in a time evolution plot form. Here the vertical axis is the range and the horizontal is the time each measurement was acquired. The signal intensity is represented by an adjustable color scale. This is used as a reference for a more precise measurement the user can perform a post analysis with the analysis software. The graphs shown here are the range corrected signal and the volumetric depolarization ratio. Make sure that the correct depolarization calibration factor (V*) is set. For more information about the depolarization calibration factor see paragraph *'7.3.9 How to Retrieve the Depolarization Calibration Constant'*. When the PBL is easily distinguishable, the program will use the measurement data to suggest a calculated height. The software also has an auto low cloud detection mode that is used in cloudy places. A low cloud can reduce the signal too much resulting in measurements of no interest. Therefore, the lidar checks the signal after a low cloud and if it is too weak the measurement will stop and will restart after a predefined time. If the signal is okay the measurement will continue normally but if the cloud insists it will reject the measurement after 100shots, stop and try again.

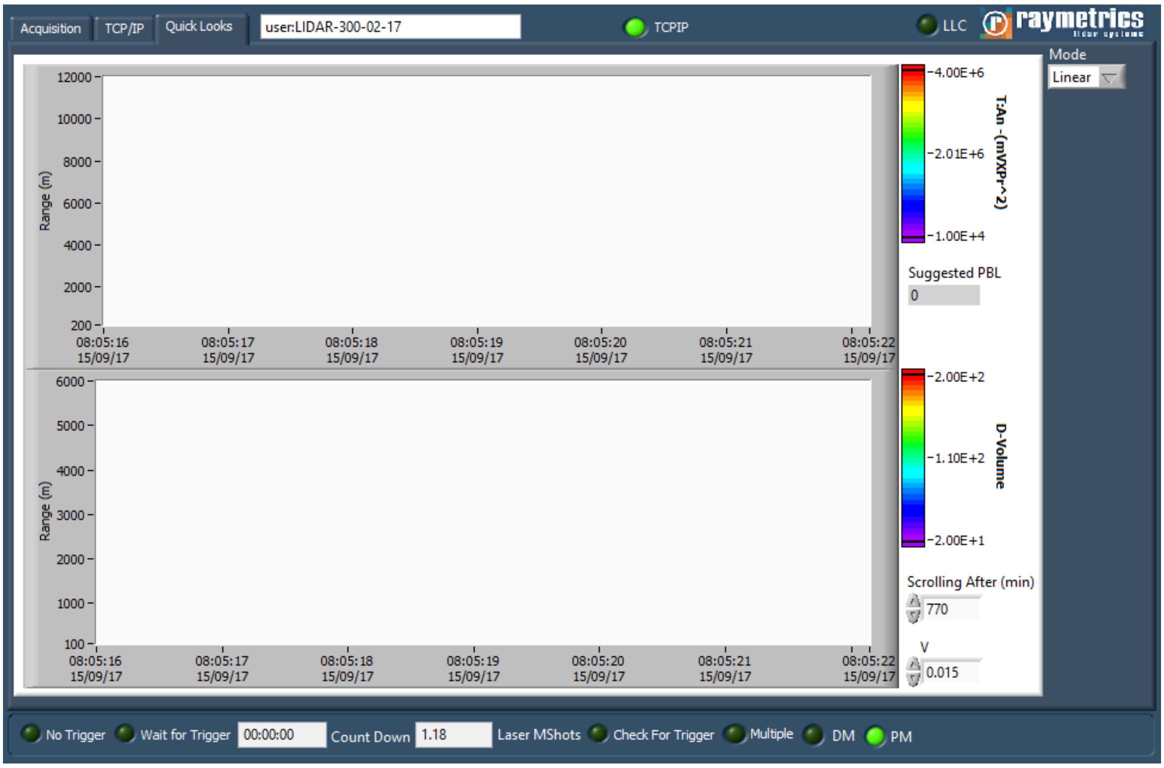



**Fig. 6.11:** Quick looks Tab Interface

Every time a new profile is acquired it is added as a strip at the end of the graph and the image is refreshed. To reduce the memory required for the program, a limited number of profiles can be shown. When the limit is reached the first profile will disappear from the left to make a space at the right for the new profile. This limit is set on the 'Scrolling After' box which sets for how long it will keep adding the profiles until the graph start to roll. For this reason, the images can be saved at any time in the folder specified. These parameters (time and folder to save to) can be set in the settings tab.

Finally, the program calls two other programs that collects information from them; one is the LPC interface and the other one is the power meter. This also means that before starting the acquisition program the LPC interface and power meter programs must be closed. The

LPC interface (shown in paragraph *'4.3.4 LPC Interface'*) gives the user the option to open and close the hatch and start a datalogging. Both functions are automatically controlled by the software, therefore the user should not interfere with these sub-programs while a measurement is taking place.

The Power meter interface is a simple display of the laser's energy. A calibrated photodiode is used to acquire the energy for each laser shot. This software communicates with the Acquisition software and saves the laser energy in the RAW data file.

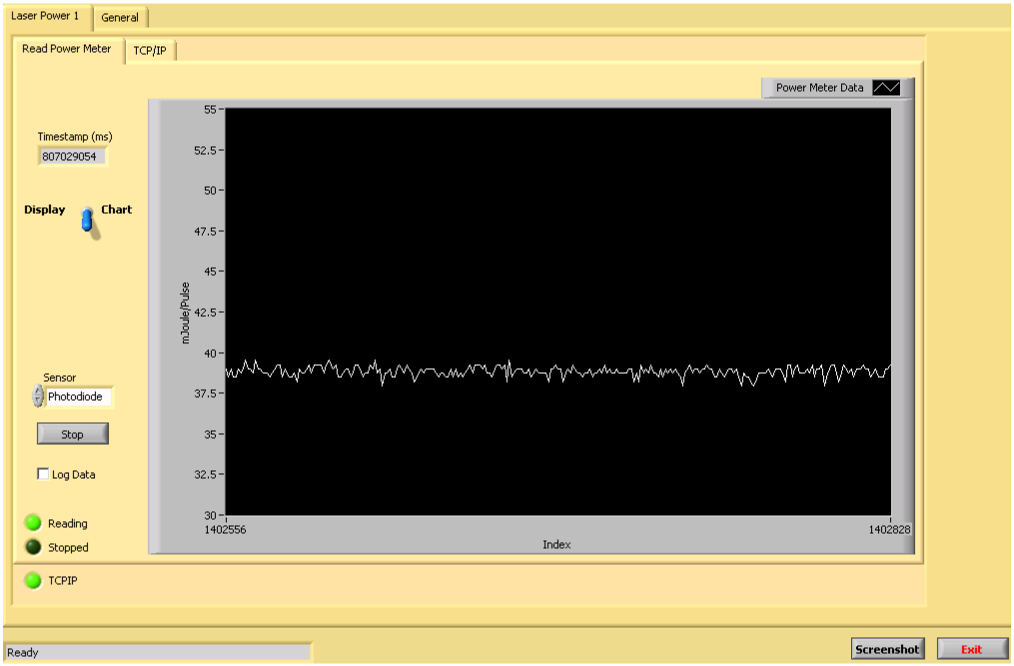



**Fig. 6.12:** Power meter Interface

## 6.3 Scanning Acquisition

One can understand that the acquisition software is used to perform measurements in a fixed position. This position can be set by the user but it will not change throughout the measurement. A scanning lidar's main purpose however, is to perform scans of a selected area. For this reason, the scanning acquisition software is used. Here the user can select amongst three modes of scan; Plan Position Indicator (PPI), Range height Indicator (RHI) and 3D scan. In the image below the differences of the PPI and RHI are explained. The 3D scan is either a series of PPI scans in different zenith angles or a series of RHI scans in different azimuth angles.

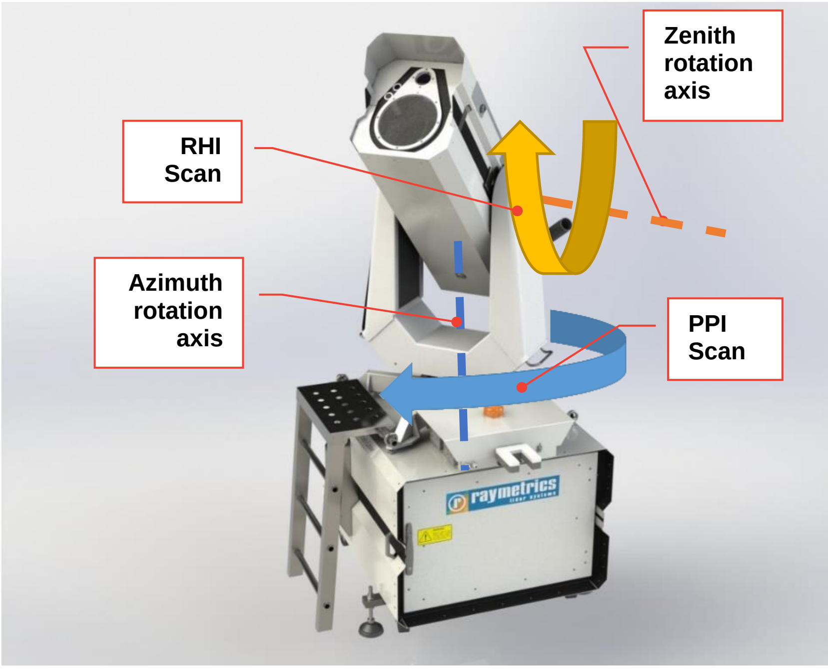
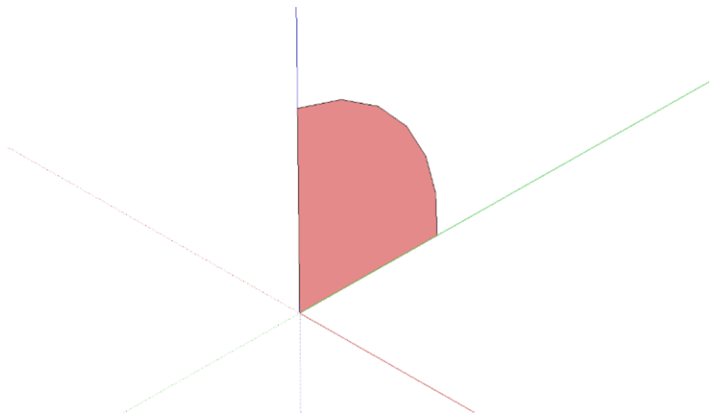


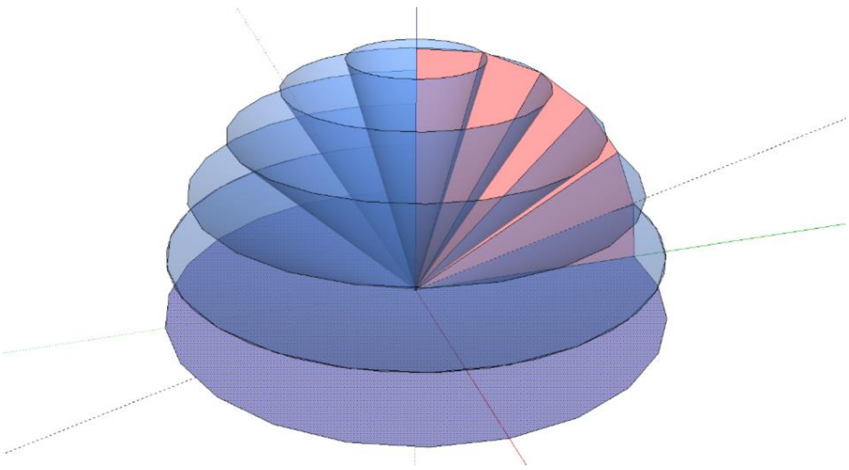

**Fig. 6.13:** Scanning Modes

Before starting an acquisition, it is important to understand the geometry of the scans. The geometry of an RHI is quite straight forward to understand.

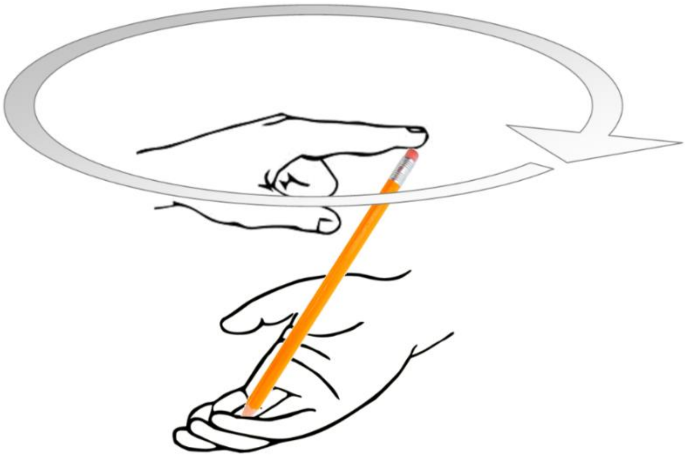


An RHI scan is a section of a circle in a specific azimuth angle. For example, let assume that we want to represent a zenith scan from 0 to -90 degrees in zenith range and positioned in 0 degrees in azimuth position. This type of scan will look like the image above. The green axis is the Y axis the red is the X and the blue is the Z.

The PPI scans however are a bit more complicated because they depend on the zenith elevation. For example, a 360 degrees scan in azimuth range and in 0 degrees in zenith will look like a whole circle on the X-Y plane but as the zenith angle increases the circle becomes a cone. As shown in the image below, the bigger the zenith angle that is chosen for a PPI scan, the more the lidar's movement will resemble a cone.



Visualizing things makes it easier to understand so a quick test can help. Take a pencil and hold it with your fingers from the top. Place the tip on the other hand hold the tip so that it stays at the same point. Tilt the pencil a little. Now move your top hand in a circle.



The pencil is the range (the maximum distance that the lidar can see). This remains constant like the length of the pencil. If you notice you will see that the pen moves on a cone.

### 6.3.1 Introduction to the Scanning Acquisition Interface

The RM-TCPIP Acquis_Scanning program is used to take scanning measurements. As seen below, the main interface resembles the acquisition software.

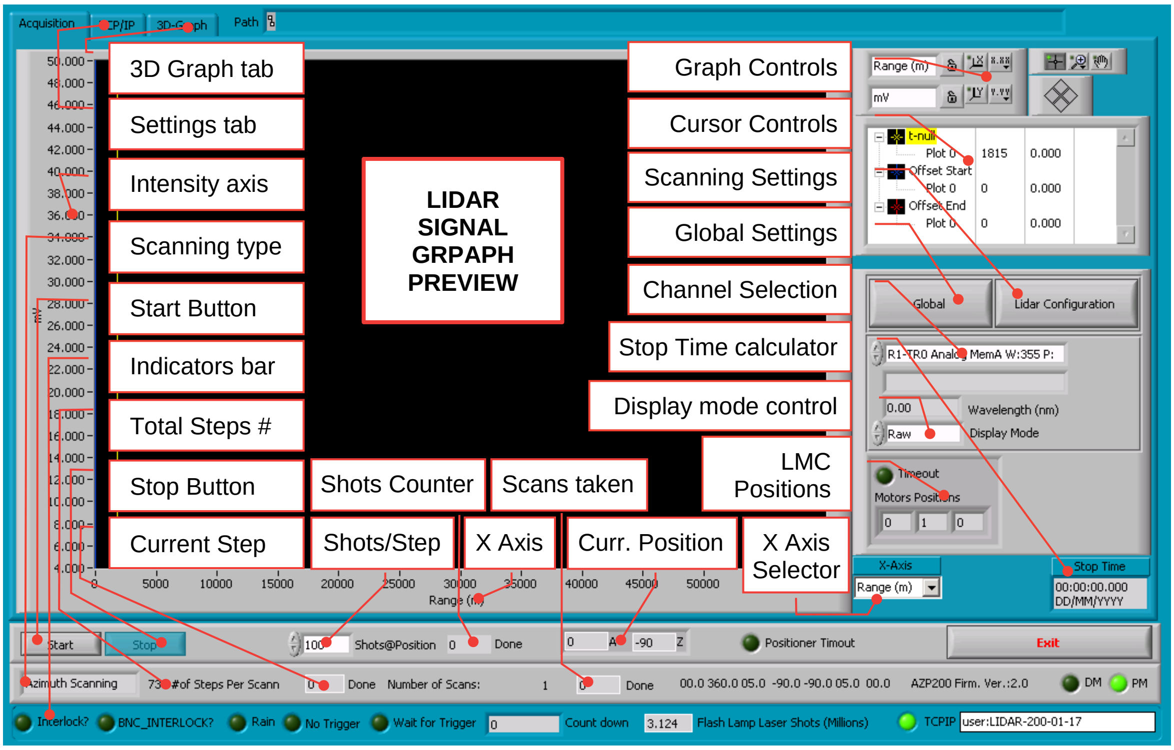



**Fig. 6.14:** Scanning Acquisition Main Interface

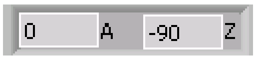
This program saves raw data files as the Acquisition (fixed-point) program but the difference is that after a profile is acquired, the Lidarhead will move to a different position to acquire the next, according to the scan that was selected. This is otherwise called a step. So, for each step the program saves a raw data file. This is done for a predefined set of angles; once all the user-selected area has been scanned, the program will stop or repeat the measurement, according to the settings.

A list of similarities with the fixed-point measuring program is presented below:

- a graph where the live signal is displayed,
- the controls and cursors of the graph,
- the channel and display mode selectors,
- the indicators for the LMC positions,
- the global settings,
- the shots per step (profile) along with the done indicator,
- the indicators bar
- and the start and stop button.

The above have been explained in detail in the *'6.2 Data Acquisition'* paragraph. Here only the extra parts will be explained. The first noticeable difference is the X axis selector; since this is a scanning lidar this can be either expressed in range as it is measured or converted into altitude.


Another noticeable difference is the position indicator. This simply indicates the azimuth and zenith angle that the head is pointing at.




Right below the position indicator are two more indicators; on the left is displayed how many scans are to be performed and on the right, there is a box that indicates how many scans have already been performed. This refers to a full set of angles, for example a PPI scan that is repeated many times.


On the right of the scans indicators is the equivalent steps indicator. On the left it is displayed how many steps will be performed for each scan and on the right, there is a box that indicates how many steps have already been performed.


The box on the most left displays the type of the scanning. This can be azimuth scan (PPI), zenith scan (RHI) or 3D scan.


Finally, one of the main differences is the Lidar configuration button. In the fixed-point program, this button opens the dataset dialog, here there are also the scanning settings that the user must set. These settings are explained in the next paragraph.


### 6.3.2 Configuring Scanning Measurements

The scanning Lidar configuration is divided into three sections; general, scanning and TRs. From the file menu, the user can load and save any configuration for these three sub settings individually. For example, on the TRs tab is the dataset which is already explained in the fixed-point measurement. The user probably has a file that was created with the acquisition program and can load it here.

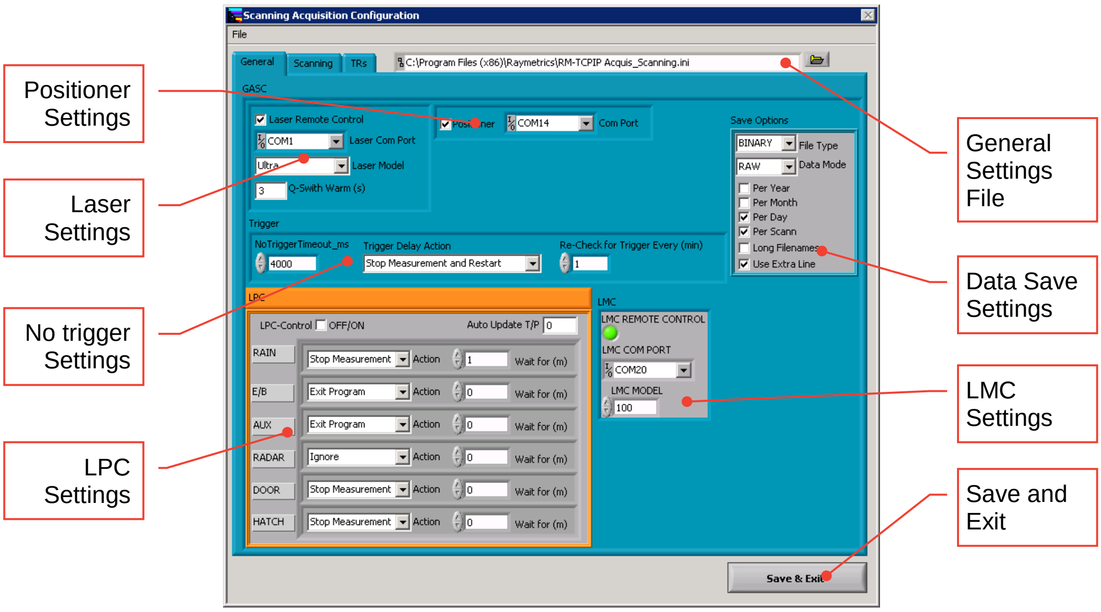
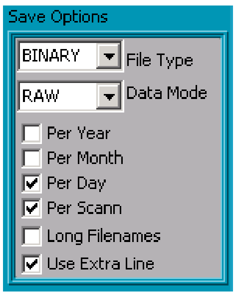



**Fig. 6.15:** Scanning General Settings

The laser, the 'no trigger', the LMC and the LPC settings are the same as those of the fixed-point acquisition program. What mainly differs here is the communication settings of the positioner and the save options. The save options give the user some advanced save features if for example the file will be in a binary format or if it will contain the RAW or RCS data. Furthermore, the user can select how the data will be organized in the folder, that is if the first four boxes are checked the program will create a folder named 2017, inside this, there will be the months folder which is in a hex number, then in every month folder will be the days folder and inside the days folder it will be the daily scans folders where the raw data files for each scan will be saved. This way the data remain organized into folders that can be then accessed easily with the analysis software. Finally, the last two options (Long Filenames and Use Extra Line) refer to an older name convention and to an old header format. Check both if your system is built after 2016.




**Note:** To use the Raymetrics analysis software the data must be RAW and saved in a binary format. Also, all the boxes shown above must be ticked.

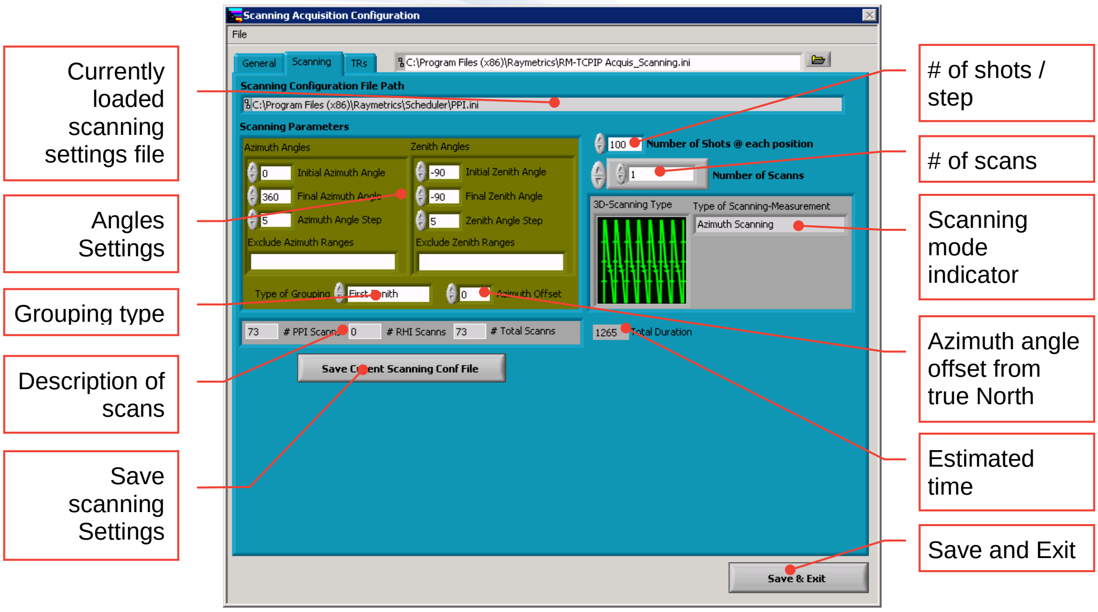


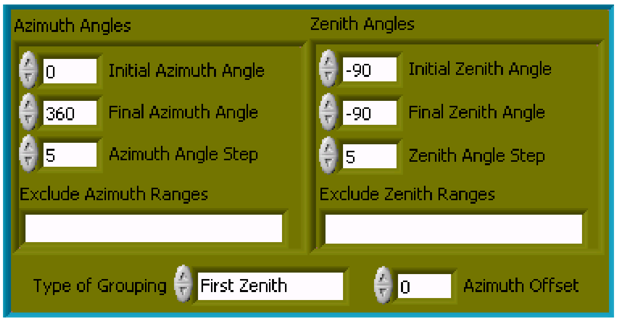

**Fig. 6.16:** Scanning General Settings

The second tab contains all information about the area that is to be scanned and how the scanner will move to perform the scans. On the top, is the indicator of the path and filename of the current scanning configuration file. This file contains all information that is described in this tab in text format.


Below the file indicator is the angles settings that describes the range of the angles and step for the azimuth and zenith movement. The parameters the user must set here are:

- The initial and final zenith angles
- The zenith step angle
- The initial and final azimuth angles
- The azimuth step angle
- The grouping type of a 3D scan.

In this example, the initial azimuth angle is 0° and final is 360° with a step of 5° degrees, 73 measurements will be taken at 0°, 5°, 10°, …, 350°, 355° and 360° degrees. The zenith angle in this case is fixed, meaning the initial and final angles are the -90°. If, in addition to the first, the zenith initial angle is 0 and final is -90° degrees, a full hemisphere will be scanned. With a step of 5° degrees also for the zenith, the total number of measurements will be 73 x 19 = 1387. This is a 3D scan and is, in fact comprised of multiple PPI scans or RHI scans depending on the chosen grouping type. The "first zenith" grouping type means that the measurement will start with an RHI scan at 0° azimuth then move to 0° zenith and 5° azimuth and repeat the RHI scan. This will continue for all 73 steps of the azimuth resulting in 73 RHI scans. If the first azimuth is selected it will result in 19 PPI scans. There is also the option to perform a measurement with the Lidarhead making in a snake-like movement that is if snake zenith is selected the measurement will start at 0° azimuth perform an RHI scan from 0° to -90° and then move at 5° azimuth and go backwards from -90° to 0°. The snake option is rarely used because of the complexity in the analysis.

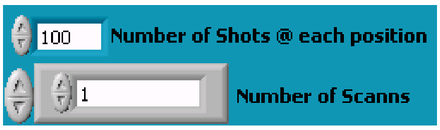



Using fixed numbers for the zenith and azimuth angles will render the measurement a fixed-point one which can be later used at the scheduler program.

The user can exclude some angles from the which can prove useful in the case that there is an obstacle that needs to be avoided. The azimuth offset refers to the angle between the true north and the 0° azimuth position of the head measured clock wise. It is very common because of space limitations, that the lidar does not point to the north at home position. The user must know the offset angle and set the number in this box so that the graphs will align with the true north. Even though, this is performed by Raymetrics during the installation the user may change the position. In this case, by using nearby targets such as buildings and then triangulating on a map, find the exact position and the offset from the north.

Below the angles setting there is a description with the total number of measurements (steps) in azimuth or in PPI, zenith RHI and total.


The number of shots describes how fast or detailed the measurement will be. Measuring with 100 shots is quite fast but with the total range will be reduced. Increasing this number, on the other hand, will result in a very long measurement.




Based on the total steps, the shots per step setting the repetition rate of the laser, the number of scans and the time required to move from one position to the other, the program estimates the required time. In this case the total steps are 73 multiplied by 100 shots divided by the repetition rate 20Hz and multiplied by the number of scans 1 results to 365 seconds for the measurement and then 12.5 seconds multiplied by 72 steps results to 900 seconds for the movement. That is in total 1265 seconds are required for this measurement.


By pressing the save button it will save the current setup to the loaded file that is indicated on top. The user can save and load different scanning configuration files using the file on the menu bar. The files are in ASCII which can also be edited with a simple text editor.

The last tab is not presented here since it is the dataset configuration that is explained in paragraph *'6.2.2 Configuring Measurements'*. Similarly to the scanning configuration the user can load and save any dataset file using the file on the menu bar. Both the scanning and the dataset configuration files and paths will be saved in the general configuration file (RM-TCPIP Acquis Scanning.ini) where are also saved the general settings from the first tab.

The user can verify the selected configurations files at the TCP/IP tab. At the same tab the user can set whether the measurement will automatically start upon program startup and if the program will park the head in zero (home) position when it exits. Finally, like the acquisition program the user can select if and where to automatically save the images from the 3D-Graph which is illustrated in the next paragraph.

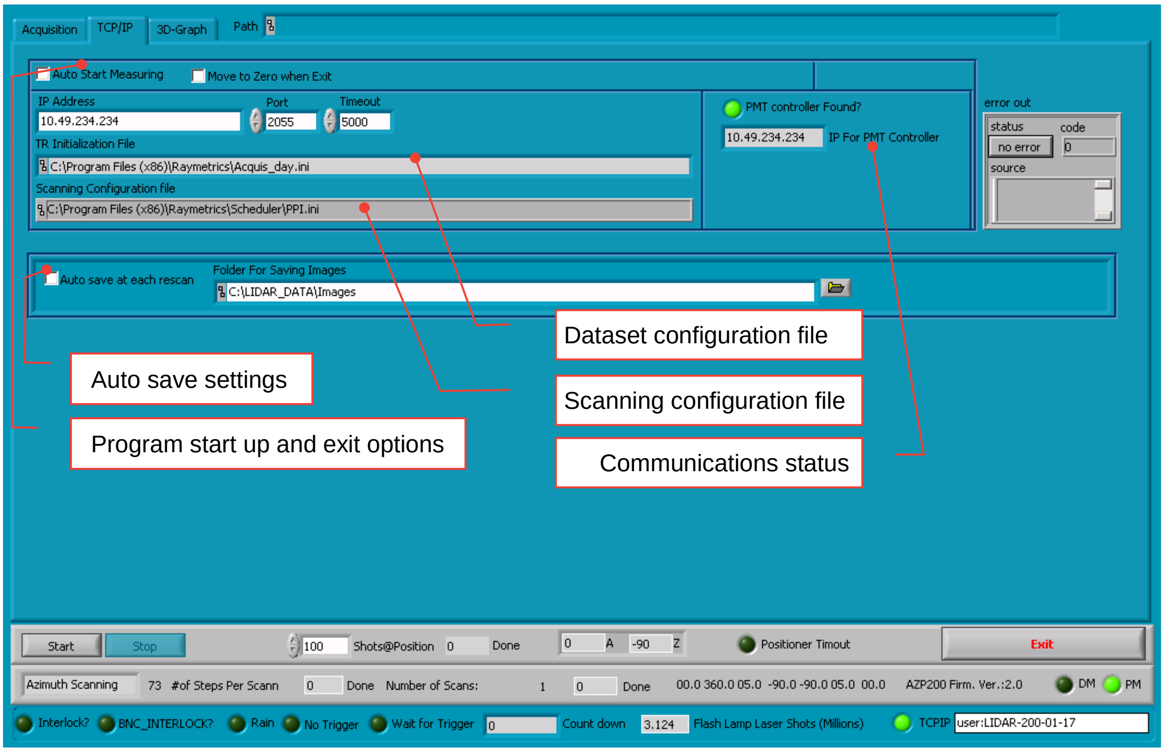



**Fig. 6.17:** Scanning Acquisition Setup Tab

### 6.3.3 Lidar Scanning Measurements

Once everything is set the measurement can begin by pressing the start button.

**WARNING:** When the Start button is pressed it automatically starts the laser light emission from the output aperture of the Laserhead. Follow the safety instructions carefully. Do NOT look directly the laser beam.

The positioner will move to the first position and the first file will be saved when all shots for this position are done. This first measurement will be plotted in the '3D-Graph' tab. The positioner will then move the head to the next position and take another measurement which in turn will be saved and added to the same plot. The user can select which product will be plotted (RCS or depolarization ratio) but this must be done before the measurement starts. If depolarization ratio is selected, make sure also that the correct depolarization calibration constant is selected. The program runs a quick data post processing and apart from the products of the plot can also recognize cloud structures and give a report of the altitude and thickness. Finally, on the right of the interface are the controls of the 3d graph. Here the user can pan, zoom in and out and rotate the graph, change the scales and create projections. To change the range of the plot (not the axes) use the "Range" box at the bottom right corner.

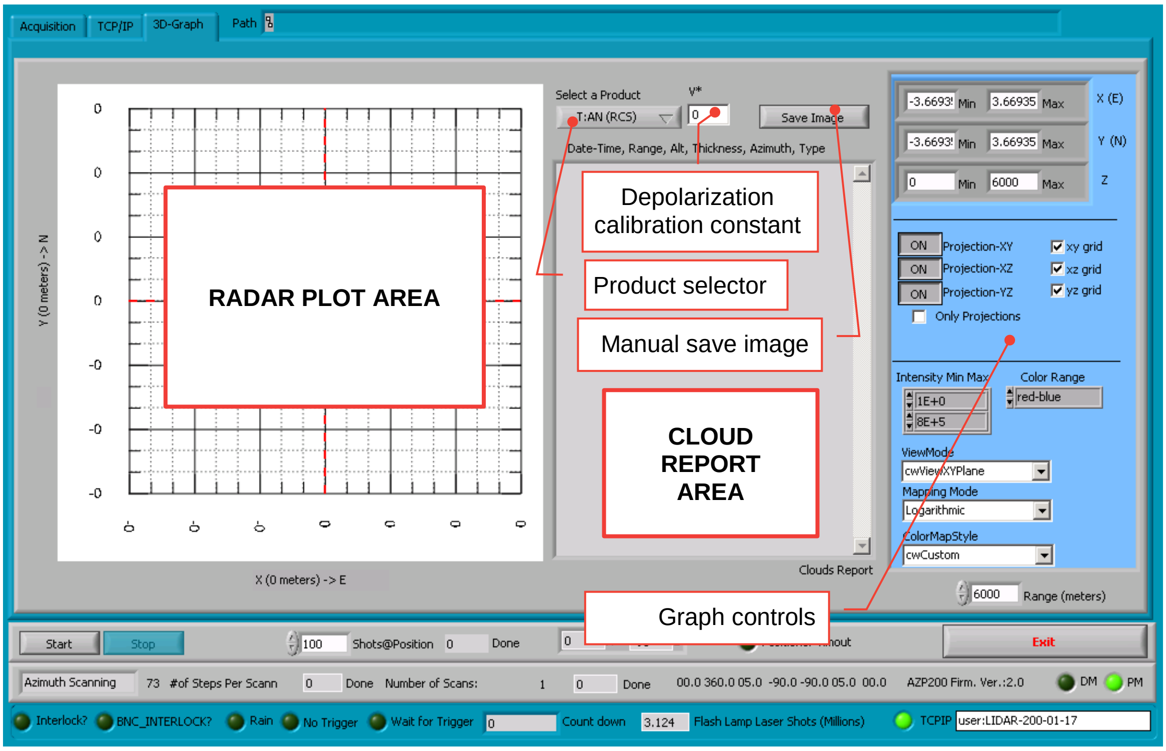



**Fig. 6.18:** Scanning Acquisition 3D-Graph

## 6.4 Measurement Scheduling

The ‘Scheduler’ program is an extremely useful tool. With this software, the user can set a series of programmed measurements daily. The main purpose of this tool is to perform Lidar measurements without the need of an operator. This, in combination with the remote setting and alert setup, allows for a fully remotely operated Lidar.

The interface has four Tabs. The main tab is the ‘Scheduler’ tab. This contains the timetable and the scheduler status information.

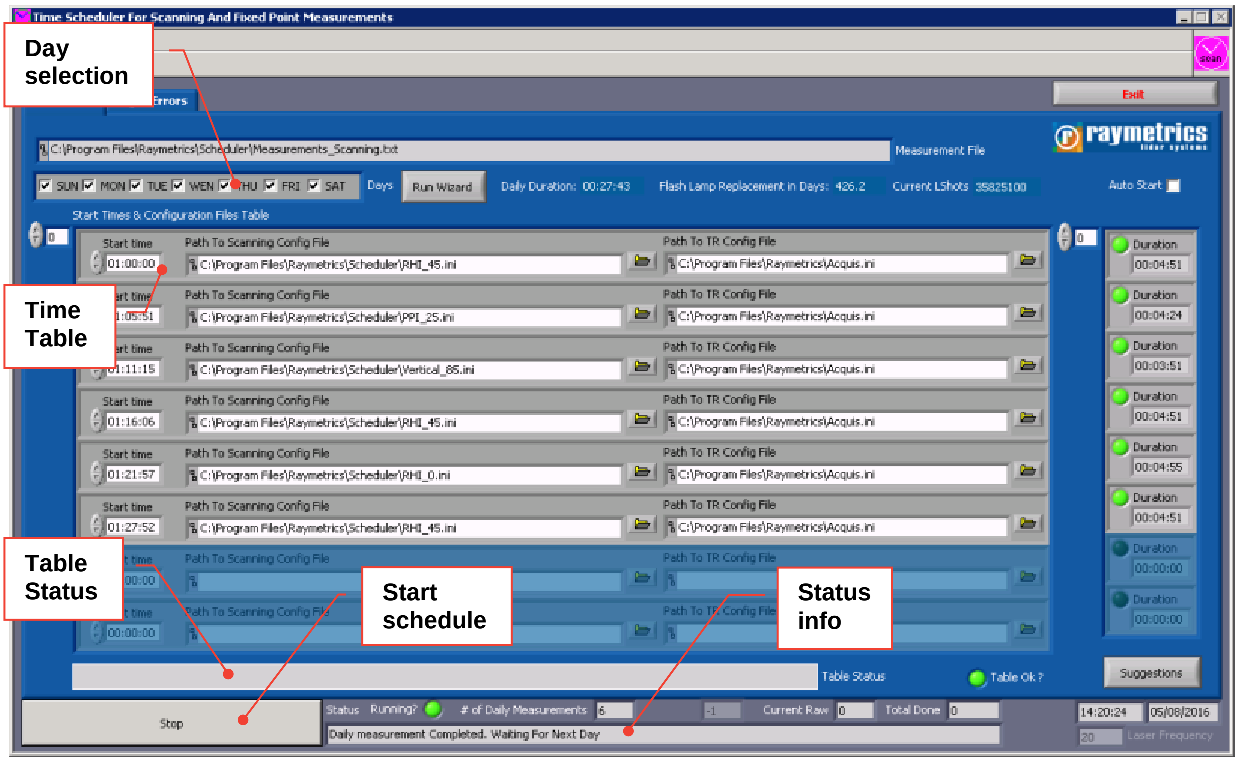



**Fig. 6.19:** Time Scheduler Main Interface

At the top of the window is the day selection area. Select here which day(s) of the week the programmed schedule will be run.

The timetable offers a wide array of inputs. As many configurations and start and stop times as needed can be added, allowing the user to conduct any number of measurements of different types. The control beside the table allows the user to navigate though the timetable. 

Each measurement requires three main parameters:

- Start time
- Scanning Configuration file to be used
- Transient Recorder Configuration (Dataset) file to be used

To make a usable timetable the user should bear in mind that the Start time of the next measurement must be later than the stop time of the previous one. Therefore, the box on the left indicates the duration of each scanning measurement. Also, the configuration files and paths to those files must be valid.

The transient recorder configuration file is the file saved with the use of the acquisition program. This file contains information of which channels are to be recorded and what should be the voltage for each PMT. See also paragraph '*6.2.2 Configuring Measurements'*.

The scanning configuration file contains the information of the scanning scheme. This can be a PPI scan, an RHI scan or a fixed-point measurement. See also paragraph '*6.3.2 Configuring Scanning Measurements'*.

There is also a wizard button that can make the scheduler configuration procedure easier especially for patterned measurement set. For instance, starting with a PPI scan then an RHI and a fixed point that repeats throughout the day. For more information click the suggestions button. Finally check the auto start box 

, to start the schedule upon program startup. In addition to this setting, if the scheduler is placed in the windows startup folder, when windows start it will automatically run the program and start the schedule. This ensures that the measurement automatically restarts after a power failure.

## 6.5 Remote Lidar Operation

The Lidar can be fully remotely controlled. When it is connected to a network it automatically acquires an IP address. Any user in the same network should then be able to connect to the Lidar's computer via Windows Remote desktop program. If this network also has internet access with the appropriate permission from the network administrator it is possible to connect externally to the Lidar from anywhere in the world. In this section, there are some practical guides on how to connect and operate the computer remotely.

### 6.5.1 Establishing a Connection

Once the Lidar is connected to an external network, Windows Remote Desktop software (or another remote desktop software) can be used to control the Lidar's computer. Follow the steps below to establish a connection from a Windows XP or later Operating System.

1. Open the network to browse all computers connected to your network.
2. Locate the computer named 'LIDAR-200-02-17' and right click.
3. In case you cannot find the Lidar computer, first make sure that the Lidar is powered on, and that the connection cable is connected to the Lidar and to the wall socket or to an

external computer; i.e. a laptop connected directly with a cross link cable. If this does not fix the problem, try using another cable or another wall socket. Note that when the lidar computer is powered on, a certain time is required for Windows to boot and connect to the network.

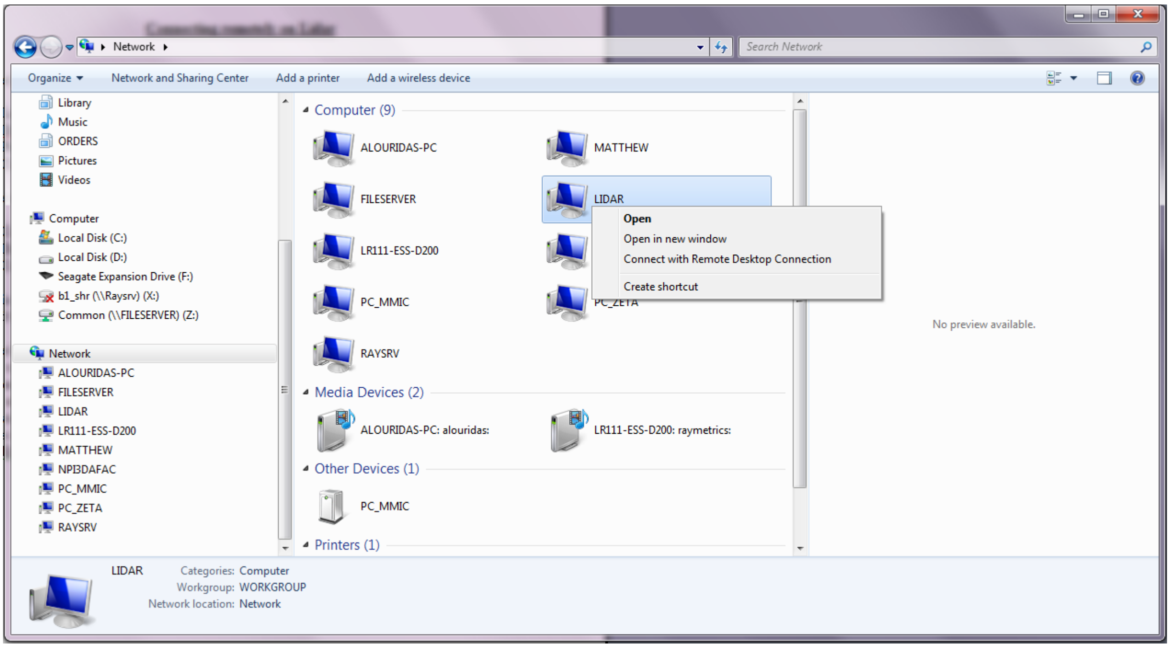
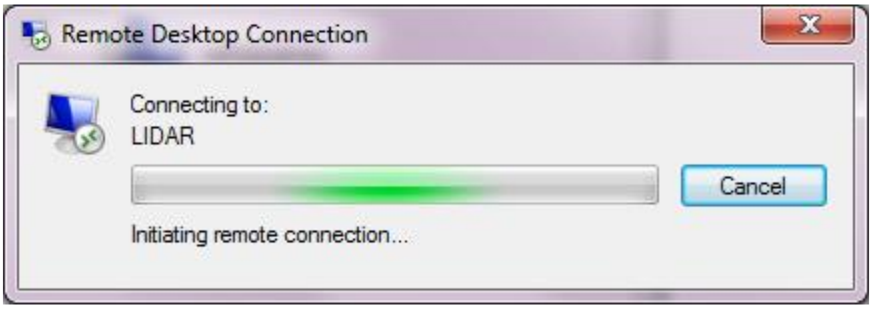
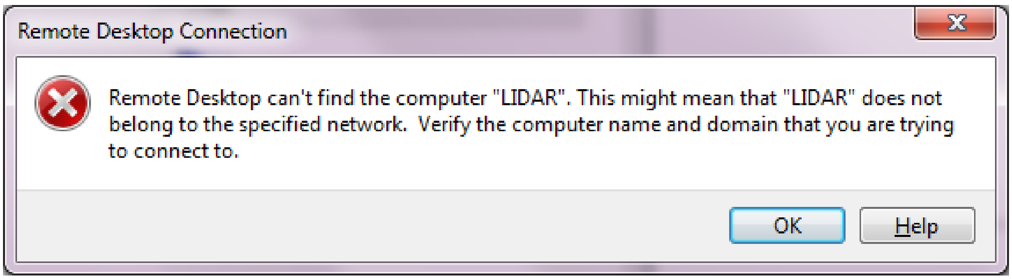



**Fig. 6.20:** Lidar Computer on A Network

4. Right click on the Lidar's Computer icon and select “Connect with Remote Desktop Connection” (RDP). The window below should appear.




5. Wait for a couple of seconds. If it takes longer than one minute then the connection probably cannot be established and the window below will appear.



6. The most common reason for this is that the computer is turned off. You can see how to remotely wake up the computer in the section '*6.5.2 Shutdown and WOL*'. If the problem persists refer to the section '*6.5.3 Remote Connection* '.
7. Key in the username and password when prompted and check 'Remember my Credentials'.

   By default, the account used has the credentials below:

   Username: u**ser**

   Password: **lidar**
8. A new window will open showing the Lidar's desktop. Use the mouse and keyboard to control the Lidar.

**NOTE:** that this is a window which you can resize, minimize and close like all windows. When you resize keep in mind that you are no longer viewing the whole screen. There might be icons missing or the taskbar may be missing, which you can view by using the scroll bars.

Also keep in mind that when the user closes the window the Lidar computer does not turn off but only the connection is closed. The computer logs off and remains turned on. If it is required to shut down the computer refer to the section '*6.5.2 Shutdown and WOL*'

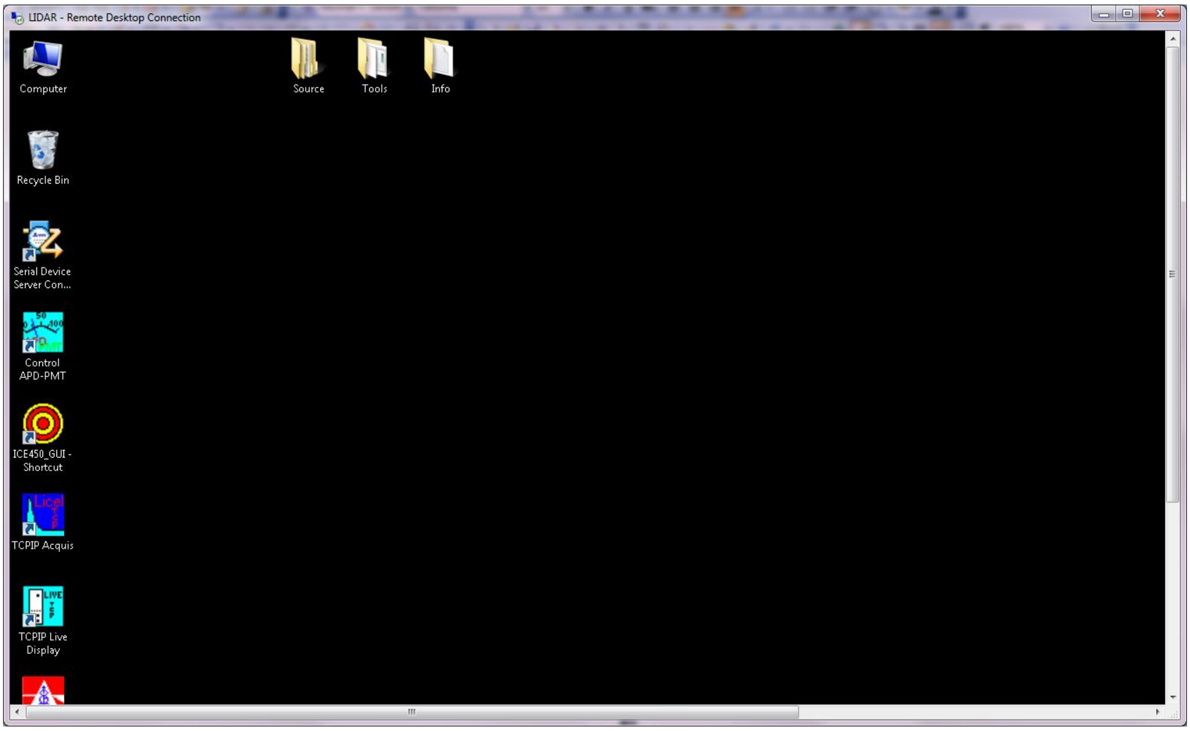



**Fig. 6.21:** Remote Desktop Window

## 6.5.2 Shutdown and WOL

If the lidar computer is running on windows 7, when connected with remote desktop, the options in the 'Start' menu are limited to 'Disconnect' and 'Lock'.


**Fig. 6.22:** Limited Shutdown Options

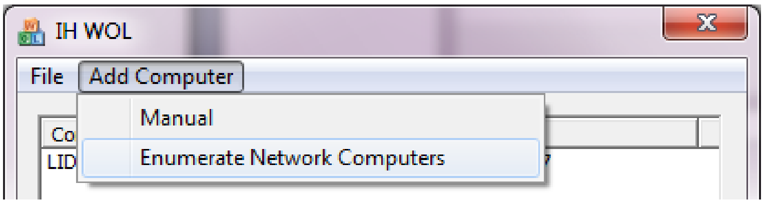
In order to shut down the computer, click 'Windows Security' right above the 'Log off' button. This will open a new screen which is shown when 'Alt+Ctrl+Delete' is press in Windows 7. From there select to shut down safely the Lidar computer.

**NOTE:** By default, the key shortcut 'Alt+Ctrl+Delete' refers to the local computer and not the Lidar’s computer. There is however the option to use this shortcut also in the remote connection. Please refer to the *'6.5.3 Remote Connection '* section.


**Fig. 6.23:** Windows Security

The next step is to turn the computer ON remotely through the LAN. This procedure is called 'Wake on LAN' and it is an event that wakes up the computer using the local network or even the internet. To do this a packet of codes must be sent from the local computer to the Lidar’s computer, which is called 'Magic Packet'. This packet is produced and sent with very simple software which is called in general 'Magic Packet Sender'. You can find many free programs over the internet. All programs need the Lidar's IP and MAC address to work; however, some require more information.

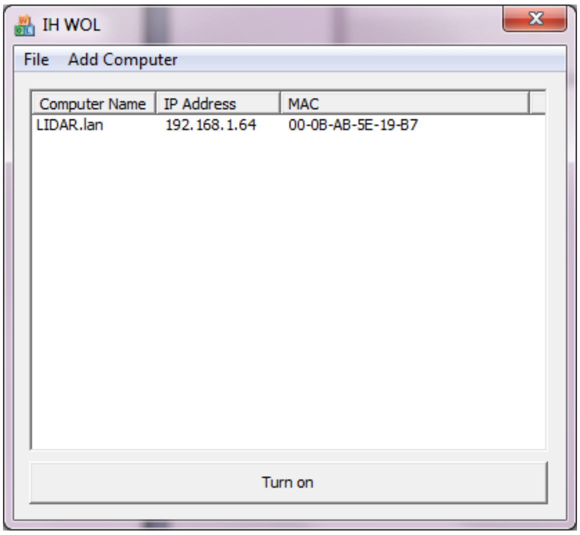
Many of these programs can scan the network and find all computers which are currently turned on and acquire automatically the Name, IP and MAC address. Below is an example of such a program.




**NOTE:** The program will not find the computer if it is turned off. Therefore, the first time the program is run, the computer must be switched on. Then the information needed can be saved to the program so that it can be used again in the future.

**NOTE:** To scan the network, permission has to be given from Windows. If prompted about security issues for this operation check the option to allow the program to perform the scan.

Once the computer's information is known, select the correct name and turn it on.

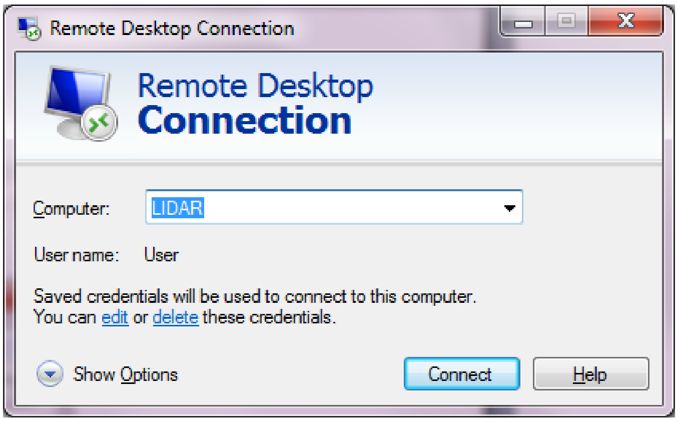



**NOTE:** The user will have to wait for a moment to let the computer start Windows before a connection can be established.

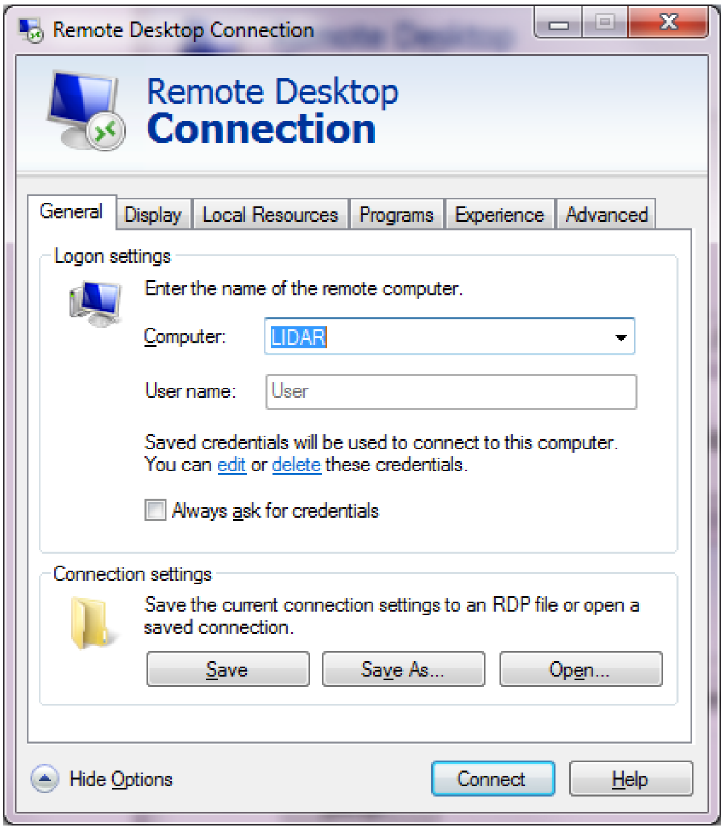
There is also the option to perform this task from a distant computer over the internet but in this case the Lidar's computer must have a static external IP address, which can be set at the network router's options. Also, it is necessary to set an access port in the firewall options. **Please consult your IT department before attempting this.**

### 6.5.3 Remote Connection

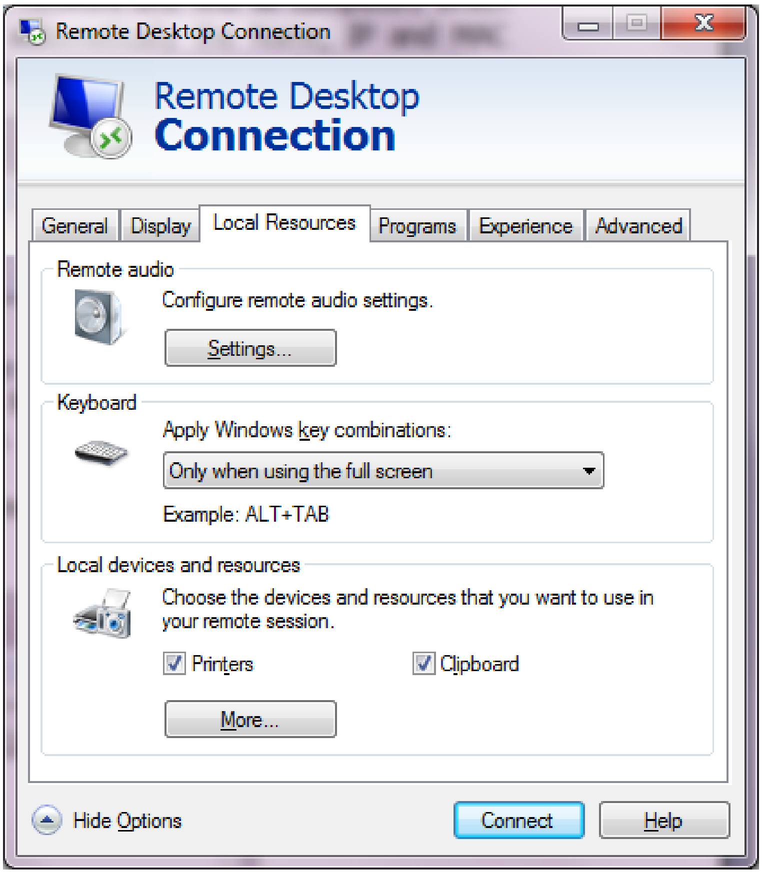
The procedure described in the section 'Establishing a Connection' is the fast way to connect. However, all options are not available this way. For more options go to 'Start -> All Programs -> Accessories -> Remote Desktop Connection' or simply type 'Remote' in the search box in the Start menu.




Click 'Show Options' to view the options tabs. There are options as to save the connection settings, select the quality of the connection, set the local resources options and set more advanced options.

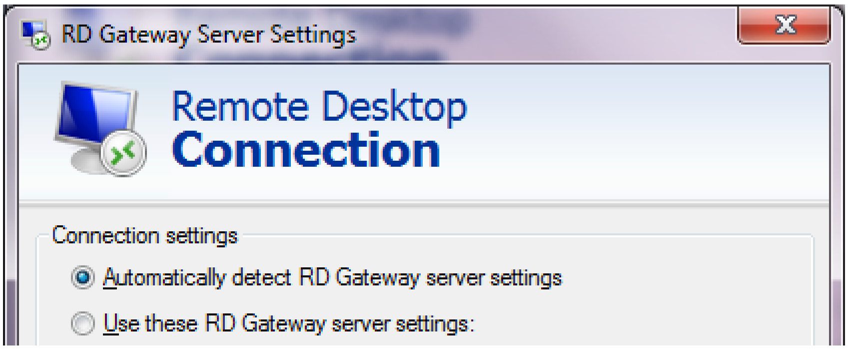


In the ‘Local Resources’ tab the user can choose how the key combinations behave such as the 'Alt+Ctrl+Delete' function. If the 'More' button is pressed the user can select to share a drive while connected, which come in handy when transferring data.




In the ‘Experience’ tab the user can select the performance depending on the connection's speed.

**NOTE:** If there is a connection problem check at the advanced tab the settings for the ‘Connect from Anywhere’ option. When using a local network select the 'Automatically Detect RD Gateway server Settings'. In some cases, this might change on its own and cause a connection problem.



# 7 LIDAR DATA PROCESSING

Once a measurement has been successfully completed, the data that was acquired will have to be processed, to extract information from them. Since data processing can be complicated in this chapter we will focus on the following sections:

- The structured of the acquired data
- Editing and working with the measurement database
- A basic analysis using the 'Data Preview and Analysis' program

Performing a precise Lidar analysis lies on the verge of art since the user must select among many parameters each of which can have great impact on the resulting analysis. Experience in combination with the capabilities of the analysis software, can create exceptional Lidar results provided that the raw data is of good quality.

The first section below refers to the data file format which is necessary to anyone who wants to use the acquired data files directly through their own software. The data is saved in binary form to reduce space. In case the user wants to convert the data in ASCII, human-readable format, we provide an extra tool with 'Data Preview and Analysis'.

Before you start analyzing the data you acquired, make sure that the database is not affected and always keep a backup of Lidar data. Remember that raw data is irreplaceable.

## 7.1 Data File Handling

The data files are saved in the folder set by the user. Apart from the data files a datalog file (datalog.dat) is also saved which contains the main information of each data file. This is automatically updated whenever a new profile is acquired and a new data file is created.

The name of the data files is given by the acquisition software automatically using the date and time of the measurement. The file naming format is explained below.

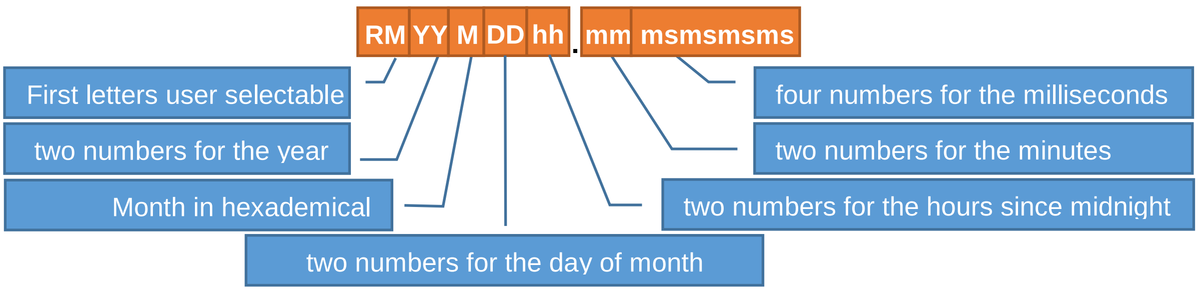



**Fig. 7.1:** Data File Name Explanation

For example, the file RM12C2815.572017 is created by Raymetrics (RM), in year 2012 (12), month December (C), day 28th (28) at 15:57 (15.57) past 2017 milliseconds (2017).

The file format is a mixed ASCII-binary format where the first lines (header) contain data related to characteristics of the measurement. Directly after the header is a carriage return and a line feed and the datasets (in 32-bit integer values) follow. Between each dataset is also a carriage return and a line feed.

```
RM12C2815.572017
ATHENS 28/12/2012 15:57:02 28/12/2012 15:57:22 0180 0029.0 0032.0 -90.0 0.0 20.0 1013.0
0000200 0010 0000200 0010 08
0000099 0030 0000099 0000 04
1 0 1 16380 1 0850 7.50 00355.p 0 0 00 000 12 000200 0.500 BT0
1 1 1 16380 1 0850 7.50 00355.p 0 0 00 000 00 000200 4.3651 BC0
1 0 1 16380 1 0850 7.50 00355.s 0 0 00 000 12 000200 0.500 BT1
1 1 1 16380 1 0850 7.50 00355.s 0 0 00 000 00 000200 4.3651 BC1
1 0 2 16380 1 0850 7.50 00387.o 0 0 00 000 12 000200 0.500 BT2
1 1 2 16380 1 0850 7.50 00387.o 0 0 00 000 00 000200 4.3651 BC2
```

**Fig. 7.2:** Sample file header

The first line contains the measurement's name which is the same as the file name, as explained above.

The second line contains more information about the location, start and stop time and the external conditions.

- Location String with maximum width 8 Letters
- Start Time dd/mm/yyyy hh:mm:ss
- Stop Time dd/mm/yyyy hh:mm:ss
- Height asl. four digits (meters)
- Longitude four digits (including minus sign). One digit for decimal points.
- Latitude four digits (including minus sign). One digit for decimal points.
- Zenith angle three digits in degrees (incl. minus sign). One digit for decimal points.
- Azimuth angle three digits in degrees. One digit for decimal points.
- Ground Temperature three digits in Celsius (incl. minus). One digit for decimal points.
- Ground Pressure three digits in hPa (incl. minus). One digit for decimal points.

The third line contains information about the lidar's offset from the North.

The fourth line contains information about the laser.

- Laser 1 Number of shots integer 7 digits (how many laser shots for one profile)
- Pulse repetition frequency for Laser 1 integer 4 digits (Usually 10 or 20)*

- Laser 2 Number of shots integer 7 digits
- Pulse repetition frequency for Laser 2 integer 4 digits
- number of datasets in the file integer 2 digits

The next lines that are in ASCII format are the dataset description. The parameters are divided by a space.

- 1 digit integer: 1 if dataset is present, 0 otherwise
- 1 digit integer: 0 for Analog, 1 for Photon counting
- 1 digit integer: 1 for Laser source 1, 2 for Laser source 2.
- 5 digits integer: Number of bins (example 16,380 x 7.5m each bin = 122,850m)
- 1 digit integer: N/A
- 4 digits integer: PMT High Voltage in volts
- 4 digits including decimal separator (.) and decimal points: Bin width in meters
- String with 5 digits: Laser wavelength in nm
- dot and letter: Polarization, o - no polarization, s - perpendicular, p - parallel
- 0 0 00 000 backward compatibility
- 2 digits integer: number of ADC bits in case of an analogue dataset, otherwise 0
- 6 digits integer: number of shots
- 1 digit real with 3 decimals: input range in mVolt in case of analogue dataset, discriminator level in case of photon counting.
- String with 2 letters: Dataset descriptor BT=analogue dataset, BC=photon counting
- And one hexadecimal number: the Transient Recorder number.

The dataset description is followed by an extra CRLF. The datasets are stored as 32bit integer values. Datasets are separated by CRLF. The last dataset is followed by a CRLF. These CRLF are used as markers and can be used as check points for file integrity.

Using the analysis software presented below the user can translate all binary files to ASCII so that external software can be used for the data analysis.

## 7.2 Data Preview

Once the ‘Data Preview and Analysis’ program is open the user can see the main interface. The window consists of a menu bar and a toolbar

With preview ‘DB’ the user can have a quick look at the database whereas through the ‘DB interface’ the database can be edited. Furthermore under ‘Tools’ in the main menu the user can convert automatically database files to an ASCII format to use them with other programs.

### 7.2.1 Database Interface

Once you've clicked 'DB', a window titled Database will appear which contains:

- the measurements table on top which shows all measurements in the database,
- a list on the right with the data files that were written during this measurement,
- an information field below the measurements table, which contains the global information of the measurement,
- another table with the recovered channels (right above the measurement table),
- two dropdown lists and a text box on the right of the window, which are used as filters,
- below this the edit database, the play and the close buttons
- and at the bottom a graph to preview the raw data of each selected channel

In the measurement table, every record represents a set of measurements. Each record has the following fields:

- User Name: The username that is entered when someone calls up the data acquisition interface.
- Location: The location which is entered during global information configuration procedure.
- Start and Stop Time and Date

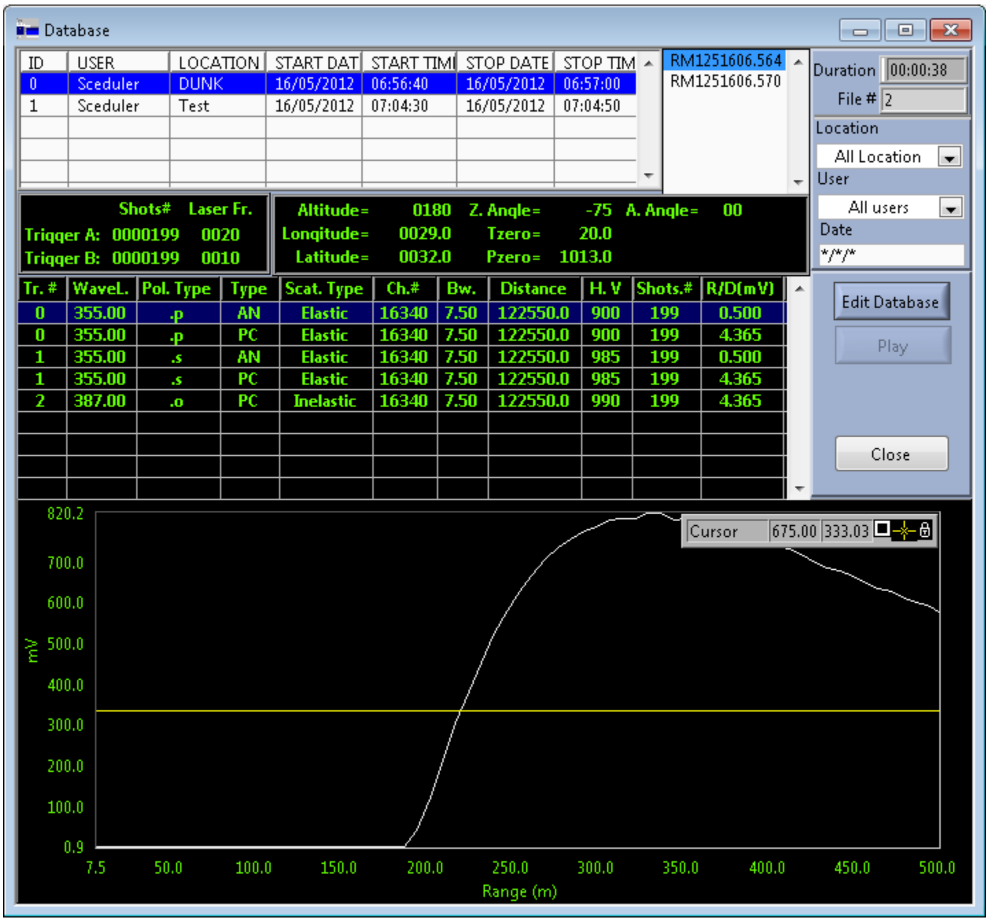



**Fig. 7.3:** Database Interface

Whenever a measurement is finished, a new record is added to the main table with the start date and time from the first filename of the measurement's set, and the stop date and time fields from the last saved file.

Choose the file on the right to be previewed and the program will load the dataset description of the selected file, displaying all the data that was collected from each channel for this specific measurement. Select a row to view a corresponding plot. Every row consists of eleven shells that are:

- Tr.: Transient Recorder device
- Wave L.: Detected wavelength
- Polarization Type: p-parallel, s – cross, o – no polarization
- Type: AN-analogue, PC – photon counting
- Scat. Type: scattering type, elastic (emitted wavelength equal to detected wavelength) inelastic (emitted wavelength not equal to detected wavelength)
- Ch#: Number of channels recorded
- Bw.: Bin width = 2 ^ (reduction number) * resolution (in meters)
- Distance: maximum distance in meters
- H. V: PMT High Voltage (V)
- Shots#: Number of laser shots emitted during the selected measurement
- R/D: For analog: input range (mV), for photon counting discriminator level.

In the next sections, there are step by step tutorials on how to edit the database.

- How to copy raw data files to create a new datalog file.
- How to work with a different database
- How To manually create a new record in the datalog.dat
- Exporting and converting data from a database

For context help just click <Control>+H. For getting help for the active window click <Control>+<Shift>+H

## 7.2.2 How to copy raw data files to create a new datalog file

Open the 'Preview DB' window and click on the 'Edit Database' Button on the right.


To create a new datalog file with part of your database (for example to distribute it to your partners) you must first select one or more records (by holding down the 'left Shift' button on your keyboard), followed by pressing the 'Copy Selection' button in the 'Edit Datalog File' interface. A 'Save As' common explorer interface appears. Choose an empty directory (or create a new one).

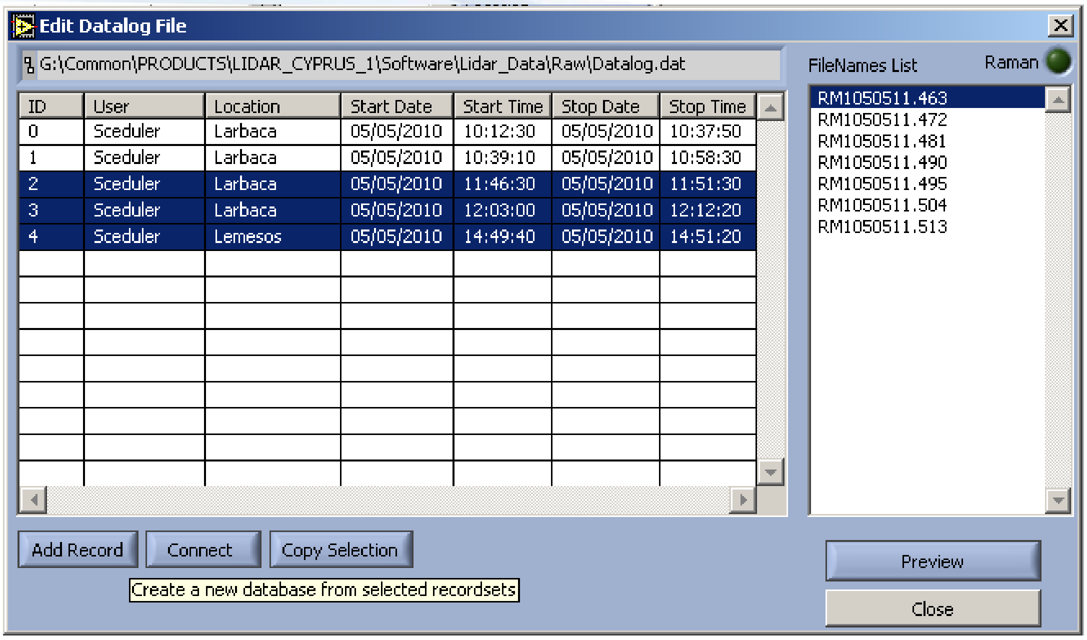



**Fig. 7.4:** Edit Datalog File Interface

Double-click on the icon for this directory (to get into it) and then click the 'Select Cur Dir' button.

A new datalog.dat file will be created with only the previously selected records. All of the associated raw datafiles will be copied inside this newly created folder (directory).

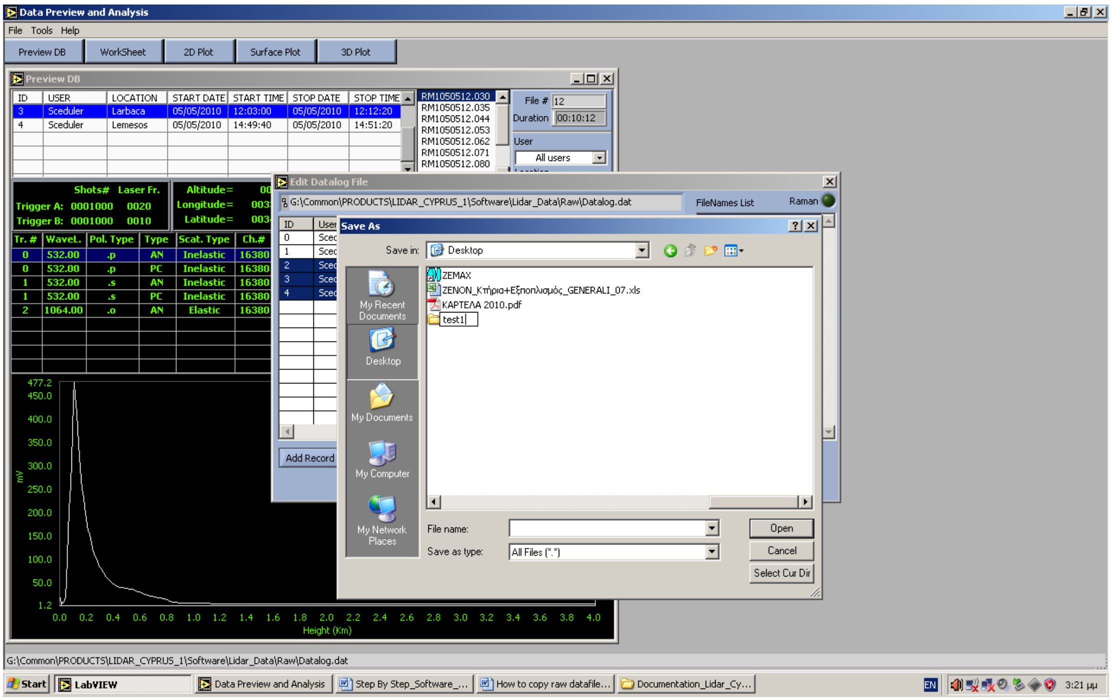



**Fig. 7.5:** Select Directory for the New Database

### 7.2.3 How to manually create a new record in datalog.dat

Sometimes users may forget to click on 'Stop' button before they exit the acquisition program (and the same problem occurs during a power failure). In that case, although all the acquired raw data files have been saved to the default location, the software fails to add a new record to the datalog.dat file describing the last measurement.

In this case, the user must manually add this new record by following the procedure below.

**NOTE:** It is suggested to make a backup of your datalog.dat file before you proceed.

Open 'Preview DB' window and click on the 'Edit Database' button as in section '*7.2.2 How to copy raw data files to create a new datalog file*'.

Click the 'Add Record' button as you see in Fig. 7.4 Add Record

Click the folder icon to open a Windows selection dialog.

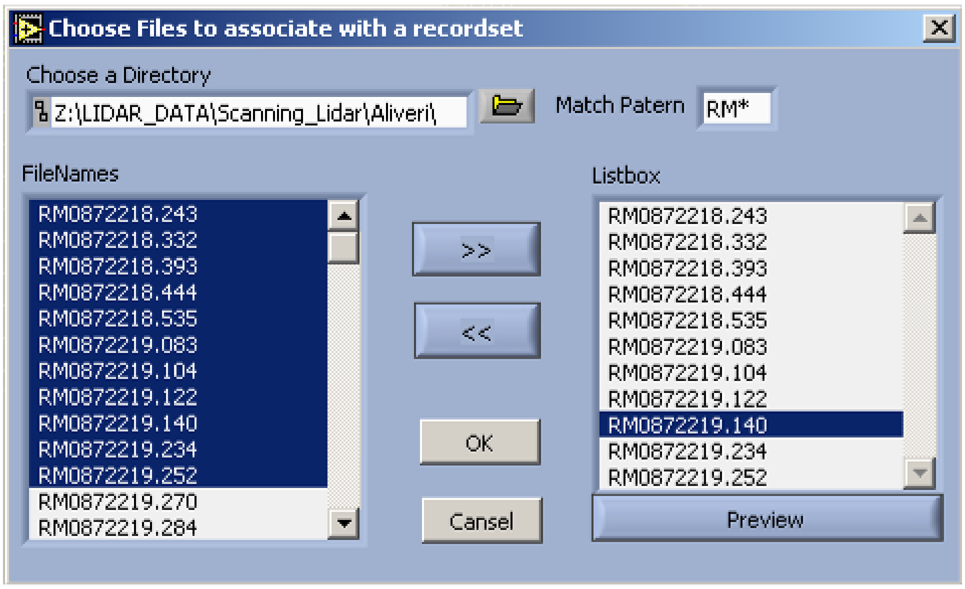



**Fig. 7.6:** Add Data Files to Recordset

Choose the directory where the raw data files are located (For example C:\lidar_data\Raw\), navigate into it and click on the 'Select Cur Dir' button. Note here that the files displayed will be those that start with the letters RM, change If different. Remember that, only the data files starting the letters chosen in the configuration window, are those that will be used throughout the analysis.

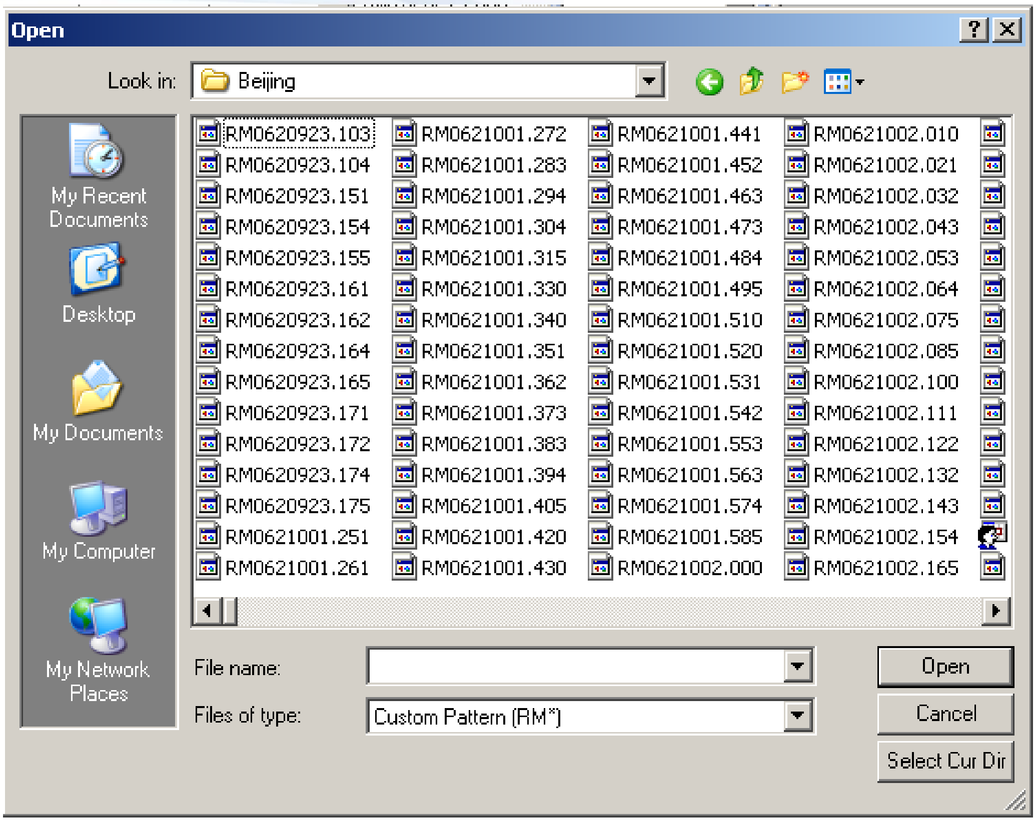


**Fig. 7.7:** Directory of Measurements Selection Dialog

All the RM files will be displayed in the list box on the left.

Select all the files you want (be sure that they are sequential and belong to the same measurement)

Click the >> button to transfer them to the list on the right and click ‘Ok’. The software then prompts the user to enter a User and a Location. Anything can be entered but it must be less than 10 characters without spaces. Click ‘Ok’.

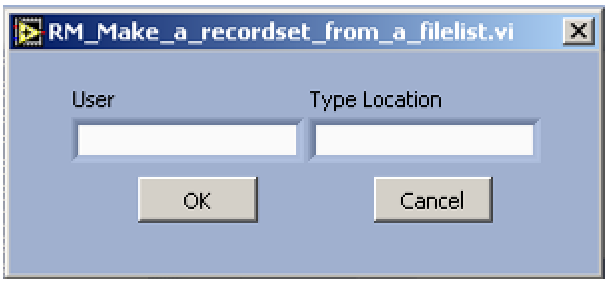


**Fig. 7.8:** Set header for Recordset

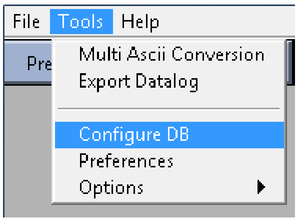
Click once more the ‘Ok’ button in the 'Edit Datalog File' interface (Fig. 7.4)

If you now reopen the ‘Preview DB’ window the new record will also appear.

### 7.2.4 How to select a different database

When you have multiple databases saved in different folders you can work with any number at any one time. Go through these steps to select another database to work with.

Close the 'Preview DB' window if it is open and go to Menu Bar and click ‘Tools->Configure DB’




A dialog opens that prompts you to configure the ‘Preview Application’. Click the Folder Icon (top right corner) of the ‘Working Data Path’ text box.  A normal Windows selection dialog opens and prompts the user to select the directory.

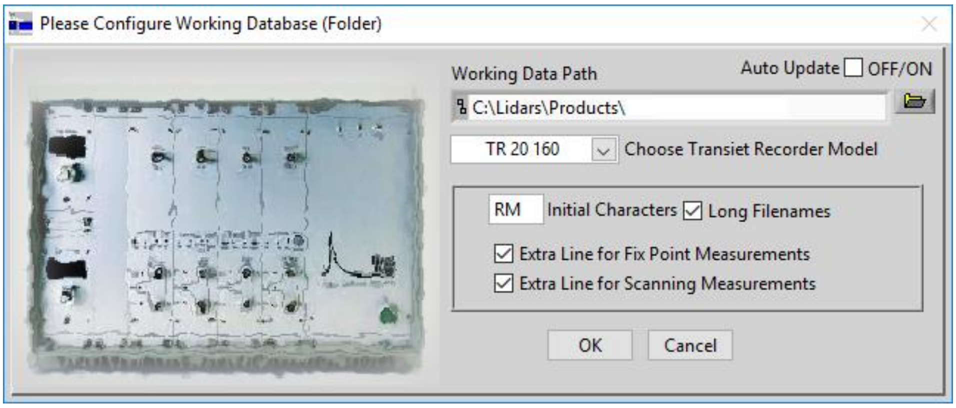



**Fig. 7.9:** Configure Preview Application Interface

Locate the directory where another datalog.dat file (with all the raw data files) exists. Note that by default there is a filter and you can only see the .dat files.

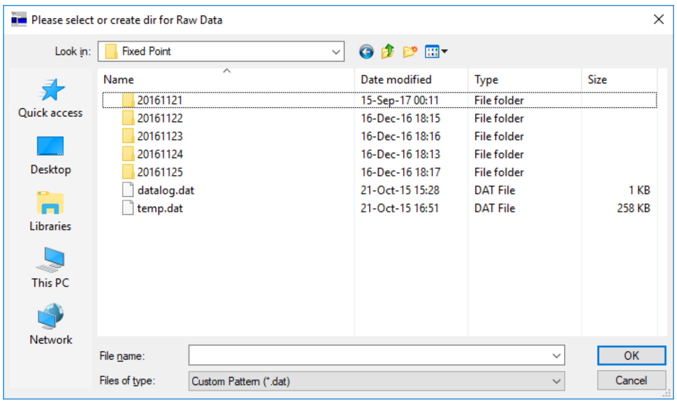



**Fig. 7.10:** Database Directory Selection

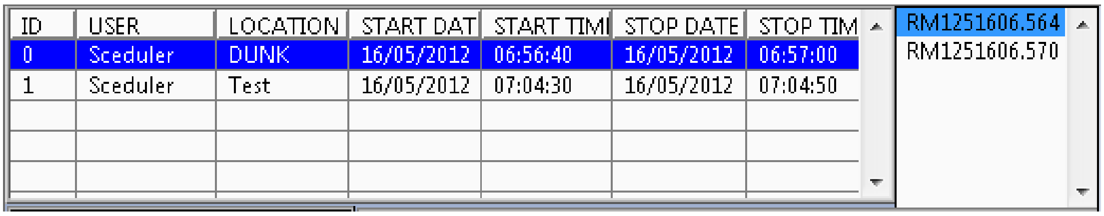
Double-click the icon of that folder to get into it and click the 'Select Cur Dir' button.

**NOTE:** Do not forget to choose the correct Transient Recorder type.

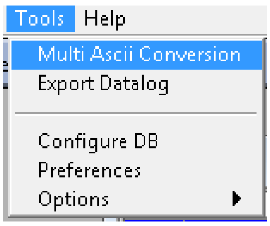
### 7.2.5 Converting binary files to ASCII

The software provides a function to convert all files of a record (measurement) from binary to ASCII format. This is useful when you want to read the files with external software.

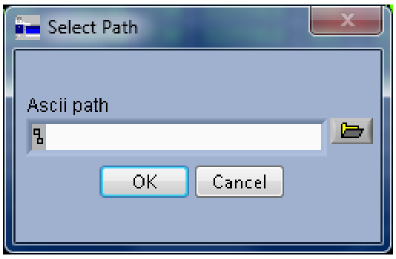
Click first the ‘Preview DB’ button to open the database. At the top of the window select in the measurement table which record to convert.




Next go to 'Menu' -> 'Tools' -> 'Multi ASCII Conversion'.




A window opens that prompts the user to select the folder where the converted data will be stored. Select a folder and click 'Select Current Dir.'

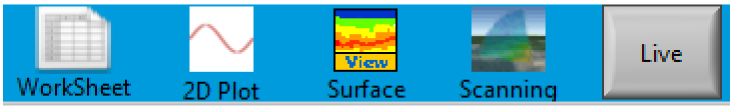



Wait until the status bar reaches the end. The data is now saved in an ASCII format. Verify if the data has been written correctly by opening one file with a text editor. Note that the raw data files have no specific extension so they are not registered to be opened by any program. However, the last digits on the filename are after a dot and Windows may recognize these as file extension.

You may also save the datalog file as a text file to use it with the converted files by going to 'Menu' -> 'Tools' -> 'Export Datalog'

## 7.3. Data Analysis

As already explained the analysis software is what analysts use to extract all the useful information from their Lidar data. Even though it provides a lot of information and functions the user should first understand the theory that lies beneath the software in order to understand the software calculates the results.




With the series of buttons shown above the user can:

- Use the 'Worksheet' interface to insert data from external files or an external database into a worksheet.
- Plot directly database data (or plot from external files) using the '2D Plot' interface.
- Create surface graphs from acquired data using 'Surface Graph' Interface
- Visualize scanning data in a 3D graph using the 'Scanning' interface.
- Watch in live streaming the post-processed data with the 'Live'

The following section contains a series of tutorials on:

- How to plot data
- How to calculate backscatter coefficient
- How to calculate aerosol extinction coefficient
- How to check lidar alignment
- How to calculate water Vapor profiles
- How to subtract the background
- How to glue analogue and photon counting signals
- How to make a scanning graph
- How to use soundings from global model data

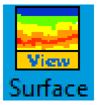
With these 9 tutorial lessons the user will understand fully how to use the program. As the analyst goes deeper into the software's capabilities more background theory is required. In some lessons, the basic theory required is given as introduction, but the analyst should look into the references in order to build a stronger Lidar knowledge.

### 7.3.1 How to Plot Data

Here is shown the way to plot your data. There are three ways to represent the data. One is a single 2D graph which can be data from a single file or a summation of multiple files. Another way is to plot the data on a surface that shows multiple files one next to the other as they evolve through time. The last is a scanning plot which also shows multiple files but in a 3D graph.

In this section, you will learn how to make a surface plot. Once you understand this you can easily also plot a 2D graph.

1. Click 'Surface Plot'.




2. Click 'Import Data'.

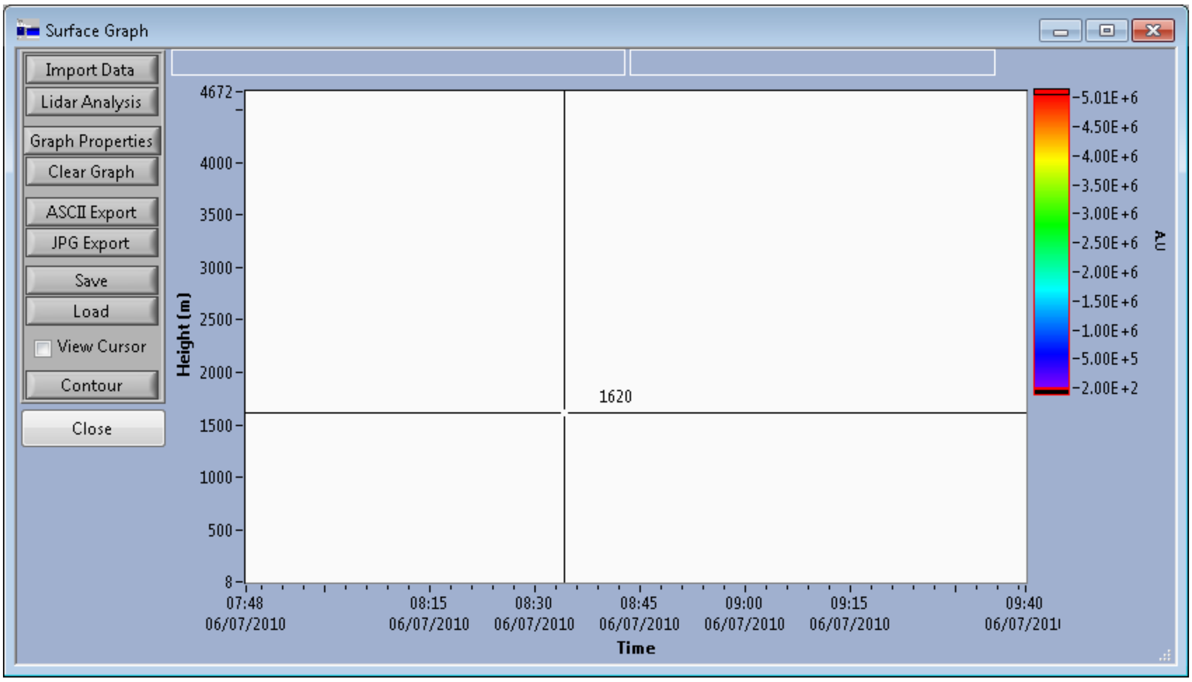



**Fig. 7.11:** Surface Graph Interface

3. Scroll up in the table if you do not see your data. Select the data in the table you wish to plot. In the right-hand column, hold the shift key to select the measurements you wish to plot. Click 'Next'.

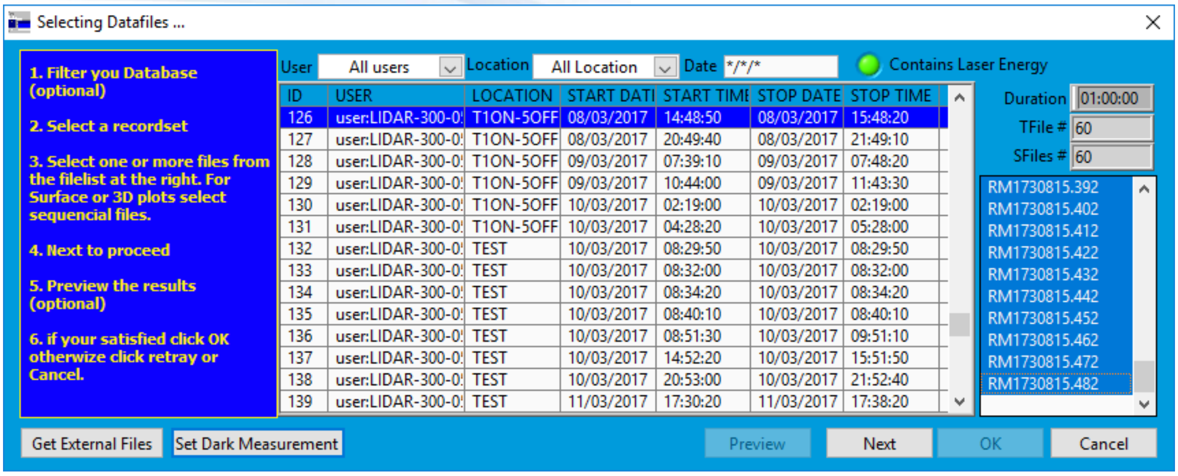



**Fig. 7.12:** Select Data Interface

4. Click 'Basic Analysis' option.

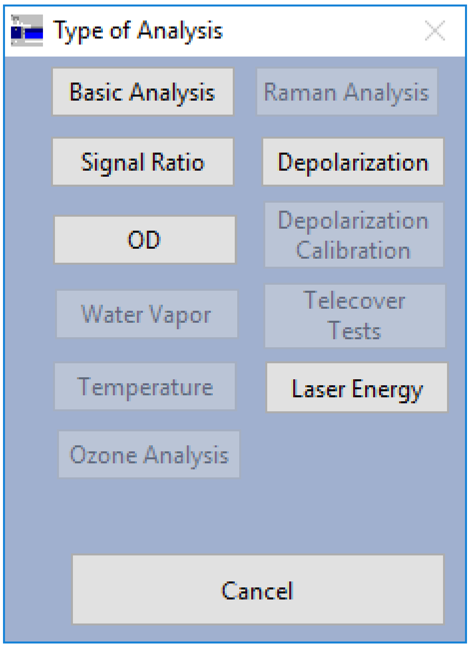



**Fig. 7.13:** Analysis Type Selection

5. Select the data type you wish to plot. For example, '355.00.p.AN' from the list on the left. From the list on the right, select 'RCS'.

**NOTE:** '532.00.p.AN' – 532.00 = wavelength in nm, p = primary (as opposed to secondary - depolarization), AN = analogue (as opposed to Photon Counting or Glued – PC and GL). Other options include calibrated signal for depolarization (b). RCS = Range Corrected Signal.

**NOTE:** Hold down the 'Ctrl' key and press 'h' for help.

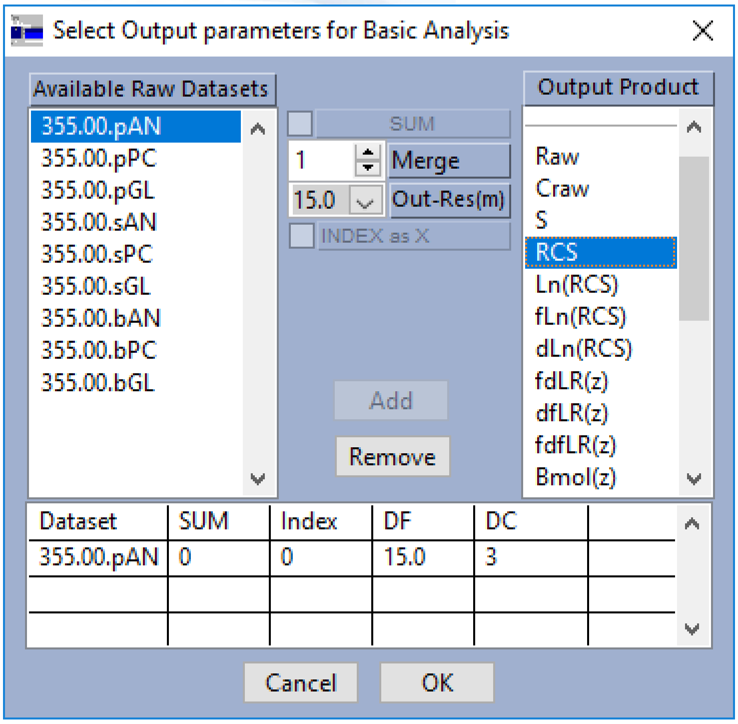



**Fig. 7.14:** Output Selection Interface

6. Click the 'Add' button. Your selection will now appear in the small data table.
7. Click 'OK' button. The software will now load your requested data.

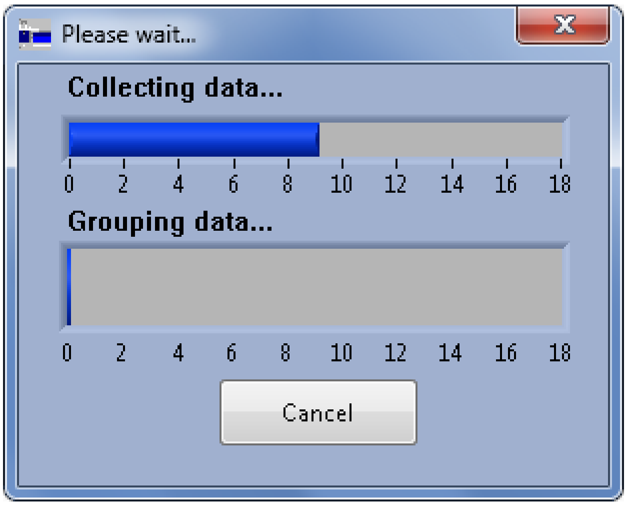



**Fig. 7.15:** Data Collection

8. After a few seconds, you will see the following blank graph.

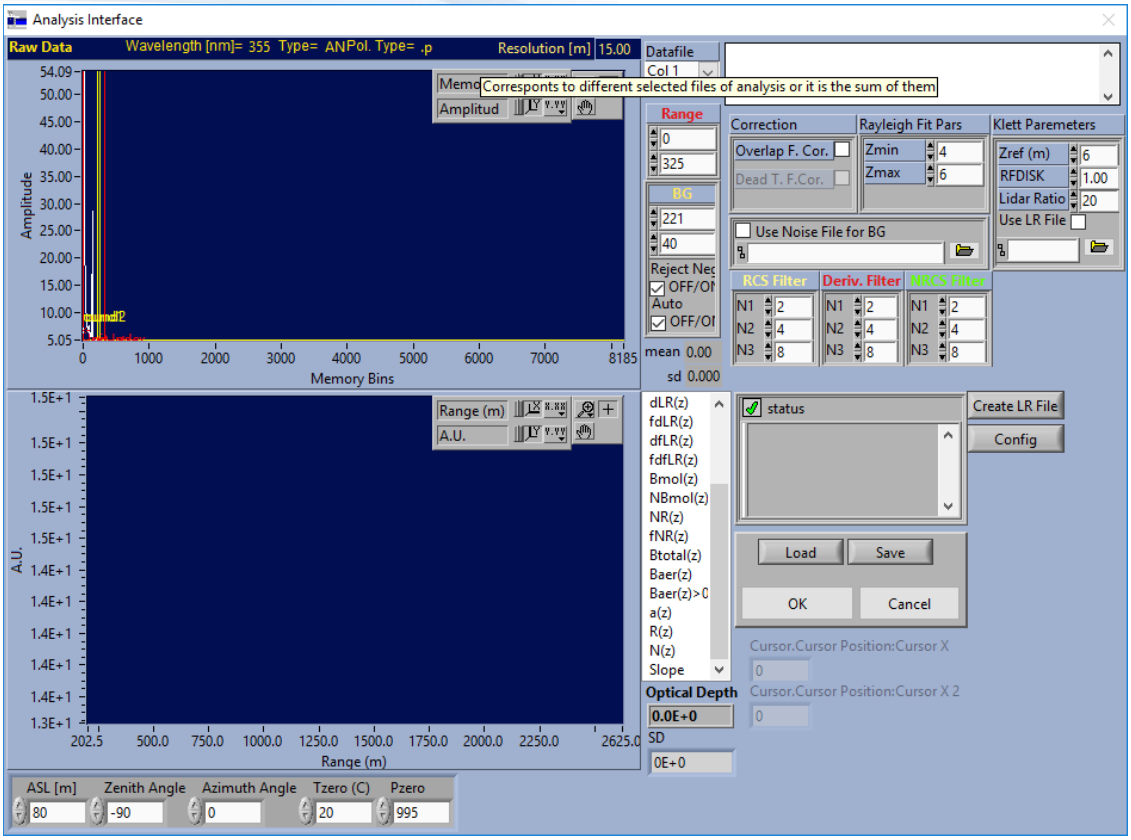



**Fig. 7.16:** Analysis Interface

9. To see the results, select a parameter from the parameter list to the right of the bottom graph (e.g. RCS(z) – Range Corrected Signal).

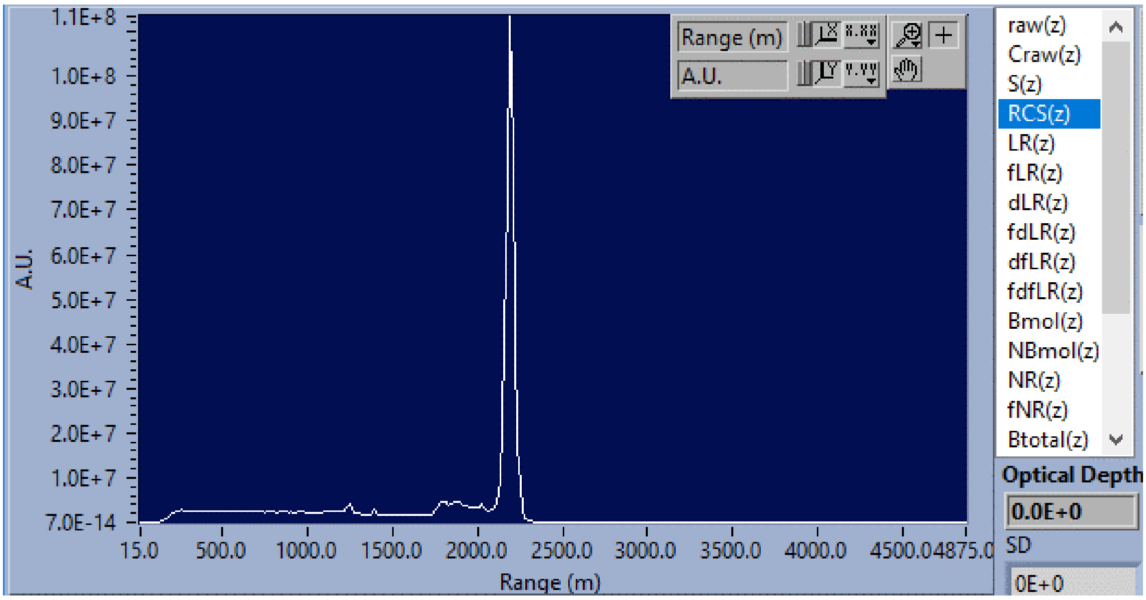



**Fig. 7.17:** Output Preview Graph

10. Click on the two red bars on the top graph and drag them to define the range (height for vertical measurements) of interest. As you drag the bars, you will see the data change on the bottom graph. You can also change the scales of the graph by simply

clicking on the minimum or maximum values on the x or y axis and typing a new value. The graph will then automatically rescale.

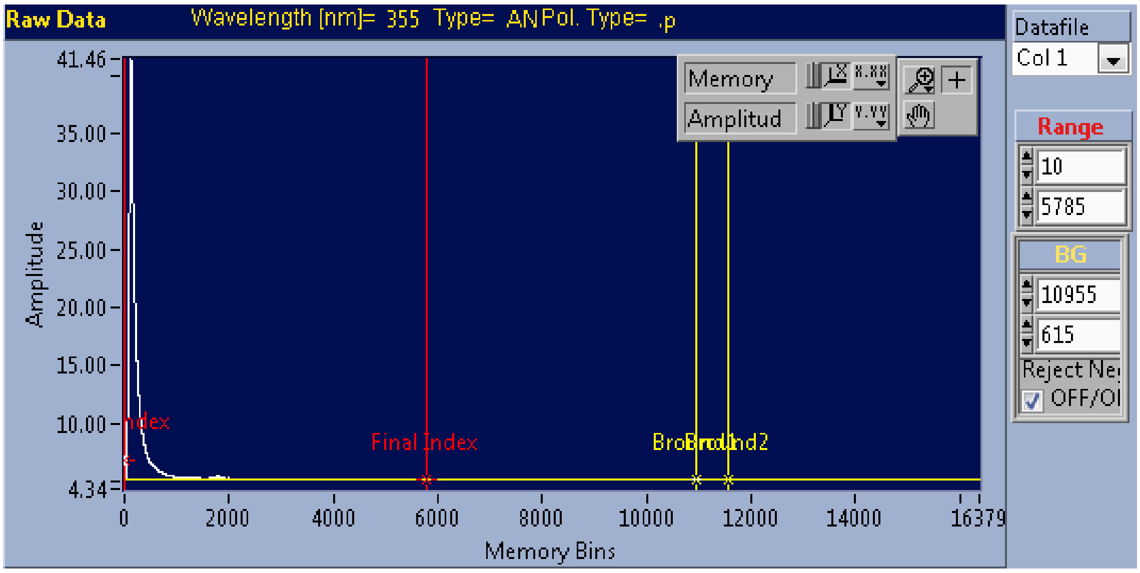



**Fig. 7.18:** Raw Data Graph – Limits and Background Selection

11. When you have the range desired, click the 'OK' button. The previous window 'Selecting Data…' (See Fig. 7.12) will appear back. Click the 'OK' button again.

12. The selected data and parameters will now be displayed on a graph. Time is on the x axis, range on the y axis, with color values showing the intensity of the signal.

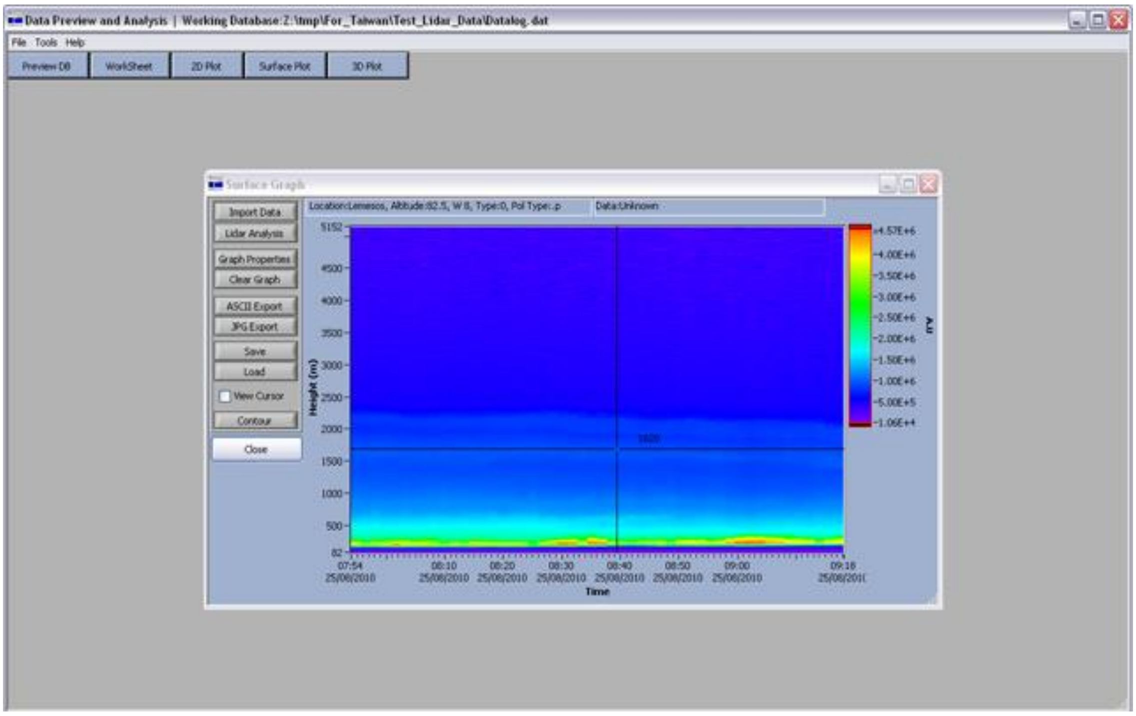



**Fig. 7.19:** Output Surface Graph

13. The image on the screen can be re-scaled by dragging on the bottom right corner of the window.

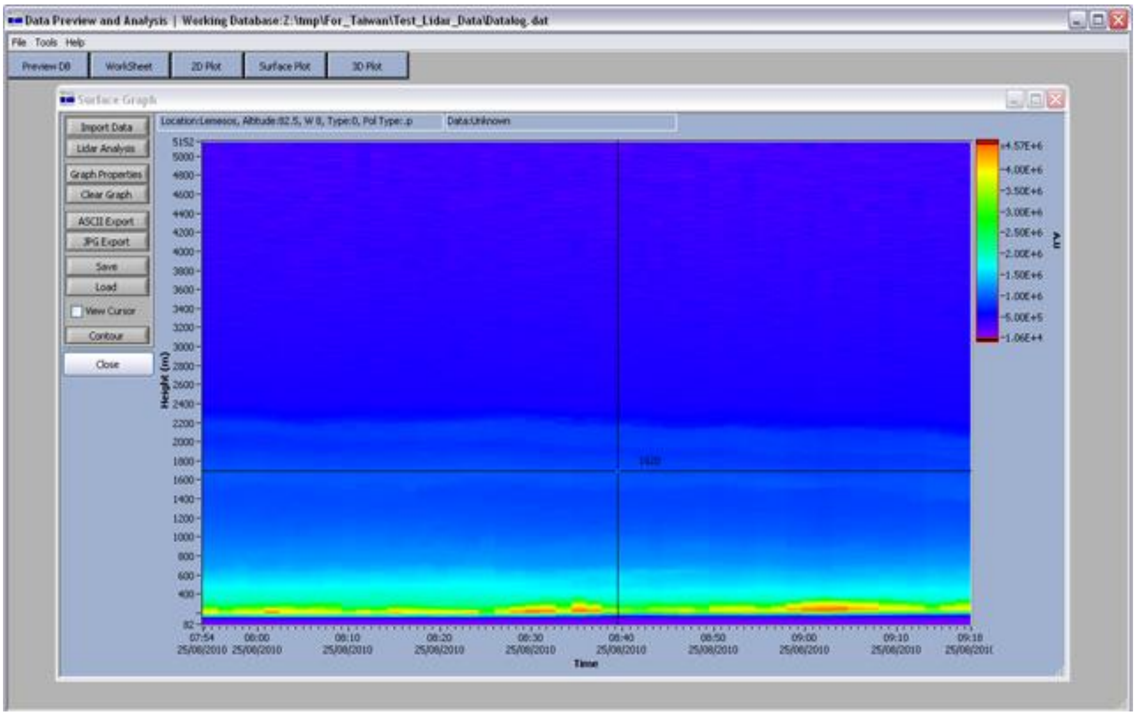



**Fig. 7.20:** Window Resize

14. Adjust the color scale of the graph by clicking on 'Graph Properties' on the left and selecting the tab 'Z-sc' (z scale).

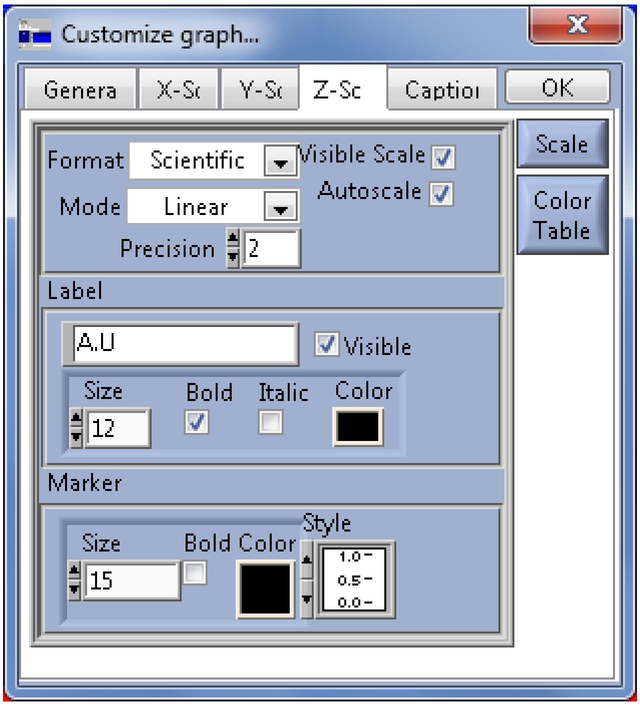



**Fig. 7.21:** Customize Graph

15. Click on the 'Color Table' button on the right. At the top of the window, click 'Choose C. Table'. Select a new color scheme (if desired) from the options (e.g. 'fire' or 'rainbow'). Click 'OK' and 'OK' again.

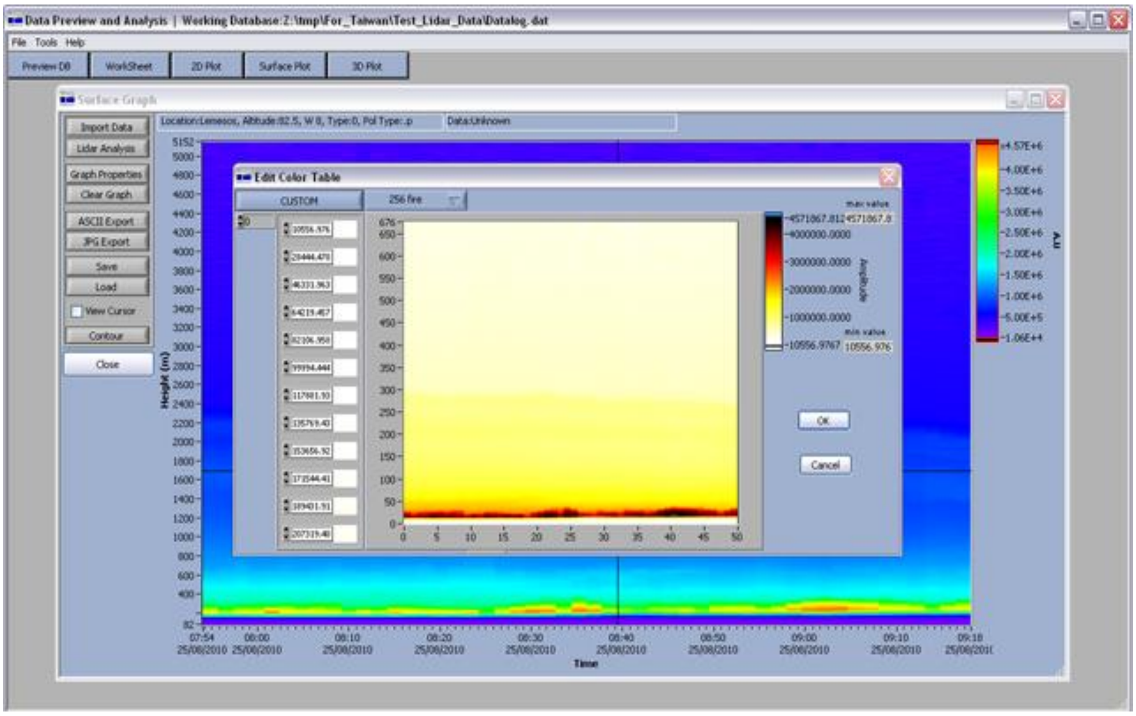



**Fig. 7.22:** Edit Color Table

16. If required, manually change values of range and signal intensity by clicking on the values on the graph axes and/or on the z scale to the right of the graph.

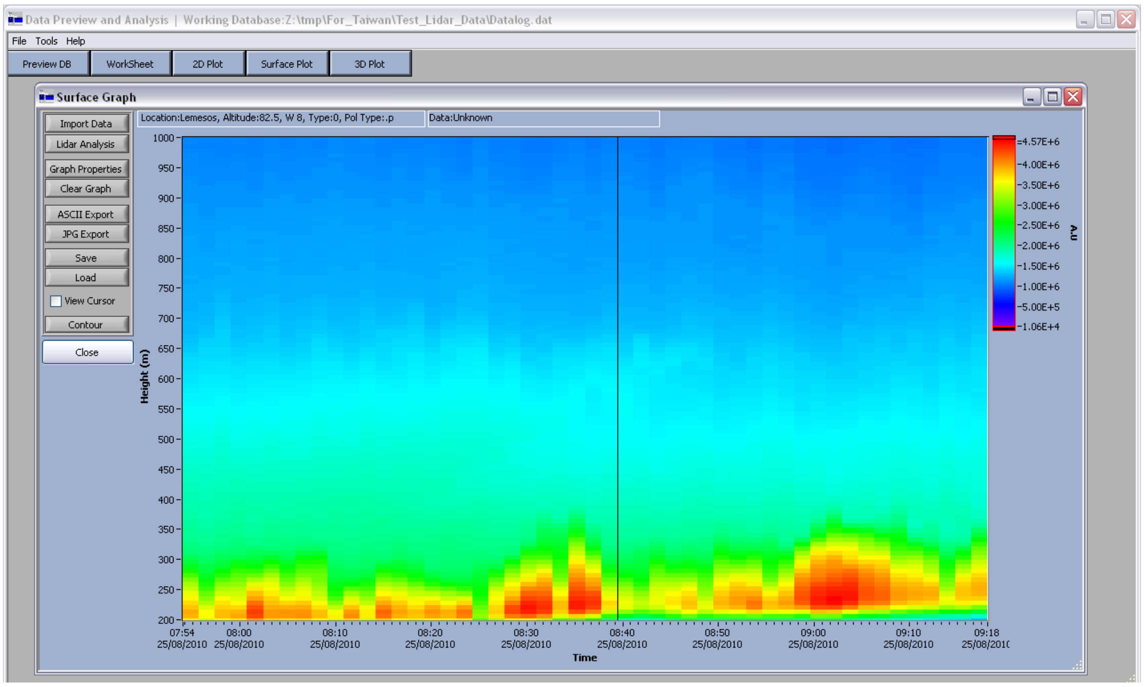



**Fig. 7.23:** Range Rescale

## 7.3.2 How to Calculate Backscatter Coefficient

1. Click '2D Plot'. 

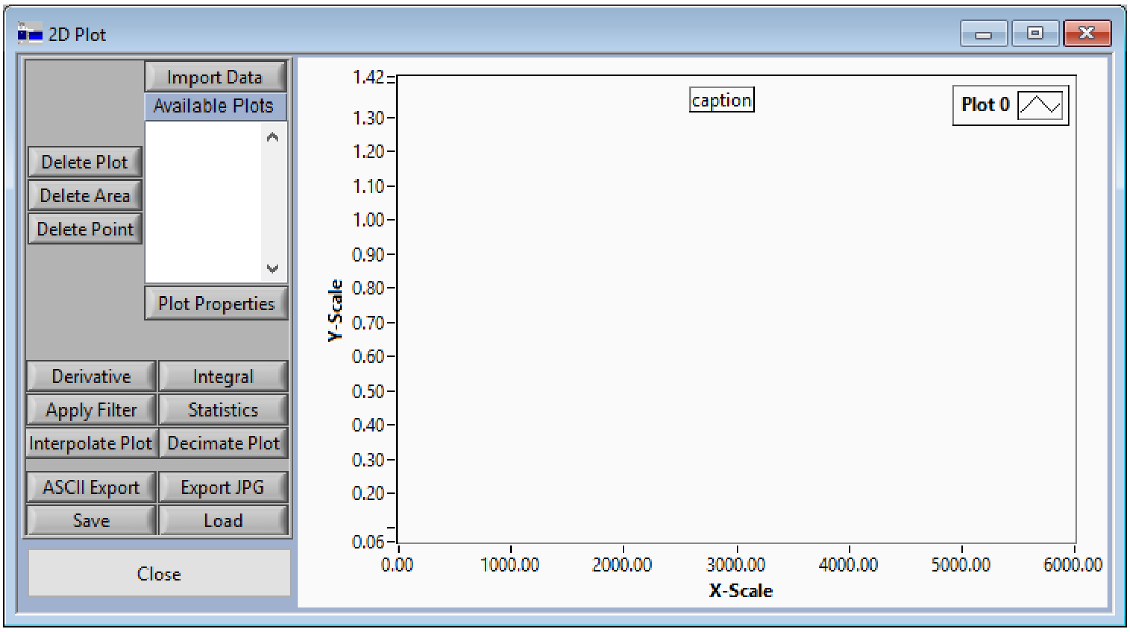




**Fig. 7.24:** 2D Plot Interface

2. Click 'Import Data' and ensure Data Source is set to 'From DB' in the drop-down list. Click 'OK'.

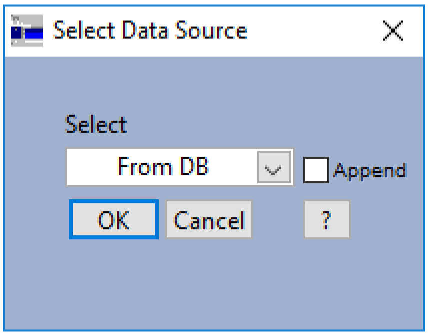



**Fig. 7.25:** Data Source

3. Select the record and the data you want to calculate aerosol backscatter coefficient for (as in previous tutorial Fig. 7.12). Make sure that the data files that you select are free of clouds. By holding the shift key, you can select multiple files which are going to be averaged (if you choose this option in the next step). Click 'Next' and select 'Basic Analysis' option (as in previous tutorial Fig. 7.13).

4. Select '355.00.p.AN' dataset. Click 'Sum' check box (if you need the average over time). Select 'Baer>0' (backscatter aerosols – positive values only) from the list on the right. Click 'Add' button and then 'OK' button.

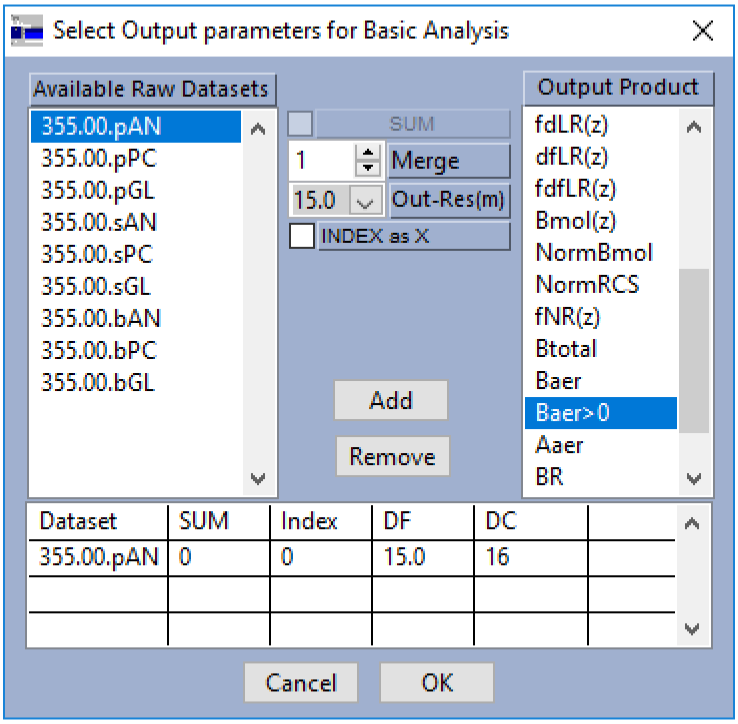
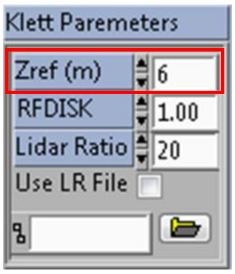



**Fig. 7.26:** Product Selection

5. Define the range of interest with the two red cursors from the top graph (as in previous tutorial Fig. 7.18).

6. Insert the maximum range (altitude in kilometers) for calculating Aerosol Backscatter coefficient in the Zref (km) box in the top right corner of the window. The atmosphere at that range should be clear enough.




7. Select Baer(z)>0 from the list in order to preview the Backscatter coefficient on the bottom graph. (Re-scale the graph if required by clicking on any value and typing a new value.)

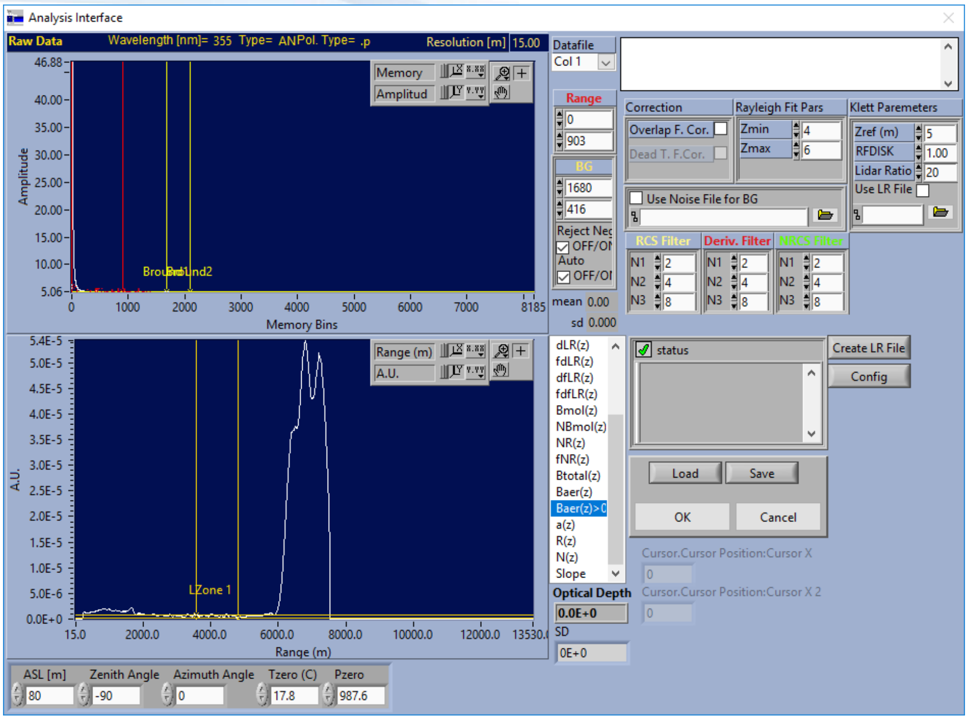



**Fig. 7.27:** Back Scatter Coefficient Preview

8. In order to check the maximum altitude to which Backscatter coefficient can be calculated without errors, select LR(z) from the list.

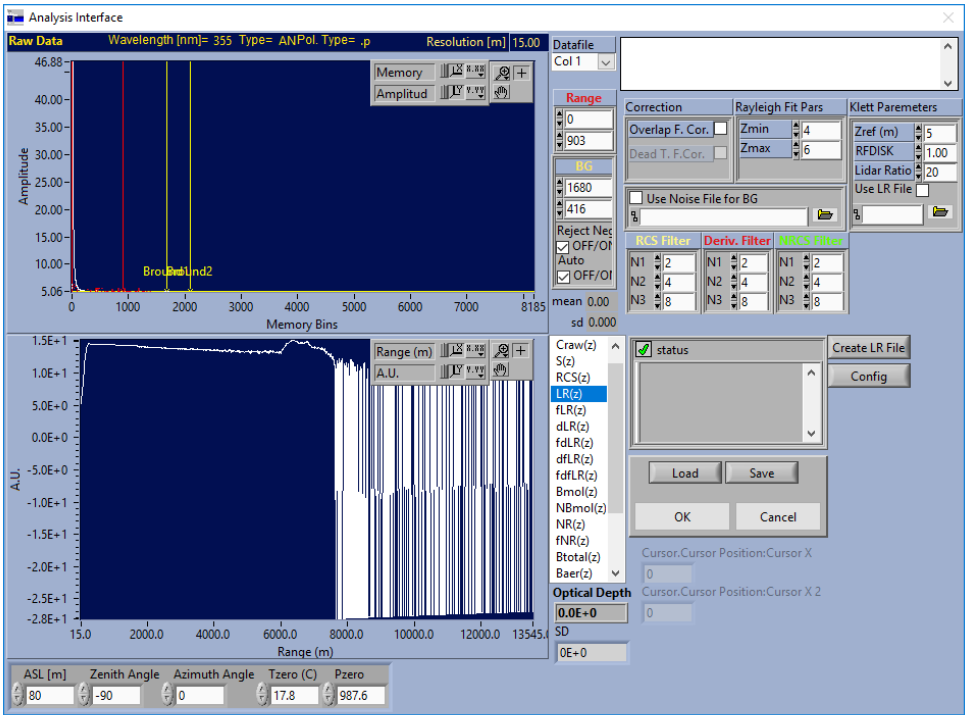



**Fig. 7.28:** Backscatter Coefficient Max Altitude

9. Locate the altitude where the first negative values appear (for example close to 7.5 km in Fig. 7.28). **This is the maximum altitude to which you can calculate backscatter coefficient without errors for the selected data.**

### 7.3.3 How to Calculate Aerosol Extinction Coefficient

1. The procedure is the same in the above tutorial '*7.3.2 How to Calculate Backscatter Coefficient*' until point 7. At this stage, instead of selecting Baer(z)>0 the user should select Aaer.

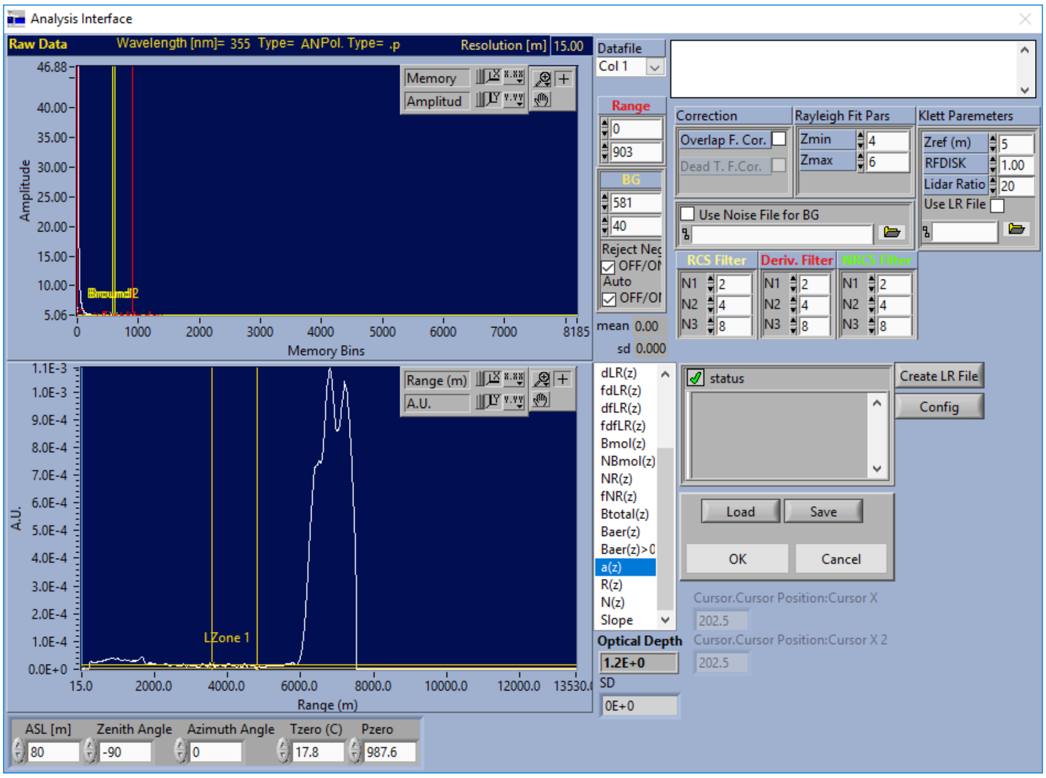
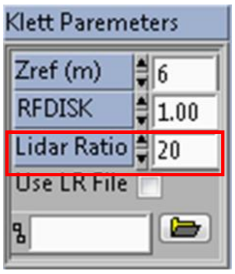


**Fig. 7.29:** Aerosol Extinction Coefficient

2. Please notice that Aaer (or a(z) denoted in the analysis interface) depends strongly on the value chosen of the Lidar ratio.




3. Continue with the rest of the procedure as described in the previous tutorials.

### 7.3.4 How to Check Lidar Alignment

For the fine alignment, the range-corrected Lidar signal (RCS) $P_{cor} = P(z) \times z^2$ is compared to the range corrected exponentially attenuated Rayleigh backscattered coefficient $\beta_{cor} = \beta_{Ray} \times z^2 \times \exp\left(-\int a_{Ray} dz\right)$, at a range interval which is considered free of any aerosol loading (pure molecular atmosphere). The molecular backscatter and extinction coefficients ($\beta_{Ray}$ and $a_{Ray}$, respectively) can be calculated either from a Standard Atmosphere (U.S.S.A 1976)[7] or more accurately from available local radiosonde data. The advantages of this method are that it does not require any extra equipment, it can be performed during daytime or night-time measurements and it is sufficiently accurate.

**NOTE:** clear sky without clouds is important, since if clouds are present the Lidar signal attenuated quickly and it is not then possible to calculate the molecular signal from experimental results.

In Fig. 7.30 a typical Lidar aligned signal is shown 'matching' the pure molecular atmosphere. The red line corresponds to the total backscatter coefficient while the black line to the calculated contribution of the atmosphere. As it can be seen, the difference between the red and black lines is due to the existence of aerosols in the measured atmosphere. From altitude ~4km and upwards the red and black lines are identical, meaning that the atmosphere is clear of aerosols.

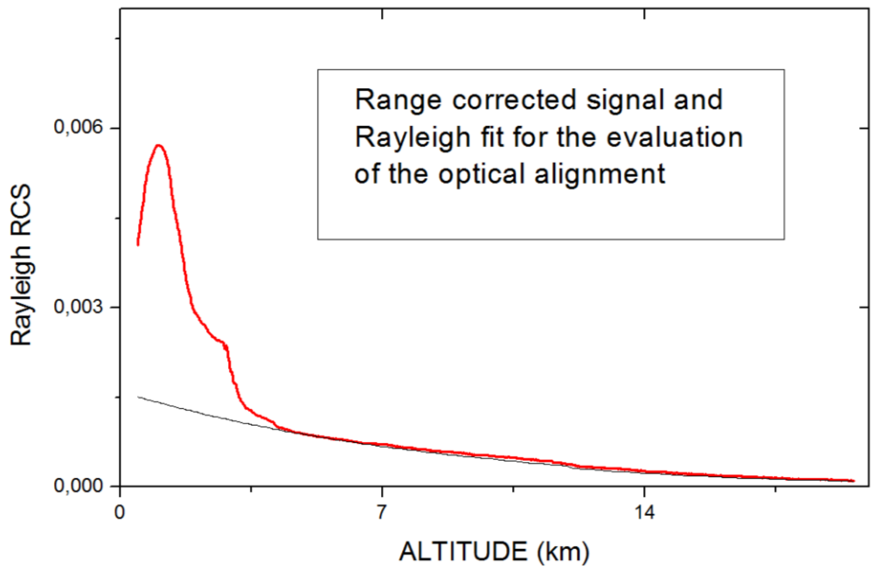



**Fig. 7.30:** Lidar Signal 'Matching' the Pure Molecular Atmosphere.

Now in the software NornBmol is the $\beta_{cor}$ from the equation above and fNR(z) is the normalized Range Corrected Signal. RCS(z) is the range-corrected Lidar signal $P_{cor}$.

$$NR(z) = RCS(z) * \frac{\sum_{Z1}^{Z2} RCS(z) \Big/ Z_2 - Z_1}{\sum_{Z1}^{Z2} \beta_{cor}(z) \Big/ Z_2 - Z_1}$$

Where $Z_2$ and $Z_1$ define a range clear of aerosols (From Rayleigh Parameters Section: Zmin(m), Zmax(m))

To check the alignment of the Lidar, follow the steps below.

1. Follow the same steps in tutorial '*7.3.2 How to Calculate Backscatter Coefficient*' until point 4. Select 355.pPC (Photon Counting Data at 355nm). Select NormBmol and fNR(z) parameters to plot (by holding <Ctrl> to select multiple options).
2. Define a range in the atmosphere where it is assumed to be free of aerosols (for example 10000 to 11000 m in the below image-example).

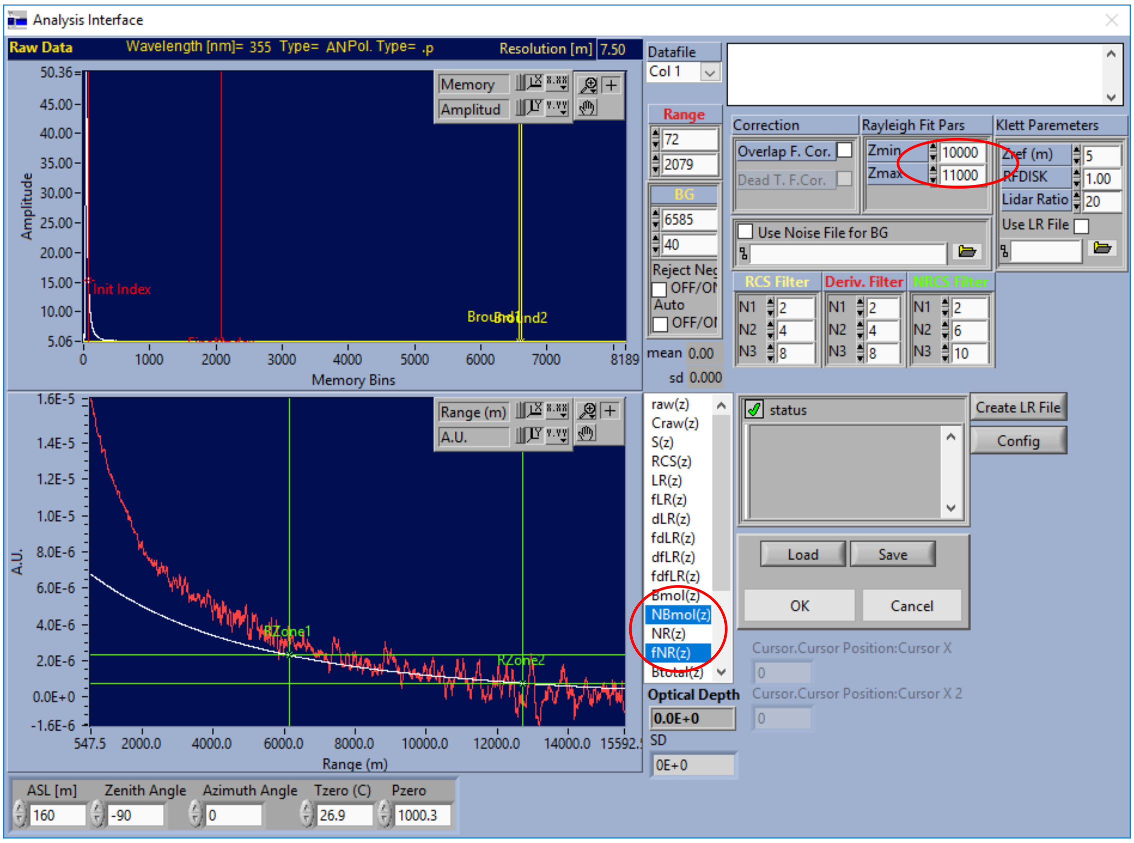



**Fig. 7.31:** Lidar signal 'matching' the pure molecular atmosphere.

A. Note that the Lidar signal fits the molecular atmosphere up to 12 km

B. All the signal bellow 8 km is higher than the molecular atmosphere

## 7.3.5 How to Calculate Water Vapor Profiles

**Before going through this tutorial make sure that your system can measure water Vapor. To measure water Vapor your Lidar should measure 408nm and 387nm Raman backscatter wavelengths.**

Water vapor profile is calculated by using the following equation:

$$m(z) = \frac{P_{\lambda,H_2O}(z)}{P_{\lambda,N_2}(z)} K = \frac{P_{\lambda,408}(z)}{P_{\lambda,387}(z)} K \quad \text{eq.1}$$

Where K is the overall system calibration constant, and P(z) is the Range Corrected Signals.

The overall system calibration constant (K) can in principle be deduced from the known Raman cross sections and the measured properties of the spectrometer used, but in practice it is determined from the comparison of the Lidar measurement with critically evaluated data from a radiosonde ascent. In the calculation of the emission ratio, there is an effect of the particle extinction which can be negligible on the mixing ratio determination under clear air conditions but must be considered if an optically dense medium like a water cloud is present.

A new and easier way for the calculation of water Vapor profiles has been developed, which is embedded in the software. Here is shown a tutorial on how to plot a 2D graph. If you want to display the temporal evolution of water vapor, open a surface graph, if you wish to analyze and do additional calculations open a worksheet.

1. Follow the same steps in tutorial '*7.3.2 How to Calculate Backscatter Coefficient*' until point 3., **but** select 'Water Vapor Analysis' in the 'Type of Analysis' dialog (as shown in Fig. 7.13.) If the selected record set does not contain any Water Vapor info (channel 408nm) the 'Water Vapor Analysis' button will not be available.
2. Select 355.pPC (Photon Counting Data at 355nm). Select NBmol and fNr(z) parameters to plot (by holding <Ctrl> to select multiple options).

A new interface appears. Using this interface is straightforward. Depending on the detected channels and the type of detection several options can appear in the Data Type list box in the top left corner of the window. For example, if your system detects only Photon Counting signals for the 408nm channel and only Photon Counting signals for 387nm channel, then you have only one option: To calculate the water vapor profile by using only Photon Counting signals. If for example your system detects Analogue and Photon Counting signals for 387 nm then you have two options to calculate the water Vapor profile. One by using only the photon counting signals for both channels and two by using Photon Counting for the 408 nm channel and Glue data for 387nm. About Gluing please look at Licel manual and at section '*7.3.7 How to Glue Analogue and Photon Counting Signals'*

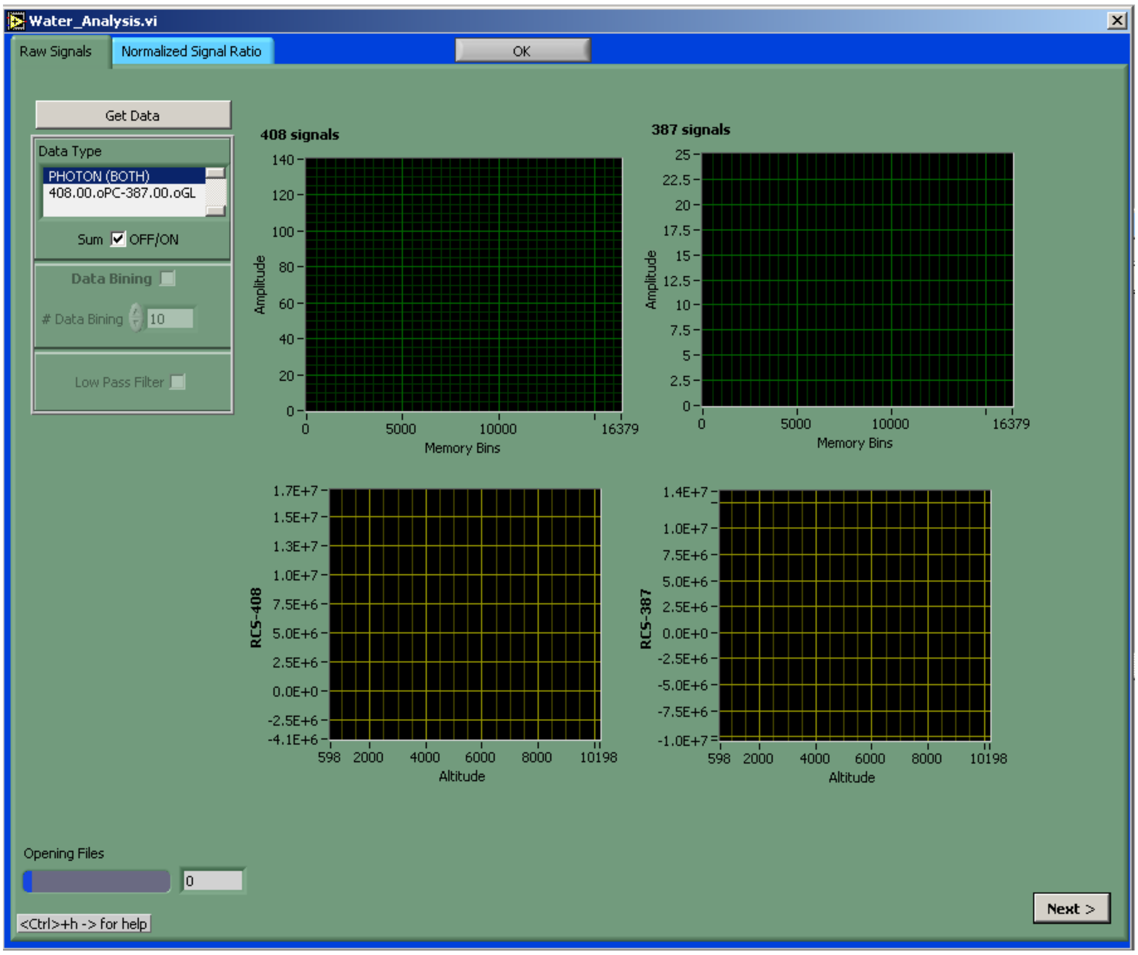



**Fig. 7.32:** Water Vapor Analysis Interface – 'Raw Signal' Tab

3. Click on the 'Sum' check box to average all the selected datafiles. In this case the temporal resolution decreases but the signal to noise ratio greatly improves, so the effective range of the profile will be increased.

**NOTE:** For surface plots (temporal evolution) this option is deactivated.

4. Click on the 'Get Data' button and a new interface will appear ('Data Pre-process') where you can subtract the background and select the range of interest (by using the two red cursors from the top graph). This process will be done twice. Once for 387nm and once for 408. After this the Range Corrected Signal will be calculated for both channels.

**NOTE:** Take into consideration that the calculations of the Range Corrected Signals for the 387nm and the 408nm must be made at the same range of interest. An easy way to select the same range, is to click on the 'Make Default' check box and then on the 'Save' button. The next time that this interface will appear it will retain the same range of interest.

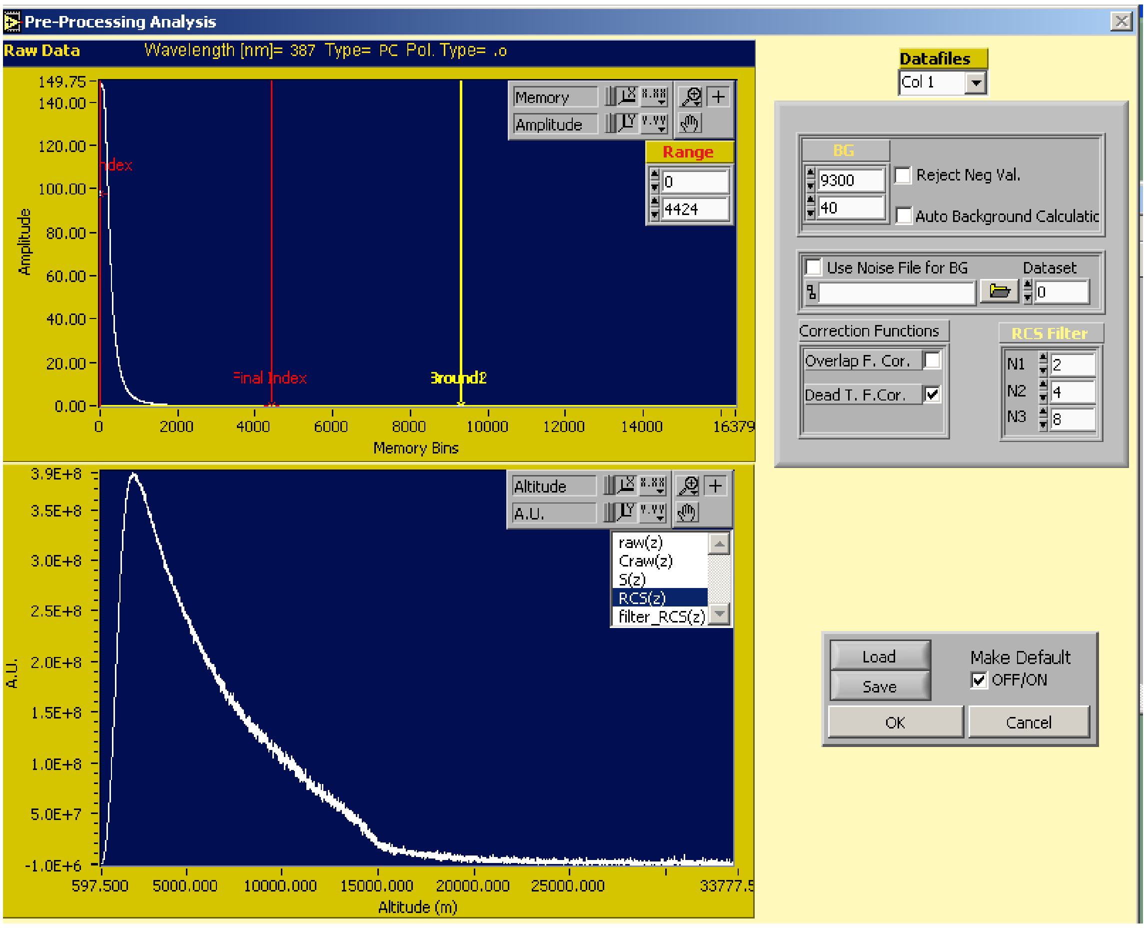



**Fig. 7.33:** Pre-processing Analysis Interface

5. When both Range Corrected Signals have been calculated the 'Pre-processing Analysis' interface closes and the program returns to the main interface. The graphs are updated and you can preview all in one graph (the 387nm and 408nm - Raw and RCS signals). Click on the 'Next' button or on the 'Normalized Signal Ratio' tab.

6. There are two graphs in the 'Normalized Signal Ratio' tab. The top one shows the signal ratio. The bottom one shows the calculated water vapor profile. Use the two yellow cursors from the top graph to zoom in to the range where the ratio profile is strong enough to calculate the water vapor profile.

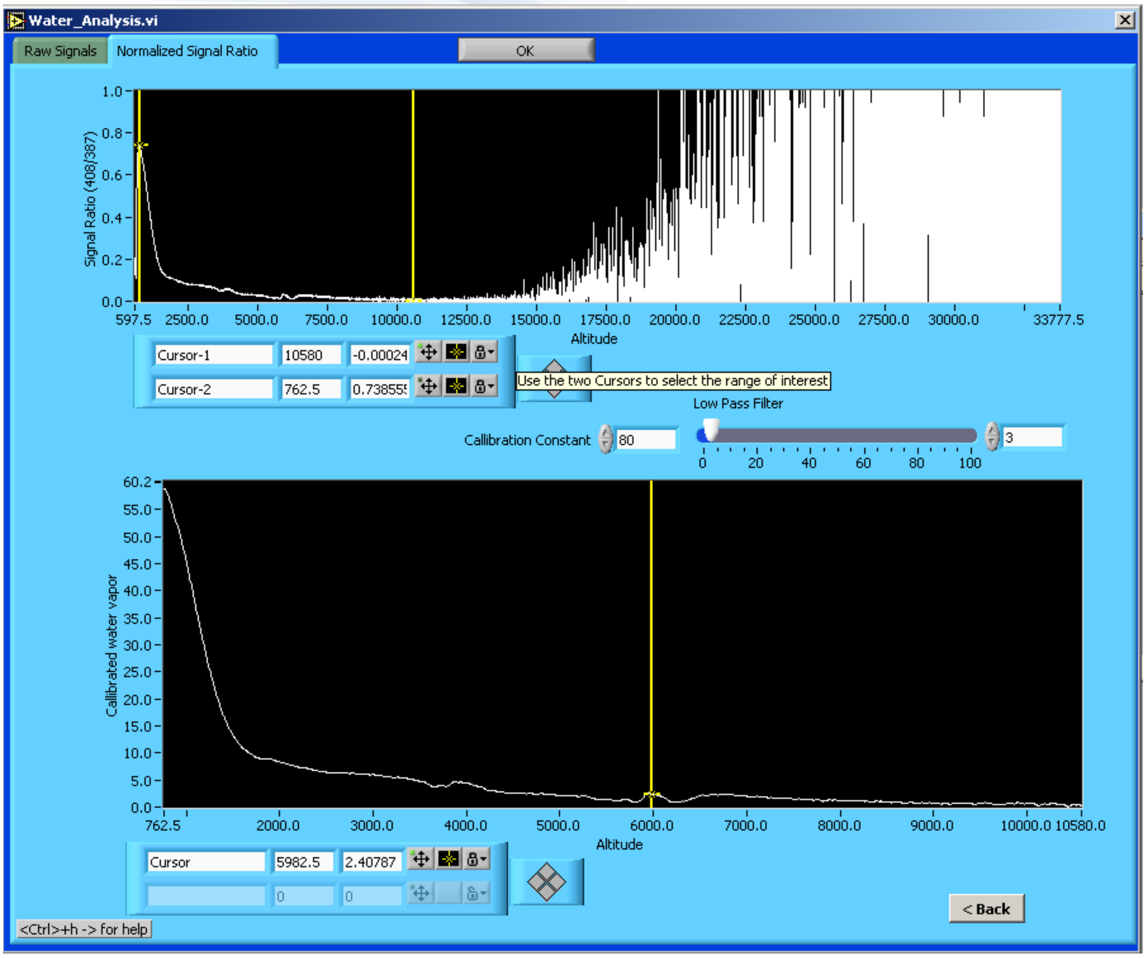



**Fig. 7.34:** Water Vapor Analysis Interface – 'Norm Signal Ratio' Tab

7. In this tab, you can adjust the calibration constant or even apply a low pass filter to the final product (zero means no filter). Finally click on the ‘OK’ button located at the top of this interface.

**NOTE:** In cases where the signal to noise ratio is too low you can try improving it by data binning of raw signals or even by applying a low pass filter. You can do this in the 'Raw Data' tab.

**How data binning works:**

Every value of the input signals corresponds to 7.5 meters (one bin) by calculating the average signal of several sequential bins (number of data binning) then the resulting signal has a spatial resolution of 7.5 * (number of data binning).

### 7.3.6 How to Subtract Background Noise

Background noise occurs due to solar or lunar background light which is collected by the telescope and electronic noise from within the system.

There are several methods for removing the background noise from a Lidar signal. The most common method is to locate a range where there is no Lidar signal and calculate the mean value at that range. Then this value is subtracted from the Lidar signal. Usually this range is at the far range (very high altitude) or at very low altitude (a few meters) if your Lidar supports pre-triggering.

However, using only very high altitudes is not best practice. Experience shows that sometimes when the signal (analogue) is too weak or decreases very fast (after a cloud) the signal is non-linear. In this case is better to select a range where the signal is quite stable and the mean value at that range is minimal, but of course, the effective range of the signal is restricted until that range.

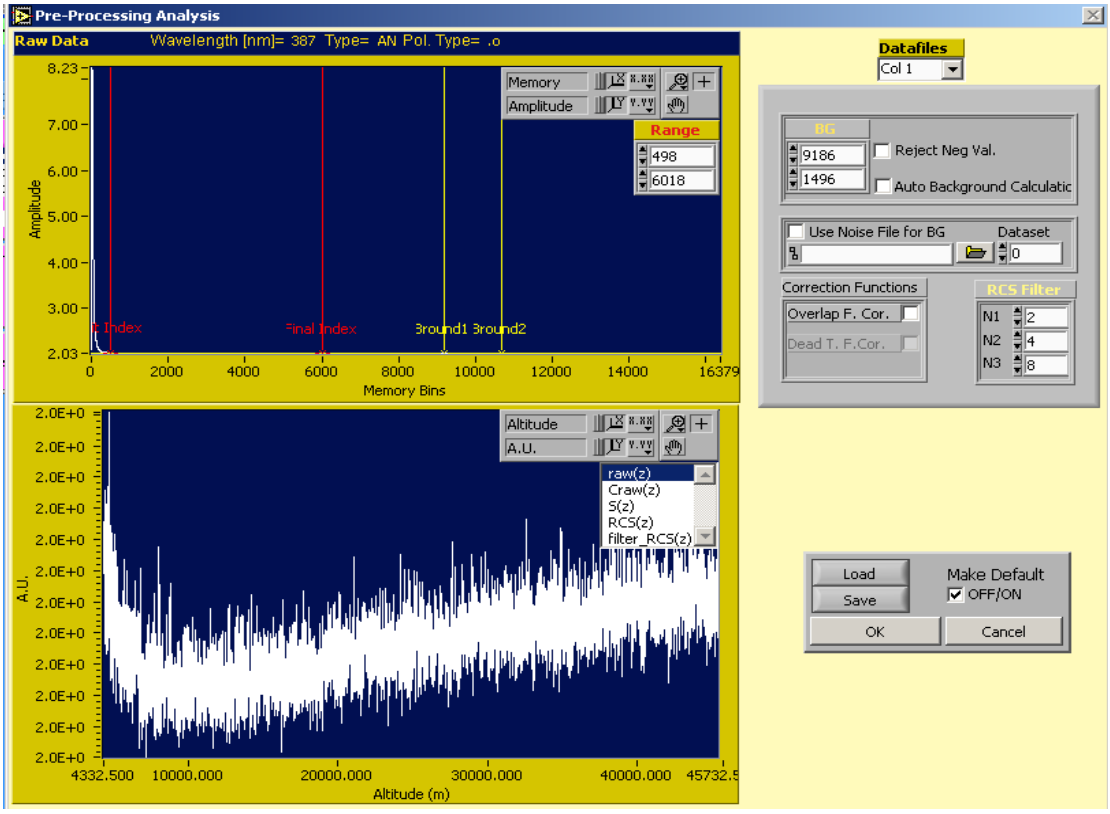



**Fig. 7.35:** Example of a Signal with Non-Linear Behavior

To calculate the background mean value at a range where the signal is minimal, the two red cursors can be used to do this by zooming.

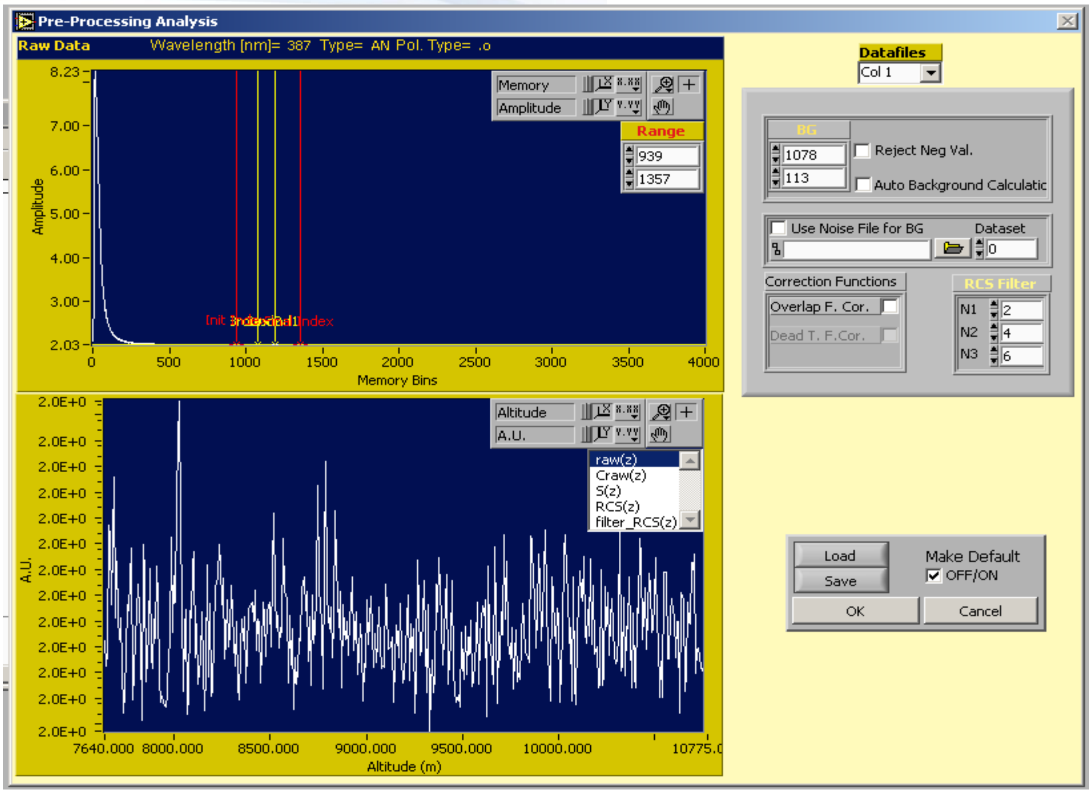



**Fig. 7.36:** Boundaries Selection

Then place the two yellow cursors somewhere in between (as shown in Fig. 7.36) to calculate the mean value.

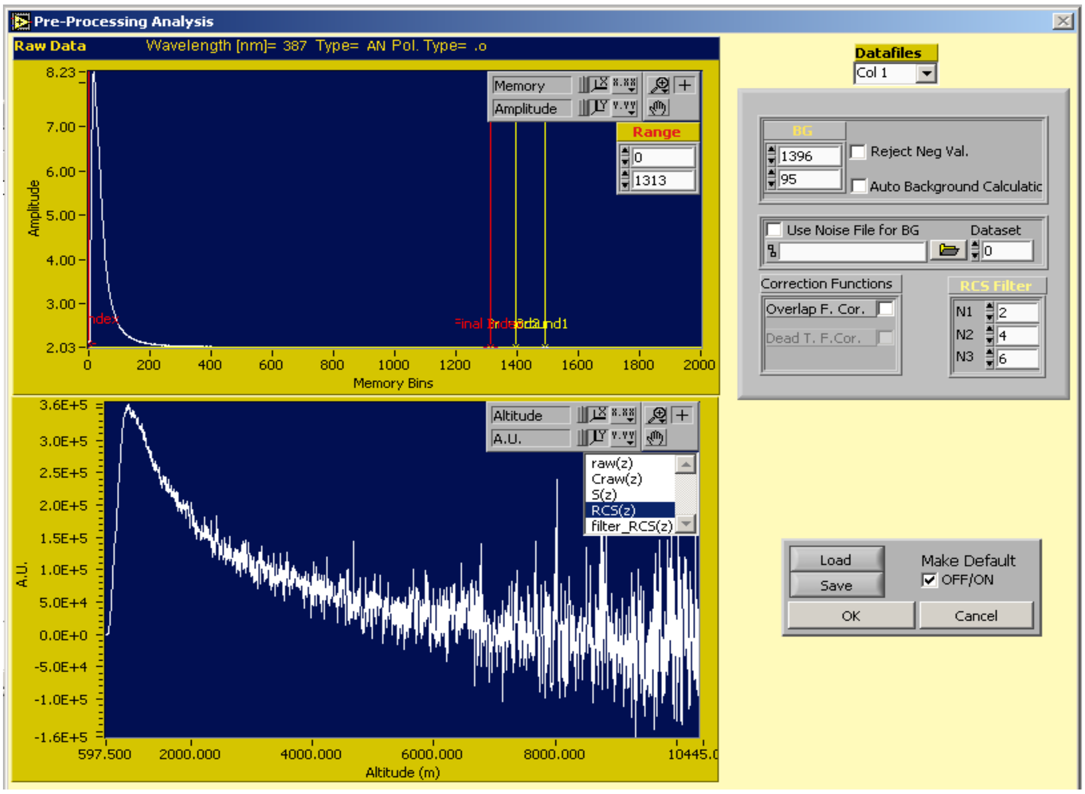



**Fig. 7.37:** Range Corrected Signal

You can see how the Range Corrected Signal (RCS) looks in Fig. 7.37.

For analogue measurements, it is suggested to use a background profile to avoid ADC slopes or electromagnetic interference being taken as a real atmospheric response. A background profile can be taken by covering the telescope and starting a normal measurement. If no light enters through the telescope the only thing that is measured is the noise from the electronics. This procedure is described in paragraph ‘*8.2.3 Dark Current Measurement’*. Alternatively, you can use an external trigger (e.g. a pulse generator) to initiate a measurement without using the laser at all. In this case you measure the electronics noise and the sun’s radiation.

Tip: Note down (e.g. by entering "Dark" as the measurement's location) which measurement is the background noise measurement (or Dark Current Measurement) so that you can select it afterwards in the software interface to subtract the background profile from the signals. This can be set once for all the analysis at the data selection interface. Find the measurement of the dark current, select the file and press “Set Dark Measurement”. You can then continue with the analysis and at the analysis interface the file will be selected.

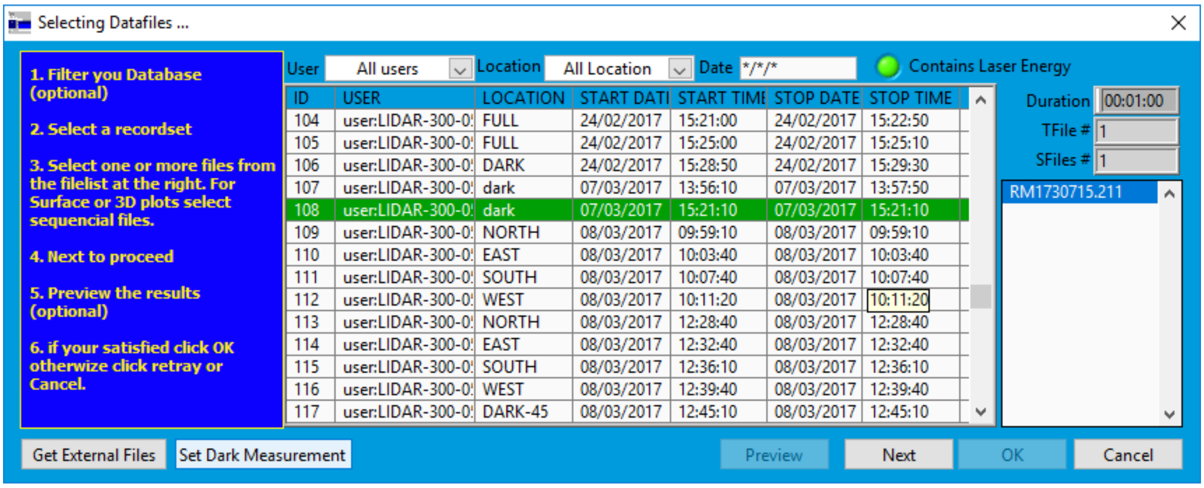



**Fig. 7.38:** Set Dark Measurement

### 7.3.7 How to Glue Analogue and Photon Counting Signals

Depending on your Lidar configuration many detected signals are recorded simultaneously by two methods; Analogue and Photon Counting method.

The combination of both signals allows for high linearity of the analogue signals for strong signals (near fields) and high sensitivity of the photon counting for weak signals (far fields). The idea is to combine the signals, at a region where both signals (analogue and photon) are valid and have a good signal to noise ratio. This method is called gluing. For a typical case, the region of the signals where they will be glued extends from 0.5 to 20 Hz in photon counting mode.

Before we glue signals, the photon counting data should be dead-time corrected (Raymetrics software does this). The dead-time corrected photon counting signal is given by the following equation:

$$S = \frac{N}{1 - N * \tau_d}$$

Where S is the corrected counts, N is the observed count rate and $\tau_d$ is the system dead-time. Raymetrics software uses a value of 260 MHz for $\tau_d$

For detailed discussion of the theory of photon counting dead-time correction please see the following paper: D. P. Donovan, et.al. 'Appl. Opt. 32, 6742-6753 (1993).

**The Gluing Procedure**

In the region where both signals are valid (between the lower toggle frequency – typically 0.5 MHz and the upper toggle frequency – typically 20 MHz) the linear regression coefficient must be found to merge the analogue data with photon counting data.

After merging the two signals, the scaled analogue signal is used above the upper toggle frequency and the photon counting signal below.

**When Gluing is Possible:**

Gluing is possible when the peak value of the dead-time corrected photon counting signal is above the maximum toggle frequency (safe values for maximum toggle frequency are between 10 MHz and 70 MHz for the dead-time corrected signal) and the background signal intensity of the dead-time corrected photon signal is below the minimum toggle frequency.

If the signal is too weak (maximum peak of photon counting signal less than 20 Hz) use only photon (gluing is not useful)

If the signal is too strong (background of the dead-time corrected signal is more than 20 MHz) use only analogue.

**Raymetrics Software**

The first step for gluing is to figure out the maximum range at which the analogue signal has good signal to noise ratio. A suggested way to do this is to remove the background noise and then to figure out the maximum height where the signal is 2 to 5 times more than LSB (the minimum change in voltage required to guarantee a change in the output code level is called the least significant bit (LSB) voltage). The resolution *Q* of the ADC is equal to the LSB voltage and depends on the full range of the pre-amplifier that you have select during the measurements. There are three possible values for the full range, 500, 100 and 20 mV and the LSB is $500/2^{12}$=122 mV, $100/2^{12}$=24.4 mV, $20/2^{12}$=4.8 mV.

Let's assume that the maximum memory bin where the signal is 5 times the LSB is Xa.

In addition, let's assume that the Photon Counting signal has a value of 50 MHz at memory bin Xp. If Xp < Xa then gluing is possible. If not then gluing is not suggested.

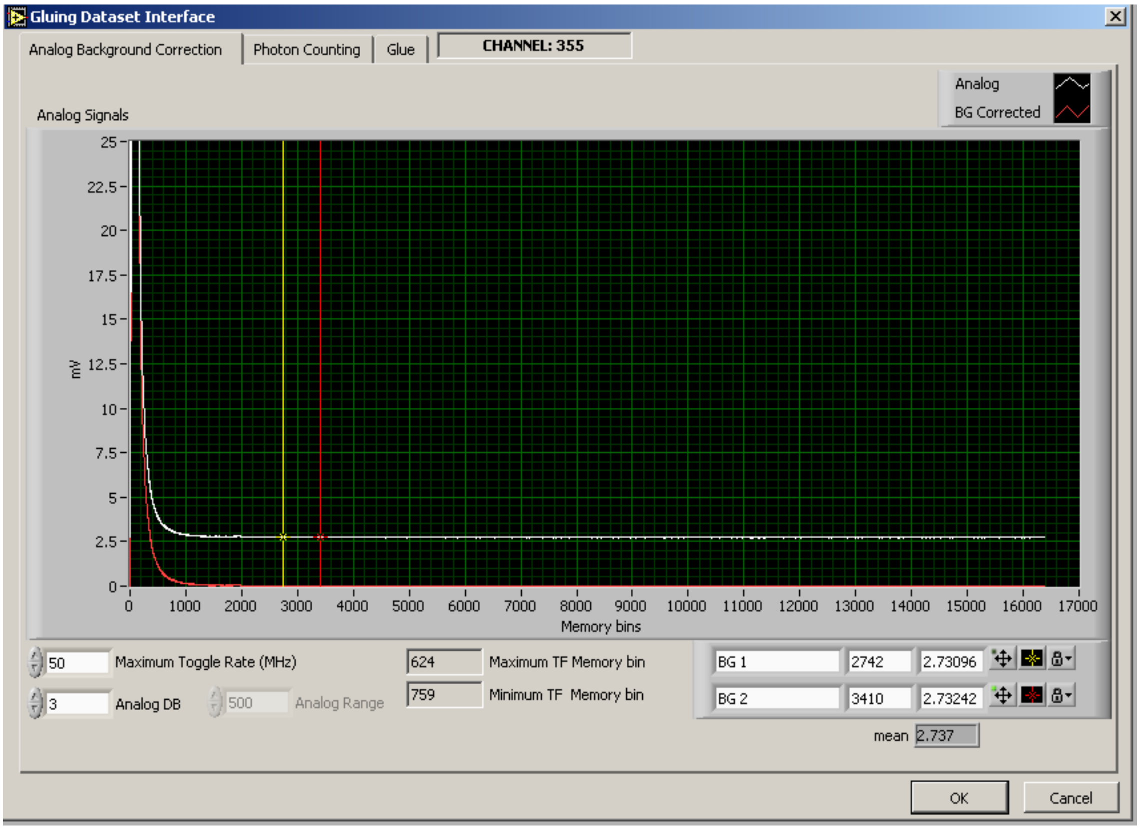



**Fig. 7.39:** Analogue Background Correction

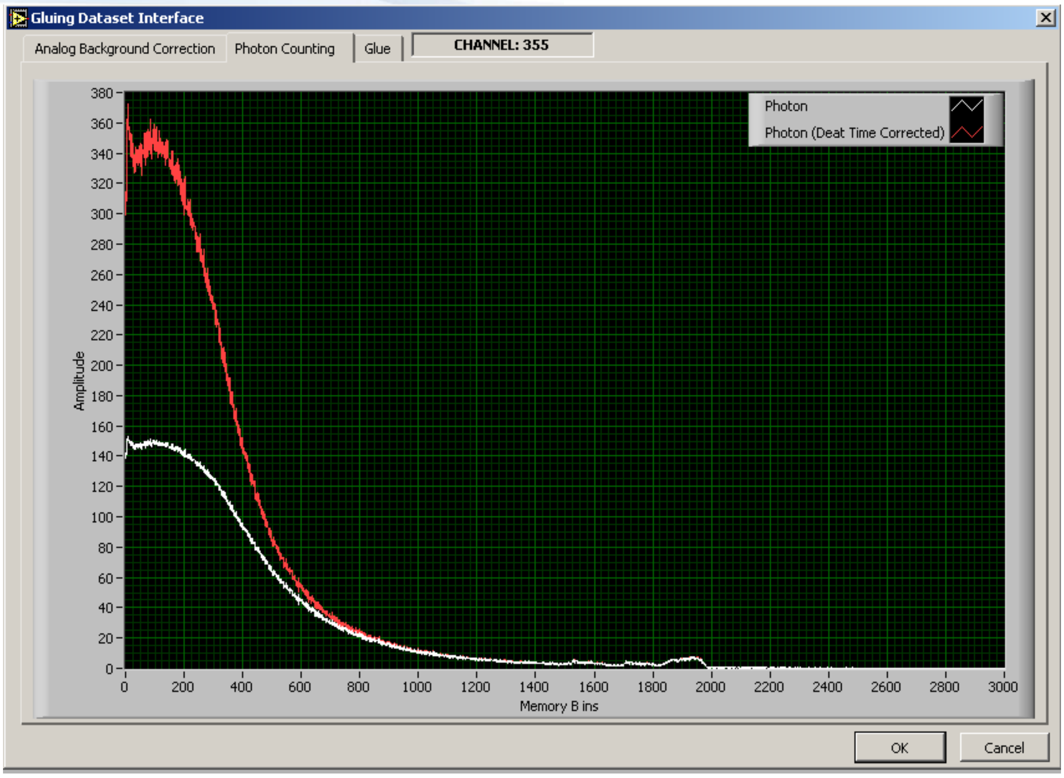



**Fig. 7.40:** Photon Counting and Dead-Time Photon Counting

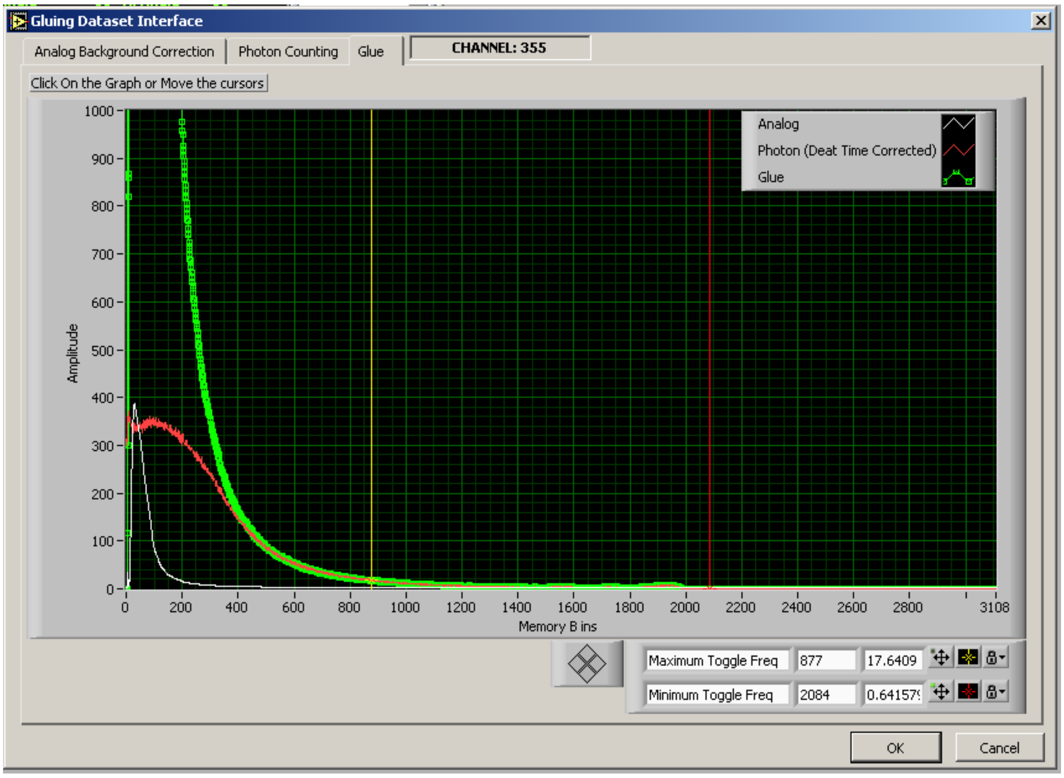



**Fig. 7.41:** Glued Signal

Use the two cursors to change the Maximum and/or Minimum Toggle Frequency (if required), or just click on the graph and then OK button.

### 7.3.8 How to Plot Scanning Data

As previously mentioned the scanning Lidar can perform RHI and PPI scans. These can be plotted as radar graphs. This tutorial shows you how to make such plots.

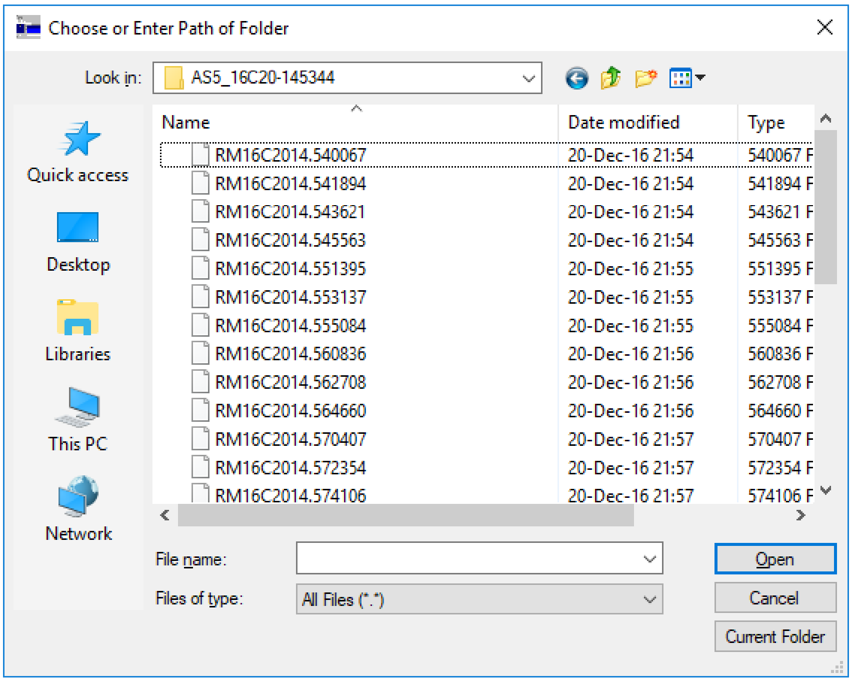
Traditionally, all radar plots are 2D images because the representation is easier to print on a paper or a screen. This means that the PPI scans are a projection of a 3D geometry on a fixed plane. The analysis program however uses advanced algorithms to produce 3D graphs which can be projected on a plane and saved as a 2D image or even more create a Google Earth file that contains a 3D model of the measurement.

It is important to know the orientation of the Lidarhead when at zero position. Normally the zero position should be at the north, however, depending on the site there might be an offset. This parameter is saved on the scanning configuration file so that the raw data files produced will contain the information which will be used by the analysis program to plot the graphs correctly.

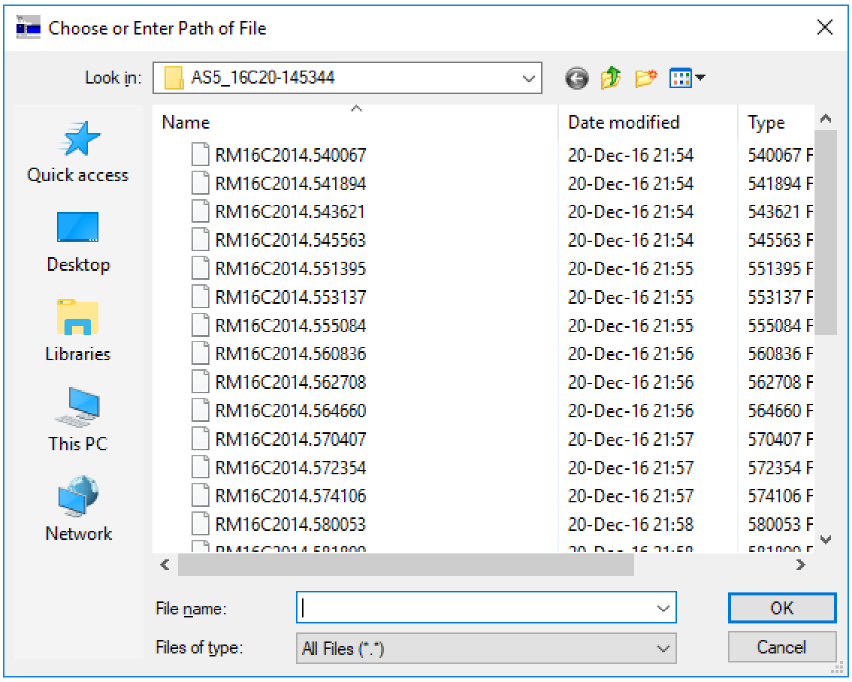
Follow the steps below to plot scanning data.

1. Click the ‘Scanning' button.


2. The first time the program run it prompts the user to select the data folder. Find the data and click ‘Current Folder’.



3. The program then asks for the first file of the data set.




4. If running for first time click again the scanning icon otherwise a new interface appears with the single profile of each file in this data set. (see in Fig. 7.43)

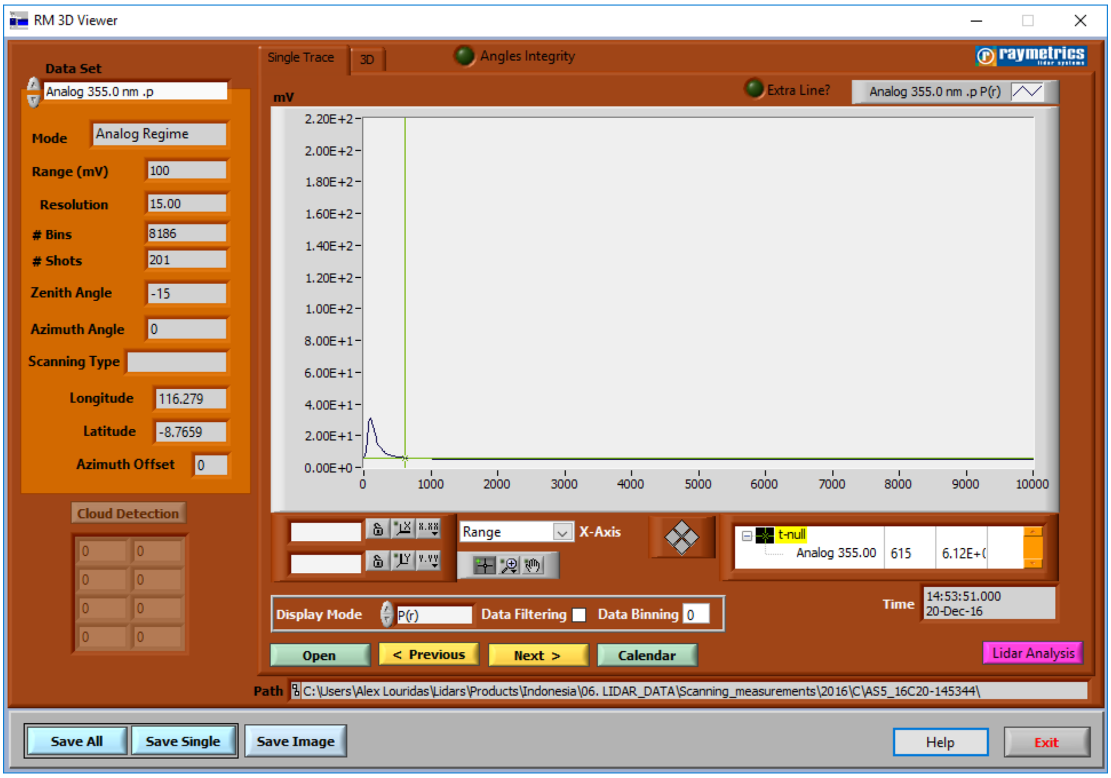



**Fig. 7.42:** 3D Viewer Interface

5. Click on the 3D tab and on the 'Plot Scan' button

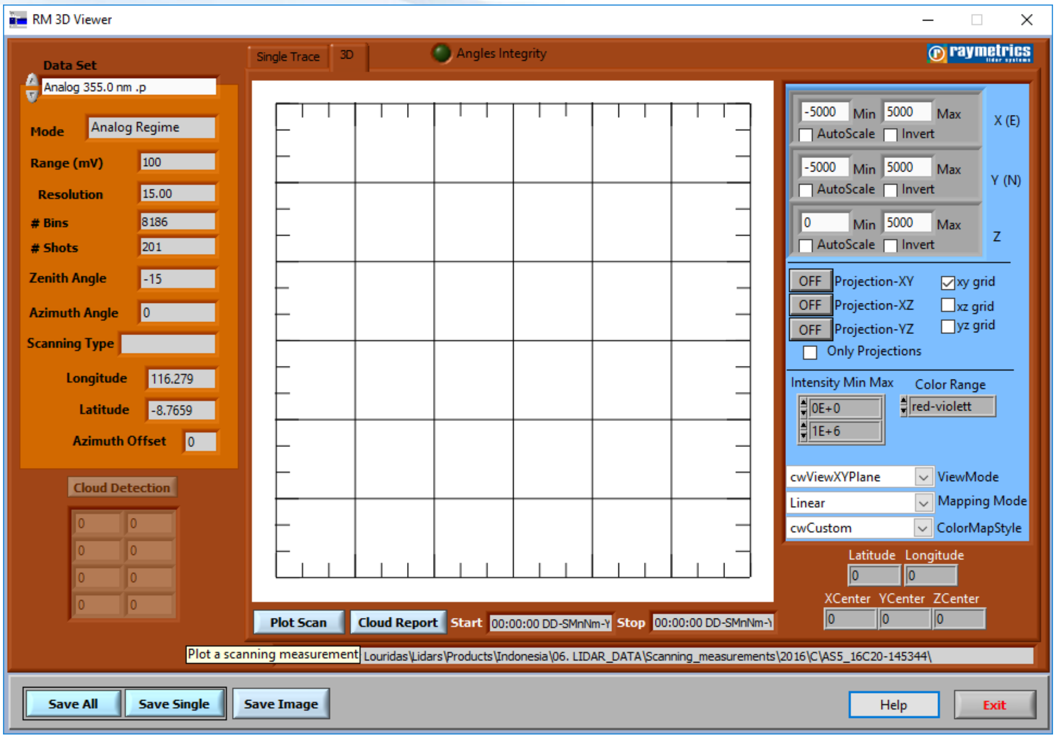



**Fig. 7.43:** 3D Viewer Interface

6. Select the first file and then the last file of the scanning measurement.
7. Follow the same procedure explained earlier in paragraph ‘*7.3.1 How to Plot Data’* to make the analysis and plot.
8. Once you complete the analysis you will have an image like the one in Fig. 7.44

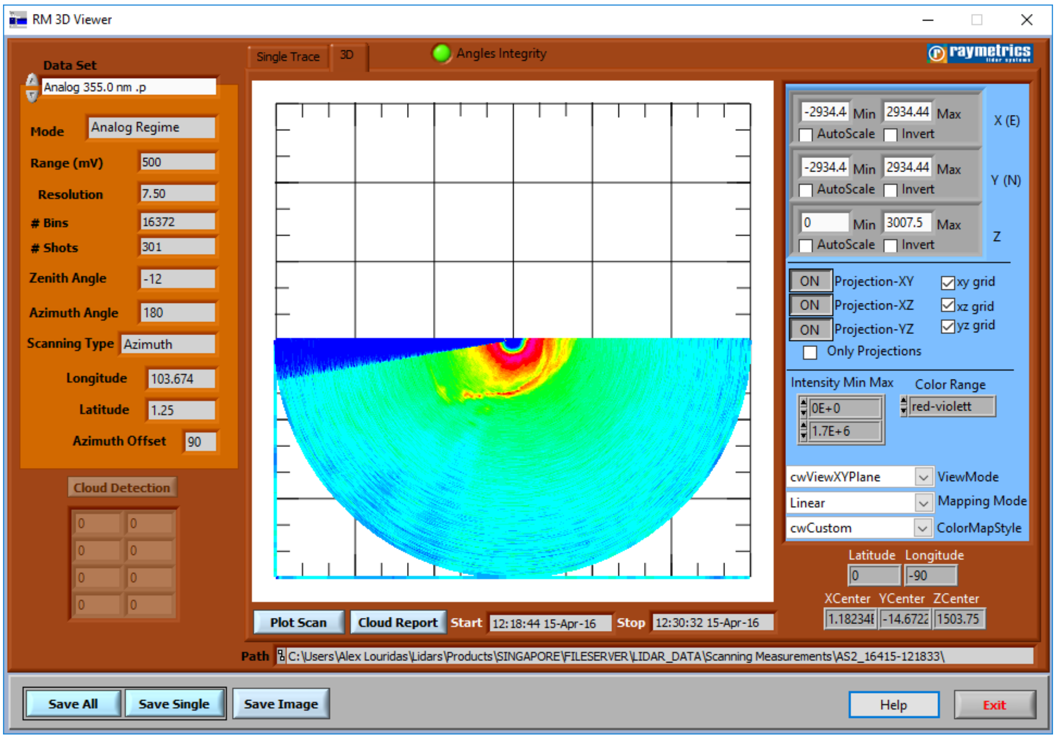
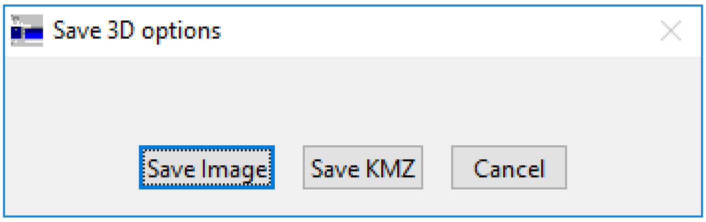



**Fig. 7.44:** 3D Plot

This graph appears as a radar plot (2D plot) but in fact it is the projection of a 3D graph ready to be saved as an image or exported in a .kmz file which can be opened with Google Earth.




If the KMZ option is selected the program will run google SketchUp to create the geometry and generate the kmz file. Next Google Earth will start and the 3D model will appear on the location of the lidar. The coordinates are used from the measurement file.

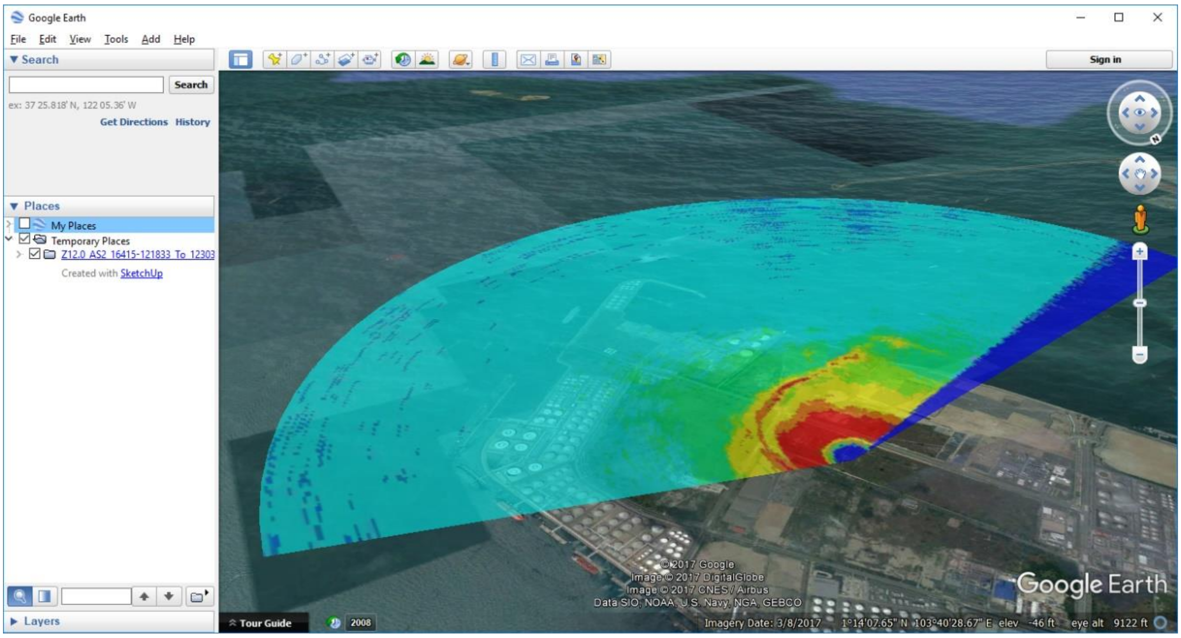



**Fig. 7.45:** 3D Plot on Google Earth

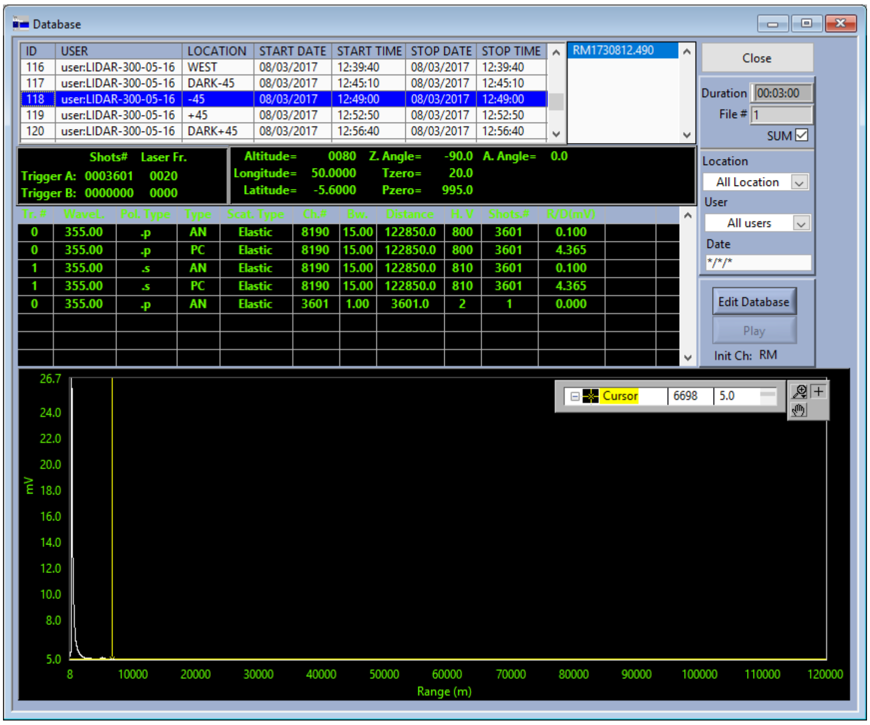
Other than the kmz file the user can rotate pan and zoom on the 3D graph. Hold the mouse left button down and drag to rotate the graph. Hold 'Alt' key with the left mouse button and drag to resize. Hold 'Shift' key with the left mouse button and drag to pan. Finally use the controls on the left to change the color scale or the axes of the graph and the projections.

### 7.3.9 How to Retrieve the Depolarization Calibration Constant

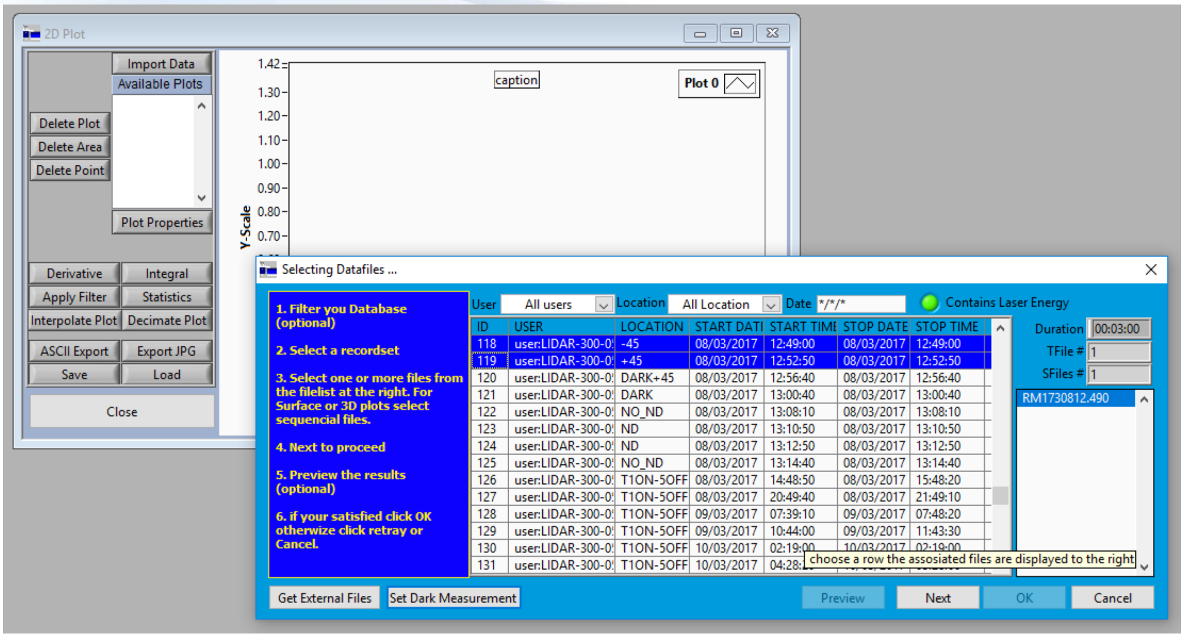
When using the lidar depolarization technique to identify the nature of the components of the atmosphere, one has to account for the impact of several parameters of their system to their calculations. These parameters are related to the optical setup of the lidar system, the transient recorders and the high voltages used on the PMTs. The depolarization calibration constant (V*) incorporates the impact of those parameters into one factor. Each time any of the aforementioned parameters is changed, V* has to be recalculated. Note that this constant is different for analog, photon counting and glued data, thus the user must follow the procedure for all data types. Here is described how to calculate the calibration constant for the analog signal.

To retrieve the depolarization calibration constant (V*) we follow the ±45° calibration method suggested by Earlinet. This procedure requires measurements taken with the WSU turned at 45. To perform the measurement, refer to paragraph *'8.2.2 ±45° Test'.* Don't forget to change the Location of the measurements to something that will help you distinguish these calibration measurements from normal ones by naming them, for example "+45" or "-45", as shown in the image below.

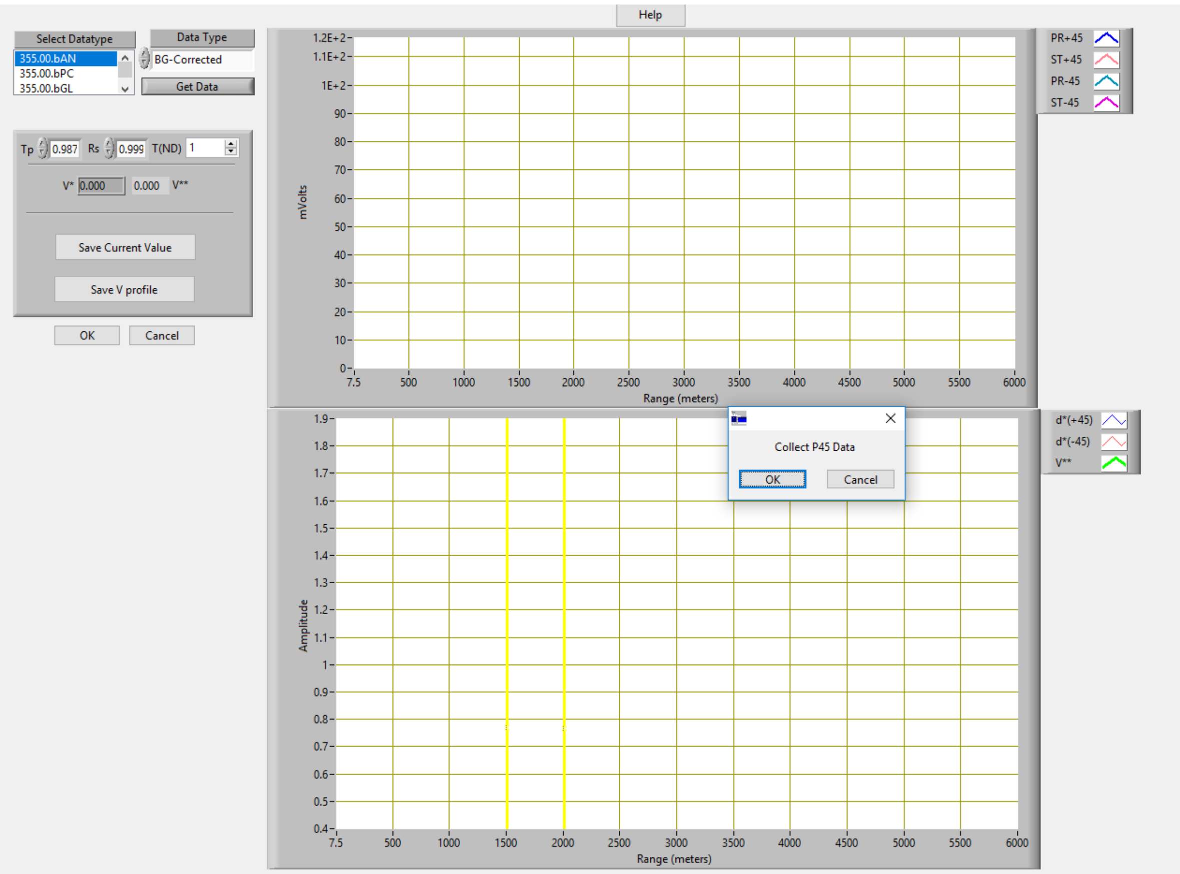
Once the data is collected run the analysis program. You can check that the data is properly saved at the database preview window.



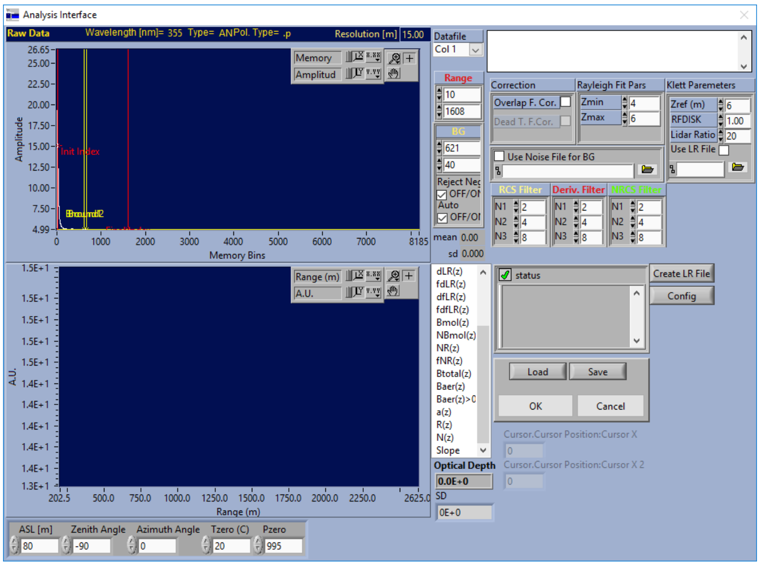

To calculate the V* run a 2D plot, import data and select both data records as shown below. Select also all data files in the window on the right.



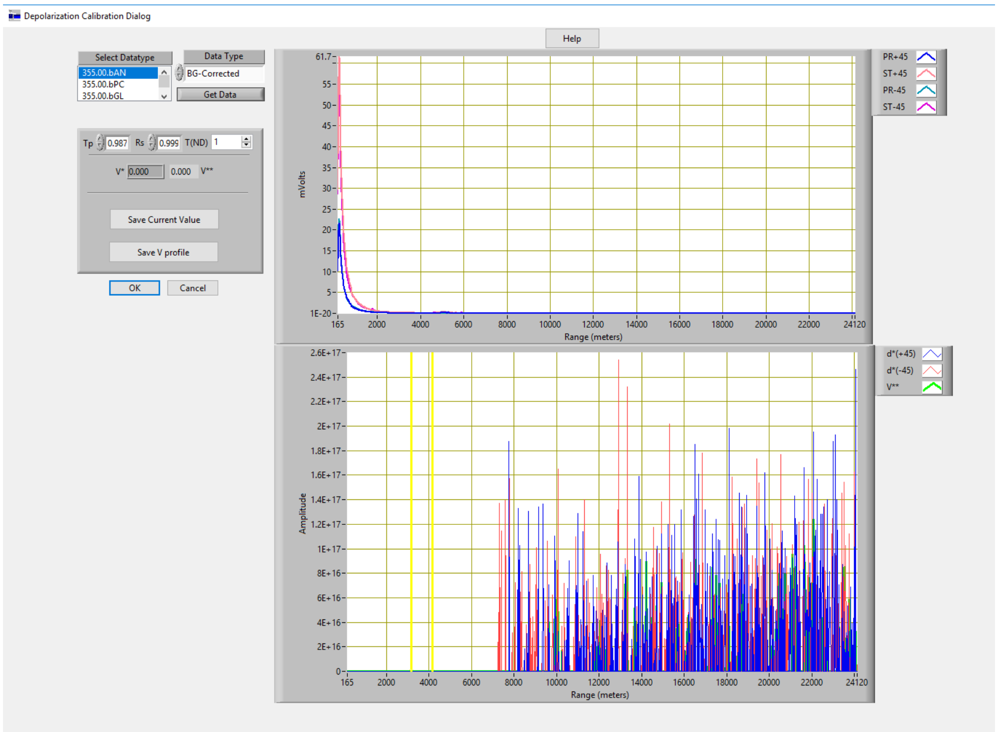
The “Type of Analysis” window appears where the depolarization calibration must be selected. Next the depolarization calibration window appears. Select the datatype, analog (AN), Photon counting (PC) or glued data (GL) and press get data. A pop up window prompts to select the data for the P45 press OK to proceed.



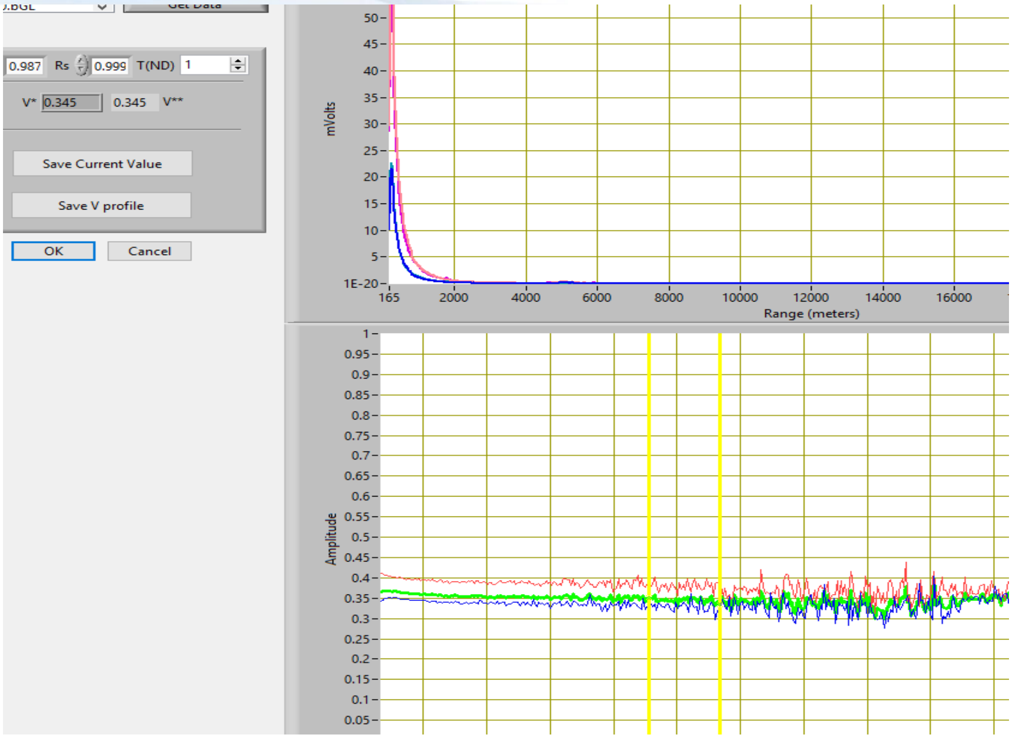
The analysis window appears where the user selects the background extraction area and the range. For better results the user can select a dark current file to remove the electronics noise.



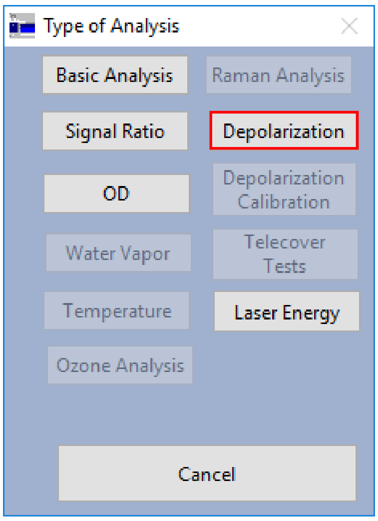
Repeat for all +45 and -45 degrees records and the V* graph should appear like the image below. As it is noticed after a certain range the signal becomes very noisy which is unusable.



By changing the scale of the graph, the V* is easily distinguished. Select an area where the graph is relatively flat. On the box on the left the value of V* is shown. By pressing “save current value” the value is saved and used for the depolarization analysis.




Finally, the result can be more accurate if an external dark current measurement is used instead of the measurement's back ground. To get a dark current file see *'8.2.3 Dark Current Measurement*'. Once the calibration constant is found it can be used in the quick looks of the acquisition program and with any depolarization ratio graph in the lidar analysis software. The depolarization ratio can be plotted as a 2D graph following the *'7.3.2 How to Calculate Backscatter Coefficient'* tutorial or as a time evolution graph following the *'7.3.1 How to Plot Data'* tutorial. For a scanning lidar see the *'7.3.8 How to Plot Scanning Data'* tutorial. The procedure is the same for all but instead of basic analysis select Depolarization.



## 7.3.10 How to Use Soundings from Global Model Data

Accurate radiosonde data from model analyses (and forecasted data) are much better than data calculated with standard atmospheres. You can find this information for free on the internet. The following section shows where you can find and how you can use the data. Go to the website: http://rucsoundings.noaa.gov/, to get model data for every location on earth on a 0.5° grid.

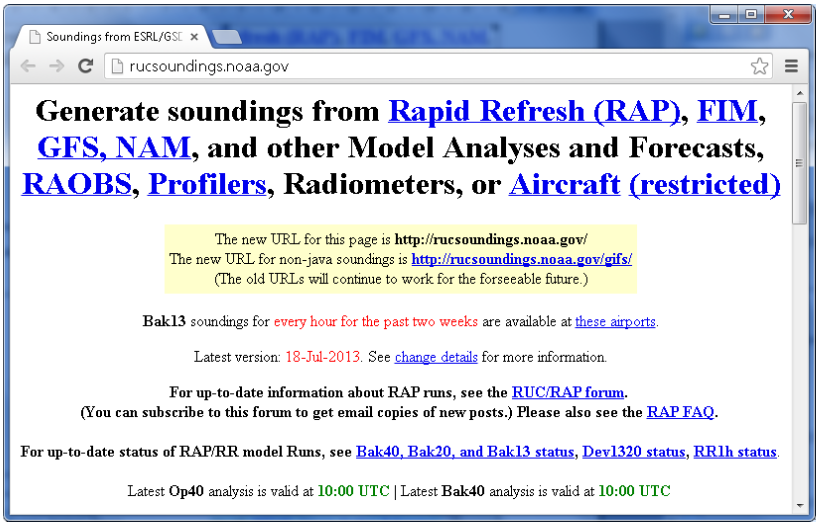



**Fig. 7.46:** Rucsoundings

1. Select FIM, 24, 12 or 8 for No. of Hours, plus your latitude and longitude (e.g. 34.7, 33.07)

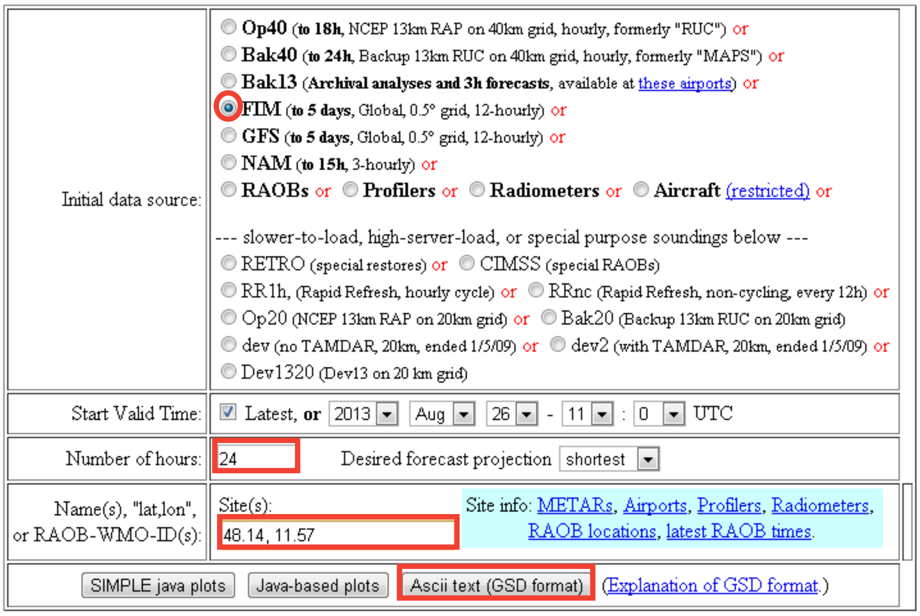



**Fig. 7.47:** Rucsoundings

2. Click on the ASCII Format (GSD).

3. On the new page that will appear use your mouse to select the data that you want.

```
FIM analysis valid for grid point 12.5 nm / 196 deg from 34.7,33.07:
FIM        0       1      Apr     2011
   CAPE      0     CIN      0  Helic      0     PW      0
      1  23062   99999  34.50 -33.00  99999  99999
      2  99999   99999  99999     68  99999  99999
      3          34.7,33.07           12     kt
      9  10061      88    201     71     45     13
      5  10019     123    205     57     46     14
      5   9946     186    207     35     48     15
      5   9846     271    211     10     52     16
      5   9735     367    212    -10     55     16
      5   9614     472    210    -29     58     17
      5   9485     586    204    -44     61     17
      5   9350     708    197    -61     64     16
      5   9210     836    191    -77     67     15
      5   9066     969    184    -93     69     14
      5   8921    1106    176   -108     71     13
      5   8775    1245    166   -123     72     12
      5   8631    1385    157   -134     72     10
      5   8489    1525    150   -139     72      9
      5   8349    1663    141   -139     73      8
      5   8212    1802    131   -136     77      7
      5   8078    1939    121   -131     82      6
      5   7946    2077    111   -129     90      5
      5   7816    2213    100   -129    103      4
      5   7688    2350     89   -129    118      4
      5   7561    2486     77   -130    137      4
      5   7437    2626     66   -130    157      4
      5   7163    2900     41   -127    187      5
      5   6537    3621    -10   -131    230     11
      5   5811    4621    -85   -179    245     19
      5   5087    5696   -168   -267    252     19
      5   4327    6862   -267   -359    249     27
      5   3571    8197   -382   -426    244     35
      5   2910    9487   -499   -548    245     40
      5   2588   10218   -560   -615    246     47
      5   2464   10554   -579   -647    247     49
      5   2352   10852   -594   -677    249     52
      5   2251   11133   -607   -697    251     54
      5   2153   11421   -615   -705    253     55
      5   2055   11719   -619   -712    254     56
      5   1954   12034   -617   -718    255     58
      5   1851   12373   -612   -722    255     62
      5   1747   12730   -604   -727    255     66
      5   1640   13125   -595   -733    256     68
      5   1510   13648   -592   -735    257     67
      5   1354   14347   -602   -746    256     63
      5   1196   15135   -617   -790    255     57
```

**Fig. 7.48:** Results Page

4. Copy the data (select and right click to copy)

5. Open a text editor and paste the data. Save the file with any name desired (e.g. Road_Data.txt). The data columns that we are interested in are column 2 (pressure in tenths of millibars), column 3 (altitude in meters) and column 4 (temperature in tenths of Celsius). Note: Raymetrics software needs to read an ASCII file with three columns separated by tab.

   a. First Column: Altitude in meters

   b. Second Column: Temperature in K

   c. Third Column: Pressure in hPa.

6. Now we need to convert the Road_Data.txt file to another ASCII formatted file suitable to be read by Raymetrics software. To do so locate the Rm_Utils.llb and run the **ROAD_GSD_to_Ascii_Format.vi**.
7. Select the file that you want to convert e.g. Road_Data.txt.
8. The software will ask to save the formatted data to another file. Then give another filename for the formatted file e.g. 'Road_Data_formated.txt' (if you like you can overwrite the original file).

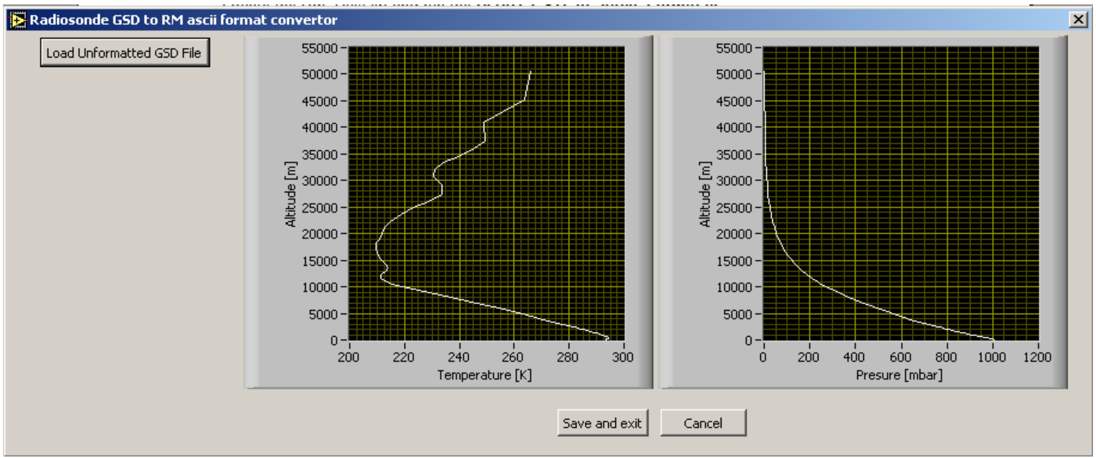
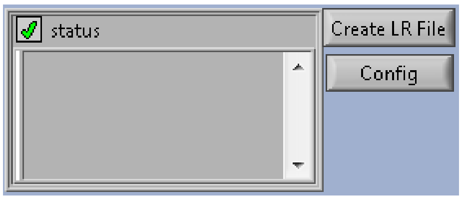
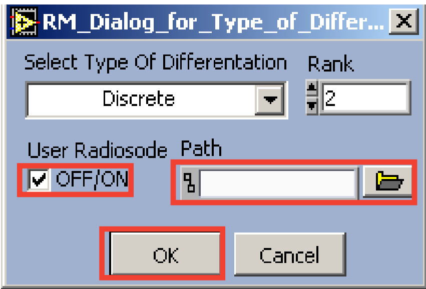



**Fig. 7.49:** Radiosonde File Convertor

9. Now in the analysis interface you can click on the Config button




10. Then click on the 'Use Radiosonde' check box and then load the formatted ASCII file by clicking on the folder icon. Then click 'Ok'.



# 8. LIDAR SYSTEM MAINTENANCE

This chapter provides information about the maintenance of the Lidar which can be divided in three types each related to the:

1. data quality and system performance which is the Lidar alignment section
2. calibration tests for proper lidar analysis which is the reference measurements section
3. hardware maintenance.

The frequency of the maintenance depends on the use and the type of the maintenance which is indicated in next sections.

## 8.1 Lidar Alignment

To acquire the best possible Lidar measurement, alignment must be performed which is steering the laser beam to the telescopes field of view. This should be performed if the lidar is relocated, on every flashlamp replacement, on season change and whenever the amplitude of the signal is low. Ideally the Lidar is aligned as illustrated in **Fig. 8.1**. As the light of the laser beam enters the telescope's Field Of View (FOV) (point A), the signal starts to increase and reaches its peak value when the entire beam is inside the field of view (point B). After this point the signal starts to decrease as the light is attenuated.

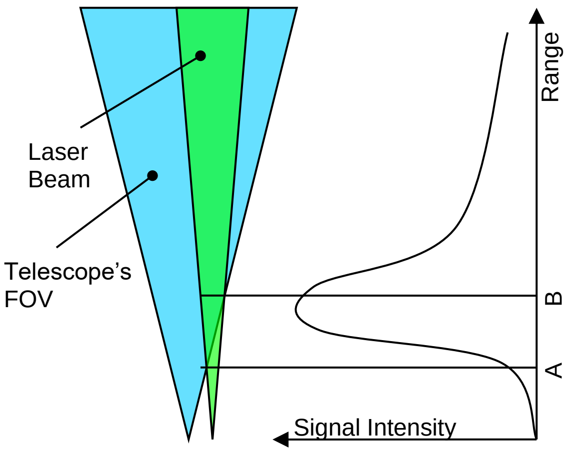



**Fig. 8.1:** Properly Aligned Lidar and Corresponding Signal

There are two ways that the Lidar can be considered misaligned. Both are shown in **Fig. 8.2**. In the first case, the laser beam is tilted away from the telescope resulting in no Lidar signal. In this case, there is only the noise from the electronics and the sun's background radiation. In the second case, the laser beam enters the telescope's FOV (point A-B) but exits after a certain point (point C-D) since the beam and the telescope FOV are not parallel. The second case is difficult to distinguish as a case of a misaligned lidar, as the signal looks like a normal Lidar signal but the effective range is reduced. The techniques to align the Lidar are described below.

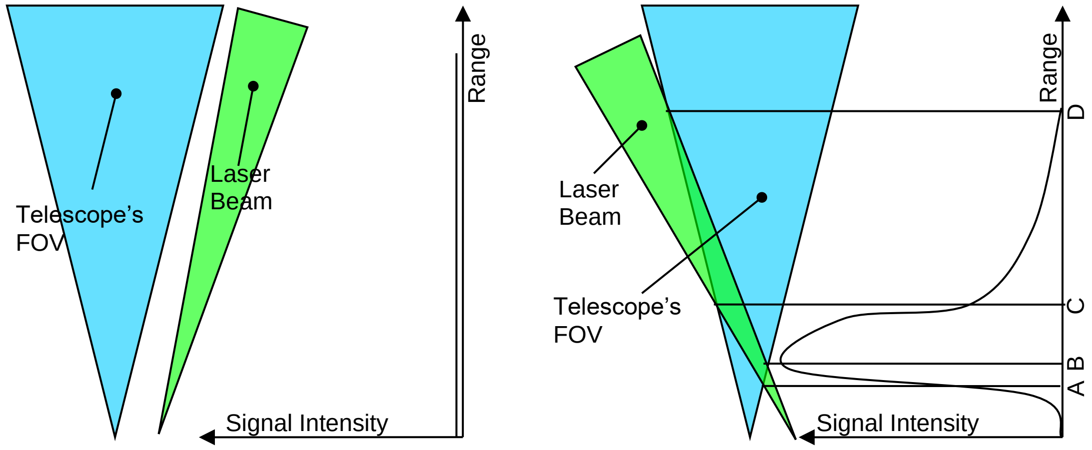



**Fig. 8.2:** Misaligned Lidar and Corresponding Signals

The next figure shows actual Lidar signals of a misaligned lidar. The black curve corresponds to a properly aligned Lidar, while the Red and Green curves (same alignment but reduced signal intensity) correspond to cases like those shown in **Fig. 8.2** b.

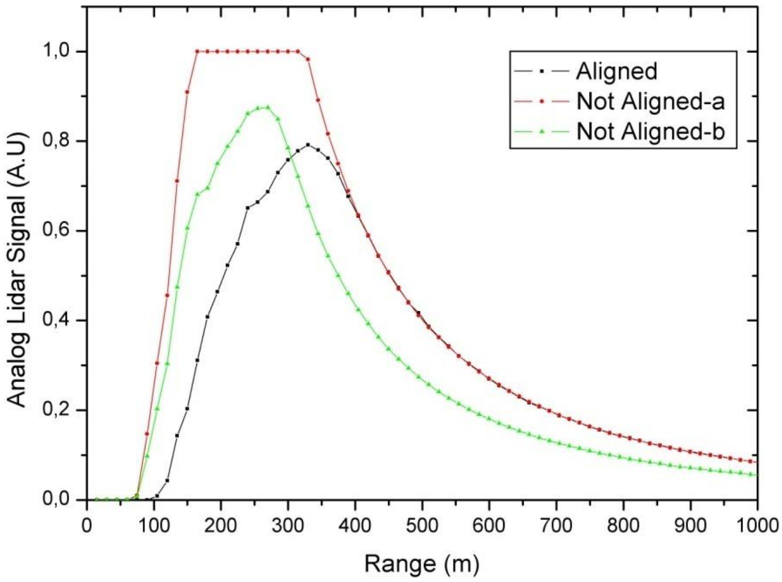



**Fig. 8.3:** Alignment Example Real Signals

A common mistake is misinterpreting the red curve as a very good alignment since this signal is very strong (it is even saturated between 150 and 350 meters). However, by reducing the signal intensity (see *'8.1.4 Signal Intensity Reduction'*) to get rid the saturation, the signal resembles the green curve, which (at the far range of the signal) has half the intensity than that of the properly aligned system (black curve). As one can see, an aligned lidar has increased signal at the far range, so it is of utmost importance that proper alignment is performed periodically to ensure that the measurements acquired are of maximum range.

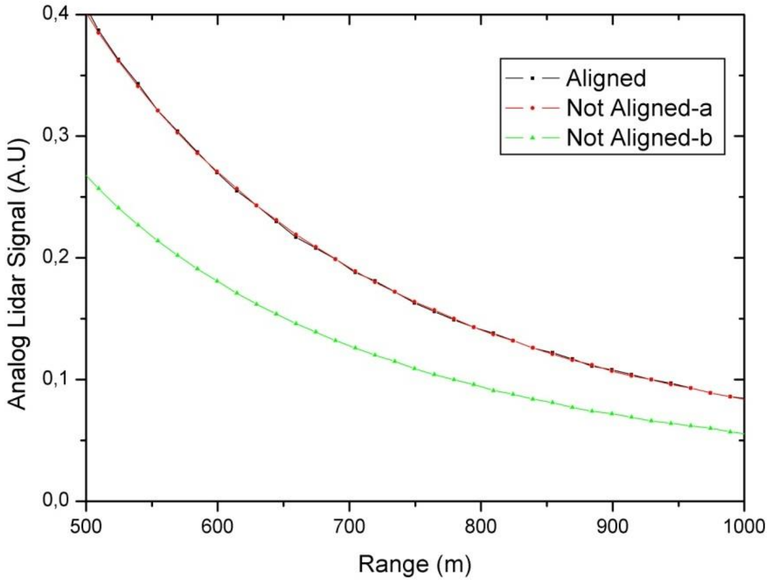



**Fig. 8.4:** Alignment Example Real Signals far filed

## 8.1.1 Laser Beam Kinematic

The Lidar alignment is achieved using a mirror mount that has two motorized actuators 'A' and 'B'. By moving the mirror mount's actuators, the laser beam is maneuvered to meet the axis of the telescope's FOV. Which actuator is to be moved is not always apparent. Following, you'll find information to become familiar with their proper use.

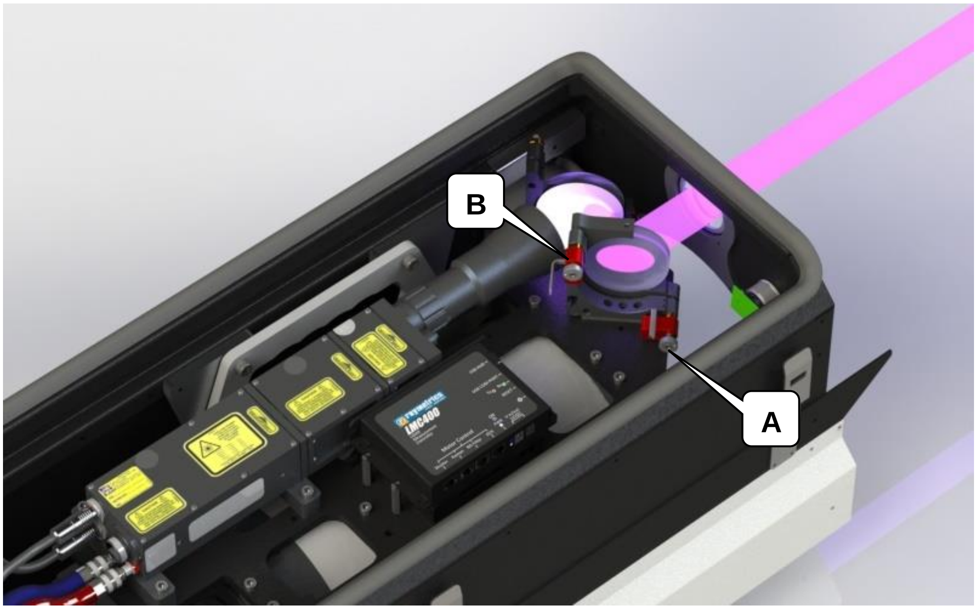



**Fig. 8.5:** Mirror Mount and Actuators

Raymetrics designs specialized lidar telescopes that have exceptionally small field of view to reduce the background noise. Because of the telescope's small FOV, the alignment is very fine. For this reason, the actuators have a very small resolution that give the user the ability to micro align the Lidar.

The next figures show the effect of actuator ‘A’ and ‘B’ on the laser beam direction.

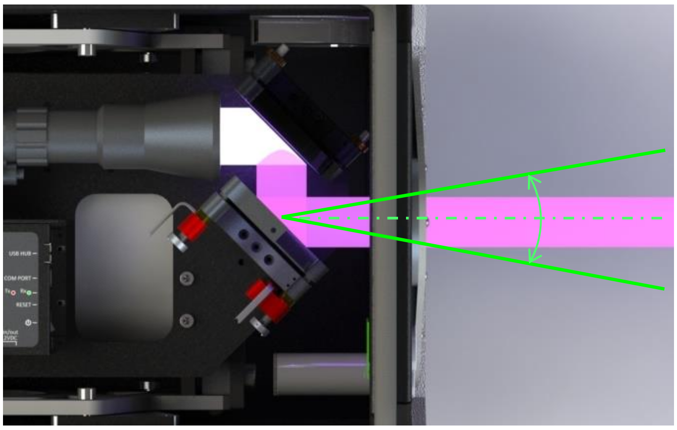


**Fig. 8.6:** Actuator ‘A’ Effect

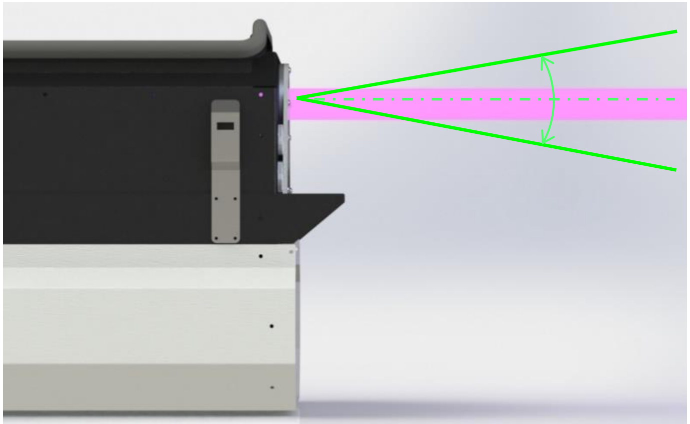


**Fig. 8.7:** Actuator ‘B’ Effect

Below is a schematic representation of the laser beam movement caused by each actuator in relation to the telescope. In short, actuator ‘B’ moves the beam in a 'vertical' direction and actuator ‘A’ moves the beam in a 'horizontal' direction.

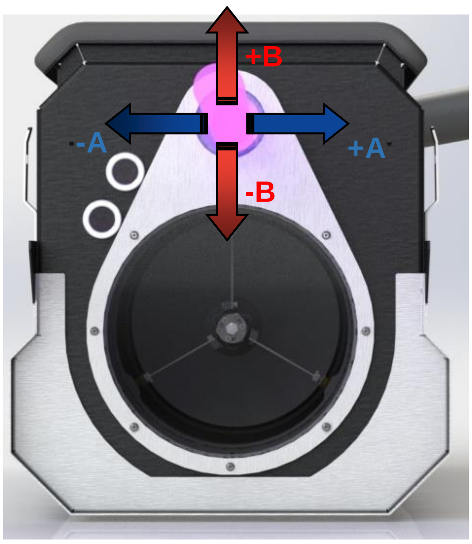



**Fig. 8.8:** Laser Beam Kinematics

### 8.1.2 Using the Alignment Software

To perform the lidar alignment the ‘Live display’ program is used which is introduced in section *‘4.3.1 Lidar Alignment*’. Following, you will find a more complete guide on how to use the program.

When the 'Live Display' program starts, it automatically attempts to communicate with all devices. In this case there are up to seven devices to communicate with:

1. Transient Recorder
2. PMT High Voltage device
3. Laser
4. LPC
5. LMC
6. Motorized Mirror Mount
7. Positioner AZP200


When the Licel devices and the rest of the hardware communicates properly with the computer, the LEDs on the top of the window turn green. If for any reason they remain red, consult section ‘*9. TROUBLESHOOTING*’ for more information about communication errors.

On the first tab, controls for the Transient Recorder can be found while the rest of the hardware can be controlled via the third tab. The parameters for the communication port are read from the programs configuration file (live display.ini). The values in the file should not be changed, unless it is done by an experienced user.

At the third tab, the laser controls can be found. The user can check the flashlamp shots (denoted in millions) and can alter the laser energy by turning the knob of the Q-switch delay (the bigger the number the smaller the energy is). By pressing the start button the laser starts emitting, unless if there is an interlock. In this case the LED on the laser's control interface is On. If the interlock comes from an external parameter, i.e. the hatch is closed, it will be indicated on the right of the control where the LPC status is displayed. If the interlock is internal check the display of the remote control of the laser and refer to troubleshooting. A short delay will ensue after pressing the Start button, which is to warmup the flashlamp before starting the Q-Switch. Furthermore, the user here can also control the slide filter modules at the LMC control box. Simply click on the slide filter to be activated and wait until the reply is sent from the controller. Finally, at the positioner control box the user can turn the Lidar head at an azimuth angle range from 7˚ to -90 ˚ degrees and at azimuth from 0˚ to 360˚ degrees. This enables the user to point the lidar at any direction of a hemisphere. The motors are equipped with encoders to maximize the accuracy. Each time the system is turned off, the positioner loses track of its last position so, upon startup, the motors will be moved to their home position. Finally, the user can set in this tab the PMTs' high voltages.

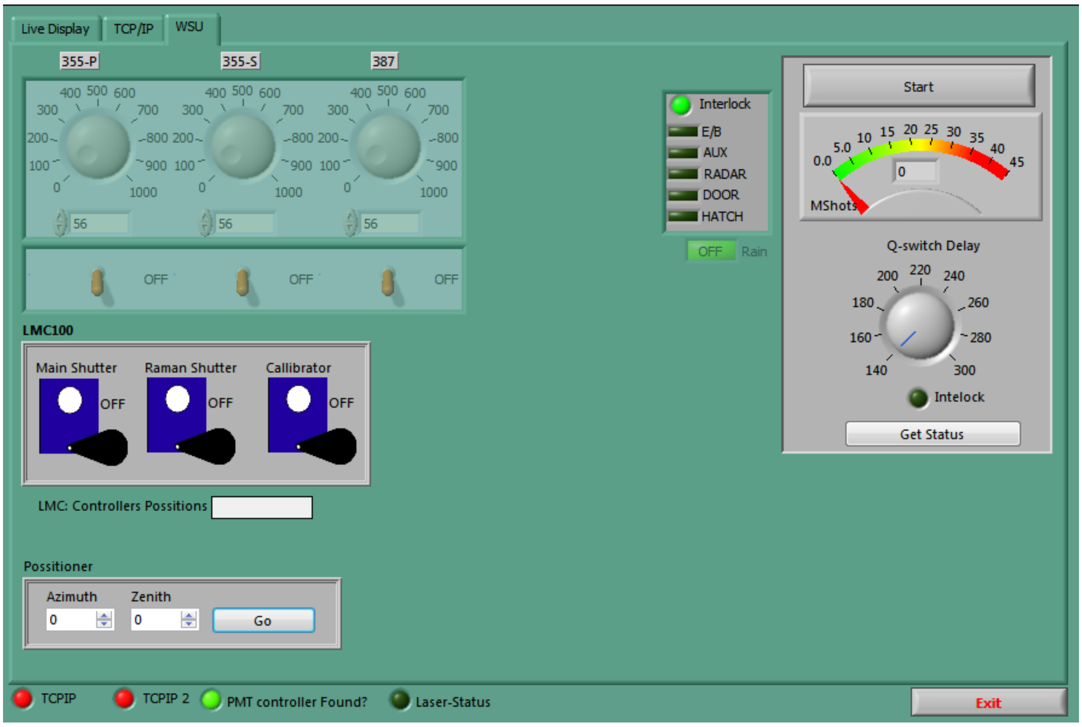


**Fig. 8.9:** Hardware Control Interface

The settings under the TCP/IP tab allow for selection of the communication port of the transient recorder.

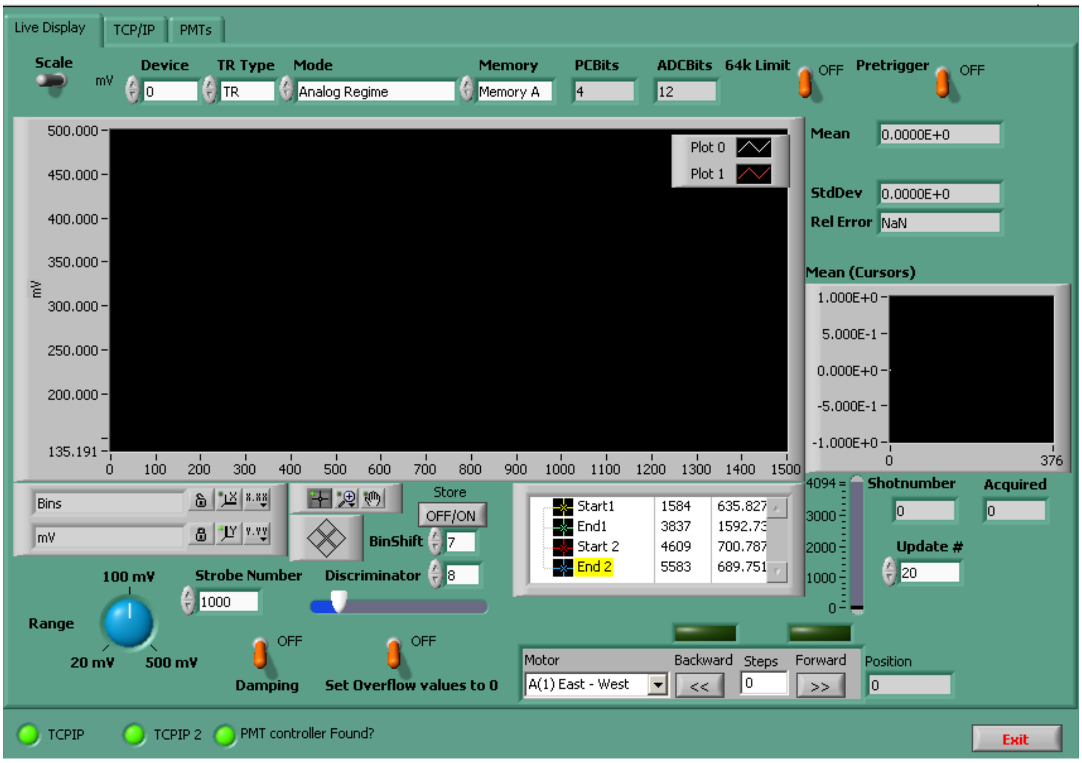
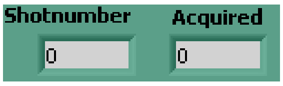


**Fig. 8.10:** Live Display Interface

When the laser is operating the 'Shot Number' indicator will increase for every trigger pulse Transient Recorder receives (or for each laser pulse if the recorder is triggered by the laser source). Next to this is the 'Acquired' indicator which shows how many profiles have been displayed so far.




Set the desired value of shots that need to be averaged per profile using the 'Update #' control. Setting this number to a high value will result in a slower updated but smoother graph. If the value is too low the graph will be affected strongly by the laser's energy oscillations resulting to a quickly refreshed but poor-quality image. It is suggested not to use a value lower than the laser repetition rate which is 20Hz.

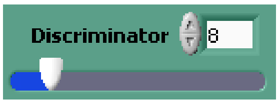

When the 'Shot Number' value is equal to the 'Update' value the averaged data from the Transient Recorder is fed to the computer and is displayed at the graph. The procedure then repeats until the laser is stopped or the exit button is pressed.

The 'Strobe Number' indicates the number of bins to be transferred from the Transient Recorder to be displayed.

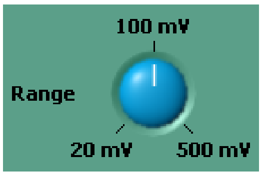

The dataset which is displayed on the graph depends on the selections made. Select desired device, TR type, and mode.


To change the High Voltage value for the PMT go to 'PMTs' tab as shown in **Fig. 8.12**. The desired value may be set either using the dial or the field directly below it. After this the PMT should be switched to the 'ON' position.

The discriminator level is the voltage threshold above which the PMT will distinguish usable signal from noise (either actual photons or random signal spikes coming from electronic noise or even temperature variations). In other words, the sensitivity of the PMT can be set using the 'Discriminator' control.

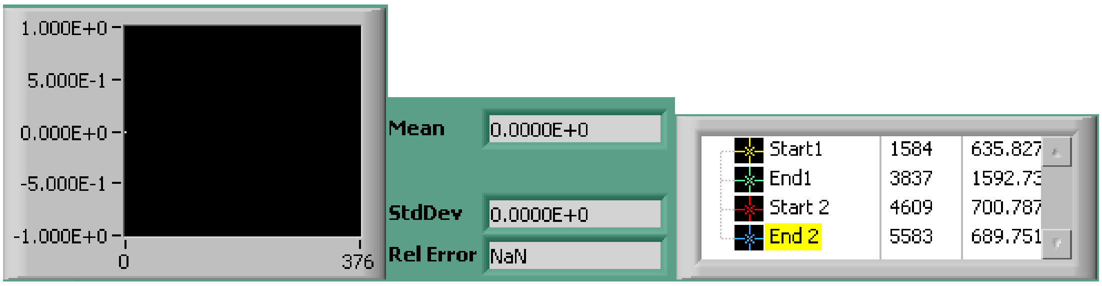


Set the analogue input range of the preamplifier (Range). The signal starts at 0 and extends to 20, 100, or 500mV. According to EARLINET suggestions the range must be twice the peak signal. When the signal is too strong it becomes saturated and the range must be increased, otherwise the PMT will be damaged. If the maximum range is selected and the signal remains saturated refer to *'8.1.4 Signal Intensity Reduction'*.

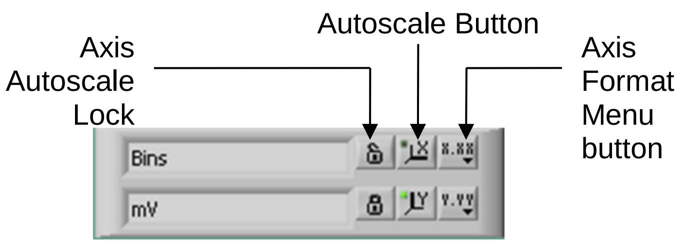



Turn on the overflow switch, to display all memory bins that overflow as 0.


The yellow and green cursors below the graph allow the selection of a region to average. The small graph in the right corner of the interface window shows the average of the region of interest. Above the graph the numerical values of the graph are displayed.




The x and y controls on the left of the window allow the user to autoscale the x or y axis. By clicking these buttons, the scale is automatically adjusted to the highest value. The lock changes from autoscale mode to fixed mode. In autoscale mode the scale is adjusted to the highest value each time the graph is updated. In fixed mode, the scale remains constant unless the user presses the x or y controls ('Autoscale' button). Default settings are autoscale for the y axis and fixed values for the x axis. The x. xx and y. yy controls allow for the specification of the format, precision and mapping modes of the x and y axis.

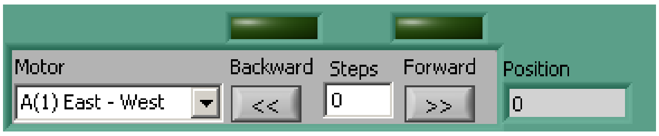


For more information about the wave-graph refer to the supplied Labview manual.

Below the graph is a 'Store' button. This can capture an image of the current profile and plot it with red coloring on the same graph. This option can be used to compare two different signals, which can be useful during the telecover test.


Below the 'Store' button is the 'Bin Shift' control. The analogue signal has a small delay compared to the photon counting signal. This difference comes from the time needed for analogue to digital conversion. In terms of signal the range is slightly increased, usually by 7 memory bins. What this control does is to shift the graph to the left so that the range shown on the graph is correct. To define the delay set the Bin Shift to 0. Normally a small reflection coming from the lidar itself is shown as a spike in the graph after some meters. The quotient of this number by the TR’s resolution is the bin shift. For example, if the spike appears at 50 meters and the resolution is 7.5 meters then the bin shift is 6.66 which rounded gives 7bins.


Finally, at the bottom of the window are controls for the motorized mirror mount. Select the motor (actuator) to be moved in the first control from the left. Next set the step size (noting that a large step is around 200 and a small step is about 20). Press the left and right arrows to move the actuator forward and backwards.




**CAUTION:** NEVER BLOCK THE EMITTED LASER BEAM, WHEN THE PHOTOMULTIPLIERS ARE SWITCHED ON. REFLECTIONS FROM THE OBSTRUCTING OBJECT WILL DAMAGE THE PMTs. IF THERE IS A REQUIREMENT TO BLOCK THE LASER BEAM (e.g. for screening purposes during alignment) THE POWER SUPPLY OF THE PMT’s AND APD MUST BE SWITCHED OFF AND THE TELESCOPE MUST BE COVERED (with a piece of soft black cloth) TO PREVENT REFLECTED LIGHT FORM ENTERING THE TELESCOPE.

**CAUTION:** NEVER DIRECT THE TELECOPE DIRECTLY TO THE SUN. THE SUN’S LIGHT WILL DAMAGE PERMANATELY THE PHOTOMULTIPLIERS.

## 8.1.3 Lidar Alignment Procedure

As previously mentioned there are two cases of misalignment; case I and II as shown in **Fig. 8.2**. The case where there is no or little signal is rather unusual and the user should run a series of diagnostic tests described in chapter *'9. TROUBLESHOOTING*'. When the lidar is misaligned as in case II, the procedure of fine alignment is followed, which can be done in two different ways. One is by increasing the intensity of the signal in the far range and the other is by performing a fast Telecover test. To verify also the alignment the user can perform a comparison with a pure molecular atmosphere model in the analysis software. For more information see section *'7.3.4 How to Check Lidar Alignment'*. Following, you'll find a detailed explanation of the two different methods to achieve the fine alignment step.

### *8.1.3.1 Intensity Maximization at Far Range*

When the intensity of the signal increases, in general it means that more light is entering the FOV of the telescope. It is very easy to increase the signal in the near range but it is also easy to misalign the Lidar as shown in case II in **Fig. 8.2**. Maximization of the signal's intensity in the far range means that as far the telescope can see there is a laser beam.

The alignment procedure is quite simple; the user selects an area on the slope of the signal's graph as far as possible and tries to maximize the mean value of this area by using the actuators. Once the mean value of the received signal in the selected range reaches its peak, another area further than the initial area is selected and the process is repeated with a smaller actuator step. The procedure is described in detail in more following steps:

1. Run the 'Lidar Alignment' program. On start up the program establishes a connection with the Licel controllers, the laser, the LMC, the motorized mirror mount and the LPC. At the bottom of the program window there are three red LEDs. If all controllers are found these should turn green. If not, there is a communication problem.


**NOTE:** Before starting the program exit all other applications. Otherwise the program will fail to establish the connections with the various hardware.

2. On the last tab (see **Fig. 8.11**) the laser controls can be found. By pressing the start button the laser starts emitting, unless if there is an interlock. In this case refer to paragraph 9.2 Emission. Once the user presses the start button, a small delay follows while the program remains idle until the Q-switch starts functioning.

**CAUTION:** BY PRESSING THE START BUTTON THE LASER STARTS EMITTING, FOLLOW THE SAFETY INSTRUCTIONS CAREFULLY.

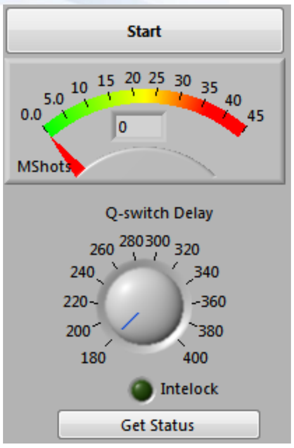



**Fig. 8.11:** Laser control

3. Next set the desired high voltage value for the first PMT (Channel 355P) and turn the PMT On. It is recommended to initially use a voltage as low as 400Volts to avoid signal saturation and work your way up until the signal is clearly received. The user can change the value and activate any PMT at any time (see **Fig. 8.12**).


**Fig. 8.12:** PMT High Voltage Control

4. Go to the 'Live Display' tab. The signal should now be visible.
5. On the right are the controls for the cursors. Right click and select 'Bring to Center'. Right click again and select 'Lock to Plot' if not selected.
6. Place the yellow cursor (start) on the graph, roughly in the middle of the falling edge of the signal.
7. Next do the same with the green cursor and place it somewhere on the graph, just before the signal becomes flat.
8. Zoom into the area using the axes scale controls . The scale is either automatically adjusted to the maximum value or it can be fixed in a specific range. Click on the switch to toggle between these two states. When the axes are fixed set the lowest and highest values close to where the selected area is.

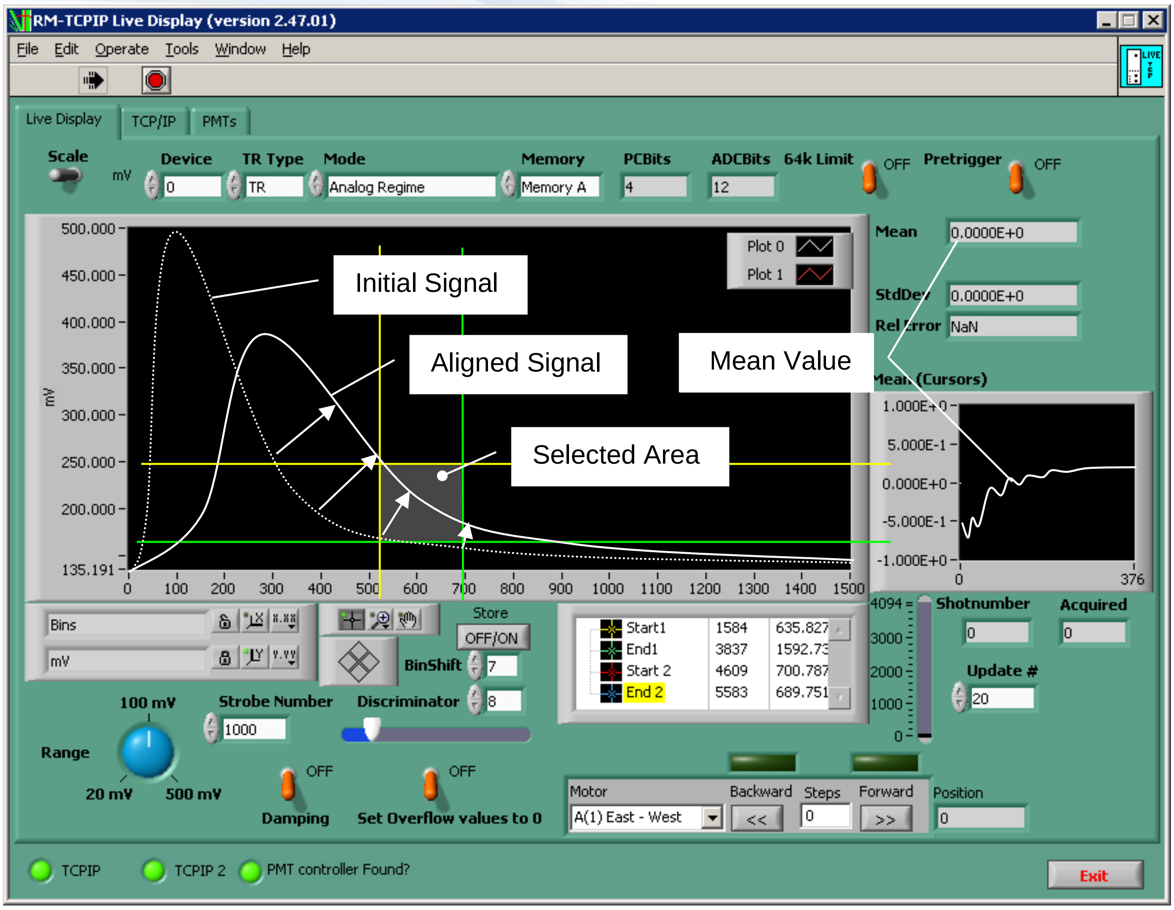
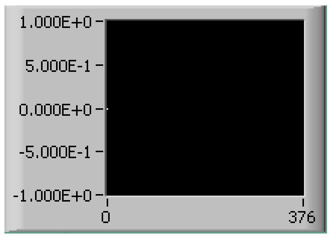



**Fig. 8.13:** Intensity Maximization Alignment Method

9. Since each profile is the product of the averaging of multiple measurements, the less measurements are acquired the faster the change in the acquired signal can be observed but the "rougher" the profile will be. The number of shots for each profile can be set using the 'Update #' input on the right. Set the number so that the image is clear and is refreshed in less than 5 seconds.


10. Once everything is set click on the small graph on the right and select clear graph. This will empty all previous values. Remember to do this each time you change the cursors on the graph. Wait for a couple of profiles to be taken so that you will have a starting view.




11. Towards the bottom of the window are the controls for the motorized mirror mount. Select the actuator to be moved in the field 'Motor' (‘A’ or ‘B’) and set the step size. This is a trial and error procedure, so it does not matter which one you select first. For the step size select a rather big step to begin with. For reference a small step size is 20 steps and a big one 200 steps.

12. Press the left << or right >> arrows to move the actuator forwards and backwards. A short, high pitched noise from the inside of the lidar enclosure indicates that the motor is working. A change in the signal should also be noticeable. The user should then wait for one or two profiles until the signal stabilizes and should notice the change in the small graph. If the mean value is getting higher, then the user should continue to move this actuator in the same direction. If the mean value is reduced the actuator should be moved in the opposite direction and the user should check if the value improves.
13. After repeating this process, the mean value will reach a point where moving the actuator in either direction results in equal reduction in the mean value. At this point the user should select the other actuator and repeat the same procedure as described above.
14. The user may have to alternate between the actuators until reaching a point where there is no improvement in the mean value. At this point an area even further than the current area should be selected, the graph should be cleared, the step size reduced, and the procedure repeated.

### 8.1.3.2 Telecover Test

The Telecover test involves isolating different parts of the telescope and evaluating the signal received from each quarter of the telescope. The telescope is divided into four quarters. Each quarter is named after the cardinal compass points for simplicity and standardization reasons. The north is always towards the laser beam. After a successful Telecover test the aligned Lidar should have identical signals in the west and the east quarter, whilst the range of the signal's peak at the south quarter is at the full overlap.

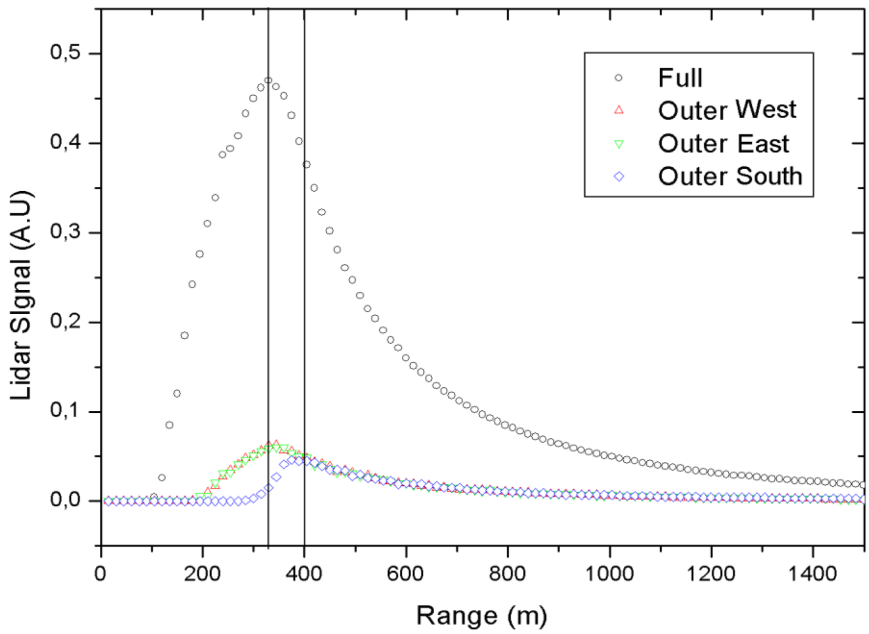



**Fig. 8.14:** Telecover Signals

Fig. 8.14 shows an example of a Telecover test from a D400 Lidar. Although the peak signal for the full telescope appears at around 320 meters the full overlap is around 400 meters, as can be seen from the Outer South signal (Fig. 8.14). In addition, the OW and OE signals are in theory identical. However, the east and west parts can never be identical because of the inhomogeneity of the optics and the PMT cathode. This means that the signal intensity cannot be used as a criterion for the comparison. The overlap range, on the other hand, is an absolute criterion.

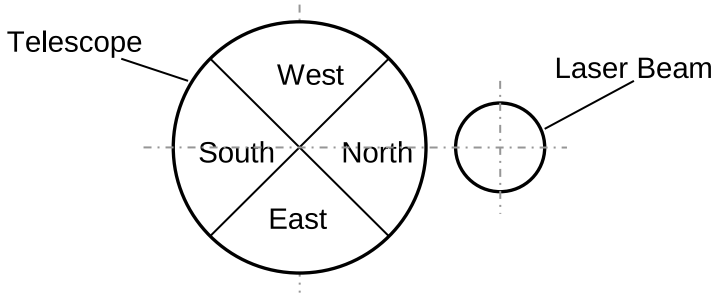



**Fig. 8.15:** Telescope Division

It should be noted that the image at the cathode is reversed. The light focuses at the field stop and then defocuses, resulting to an upside down and mirrored image. This doesn't make any difference in the alignment if it is performed using the signal but in case a camera is used the image will not be as expected because of this.

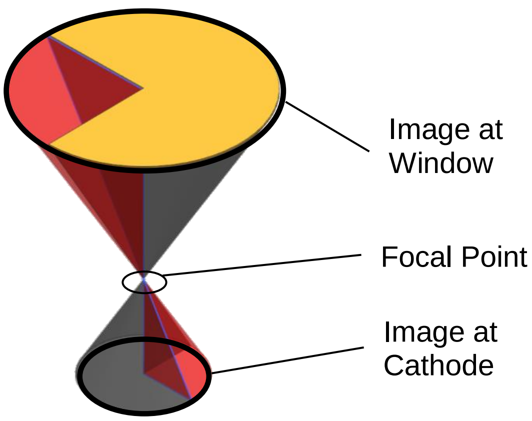



**Fig. 8.16:** Image Inversion

To make the Telecover test even more precise each quarter can be divided into two equal areas: inner and outer. This needs to consider the blind spot of the telescope created by obscuration from the secondary mirror. The telescope is therefore labeled with two letters: the first letter is either O for outer or I for inner, while the second letter is W, E, S or N, standing for West, East, South and North respectively.

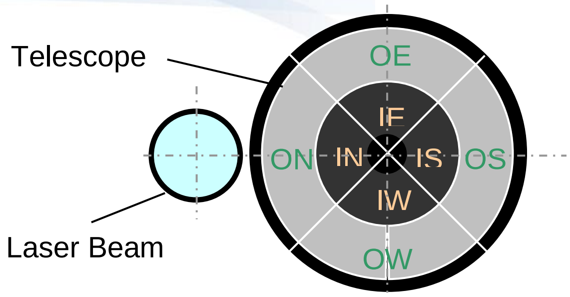



**Fig. 8.17:** Detailed Telescope Division

The fine alignment procedure using this method is described below.

1. Exit all running programs and run the 'Lidar Alignment' program and follow the steps 2 - 4 described in paragraph ‘*8.1.3.1 Intensity Maximization at Far Range*’ to set the high voltage to the PMTs and to start the laser.

**CAUTION:** THE LASER IS NOW EMITTING, FOLLOW THE SAFETY INSTRUCTIONS CAREFULLY.

2. Place the cover on the telescope’s window so that light enters only from the south side caring not to expose your skin to the beam coming out of the aperture.
3. Using actuator ‘B’ shift the peak of the curve on the live display until the desired full overlap is reached. This system’s full overlap is by default at 170meters.

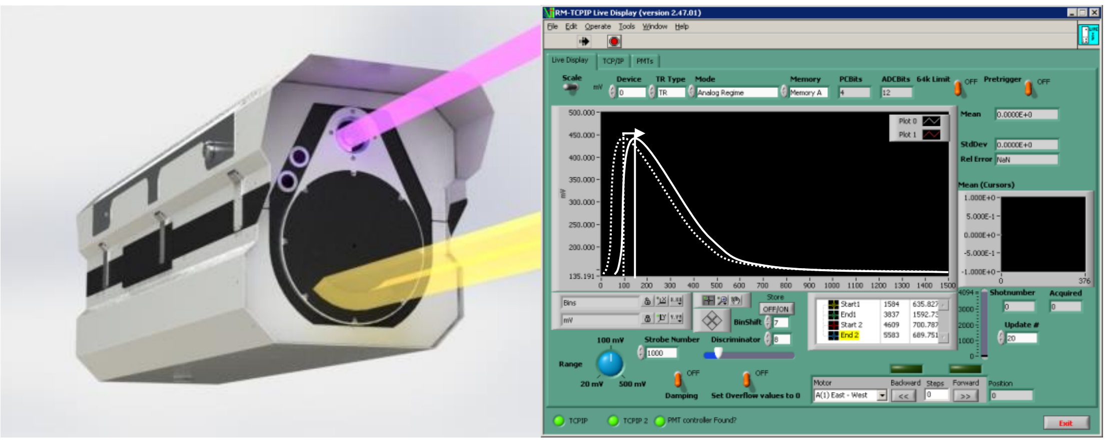


**Fig. 8.18:** Full Overlap Alignment

4. Rotate the cover so that light only from the east side enters the telescope. Place a second cursor on the peak of the curve on the graph making sure that the cursor is unlocked.
5. Rotate the cover so that light enters only from the opposite side (west side).
6. Using actuator ‘A’, try to achieve the same overlap as the cursor placed previously. Once you are close place third cursor there.

7. Finally rotate the cover back to the opposite side (east side) and repeat the last steps until the two curves have the same overlap. This means that the telescope is symmetrical to the laser beam. The lidar is now aligned.

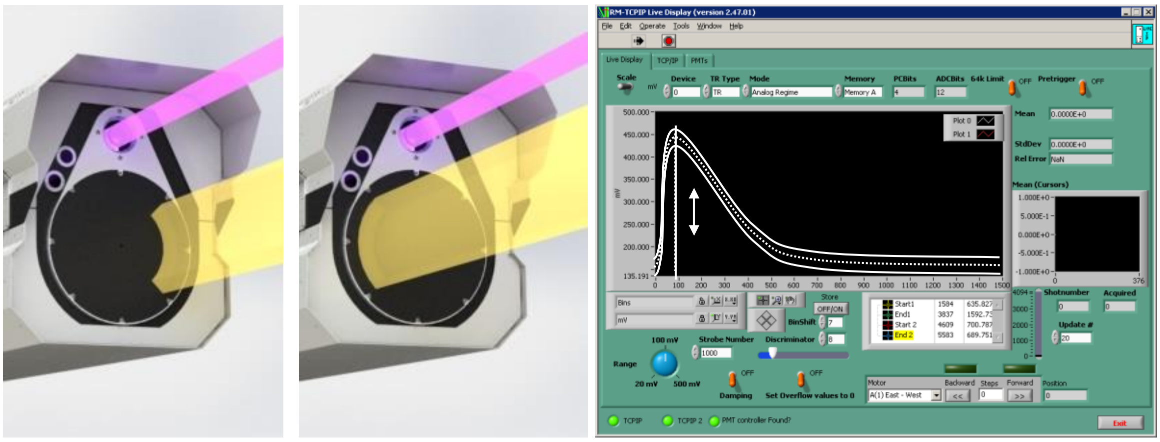


**Fig. 8.19:** Symmetry Alignment

**CAUTION:** When the telecover test has been completed, always remove the telecover tool on top of the window. The Lidarhead/hatch may move at any time resulting to damage.

A quick way to establish whether the system is aligned, is to make a Telecover test using only the OS area. The results in the Lidar signals as seen in the image below are from a D400 telescope. Based on theoretical calculation the OS (outer south) part a signal from properly aligned Lidar gives an overlap of around 380 meters. Any other value indicates that the Lidar is misaligned. Therefore, for this specific Lidar configuration, the overlap should be around **170 meters** (with factory set value for the telescope FOV).

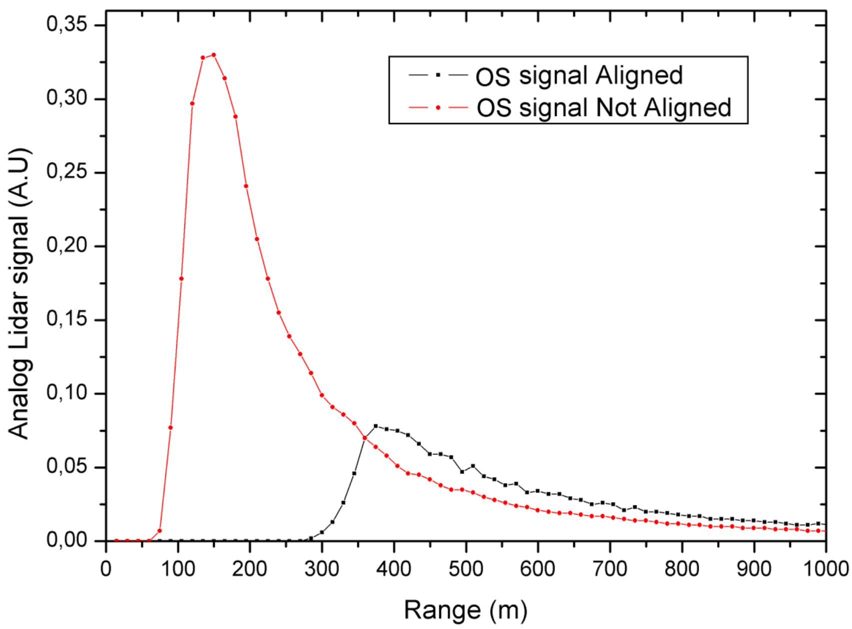



**Fig. 8.20:** Quick Alignment Verification

### 8.1.4 Signal Intensity Reduction

Having a strong signal may seem ideal but it can, in fact, damage the PMT. The High Voltage setting must follow the average maximum anode current of the PMT. The average current for Raymetrics Lidar systems is 100 µA which means 5 mV. The value of 5 mV should never be exceeded for longer than 30 seconds.

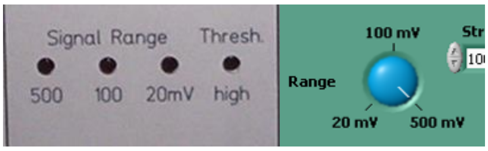
However, the peak signal can significantly exceed the background average level as long as the integral current is below 100 µA. The analogue signal should fit into the input range of the preamplifier and the ADC. Due to the fluctuations of the Lidar signal the following rule of thumb will keep the signal inside the ADC range.

**The analog backscatter signal should be about half (+/-10%) of the preamplifier full range. This can be checked after the Lidar is fully aligned.**

For a 20-mV range, this corresponds to 10 mV. For a 100mV input range this corresponds to 50mV. For a 500mV input range this corresponds to 250 mV.

**CAUTION:** Signals should not exceed 500 mV for more than 10 µs (i.e. 3000 meters or 400 memory bins) or 100 mV for more than 50 µs (i.e. 15000 meters or 1200 memory bins).

The signal input range is user configurable through the software. Before concluding that the signal is too strong, it should be first ensured that the range is properly selected. By default, the range is set to 100mV (i.e. not allowing voltages above that) and if the signal received is more than 100mV, it will look as if the signal is saturated. In this case turn the dial to 500mV.




**The max. PMT voltage of 1000V (High Voltage HV) should not be applied for more than 30 seconds.**

Background and peak signals which are too high will introduce artefacts and shorten the lifetime of the PMTs. There are four ways to reduce the signal intensity:

- Laser energy reduction (via the Q-Switch delay)
- Field stop diameter reduction
- PMT HV reduction
- Use of filters in the eyepiece

The two first should not be preferred because they affect all detected wavelengths including Raman signals which are by their nature already weak. If, however only backscatter signals are being used, then these are the simplest solutions. Reducing the field stop diameter will also increase the overlap and reduce the effective range.

Reducing the applied HV appears to be useful at first glance, but is not an ideal long-term solution. The PMT cathode can accept only a limited number of photons over its lifetime; exposing the tube to a constant DC light will shorten its lifetime. The best solution is therefore to place neutral density filters (or a color filter) in front of the PMT or to use a narrower interference filter (costly solution).

Below are presented all solutions in detail. The most effective depends on the Lidar type and on the experience of the user.

*1. Decreasing the Laser Output Energy*

Operation at a decreased energy level is useful when starting an experimental setup or testing equipment and extensive saturation in the Lidar signal that is detected. A simple way to decrease the energy is to increase the flashlamp Q-Switch delay to a value that is higher than the optimum (highest power) delay using the Laser’s remote control box.

**CAUTION:** The laser manufacturer advises NOT to decrease the high voltage of the flashlamp(s) to reduce the output energy, as this will cause a change in beam characteristics. Divergence and alteration of the position of the focal point may cause damage to the laser’s internal optics. The user therefore does this at their own risk.

To adjust the output energy:

1. Select 'Q-Switch' from the Main menu on the Laser’s remote control box.

2. Press the 'Enter Menu' button.

3. Select 'Flashlamp / Q-Switch delay' (FLQS Dly) from the Q-Switch menu.

4. Use the 'Increase Value' or 'Decrease Value' buttons on the Remote Box to adjust the output energy to the desired value.

5. Go to the main menu and select save configuration.

**CAUTION:** Do not attempt to modify the pumping power by increasing the flashlamp energy with the Remote Box of the PCC. This energy has been factory-set for optimal laser performance. Adjust the flashlamp energy with the Remote Box only if the flashlamp efficiency decreases. Please contact Quantel Customer Service Department to ascertain the origin of any efficiency decrease.

*2. Field Stop Diameter Reduction.*

This is only suggested for users who have advanced Lidar knowledge as reducing the field stop will affect the range and the overlap. This may drastically affect the Lidar's performance.

As shown in **Fig. 3. 8** Telescope Main Components", on top of the optical unit lies the focal plane. Where a calibrated adjustable iris is located. An Allen key can be used to unlock and turn the external ring to reduce or increase the diameter of the iris. The Optical unit must not be turned however as this will defocus telescope.

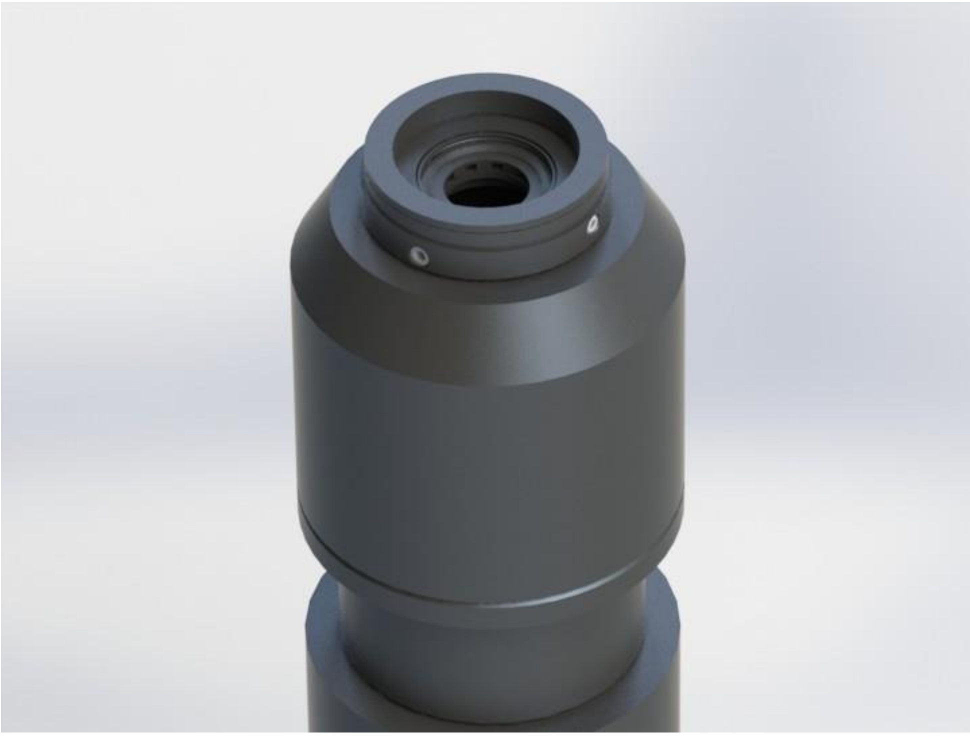


**Fig. 8.21:** Optical Unit with Iris

*3. Decrease the HV Power Supply of the PMTs.*

This is a good solution when the signal intensity is already close to the required level. The signal can be increased or decreased by changing the HV. However, it should be noted that the value should not be lower than the suggested range (800-950V) to have a linear behavior of the PMTs for every detected channel.

*4. Use Color or ND Filters*

Absorptive ND filters are the suggested solution, although a reflective ND is also a good solution. Another good solution is to use color filters. Interference filters can also be used which will decrease the OD however it is a costly solution. Please contact Raymetrics for the best suggestions for which filters are optimal. However before contacting us, note that we will require raw datafiles before providing a recommendation.

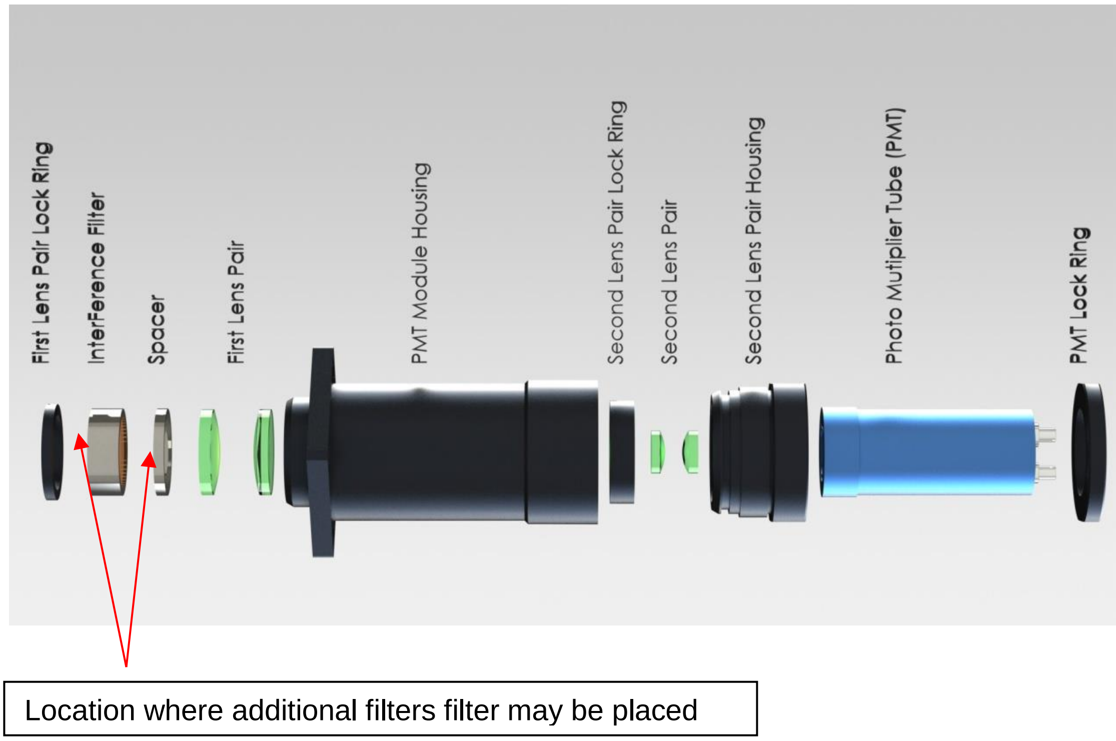
General Instructions for Adding Filters

**1.** Unplug both cables from the PMT

**2.** Remove the Detection Module from the Wavelength Separation Unit

**3.** Place the filter carefully in the appropriate position

**4.** Place the Detection Module back in position.




**Attention:** It is recommended that photomultipliers are protected from excessive light during installation of the color filters. After illumination, the dark current (noise) will be temporarily increased

**Do not remove the interference filter which is located just in front of the PMT**.

**NOTE:** Final optimization of the system will be done in-situ by Raymetrics engineers during the installation and training period.

## 8.2 Reference Measurements

Part of the maintenance is to perform the reference measurements. There are three types of measurements:

1. Telecover test
2. ±45° Test (depolarization)
3. Dark current measurement.

Each one has its own purpose; the telecover measurement is related to the lidar's alignment and thus the quality of the data, the ±45° test is used to find the depolarization calibration constant and the dark current is used acquire a profile that can be subtracted from any measurement to reject the noise from the electronic parts of the system. All these reference measurements ensure that your future data is of high quality.

The occasions when all of the measurements should be performed are:

1. When an optical component is changed i.e. a lens a filter of the WSU a dichroic mirror.
2. When the High Voltage (HV) of the PMT for 355nmP or 355nmS is changed.

The occasions when only the telecover should be performed are:

1. Every time the flashlamp is changed
2. Or when the lidar is realigned.

As a quick reference, the channels and the slide filters are denoted at the image below.

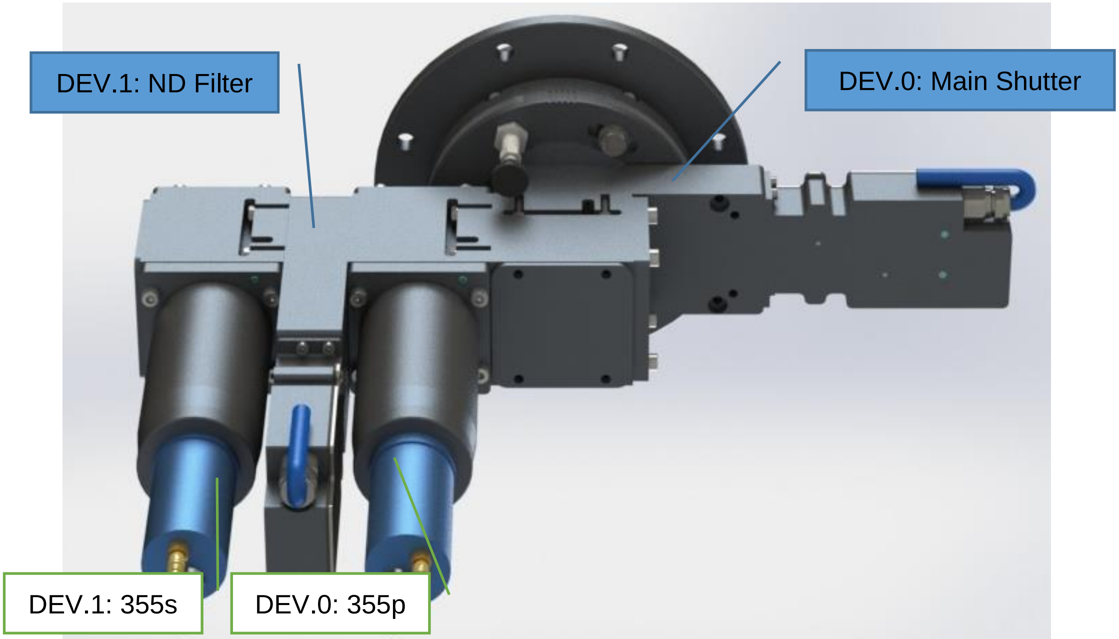



**Fig. 8.22:** WSU Channels Reference

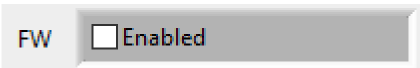
### 8.2.1 Telecover Test

The telecover is performed to check the lidar's alignment and telescope's collimation. At this test the telescope is covered leaving only 1/8th of its surface uncovered. This is performed sequentially for four sections of the telescope North, East, South and West. At the end of these another measurement is needed at North to compare with the first in case the atmosphere changed during the test. Follow the steps below to perform the telecover test.

1. Exit any running program and close the window if it remains open.
2. Run the RM-TCPIP Acquis.exe
3. At the first tab click "Dataset"
4. A window open where the settings for the recorders are (see **Fig. 6.7:** Transient Recorder Configuration). The main channel needed for the test is 355P but the other channels can be used as well. Select the following channels both analog and photon:

   - Rack 1 – Transient Recorder 0 (DEV:0) – 355 P **Active**
   - Rack 1 – Transient Recorder 1 (DEV:1) – 355 S **Active**

The HV values should be the ones that are tested during the lidar alignment. In case the 387 channel is deactivated check the LMC tick box at the corresponding tab (DEV:2). This will enable the shutter in front of the 387 PMT.




5. Press the "Save and Exit" button to load the new configurations
6. Click "Global" at the main interface (see **Fig. 6.9:** Global Settings)
7. Type at the "Location" NORTH and select the azimuth and zenith angle that is appropriate to perform the telecover test (as vertically as possible).
8. Place the telecover at the North part of the telescope.
9. Set 2 profiles at the "Acquisitions of" box each one for 1200shots at the main interface and press the start button
10. Wait for 2 minutes and when the measurement is finished change the name of the location to "EAST" at the Global settings.
11. Place the telecover at the east part and press the start to take another two profiles for this part.
12. Repeat the procedure of step 10 and 11 for the SOUTH, WEST and NORTH2
13. Once all the tests are done remove the telecover from the telescope and set the location back to "Full"

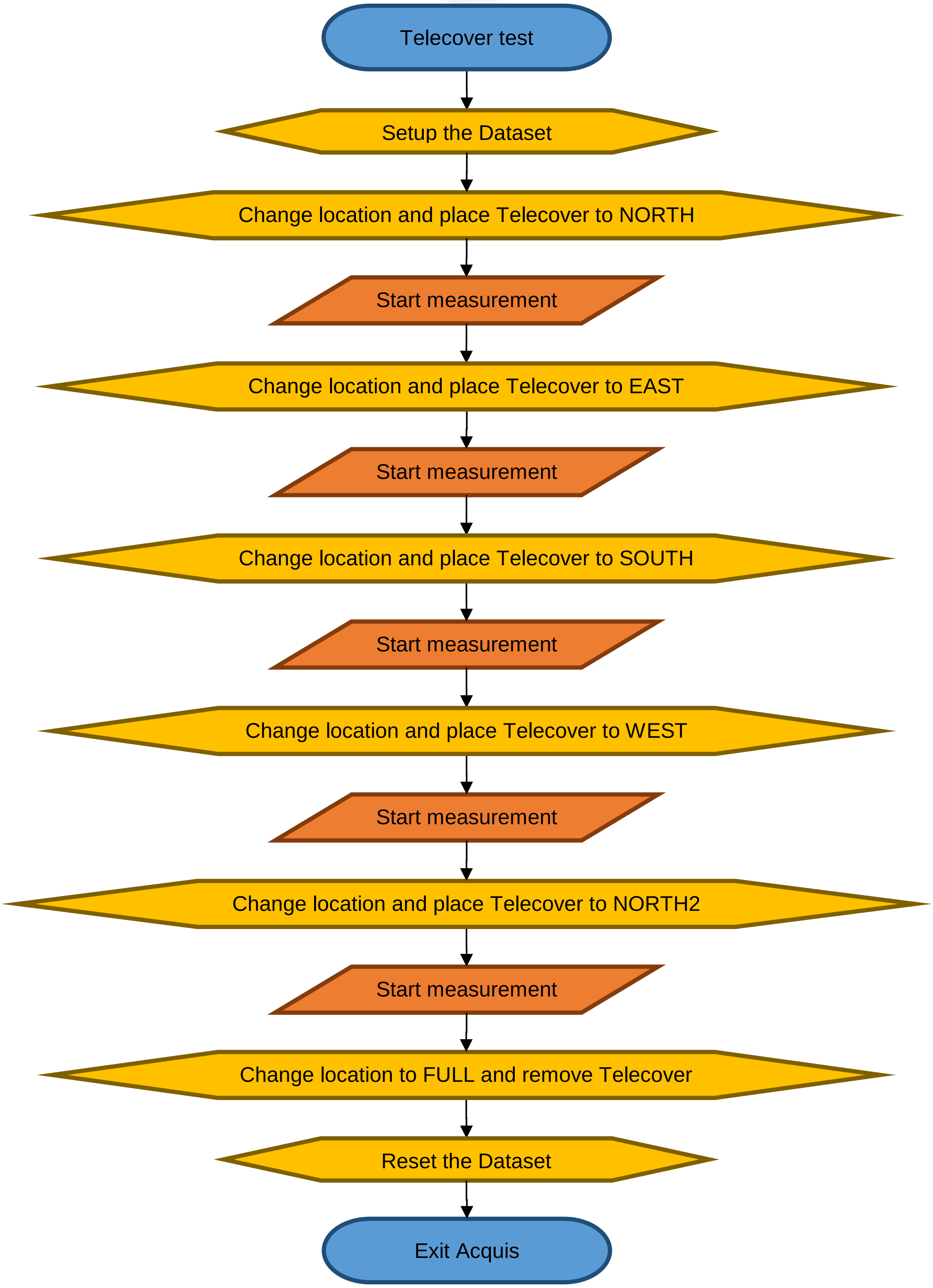



**Fig. 8.23:** Telecover Procedure Block Diagram

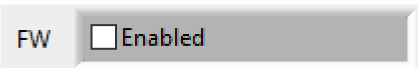
### 8.2.2 ±45° Test

The ±45° Test is performed to calculate the depolarization calibration constant (V*). In this section only the measurement is presented, for the calculation refer to paragraph *'7.3.9 How to Retrieve the Depolarization Calibration Constant*'. At this test the WSU is turned at 45° degrees clockwise (plus) and at 45° counter clockwise (minus) from the zero position. To turn the WSU the user must pull the plungers and turn at the desired direction for a few degrees. Release the pins and keep turning to the same direction until a click sound is heard. The plungers go into a hole that is manufactured precisely at 45 degrees (See **Fig. 3.13:** WSU ±45° polarization calibration procedure).

Follow the steps below to perform the ±45° Test.

1. Exit any running program and close any program window that remain open.
2. Run the RM-TCPIP Acquis.exe
3. Select at Dataset window (see **Fig. 6.7:** Transient Recorder Configuration) for the active channels both analog and photon Mem and HV for the PMT as it was found during the alignment procedure. For the deactivated channels set the HV to 0. Use the following setup.
   - Rack 1 – Transient Recorder 0 (DEV:0) – 355 P **Active**
   - Rack 1 – Transient Recorder 1 (DEV:1) – 355 S **Active & FW Checked***
4. Type at Global window "-45" under location. (see **Fig. 6.9:** Global Settings)
5. Remove the cover of the lidar head and remove the dehumidifier. **
6. Turn the WSU counter clock wise at -45 degrees as described above.
7. Start a measurement of two profiles each of 1200shots
8. Type at Global window "+45" under location.
9. Turn the WSU counter clock wise at +45 degrees as described above.
10. Start a measurement of two profiles each of 1200shots
11. Turn the WSU at 0 degrees
12. Place the dehumidifier and the cover of the lidar head back.
13. Type "Full" at the location in the global settings.
14. Uncheck the FW box of DEV.1.

* "FW Checked" means that the corresponding box should be ticked.




** Removing the dehumidifier is only for better access, it is not necessary for the measurement.

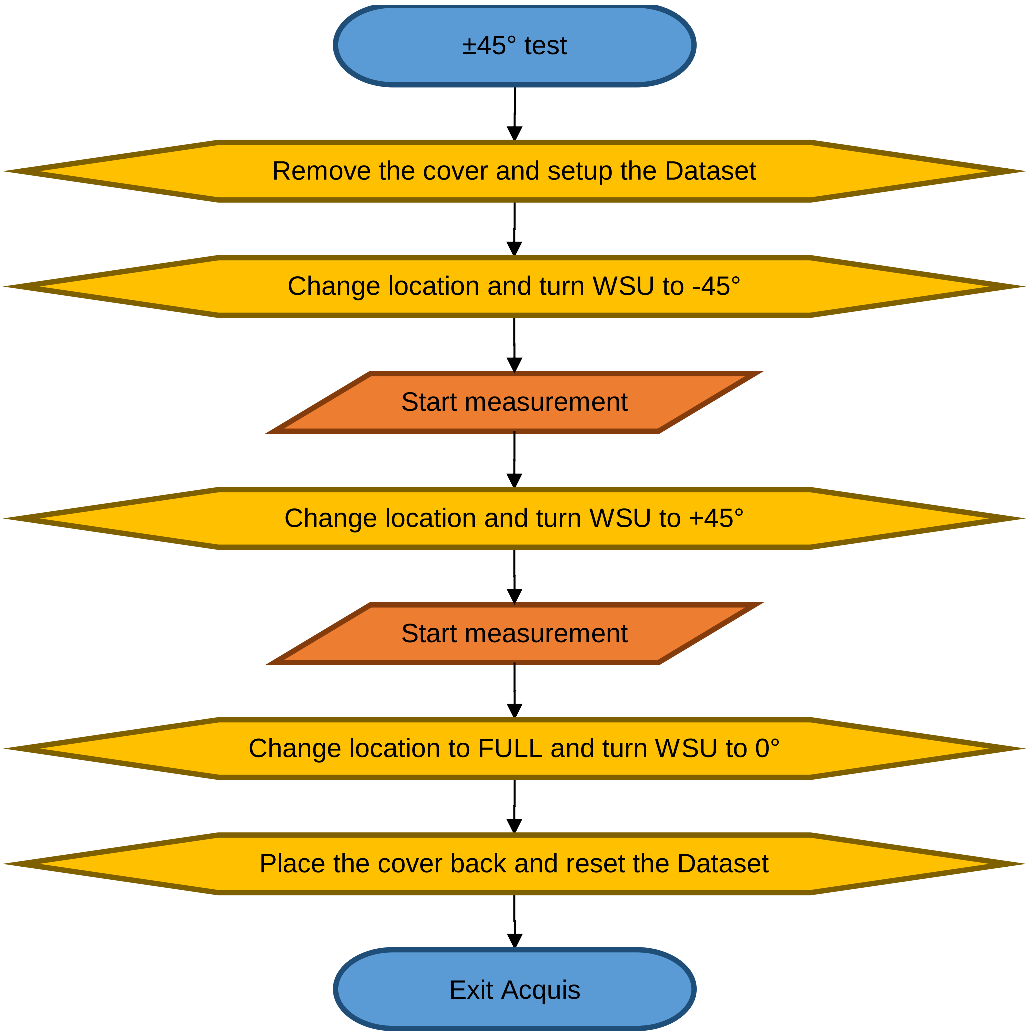



**Fig. 8.24:** ±45° Procedure Block Diagram

### 8.2.3 Dark Current Measurement

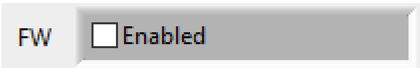
The Dark Current Measurement is essential to extract the electronics' noise from any measurement. At this test the main shutter of the WSU will be used to block the incoming light from the telescope. A reference normal measurement is also taken.

Follow the steps below to perform the Dark Current Measurement.

1. Exit any running program and close the window if it remains open.
2. Run the RM-TCPIP Acquis.exe
3. Select at Dataset window (see **Fig. 6.7:** Transient Recorder Configuration) for the all channels both analog and photon Mem and HV for the PMT as it was found during the alignment procedure. Use the following setup:
   - Rack 1 – Transient Recorder 0 (DEV:0) – 355 P **Active & FW Checked***
   - Rack 1 – Transient Recorder 1 (DEV:1) – 355 S **Active**

4. Type at Global window “DARK” under location. (see **Fig. 6.9:** Global Settings)
5. Start a measurement of two profiles each of 1200shots
6. Type “Full” at the location in the global settings.
7. Uncheck the FW box of DEV.0.
8. Start a measurement of five profiles each of 1200shots

* “FW Checked” means that the corresponding box should be ticked.



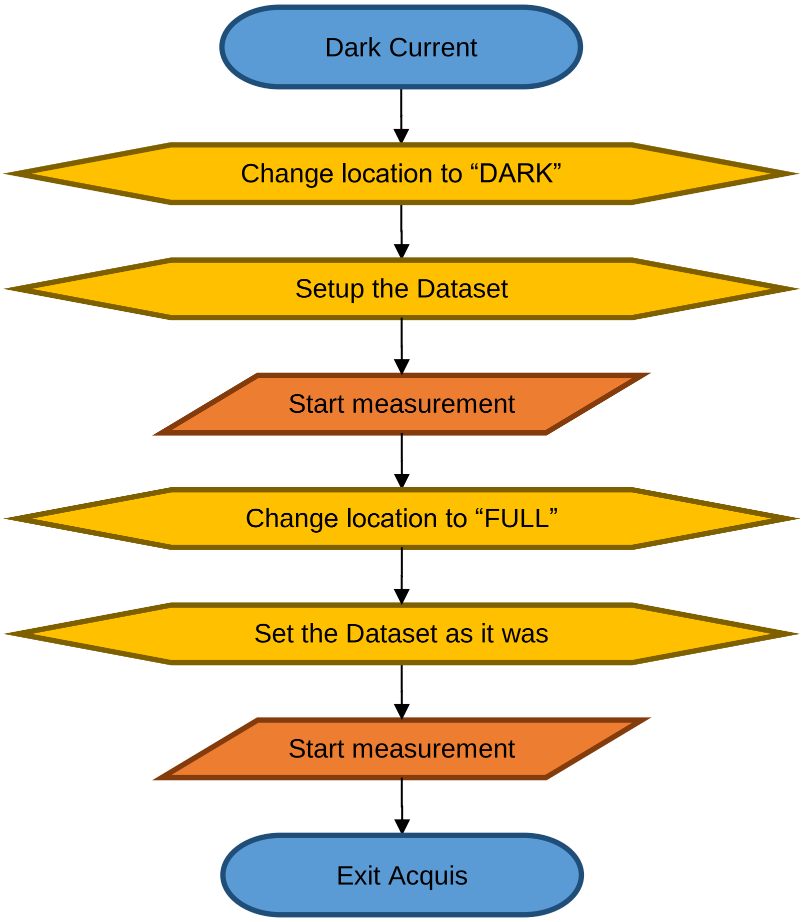




**Fig. 8.25:** Dark Current Procedure Block Diagram

# 8.3. Hardware Maintenance

## 8.3.1 Laser System and Optical components

### *8.3.1.1 Laser System*

Regular maintenance is crucial for the ling life and high performance of the laser inside your lidar. The maintenance procedure includes flashlamp, water and deionization cartridge replacement. Please, refer to the Laser instruction manual for a detailed description of the laser's maintenance procedures.

To access the Laserhead, power supply units PDU and LPC refer to paragraph *'8.3.3 Components Accessibility'*. Shut down the laser and remove the covers from the emission unit.

**CAUTION:** Check the number of flashlamp shots frequently and replace whenever needed (do not exceed 50 million shots). Operating the laser with a flashlamp that has exceeded its nominal lifetime will damage the laser cavity.

**CAUTION:** Never operate the laser using water of a different specification than is stated in the manuals. Frequently replace the deionizing cartridge and water to keep the water's purity as high as possible.

### *8.3.1.2 Reflective Mirrors*

The reflective mirrors of the emitter are aligned in factory and they should not be touched. However, if the laser output beam profile is not circular, it means that the beam is probably being cropped somewhere along the light path. Operating the lidar in such condition will eventually damage the coatings. To realign the mirror, first reduce the energy of the laser and then place a piece of white paper in front of each optical component to locate where the beam is being cropped. This reveals the shape of the laser beam profile. Move the actuators of the mirror in front of the beam expander until the beam becomes circular again. Next check that the output beam is close to the center of the laser window. The lidar can now be aligned using the final mirror.

### *8.3.1.3 Telescope*

If a lidar is relocated regularly, the telescope may eventually become misaligned. The key indication of a misaligned telescope is a low lidar signal for all channels which cannot be fixed by aligning the lidar as explained in paragraph *'8.1 Lidar Alignment'*. If this occurs, do not attempt to align the telescope, contact Raymetrics.

#### 8.3.1.4 Cleaning the Optical Components

All optical elements are delicate and should be handled as carefully as possible. The glass and AR or HR coated surfaces will be damaged by any contact, especially if abrasive particles have come into contact with the surface. In most cases, it is best to leave minor dust on the surface than to risk scratching the glass by incorrect cleaning.

The Lidar enclosure provides dust protection for the optical components, therefore, never operate the Lidar without the protective housing. Depending on the type of dirt follow the instructions below to clean the optics.

*Hard particles:*

Use of oil-free dry air or nitrogen under moderate pressure is the best tool for removing hard particles that can scratch the surface of your optics. In case these are not removed rinse with distilled water.

*Soft particles or dust:*

In cases of dust, which commonly appears on the windows, flood the surface of the window with distilled water and remove the water gently with a clean and soft cotton cloth. Do not leave any drops of water on the surface as these will leave a stain once they have dried out. Use absorbent wipers such as Kimwipes™, to finish the drying process.

*Oil stains or fingerprints:*

This case is the most difficult to clean. Please follow the procedure described below carefully to avoid damaging the coating:

1. The use of powder-free gloves will help to keep fingerprints off the optics during cleaning.
2. Clean the optical part using an absorbent wiper such as Kimwipes™, not lens paper. Use enough tissues so the solvents that will be used for cleaning do not dissolve any dirt from your gloves which can penetrate the tissues and reach the coated surface.
3. Soak the tissues el with an anhydrous reagent grade ethanol.
4. Drag the trailing edge of the ethanol-soaked wiper across the surface of the component, moving in a single direction. A minimal amount of pressure should be applied while wiping, as too much pressure will damage the component.
5. If the surface requires additional cleaning, use a new wiper before repeating the process.

The purpose of the solvent is only to dissolve any adhesive contamination that is holding the dust on the surface. The wiper needs to absorb both the excessive solvent and entrap the dust so that it can be removed from the surface. Surface coatings on interference filters and dichroic mirror are typically less hard than the substrate. It is reasonable to expect that any cleaning will degrade the surface at an atomic level. Consideration should be given as to whether the contamination in question is more significant to the application than the damage that may result from cleaning the surface.

**NOTE:** In many cases, the AR coatings that are provided allow maximum light emission and hence, amplify the existence of contamination on the surface.

### 8.3.2 Positioner Maintenance

A basic maintenance of the positioner's mechanism will ensure its good operation. Depending on the usage of the lidar, the worm gear and wheel must be greased and the timing belt that transfers the movement to the worm gear wears out. As a general guideline, the wheels must be greased every two flashlamp changes or once per six months whichever comes first. The belt can be changed whenever it seems worn or every two years. To remove the belt, the bottom screw of the motor base must be unscrewed as shown in Fig. 8.26 and the motor will be able to move towards the wheel. If it is not moving loosen the screws of the base. Once the motor is at the upper position the belt is loose and can be replaced.

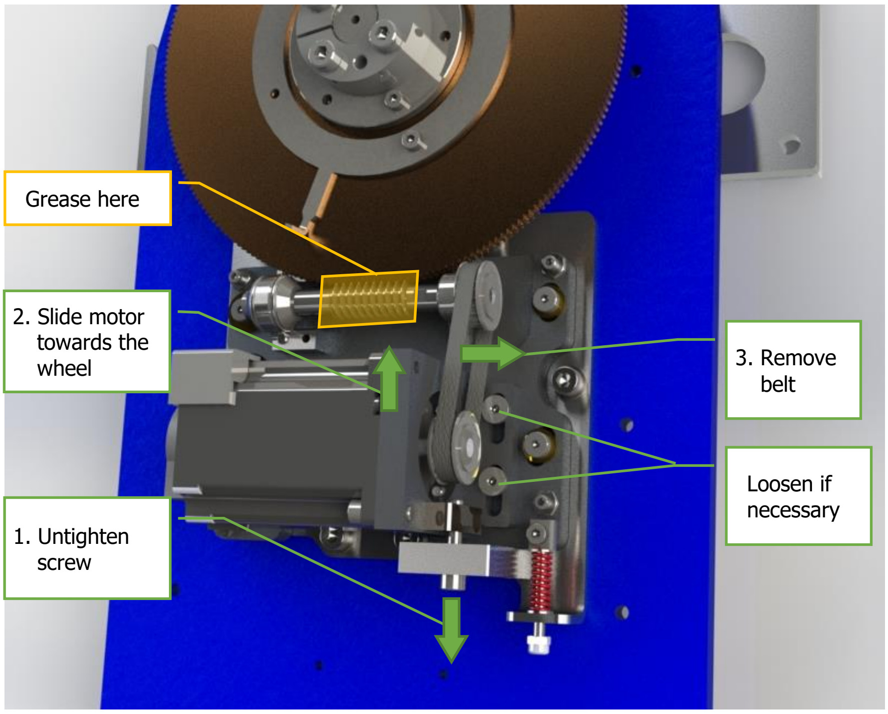



**Fig. 8.26**: AZP Maintenance

### 8.3.3 Components Accessibility

When it comes to maintenance one of the biggest concerns is the downtime and the level of technical experience of the maintenance personnel. With a user friendly oriented design Raymetrics offers easy access to all components. All Lidars come with a tool case where the user can find the required tools and some spare parts. Below are described how to access the main components of the Lidar.

- *Lidarhead*
    1. Unlock and remove the cover to reveal the latches
    2. Turn the latches one by one and pull them out of their hole.
    3. Pull the cover upwards evenly, taking care to prevent the latches from hooking into their holes while pulling the cover
    4. Use the side ladder to access the head's components.

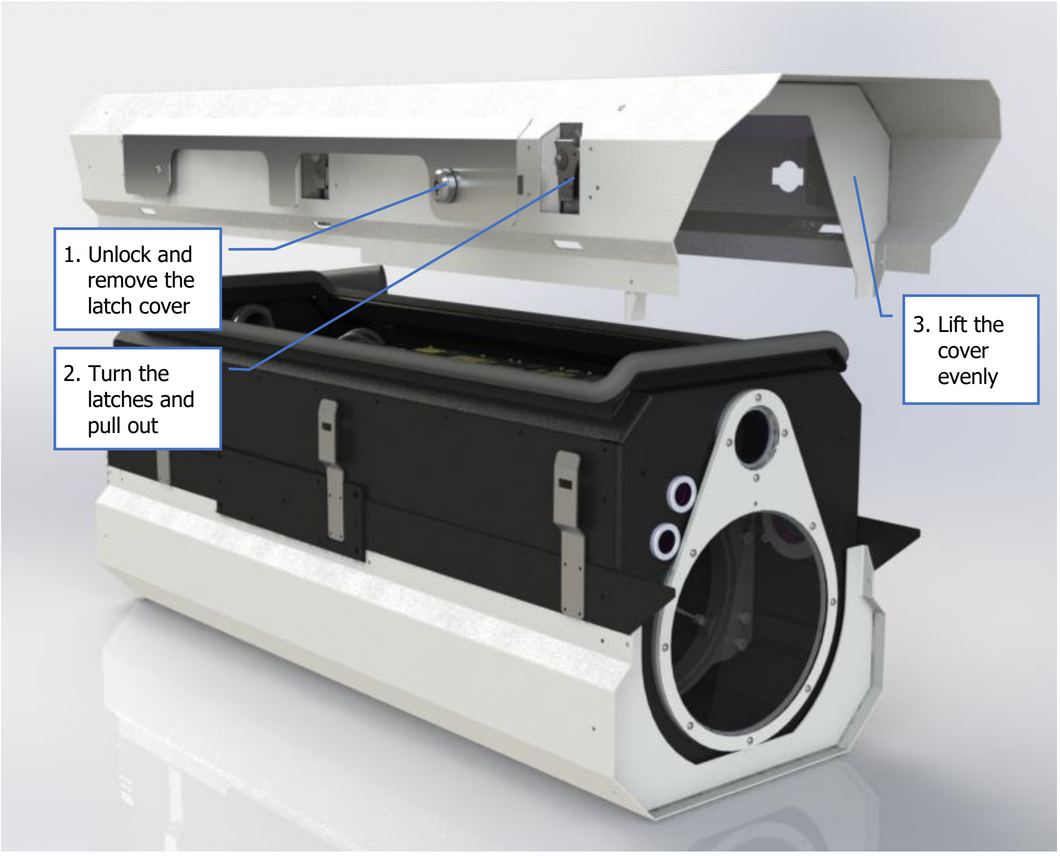



**Fig. 8.27:** Lidarhead Access

- *PDU*
    1. Remove the four Torx screws that mount the PDU on the rack.
    2. Pull out the whole PDU towards you.
    3. Once fully out rotate downwards the PDU to have access to the connectors.

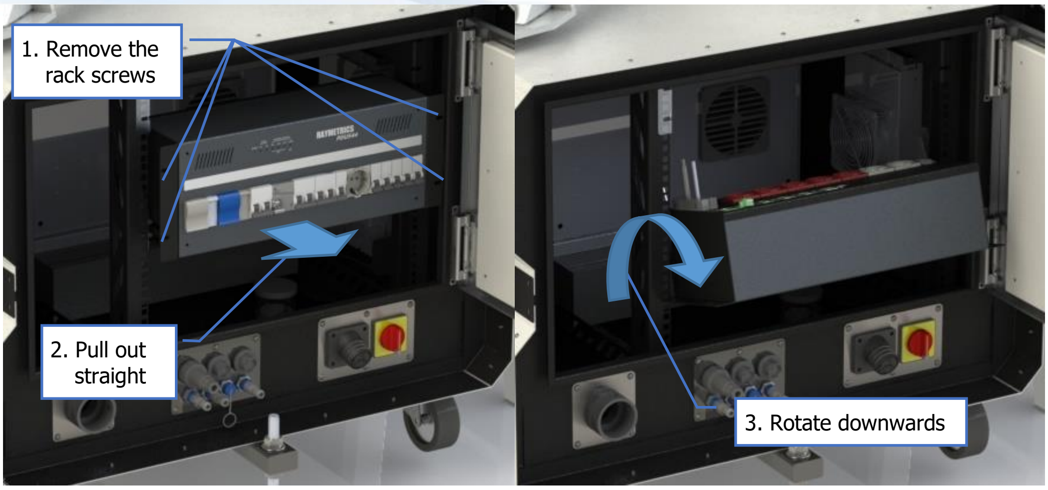



**Fig. 8.28:** PDU Access

- *LPC*
    1. Turn the screws on the side of the panel to unlock it.
    2. Pull out the LPC watching your fingers all the time.
    3. To push back, first press both safeties on the side of the slides
    4. Push the panel and turn the screws on the side to lock it.

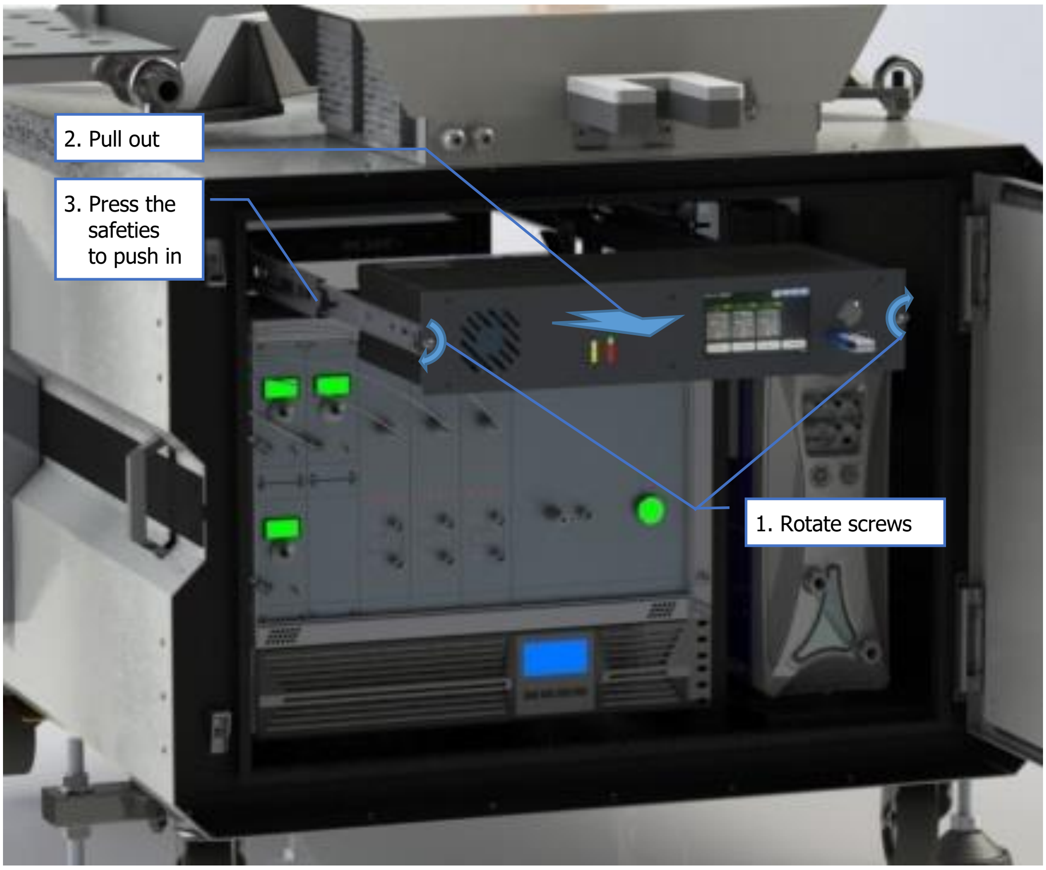



**Fig. 8.29:** LPC Access

- AZP
    1. Pull upwards the side covers
    2. Turn the inner covers horizontally.
    3. Pull the middle cover evenly.

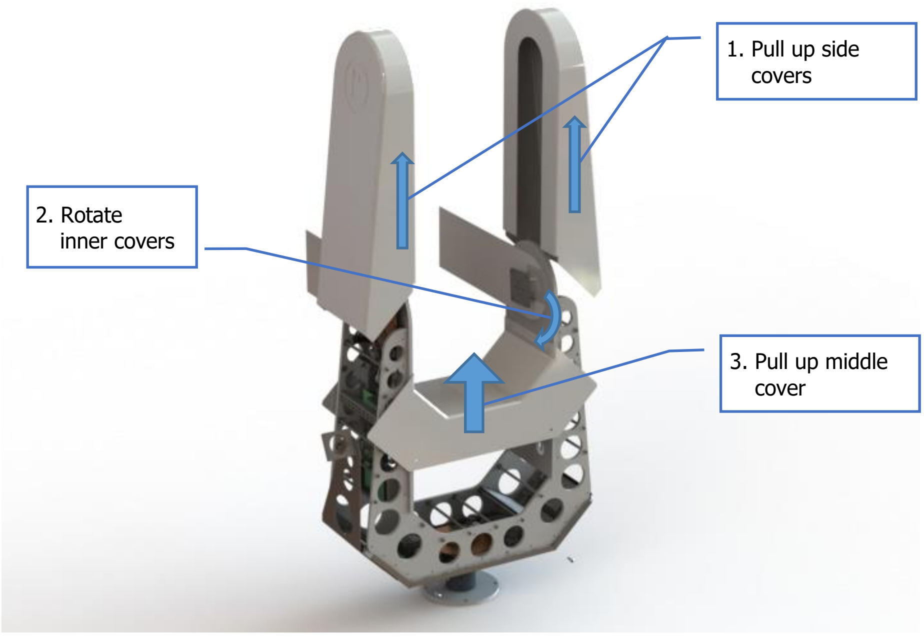



**Fig. 8.30:** AZP Access

- *PSU box*
    1. Unlock the latches on both sides of the cover.
    2. Pull the cover upwards.
    3. Disconnect the beacon's cable

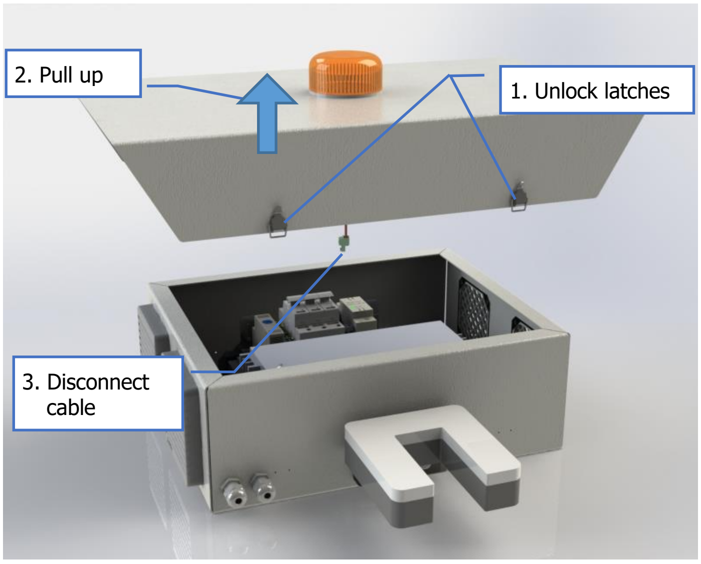



**Fig. 8.31:** PSU Box Access

# 9. TROUBLESHOOTING

This chapter addresses some of the problems you might encounter while running your Lidar system and indicates ways how to solve these problems.

## 9.1 Lidar

| PROBLEM | POSSIBLE CAUSES | CORRECTIVE ACTION |
|---|---|---|
| LIDAR dead (no power) | AC mains | Check power source. Inspect power cord. |
| | Main circuit breaker | Check the main circuit breaker and the protection breaker. |
| | UPS OFF | If the UPS has power but does not turn ON, please refer to the manufacturers manual. |
| AZP has no communication with the computer. | AZP controller OFF | Verify that the AZP is on and all cables are connected and that the emergency button is not pressed. |
| | Bad connection | With a multimeter check that the communication cable is OK. |
| | AZP controller failure | Unplug and plug again the device. On startup, the motors move to the home position. If it is moving but still there is no communication the controller needs replacement. |
| AZP is not moving | Bridge overload | The bridge has several safeties. A wrong setting can result to no movement. Contact Raymetrics. |
| | Bad connection | Verify that the cables for the motors are connected properly. |
| | Motor Failure | Connect to the controller and read the error message and report to Raymetrics. |
| AZP does not complete the movement | Obstacle | Make sure that nothing is blocking the movement. |
| | Dirt or wear makes the movement difficult | Clean up and grease the gears. |
| Computer is down | LPC Command | The LPC can shut down the computer. Reset the LPC |
| | Power supply | Verify that LPC is ON and the power LED of the 12V at the PDU is on otherwise the PSU needs replacement. |
| | Computer failure | If the computer has power but does not turn on it needs to be sent back to the factory. |
| Air conditioning not working | No power | Turn the breaker on and check the connection and power cable. |
| | Wrong setting | In high or low temperatures, the AC fails to keep the temperature steady. Read the manufacturers manual to change the setting. |
| | PSU fail or burned fuse | Open the PSU box and check the fuses and the power from the PSU. |
| | Controller board | Locate the controller. If the LEDs are off the board needs replacement. |
| Laser has external interlock | Emergency pressed | Turn the emergency button of the lidar. |
| | External panel | Verify that the switches connected to the external panel are functioning properly. |
| | Wrong cover switch location | Open the head cover and hold the switch pressed down. If the interlock is off then move of the switch closer to the cover. |
| | Cover switch failure | Open the head cover and hold the switch pressed down. If the interlock is still on the door switch needs to be replaced. |
| | Bad connection | Check that the BNC cable from the LPC to the Laser's interlock is connected. |

## 9.2 Emission

| PROBLEM | POSSIBLE CAUSES | CORRECTIVE ACTION |
|---|---|---|
| Laser dead (no power) | AC mains | Check power source. Inspect power cord |
| | Blown fuse(s) | Check fuses on back panel T10A/250V, QTY 2 and replace if necessary. |
| NO Simmer, NO Interlocks Three audible clicks from ICE450 | Faulty laser I/O cable | Verify laser I/O cable connectors are fully inserted and thumbscrews are tightened. Visually inspect high current contacts on both ends of the laser I/O cable for carbon film or pits caused by poor connector insertion and arcing. |
| The control unit starts and after a few seconds turns off. | Low coolant level | If the reservoir is not filled a flow interlock appears in the LCD screen. Add coolant to the reservoir. |
| Flashlamp does not lamp. | Flashlamp is not enabled | Verify that both the 'flashlamp ready' light and the 'flashlamp start' light on the Remote Box are illuminated. |
| | Simmer Problem | Either ionized, or contaminated coolant, or a degraded flashlamp may be the cause. Coolant should indicate a resistivity of 100kΩ-cm to 5MΩ-cm for proper operation. If coolant resistivity is less than 100kΩ-cm, replace the coolant. If the lamp still does not simmer replace the flashlamp. |
| | Charger Latch-up | If the ICE450 makes a squealing or hissing sound when the high voltage is enabled, and the simmer LED is illuminated but the flashlamp does not flash, **disable the high voltage immediately**. A component inside the ICE450 has most likely failed and the high voltage charger is attempting to charge into a short circuit. If the ICE450 is operated in this mode for longer than a few seconds additional electronics damage may occur. |
| Flashlamp does not fire. NO Interlocks | Flashlamp is not in Internal Mode | Verify that 'Internal sync' is selected in the flashlamp menu. |
| | Flashlamp is broken | If, after pressing the 'Flashlamp Ready' button, the 'ready' light does not light, nor is there a visible flashlamp flash, the flashlamp may need to be replaced. |
| Flashlamp does not fire. Interlock **'emergency stop button pushed'** | The red button on Remote Box is pushed in. | Pull the button out. If that does not work, there may be an open circuit in the Remote Box, cable, or internal harness. |
| Flashlamp does not fire. Interlock **'BNC Intlk in on** ICE450 **front panel'** | The 'INTLK In' connector on the front panel is open. | Connect a shorting plug, to the 'Interlock In' BNC on the front panel. If that does not work, there may be a problem with the shorting plug. |
| Flashlamp does not fire. Interlock **'thermal sensor on Laserhead'** | The thermostat in the Laserhead is open. | Allow the head to cool down. If that does not work, there may be an open-circuit in the Laserhead or in the Laserhead I/O cable |
| Flashlamp does not fire. Interlock **'flashlamp disabled time out delay expired'** | The flashlamp timeout has expired. | Either disable timeouts or change the flashlamp timeout to 00:00. |
| Flashlamp does not fire. Interlock **'heater over temp'** | The coolant heater is too hot. | Turn off power to the ICE450 and allow it to cool down. If that does not work, contact Raymetrics. |

| | | |
|---|---|---|
| Flashlamp does not fire. Interlock **'charger/simmer over temp'** | The Charger inductor is too hot. | Turn off power to the ICE450 and allow it to cool down. Verify that air flow is not obstructed at the front or back of the ICE450 and correct if necessary. If that does not work, contact Raymetrics. |
| Flashlamp does not fire. Interlock **'low coolant temperature'** | The coolant is not warm enough for proper operation. | Give the ICE450 time to warm the coolant. If that does not work increase the temperature of the cabinet's thermostat. |
| Flashlamp does not fire. Interlock **'high coolant temperature'** | The coolant is too warm for proper operation. | Turn off the ICE450 and allow it to cool down and decrease the temperature of the cabinet's thermostat. |
| Flashlamp does not fire. Interlock **'low coolant flow'** | The coolant is not flowing properly. | There may be an obstruction in the coolant lines. Examine the lines and make sure they are not kinked or otherwise obstructed. |
| Q-Switch does not start. Interlock **'Q-S disabled Please wait for 8 seconds'** | There is no problem. This is normal. | Wait until the 8 second timeout expires, then activate the Q-Switch. |
| Q-Switch does not start. Interlock **'Q-S disabled coolant temperature under limit'** | The coolant temperature is below the minimum Q-Switch operating temperature. | Allow the coolant to warm up. |
| Q-Switch does not start. Interlock **'Q-S disabled time out delay expired'** | The user-set timeout period expired. | Disable timeouts or set the Q-Switch timeout to 00:00. |
| Energy is low | Cold Flashlamp | This is normal wait for 10 minutes to reach the desired energy. |
| | Flashlamp Degradation | If output energy is slightly below normal level, it may suggest gradual lamp degradation. If significant lamp degradation is suspected, replace the flashlamp. |
| | Coolant Degradation | Inspect the coolant for clarity. Replace if necessary. |
| | Incorrect Q-Switch Delay | Check that the Q-Switch delay is set to 135μs with respect to the flashlamp. |
| | Resonator Misaligned | If beam quality has degraded, it may suggest that the resonator needs realignment. Contact Raymetrics or Quantel for more details. |
| Coolant leak | DI Cartridge installation | Verify that DI cartridge is locked in place and fittings are fully inserted. |
| | Laserhead O-rings | Inspect O-rings on coolant line connectors at Laserhead for damage and replace if necessary. |
| RS232 port does not operate: no communications. | Serial port disabled | For safety reasons, the serial port is disabled when any button is pressed on the Remote Box. In the 'system' menu, turn serial port ON. |
| | Baud rate incorrect. | See ICE450 User's manual Chapter 5, Serial Protocol Description for correct baud rate setting. |

For further information on laser troubleshooting please refer to the laser's instruction manual for an additional troubleshooting list.

## 9.3 Detection

| PROBLEM | POSSIBLE CAUSES | CORRECTIVE ACTION |
|---|---|---|
| Dead (no power) | AC mains | Check power source. Inspect power cord |
| | Blown fuse(s) | Check fuses on back panel and replace if necessary. |
| No signal for all channels | HV Power supply off. | Turn on the PMT power supply and apply the specified voltage. |
| | No connection. | Check that all connectors are in place. |
| | Laser is not emitting. | Turn on the laser (flashlamp – Q-switch) |
| | Lidar is misaligned. | **Reduce the energy** of the laser so that the light can be hardly seen when placing a piece of white paper above the widow of the emission unit. Raise the paper and tilt it in a way so that the light is reflected directly into the telescope. If the Lidar is misaligned then you should see the signal changing. Realign the Lidar (see paragraph '*8.1 Lidar Alignment*') **CAUTION! If the energy is high the PMTs will be destroyed.** |
| No signal at one of the channels. | Broken connector or cable. | To verify which cable is fault, connect the HV and signal cable (one at a time) to another working device. |
| | HV power supply broken. | If the cables are OK connect the HV cable of a working channel to the HV power supply that is not working. If there is no signal then the HV power supply is broken. |
| | TR Device broken. | If the cables are okay connect the signal cable of a working channel to the TR device that is not working. If there is no signal at the non-working channel then the TR is broken. |
| | The PMT is burned. | If the cables, the HV power supply and the TR device are okay then the PMT is burned probably due to excess of light exposure. |
| No acquisition in one of the channels | Wrong dataset configuration. | Verify that the button is red next to 'analogue or photon Mem I' for the corresponding device in the dataset of the acquisition program. |
| Cannot change high voltage | HV power supply switch. | Switch to manual position for manual HV application or to remote for application via the computer |
| High voltage is unstable | Bad connection. | If the variation is higher than 5 volts **switch off the HV power supplies immediately**. The connector is broken. |
| No TCP/IP connection | Communication crash | Run Licel's 'Search Controllers' program. If all devices are detected the buffer is full. Restart all the devices. |
| | Wrong IP address. | Run Licel's 'Search Controllers' program. If the devices are not detected make sure that the computer's IP address belongs to the same network as Licel's device and change the computer's IP if necessary. |
| | Broken connector or cable. | Check that the lights illuminate on the Ethernet switch. Make sure that the cable clicks when it is connected on the switch, if not change the cable. |

For further information on Licel's electronics please refer to Licel's instruction manual for an additional troubleshooting list.

# 10. LIDAR TECHNICAL SPECIFICATIONS & DRAWINGS

## 10.1 Technical specs S/N 200-02-17

| Emitter | |
|---|---|
| **Pulsed Laser Source** | Nd:YAG (Quantel ULTRA100 Series) |
| **Laser Class** | IV |
| **Primary Wavelength** | 355 nm (532nm and 1064nm damped) |
| **Energy / Pulse** | 32.3mJ |
| **Repetition Rate** | 20Hz |
| **Near Field Beam Diameter** | 3.60mm |
| **Pulse Width** | 4.50nsec |
| **Beam Expansion** | x10 |
| **Laser Beam Divergence** | 0.70mrad |
| **Motorized Alignment** | Yes |

| Receiver | | |
|---|---|---|
| **Telescope Type** | Cassegrain | |
| **Primary Diameter** | 200mm | |
| **Secondary Diameter** | 48mm | |
| **F #** | F4 | |
| **Focal Length** | 800mm | |
| **Default Field Of View** | 2.3 mrad (adjustable from 0.5 to 3mrad) | |
| **Overlap** | 170m | |
| **Detected Elastic Backscatter Wavelengths** | 355nm P polarization | Analogue + Photon Counting |
| | 355nm S polarization | Analogue + Photon Counting |
| **Interference Filter Bandwidth** | IFF355 | CWL 354.85nm |
| | | BW 0.55nm |
| | | **OD<6** |

| SERIAL | TYPE | CATHODE LUMINOUS SEN (μA/lm) | ANODE LUM. SENS A/lm | ANODE DARK C (nA) | CATHODE BLUE SEND INDEX | REC. OPERATING VOLTAGE Volts |
|---|---|---|---|---|---|---|
| **BKA0441** | R9880U-113 | 126 | 285 | 0.02. | 13.6. | 800-950V |
| **BKA0450** | R9880U-113 | 110 | 267 | 0.02. | 13.1. | 800-950V |

(PMT Characteristics)

| Control Unit | | |
|---|---|---|
| **Transient Recorder** | Manufacturer | Licel |
| | Type | 20-12bit |
| | Spatial Resolution | 7.50m |
| **Computer** | Manufacturer | Raymetrics |
| | Motherboard | Commell LS-576 |
| | CPU: | Intel® Core™ i3 2.4GHz |
| | VGA: | Intel® HD Graphics 4000/2500 Technology |

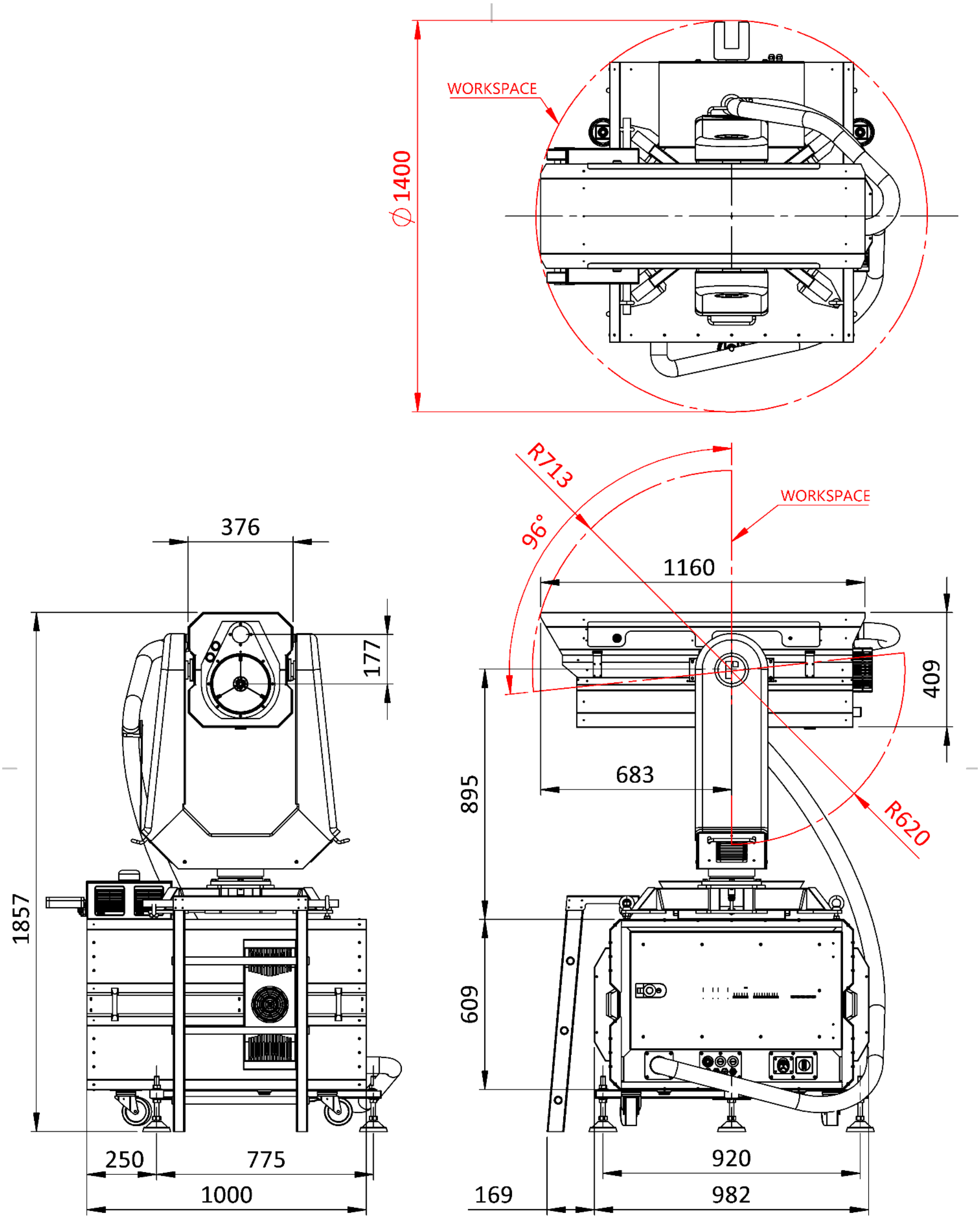
| | | |
|---|---|---|
| | Ethernet: | 1 x Intel 82579LM Gigabit LAN (Support iAMT8.0)<br>5 x Intel 82574L Gigabit LAN |
| | Storage: | SATA HDD 500Gb |
| | RAM: | 4Gb |
| | Chipset | Intel® QM77 Express chipset |
| **Software** | OS: | MS Windows 10 Professional |
| | Backup: | Software for data backup |
| | Alignment: | Lidar System Checking and Alignment |
| | Acquisition: | Data Acquisition (with real time data display) |
| | Analysis: | Data Analysis |
| | Control SW | Laser Control, Scheduler, PMT HV Control |
| **Enclosure** | Manufacturer: | Raymetrics SA |
| | Material: | Aluminum sheet steel double walled |
| | Main Plug: | Bulgin IP68 panel mount plug 32A |
| | Main Switch: | Schneider electric IP66 industrial switch |
| | External USB | Bulgin IP68 panel mount USB A Type |
| | Ext. Ethernet | Bulgin IP68 panel mount RJ45 |
| | Ext. Interlocks | Bulgin IP68 2 pin female socket Straight PCB |
| **General** | IP protection: | Control enclosure: IP66 |
| | | Lidarhead enclosure: IP68 |
| | HVAC | 550W cooling output 500W Heating output |
| | Dimensions: | 1000mm x 1850mm x 1200mm WxHxD |
| | Weight: | 385 kg |
| | Voltage | 220~240VAC 50/60Hz |
| | Power | 500Watt Idle, 2220Watt Operation, 20A Peak current |
| | Temperature* | Operating: -20ºC to 45ºC, Storage: -20ºC to 50ºC |
| | Humidity | Operating: 10 to 80% non-condensing (+5 to 28ºC)<br>Storage: 10 to 90% non-condensing (+5 to 28ºC) |
| | Automation | LPC, PDU on UPS |

| LIDAR Performance | |
|---|---|
| **Lidar type** | Biaxial |
| **SNR > 10** | (10 minutes average for backscatter) 10km |
| **Depolarization Calibration (+/- 45°)** | Mechanical |
| **Depolarization offset correction** | Mechanical |
| **Upgradable channels** | 387nm & 532nm, 1064nm Emitter ready |
| **Scanning 3D** | Yes |
| **Max Backscatter Effective range**** | 10 km |

*Below 0ºC only with Ethylene Glycol and water mixture

**Depending on the atmosphere's conditions

## 10.2 Lidar Dimensions



# 11. LIMITED GUARANTEE

**NOTICE**

Raymetrics SA reserves the right to make improvements of the products described in this Manual at any time and without notice. Thus, all specifications of this Lidar system or sub-systems are subject to change at any time and without notice.

Raymetrics SA shall not be liable for errors contained in this Manual or for incidental or consequential damages regarding the furnishing, performance or use of this material.

***WARRANTIES***

Raymetrics SA, as well as the Lidar-components providers (laser source, acquisition electronics, photo-multiplier tube (PMT), computer, Digital acquisition PC-card and cables) guarantee the products or sub-systems of this Lidar system to be free from defects in materials and faulty workmanship under normal use for a period of 12 months after the date of the original purchase and following the delivery to the site (for details see the Instruction Manuals of the Lidar sub-systems providers). Laser flashlamps are guaranteed for 30 million shots or 1 year whichever comes first.

This warranty does not cover:

- equipment or components where the original identification markings have been altered or removed or if any parts have been replaced by other components
- equipment or components that have become defective due to mishandling, erroneous use, accidental alteration, improper operation, or any other cause, without the prior written agreement of Raymetrics SA.

The cost and terms of non-warranty service are fixed by Raymetrics SA and the Lidar sub-systems providers and are subject to change.

***RETURNS, ADJUSTMENTS AND SERVICE***

If warranty, service or general repair of a Raymetrics SA Lidar system is requested by the customer which requires the product's return to Raymetrics SA, the terms of such return include the following:

a) Freight and insurance (CIF) charges are pre-paid by the customer, who also takes all the risks of loss, damage or delay in shipment,

b) The Lidar system must be packed in the original containers provided by Raymetrics SA. All water must have been drained from the Laserhead according to the laser manufacturer rules, prior to packing.
c) Prior to sending the product back to Raymetrics SA the customer must obtain a written authorization for the product return for service.
d) After the product receipt Raymetrics SA reserves the right to fully inspect the Lidar system and determine the cause of failure and warranty status. If the product has suffered damage during the shipment Raymetrics SA has no obligation to perform a warranty repair.
e) If the warranty of the product has expired the customer will be advised of the cost of such repair and a written purchase order for the repair and service work will be required before the performance of the work.
f) If the product is still under warranty status it will be repaired or replaced free of charge in accordance with the terms of the Raymetrics SA and Lidar components providers. Finally, the warranty period for a replaced or repaired component will be only the period remaining on the original product, thus no extra warranty is provided by such repair.
g) In cases where components must be shipped back to the original manufacturer for analysis or repair, the manufacturer’s decision on the cause of damage shall be final. Reports from manufacturers can be supplied.

# REFERENCES


1. Ancellet, G., A. Papayannis, G. Mégie, J. Pelon, '*Tropospheric Ozone Measurements Using a Nd: YAG Laser and the Raman Shifting Technique*', Journal of Oceanic and Atmospheric Technology, 6, 832-839, 1989.

2. Measures, R., *Laser Remote Sensing: Fundamentals and Applications*, Wiley, New York, 1984.

3. Klett, J., '*Lidar inversion with variable backscatter/extinction ratios*', Applied Optics, 24, 1638-1643, 1985.

4. Ansmann, A., U. Wandinger, M. Riebesell, C. Weitkamp, and W. Michaelis, '*Independent measurements of extinction and backscatter profiles in cirrus clouds using a combined Raman elastic-backscatter Lidar*,' Applied Optics, 22, 2257-2264, 1992.

5. Chazette, P., David, C., Lefrere, J., Godin, S., Pelon, J. and Megie, G., *Comparative Lidar study of the optical and dynamical properties of stratospheric post-volcanic aerosols following the eruption of the El Chichon and Mount Pinatubo*, J. Geophys. Res., 100, 23, 195-207, 1995.

6. Boesenberg, J., Timm, R., and Wulfmeyer, V., *Study of retrieval algorithms for a backscatter Lidar*. Final Report, MPI Report No 226, pp. 1-66, 1997.

7. *U.S. Standard Atmosphere*, NOAA, NASA, USAF, U.S. Government Printing Office, Washington D.C., 227, (1976).

Also

8. V. Matthias, V. Freudethaler, A. Amodeo, I. Balin, D. Balis, J. Bosenberg, G. Chourdakis, A. Comeron, '*Aerosol Lidar intercomparison in the framework of EARLINET: Part I- Instruments*', Applied Optics, 43, 961-976, 2004.

9. G. Chourdakis, A. Papayannis and J. Porteneuve, '*Analysis of the receiver response for a non-coaxial Lidar system with fiber-optic output*', Applied Optics, 41, 2715-2723, 2002.

10. A. Papayannis, G. Chourdakis, 'The EOLE project, Part II: *Aerosols measurements over Athens, Greece', International Journal of Remote Sensing*, 23, 179-196, 2002.

11. D. Balis, C. Zerefos, V. Amoiridis, C. Meleti, A. Balis, A. Kazantzidis, A. Papayannis, G. Chourdakis, G. Tsaknakis and T. Trickl, '*Study of the aerosol effect on the UV-B irradiance at the earth's surface cases studies selected from urban sites in the frame of the Earlinet project*', Journal of Aerosol Science, 32, 391-392, 2001.

12. V. Matthias, V. Freudethaler, A. Amodeo, I. Balin, D. Balis, J. Bosenberg, A. Chaikovski, G. Chourdakis, A. Comeron, Arnoud Delaval, F. Di Tomasi, R. Eixman, A. Hagard, L. Komguem, S. Kreipl, R. Matthey, V. Richi, J. A. Rodrigues, U. Wandiger, X. Wang, '*Intercomparison of 15 aerosol Lidar systems in the frame of EARLINET*', Journal of Aerosol Science, 32, 397-398, 2001.

# APPENDIX A

## A1 How To Control The Laser

Basically, there are three major ways to control laser. The first is to use the Remote Box; the second is to use 'Laser Control' program from Raymetrics; the third is to use the external trigger. The section below describes mainly the second and the third options. For more info about the Remote Box please read the Laser Manuals.

**NOTE:** For optimum laser energy

1. The resulting Q-Switch Delay should be 140μs.
2. Do not change the frequency. For GRM lasers this should be 20Hz.

**Communication**

The primary communications and control is via the RS-232 port located on the ICE450 front panel (for the Rack mounted version of the ICE450 it is on the back panel). The ICE can be set to lock out front panel key control and avoid conflict with RS-232 communications.

The serial communications configuration is:

- 9600 baud
- 8 data bits
- no parity
- 1 stop bit
- no flow controls
- No hardware handshaking is utilized.

**Important Note:** Usually the ICE450 is connected physically (through RS-232) to the Lidar computer. In that case you must use remote desktop to connect to the Lidar's computer and then use the *'Laser Control'* program (or the *'ICE450_GUE'* program). In some cases, the Laser is connected to a Serial-To-Ethernet converter. If this is the case you must create a virtual com port to your computer (by using Serial Device Server Configuration Utility) and run the *'Laser Control'* program from your computer. In most of the cases the Laser is connected on Port 2 of the Serial-to-Ethernet converter with IP address 10.49.234.232.

### A1.1 Manual Laser Operation Mode

Use Manual Mode for the normal operation of the Power Supply and flashlamp. Press the 'ready' button on the Remote Box to initiate simmer current in the flashlamp. The PCC generates a flashlamp discharge as part of establishing simmer. Verify that the LASER ON indicator is illuminated on the front panel of the PCC. Please be advised not to perform laser emission (Q-switching) in this mode.

1. Press the Flashlamp Start button.
2. The PCC generates flashlamp pulses at the rate specified by the 'frequency' setting in the Flashlamp menu. This setting is adjustable.
3. For Gaussian Resonator (GRM) type Laserheads, the frequency is pre-set by Quantel. **Please do not adjust the frequency setting for GRM heads.**
4. Wait for 2 seconds
5. Press the Q-Switch Start button (Figure 5, [7]).
6. The PCC starts generating Q-switch pulses internally. These occur after the flashlamp pulse at a time specified by the 'FLQS delay' setting in the Q-switch menu.

**Adjusting this delay is one method of adjusting the optical energy of a laser pulse.**

**NOTE:** For this mode, the only necessary physical connection between the PCC and the Transient Recorder is a BNC 50-Ohm cable from Q-Switch out to the Rack Trigger input of the Transient Recorder

**NOTE: Q-Switch Out**: This BNC Connector allows synchronization to the laser Q-Switch trigger. The Q-Switch trigger corresponds to the rising edge of this positive signal (5V, 50 mA max and > 10 μS pulse width).

## A1.2 Laser Control Program

The *'Laser Control'* Program provides a user-friendly GUI for every day operation and control of the laser. The program does not require installation to your computer. To run it copy the .exe and .ini files to your computer.

When the program starts first it tries to find the laser at the serial port as specified in the ini file. In our example, this is COM8

Example of Laser_Control.ini

*[Laser_Control]*
*prefDlgTestData=1234*

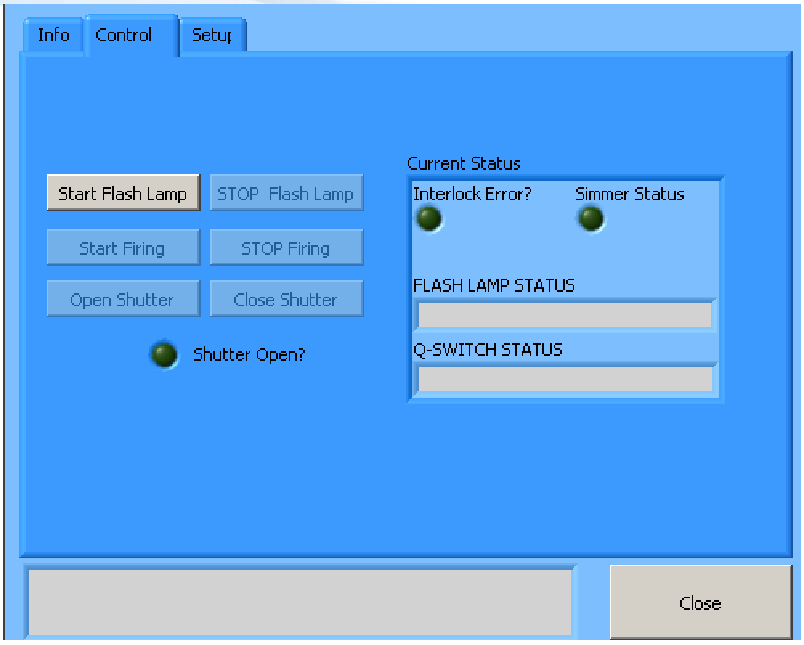
*useLocaleDecimalPt=False*

*postScriptLevel2=False*

*[Communication]*

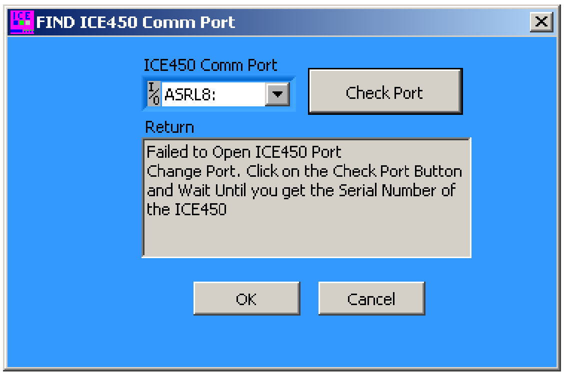
*Com Port=ASRL8::INSTR*

If successfully connected, the program starts and the version of the laser and its status appears.




After this click the 'Start Flash Lamp' button to start the flash lamp. Wait until ‘Simmer Status’ Led goes green. Wait a couple of seconds more and then click on the activated 'Start Firing' button to start emission of laser pulses. (Note: To stop the laser, follow the directions in reverse direction. If the laser is equipped with an automated shutter, click on the 'Open Shutter' button to start emission.

However, if the program fails to connect with the laser then another window appears giving user the option to try a different COM port.




Select an available COM port from the drop-down list and click the 'Check Port' button. If successfully connected (in which case the message returned should be like ‘ICE450 x.xx’) click the OK button. If the connection was unsuccessful try a different COM port.

For more information about ‘INFO and Setup’ please read the laser manual.

**Troubleshooting**

1. The software fails to start
   - Make sure that your computer has the correct Labview runtime engine installed.
2. The software starts successfully but cannot communicate with the laser.
   - Make sure that your laser is powered on.
   - Make sure that you have assigned the correct COM port
   - Make sure that laser serial cable is correctly attached to the Lidar's computer or to the Serial-to-Ethernet converter as well as to your computer.
3. Software runs and communicates successfully but the laser does not start firing (or there is an interlock error message)
   - In these cases, try to control your laser manually (by using the remote box or the software provided by laser manufacturer). Consult the Laser user manual.

Before contacting Raymetrics please try to identify the problem and send screen shots and a detailed description of the message that can be found on the LCD display of the Lasers Remote Box.

## A1.3 Flashlamp in Internal Mode and Q-switch in External Mode

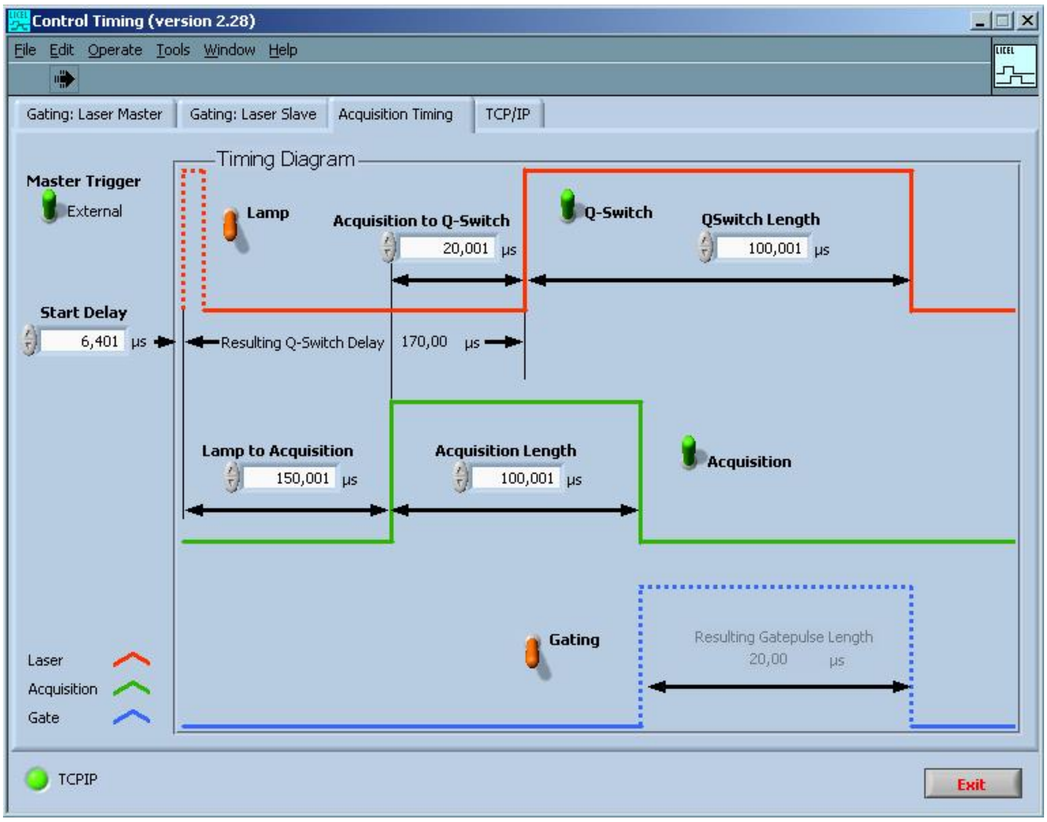
In this configuration, the PCC generates the flashlamp pulse signals and an external source (Trigger Generator) generates the Q-switch trigger signals. This may be useful when you:

a. Require better resolution for the Q-switch delay than is available using the PCC since the Lamp Out signal is a copy of the actual flashlamp trigger.
b. Require pretrigger function.

To use this mode, select internal flashlamp sync and external Q-switch sync as follows:

1. From the main menu, go into the Flashlamp menu and select flash sync 'INT'.
2. Return to the main menu.
3. Enter the Q-switch menu and select QS Sync 'EXT'.
4. Open *‘Control Timing*’ program (from Licel menu)
5. Click on the ‘Acquisition Timing’ tab.
6. Switch ‘Master Trigger to External’ (up position)

For optimum laser energy the resulting Q-Switch Delay should be 140μs. For example, if you need 20 μs of pretriggering then Lamp to Acquisition should be 120μs + 20μs Acquisition to Q-Switch. If no pretrigger is required then put Lamp to Acquisition at 140μs and Acquisition to Q-Switch at 0 μs.




Now you can switch the laser on and off by switching the 'Q-Switch' knob.

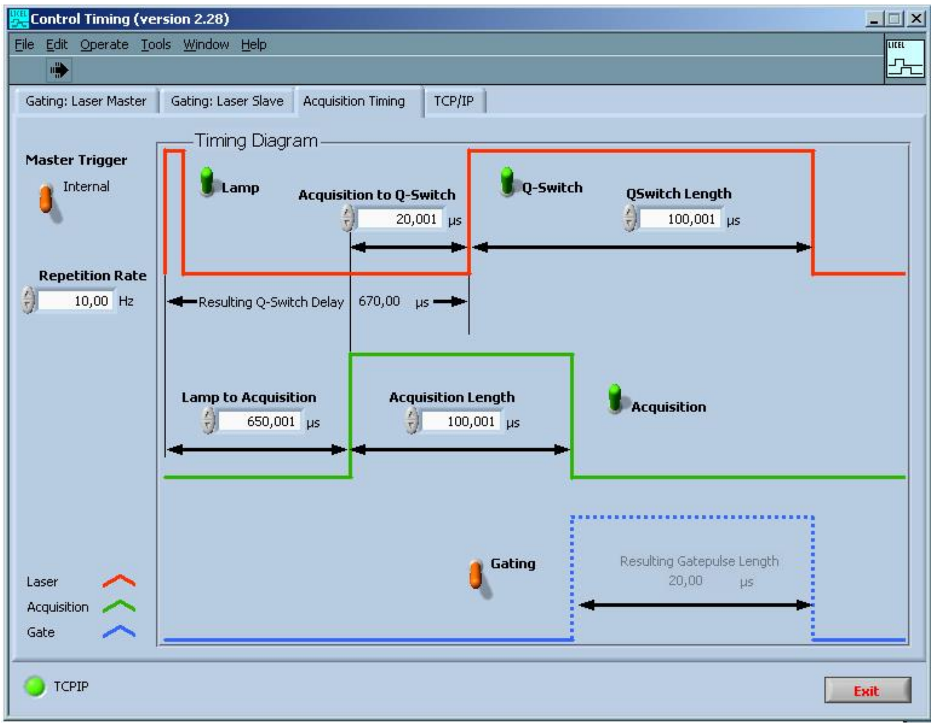
## A1.4 Flashlamp and Q-switch in External Mode

In this configuration, an external source (Trigger Generator) generates both the flashlamp trigger and the Q-switch trigger.

To use this mode, select external flashlamp sync and external Q-switch sync as follows:

1. From the main menu, go into the Flashlamp menu, and select flash sync 'EXT'.
2. Return to the main menu.
3. Enter the Q-switch menu and select QS Sync 'EXT'.
4. Open *'Control Timing*' program (from Licel menu)
5. Click on the 'Acquisition Timing' tab.
6. Switch 'Master Trigger' to Internal (up position)

For example, if you need 20μs pretriggering then Lamp to Acquisition should be 620μs + 20μs Acquisition to Q-Switch. If no pretrigger is required then set Lamp to Acquisition at 640μs and Acquisition to Q-Switch at 0μs. **Note:** There is a processing delay of 500μsec between the external flashlamp trigger input and the actual flashlamp activation.




**NOTE:** Always switch off the Q-Switch knob before you switch off the 'Lamp' knob.

# A2 How To Work Via An External Computer

If for any reason you want to use another computer you must setup the communications and install the programs for the Lidar. You can use any computer that you want that has Windows XP OS and later.

**Communications Setup**

Communications are with Licel's controllers, the Laser and positioner (if your system is equipped with one).

Licel has a LAN based communication. Lidar's TR IP address is by default: 10.49.234.234. Therefore the user's PC should belong to the same subnet class:

10.49.234. xxx

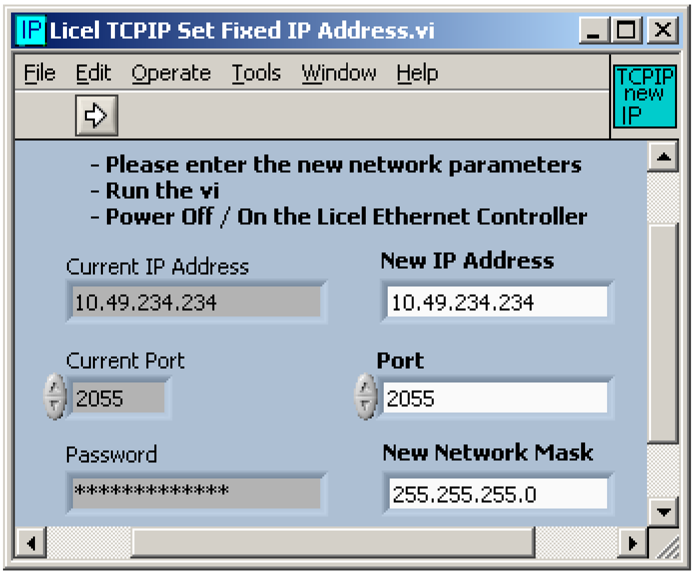
Where xxx is any number from 0 to 254.

**NOTE:** Do not use numbers for xxx from 230 up to 237. These ranges are reserved for Lidar hardware.

**To change the user's or Lidar's PC TCP IP address,** read windows documentation or consult your system administrator

**To change the Transient Recorder TCP IP address,** run the program *'TCPIP Set Fixed IP Address'* program.

Usually this is located in the following folder on the Lidar PC: C:\Program Files\Licel\Configure\ TCPIP Set Fixed IP Address.exe




For more information please refer to Licel's documentation

The laser and positioner (if applicable) have an RS232 communication so they require serial ports unless there is an Serial-to-Ethernet converter installed in your system. This device needs separate installation but gives the option to connect all devices on an Ethernet switch to which you also connect your computer. This makes the connection very easy. Otherwise you have to use the external USB port with an RS232 to USB adaptor to connect to your computers USB port. If there is more than one device with an RS232 port use a hub and separate RS232 to USB adaptors for each device.

**Lidar Software Installation**

First install Licel's software (this step is not absolutely required but it is recommended)

If your PC does not have Labview runtime library (*LVRunTimeEng*) version 10 or later, it must be installed. You can download this file from www.ni.com or you can find it into programs folder that Raymetrics supplies to users.

In addition, if the user's PC does not have visa301 runtime library (*visa301runtime*), this also must be installed. You can download this file from www.ni.com or you can find into programs folder that Raymetrics supplies to users.

When everything is set, make a copy of the '.ini' files from the Lidar's computer.

# APPENDIX B

***SUMMARY OF LIDAR THEORY***

**CONTENTS**

## B1 Introduction

In its simplest from, the detected Lidar signal can be written as

$$P(R) = KG(R)\beta(R)T(R) \quad \text{eq. 1}$$

The power P received from a distance R is made up of four factors.

1. The first factor, K , summarizes the performance of the Lidar system

2. The second, G(R), describes the range-dependent measurement geometry

**NOTE:** These two first factors are completely determined by the Lidar setup and can thus be controlled by the experimentalist. The information on the atmosphere, and thus all the measurable quantities, are contained in the last two factors.

3. The term β (R) is the backscatter coefficient at distance R.

4. The term T (R) is the transmission term and describes how much light gets lost on the way from the Lidar to distance R and back.

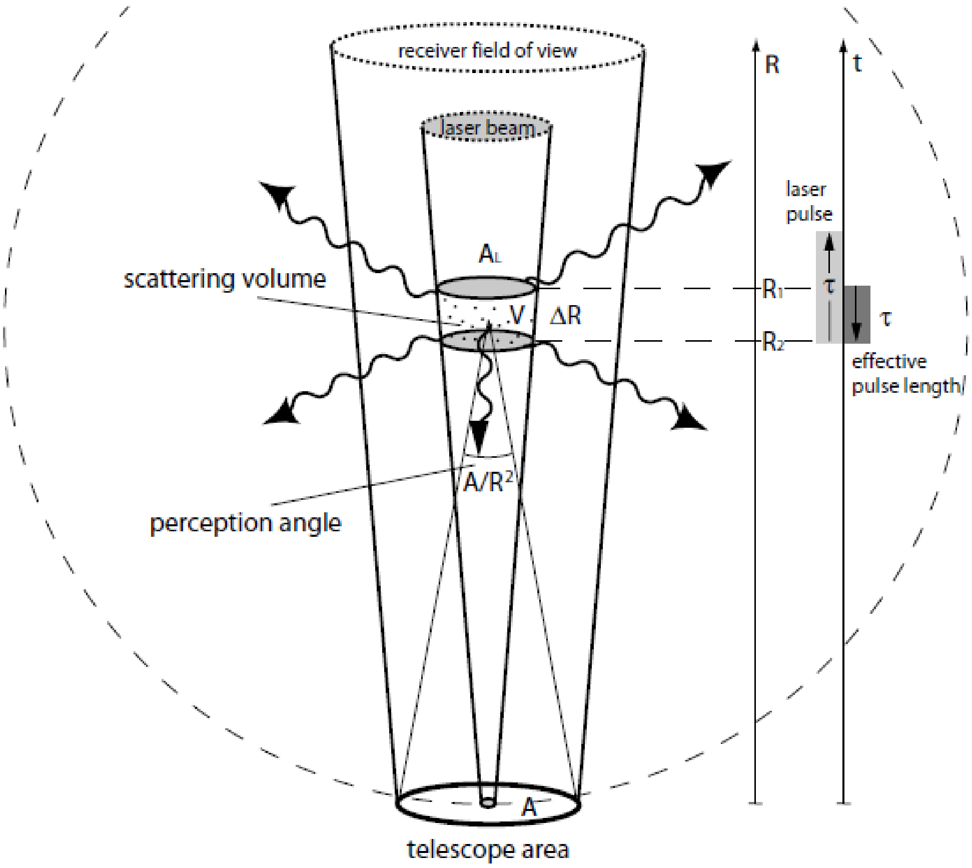



**Fig. B1**

In a more analytic form the term K is given by the following equation

$$K = P_0 \frac{c\tau}{2} An \quad \text{eq. 2}$$

$P_o$ is the average power of a single laser pulse and τ is the temporal pulse length.

Hence $E_o = P_o * \tau$, is the pulse energy and c*τα is the length of the volume illuminated by the laser pulse at a fixed time. The factor ½ appears because of an apparent 'folding' of the laser pulse through the backscatter process. A is the area of the primary receiver optics responsible for the collection of backscattered light (usually the primary mirror of a telescope) and n is the overall system efficiency which includes the optical efficiency of all the elements that transmit and receive light.

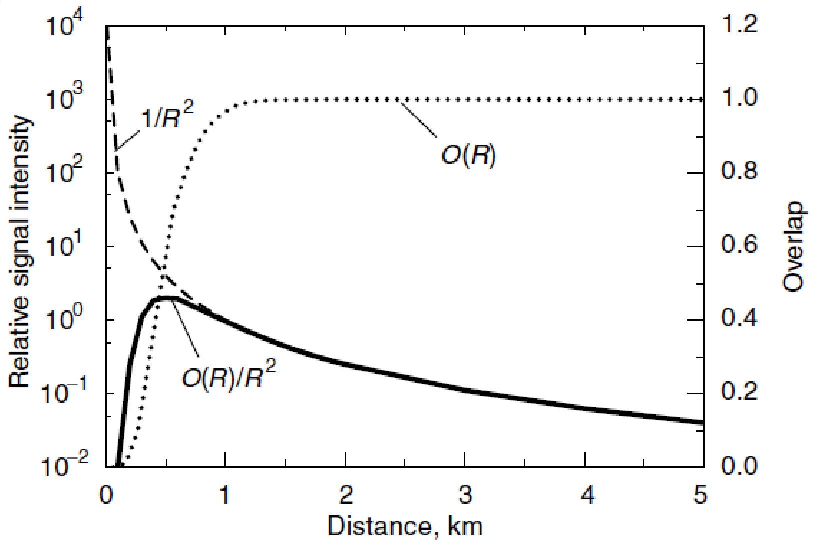
The geometric factor G(R) can be given from the following equation:

$$G(R) = \frac{O(R)}{R^2} \quad \text{eq. 3}$$

and includes the laser-beam receiver-field-of-view overlap function O(R) described before and the term $R^{-2}$. The quadratic decrease $1/R^2$ of the signal intensity with distance is due to the fact that the receiver telescope area makes up a part of a sphere’s surface with radius R that encloses the scattering volume. If we imagine an isotropic scattered at distance R, the telescope area A will collect the fraction $I_C$:

$$\frac{I_C}{I_S} = \frac{A}{4\pi R^2} \quad \text{eq. 4}$$

of the overall intensity $I_S$ scattered into the solid angle 4π . In other words, the solid angle $A/R^2$ is the perception angle of the Lidar for light scattered at distance R. The factor 4π does not appear explicitly in the Lidar equation because it cancels out by the definition of the backscatter coefficient β as we will see below. It is primarily the $1/R^2$ dependence that is responsible for the large dynamic range of the Lidar signal. If we start detecting a signal with O(R)=1 at a distance of 10 m, the signal will be 6 orders of magnitude lower at 10 km distance just because of the geometry effect. To what extent Lidar is a *range-resolving and remote* measurement technique depends on our ability to compensate for this effect.




Graph 1: Influence of overlap function O(R), at Lidar signal

## B1.1 About Backscatter Coefficient β(R,λ)

The backscatter coefficient β(R, λ) is the primary atmospheric parameter that determines the strength of the Lidar signal. It describes how much light is scattered into the backward direction, i.e., towards the Lidar receiver. In the atmosphere, the laser light is scattered by air molecules and particulate matter, i.e., β (R, λ) can be written as

$$\beta(R,\lambda) = \beta_{mol}(R,\lambda) + \beta_{aer}(R,\lambda) \quad \text{eq.5}$$

Molecular scattering (index mol), mainly occurring from nitrogen and oxygen molecules, primarily depends on air density and thus decreases with height, i.e., backscattering decreases with distance if the observation is made from the ground. Particulate scattering (index aer for aerosol particles) is highly variable in the atmosphere on all spatial and temporal scales. Particles represent a great variety of scatterers: tiny liquid and solid air-pollution particles consisting of, e.g., sulfates, soot and organic compounds, larger mineral-dust and sea-salt particles, pollen and other biogenic material, as well as comparably large hydrometeors such as cloud and rain droplets, ice crystals, hail.

## B1.2 About Extinction Coefficient, α(R,λ)

The last term in the Lidar equation, we have to consider the fraction of light that gets lost on the way from the Lidar to the scattering volume and back. The transmission term T(R) can take values between 0 and 1 and is given by

$$T(R,\lambda) = \exp\left[-2\int_0^R a(r,\lambda)dr\right]$$ eq. 6

This term results from the specific form of the Lambert–Beer–Bouguer law for Lidar. The integral considers the path from the Lidar to distance R. The factor 2 stands for the two-way transmission path. The sum of all transmission losses is called light extinction, and α(R,λ) is the extinction coefficient. Extinction can occur because of scattering and absorption of light by molecules and particles.

## B1.3 The Lidar Equation

Below is the extensive form of the well-known Lidar equitation

$$P(R,\lambda) = P_0 \frac{c\tau}{2} An \frac{O(R)}{R^2} \beta(R,\lambda) \exp\left[-2\int_0^R a(r,\lambda)dr\right]$$ **eq. 7.1**

Or

$$P(R) = \frac{n \times P_o \times A \times O(R) \times [\beta_{mol}(R) + \beta_{aer}(R)] \times \exp[-2\int_0^R [a_{mol}(r) + a_{aer}(r)]dr}{R^2} + P_{bgr}$$ **eq. 7.2**

In equation 7.2 wavelength dependence λ have been omitted for simplicity. In addition a new term $P_{bgr}$ is the background noise that comes from atmospheric defused light (daytime) and the electronic noise.

In any form of the eq. 7 has two unknown quantities (β and α). So this is an intrinsic problem of an elastic backscatter Lidar. One has to measure two quantities with only one equation. Several solutions (depending on different assumptions) have been proposed in literature in order to solve the Lidar equation.

**NOTE:** Raymetrics Software uses the Inver Klett-Fernard method (Far-end solution)

# B2 Summary of Solutions to The Lidar Problem

There are three basic inversion methods commonly used to find extinction coefficient. These methods are:

## B2.1 The Slope Method

This method is useful for homogeneous atmospheres. In many cases, atmospheric horizontal homogeneity is a reasonable assumption. With the slope method, a mean value of the extinction coefficient over the examined range in a homogeneous atmosphere is obtained.

One can reform the eq. 7.1 at the following form:

$$P(R) = C_0 T_0 \frac{\beta(R,\lambda)}{R^2} \exp\left[-2\int_{R_0}^{R} a(r,\lambda)dr\right] \quad \textbf{eq. 8}$$

$C_0$ is the system constant and $T_0$ is an unknown, two-way transmission term from ground to $R_0$ ($R_0$ is where the overlap function O(R)=1).

$$T_0(R) = \exp\left[-2\int_{0}^{R_0} a(r,\lambda)dr\right]$$

In a homogeneous atmosphere we can assume that

α(r)=α=constant and β(r)=β=constant

In that case we get

$$P(R) = C_0 T_0 \frac{\beta(R,\lambda)}{R^2} \exp\left[-2(R-R_0)a\right]$$

Then we define the Range Corrected Signal as:

$$RCS(R) \equiv P(R)R^2 = C_0 \beta e^{-2\alpha R},$$

Taking the natural logarithm, we get the following (singe β and α are assumed range independent for homogeneous atmospheres:

$$Z(R) = B - 2\alpha R \quad \textbf{eq. 9}$$

Where

$$B \equiv \ln(C_0 \beta)$$

The linear dependence of Z(R) on range R, is a key factor when seeking the simplest solution to the Lidar equation. It allows determination of the α by linear square fit. In addition the estimate of the standard deviation of the linear fit for Z(R) can be used to estimate the degree to which the assumption of atmospheric homogeneity is valid.

**NOTE:** As always before you apply such a solution you have first to subtract background noise from the Lidar signals

## B2.2 Inverse Klett-Fernard Method (Using Raymetrics Software)

$$\beta(R) = \frac{RCS(R) * \exp\left(2*(L - L_{mol})*\int_{R}^{R_{ref}} \beta_{mol}(r)dr\right)}{\frac{RCS(R_{ref})}{C*\beta_{mol}(R_{ref})} + 2*L*\int_{R}^{R_{ref}} RCS(R')*\exp\left(2*(L - L_{mol})*\int_{R'}^{R_{ref}} \beta_{mol}(R'')dR''\right)dR'}$$ **eq.10**

Where

$$C = \frac{\beta_{mol}(R_{ref}) + \beta_{aer}(R_{ref})}{\beta_{mol}(r)}$$ **eq.11**

if the reference point $R_{ref}$ is in a clean atmosphere (for example free troposphere without aerosols) then it is safe to assume that $\beta_{aer}(R_{ref})=0$ so C=1

$$L_{mol}(r) = \frac{a_{mol}(r)}{\beta_{mol}(r)} = \frac{8\pi}{3}$$ **eq.12**

and

$$L(R) = \frac{a_{aer}(R)}{\beta_{aer}(R)} = const$$ **eq.13**

L(R) is the aerosol Lidar ratio and depends on particle size distribution, complex refractive index, the shape of aerosols, relative humidity height and wavelength.

## B3 Introduction To Raman Lidar

As we saw above by measuring only the elastically backscattered signal we have to make an assumption for the Lidar ratio in order to solve the Lidar equation. This introduces errors since we know that the Lidar ratio is not constant and depends on height relative humidity (which varies strongly by height) and other microphysical parameters.

However by measuring simultaneously the inelastically (Raman) backscattered signal by Nitrogen we get two equations with two unknowns. So the problem now can be solved. The determination of the particle extinction coefficient from molecular backscatter signal is rather straightforward and there is no need for Lidar-Ratio assumptions. However it should be pointed out that Raman signals can be 1000 times weaker than elastic signals so the background noise reduces significantly the range of measurements of such signals. Practically speaking, Raman signals can only be detected at night time.

As shown previously the power received from the distance R for an elastic channel is given by the equation:

$$P(R) = \frac{n \times P_o \times A \times O(R) \times [\beta_{mol}(R) + \beta_{aer}(R)] \times \exp[-2\int_0^R [a_{mol}(r) + a_{aer}(r)]dr}{R^2} + P_{bgr}$$

For simplicity we rewrite the equation in the following form (for the $R>R_0$ where $O(R)=1$)

$$P(R,\lambda_L) = \frac{C \times [\beta_{mol}(R,\lambda_L) + \beta_{aer}(R,\lambda_L)] \times \exp[-2\int_{R_0}^R [a_{mol}(r,\lambda_L) + a_{aer}(r,\lambda_L)]dr}{R^2} \quad \textbf{eq. 14}$$

where $\lambda_L$ is the laser emitted wavelength.

The power received from distance R from a Raman channel is given from the following equation:

$$P(R,\lambda_R) = \frac{C \times \beta(R,\lambda_L,\lambda_R)}{R^2} \exp\left[-\int_0^R [a(\lambda_L,r) + a(\lambda_R,r)]dr\right] \quad \textbf{eq. 15}$$

$$\beta(R,\lambda_L,\lambda_R) = N_R(R) \frac{d\sigma(\lambda_L,\lambda_R,\pi)}{d\Omega} \quad \textbf{eq. 16}$$

Where $\lambda_R$ is the Raman shifted wavelength from the Raman-active gas (usually nitrogen at 387 nm)

Eq.15 has two main differences from eq.14. First the -2 factor is no longer present since the extinction in this case happens only one way (returning to the Lidar receiver). The Raman backscatter coefficient (eq.16) is given by the molecular number density N(R) of the Raman-active gas (usually nitrogen at 387 nm) and the differential Raman cross section for the return direction.

By using the above three equations we can get:

$$a_p(\lambda_L, R) = \frac{\frac{d}{dr}\left[\ln \frac{N_R(R)}{R^2 P(R)}\right] - a_{mol}(\lambda_L, R) - a_{mol}(\lambda_L, R)}{1 + \left(\frac{\lambda_L}{\lambda_R}\right)^k}$$

**eq. 17**

The above equation is valid for $R > R_o$ in other words where O(R) = 1

In addition:

$a(\lambda_L, R) = a_{aer}(\lambda_L, R) + a_{mol}(\lambda_L, R)$ and $a(\lambda_R, R) = a_{aer}(\lambda_R, R) + a_{mol}(\lambda_R, R)$

and

$$\frac{a_{aer}(\lambda_L, R)}{a_{aer}(\lambda_R, R)} = \left(\frac{\lambda_R}{\lambda_L}\right)^k$$

The aerosol backscatter coefficient is given from the following equation:

$$\beta_{aer}(\lambda_L, R) = -\beta_{mol}(\lambda_L, R) + \left[\beta_{aer}(\lambda_L, R_{ref}) + \beta_{mol}(\lambda_L, R_{ref})\right] \times \frac{P(\lambda_R, R_{ref})P(\lambda_L, R)N_R(R)}{P(\lambda_L, R_{ref})P(\lambda_R, R)N_R(R_{ref})} \times$$
$$\frac{\exp\left\{-\int_{R_{ref}}^{R}\left[a_{aer}(\lambda_R, r) + a_{mol}(\lambda_R, r)\right]dr\right\}}{\exp\left\{-\int_{R_{ref}}^{R}\left[a_{aer}(\lambda_L, r) + a_{mol}(\lambda_L, r)\right]dr\right\}}$$

**Eq.18**

Once more usually at $R_{ref}$

$$\beta_p(\lambda_L, R_{ref}) + \beta_{mol}(\lambda_L, R_{ref}) \cong \beta_{mol}(\lambda_L, R_{ref})$$

## B3.1 Molecular Backscatter Coefficient

For elastic or Raman backscatter Lidars one must calculate the molecular backscatter coefficient.

$$a_m(R) = N(R)\sigma = \mathrm{N}(R)\frac{24\pi^3}{\lambda^4 N_s^2}\frac{\left(n_s^2(\lambda)-1\right)^2}{\left(n_s^2(\lambda)+2\right)^2}F_k$$

Since

$$L_{mol} = \frac{a_m}{\beta_m} = \frac{8\pi}{3}$$

Then

$$\beta_m(R) = \mathrm{N}(R)\frac{9\pi^2}{\lambda^4 N_s^2}\frac{\left(n_s^2(\lambda)-1\right)^2}{\left(n_s^2(\lambda)+2\right)^2}F_k \quad \textbf{Eq.19}$$

The values for $n_s$ and $F_k$ can be taken from the table below

| **λ** | **ns-1** | **Fk** | **ns** | **(ns^2-1)^2/(ns^2+2)^2** |
|---|---|---|---|---|
| **nm** | **x1E-8** | | | |
| **266** | | **1,06** | **1,000294650** | **3,85823E-08** |
| **289** | | **1,057** | **1,000291880** | **3,78603E-08** |
| **299** | | **1,056** | **1,000290860** | **3,75961E-08** |
| 308 | 29047,7 | 1,05575 | 1,000290513 | 3,75065E-08 |
| **316** | | **1,0551** | **1,000289140** | **3,71528E-08** |
| 351 | 28602,7 | 1,05308 | 1,000285983 | 3,63460E-08 |
| 354,814 | 28572,4 | 1,0529 | 1,000285745 | 3,62854E-08 |
| 355 | 28570,2 | 1,05289 | 1,000285745 | 3,62854E-08 |
| 386,8 | 28350,2 | 1,05166 | 1,000283480 | 3,57125E-08 |
| 400 | 28275,2 | 1,05126 | 1,000282764 | 3,55325E-08 |
| 407,663 | 28235,1 | 1,05105 | 1,000282407 | 3,54427E-08 |
| 510,6 | 27869,4 | 1,04922 | 1,000278711 | 3,45212E-08 |
| 532 | 27819,9 | 1,04899 | 1,000278235 | 3,44032E-08 |
| 532,221 | 27819,4 | 1,04899 | 1,000278235 | 3,44032E-08 |
| 607,6 | 27686,3 | 1,04839 | 1,000276804 | 3,40504E-08 |
| 710 | 27570,4 | 1,0479 | 1,000275731 | 3,37870E-08 |
| 800 | 27503,8 | 1,04763 | 1,000275016 | 3,36119E-08 |
| 1064 | 27397,5 | 1,04721 | 1,000273943 | 3,33502E-08 |
| 1064,442 | 27397,4 | 1,04721 | 1,000273943 | 3,33502E-08 |

N(R) is the atmospheric number density and can be easily calculated by using several atmospheric models or by using Radiosonde measurements.

$$N(R) = N_s \frac{T_o}{P_o} \frac{P(R)}{T(R)}$$

$N_s$ molecular number density for standard atmospheric conditions at ground level. $N_s$=2.5477*$10^{19}$cm$^{-3}$, $P_o$=1013.25 hPa and $T_o$=15 °C

## B3.2 Other Lidar Equation Solutions

### *B3.2.1 Solutions for one component atmospheres:*

In a more generic form the equation 8 can be written as below:

$$P(R) = C_0 T_0 \frac{\beta_{aer}(R) + \beta_{mol}(R)}{R^2} \exp\left[-2\int_{R_0}^{R} [a_{aer}(r) + a_{mol}(r)]dr\right]$$ **Eq. 20**

Now we define two new quantities

$$\bar{L}(R) = \frac{\beta_{aer}(R)}{a_{aer}(R)}$$

Where

$$\beta_{aer}(R) \equiv \beta_{aer}(R, \theta = \pi)$$

backscatter coefficient (θ=π) and

$$a_{aer}(R) = \beta_{aer}(R,\theta) + \alpha^{A}_{aer}(R).$$

So we can write

$$\bar{L}(R) = \frac{\beta_{aer}(R)}{\beta_{aer}(R,\theta) + a^{A}_{aer}(R)}$$

Here the extinction is split into scattering in all directions and into extinction because the absorption processes. In the same way we define

$$\bar{L}_{mol}(R) = \frac{\beta_{mol}(R)}{\beta_{mol}(R,\theta) + a^{A}_{mol}(R)}$$

In the case of one component atmosphere with no absorption, the solution to the Lidar equation can be written as

$$a_{aer}(R) = \frac{RCS(R)}{C' - 2\int_{R_0}^{R} RCS(r)dr}$$ eq.21

Where

$$C' = C_0 T_0 \overline{L}_{aer} \text{ eq. 22}$$

for a single component atmosphere well mixed $\overline{L}_{aer}$ does not depend on range (R).

To find aerosol extinction coefficient from eq. 21 we need to know C' (which is called sometimes Lidar calibration constant). This is not an easy task. Even if we know $C_0$ the other two parameters can be determined only during measurements. However in order to calculate $\alpha_{aer}$ we need two know only the product which means only the C' and not the individual components of eq. 22. The simplest way to determine the C' is to establish a boundary condition of the equation at some point of the Lidar measurement range. This makes it possible to find the constant C' and then to use it to determine $\alpha_{aer}$ over the total measurement range.

If we know the value of $\alpha_{aer}$ at a specific point $R_{ref}$ which is inside the measuring range then

$$C' = \frac{RCS(R_{ref})}{a_{aer}(R_{ref}) \exp\left[-2 \int_{R_0}^{Rref} RCS(r) dr\right]}$$

We are reminded here that $R_0$ is the range where O(R)=1

By replacing C' into eq. 21 we get finally

$$a_{aer}(R) = \frac{RCS(R)}{\frac{RCS(R_{ref})}{a_{aer}(R_{ref})} + 2 \int_{R}^{R_{ref}} RCS(r) dr}$$ Far range solution $R_{ref} > R$

$$a_{aer}(R) = \frac{RCS(R)}{\frac{RCS(R_{ref})}{a_{aer}(R_{ref})} - 2 \int_{Rref}^{R} RCS(r) dr}$$ Near range solution $R_{ref} < R$ (and close to $R_0$) **Eq. 23**

The most stable solution for $\alpha_{aer}$ is the far range solution. Such solution is given by Klett.

**Optical Depth Solution**

Another way to solve the problem is to use total path transmittance over the Lidar operating range as a boundary solution. Once more this solution is applied with the assumption that the Lidar ratio is constant (one component atmosphere). We define the upper Lidar measuring limit $R_{max}$ which is usually taken as the range at which the signal-to-noise ratio reaches a certain threshold value. In this solution the two way transmittance $T_{max}$ is used as a boundary solution.

$$T_{\max} = \exp\left[-2\int_{R_0}^{R_{\max}} \alpha_{aer}(r)dr\right] \quad \textbf{eq. 24}$$

$$a_{aer}(R) = \frac{1}{2}\frac{RCS(R)}{\dfrac{I_{\max}}{1-T_{\max}} - \int_{R_0}^{R} RCS(r)dr} \quad \textbf{eq. 25}$$

$$I_{\max} = \int_{R_0}^{R_{\max}} RCS(r)dr \quad \textbf{eq. 26}$$

If we define the aerosol optical depth as

$$AOD = \int_{R_0}^{R_{\max}} \alpha_{aer}(r)dr \quad \textbf{eq.27}$$

Then we get $T_{\max} = \exp(-2AOD)$

$T_{max}$ is the quantity we need to know in order to calculate $\alpha_{aer}$. For real atmospheric conditions it is a finite positive value ($0<T_{max}<1$).

### B3.2.2 Solutions for two component atmospheres:

$$P(R) = C_0 T_0 \frac{\overline{L}_{aer}(R) * a_{aer}(R) + \overline{L}_{mol}(R) * a_{mol}(R)}{R^2} \exp\left[-2\int_{R_0}^{R}[a_{aer}(r) + a_{mol}(r)]dr\right]$$

**Far-end boundary point solution**

$$a(R) = \frac{RCS(R)}{\dfrac{RCS(R_{ref})}{a(R_{ref})} + 2\int_{R}^{R_{ref}} RCS(r)dr} \quad \textbf{eq.28}$$

where

$$a_{aer}(R) = a(R) - L(R)\beta_m(R) \quad \textbf{eq.29}$$

If Rref is in the free troposphere (atmosphere without aerosols) then

$a_{aer}(R_{ref}) = 0$ and $a(R_{ref}) = L(R_{ref})\beta_m(R_{ref})$

**Optical Depth Solution:**

$$a_{aer}(R) = \frac{1}{2}\frac{RCS(R)}{\dfrac{I_{\max}}{1-V_{\max}^2} - \int_{R_0}^{R} RCS(r)dr}$$

Where once more the Imax is given from eq.26 and

$$V_{\max} = T_{\max}\exp\left[-(\frac{L(R)}{L_m} - 1)\int_{R_0}^{R_{\max}} a_m(r)dr\right]$$

$$T_{\max} = \exp\left[-\int_{R_0}^{R_{\max}} a(r)dr\right]$$ if we know the Optical Depth

$$OD = \int_{R_0}^{R_{\max}} a(r)dr$$

Then we can calculate $T_{max}$ and $V_{max}$

## B4 Signal To Noise Ratio

The SNR of the echo Lidar signal is obtained by the following equation:

$$S/N = \frac{Ips}{\sqrt{2eFB(Ips + Ipb + Id)}}$$

Where Id is the PMT's anode dark current (with typical values of about 1nA), $I_{pb}$ is the anode current due to background radiation signal, $I_{ps}$ is the anode average output current of the echo Lidar signal, B is the bandwidth of the system, e is the electric charge and F is the noise component (noise figure) produced in the multiplication process in the PMT. F indicates how much the signal to noise ratio will degrade between the input and the output of the PMT.

Usually $F = \dfrac{\delta}{\delta + 1}$ where δ is the secondary emission ratio and is a function of the interstate voltage of dynodes. Typical values for δ are between 3 and 7.

The output current at the anode $I_p=\mu*I_c$ where μ is the gain and changes in relation to the supply voltage V to the PMT. Typical values are around $2x10^6$.

$I_c$ is the photocurrent produced at the photocathode of the PMT and is calculated from the following equation.

$I_c = S_c P$ (A),

Where P is the incident radiant flux (W) and $S_c$ is the cathode radiant sensitivity (A/W). Typical values for $S_c$ are around 120 mA/W

The radiation power (W) arising from natural sources (background radiation) accepted by the receiver optics can be expressed in the form:

$$P_b = \chi \mathrm{A}\Omega S_b(\lambda) K_0(\lambda)$$

χ is overall optical system efficiency, A is the area of primary receiver optics responsible for the collection of backscattering light ($m^2$), Ω is its acceptance solid angle, and $K_0(\lambda)$ is termed the filter function of the receiver system.

$$K_0(\lambda) \equiv \int_{\Delta\lambda} \xi(\lambda') d\lambda'$$

The $S_b$ represents the spectral radiance of the sky background ($Wm^{-2}sr^{-1}nm^{-1}$).

At wavelengths within the visible range, a typical value for $S_b$ is about 0.1 (Pratt, 1969) at sea level for a zenith angle of 45 degrees, with excellent visibility (for moonlight its value is approximately $1x10^{-12}$). For 355nm it is about $1x10^{-4}$.

The power of the echo Lidar signal corresponding to a distance R for a Raman channel can be written as:

$$P_{N2}(R) = \frac{\chi E_0 AQ(R) c N_{N2} \times \left.\dfrac{d\sigma}{d\Omega}\right|_{\mathrm{N2}}}{R^2} \exp\left[-\int_{R_0}^{R} \left[a_{aer}(x,\lambda_L) + a_{mol}(x,\lambda_L) + a_{aer}(x,\lambda_{N2}) + a_{mol}(x,\lambda_{N2})\right] dx\right]$$

$E_0$ is the energy of a single laser pulse (J), c is the velocity of light (m/s). The term Q(R) is the laser beam receiver field of view overlap function, describing the range-dependent measurement geometry, and can take values from 0 to 1. N is the atmospheric number density of Nitrogen (for simulation we use the USSA76 standard atmospheric model) and dσ/dΩ is the Raman backscatter cross section (1000 times smaller than elastic backscatter cross section).

$\alpha_{mol}(R,\lambda)$ is the extinction coefficient for laser and Raman wavelengths and is estimated from USS76 standard atmospheric models.

Extinction at the Raman wavelength is estimated from the following equation.

$$a_{aer}(R,\lambda_{\mathrm{N}_2}) = \frac{a_{aer}(R,\lambda_L)}{\left(\dfrac{\lambda_{\mathrm{N}_2}}{\lambda_L}\right)^{\gamma}}$$

For the simulation the following equation was used for calculating the backscatter coefficient:

$$\beta_{aer} = \left\{2.47\times10^{-6}\exp\left(\frac{-R}{2000}\right) + 5.13\times10^{-9}\exp\left(-\frac{\left(\dfrac{R}{1000}-20\right)^2}{36}\right)\right\}\left(\frac{532}{\lambda}\right)$$

*(Horst Jager, et. al., Appl. Opt., 30(1), pp. 127-136, 1991)*

In the next step we introduced the particle extinction to backscatter ratio (Lidar Ratio):

$$L_{aer}(\lambda,R) = \frac{\alpha_{aer}(\lambda,R)}{\beta_{aer}(\lambda,R)}$$

in analogy to molecular Lidar ratio

$$L_{mol}(\lambda) = \frac{\alpha_{mol}(\lambda)}{\beta_{mol}(\lambda)} = \frac{8\pi}{3}sr$$

In contrast to the molecular Lidar ratio, the particle Lidar ratio in general is range dependent because it depends on the size distribution, shape and chemical composition of the particles. For our simulation we used a constant value of 35 sr.

For horizontal measurement simulation we used the following equation:

$$a_{aer} = 2\times10^{-4}\left(\frac{532}{\lambda}\right)$$ for λ=355 nm

This gives a value of:

$\alpha_{aer}=3\mathrm{x}10^{-4}$ (1/m) and $\beta_{aer}=8.5\mathrm{x}10^{-6}$ [1/(m*sr)]

## B5 Calibration Methods

A Lidar system can be divided into two main functional units: the opto-mechanical transmitter-receiver unit, and the electronic data acquisition unit, each of which needs special tools for testing. The main problem of the transmitter-receiver unit is the a priori unknown range-dependent transmission, which enters as a factor into the Lidar equation. Usually only the incomplete overlap between the fields of view of the transmitter and the receiver is considered by the so-called overlap function, but several other opto-mechanical features potentially have an influence, e.g. the incident angle dependence of the transmission of optical coatings of beam splitters and interference filters, cropping of the light beam by mechanical apertures, and the spatial inhomogeneity of the sensitivity of the light detectors.

**Methods that Raymetrics follows to calibrate and test its instruments:**

**Rayleigh Fit / Matching Method**

The transmitter-receiver overlap has its main impact in the near range of the signal, but if the transmitter is not well aligned, the far range of the signal might also be affected. A well-known check for the latter problem is a fit of the far range Lidar signal (assuming clear air in the upper troposphere) to the calculated clear air Rayleigh signal, the so called 'Rayleigh fit' or 'matching method'. Raymetrics provides software tools for easy Rayleigh fit calibration. This calibration procedure can be done in the field very easily and takes less than one minute.

**Telecover Test**

Before the shipment of any of our Lidar systems, extensive performance tests and calibration procedures are performed. One of the tools that Raymetrics uses for checking Lidar instrumentation is the newly developed 'Telecover Test', which is strongly suggested by EARLINET.

Raymetrics in addition provides all of the hardware and software required for such tests with all of our Lidar systems.

**Electronic Data Acquisition**

Light measurement is done in two ways in Lidar systems: in analogue mode, measuring the electron current from a detector after sufficient amplification with preamplifiers, and/or by means of counting amplified pulses of individual photons (photon counting method). Raymetrics uses special pulse generator techniques to calibrate and adjust analogue and photon counting measurements. It is well known, especially in analogue detection mode, that the main problem is various signals inducing signal distortions. If these distortions are neglected, errors of the Lidar signal inversion on the order of magnitude of 100% can result, although the distortion might be very small compared to the maximum signal. The Lidar signal should only be used over ranges where these errors are acceptable. This can be tested with a specially designed pulse generator.

**Calibrating the 'Ranging'**

In Lidar technologies two errors commonly occur if special attention is not paid:

There is always a delay between the emitted pulse and the data acquisition process, especially for analogue mode due to delays related to the pre-amplification process. But this is true as well in Photon Counting mode, although the phenomenon is not so pronounced. These delays reduce the accuracy of ranging of a Lidar.

Raymetrics uses special optical triggering that eliminates any delay in photon counting mode. In addition we use a near range target with a defined distance to the Lidar that produces a signal peak for Zero-bin calibration in analogue and photon counting modes. If such a target is not available we use a special procedure with an optical fibre to calibrate the 'ranging' of our systems.

**Calibration Method for Depolarization Lidar**

For calibration of the linear depolarization channels there are several methods, such as:

1. Rayleigh method (0$^o$)
2. 45$^o$ method
3. +/- 45$^o$ method
4. Multi-rotation-angle fit method
5. Three signal method
6. Unpolarized light source

**1) Rayleigh method (0$^o$)**

This method is based on knowledge of the molecular linear depolarization ratio in an aerosol-free calibration range. However, since we can never be sure that the aerosol free region that we have assumed really is free, this method introduces many errors. It has been proved that this can give errors up to 260%. In addition this method cannot provide a range dependent calibration factor.

**2) 45$^o$ method**

With this method a 45$^o$ angle is produced between the laser polarization plane and the PBC. Rotation can be achieved mechanically, by using a half-wave plate or by the rotating of a polarizing sheet filter. This method is fast and has relatively few errors. However it gives large errors when there is a small angle difference between the laser polarization plane and the PBC at the default position (0$^o$).

**3) +/- 45$^o$ method**

With this method the polarization plane of the PBC is turned +45 and -45 degrees from the default position (0$^o$). This method is fast accurate and it is 100 times less sensitive to errors produced by a small angle $\gamma$ from the default position (0$^o$) compared to the 45$^o$ method.

**4) Multi-rotation-angle fit method**

With this method the PBC is rotated to several angles. It is a good method but it is time consuming and sensitive to atmospheric changes during the calibration procedure. In addition it exhibits low accuracy of the calibration constant.

**5) Three signal method (detection of the total, cross and parallel signals separately)**

With this method the Lidar detects a fraction of incoming light and the rest is beam-split by a Polarizing Beam Splitter. However such a set-up increases the cost of the instrument significantly (three deferred detected channels instead of two) and depends on large differences in $\delta(R)$.

**6) Unpolarized light source**

The beam path of rays from an unpolarized light source through the receiver optics is used. This method has many disadvantages and introduces errors.

**Summary of theory for depolarization calibration**

The total backscattering power P(r) is given by the Lidar equation:

$$P(R) = \frac{\chi \mathrm{E}_0 \mathrm{A} Q(R) c \beta(R,\lambda) \mathrm{T}(R,\lambda)}{2R^2}$$

For simplicity, we form the equation in the following way:

$$P(r) = C\frac{\beta(r)\mathrm{T}(r)}{r^2}$$

The backscatter power **before the PBC** can be written as:

$$P(r) = C_{II}\frac{\left(\beta_{\mathrm{II}}^{aer} + \beta_{\mathrm{II}}^{mol}\right)\mathrm{T}(r)}{r^2} + C_{\perp}\frac{\left(\beta_{\perp}^{aer} + \beta_{\perp}^{mol}\right)\mathrm{T}(r)}{r^2}$$

The linear volume depolarization ratio $\delta^v$ is given by:

$$\delta^v(r) = \frac{\beta_{\perp}(r)}{\beta_{\mathrm{II}}(r)} = \frac{P_{\perp}(r)}{P_{\mathrm{II}}(r)}$$

However, the measured signal ratio $\delta^*$ is given by:

$$\delta^*(r) = \frac{P_R(r)}{P_T(r)}$$

Where $P_R$ and $P_T$ are the reflected and transmitted signals from the PBC and are the ones which are recorded.

$$P_R(\phi) = \left[P_p(\phi)R_p + P_s(\phi)R_s\right]V_R \text{ and } P_T(\phi) = \left[P_p(\phi)T_p + P_s(\phi)T_s\right]V_T$$

Where $V_R$ and $V_T$ include the optical transmittances of the receiver and the electronic amplification in each channel.

In addition, the power components with respect to the incident plane of the PCB are:

$$P_s(\phi) = P_{II}\sin^2(\phi) + P_{\perp}\cos^2(\phi) \text{ and } P_p(\phi) = P_{II}\cos^2(\phi) + P_{\perp}\sin^2(\phi)$$

Φ is the angle between the plane of polarization of the laser and the incident plane of the PCB.

Combining the above equations we get:

$$\delta^*(\phi) = V^* \frac{\left[1+\delta^v \tan^2(\phi)\right]R_p + \left[\delta^v + \tan^2(\phi)\right]R_s}{\left[1+\delta^v \tan^2(\phi)\right]T_p + \left[\delta^v + \tan^2(\phi)\right]T_s}$$

Where $V^*=V_R/V_T$ and R, T are the transmittance and reflectance of the PBC.

In order to retrieve the total backscatter power P and $\delta^v$ from the measurements we need to know the $V^*$ which is the calibration constant and we can get it through several methods.

For φ=0 we get:

$$V^* = \frac{T_p + \delta^v T_s}{(R_p + \delta^v R_s)}\delta^*(0^0)$$

If we know $\delta^v$ for some range of the Lidar signal, we can determine V* (for example by using the linear depolarization ratio of air molecules). However a very low amount of strong depolarization aerosols, in the assumed clean range, causes very big errors on $\delta^v$ and thus of V*. So this method cannot be used for reliable data.

Another method is to turn 45 degrees (45-calibration method). φ=45 in that case:

$$V^* = \frac{T_p + T_s}{R_p + R_s}\delta^*(45)$$

As can be seen, the calibration constant does not depend on $\delta^v$. However it is very difficult and practically impossible to measure exactly the angle between the laser and the PBC. An error γ of the order of 1 degree causes a large error in V*.

With the proposed method, we calculate V* from two subsequent measurements at exactly 90 degrees (φ=45+γ and φ=-45+γ) in that case:

$$V^* = \frac{T_p + T_s}{R_p + R_s}\sqrt{\delta^*(45) + \delta^*(-45)}$$

With this method (+/- 45 calibration method) it can be shown that the errors γ compensate each either over a large range of γ.

**Retrieving of the linear depolarization ratio $\delta^v$ and linear aerosol depolarization ratio $\delta^p$**

If we know the calibration constant then:

$$\delta^{\nu}(r)=\frac{P_{\perp}(r)}{P_{\text{II}}(r)}=\frac{P_s(r)}{P_p(r)}=\frac{\frac{\delta^*(r)}{V^*(r)}T_p-R_p}{R_s-\frac{\delta^*(r)}{V^*(r)}T_s}$$

The total echo power is given by:

$P(r)=V^*(r)P_T(r)+P_R(r)$

$$\delta^{aer}=\frac{(1+\delta^m)\delta^{\nu}R-(1+\delta^{\nu})\delta^m}{(1+\delta^m)R-(1+\delta^{\nu})}$$

$\delta^m$ can be determined with high accuracy from radiosonde data (or by using a model).

$$R=\frac{\beta^m+\beta^{aer}}{\beta^m}$$

Where $\beta^{aer}$ is retrieved from the total signal P using the Fernald/Klett inversion with a reference value $\beta^{aer}(r_{ref})$ at a reference range and known range dependent Lidar ratio L(r) (retrieved by an additional measurement with a Raman Channel).

**Theory and the Inversion Problem of Lidar Technique**

The power of the echo Lidar signal corresponding to a distance R can be written as

$$P(R)=\frac{\chi \mathrm{E}_0 \mathrm{A} Q(R) c \beta(R,\lambda) \mathrm{T}(R,\lambda)}{2R^2} \quad \text{eq. 1}$$

$E_0$ is the energy of a single laser pulse (J), c is the velocity of light, m/s. The term Q(R) is the laser beam receiver field of view overlap function, describing the range-dependent measurement geometry and can take values from 0 to 1. The β(R,λ) is the backscatter coefficient (1/(m*sr)) and it stands for the ability of the atmosphere to scatter light backwards. T(R) is the transmission term and describes how much light gets lost on the way from the Lidar to distance R and back.

$$T(R,\lambda)=\exp\left[-2\int_0^R \alpha(R',\lambda)dR'\right]$$

The factor 2 stands for the two-way transmission path.

$\beta(R,\lambda) = \beta_{mol}(R,\lambda)+\beta_{aer}(R,\lambda)$ and $\alpha(R,\lambda) = \alpha_{mol}(R,\lambda)+\alpha_{aer}(R,\lambda)$

$\alpha(R,\lambda)$ is the extinction coefficient.

Here we can rewrite the Lidar equation as

$$P(R) = C_0 \frac{\beta_\pi(R,\lambda)}{R^2} \exp\left[-2\int_0^R a(R,x)dx\right]$$

The factor $C_0$ is the Lidar system constant. One of the limitations of this equation is that includes more than one unknown. Therefore, it is considered to be mathematically ill posed and thus indeterminate. Such an equation cannot be solved without either a priori assumption about atmospheric properties along the Lidar range or the use of independent measurements of the unknown atmospheric parameters. Usually the use of a priori assumptions is the most common method.

Generally, the extinction coefficient. profile is the parameter of primary interest. A potential way to overcome this problem might be to make independent measurements of backscattering by the use of a combined Raman-elastic backscatter Lidar method (This method is used at our Raman Lidar Systems).

In order to extract a $\alpha(R)$ profile the calibration factor $C_0$ must be known and in addition, the relationship between backscatter and total extinction must in some way be established (Raman Lidar) or assumed (Klett solution)

$$P(R) = C_0 T_o^{\,2} \frac{\beta_\pi(R,\lambda)}{R^2} \exp\left[-2\int_{R_0}^R a(R,x)dx\right] \quad \text{eq. 2}$$

Where

$$T_o = \exp\left[-\int_0^{R_0} a(R,x)dx\right]$$

**Methods-Solution for the Inversion of the Lidar Equation and Lidar Calibration**

The simplest method is based on an absolute calibration of the Lidar system using only Co, whilst the other factors in the Lidar equation remain unknown (for example the two way atmospheric transmittance over the incomplete overlap zone). All self-sufficient elastic Lidar signal inversion methods developed to date require the use of one or more a priori assumptions that are chosen according to the particular optical situation. There are three basic inversion methods that Raymetrics uses depending on the Lidar type and the applications:

1. Slope method: This method is used for homogeneous atmospheres. In many of the cases, horizontal homogeneity is a reasonable assumption. With the slope method a mean value of α over the examined range in a homogeneous atmosphere is obtained.
2. The boundary point solution: This requires knowledge of or an a priori estimate of α at some point within the measurement range.
3. The optical depth solution: Here the total optical depth or transmittance over the Lidar measurement range should be known or assumed. In case of a clear and moderately turbid atmosphere the total α (or optical depth) is found be a solar radiometer.

In case of a two component atmosphere (with is the most usual case especially for vertical pointing systems)

The Lidar equation can be written as:

$$P(R) = C_0 T_o^{\,2} \frac{\beta_{aer}(R) + \beta_{mol}(R)}{R^2} \exp\left[ -2 \int_{R_0}^{R} \left[ a_{aer}(x) + a_{mol}(x) \right] dx \right]$$

In that case the backscatter coefficient can be found from the following equation:

$$\beta_{aer}(R) = -\beta_{mol}(R) + \frac{RCS(R) \exp\left\{ 2 \int_{R}^{Rref} \left[ L_{aer}(R) - \frac{8\pi}{3} \right] \beta_{mol}(x) dx \right\}}{C + 2 \int_{R}^{Rref} \left[ L_{aer}(x) RCS(x) \exp\left( \int_{x}^{Rref} \left[ L_{aer}(z) - \frac{8\pi}{3} \right] \beta_{mol}(z) dz \right) \right] dx}$$

This equation is solved iteratively downwards and gives the calibration constant of the instrument

$$C = \frac{RCS(R_{ref})}{\beta_{aer}(R_{ref}) + \beta_{mol}(R_{ref})}$$

Calibration at height $R_{ref}$ gives the system constant C.

**Hardware Solution to the Inversion Problem**

Use of Nitrogen Raman scattering for extinction measurements

Similar to an elastic Lidar, a Raman channel detects the inelastic backscatter Raman shifted radiation. Atmospheric gases like nitrogen and oxygen interact with the emitted radiation via the Raman Scattering process, causing light of longer wavelengths to be scattered. Thus in addition to elastically backscattered signal an extra backscattered wave-shifted component is detected. Because of the small value for the cross-sections of Raman scattering (so the small backscatter coefficient) the number of photons returning to the Lidar is small. **Because the probability of Raman scattering is proportional to $\lambda^{-4}$ the use of short wavelengths increases the magnitude of signal.**

In addition the discrimination of Raman Photons from the background light is a problem. So operating at UV where the background radiation is smaller, it is strongly suggested. Since deep UV is strongly absorbed by Ozone and because the molecular scattering is reduced at longer wavelengths the optimum solution is around 350 nm. However discriminating Raman scattered photons from solar background is still an issue and requiring special measures. If the system is expected to operate during the day, the use of extremely narrow field of view in the receiving optics is required. For biaxial system this is almost impossible since the overlap is getting too high. In addition the system is getting susceptible to misalignments which are not good for an operational Lidar that have to be moved.

$$P_{N2}(R) = C_{N2}\frac{Q(R)N_{N2}\times\left.\frac{d\sigma}{d\Omega}\right|_{\mathrm{N2}}}{R^2}\exp\left[-2\int_{R_0}^{R}\left[a_{aer}(x,\lambda_L)+a_{mol}(x,\lambda_L)+a_{aer}(x,\lambda_{N2})+a_{mol}(x,\lambda_{N2})\right]dx\right]$$

Finally we can get

$$a_{aer}(R,\lambda_L) = \frac{\frac{d}{dR}\left[\ln\left(\frac{N_{N2}}{RCS_{N2}(R)}\right)\right]-a_{mol}(x,\lambda_L)-a_{mol}(x,\lambda_{N2})}{1+\left(\frac{\lambda_L}{\lambda_{N2}}\right)^{\gamma}}$$

$\alpha_{mol}$ are well known and can be found from Rayleigh scattering theory. The dominator corrects for the small difference in particulate attenuation between the laser and Raman scattered wavelengths. In horizontal direction for visibility from 3 to 20 km it is close to 1.3.

Finally when the Raman technique is used, the aerosol backscatter coefficient can be determined by reference to the signal at some height. The conventional assumption is made of the existence of an aerosol free area somewhere within Lidar measurements range $\beta_{aer}(R_{ref})=0$.

$$\beta_{aer}(R,\lambda_L) = -\beta_{mol}(R,\lambda_L)+\left[\beta_{aer}(R_{ref},\lambda_L)+\beta_{mol}(R_{ref},\lambda_L)\right]\frac{P(R_{ref},\lambda_{\mathrm{N2}})P(R,\lambda_L)N_{N2}(R)}{P(R_{ref},\lambda_L)P(R,\lambda_{N2})N_{N2}(R_{ref})}\exp\left[-\int_{R}^{R_{ref}}\left[a_{total}(x,\lambda_L)-a_{total}(x,\lambda_{N2})\right]dx\right]$$

Usually at $R_{ref}$ $\beta_{aer}(R_{ref},\lambda_L)+\beta_{mol}(R_{ref},\lambda_L)\cong\beta_{mol}(R_{ref},\lambda_L)$

# B6 Polarization Lidar Basics

## B6.1 Introduction

### *B6.1.1 Aerosols' Properties And Depolarization*

***Shape, size distribution and composition of aerosol particles influence their scattering characteristics*** and thus the radiative impact. ***The polarization Lidar technique*** (Sassen, 1991; Sassen, 2005) is a well-established method to distinguish ice clouds from water clouds and to identify layers with ice crystals in mixed–phase clouds. Freudenthaler et al. (1996) applied a scanning polarization Lidar to study the evolution of contrails. The technique has been used to identify the type of polar stratospheric clouds (Sassen, 2005) and volcanic ash in the troposphere and stratosphere (Sassen et al., 2007). The polarization Lidar is also well suited for aerosol profiling and allows us to unambiguously discriminate desert dust from other aerosols. Based on model calculations, it has been demonstrated that the spectral dependence of the dust linear depolarization ratio is sensitive to the size distribution of the nonspherical scatterers. Thus, observations of the linear depolarization ratio at several wavelengths may be used in retrieval schemes (Dubovik et al., 2006) to improve the estimation of the microphysical properties of dust from optical measurements (Weinger et al., 2008). First dual-wavelength aerosol polarization Lidar measurements were presented by Sugimoto et al. (2002).

### *B6.1.2 Overview of Lidar Linear Depolarization*

Lidar often uses polarized laser beams for sounding the atmosphere, and depolarization measurements have long been used in lidar investigation. ***The main application of depolarization measurements is the discrimination and the extent of liquid and solid phase clouds and aerosols***. Lidar signal is the superposition of scattering that is due to molecules and scattering that is due to particles that are greater than the typical dimensions of atmospheric molecules. Molecular backscattering follows Rayleigh theory, in which case changes in polarization are due only to the polarizability of molecules: The contribution to the orthogonal polarization is ;1%.2 Scattering processes on aerosols must be treated by means of Mie theory if particles are spherical or with Stokes matrix if particles are non-spherical. From Mie theory the polarization of incident light is conserved after backscattering, whereas backscattering on solid particles can change the polarization direction. If a laser beam is emitted with a definite polarization, the presence of polarized light in the perpendicular component denotes the presence of backscattering from nonspherical particles. Hence polarized backscattering, parallel to the laser polarization is considered, and depolarization is used to refer to the perpendicular component of polarized backscattered light. ***Three points*** must be taken into account during treatment with depolarization studies: 1. multiple scattering processes induce depolarized backscattering even in the presence of spherical scatterers, 2. particles with small dimensions compared with the lidar wavelength do not show depolarization even if they are not spherical and 3. emitted light polarization must remain stable throughout the measurement.

### B6.1.3 Polarization Method Applied to Modern Lidar Systems: Theory and Methodology

Measurements of the ***linear depolarization ratio δ*** with lidars are often performed with the aim to just discern between the dry, the liquid and the ice phase of aerosols and clouds in the profiles of one lidar system, which requires only a relative measure of $\delta$ with a low accuracy of the absolute values. The total backscattered power $P(r)$ with their dependence on the distance $r$ from the lidar is described by the lidar equation

$$P = \frac{\eta\beta(r)\tau^2(r)}{r^2} \qquad (1)$$

where $\eta$ is the system constant, $\beta$ the backscatter coefficient and the factor $\tau^2$ accounts for the atmospheric transmittance on the way from the lidar to the scattering volume, and back. For the determination of $\delta$ the lidars used in this study measure the atmospheric backscatter signals in two receiver channels, parallel- and cross-polarized with respect to the plane of the linear polarized output of the laser beam. The two polarization components are separated in the receiver by means of ***polarizing beam splitter cubes (PBC).*** But this separation is not perfect. Furthermore the polarizing beam splitter might be misaligned with respect to the plane of polarization of the emitted laser beam, and additionally, a rotation of the polarization plane is used for the relative calibration of the two receiver channels. Therefore, we show the necessary equations of the angle $\phi$ between the plane of polarization of the laser and the incident plane of the polarizing beam splitter cube, according to Fig. B2.

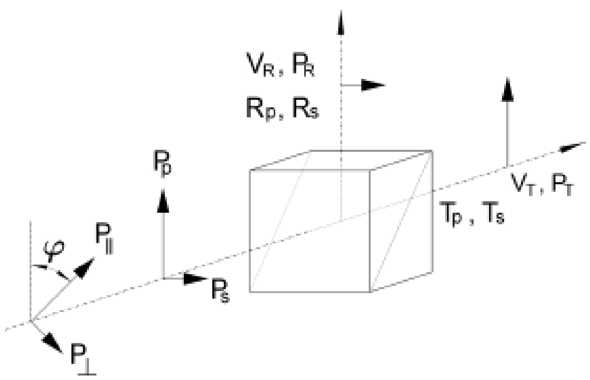


***Fig. B2*. Signal power components in a receiver of a depolarization lidar with a polarizing beam splitter cube with reflectivity $R_p$ and $R_s$ and transmittances $T_p$ and $T_s$ for linearly polarized light parallel (p) and perpendicular (s) to the incident plane of the polarizing beam splitter. $P_R$ and $P_T$ are the measured quantities in the reflected and transmitted path, respectively, and $V_R$ and $V_T$ are the corresponding amplification factors including the optical transmittances.**

The backscatter powers before the PBC are (skipping the range dependence in the following for convenience)

$$P_{\perp} = \frac{\eta_{\perp}\left(\beta_{\perp}^{p} + \beta_{\perp}^{m}\right)\tau^{2}}{r^{2}},$$
$$P_{\parallel} = \frac{\eta_{\parallel}\left(\beta_{\parallel}^{p} + \beta_{\parallel}^{m}\right)\tau^{2}}{r^{2}}, \quad (2)$$

with the system constants $\eta\parallel$ and $\eta\perp$ including here only the laser power and the telescope aperture, assuming negligible diattenuation of the optics before the PBC, for example, a telescope or dichroic beam splitters. The backscatter coefficient $\beta$ is split up in the parallel- ($\beta$_) and cross-polarized ($\beta\perp$) components of the backscatter from particles ($\beta^p$) and from molecules ($\beta^m$). The total backscatter power $P$ and the total backscatter coefficient $\beta$ are the sum of both polarized components:

$$P = P_{\parallel} + P_{\perp}. \quad (3)$$

The ratio of the total backscatter coefficient to the molecular component is called the backscatter ratio **R**

**R** = *βm* + *βp βm* , (4)

and the ratio of the total cross- to the total parallel-polarized backscatter coefficient is called the linear volume depolarization ratio $\delta^v$:

$$\delta^{v} = \frac{\beta_{\perp}}{\beta_{\parallel}} = \frac{P_{\perp}}{P_{\parallel}}. \quad (5)$$

The power components with respect to the incident plane of the PBC are

$$P_s(\varphi) = P_{\parallel}\sin^2(\varphi) + P_{\perp}\cos^2(\varphi),$$
$$P_p(\varphi) = P_{\parallel}\cos^2(\varphi) + P_{\perp}\sin^2(\varphi). \quad (6)$$

The subscripts p and s denote the planes parallel and perpendicular to the incident plane of the PBC (see Fig. 1), respectively, and $\phi$ is the angle between the plane of polarization of the laser and the incident plane of the PBC. Depending on this angle, the cross polarized signal $P\perp$ can be measured in the reflected (for $\phi = 0^\circ$) or in the transmitted path ($\phi = 90^\circ$). Hence, we denote the power measured in the reflected and transmitted paths with the subscripts R and T, respectively. Behind the PBC the total reflected ($P_R$) and transmitted ($P_T$) power components are

$$P_R(\varphi) = [P_p(\varphi)R_p + P_s(\varphi)R_s]V_R,$$
$$P_T(\varphi) = [P_p(\varphi)T_p + P_s(\varphi)T_s]V_T. \qquad (7)$$

The amplification factors $V_R$ and $V_T$ include the optical transmittances of the receiver and the electronic amplification in each channel. $P$R and $P$T are the quantities we actually record with the data acquisition. For the following it is convenient to introduce a relative amplification factor $V*$ and the measured signal ratio $\delta*$

$$\delta^*(\varphi) = \frac{P_R(\varphi)}{P_T(\varphi)}, \quad V^* = \frac{V_R}{V_T}. \qquad (8)$$

With eqs. (6)–(8), we achieve

$$\delta^*(\varphi) = V^* \frac{[1 + \delta^v \tan^2(\varphi)]R_p + [\tan^2(\varphi) + \delta^v]R_s}{[1 + \delta^v \tan^2(\varphi)]T_p + [\tan^2(\varphi) + \delta^v]T_s}. \qquad (9)$$

### B6.1.4 Retrieval of the Linear Volume Depolarization Ratio $\delta^v$

Once $V*$ is known, we get $\delta^v$ with eqs. (5) and (6), for a regular measurements at $\phi = 0^\circ$:

$$\delta^v = \frac{P_\perp}{P_\parallel} = \frac{P_s}{P_p}, \quad \varphi = 0^\circ. \qquad (10)$$

As for commercial PBCs, $R$s is usually much closer to 1 than $T$p, the noise and error caused by the cross-talk from the strong parallel-polarized signal to the weaker cross-polarized signal are reduced if the parallel polarized signal is detected in the reflected s-branch of the PBC. For this setup $\phi = 90^\circ$, and we get

$$\delta^v = \frac{P_\perp}{P_\parallel} = \frac{P_p}{P_s}, \quad \varphi = 90^\circ. \qquad (11)$$

From eqs. (5)–(8) follows

$$\frac{P_s}{P_p} = \frac{\frac{\delta^*}{V^*}T_p - R_p}{R_s - \frac{\delta^*}{V^*}T_s} \qquad (12)$$

And

$$P = P_p + P_s = \frac{V^* (R_s - R_p) P_T + (T_p - T_s) P_R}{V_R (T_p R_s - R_p T_s)}. \quad (13)$$

The knowledge of $V_R$ is not necessary, as we only need a relative signal for the lidar signal inversion with the Fernald/Klett retrieval (Klett, 1985; Fernald, 1984), and thus we can set it to $V$R = 1. In case the parameters of the polarizing beam splitter cube are

$T$s = 1 − $R$s, $R$p = 1 − $T$p, (14)

### B6.1.5 Retrieval of the Linear Particle Depolarization Ratio $\delta^P$

The $\delta^p$ can be calculated from eqs. (2)–(5) using

$$\delta^p = \frac{\beta^p_\perp}{\beta^p_\parallel} = \frac{(1+\delta^m)\,\delta^v R - (1+\delta^v)\delta^m}{(1+\delta^m)R - (1+\delta^v)} \quad (15)$$

with the height in dependent linear depolarization ratio of air molecules:

$$\delta^p = \frac{\beta^p_\perp}{\beta^p_\parallel} = \frac{(1+\delta^m)\,\delta^v R - (1+\delta^v)\delta^m}{(1+\delta^m)R - (1+\delta^v)} \quad (16)$$

which can be determined with high accuracy (Behrendt and Nakamura, 2002). The backscatter ratio **R** can be retrieved from the total signal $P$ using, for example, the Fernald/Klett inversion with a reference value $\beta$p($r$0) at a reference range $r$0 and known range-dependent lidar ratios $S$

$$S = \frac{\beta^P}{\alpha^P}, \quad (17)$$

where $\alpha^p$ is the particle extinction coefficient. $S(r)$ must be retrieved by an additional measurement, for example, with a Raman channel. The values of $\delta^v$ and R are subject to systematic and statistical (noise) errors.

## B6.2 Experiments and Results

### B6.2.1 Results and Comparison

During Saharan Mineral Dust Experiment (SAMUM), it was attempted to measure a possible wavelength dependence of the dust particle linear depolarization ratio $\delta^p$, with four different lidar systems at four wavelengths as inputs for model calculations of $\delta^p$ regarding the particles shapes and size distribution. Thus, the uncertainty of the absolute values must be known and should be small compared with the expected natural variance. The paper presents linear particle depolarization ratio $\delta^p$ measurements at four wavelengths. However, MULIS (532 nm) and the airborne DLR-HSRL (532 and 1064 nm) provided the most accurate measurements of the linear depolarization ratio. These lidar measurements represent the backbone of the entire SAMUM polarization lidar activity. First, we compare the height resolved profiles of $\delta^p$ of all lidars at four dates with coincident measurements in Fig. B3. The lidar ratios *S* used for the depolarization retrieval of MULIS at 532 nm were adopted from the coincident DLR-HSRL measurements with errors in the range of ±5 sr. For non-coincident measurements *S* is assumed to be 50 sr ± 10 sr.

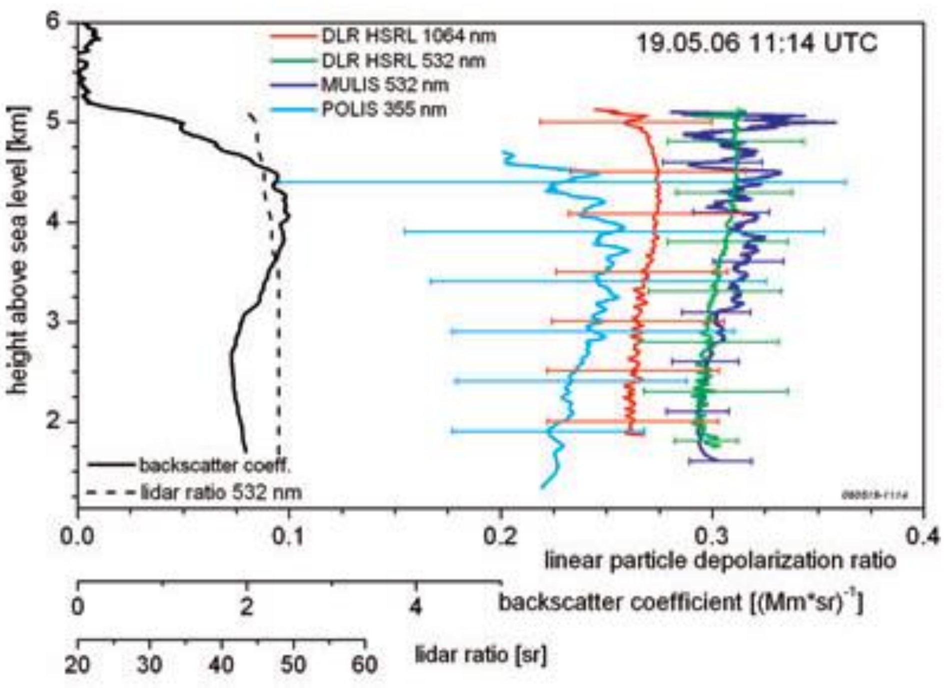



***Fig. B3. Particle linear depolarization ratio profiles on 19 June 2006 at several wavelengths. The error bars indicate the systematic uncertainties***

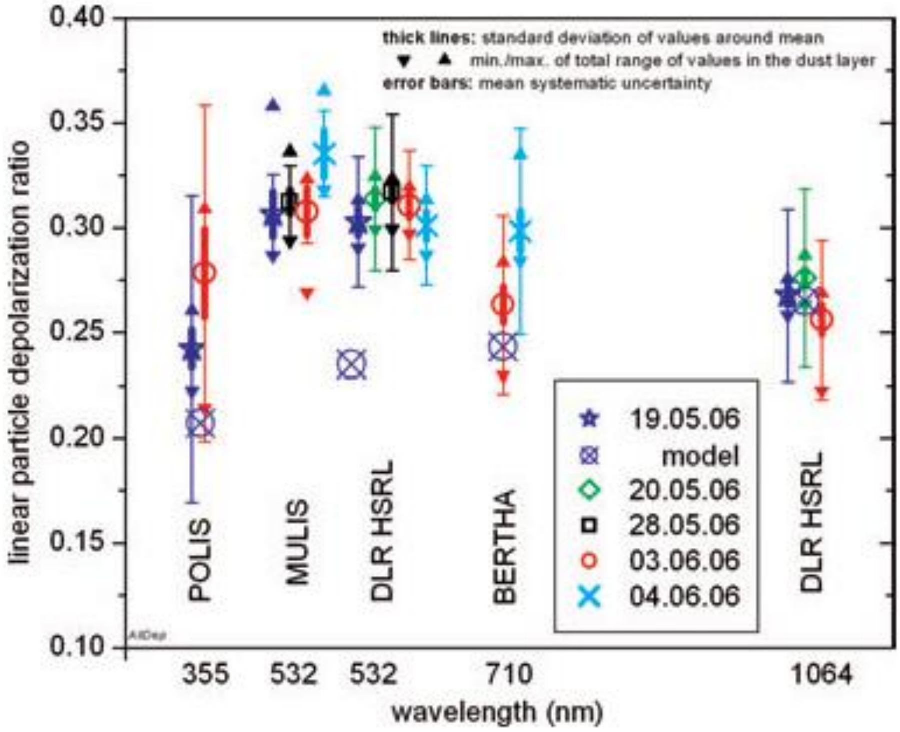



***Fig. B4. Mean linear depolarization ratio of particles in the dust layer over the wavelength of the four lidar systems at four different dates during SAMUM 2006 and results of model calculations for the reference case 19 May 2006 (Wiegner et al., 2008).***

The linear depolarization ratio was measured with MULIS continuously during SAMUM. Retrievals of the linear particle depolarization ratio δp at selected dates, together with error bars and statistical information are displayed in Fig. B5 and listed in Table 2, together with the measurements from the other lidars

from Fig. B4. The full ranges of the δp values are often asymmetric to the mean towards smaller δp. These smaller values mostly stem from the dust layer top caused by temporal averaging of the lidar measurements with changing dust layer top height.

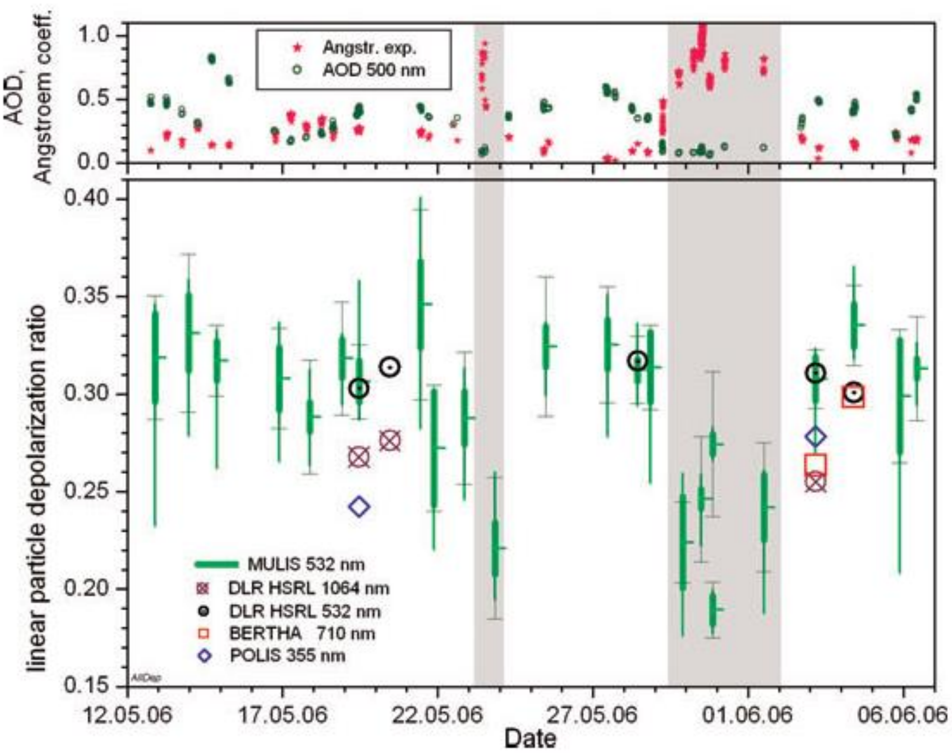



***Fig. B5. Mean linear particle depolarization ratio δp in the dust layer over Quarzazate during the SAMUM 2006 period for selected dates (lower plot) and aerosol optical thickness at 500 nm and Angstrom exponent (440–870 nm) from SSARA sun photometer at Quarzazate (upper plot).***

The AOD at 500 nm and the AE (440–870 nm) derived from the SSARA measurements temporally closest to the MULIS measurements are displayed on top of Fig. B5. For night time, when no sun photometer data were available, the AE values were interpolated and the AE errors show the slope. Comparing the time-series in Fig. B5 we see low δp and high AE in the shaded time periods, and high δp and low AE else, whereas there is no evidence for a correlation between δp and AOD, as expected.

More details and information about this field campaign can be found at [11].

# 1. REFERENCES

[1] Sassen, K. 2005. Polarization in lidar. In: *Lidar* (ed. C. Weitkamp). Springer, New York, 19–42.

[2] Sassen, K. 1991. 'The polarization lidar technique for cloud research: a review and current assessments. *Bull. Am. Meteorol. Soc.* **72**, 1848– 1866.

[3] Freudenthaler V. et al, 'Depolarization ratio profiling at several wavelengths in pure Saharan dust during SAMUM 2006', *Tellus* (2009), 61B, 165–179.

[4] Cairo F., Donfrancesco G. Di, Adriani A., Lucio Pulvirenti, and F. Fierli, Comparison of various linear depolarization parameters measured by lidar, *APPLIED OPTICS,* 20 July 1999 y Vol. 38, No. 21, pp. 4425-4432.

[5] Sassen, K., Zhu, J., Webley, P., Dean, K. and Cobb, P. 2007. Volcanic ash plume identification using polarization lidar: Augustine eruption, Alaska. *Geophys. Res. Lett.* **34**, doi:10.1029/2006GL027237.

[6] Freudenthaler, V., Homburg, F. and Jager, H. 1996. Optical parameters of contrails from lidar measurements: linear depolarization. *Geophys. Res. Lett.* **23**, 3715–3718.

[7] Dubovik, O., Sinyuk, A., Lapyonok, T., Holben, B. N., Mishchenko, M. and co-authors. 2006. Application of spheroid models to account for aerosol particle nonsphericity in remote sensing of desert dust. *J. Geophys. Res.* **111**, doi:10.1029/2005JD006619.

[8] Wiegner, M., Gasteiger, J., Candler, K., Weinzierl, B., Rasp, K. and co-authors. 2008. Numerical simulations of optical properties of Saharan dust aerosols with special emphasis on the linear depolarization ratio. *Tellus* **61B**, doi:10.1111/j.1600-0889.2008.00381.x.

[9] R. Agishev, B. Gross, F. Moshary, A. Gilerson, **'Development of a SNR parameterization scheme for general lidar assessment,'** *Appl. Phys.* B 00, 1–12, 2005.

[10] QIU Zong-jia, CHEN Si-ying*, ZHANG Yin-chao, WANG Yu-zhao, NI Guo-qiang, '**Weak signal detection system and noise analysis for aerosol detection Lidar,'** *International Symposium on Photoelectronic Detection and Imaging 2009: Laser Sensing and Imaging,* SPIE 2009.

[11] R.M. Measures, *Laser Remote Sensing: Fundamentals and Applications,* Wiley, New York, 1994.

[12] Hamamatsu Photonics, *Photomultiplier Tubes*, Technical Manual.

**Summary of equations for backscatter coefficient. calculation**

**Invert Klett Technique (Far – end solution)**

$$\beta(r)=\frac{RCS(r)*\exp\left(2*(LR-LR_{mol})*\int_{r}^{r_{ref}}\beta_{mol}(r')dr'\right)}{\dfrac{RCS(r_{ref})}{C*\beta_{mol}(r_{ref})}+2*LR*\int_{r}^{r_{ref}}RCS(r')*\exp\left(2*(LR-LR_{mol})*\int_{r'}^{r_{ref}}\beta_{mol}(r'')dr''\right)r'}$$

$$\beta(r)=\beta_{mol}(r)+\beta_p(r)$$

Where

p is for particles (aerosols) and mol for molecular (Rayleigh)

$LR_{mol}(r)=\dfrac{a_{mol}(r)}{\beta_{mol}(r)}=\dfrac{8\pi}{3}$ , $LR(r)=\dfrac{a_p(r)}{\beta_p(r)}=const=LR$

$RCS(r)=P_c(r)*r^2$ This is the Range Corrected Signal.

$P_c(r)$ is the background corrected lidar signal.

$C=\dfrac{\beta_p(r_{ref})+\beta_{mol}(r_{ref})}{\beta_{mol}(r_{ref})}$ Usually at $r_{ref}$ we assume that $\beta_p(r_{ref})=0$ so C=1.

In any other case you can try different values for C.

**How you can calculate the** $\beta_{mol}(r)$

$$\alpha_{mol}(r) = \frac{8\pi^3}{3} \cdot \frac{\left(m_{air}{}^2 - 1\right)^2}{\lambda^4 N_S{}^2} \cdot \frac{6+3\delta}{6-7\delta} \cdot N_S(r) \cdot \frac{T_0}{p_0} \cdot \frac{p(r)}{T(r)}$$

$$\beta_{mol}(r) = \frac{\alpha_{mol}(r)}{LR_{mol}} = \frac{3}{8\pi} \cdot \alpha_{mol}(r)$$

$T_0$ = 288.15 K

$p_0$ = 1013 hPa

$$m_{air}{}^2 - 1 = \left| \begin{array}{l} 5.7148 \cdot 10^{-4} \rightarrow 355 \\ 5.5647 \cdot 10^{-4} \rightarrow 532 \\ 5.48 \cdot 10^{-4} \rightarrow 1064 \end{array} \right.$$

$$\delta = \left| \begin{array}{l} 0.0301 \rightarrow 355 \\ 0.0284 \rightarrow 532 \\ 0.0273 \rightarrow 1064 \end{array} \right.$$

$$N_S(r) = N_{S0} \cdot \frac{p_g}{T_g} \cdot \frac{T_0}{p_0} \cdot \exp\left(-\frac{r}{10200}\right)$$

$N_{S0}$ = 2.547 $10^{25}$ molecule/$m^3$

in troposfera (0 → 12000 m):

$T(r) = T_g - \gamma \cdot r$ γ= 0.0065 K/km

$$p(r) = p_g \cdot \left[1 - \frac{T(r)}{T_g}\right]^{\frac{M \cdot g}{\gamma \cdot R}}$$

unde: M = 0.0289644 kg/mol

g = 9.81 m/s$^2$

R = 8.31432 J/K

Tropopause (12000 → 15000 m)

$$T(r) = T(r = r_{troposhere} = const)$$

$$p(r) = p(r = r_{troposhere}) \cdot \exp\left\{-\frac{M \cdot g}{T(r = r_{troposhere}) \cdot R} \cdot (r - r_{troposhere})\right\}$$