SolPol installation and operation manual

Release 0+unknown

Lilly Daskalopoulou

Sep 10, 2023

CONTENTS:

– your gateway to unraveling sunlight's enigmatic secrets !

As a state-of-the-art Solar Polarimeter, SolPol opens a window to the captivating realm of light polarization, offering a unique perspective on our nearest star.

Delve into the fundamental principles of polarization, master the art of precision instrument installation, and embark on an illuminating journey through the solar cosmos.

Whether you're an intrepid researcher, a curious mind, or an aspiring solar enthusiast, this manual will guide you through every facet of SolPol's operation, installation, and the mesmerizing phenomena it unveils. As you navigate through these pages, you'll uncover the essence of SolPol's capabilities, learn to wield its technological prowess, and decode the language of polarization to decipher the Sun's hidden narratives.

Step into the realm of SolPol and may your journey be as illuminating as the light itself.

CHAPTER

ONE

INTRODUCTION TO SOLPOL

Incoming solar radiation is considered unpolarized before it enters the Earth's atmosphere.

Throughout its propagation in the atmosphere polarization changes, through the absorption and scattering interactions with various atmospheric components including aerosol particles, water droplets,ice crystals and molecules. The transmitted (direct) sunlight is always unpolarised, except when it propagates through oriented particles in the atmosphere.

Interpreting linear polarization measurements in the direct direction, i.e. measurements taken when the observer looks directly towards the illuminating object, can be challenging due to the overwhelming intensity of light and secondary sources of linear polarization in the observational line-of-sight.

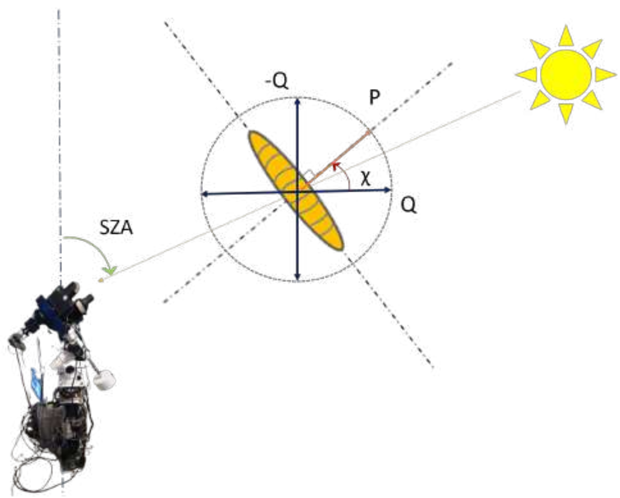
1.1 Brief Overview

SolPol (**Sol**ar **Pol**arimeter) is an experimental ground-based solar polarimeter used for direct sunlight polarization measurements. It operates both under laboratory and field conditions depending on the application at hand and provides near real-time observations of the complete Stokes vector, *[I,Q,U,V]*.

The instrument was initially developed at the University of Hertfordshire (UH) and was used both in-lab and mounted on an astronomical telescope, so as to acquire both linear and circular polarization signatures.

It was, after that, kindly conferred to the National Observatory of Athens (NOA) within the framework of the D-TECT project and operated on-demand from the PANGEA (PANhellenic GEophysical observatory of Antikythera) station.

The instrument's robust design allows for measurements under diverse environments, while its tracking capabilities opt for continuous monitoring of the sunlight polarization state.



SolPol measures:

i. the **Total Intensity** (TI) of the incoming light, expressed by the I Stokes parameter

ii. the **Linear Polarization** (LP), expressed by the Q and U Stokes parameters,

and

ii. the **Circular Polarization** (CP), expressed by the V Stokes parameter,

from the solar disk and as light tarvels through the entire atmospheric columm.

Depending on its limiting field-of-view aperture and the choice of mounting element (to be continued).

1.2 Importance of Applications

CHAPTER

TWO

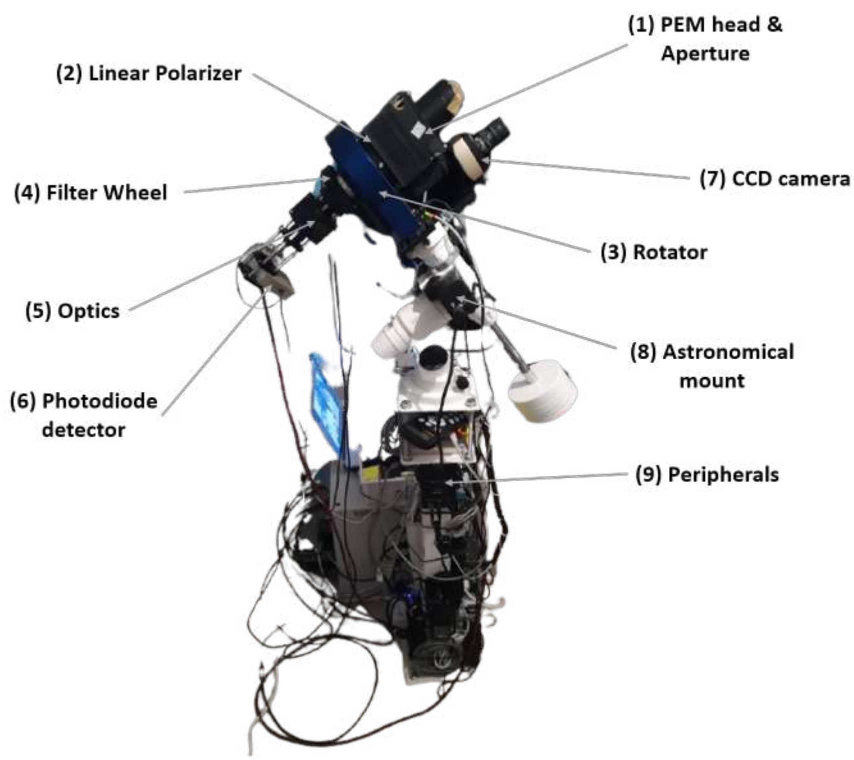
INSTRUMENT OVERVIEW

2.1 Design

The design of SolPol is quite robust and follows that of its astronomical counterpart and predecessor, PlanetPol (Bailey et al., 2008; Hough et al., 2006).

The entire assembly can be rotated about its optical axis by **45 degrees** for the complete Stokes vector measurement and so that biases can be removed.

SolPol measures the polarization fractions of **linear polarization** - expressed by the *Q* and *U* Stokes parameters - and **circular polarization** - expressed by the V Stokes parameter - from the whole solar disk and the entirety of the atmospheric column, depending on its limiting field-of-view aperture and the choice of mounting telescope.



The polarimeter assembly includes:

(1) a **P**hoto **E**lastic **M**odulator (**PEM**) head with a field of view limiting aperture,

(2) a **L**inear **P**olarizer (**LP**),

(3) a field camera **Rotator**,

(4) a filter wheel with several **N**eutral **D**ensity (**ND**) filters,

(5) an imaging Galilean **telescope**,

(6) a large area photodiode **detector**,

(7) a **CCD** camera for effective Sun tracking,

(8) an **EQ3** equatorial astronomical mount with SynScan,

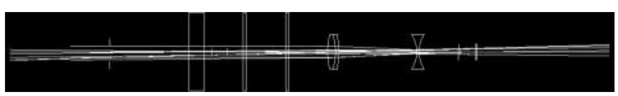
(9) **Peripherals** for data acquisition →

- a low-noise **amplifier**
- an **oscilloscope**
- a servo **stepper motor** controller
- an **A**nalog-to-**D**igital **C**onverter (ADC)
- the PEM **head controller**, and
- a PC-based **control unit**

Tip: Familiarize

SolPol is a complex instrument to the untrained eye. Take some time to visually recognize the instrument components !

There are **no optical elements** before the PEM, followed by the linear polarizer (see optical path pic). The ND filters establish the signal levels at the 1 cm silicon diode detector, which uses a transimpedance amplifier to generate the signal voltage.



Light beams meet from left to right: 5.5 mm aperture stop, PEM, linear polarizer, neutral density filters, Lens 1 & 2 Galilean telescope, 3.5mm field stop, photodiode detector.

The filter wheel contains six filters: 3 x **RGB broad band** filters with measured transmission curves - 3 x **40 nm narrow band** filters at 400, 550, and 700 nm centre wavelengths.

Note: Spectral range

SolPol currently operates **only** at 550 nm.

Then, the 12-bit ADC records the diode signal and the lock-in amplifier records the first and second harmonic modulation signals, which are modulated by the PEM. Polarizer position and instrument rotation are controlled from a LabView virtual instrument program, which also controls data recording.

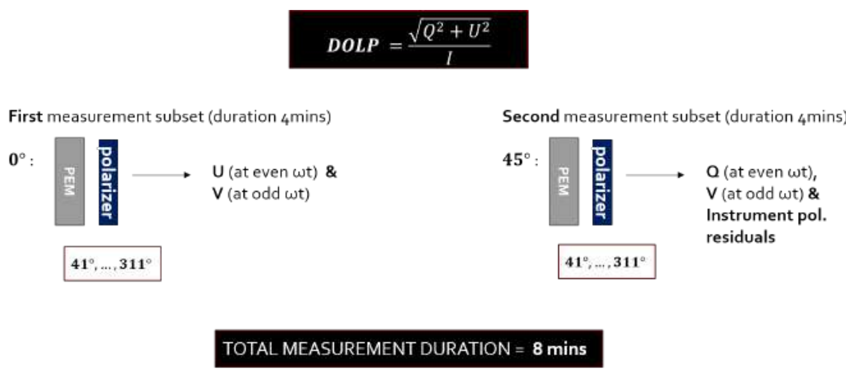
A video of SolPol slewing towards the Sun !

2.2 Measurements

The **first** observing sequence is performed with the assembly at the rest position (**0**°) and the rotating of the linear polarizer in steps of **90**° (see *Instrument Rotation* schematic). For a complete polarizer rotation of 360 degrees, the instrument acquires measurements for **four minutes**. The specific sequence provides measurements of three of the four Stokes parameters, I, Q and U.

This is followed by the **second** observing sequence, performed after the rotation of the entire assembly, about the PEM crystal optical axis, over **45**°. This observing sequence provides measurements of the fourth Stokes parameter, V and measurements for the removal of the biases and residual polarizations due to high frequency strain of the PEM for another **four minutes**.

Tip: Each full measurement cycle has a duration of **eight minutes**.



Ultimately, in this duration we measure the voltage output (in Volts) from the DC and AC channels of the lock-in apmlifier. This translates to:

$$v_{dc} = \frac{I}{2}$$
$$v_{1\omega} = \frac{VJ_1(A)}{\sqrt{2}}$$
$$v_{2\omega,0^\circ} = \frac{UJ_2(A)}{\sqrt{2}}$$
$$v_{2\omega,45^\circ} = \frac{-QJ_2(A)}{\sqrt{2}}$$

where $J_n(A)$ are the n-order Bessel functions, specifically, $J_1(A) = 0.7342$ and $J_2(A) = 0.6106$ are the channel efficiencies.

Also:

$$I = I_{measured} - I_{mean,dark}$$

since one must always subtract the mean DC signal of the *Dark Measurements* performed from the regular measurement.

If you are keen on learning the mathematical derivation of all measurement parameters, go to *SolPol Principle of Operation*.

2.3 Capabilities & Specifications

The capabilities of direct sun polarimetric measurements are discussed in Kemp et al. (1987) and Kemp and Barbour (1981), setting the detection threshold as low as sensitivities of the order of 10^{-7}, for perturbations to the polarization of the forward scattered light.

SolPol measures the degree of linear and circular polarization, i.e., **DOLP** and **DOCP**, with an absolute accuracy of 1% and precision of 1 part per million (ppm) in polarization terms (see *SolPol Principle of Operation*).

It can be installed and operated 24/7 in diverse environments, according to installation requirements (see *Installation & Setup*).

2.3.1 System Components

For the individual **instrument parts** and their **technical specifications** see below:

- Hinds Instruments **Photoelastic Modulator** - Series II FS47 (Optical head & Electronic head),

  - **Material**: Fused siclica resonant crystal with stress-induced birefringence
  - **Operation Range**: 400 nm -750 nm
  - **Stress-type**: Mechanical via standing acoustic waves by transducer at freq. of **47 kHz**
  - **Principle**: Different polarization states are refracted on different directions due to birefringence
  - **Light-path**: Fundamental vibration along the crystal optical axis
  - **Use**: Can be used as any retardation plate between $\lambda/4$ to $\lambda/2$
  - **Modulation efficiencies**: 0.7342 (ω) and 0.6106 (2ω) - same for dark measurements
  - **Cost**: ~ 12 k£

! **Limitations**: mixing of linear & circular polarizations produced by residual strain in the crystal.

Note: For a detailed description of the PEM operation go to *PEM operation principle*.

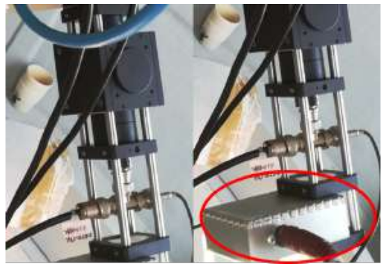
- Rotatable Thorlabs Film **Linear Polarizer**,
  - optical axis initially **aligned** with PEM axis
  - attached to Thorlabs Heavy Duty rotation stage (see pics)
  - rotated through a Thorlabs K-cube stepper motor controller for 41° to 311°
    - rotation control by the APT Thorlabs software

- Optec Inc. PYXIS 3-inch camera field rotator.

The Pyxis is a simple rotator used to attach CCD cameras on large telescopes for rotating the viewing field of the camera on long exposures. In SolPol, it is used to rotate the entire instrument assembly from 0° to 45°.

- NAUTILUS Rotating Filter Wheel,
  - Available **slots**: 7
  - 3 x **RGB broad band** filters
  - 3 x **40 nm narrow band** filters at 400, 550, and 700 nm
  - **Current operation**: at 550 nm

- **Galilean Telescope** and 1-cm silicon **Photodiode detector**.



- OpticStar CCD camera for Sun tracking, controlled by the OpticStar view software.

- SR830 DSP Lock-In Amplifier, amplification through transimpedence.

- Hinds Instruments PEM 100 head controller unit

2.3.2 Instrument Rotation

The measurement sequence of SolPol includes a rotation of the whole instrument assembly by 45° from the zero position (see XX). The relative position of the PEM and linear polarizer for each rotation state, is shown in the following figure.

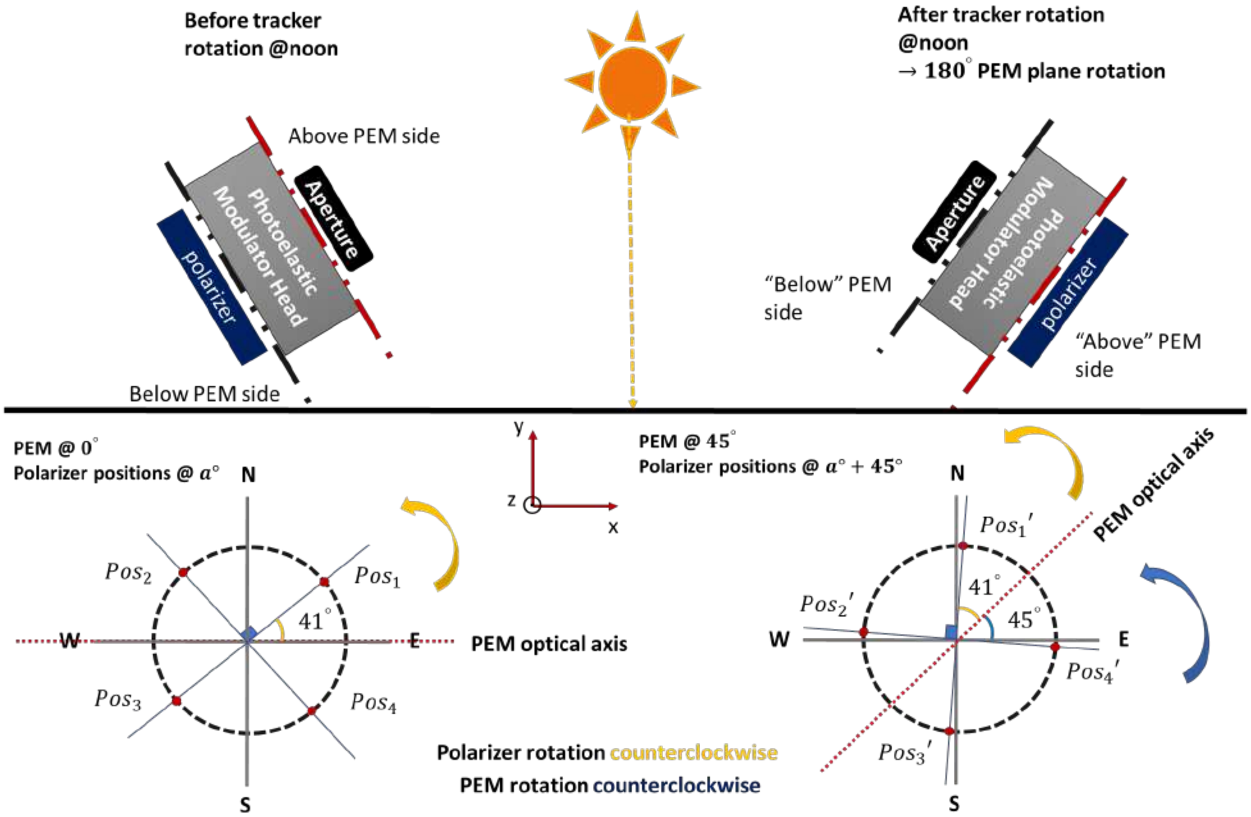


Fig. 1: SolPol assembly positioning as seen from the incoming sunlight reference frame. Left arrangement: The initial sequence begins with the PEM and linear polarizer at the rest position of 0°, then the polarizer rotates by 90° starting from 41° (Pos1), to 131° (Pos2), 221° (Pos3) and 311° (Pos4) counter-clockwise. A complete polarizer rotation with the PEM at 0° provides measurements of the U Stokes parameter. Right arrangement: assembly rotation by 45° and subsequent similar rotation of the polarizer by 90° intervals from Pos1' to Pos4'. This configuration provides measurements of the Q Stokes parameter.

CHAPTER

THREE

INSTALLATION & SETUP

SolPol has three installation modes:

Mode (1) at controlled laboratory conditions,

Mode (2) at observatories where it can be operated under diverse conditions, and

Mode (3) as a mobile instrument on experimental campaigns

All three modes share similar installation characteristics and can be adapted according to demand.

Below, you can find the complete installation guide of SolPol, either as a standalone instrument or as part of a general housing.

3.1 Instrument Needs

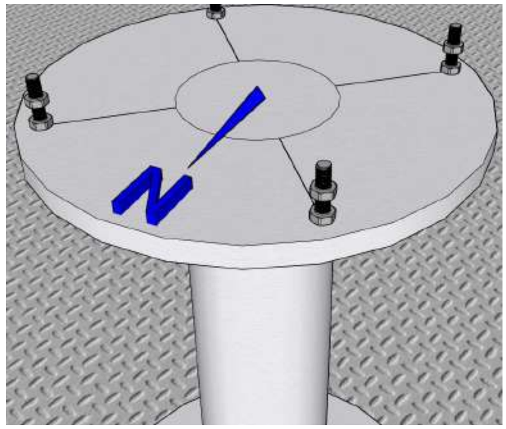
Power Needs

- Power supply: Mains **220 V AC / 50 Hz**
- Default outlet: three-pin **type G** (UK optional, can be changed with multiple adapter options)
- Power consumption: (?)

Mounting

- Current: Skywatcher EQ3 SynScan GoTo equatorial mount.
- Recommended upgrade: Skywacther HEQ5 Pro SynScan GoTo equatorial mount for better stability and tracking accuracy.
- Permanent platform: a steel base that fits the EQ3 adapter should be built for the instrument beforehand with a clear positioning towards the true North.

  See the following sketch of a custom base:



Tip: Consider Re-Designing

If you're planning a mount upgrade, take this opportunity to consider a re-design.

- Tripod: standard steel tripod for EQ3-2 mounts, mobile.

Data Transfer

- Through PC control via Ethernet/ WiFi: approx. 10 Kb/s
- Remote access capabilities via remote clients, e.g. Windows Remote Desktop, Anydesk etc.

Software

- OS: Windows 10
- Current state: `solpol.exe` with Windows 10 drivers

3.2 Physical Installation Requirements

We will specify the basic physical requirements and space needs for SolPol.

Caution: Do **not** plug in any power or connection cables at this stage. Ensure all connections are made after following the proper setup procedures to avoid potential damage or hazards.

3.2.1 Mode (1)

When in **Mode (1)** a typical optical table will suffice for the instrument set-up. Custom solutions can be applied on spot.

3.2.2 Mode (2)

- if SolPol operates as a **standalone**, then at least a 3-meter astronomical dome is advised for the instrument protection from extreme weather conditions.

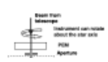
  (see  &  set-up at the PANGEA observatory, Antikythera)

! Proceed by initially **configuring** the astronomical mount on the designated base, **followed** by firmly **securing** the instrument.

1. **Place** mount on the base, adjust to base adapter until perfect fit.
2. **Tighten** base skrew and simultaneously adjust the EQ azimuth fine adjustments so that the mount points to marked true North.
3. **Adjust** mount latitude indication by the **altitude adjustment bolts**, wrt the installation location.
4. **Tighten** both mount brakes on **"Home position"**.
5. **Handle** SolPol carefully from the **rails** and place it on the top side of the mount.
6. **Secure** SolPol on the mount by completely tightening the **base screw** and then fine tune with the **smaller side skrew** until tight.
7. **Re-check** latitude indication and mount buble level.
8. **Loosen** azimuth brake by **carefully** holding the instrument and make sure it is completely **balanced** in the horizontal direction.
9. **Retract** to initial position and **secure** brake again.
10. **Perform** polar alignment.

Tip: For **optimal** results, it's recommended to typically perform *Polar alignment* every night with clear skies, just before each scheduled measurement day.

- if SolPol operates as **part of an astronomical telescope**, then it should be mounted **after** the telescope beam.

  (see the  for telescope set-up of the SolPol predecessor, PlanetPol)

3.2.3 Mode (3)

When in **Mode (3)** and if there is no allocated housing with the above specifications for the instrument, use the tripod configuration as follows:

1. **Secure** a 3x3 m flat space, that will ensure Sun tracking with **no obstacles** in the instrument line-of-sight - preferably on a building rooftop.
2. Fully **extend** tripod legs and **loosen** the base skrew.
3. **Fix** astronomical mount to the tripod, by securing tightly the **base skrew** and adjusting the EQ **azimuth fine adjustments**.

   ! For **EQ3**: mount weights should be secured to the outmost far position of the bracket for SolPol balancing.

4. **Mark** the **Magnetic North (N)** with a compass and adjust the tripod so that the mount **polarscope** is roughly aligned with it.
5. Temporarily **tighten** both mount brakes on **"Home position"**.

6. **Place** the tripod firmly on the ground (looking to the North) and **level** according to tripod bubble indication.

Tip: Offset Acceptance and Compensation

A few degrees of offset are acceptable and will be compensated for through the *Polar alignment* process.

7. **Secure** tripod with master lock **tie-downs** at each side, as shown in the picture.

Attention: At this point, tripod leveling is likely compromised. **Double-check** the tripod bubble level, and consider re-adjusting it using an external level to ensure accurate alignment.

8. **Secure** SolPol on the mount rails by completely tightening the **base screw** and then fine tune with the **smaller side skrew** until tight.
9. **Adjust** mount latitude indication by the **altitude adjustment bolts**, wrt the installation location.
10. **Loosen** azimuth brake by carefully holding the instrument and make sure it is **completely balanced** in the horizontal direction. **Retract** to initial position and secure brake.
11. **Recheck** instrument alignment and leveling.
12. **Perform** polar alignment.

3.3 Electrical Setup & Connectivity Guidelines

SolPol, in its current version, is a bit complex in terms of connectivity and cable management as it relies on peripherals for the rotator control, filter usage and eventually the signal acquisition.

3.3.1 Cable Inventory

Tip: All USB cables and RS232 - RJ11 connectors are **labelled** in each end. Match **cable codes** with SolPol **components**.

2 x RS232-to-RS232 long cables (beige)

1 x BNC Male-to-Male cable short (blue)

1 x 4-pin S-Video Male-to-Female cable long (brown)

3 x BNC Male-to-Male long cables (black)

1 x Adapter BNC Male to 2 BNC Female

2 x IEC 60320 C13 & C14 power cords (black)

2 x Mini USB cables, short

2 x DC barrel jacks short (black)

3 x 12 VDC power supplies

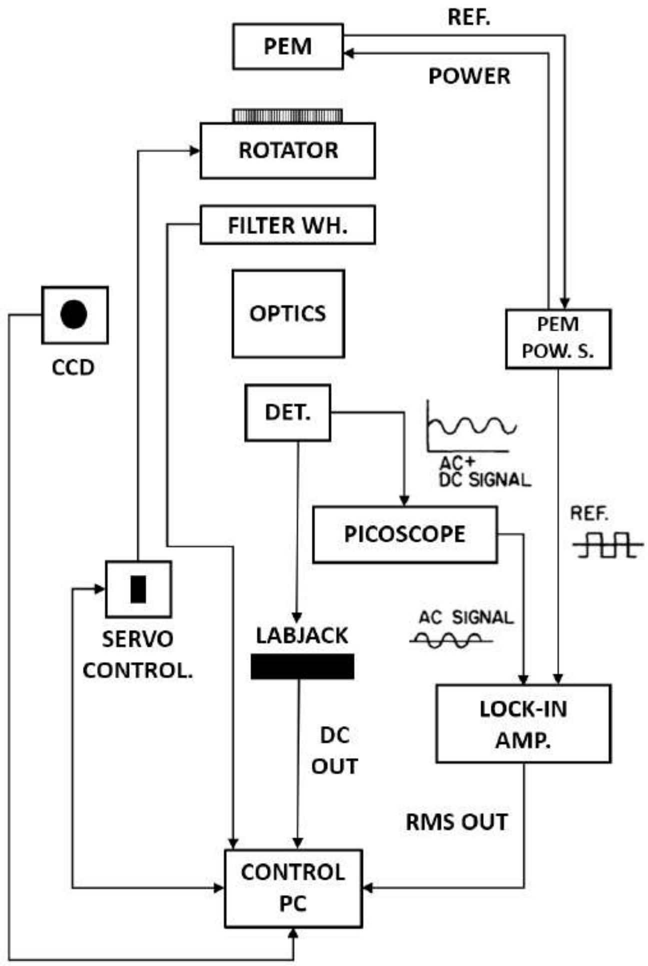
2 x Type-B USB cables

(needs update…)

Attention: Cable **color-coding** may varry on latest instrument version !

3.3.2 Connect Instrumennt

The basic **connection diagram** of the instrument and its components is seen below:



Let's start top down !

- PEM Optical head connected to the Electrical head via a short BNC connector cable (light blue, usually on the PEM).

- PEM Electrical head powered by the PEM controller via an RS232-to-RS232 connector cable

label: `PEM HEAD`, clr: beige

- PEM Optical head communicates with the controller via an RS323C connector cable

  DCE port, clr: beige

- PEM controller gives reference frequency to the lock-in amplifier via a BNC cable

  label: `REF f`, clr: black

- Rotator connected to Servo controller via an RJ11-to-RS232 cable for rotation control. Rotator powered via a 12 V DC power supply.

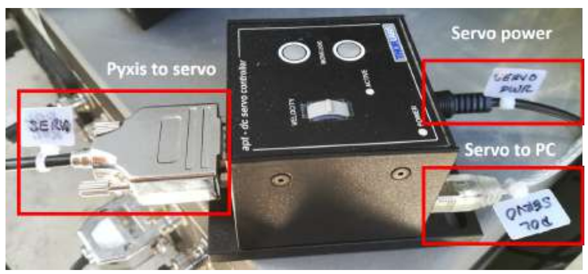
  label: `SERVO`, clr: black

- Servo powered via a 12 V DC power supply with barrel jack.

  label: `SERVO PWR`, clr: black

- Servo connected to PC control unit via a Mini USB cable.

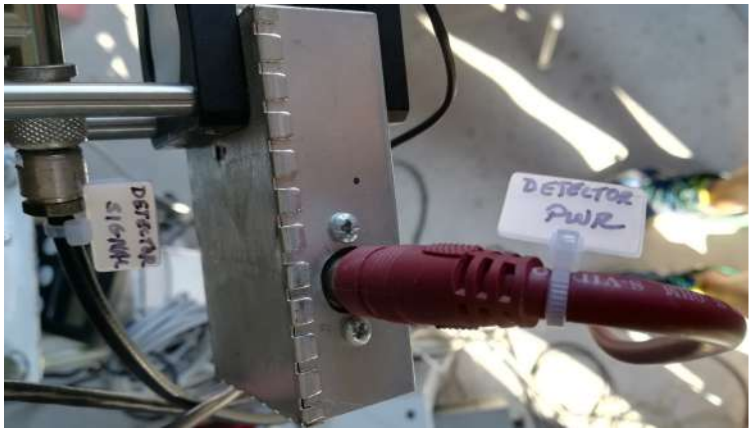
  label: `POL SERVO`, clr: black



- Filter wheel connected to PC control for power & comms via Type-B USB cable.

- Detector power through S-Video cable, detector signal to picoscope and from there the DC part to labjack.

  label: `DETECTOR PWR`, clr: brown, label: `DETECTOR SIGNAL` clr: black



- Picoscope powered via a Type-B USB cable and BNC adapter Male to 2 Female connected to channel A for signal branching.

label: `PICOSCOPE`, clr: black

- Lock-in powered by mains, reference frequency in from PEM and A/I in front lock-in side. Lock-in comms to PC control via an RS232 connector cable.

label: `LOCK-IN A/I`, clr: black, label: `REF IN`, clr: black, label: `LOCK-IN RS232`, clr: black

- Labjack connection to detector on AIN1 and GND. Labjack powered by a Type-B USB cable.

label: `LABJACK`, clr: white

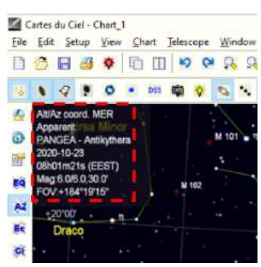
Eventually, after all USB cables are connected to the respective USB hubs or available PC ports, you will end up with something like this:

3.3.3 Connect Mount

Note: Remote connection

Tracker at its current state is controlled only via the PC by bypassing the hand-controller.

1. Connect mount **motor cables**, one way.
2. Connect the other **motor cable** to **tracker controller**.
3. Connect **RJ45** port to EQdir adapter device for EQmod to bypass the hand-controller.
4. Power on **EQdir** via the **mini USB** cable to the PC control (red light on).
5. Connect tracker **power supply**.
6. Initialization **sound on**.
7. On PC control unit, open `CartesduCeil.exe` free and open source planetarium program.
    - If in **Antikythera**: Make sure on the top left corner of panel interface, it writes **"PANGEA-Antikythera"**.

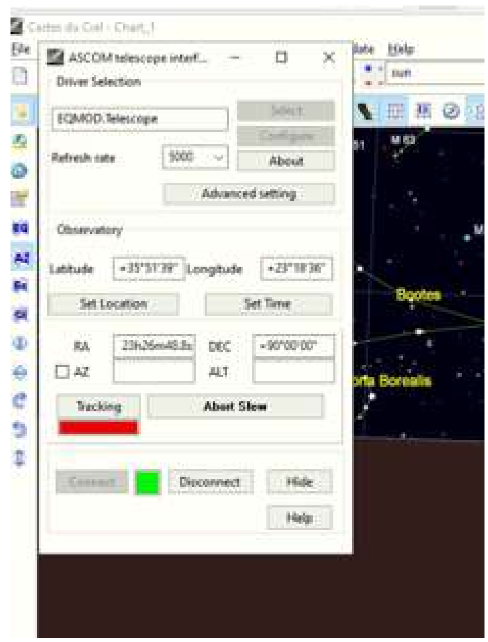


    - If in **another observatory**: Adjust accordingly from Cartes settings.

8. Grey ribbon tab press **Telescope** from dropdown → **Connect Telescope** → pops up **ASCOM tab**, press **Connect** → connection sound on.

   How that looks:

9. **EQmod** telescope tab pops → **Parked** sign on.

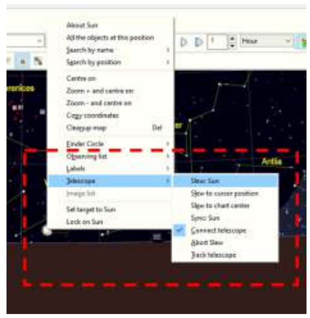
   

Tip: Home / Park position

Should be always the one from **Mode (2)- Step 4**.

! Tracking test sequence - duplicated in *Track Object*

1. Press **'Unpark'** in Eqmod to unlock mount positioning.
2. **Slew** to object (Sun or for Any object process is the same):
   - In **CartesduCeil** search tab insert **Sun** and find in planetarium → right click in Sun's position → select **Telescope** → **Slew: Sun**



> **Caution: Tracker Slewing**
>
> Tracker starts moving towards Sun, beware of **jammed cables** !

3. Enable **solar tracking** → press track rate **Solar**.

3.4 Calibration Procedures

There are a few calibration procedures for SolPol that can be performed under ambient measurement conditions and are **imperative** for the instrument smooth operation.

The absolute calibration procedures for the PEM crystal's peformance or the broader optical parameters of SolPol (e.g. radiometric or temperature calibration) are not covered within this manual's scope. These processes necessitate dedicated infrastructure and in-lab preparations.

3.4.1 Polar alignment

This procedure is a **standard process** for most astronomical instruments and ensures consistent object tracking, especially for the case of SolPol that is designated to track the solar disk for extended periods of time. It is performed under **clear night skies** by recognizing the position of **Polaris** (α Ursae Minoris) and fine tuning the astronomical mount.

It should be performed **typically** after each measurement day, if applicable !

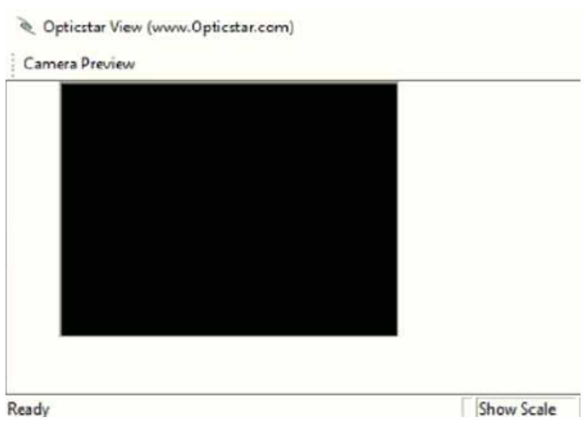
For a comprehensive **tutorial** follow the link !

3.4.2 Sun Centering

In order to track the Sun with a stable rate through the day, we need to center it on SolPol's FOV. This is an instrument specific sequence and we are aided by the CCD camera, which is aligned with the instrument in the mount rails.

For the Sun centering process follow the steps:

1. Power-on **tracker** and initialize **track Sun** sequence → see details in *Connect Mount* .
2. Power-on the **CCD camera** by connecting the USB on PC operation.
3. **Remove** the lens protective cover.
4. Place **Sun filter** in front of the camera lens (if not already installed).
5. Double-click on `Opticstar View` interface icon.
6. This should open the following window:



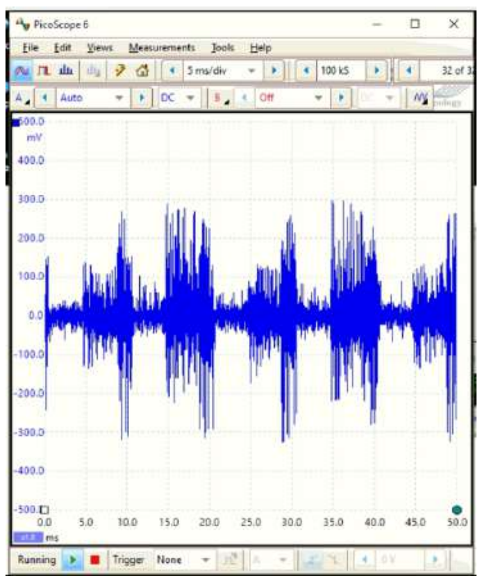
Sun might not appear immediately on screen

7. At EQmod tab press **N-S** & **W-E** buttons for tracker to move (see pic).

8. Slowly bring Sun to the CCD's panel.

Note: Depending on the Sun's position it will appear in a different place on the camera panel.

9. Open the oscilloscope from `picoscope.exe`, which should show a voltage range like in the picture if the Sun is not centered:



10. Adjust Sun's position to the point where the signal in Picoscope is **maximized** and leave CCD panel open to Desktop.

    - max. at **mean 12 V** (without an ND filter)
    - optimal position at camera panel **center**

11. Laslty, **visually check** if the instrument is pointing towards the Sun's center.

Tip: Good Practice

Make sure on large tracking durations that the Sun remains on the same spot in the screen. This means that an **optimal** polar alignment was performed.

If Sun diverges significantly during or after each measurement, repeat steps !

3.4.3 Dark Measurements

Dark measurements involve taking readings or images when no light or signal is present, essentially capturing the instrument's inherent noise or baseline signal. These measurements help account for any sensor noise, electronic noise, or other background signals that might affect the accuracy of subsequent measurements.

By **subtracting** the dark measurement data from the actual measurements, the instrument's true signal can be more accurately determined.

As in any other polarimeter, SolPol dark measurements should be performed **before AND after** each measurement sequence to ensure a dense dataset for comparison. These measurements are best performed with:

Prerequisites

i. A **closed** dome shutter.

ii. The mount is properly **powered** and **tracking**.

iii. Installation of a **darkening shutter** that completely covers the SolPol aperture.

Note: To better comprehend the Dark Measurements sequence, one must proceed to the **Operation** section and fully understand how to acquire a proper measurement with the instrument.

Therefore, for a detailed description go to → *Prepare Measurement* and repeat steps by simultaneously satisfying prerequisites (1) to (3).

CHAPTER

FOUR

OPERATION

4.1 Powering On & Off

Please follow each of the steps, in specific order, to ensure optimal instrument power up:

Step 1: Physically **inspect** all RS232/RJ11 ports and ensure that they are properly **connected** to each component.

Note: If the instrument is **hood-protected**, remove it carefully and then proceed to **Step 1**.

Step 2: Ensure that **all USB cable** connections are intact and properly connected either to the individual USB hubs or the PC control ports.

Step 3: Check all **electrical connections** and **power supply** sockets on the extension cord.

Step 4: Plug-in extension cord to **mains socket** and expect →

- Initialization **sound on**
- Mount makes slight **power up noise**
- Filter wheel should start **internal rotation**
- Instrument starts **rotating**, if rotator powered correctly. **Unplug** and **plug** the power supply on the Pyxis, if not !

Attention: Cable Jamming

When rotation starts be extra careful with the hanging cables from the PEM and detector. They tend to **block motion** !

Step 5: Wait for PC to fully boot.

Step 6: Familiarize with the interface and software to be operated in the next section.

Power-off

Visit after measurement sequence end !

- To power off the instrument → Close `solpol.exe`, `OpticstarView.exe`, `PicoScope6.exe` → Park to **'Home Position'** and **Disconnect** Telescope → unplug USB hub → close PC → **Unplug** mains power socket.
- **Cover** instrument to ensure no humidity is accumulated in the PEM head.

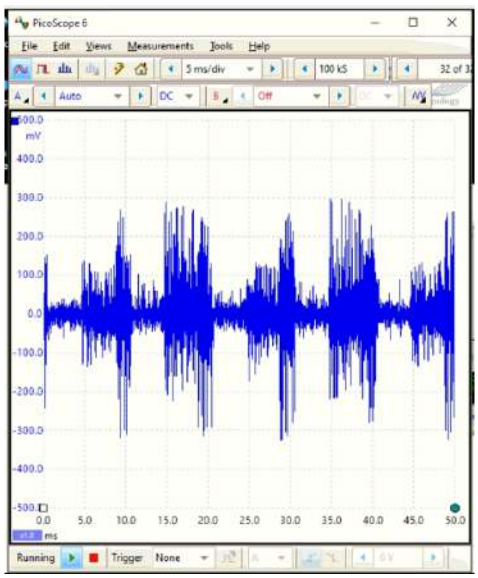
4.2 User Interface & Control Panels

The basic software used for the instrument operation is the following:

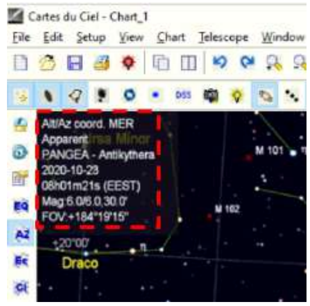
Note: Instrument current drivers are for W10.

- `OpticstarView.exe` - for the CCD camera operation and *Sun Centering* process.

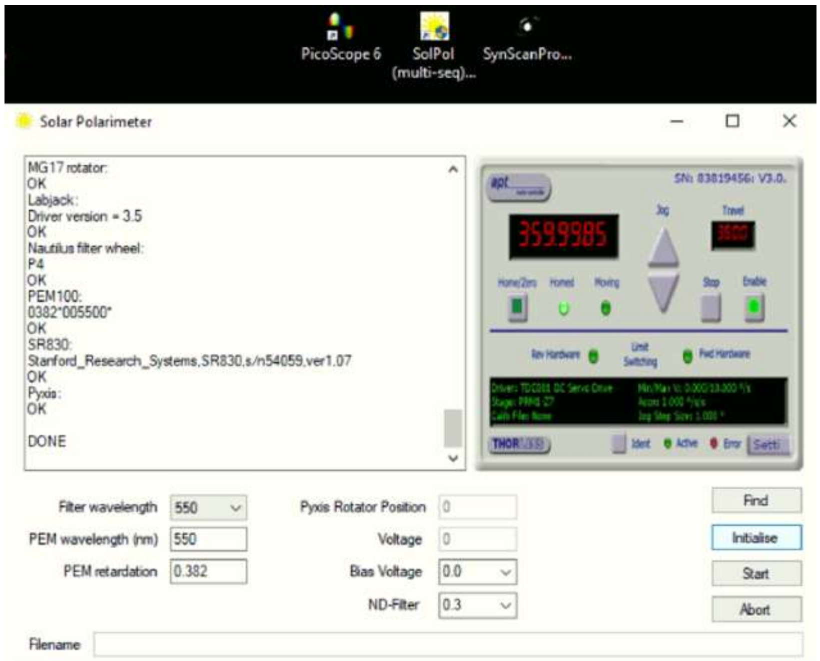
- `PicoScope6.exe` - for the oscilloscope initialization, used in *Sun Centering* and monitoring signal throughout the measurement sequence.



- `CartesduCeil.exe` - for the planetarium program Cartes du Ceil, used for spotting and tracking object in the sky.



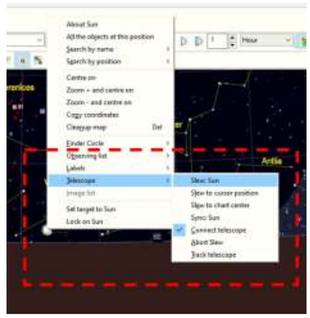
- `solpol.exe` - for the SolPol operation and measurement sequences.



4.2.1 Track Object

In order to perform any measurement with SolPol, you first must properly **align the mount** (see *Connect Mount* and *Polar alignment*) and then consistently **track** the stellar object (*Sun Centering*).

1. Press **'Unpark'** in Eqmod to unlock mount positioning.
2. **'Slew'** to object (Sun or for Any object process is the same):
   - In **CartesduCeil** search tab insert **Sun** and find in planetarium → right click in Sun's position → select **Telescope** → **'Slew: Sun'**



> **Attention: Tracker Slewing**
>
> Tracker starts moving towards the Sun, beware of **jammed cables** !

3. Enable **solar tracking** → press track rate **Solar**.

1. When finished, return to 'Home Position' by pressing **'Park'** and expect mount to move back to initial position.
2. Then, go to Cartes ribbon → **Telescope** → **Connect telescope** → **Disconnect** in ASCOM pop-up → red light on and pop-up closes.

4.2.2 Prepare Measurement

1. Open `solpol.exe` → Press **Find** button, to find all the instrument components.
    - Wait until indication **'All peripherals found'** appears in the SolPol interface !
    - If indication **'Not all Peripherals found'** appears, unplug and plug the component that is missing !

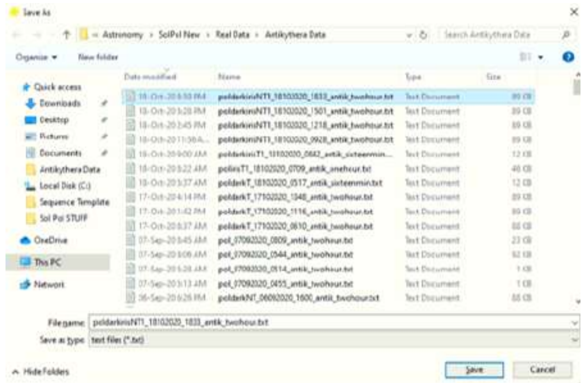
> **Tip: Device Manager** (W10) is your friend. Use it to locate all the used Ports and their type.

2. Choose **Filter wavelength** equal to **550nm** from the dropdown, if not already checked.
3. Filter wheel should be rotating, listen to it.
4. Press **Initialize** to give initial parameters to instrument components.
    - Polarizer should be rotating, wait until **DONE** appears.

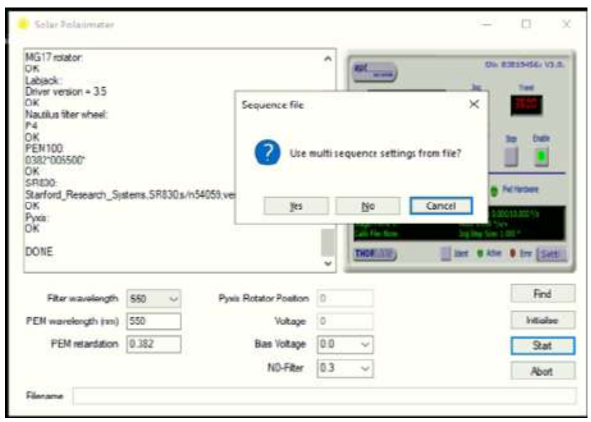
SolPol is set-up and ready !

4.3 Data Acquisition & Recording

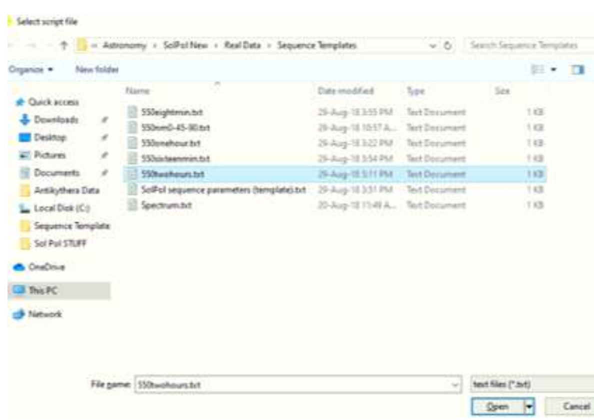
1. Begin data acquisition → Press **Start** in `solpol.exe`, filename window pops up.



2. Name file as in example: if **dark measurement** → *poldark*, if **normal measurement** → *pol* and as time insert the exact PC time in UTC.
3. Press **Save**



4. Sequence file pops up → Press **Yes** → choose appropriate sequence file from the available choices (see pic).
   - e.g. `550twohours.txt`



Note: Choose sequence according to current measurement needs.

5. Press **Open** & you're good to go !

4.3.1 Tips on Measurement details

Tip: No1

Perform always **BEFORE** measurement :underline: *day*:

- a *Polar alignment* !
- the *Sun Centering* to ensure maximum signal !

Perform **BEFORE** & **AFTER** each measurement :underline: *sequence*:

- a **visual inspection** of all cables/connections !
- brief *Dark Measurements* (e.g. 16 min in duration) to deduce instrument noise level !

Tip: No2

- If multiple USB connections fail, consider a **PC reboot**.
- **Do not interfere** with the data acquisition file while measuring, it is updated in real-time !
- Always **park** the mount before each measurement day end !
- Keep your **logbook tidy** ! See the *Logbook template*.

CHAPTER

FIVE

MAINTENANCE & TROUBLESHOOTING

5.1 Routine Maintenance Procedures

5.2 Cleaning Optics & Components

5.3 Identifying & Resolving Common Issues

5.4 Logbook template

Date = 2023-09-10

- **Operator Name**:

Atmospheric Conditions:

- **Actions Taken**: <List of Actions and Changes Made>

- **Issues Encountered**: <List of Issues or Problems Faced>

- **Maintenance Actions Taken**: <List of Maintenance Actions Performed>

- **Upcoming Maintenance**: <List of Scheduled or Planned Maintenance>

- **General Comments**: <Any Additional Notes or Comments>

Note:

- Type your info on the placeholders and text boxes with specific information for each entry.
- Use bullet points or subheadings to organize information within each section.
- You can add more sections or details as needed based on your instrument and data collection requirements.

Tip: You may duplicate the sections above for each day of operation.

CHAPTER

SIX

DATA ANALYSIS

6.1 Raw Data Pre-Processing

6.2 Stokes Vector Calculation

6.3 Interpretation of Polarization Signatures

CHAPTER SEVEN

ADVANCED TECHNIQUES

7.1 Desert Dust Orientation

As discussed in Bailey et al. (2008) and Ulanowski et al. (2007a), in case of aligned particles in the atmosphere, DOLP is expected to increase over larger solar zenith angles (SZA) since the direct sunlight travels through a larger airmass, and the effect of the dichroic extinction increases. With the increase of the SZA, the particle alignment angle changes with respect to the direction of observation, which is expected to influence the dichroic extinction and the measured linear polarization.

7.2 Polarimetric Signatures of Biological Materials

of scattered light from biological materials and cyanobacteria, to demonstrate the detection capabilities of potential life presence on exoplanetary atmospheres.

7.3 Exoplanetary Detection

CHAPTER

EIGHT

SAFETY GUIDELINES

8.1 Handling Optics

8.2 Electrical Safety Precautions

8.3 Environment & Site Safety

CHAPTER

NINE

GLOSSARY OF TERMS

δ
: Induced retardation by the PEM

ω
: Principal resonant frequency of the photoelastic crystal, for SolPol at 47 kHz

A
: Peak modulation amplitude, for SolPol equals to 2.4048

ADC
: Analog-to-Digital converter

CP
: Circular Polarization

EQ3 SynScan
: The current astronomical mount of SolPol

FOV
: field-of-view

$\mathbf{I_{dark}}$
: The voltage measured by the instrument during dark measurement sequences

Lock-in
: The SR830 DSP Lock-in Amplifier

LP
: Linear Polarization

ND filter
: Neutral Density filter

NOA
: National Observatory of Athens

PANGEA
: PANhellenic GEophysical observatory of Antikythera

PEM
: Photoelastic Modulator

rms
: root mean square

SolPol
: Solar Polarimeter

SZA
Solar Zenith angle

TI
Total Intensity

UH
University of Hertfordshire

9.1 Definitions of Key Polarimetry Concepts

Birefringence
The optical property of a material having a refractive index that depends on the polarization and propagation direction of light. Light rays with perpendicular polarizations propagate one in the direction of the optical axis (ordinary beam) and the other on the direction imposed by the material (extraordinary beam).

Dichroic extinction
Extinction by aligned grains of dust, which causes starlight polarization. Light with its polarization vector lying along the projected long axis of the grain is absorbed more than light of the orthogonal polarization.

Dichroism
See Dichroic Extinction

DOCP
Degree of Circular Polarization, defined as the square root of the normalized V Stokes parameter

DOLP
Degree of Linear Polarization, defined as the square root of the normalized Q plus the normalized U Stokes parameters

Forward scattering
Light scattering towards the direct direction, aka at zero degrees

I
The first Stokes parameter (I), denotes the total light intensity

Mueller matrix
A 4x4 scattering matrix containing the linear relationship between polarization states of the incident light beam and the emerging light beam after passing through polarizing elements. Technique employed in Mueller polarimeters. when they obtain all the matrix elements.

Q
The second Stokes parameter (Q), denotes linearly polarized light state at 0 and 90 degrees

Stokes vector
Vector describing the complete light polarization state as [I,Q,U,V], at either point of the optical path.

U
The third Stokes parameter (U), denotes linearly polarized light at 45 and -45 degrees

V
The fourth Stokes parameter (V), denotes circularly polarized light

CHAPTER

TEN

APPENDICES

10.1 Fundamentals of Polarimetry

10.2 Stokes Parameters & Polarization States

10.3 Polarization Modulation Techniques (?)

10.4 SolPol Principle of Operation

SolPol measures the polarization fractions of linear polarization (expressed by the Q and U Stokes parameters) and circular polarization (V Stokes parameter) from the whole solar disk and the entirety of the atmospheric column, depending on its limiting field-of-view aperture and the choice of mounting telescope. The measurements of the degree of linear and circular polarization (i.e., and , respectively, e.g., general expression from Hansen and Travis 1974) have an absolute accuracy of 1% and precision of 1 part per million (ppm, 10-6) in polarization terms.

The first observing sequence is performed with the assembly at the rest position (zero degrees) and the rotating of the linear polarizer in steps of 90 degrees. The corresponding relative positions of the PEM and linear polarizer for the assembly rotation is shown in XXX. For a complete polarizer rotation (360 degrees) we acquire measurements for four minutes. The specific sequence provides measurements of three of the four Stokes parameters. This is followed by the second observing sequence, performed after the rotation of the entire assembly, about the PEM crystal optical axis, over 45 degrees. This observing sequence provides measurements of the fourth Stokes parameter (V), and measurements for the removal of the biases and residual polarizations due to high frequency strain of the PEM for another four minutes.

Therefore, each full measurement cycle has a duration of **eight minutes** in total and is comprised of two distinct sets:

i. solar irradiance measurements on four positions of the linear polarizer at **41**°, **131**°, **221**° and **311**° with the assembly being at 0°, this configuration provides measurements of the I, U and V Stokes parameters, and

ii. measurements for the same relative positions of the linear polarizer, but the whole assembly is being rotated by **45**° which provides measurements of the I, Q and V Stokes parameters. Measuring I and V twice provides information for the removal of biases and residual polarization in the measurements.

The Stokes vector of light that reaches the PM can be expressed using the Mueller formulation (e.g., Van de Hulst, 1957), considering as reference coordinate system the one of the incoming sunlight, as in (1):

(1) where is the Stokes vector of the input light polarization state, is the output polarization state with the assembly at zero degrees,

(2) is the Mueller matrix of the linear polarizer at each position angle (41°, 131°, 221°, 311°) and

(3) is the Mueller matrix of the PEM that induces an input sinusoidal retardation of XX, for A the peak modulation amplitude and ω: the modulation frequency.

When the whole assembly is rotated by 45°, the reference coordinate system is rotated by the same angle, hence is the Stokes vector of the output light for this rotational scheme. The incoming sunlight at each α° position, appears to be rotated by an angle of -45° and is calculated through the rotation matrix as (as in Freudenthaler, 2016, S.5.1.7; Martin et al., 2010; Supplementary material/SolPol manual, Eq. 8).

We utilize a Bessel functions expansion of the retardation δ and derive the measurements of the Stokes parameters of the incoming sunlight, at detector level, as a function of the linear polarizer angles and the assembly rotation (see Figure XX). The XX are the n-order Bessel functions and, for the specific PEM, the modulation amplitude is fixed at A = 2.4048 so that, which makes the Q- and U-dependent direct-current (DC) terms equal to zero. Third order and above harmonic frequency terms are considered negligible, O(n >2) = 0. We, then, must sum over the four linear polarizer orientations per each assembly position, in order to eliminate the dependent terms on the I derivation, while the marginal residuals on the other Stokes parameters are also accounted for *Raw Data Pre-Processing*.

The following table shows the measurements at the detector, as a function of a. the Stokes components, b. the linear polarizer angles (α°), and c. the rotation of the assembly.

n	I'	Assembly without rotation	Assembly rotated at 45°
0	DC	$1/2\ [I + Q \cos(2\alpha) + UJ_0(A) \sin(2\alpha)]$	$1/2\ [I - QJ_0(A) \sin(2\alpha) + U \cos(2\alpha)]$
1	1ω t	$VJ_1(A) \sin(\omega\ t) \sin(2\alpha)$	$VJ_1(A) \sin(\omega\ t) \sin(2\alpha)$
2	2ω t	$UJ_2(A) \cos(2\omega\ t) \sin(2\alpha)$	$-QJ_2(A) \cos(2\omega\ t) \sin(2\alpha)$

where $J_n(A)$ are the n-order Bessel functions and, for the specific PEM, the modulation amplitude is fixed at A = 2.4048 so that $J_0(A)=0$, which makes the Q- and U-dependent DC terms equal to zero. Third order and above harmonic frequency terms are considered negligible, O (n > 2) $\rightarrow$ 0.

10.4.1 PEM operation principle

The SolPol **PEM type SII FS47** is comprised of a fused silica crystal bar with photoelastic capabilities and a piezoelectric transducer. If the optical element is compressed or stretched it induces a retardation (i.e. phase difference between the polarization components) of the incoming light. The strain stress in the PEM crystal is induced by standing mechanical acoustic waves, which are produced by the transducer, attached to the head.

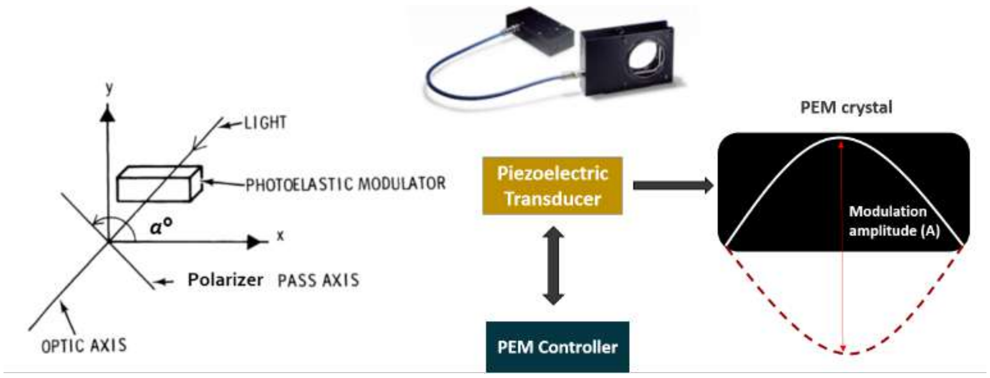
The resulting retardation is time-periodic, and is provided by:

$$\delta\ (t) = A\sin\ \omega\ t$$

where δ is the retardation of the PEM and A is the peak amplitude. The resonant frequency, ω of the PEM is set at 47 kHz.

The **PEM controller** unit performs many functions in the photoelastic modulator system. Its primary function is to control the peak retardation of the photoelastic modulator optical head. It does this by providing a DC voltage signal to the electronic head which determines the transducer vibration amplitude and thus the strain amplitude in the optical element (see pic). A current feedback loop from the electronic head enables the controller to maintain stable peak retardation levels.

For SolPol, the PEM is **calibrated** by the Bessel function zero methods which can be found in the manufactirers user manaul. Concerning this merhod, the DC term is kept invariable, independent of the birefringence. The DC intensity also becomes independent of changes attributed to the optical system, such as angular position of the polarizer. Normalization of the AC signals by the DC signal, renders the ratio independent of fluctuations from the intensity source.



10.5 Reference Charts & Diagrams

10.6 Recommended Reading Resources

CHAPTER

ELEVEN

INDICES AND TABLES

- genindex
- modindex
- search

INDEX