

User Guide

Novoptel

PM1000 Polarimeter



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Revision history

Version	Date	Remarks	Author
0.2.1	26.01.2015	Draft version	B. Koch
0.2.2	27.02.2015	Register and operation description updated	B. Koch
0.2.3	04.03.2015	Operation description updated	B. Koch
0.2.4	11.03.2015	Description of measurement data files	B. Koch
0.2.5	21.07.2015	Description of PDL measurement	B. Koch
0.2.6	24.07.2015	Remove obsolete registers 96 to 102	B. Koch
0.2.7	05.04.2016	Includes all functions until firmware 1.0.2.1	B. Koch
0.2.8	20.06.2016	GUI v1.0.7.1, firmware 1.0.3.1: 100 MS/s Poincaré live view, delay of BNC trigger input, optional 720p60 output	B. Koch
0.2.9	24.01.2018	GUI v1.0.9.5, firmware 1.0.4.5: Add description of laser modulation / demodulation, high-sensitivity mode	B. Koch
0.3.0	20.08.2018	GUI v1.1.0.0, firmware 1.0.5.0: Simultaneous recording and data transfer; variable pre- and post-trigger data	B. Koch
0.3.1	02.05.2019	Firmware 1.0.5.1: Power transient detection, LAN	B. Koch
0.4.0	09.06.2020	GUI 2.0.0.0; firmware 1.0.6.0: Dynamic undersampling, laser sweep	B. Koch
0.4.1	28.07.2020	Add USB 3.0 transfer protocol and SDRAM data transfer	B. Koch
0.4.2	27.08.2020	Minor changes in Register description; retrigger during long events (firmware 1.0.6.2)	B. Koch
0.4.3	12.05.2021	Add registers for trigger input 2 (from laser, fw 1.0.6.6); add scrambler voltage calibr. for <4 SOPs; configuration files	B. Koch
0.4.4	12.07.2021	PM1000 clock drift compensation during SOP event recording (fw 1.0.7.0). Register for reference SOP table	B. Koch
0.4.5	06.04.2022	Specifications added	R. Noe
0.4.6	18.08.2022	Modification of reference SOP table registers (fw 1.0.7.2), extend description of Wavelength sweep, PPS synchronization (fw 1.0.8.3)	B. Koch
0.4.7	12.10.2022	PDL/DOP re-calibration (GUI 2.0.3.4)	B. Koch
0.4.8	04.11.2022	PDL/DOP re-calibration of DUT-path (GUI 2.0.3.5)	B. Koch

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Specifications

Absolute maximum ratings

Parameter	Value	Remarks/Conditions
Supply voltage	-0.3...+5.5 V	
Voltage at all logical ports	-0.3...+3.6 V	
Optical input power	+15 dBm	
Storage temperature	-40...+85°C	
Operating temperature	-10...+70°C	

Characteristics

Parameter	Value	Remarks/Conditions
Wavelength/frequency range (covered if letter is included in part number)	1501...1647 nm (1) 199.8...182.0 THz	CL = C band, L band
	tbd	S = S band
	tbd	E = E band or portions thereof
	1260...1360 nm (1)	3 = O band
	1488, 1470, 1462, 1456, 1443, 1427 nm	Examples of other possible calibration wavelengths
Maximum optical input power in normal operation	+4 dBm	For full usage of internal voltage ranges. Optical power is calibrated vs. wavelength with state-of-the-art power meter.
Recommended input power range, analog bandwidth and Stokes parameter noise at maximum input power	-18...+4 dBm, ~25 MHz, ~3.5·10 ⁻⁴ rad	Standard input power range 1
Recommended input power range, analog bandwidth and Stokes parameter noise at maximum input power	-36...-14 dBm, ~1 MHz, ~2.5·10 ⁻⁴ rad	Optional input power range 2
Degree-of-polarization (DOP) accuracy	±1% ±0.1%	Typically After user calibration, typically
State-of-polarization (SOP) accuracy	<0.01 rad typically <0.003 rad	Estimated, after user calibration, or as small as the DOP accuracy
Maximum sampling frequency	100 MHz	Usable sampling frequency is 100 MHz * 2 ^{-ATE} , where ATE is the averaging time exponent 0, 1, 2, ..., 26.
Memory	64 MSamples	Full Stokes vector states
PER measurement range	0...>50 dB	
PER resolution	0.01 dB	
Optical power uncertainty	±0.25 dB	Clean connectors
Supply voltage	+4.75...5.25 V	
Supply current	0.8 A or tbd	1.5 A if temperature control is enabled
Logical port levels	LVC MOS33	3.3 V CMOS logic
Recommended temperature	0°C...50°C	For best accuracy
Return loss	55 dB	APC connector
	45 dB	PC connector
Dimensions	160 x 105 x 24 mm	Board alone
	235 x 200 x 90 mm	Standard case (+ power supply 100...240V)
	1U 19"	Rackmount (+ power supply 100...240V)
Interfaces	USB3.0, SPI, JTAG LAN, SPI8	Standard
		Optional; SPI8 = octal SPI, 8 parallel bits

Software	included	
Minimum measurement duration of Mueller matrix	5.12 us	Together with EPS1000
PDL measurement range	<0.01...>60 dB	Together with EPS1000

(1) Current ranges. May be adapted according to laser availability.

Introduction

The PM1000 polarimeter measures all 4 Stokes parameters at a sampling rate of 100 MHz. Optionally, the samples are averaged to increase accuracy at low optical input power. Furthermore, three normalization modes can be chosen. The calculated states of polarization (SOPs) are displayed on a Poincaré sphere at a connected monitor. This allows the polarimeter to be used without extra computer. The external monitor shows the realtime Poincaré sphere display at up to 50 MHz (at 100 MHz, only every second sample is displayed).

To explore the temporal evolution of the polarization, the user can switch the display to oscilloscope view. In this mode, the Stokes parameters are recorded in the polarimeter's memory and then plotted over time. The memory size is 4.3 Gb, i.e. 67 M polarization states can be recorded. The user can shift the oscilloscope plot and zoom into via the front control buttons.

The recording process can be triggered either externally by a BNC input signal or internally by defined SOP or input power events. Pre- and post-trigger data is stored. The memory can be read out via the SPI or USB interface. To configure the polarimeter, a graphical user interface (GUI) can be started on a PC that is connected to the polarimeter by USB. The GUI can also load screenshots of the connected monitor to the PC and display the Poincaré sphere.

Ultimate longterm accuracy can be achieved if the built-in temperature control is enabled (since 2022).

Rear panel

Figure 1 shows the rear panel of the PM1000.

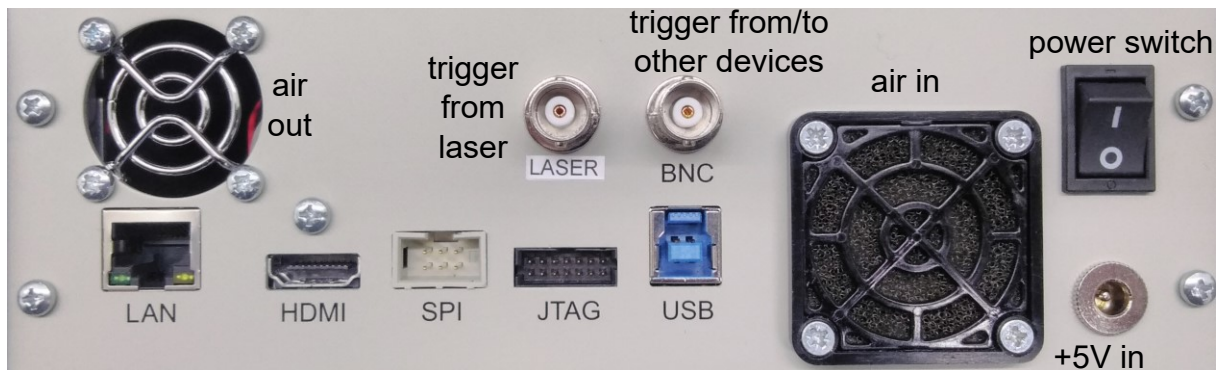


Fig. 1: PM1000 rear panel (with explanations added)

External monitor

A monitor can be connected to the HDMI output to display a polarimeter screen with 1280 x 720 pixels (“720p”, now default) at 60 Hz. A HDMI to DVI cable is included. It must be ensured that the connected monitor supports the chosen display standard!

Fundamental PM1000 configuration

Optical frequency

The optical frequency value can be adjusted to match that of the analyzed optical input signal.

Averaging time (ATE)

For accurate SOP measurement at lower optical input powers, internal averaging after the 100 MS/s AD conversion is recommended. The averaging time is denoted by the averaging time exponent (ATE). 2^{ATE} samples are averaged and an effective conversion time of $2^{\text{ATE}} \cdot 10$ ns is achieved. ATE ranges from 0 (100 MS/s) to 20 (95.4 S/s).

Normalization mode

The PM1000 provides three choices for the normalization of Stokes parameters/ vectors:

- Standard normalization: Stokes vectors are normalized to unit length. Regardless of power and DOP, they appear at the surface of the Poincaré sphere.
- Exact normalization: Stokes vectors are normalized only with respect to optical power. For $\text{DOP} < 1$ (or $\text{DOP} = 0$) they appear inside (or in the center of) the Poincaré sphere.
- Non-normalized: Stokes vectors are normalized only with respect to a user-defined power value, 1 mW by default. This means that DOP and optical power determine the length of the displayed Stokes vector up to a maximum length of 1.

Memory exponent (ME)

The memory exponent (ME) defines the size of the internal memory block that is being written into. The smallest block is achieved with $\text{ME}=10$ ($2^{10} = 1024$ SOPs). The largest block is achieved with $\text{ME}=26$ ($2^{26} = 67,108,864$ SOPs).

The memory recording time is derived from ME, ATE and the sampling time 10 ns. At highest speed ($\text{ATE}=0$), the memory is filled within 0.67 seconds, since $2^{26} \cdot 2^0 \cdot 10$ ns = 0.67 s.

Register description

Basic functions of the PM1000 are configured using the front control buttons. Advanced functions can be controlled through the USB, LAN or SPI port by reading and writing to internal registers, which are described in the following table. Note that the register addresses have an offset of 512. This allows a Novoptel PM1000 polarimeter and an EPS1000 polarization scrambler/transformer to be connected to a shared single SPI port. All undefined registers are reserved and should not be written into.

Register address	Name	Bit(s)	Read/Write	Function
512+0	ALM			Internal alarm code. The alarm can be cleared by writing "0" to this register. This is successful only if the alarm condition is no longer present.
		0	R/W	Alarm condition present.
		1	R/W	Optical input over range.
		2	R/W	Optical input under range.
		4	R/W	Critical board temperature.
512+1	ATE	9..0	R/W	Averaging time exponent (ATE), integer range 0 to 20.
512+2	PC1	15..0	R	Photocurrent 1, 16 bit unsigned, averaged according to ATE.
512+3	PC2	15..0	R	Photocurrent 2, 16 bit unsigned, averaged according to ATE.
512+4	PC3	15..0	R	Photocurrent 3, 16 bit unsigned, averaged according to ATE.
512+5	PC4	15..0	R	Photocurrent 4, 16 bit unsigned, averaged according to ATE.
512+6	LPC2	15..0	R	Latched copy of photocurrent 2, updated on any read of PC1.
512+7	LPC3	15..0	R	Latched copy of photocurrent 3, updated on any read of PC1.
512+8	LPC4	15..0	R	Latched copy of photocurrent 4, updated on any read of PC1.
512+9	PCFP	15..0	R	Floating point position of photocurrent 1 to 4, updated on any read of PC1.
512+10	S0uWU	15..0	R	Input power in μW , integer part.
512+11	S0uWL	15..0	R	Input power in μW , fractional part. Updated at last read of S0uWU.
512+12	S1uWU	15..0	R	S1 of Stokes vector normalized to 1 μW , integer part. Offset= 2^{15} .
512+13	S1uWL	15..0	R	S1 of Stokes vector normalized to 1 μW , fractional part. Updated at last read of S1uWU.
512+14	S2uWU	15..0	R	S2 of Stokes vector normalized to 1 μW , integer part. Offset= 2^{15} .
512+15	S2uWL	15..0	R	S2 of Stokes vector normalized to 1 μW , fractional part. Updated at last read of S2uWU.
512+16	S3uWU	15..0	R	S3 of Stokes vector normalized to 1 μW , integer part. Offset= 2^{15} .
512+17	S3uWL	15..0	R	S3 of Stokes vector normalized to 1 μW , fractional part. Updated at last read of S3uWU.
512+18	LS1uWU	15..0	R	Latched copy of S1uWU, updated on any read of S0uWU

512+19	LS1uWL	15..0	R	Latched copy of S1uWL, updated on any read of S0uWU
512+20	LS2uWU	15..0	R	Latched copy of S2uWU, updated on any read of S0uWU
512+21	LS2uWL	15..0	R	Latched copy of S2uWL, updated on any read of S0uWU
512+22	LS3uWU	15..0	R	Latched copy of S3uWU, updated on any read of S0uWU
512+23	LS3uWL	15..0	R	Latched copy of S3uWL, updated on any read of S0uWU
512+24	DOPSt	15..0	R	Degree of polarization (DOP), 16 bit unsigned, 15 fractional bits
512+25	S1St	15..0	R	S1 of Stokes vector "Standard Normalization", 15 fractional bits. Offset= 2^{15} .
512+26	S2St	15..0	R	S2 of Stokes vector "Standard Normalization", 15 fractional bits. Offset= 2^{15} .
512+27	S3St	15..0	R	S3 of Stokes vector "Standard Normalization", 15 fractional bits. Offset= 2^{15} .
512+28	LS1St	15..0	R	Latched copy of S1St, updated on any read of DOPSt
512+29	LS2St	15..0	R	Latched copy of S2St, updated on any read of DOPSt
512+30	LS3St	15..0	R	Latched copy of S3St, updated on any read of DOPSt
512+31	DOPEx	15..0	R	Degree of polarization (DOP), 16 bit unsigned, 15 fractional bits
512+32	S1Ex	15..0	R	S1 of Stokes vector "Exact Normalization", 15 fractional bits. Offset= 2^{15} .
512+33	S2Ex	15..0	R	S2 of Stokes vector "Exact Normalization", 15 fractional bits. Offset= 2^{15} .
512+34	S3Ex	15..0	R	S3 of Stokes vector "Exact Normalization", 15 fractional bits. Offset= 2^{15} .
512+35	LS1Ex	15..0	R	Latched copy of S1Ex, updated on any read of DOPEx
512+36	LS2Ex	15..0	R	Latched copy of S2Ex, updated on any read of DOPEx
512+37	LS3Ex	15..0	R	Latched copy of S3Ex, updated on any read of DOPEx
512+38	EPow	15..0	R/W	Reference power level in μW for non-normalized Stokes vectors to reach a length of 1.
512+39	S1Nn	15..0	R	S1 of Stokes vector "Non-normalized", 15 fractional bits. Offset= 2^{15} .
512+40	S2Nn	15..0	R	S2 of Stokes vector "Non-normalized", 15 fractional bits. Offset= 2^{15} .
512+41	S3Nn	15..0	R	S3 of Stokes vector "Non-normalized", 15 fractional bits. Offset= 2^{15} .
512+42	LS2Nn	15..0	R	Latched copy of S2Nn , updated on any read of EPow
512+43	LS2Nn	15..0	R	Latched copy of S2Nn , updated on any read of EPow
512+44	LS3Nn	15..0	R	Latched copy of S3Nn , updated on any read of EPow
512+45	S3Sign	0	R/W	If 1 (default), sign of S3 is chosen so that transversal directions x and y form a right-handed coordinate

				system with propagation coordinate z.
512+46	SINrm	1..0	R/W	Stokes parameters/vector normalization mode, see section <i>Fundamental PM1000 configuration</i> . “00”: Non-normalized “01”: Standard normalization “10”: Exact normalization
512+48 ... 512+63	UCal	15..0	R/W	User calibration matrix M with elements M00, M01, M02, M03; M10, M11, M12, M13; M20, M21, M22, M23; M30, M31, M32, M33. Non-normalized Stokes vector = M · (photocurrent vector).
512+64	UCalSL	3..0	R/W	Floating point position of user calibration matrix.
512+65	SelUCal	0	R/W	“1” switches to user defined calibration matrix.
		1	W	“1” writes user calibration matrix to flash RAM.
512+66	WLBand	9..8	R	Number of available wavelength bands
		1..0	R/W	Index of current wavelength band
512+67	MinFreq	15..0	R	Minimum extrapolated optical frequency in GHz/10, 16 bit unsigned.
512+68	MaxFreq	15..0	R	Maximum extrapolated optical frequency in GHz/10, 16 bit unsigned.
512+69	CurFreq	15..0	R/W	Current optical frequency in GHz/10, 16 bit unsigned.
512+70	MinCalFr	15..0	R	Minimum calibrated optical frequency in GHz/10, 16 bit unsigned.
512+71	MaxCalFr	15..0	R	Maximum calibrated optical frequency in GHz/10, 16 bit unsigned.
512+72		0	W	SDRAM write trigger. Any write of “1” to this register bit will trigger a recording of the sampled SOPs in the SDRAM. Recording period is defined by averaging ATE (register 512+1). 2 ^{ME} samples will be recorded, defined by the memory exponent ME (register 512+73). Writing of “0” into this bit will stop any recording in progress. ⁽³⁾
			R	SDRAM busy. “1” if recording is in progress.
		1	R	“1” if post-trigger data recording is in progress.
		2	R/W	Continuous cyclic memory recording enabled (1) or disabled(0)
		3	R	“1” if a full memory block was recorded since the last trigger
			W	“1” enables automatic retrigger for next memory block, but stops at block defined in register (512+82).
		4	R	“1” if SDRAM is busy due to oscilloscope display
			W	“1” enables “endless” retrigger for next memory block. Restarts in block 0 if end or memory is reached, pauses if block number specified in register (512+82) is reached. ⁽¹⁾
		5	R	“1” if SDRAM is busy due to Poincaré sphere display
			W	“1” enables recording of one SOP at each rising edge of signal applied to BNC input.
6	W	“1” enables recording of one SOP at each falling edge of signal applied to BNC input.		
7	W	If “1”, an SOP will be recorded at next rising or falling edge of signal applied to BNC input.		

		8	R/W	Enables dynamic undersampling ⁽³⁾
		9	R/W	If "1", Timestamps in recorded data will have a "Seconds" and a "Nanoseconds" part. Upon each rising edge of a 1PPS signal applied to BNC port, the "Seconds" part is increased by 1 and the "Nanoseconds" part is reset to 0. This way, the PM1000 synchronizes to a PPS-source every second. In addition, a second timestamp will be included every second containing the level of the "Nanoseconds"-counter when the next PPS-edge occurred. This information can be used to also correct the timestamps between the PPS edges.
		10	R/W	Enables retriggering during long events ⁽⁴⁾
		11	R/W	If "1", a 1PPS signal is generated at the BNC port, which is now an output, so the PM1000 serves as an 1PPS source using its internal clock. This way 2 PM1000s can be synchronized if no 1PPS-source is available. The accuracy of this 1PPS signal is limited by the accuracy of the internal clock oscillator. ⁽⁸⁾
		15	R	"1" if endless block retrigger is paused ⁽¹⁾
512+73		4..0	R/W	SDRAM memory exponent ME (max. 26)
512+74		3..0	R/W	Negative exponent for 16 bit power vector recorded to SDRAM. The recorded data represents power in μ W left-shifted bitwise by this value. The shifting reduces quantization errors when recording at low input powers.
512+75		0	R/W	"0" selects Power+Stokes to be recorded, "1" selects DOP+Stokes
		1	R	Power/DOP selection updated at last SDRAM trigger
512+76		15..0	R	Current write address of SDRAM, bits 15..0
512+77		9..0	R	Current write address of SDRAM, bits 25..16
512+78		15..0	R	The number of recorded Blocks after last SDRAM trigger
512+79		15..0	R/W	Selects a memory block
512+81		9..0	R/W	The stop address in the selected memory block, bits 25..16. Used in combination with register (512+96). ⁽⁷⁾
512+82		15..0	R/W	Maximum number of memory blocks (events) in event recording. Default is 512. Recording is paused when it reaches the block defined by this register. ⁽¹⁾
512+83		15	R/W	Defines power event trigger source: "0": Selects power deviation from reference "1": Selects power gradient (power increases or decreases by more than given factor within given time) ⁽²⁾
		14..0	R/W	Factor (>1) for power gradient detection as 15 bit unsigned including 10 post-comma bits ⁽²⁾
512+84		15..0	R/W	Input power trigger threshold in μ W
512+85		15..0	R/W	Input power reference in μ W
512+86		0	R/W	Define reference for internal trigger signal: "0": External Stokes vector "1": Internal delayed Stokes vector
		6..1	R/W	Number of clock cycles -1 for Stokes vector delay
		10..7	R/W	Exponent for clock division of Stokes vector delay
512+87		15..0	R/W	Stokes parameter 1 of external Stokes vector

				reference. 15 fractional bits. Offset= 2^{15} .
512+88		15..0	R/W	Stokes parameter 2 of external Stokes vector reference. 15 fractional bits. Offset= 2^{15} .
512+89		15..0	R/W	Stokes parameter 3 of external Stokes vector reference. 15 fractional bits. Offset= 2^{15} .
512+90		15..0	R	Current internal SOP trigger signal
512+91		15..0	R/W	Trigger threshold for internal SOP trigger signal
512+92		0	R/W	"1" enables SOP event triggering.
		1	R/W	"1" enables SOP event gating.
		2	R/W	SOP event triggering/gating: "0": Active high/rising edge. "1": Active low/falling edge
		3	R/W	"1" enables external triggering through BNC.
		4	R/W	"1" enable external gating through BNC.
		5	R/W	External triggering/gating: "0": Active high/rising edge. "1": Active low/falling edge
		6	R/W	"1" enables input power event triggering.
		7	R/W	"1" enables input power event gating.
		8	R/W	Input power triggering/gating: "0": Active high/rising edge. "1": Active low/falling edge
	12..11	R/W	Trigger2 input (from laser) configuration: "00": Ignore trigger2. No timestamps "10": Record all SOP vectors according to registers (512+96) and (512+81) after rising edge of trigger2. Add a timestamp after every first SOP vector of a cycle defined by register (512+103). "01": Record one SOP vector cycle defined by register (512+103) upon each rising edge of trigger2. Add a timestamp after every first SOP vector of a cycle.	
512+93		15..0	R	Bits 47..32 of internal microseconds counter. Bits 31..0 are frozen when reading this register. ⁽⁶⁾
512+94		15..0	R	Bits 31..16 of internal microseconds counter. ⁽⁶⁾
512+95		15..0	R	Bits 15..0 of internal microseconds counter. ⁽⁶⁾
512+96		15.0	R/W	Memory (SDRAM) recording stop address: If >0, the memory recording will stop at this address. If 0, recording will stop at the address $2^{ME}-1$. Used in combination with register (512+81).
512+103		10..0	R/W	Number of SOPs to be recorded for one Mueller matrix. Used in combination with register (512+92). ⁽⁵⁾
512+104		15..0	W	Code 39293 triggers SDRAM USB high speed transfer. Code 39294 triggers SDRAM LAN high speed transfer.
512+105		15..0	R/W	Bits 15..0 of SDRAM high speed read address
512+106		9..0	R/W	Bits 25..16 of SDRAM high speed read address
512+107		15..0	R/W	Number of addresses to be transferred in SDRAM high speed mode.
512+108		15..0	R/W	Power threshold in μW under which SOP triggers are blocked ⁽¹⁾ . Default value: 1 μW
512+110 ... 512+125		15..0	R	Factory calibration matrix M with elements M00, M01, M02, M03; M10, M11, M12, M13; M20, M21, M22, M23; M30, M31, M32, M33. Non-normalized Stokes vector = M · (photocurrent vector).
512+126		3..0	R	Floating point position of factory calibration matrix.
512+127		15..0	R/W	Delay for optional trigger input 2 (from laser) in

				microseconds
512+128		15..0	R	Firmware version as 4 digit BCD
512+129		15..0	R	Device DNA word 3 (DNA bits 63...48) (same as read via JTAG)
512+130		15..0	R	Device DNA word 2 (DNA bits 47...32) (same as read via JTAG)
512+131		15..0	R	Device DNA word 1 (DNA bits 31...16) (same as read via JTAG)
512+132		15..0	R	Device DNA word 0 (DNA bits 15...0) (same as read via JTAG)
512+133		15..0	R	Module Serial Number
512+134		15..0	R	Maximum input power in μ W
512+144		15..0	R	Module Type as 32 character string. Beginning at 512+144, each Register contains two bytes, representing two ASCII-coded characters.
...				
512+159				
512+186		0	R/W	Selects display type at connected monitor: "0" selects Poincaré sphere live view "1" selects Poincaré sphere memory view
512+187		0	R/W	"1" enables automatic Poincaré sphere refresh
512+188		15..0	R/W	Automatic Poincaré sphere refresh period in milliseconds, 16 bit unsigned
512+189		15..0	W	Any write transaction to this register clears the Poincaré sphere on the connected monitor.
512+201		1..0	R/W	Determines the pre-trigger data amount ⁽¹⁾ "00": 50%, "01": 25%, "10": 12.5%
512+202		15..0	R/W	Stokes parameter threshold for dynamic undersampling as integer in $\text{rad} * 2^{15}$
512+203		0	R/W	"1" enables synchronization of averaging to edge of sync signal at BNC input ⁴⁾
512+204		4..0	R/W	If >0: Maximum ATE during dynamic undersampling
512+207		0	R/W	"0" freezes HDMI frame buffer
512+220		0	R/W	1 (default): Enable bit-shift of ADC values to reduce quantization errors.
		1	R/W	1 (default): Increase averaging at low input power to reduce noise.
512+226		15..0	R/W	BNC input debounce time * 10 ns. At 50 (default), the status of the input is adopted after 500 ns without toggling.
512+227		8..0	R/W	BNC input delay time * 10 ns. At 10 (default), the signal is delayed by 100 ns. Bits 8 and 7 exist only in firmware 1.0.3.1 or newer
		12..9	R/W	Only in firmware 1.0.3.1 or newer: Clock exponent for BNC input delay line.
		15..13	R/W	Only in firmware 1.0.3.1 or newer: Number of BNC trigger events that are ignored after every activation of a recording.
512+229		15..0	R	Returns the power histogram count according to histogram address and bit selector
512+230		9..0	R/W	Histogram address
		15..14	R/W	Histogram bit selector "00": Bits 15..0 of histogram count are read "01": Bits 31..16 of histogram count are read "1X": Bits 47..32 of histogram count are read
512+231		15..0	R	Returns the SOP speed histogram count according

				to histogram address and bit selector
512+232		3..0	W	Histogram control Bit 0: "1" starts the SOP speed histogram count. Bit 1: "1" stops the SOP speed histogram count. Bit 2: "1" starts the power histogram count. Bit 3: "1" stops the power histogram count.
512+234		3..0	R/W	SOP speed histogram right shift bits. With a value he given by this register, the maximum histogram bin (address 1023) refers to $8 \text{ rad} / 2^{he}$.
512+236		5..0	R/W	Number of clock cycles for SOP speed interval
		10..6	R/W	Exponent for clock division of SOP speed interval
512+237		1..0	R/W	Input power histogram selector "00": The current input power value is recorded "01": The power difference between current and delayed value is recorded
		6..3	R/W	Power histogram right shift bits. With a value he given by this register, the maximum histogram bin (address 1023) refers to $8192 \mu\text{W} / 2^{he}$.
512+238		5..0	R/W	Number of clock cycles for power interval
		10..6	R/W	Exponent for clock division of power interval
512+300		15..0	R/W	Reference Timestamp Bits 63..48 ⁽³⁾
512+301		15..0	R/W	Reference Timestamp Bits 47..32 ⁽³⁾
512+302		15..0	R/W	Reference Timestamp Bits 31..16 ⁽³⁾
512+303		15..0	R/W	Reference Timestamp Bits 15..0 ⁽³⁾
512+430		1..0	R/W	Status of the optional optical switches. Bit 0 refers to first switch, Bit 1 to second switch. Usually first switch is REF/DUT and second switch inverts light path through DUT.
512+445		1	W	"1" will reset the table to the first entry ⁽⁷⁾
		0	W	"1" will launch a trigger event (manual trigger) ⁽⁷⁾
		9..0	R	Read current Ref. SOP table position ⁽⁷⁾
512+446		5..0	W	Ref. SOP table memory write trigger. ⁽⁷⁾ Bit 0: Write table memory vector 00 Bit 1: Write table memory vector 01 ... Bit5: Write table memory vector 05
512+447		8	R/W	Enable (1) or disable (0) ref. SOP table ⁽⁷⁾
		1	R/W	Enable (1) or disable (0) continuous table execution ⁽⁷⁾
		0	R/W	Table execution in row (1) or table (0) mode ⁽⁷⁾
512+448		10..0	R/W	Length of current table in table memory ⁽⁷⁾
512+449		9..0	R/W	Table memory input address ⁽⁷⁾
512+450 ... 512+454		15..0	R/W	Table memory input vector 00 to 05. See section "Table memory". ⁽⁷⁾
512+460 ... 512+464		15..0	R/W	Table memory output vector 00 to 04. See section "Reference SOP table memory". ⁽⁷⁾

(1) Only applicable since firmware 1.0.5.0

(2) Only applicable since firmware 1.0.5.1

(3) Only applicable since firmware 1.0.6.0

(4) Only applicable since firmware 1.0.6.2

- (5) Only applicable since firmware 1.0.6.6
- (6) Only applicable since firmware 1.0.7.0
- (7) Only applicable since firmware 1.0.7.1
- (8) Only applicable since firmware 1.0.8.3

Ref. SOP table memory

Since firmware 1.0.7.1, the reference SOP for the triggering and tracking function can be taken from an internal table memory. The table memory is either triggered row by row by an external signal at the BNC port of the polarimeter, or it runs in continuous mode with dwell times specified in each table row.

Vector	Meaning
00	Table dwell time in multiples of 40 ns, minus 1, Bits 15..0
01	Table dwell time in multiples of 40 ns, minus 1, Bits 31..16
02	Stokes parameter 1 as 16 bit signed integer with 15 fractional bits
03	Stokes parameter 2 as 16 bit signed integer with 15 fractional bits
04	Stokes parameter 3 as 16 bit signed integer with 15 fractional bits

For a dwell time of 200 ns, a value of 4 must be written into Vector 00, since $(4+1)*40\text{ns}=200\text{ns}$. A Stokes parameter of +0.123 must be written as 4030 since $\text{round}(0.123*2^{15}) = 4030$. A Stokes parameter of -0.123 must be written as 61506 since $2^{16}-\text{round}(0.123*2^{15}) = 61506$.

Operation of the instrument via front control panel

The polarimeter firmware provides a cyclic menu, the keywords of which are shown on the OLED display. The menu structure is

Optical band
Optical frequency
Averaging time (ATE)
Normalization mode
Sphere: live / memory
Rotate horizontal
Rotate vertical
Memory exponent (ME)
Reset dark current
Factory / User calibration
Configure LAN

The control buttons *UP* and *DOWN* let you to navigate through the menu. The control buttons *LEFT* and *RIGHT* change a selected setting or value. The menu points shown in grey are optional.

Reset dark current

Especially at low input powers, recalibration of the 4 photodetectors' dark currents can improve measurement accuracy. Use the *UP/DOWN* buttons to navigate through the menu until *Reset dark current* is displayed. Disable any optical input signal and press the *RIGHT* button twice. The new dark current values are then stored in the correspondent registers. To permanently store the new dark current values in the PM1000 please refer to the section *User calibration set*.

Sphere: live / memory

This menu item lets you select between the following display modes:

Poincaré live

The current SOP is displayed as a point in or on the Poincaré sphere. The SOPs are plotted in red if they lie on the front side of the sphere and blue if they lie on the back side. Points of past SOPs are kept in infinite persistence. According to the selected ATE (averaging) value, new points are plotted with a frequency of up to 50 MHz. Pushing the center button or rotating the sphere clears the SOPs on the sphere.

Poincaré memory

SOPs stored in the memory are being displayed. This is useful if you want to explore the evolution of a recorded SOP event in the Stokes space. If the sphere is rotated, memory data is loaded anew.

Factory / User calibration

By default, the PM1000 uses an internal factory calibration set which is valid for the specified wavelength range. By the GUI, the user can also write/read user calibration data to/from the polarimeter which is valid for only one specific wavelength. The user calibration can be stored permanently in the polarimeter so that it can be accessed through the polarimeter menu without a PC.

Connecting the instrument to a PC via USB

The instrument communicates via the USB IC FT232H (USB 2.0 version) or FT601Q (USB 3.0 version) from FTDI (Future Technology Devices International Limited, <http://www.ftdichip.com>).

The Novoptel PM1000 Graphical User Interface (= GUI) is compiled on a Microsoft Windows 10 64 Bit system. It is recommended to set the DPI scaling to 100%. For reliable data transfer, the USB cable should be as short as possible, and there should be no USB HUB in between the PC and the device.

Installing the USB driver

Execute the installation program of the provided USB driver (*CDM21228_Setup.exe* for instruments with black USB 2.0 socket, *FTD3XXDriver_WHQLCertified_v1.3.0.4_Installer.exe* for instruments with blue USB 3.0 socket). You will find more detailed information about the driver at <http://www.ftdichip.com/Support/Documents/InstallGuides.htm>.

Connecting the instrument

After the driver has been installed successfully, connect PC and instrument using the provided USB cable. Wait until Windows has recognized the USB device and shown an acknowledgement message. Power the instrument with the provided power supply and switch it on.

Operation of the instrument via graphical user interface

Standalone GUI

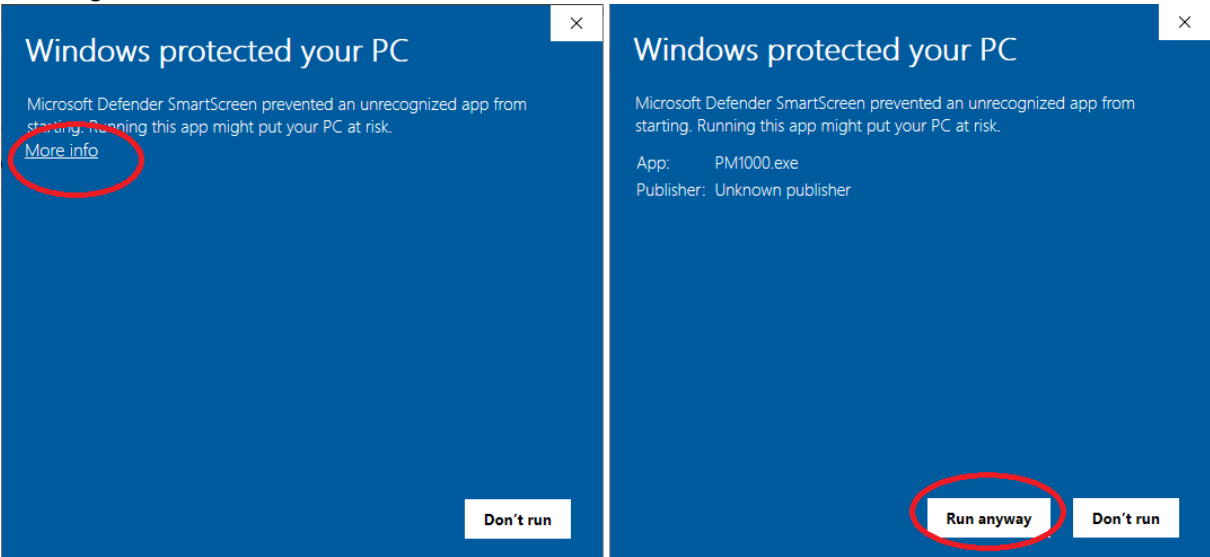
The current GUI is available as a standalone executable that does not need installation. If you have an older version with installer, please follow the steps described below.

Installing GUI

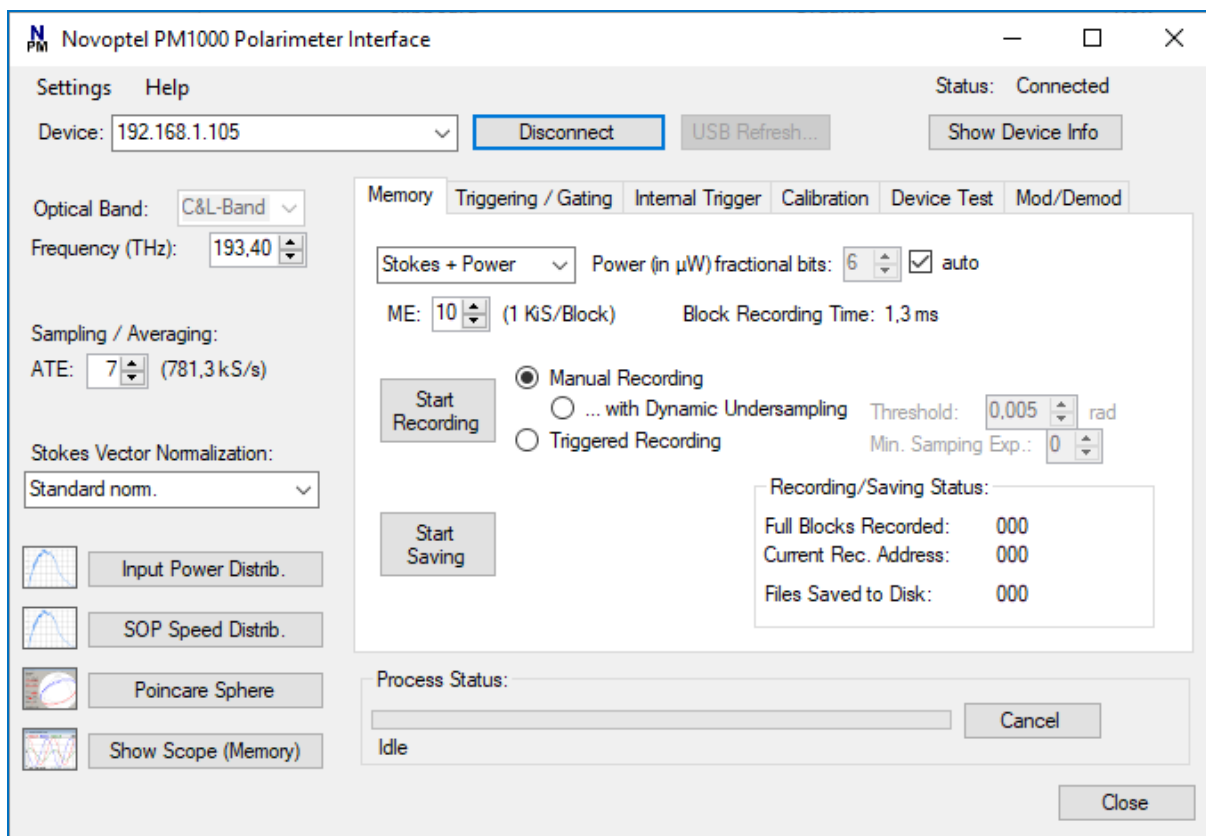
Any previous version of the graphical user interface has to be uninstalled first. For installation, execute *setup.exe* in the folder *PM_GUI_XXXX*, where *XXXX* refers to the GUI version. Follow the instructions of the installation dialogue.

If not found on the PC, Microsoft .NET Framework 4.5 will be installed during installation of the GUI.

While installing a recently released GUI on Windows 10, you may receive a SmartScreen warning:



Microsoft Windows SmartScreen may flag newly uploaded files that have not built up a long enough history. You can install the GUI by clicking “More info” and then “Run anyway”.



The software launches automatically after installation. If you want to launch the software later manually, select *Programs\Novoptel\PM_GUI* from the Windows Start Menu.

Basic operation

Selecting one of the attached instruments

If you have attached only one Novoptel polarimeter by USB, the GUI automatically selects this one. If you have attached more than one instrument by USB, select the desired one from the drop-down list next to *Device* and click *USB/LAN Connect*.



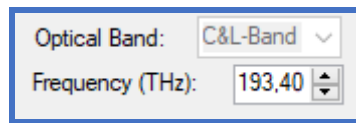
If a connected instrument does not appear in the list, click the *USB Refresh...* button. Subsequently, you can launch further instances of the GUI and connect them to further instruments.



To connect to an instrument within the same LAN, type the instrument's IP address into the field next to *Device* and press *USB/LAN Connect*. You can change the instrument's network settings using the front buttons.

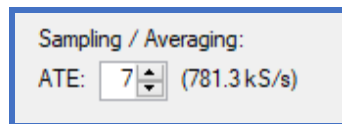
Setting the optical frequency

If the polarimeter is equipped with optional, additional optical bands, the GUI lets you select the desired band from a drop-down list.



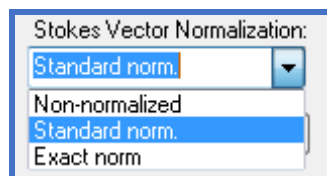
Type the optical frequency in THz with up to two positions after decimal point into the field besides *Frequency* and press Enter or tune the frequency with the up and down buttons. Outside the calibrated frequency range, the polarimeter matrix will be extrapolated. Measurements in the extrapolated range will be less accurate than in the calibrated range. If a frequency in the extrapolated range is selected, a warning message will be displayed.

Setting the averaging time exponent (ATE)



Type any valid ATE value between 0 and 20 into the box and press Enter or adjust the ATE with the up and down buttons. The resulting conversion rate is displayed at the right of the box. Averaging time is $10 \text{ ns} \cdot 2^{\text{ATE}}$.

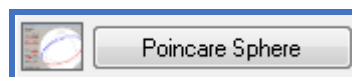
Selection of a normalization mode



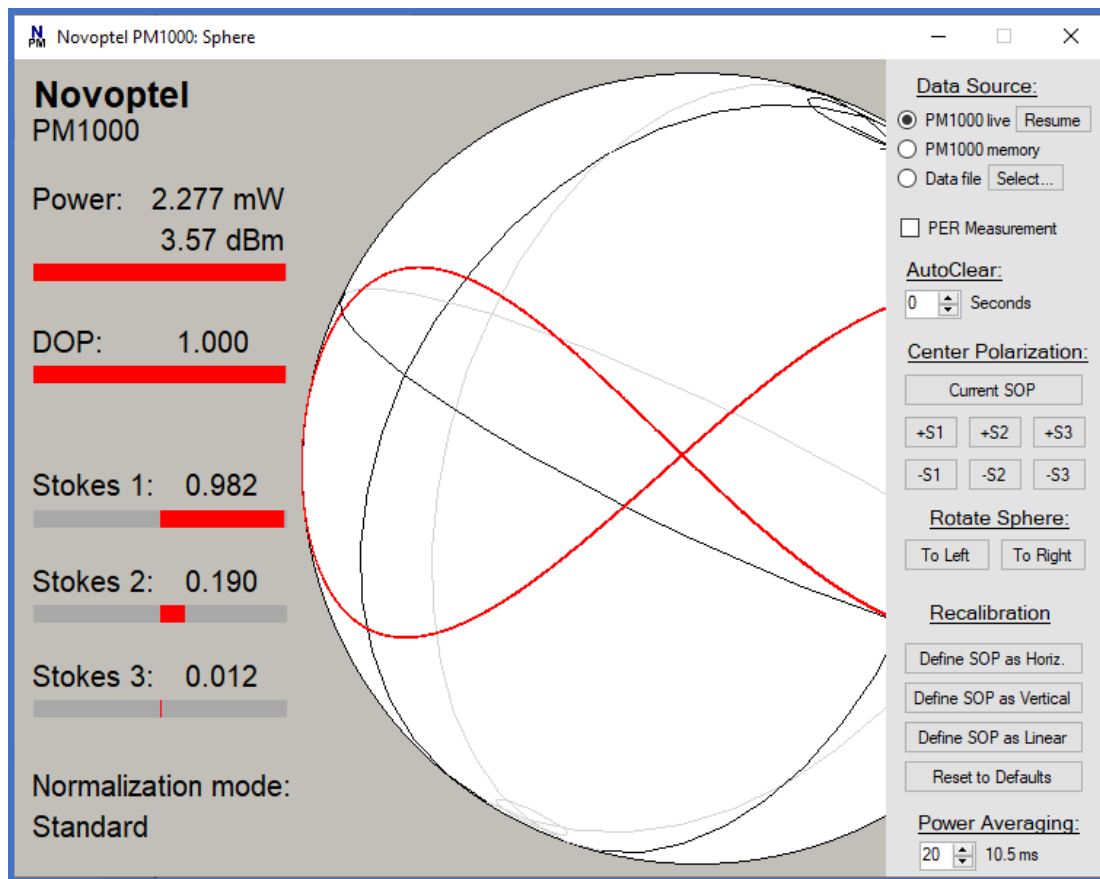
Select the desired normalization mode from the drop-down list. See section *Fundamental PM1000 configuration* for the definition of normalization modes.

Poincaré sphere display

With firmware 1.0.3.0 and GUI 1.0.7.0 or newer, the actual SOP samples can be displayed in infinite persistence mode on the Poincaré sphere in the GUI at full sampling speed of 100 MHz. The display can be cleared by rotating the sphere with the mouse. The Poincaré sphere window opens after pressing *Poincare Sphere*.



The sphere window can be resized by moving the window corners with the mouse. Power, degree-of-polarization (DOP) and the three Stokes parameters are displayed as color bars and text.



The orientation of the Poincaré sphere can be changed by moving the mouse on the sphere with left button pressed. If the mouse is moved to the upper right corner, a menu will open.

The endless plotting of SOPs can be paused by clicking on the *Resume/Pause* button. The sphere window can also be used to display SOP samples that have previously been stored in the PM1000 internal memory, or loaded from files. This is done by selecting *PM1000 memory* or *Data file* instead of *PM1000 live*. After every window resize or sphere rotation, the memory will be loaded again. The loading progress is displayed in the lower right corner.

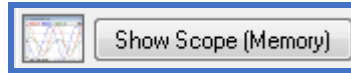
If *PER Measurement* is activated, the GUI will analyze the current SOP trajectory. From the maximum peripheral diameter of the trajectory, a PER value will be calculated and displayed. Moving the trajectory to the center of the screen improves accuracy.

The user can calibrate the orientation of the sphere according to his needs. First, horizontal or vertical polarization should be defined with the buttons *Define SOP as Horiz.* or *Define SOP as Vertical*. This redefines the S_1 axis, while the rotation about the S_1 axis is still undefined. This orientation can now be defined by the button *Define SOP as Linear* with a linear input signal having an azimuth angle $>0^\circ$, $<90^\circ$. The more the azimuth angle differs from 0° and 90° , the better. *Reset to Defaults* will restore factory settings. To store the new orientation permanently, go to the *Calibration* tab on the main window and press *Rewrite PM1000 Flash Memory*.

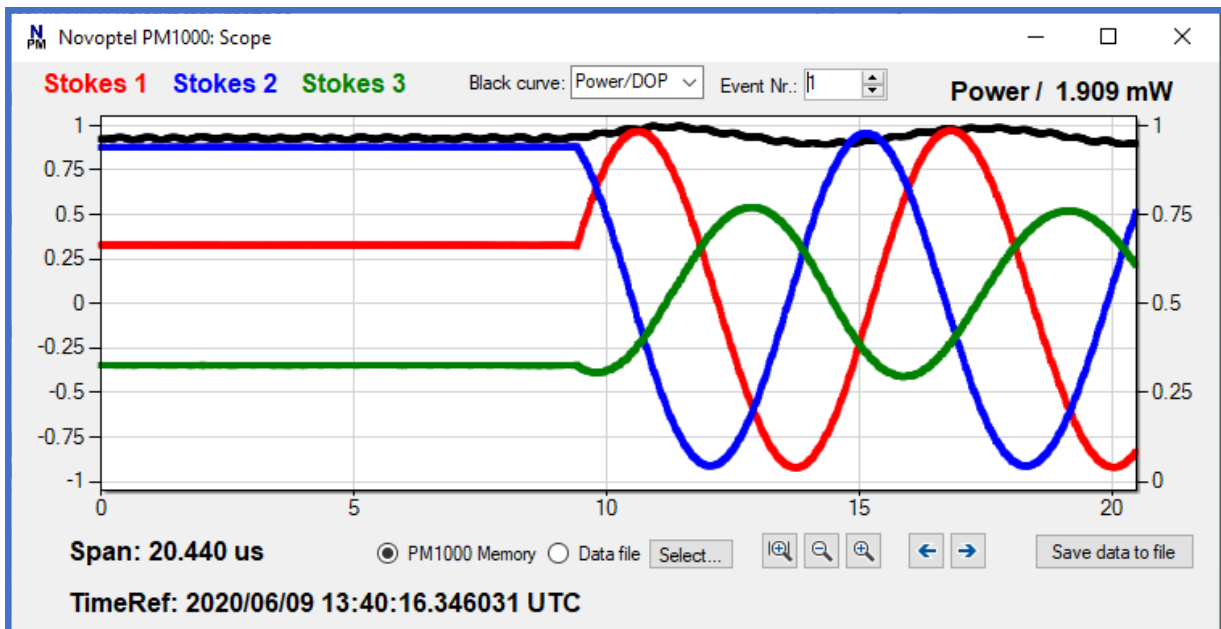
The power value displayed near the top, left of the Poincaré sphere, is averaged to suppress power fluctuations. The averaging time can be adjusted by changing the value below the label *Power Averaging*.

Oscilloscope plot

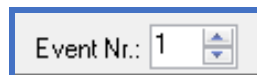
The stored Stokes parameters can also be displayed in an oscilloscope plot over time by pressing *Show Scope (Memory)*.



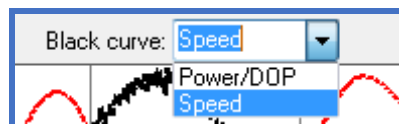
Four traces are being plotted in the new window: The three Stokes parameters S_1 - S_3 plus either power or DOP, whichever has been selected for memory recording, see section *Memory configuration*. In the plot, the DOP will be normalized to 2, which means that a DOP of 1 will appear in the middle of the y-range. The power curve is normalized to the maximum value in the data set and refers to the y-axis on the right side of the plot. The maximum power value is displayed in mW in the top right corner of the plot.



The plot can be zoomed in/out and shifted right and left. When more than one SOP event has been recorded, the different events can be selected for plotting by up and down buttons:



The GUI oscilloscope plot allows to derive the SOP changing speed from the stored SOP samples.

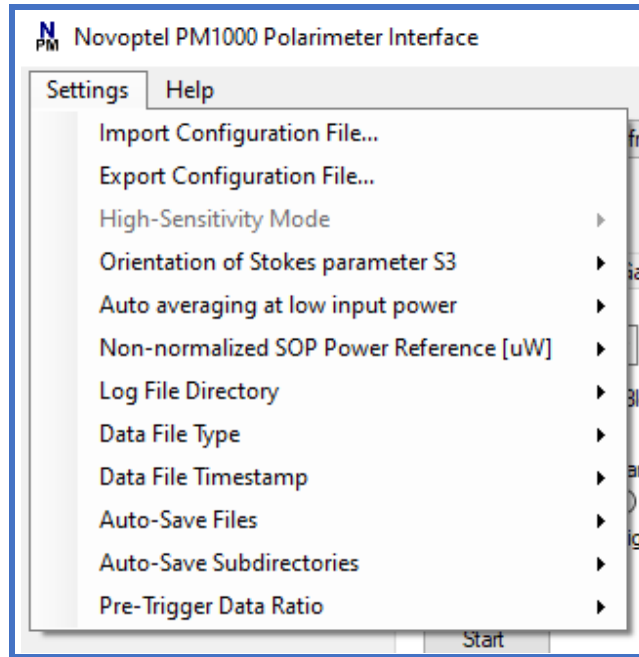


After selecting *Speed* from the drop-down list, the black curve in the plot will show the SOP speed instead of Power or DOP. The SOP speed plot is normalized to its maximum, which is displayed at the upper right of the plot. Since the SOP speed is calculated sample-to-sample, it will contain a lot of noise when observing slow SOP changes with small ATE.

For deeper SOP analysis with other programs like Matlab, the data displayed in the oscilloscope plot can be stored into a file on the computer by pressing *Save data to file*.

User Settings

Various settings can be set in the drop-down menu *Settings* of the GUI. Most of the settings will be stored in the user's application data directory, so that it will be remembered until the GUI is uninstalled.



Configuration Files

The current configuration can also be saved to ("*Export Configuration File...*") and loaded from ("*Import Configuration File...*") files on disk. This includes basic settings such as optical frequency and averaging, but also the trigger configuration.

High-Sensitivity Mode

Optionally, the PM1000 is equipped with a high-sensitive mode, in which very weak signals are measured with reduced noise at the cost of bandwidth. The GUI will display a message once the PM1000 is in the high-sensitivity mode. The user can let the polarimeter switch between the modes automatically (*Auto*) or force the polarimeter into the high-sensitivity mode (*ON*) or into the normal mode (*OFF*). When measuring intensity-modulated signals, the automatic mode selection can become unreliable and the user should determine one of the modes himself.

Orientation of Stokes parameter S_3

Two sign conventions exist for Stokes parameter S_3 . Transversal directions x and y form a right-handed coordinate system either with propagation coordinate z or time t . Ellipse handedness is defined when looking in direction of that axis z or t . For more information,

please refer to Application Note 3: “Mueller matrix measurement with PM1000 and EPS1000”. Default factory setting is for x, y, z right-handed.

Auto-Averaging at low input power

If the optical signal is very weak, the polarimeter will reduce noise by averaging. If high speed sampling is required and noise is tolerable, the user can disable the automatic averaging here.

Non-normalized SOP Power Reference

In Non-normalized mode, Stokes vectors are normalized only with respect to a user-defined power value, 1 mW by default. Here the power reference value can be defined in μW .

Log File Directory

By default, the log files are stored in the user’s application data directory. Hence they will be deleted when the GUI is uninstalled. In the *Settings* menu, the user can set the log file directory to *Desktop* instead

Data File Type

The memory data can be saved in binary or text file format. The binary format uses less disk space and works faster, whereas the text format allows an easier processing of data with external programs. The data type can be chosen in the menu strip *Settings->Select Data File Type*.

Both file types start with an ASCII text header for additional data, e.g. sampling and averaging time. Sample scripts for opening and plotting data in Matlab can be provided by Novoptel. They are described at the end of this document.

Data File Timestamp

The timestamp in the data files can be referred to the local time or to UTC (Coordinated Universal Time).

Auto-Save Files

During trigger-event recording, two types of files can be created:

- A single index file that includes a timestamp and the trigger source
- One data file with recorded pre- and post-trigger data for each trigger event.

Auto-Save Subdirectories

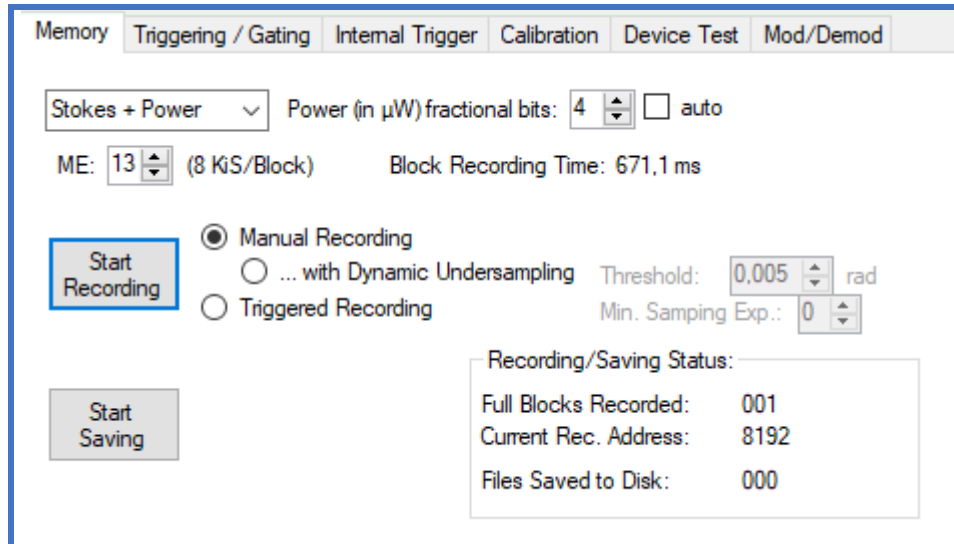
The number of files saved is only limited by disk space. Even if there is disk space available, Windows sometimes blocks file creation in directories that already contain many ten thousand files. If this setting is activated, the GUI will create a new directory at the beginning of a measurement and every time the current directory is blocked.

Pre-Trigger Data Ratio

Selects the amount of pre-trigger data: 50% (default), 25% or 12.5%.

Memory configuration

The PM1000 internal memory allows to store up to 67 M SOP samples (2^{ME} , between 2^{10} and 2^{26}) at a rate of up to 100 MS/s. It is configured in the *Memory* tab of the main tab control.



Memory exponent (ME)

The block size of the memory is defined by a memory exponent (ME) between 10 and 26, see section *Fundamental PM1000 configuration*. The memory block recording time, derived from block size and averaging time, is displayed accordingly. There are $2^{(26-ME)}$ memory blocks.

Power or DOP recording

The memory stores 4 Stokes parameters at once. For the parameter S_0 , the GUI allows to select either optical power or degree-of-polarization (DOP) for recording. If power is selected, the unit of S_0 will be μ W. To increase accuracy, the 16 bit integer value can be shifted bitwise to add some fractional bits before recording. If the option *auto* is selected, the number of fractional bits will be selected automatically according to the current input power level.

Timestamps

When starting a recording, a 64 Bit reference timestamp will be written into the timestamp registers, (addresses 512+300 to 512+303). The upper 37 Bit refer to the seconds elapsed since 12:00:00 midnight, January 1, 0001 in the Gregorian calendar. The lower 27 Bits refer to 10-ns-ticks elapsed in the current second.

The 64 Bit relative timestamps in the memory are referred to the reference timestamp. The upper 8 Bits of the relative timestamp are the timestamp indicator (all "1", which can be excluded for the S_0 Stokes parameter). The lower 56 Bit differ depending on recording mode:

Trigger-event recording:

Bits 55 down to 53: Code for last trigger source.

Bits 52 down to 48: Reserved.

Bits 47 down to 0: Counter for elapsed Microseconds.

Dynamic undersampling:

Bits 55 down to 0: Counter for elapsed Nanoseconds. 56 Bits suffice for > 1 year uninterrupted recording.

Synchronized to 1PPS-source:

Timestamp 1:

Bit 55: Reserved

Bits 54 down to 30: Number of rising edges of 1PPS-signal after start of recording

Bits 29 down to 0: Number of nanoseconds (by internal clock) after last rising 1PPS-edge

Timestamp 2:

Bits 55 down to 30: Reserved

Bits 29 down to 0: Count of the internal nanoseconds counter between the last two 1PPS-edges

Timestamps 1 are synchronized to the 1PPS-source every second. *Timestamps 2* allow to correct the nanoseconds part of the *timestamps 1* according to the difference of internal and 1PPS clock in the last second.

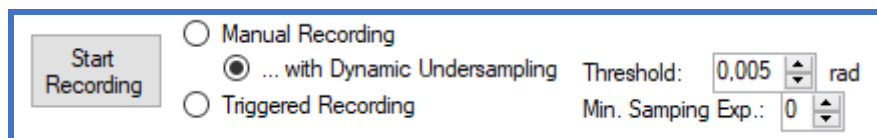
Manual recording

The polarimeter will just record a number of samples according to ME after the user presses *Start Recording*, and then stop. The Memory will contain only SOP data, the timestamp registers contain the timestamp of the SOP at address 0.

In all recording modes, the button *Start Recording* (which by starting became “*Stop Recording*”) can be pressed a second time to stop the recording immediately.

Dynamic Undersampling

If the SOP is to be logged for a long time, the polarimeter can save memory space by dynamically undersampling the data: An SOP is only recorded if one of the Stokes parameters differ by a given threshold from the last saved SOP.



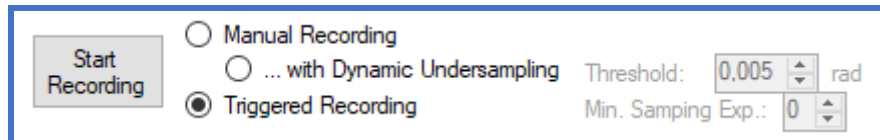
If the optical signal contains a lot of noise, the amount of recorded SOPs can still be very high. To reduce the amount of data, increase either ATE or the Stokes parameter threshold. In the latter case, the recording has to be stopped and started again for the changes to take effect. In the memory, each SOP is followed by a timestamp with one exception: If the time difference of two samples is 10 ns (which is only possible with ATE=0), the timestamp is skipped. Also here, the memory timestamps are relative to the timestamp in the timestamp register.

The memory block size in this mode is always 2^{25} addresses, which should normally contain 2^{24} SOPs and 2^{24} relative timestamps. There are two such blocks available. When file saving is active, the data from the block that is actively recording is already transferred to the PC and written into the file up to the current recording address. When the polarimeter has reached the end of the second block, it will overwrite the first block, but only if the GUI has finished saving the data from the first block. The GUI will create a new file for each block, so

that a file usually contains not more than 2^{24} SOPs. This limits the file size to about 256 MB in binary format or about 800 MB in text format.

Triggered recording

The checkbox *Triggered Recording* enables the continuous, cyclic recording mode, which is useful for detecting and recording rare SOP events. In this mode, each memory block is like a ring memory in which the measurement process is repeated without interruption until a trigger event occurs. This trigger event can be launched from an internal or external signal, see next section. After a trigger event, a defined amount of post-trigger data is still recorded, see *Pre-Trigger Data Ratio* in the previous section.



After the last of the post-trigger samples is recorded, the polarimeter will write a relative timestamp into the memory both to mark the stop position in the block and to allow calculation of the trigger event time. The timestamp in the memory is relative to the timestamp in the timestamp registers.

After that, the recording will continue in the next memory block, expecting the next trigger event. The maximum number of events n depends on the memory block size defined by ME: $n=2^{26-ME}$. This means that at an ME of 26 (whole memory as one block), only one event is recorded.

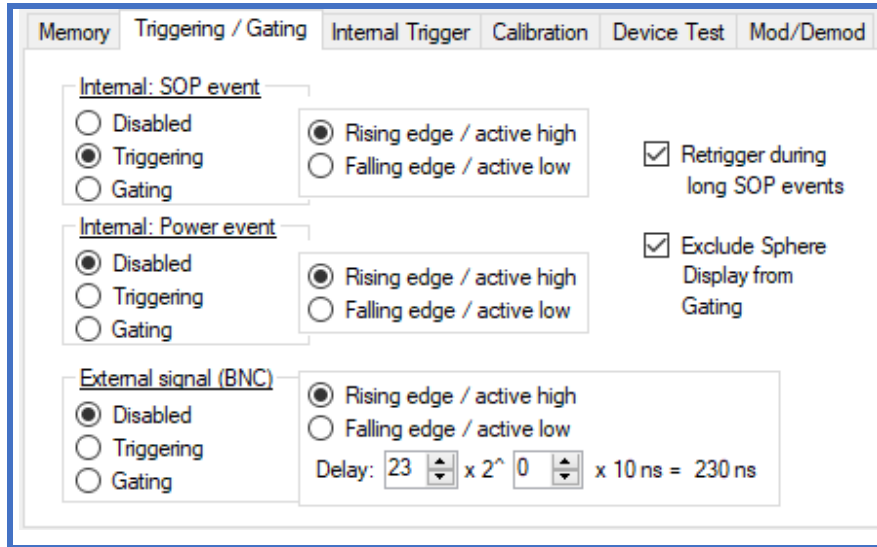
Saving the event data to files

After clicking on *Start Saving* and selecting a file name, the GUI downloads the event data already while the next events are being recorded. Once the recording reaches the end of the memory, the polarimeter will start over from the first block. If the events occur faster than the data transfer of one block, the polarimeter will fill only as many block as are still available. So, if downloading lags recording by the full memory size, trigger events or records will be missed. The GUI will mark a block as available for the next recording after it has downloaded its data. This way, the number of files is only limited by disk space, and also fast subsequent events are recorded without having to wait for file transfer between the events.

If the recording has been stopped manually, the polarimeter will continue downloading the rest of the events until the user clicks *Stop Saving*.

Triggering and gating

The *Triggering / Gating* tab of the GUI allows to enable triggering or gating of the memory recording. Triggering means that the cyclic measurement process is stopped after recording of post-trigger samples. Gating means that the recording process will be paused as long as the gating signal is active.



The SOP event triggering / gating signal is the result of an internal Stokes vector multiplication, see next section. The external triggering / gating signal is a LVCMOS33 (0 V / +3.3 V) signal that is applied to the BNC connector at the rear panel of the instrument.

Retriggering

If “Rising edge” is selected, an SOP trigger is launched only in the moment the trigger threshold is surpassed. If it is surpassed already before starting the recording, the trigger launches only once eventually the trigger threshold is underrun and surpassed again. Until then, the SOP event is not recorded. The same applies for SOP events that last longer than the recording time of the post-trigger samples, where only the one block containing the beginning of the event will be recorded. In both situations, activation of “Retrigger during long SOP events” will launch additional triggers if a level higher than the trigger level is detected. An SOP event lasting longer than the post-trigger recording time will then seamlessly continue in the next recording block.

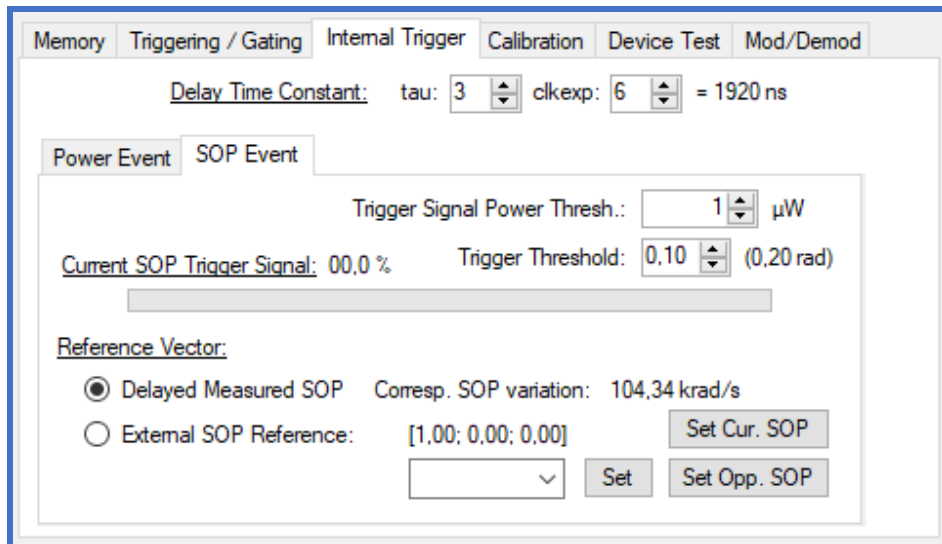
Internal trigger configuration

The internal trigger signals can be configured in the *Internal Trigger* tab of the GUI. There are two basic internal trigger sources: SOP events and power events.

If the PM1000 is equipped with a digital feedback interface to the EPS1000 for SOP tracking, the *External SOP Reference* serves as the target SOP for the tracking function.

SOP Event

The SOP event trigger signal is the length of a difference vector between the current and a reference Stokes vector, normalized to a maximum of 1 (rather than the diameter 2 of the Poincaré sphere). It is therefore a function of the angle δ between the two Stokes vectors: Trigger signal = $0.5 \cdot |S_{\text{cur}} - S_{\text{ref}}| = \sin(\delta/2)$. For small δ it holds trigger signal $\approx \delta/2$.



For triggering, the trigger signal must surpass the trigger threshold. The trigger threshold can be adjusted between 0 (trigger signal always high) and 1 (trigger signal always low) in steps of 0.01.

At very low input power and small ATE, noise can lead to high calculated SOP changes and create unwanted trigger edges. The trigger can be blocked if the power drops below an adjustable power threshold (“*Trigger Signal Power Thresh.*”), which is 1 µW by default.

Delayed measured SOP for reference

The reference Stokes vector can be chosen to be a copy of the permanently measured SOP that has been delayed by a specified time. The delay time, see top of the figure above, is specified by the number of clock cycles, τ , and an exponent for clock division, $clkexp$. Based on an initial clock period of 10 ns, the delay T_d can be calculated by $T_d = 10 \text{ ns} \cdot \tau \cdot 2^{clkexp}$. By the angle δ and the time T_d , a certain SOP changing speed δ/T_d is specified. The PM1000 will be triggered whenever the optical input signal surpasses this speed. In the figure above, 0.2 rad within a delay time of $10 \text{ ns} \cdot 3 \cdot 2^6 = 1920 \text{ ns}$ means a SOP speed of 103.34 krad/s. Please note that for correct operation, the delay time should always be longer than the averaging time (set by ATE).

External (user-specified) SOP for reference

It is possible to define an arbitrary Stokes vector as reference. To do so, enter three Stokes parameters, separated by semicolons, in the text field of the drop-down box and press *Set*. The Stokes vector will be normalized and transmitted to the polarimeter. One can also select one of the predefined Stokes vectors from the drop-down list. Or, set the current measured SOP as reference by pressing the button *Set Cur. SOP*. For all entered reference SOP, you can go to the orthogonal SOP by pressing *Set. Opp. SOP*.

Some applications may require the reference SOP and/or the calibration frequency to change over time, for example during a laser sweep. This can be achieved by writing the desired parameters into a table memory, see the chapter “Table memory”. Execution of the table is either triggered by a rising edge at the BNC input or by writing to the corresponding register via USB, LAN or SPI. There are two basic trigger modes, row or table:

Row Trigger Mode

In row trigger mode, the rows of the stored table are executed one-by-one upon a trigger event. After the last table row, the counter starts over from the first table row.

Table Trigger Mode

In table trigger mode, the counter starts over from the first table entry upon every trigger. Subsequent rows are executed after the dwell time delay specified in each row. After the last table row, the row counter is halted until the next trigger event occurs.

Continuous Mode

In continuous mode, the counter is not halted after the last row but executes the table continuously according to the dwell times specified in each row.

Power Event

The polarimeter can also trigger on input power events.

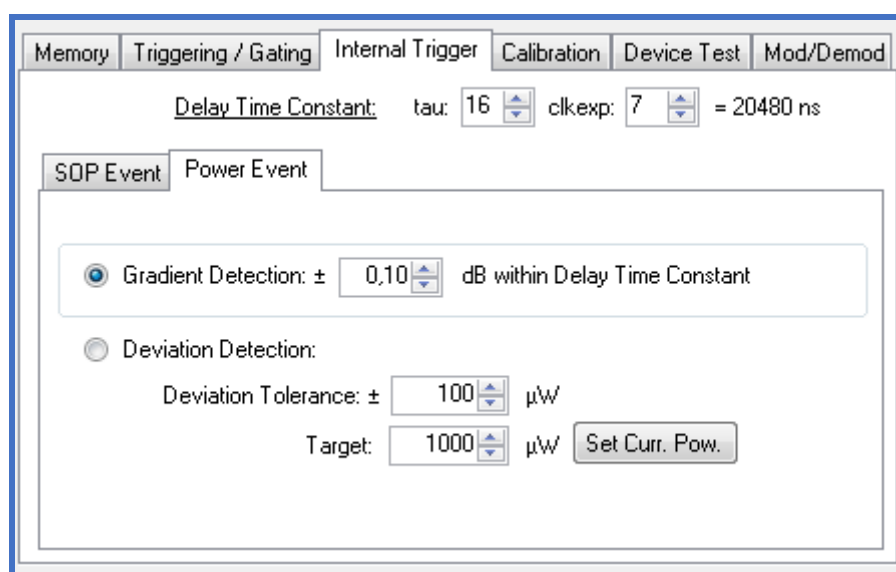
Gradient detection

This function allows triggering on power transients, for example if the power changes by more than ± 0.1 dB within 1 μ s. Here the same delay time constant is used as for SOP events. The power changing threshold can be given in dB in the GUI in steps of 0.01 and will be written as a factor in the PM1000 registers (see register description). The internal error signal changes from “0” to “1” when the power has increased or decreased by more than this factor during the delay time constant.

Deviation detection

This function changes the internal trigger signal from “0” to “1” when the current input power differs from a target power by more than a deviation tolerance, which acts as a threshold. Target and deviation tolerance powers are given in μ W. One can set the current input power as target power by pressing the button *Set Curr. Pow.* in the GUI.

If this signal is used for gating of SOP recording, “*active low*” has to be selected in the *Triggering/Gating* tab in order to let the samples with power within the deviation tolerance pass the gate.



Clock drift compensation

The *Triggered Recording* process may run for days or even for unlimited time collecting events to be captured. During this, the internal microsecond-counter of the polarimeter will drift away from the Windows PC clock. The latter may be synchronized to the true time by appropriate measures. From polarimeter firmware 1.0.7.0 on, the GUI will read the internal microsecond-counter at time of data downloading and compare it to the elapsed time derived from the PC clock. It will calculate the deviation between the two clocks and create a second, corrected timestamp for the captured data. In the created data files, the original timestamp is either called *Timestamp* or *TimestampUTC* depending on chosen time format whereas the corrected timestamp is either called *Timestamp_Win* or *TimestampUTC_Win*.

In *Triggered Recording* mode, both timestamps refer to the first SOP in the file. *Timestamp* or *TimestampUTC* differs from file to file.

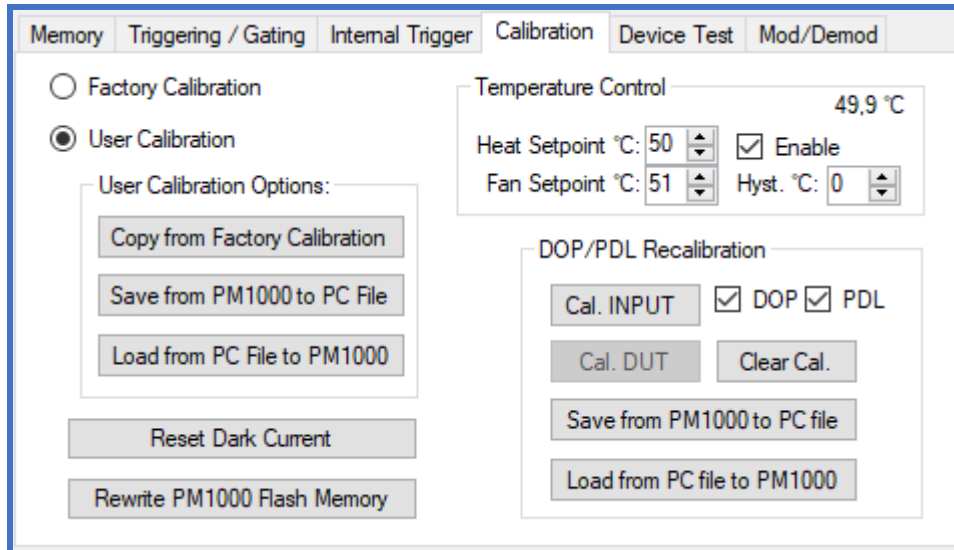
In *Dynamic Undersampling* mode, *Timestamp* or *TimestampUTC* refers to the time when recording was activated and serves as a reference for the individual SOP timestamps. *Timestamp* or *TimestampUTC* is the same in all data files of a common recording. *Timestamp_Win* or *TimestampUTC_Win* is the time of the first SOP in a file, corrected by the PC clock at time of downloading. All time corrections are applied only in integer microseconds.

Time stamp calibration

Due to varying USB latency, all timestamps in the polarimeter have an additional common error offset of up to a few milliseconds. If higher accuracy is required, the user can additionally activate *External signal* triggering in *Triggered Recording* mode and provide an event at the BNC port at a defined time. By analyzing the polarimeter clock timestamp in the created file for this event, he can correct all other timestamps and reduce the error down to 1 microsecond. If events are provided at the BNC port from time to time and are captured by *External signal* triggering, also polarimeter clock drift can be compensated with high accuracy.

User calibration set

By default, the polarimeter uses the internal factory calibration set. Using the GUI a user calibration set can be loaded to and from the polarimeter. It can also be stored in the polarimeter's permanent memory (Flash) by pressing the button "*Rewrite PM1000 Flash memory*" to be able to access it without GUI



The Flash rewriting function also permanently stores the current dark current values that can be recalibrated using the front control buttons or by pressing the button *Reset Dark Current*.

Also stored are the user rotation matrixes from the recalibration function in the Poincaré sphere window.

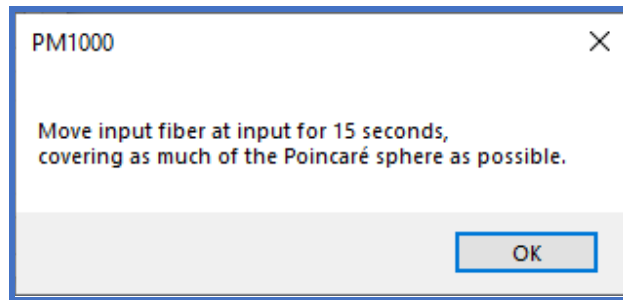
Temperature Control

The PM1000 can stabilize the internal board temperature with a heater (only with S/N \geq 102) and a cooling fan. The heater will be activated if the temperature falls below the heat setpoint. The fan will be activated if the temperature exceeds the fan setpoint plus half of a hysteresis. The fan will be deactivated if the temperature falls below the fan setpoint minus half of the hysteresis. Whenever the fan is activated, the heater is deactivated. Example values are heat setpoint 50°C, fan setpoint 51°C and fan hysteresis 0°C.

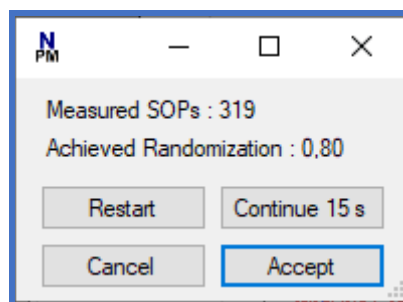
PDL/DOP Recalibration

A recalibration procedure modifies the factory calibration to improve accuracy for a fixed input signal frequency and board temperature. It can also be used to improve accuracy for a signal frequency that is not covered by the factory calibration. The user can select to modify DOP, PDL or both. DOP recalibration improves the DOP error, e.g. the deviation of the measured DOP value from "1" at fully polarized input signal with arbitrary input polarization. PDL recalibration reduces the differences in the measured power value of an input signal with constant power at different input polarizations.

To recalibrate, press the button *Cal. INPUT*. The PM1000 will show a message:



The time starts after pressing *OK*. Move the fiber at the input of the PM1000 and observe the SOP trajectory on the Poincaré sphere. Try to cover as much of the sphere as possible. If the input fiber to the PM1000 is short, it is recommended to insert a longer patchcord. Be careful not to bend the fiber so much that the signal is attenuated. Assure that no element with PDL (e.g. a connector) is placed between the moved fiber and the PM1000 input.



After the measurement time of 15 s, the PM1000 displays the achieved randomization value, which is “0” for the worst, and “1” for the best case. You can either restart, continue (for another 15 s), cancel, or accept the measurement. Once accepted, the new calibration set will be calculated and loaded to the PM1000 as user calibration set. It can be stored in the PM1000 flash memory or saved to a file as described above.

Assume the polarization change speed on the Poincare sphere is v , given in rad/s. During the chosen averaging time $10 \text{ ns} \cdot 2^{\text{ATE}}$ the arc has an arclength $= v \cdot 10 \text{ ns} \cdot 2^{\text{ATE}}$. For small arclengths the expected DOP = 1 is reduced to $1 - \text{arclength}^2/24$. So, after DOP calibration a signal with constant polarization will be displayed with a DOP of about $1 + \text{arclength}^2/24 > 1$. Let us assume we want to limit this DOP error to 0.001. This corresponds to a permitted arclength = 0.15 rad. If your speed is $v = 30 \text{ rad/s}$ this permits ATE up to 19. If $v = 1 \text{ krad/s}$ due to occasional glitches of twisted fiber in a moved manual polarization controller this permits ATE up to 14.

PDL Recalibration of DUT Path

The optional optical switch for switching between internal reference and external DUT path has some loss and PDL. While above described method calibrates PDL for the internal reference path and DOP of both paths, insertion loss and PDL of the DUT path will remain. It can be observed when measuring the Mueller matrix of a patchcord connected as the DUT. Hence especially when measuring devices with small PDL, calibration of the DUT path is recommended. To do so, connect an SMF patchcord between the DUT ports and generate a table for Mueller matrix measurement with EPS1000 as described in the next chapter *Device Test* and press *Cal. DUT*. During a time of 15 s, move the patchcord as described before for *PDL/DOP Recalibration* while PM1000 continuously measures Mueller matrix data.

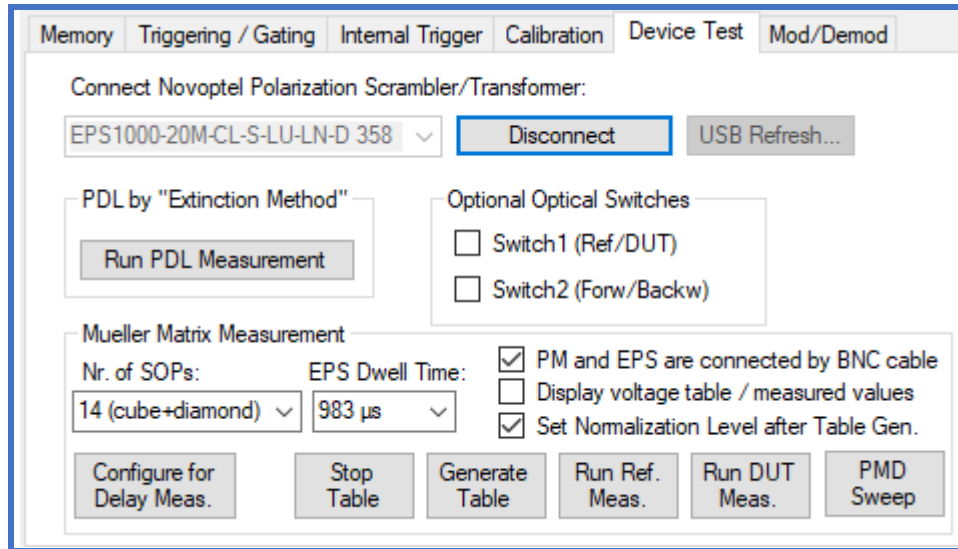
Be even more careful not to change the SOP significantly during the measurement time for 1 Mueller matrix, for example 14 states with 983 μs each = 13.76 ms. If results are unsatisfactory, e.g. you still see significant PDL in the Mueller matrix of the patchcord, slow down the patchcord movement during calibration, select a smaller dwell time of the SOP states, or select a constellation with fewer SOP states.

You can undo the DUT path calibration by pressing *Clear Cal.* Pressing *Save from PM1000 to PC file* saves the calibration matrices to a text file in Matlab readable format. The files contain

1. The general polarimeter calibration matrix $MMinv$ for which the DUT path recalibration was performed. This is usually the user calibration matrix, which has already been improved by the reference path calibration before.
2. The matrix $DUTDUT1$, which is the Mueller matrix obtained from a measurement of the DUT path containing only a patchcord, and a measurement of the internal reference path. This matrix contains the insertion loss of the optical switch and the connectors.
3. The matrix $PDLkorr$ for correction of PDL, and
4. The matrix $DEPkorr$ for correction of DOP.

Device Test

If available, a Novoptel polarization scrambler/transformer (e.g. EPS1000 or EPX1000) can be controlled by the GUI to measure polarization dependent loss (PDL) and the Mueller matrix of a connected device under test or simply align the scrambler/transformer output SOP to a specified vector.

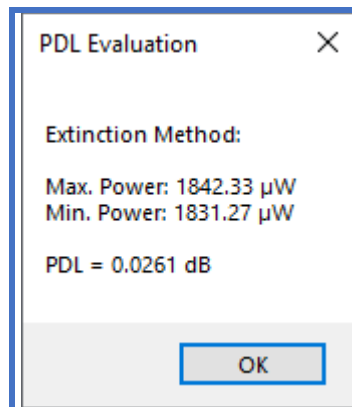


Optional Optical Switches

If the polarimeter is equipped with one or two optical switches, they can be operated from the GUI.

PDL by Extinction Method

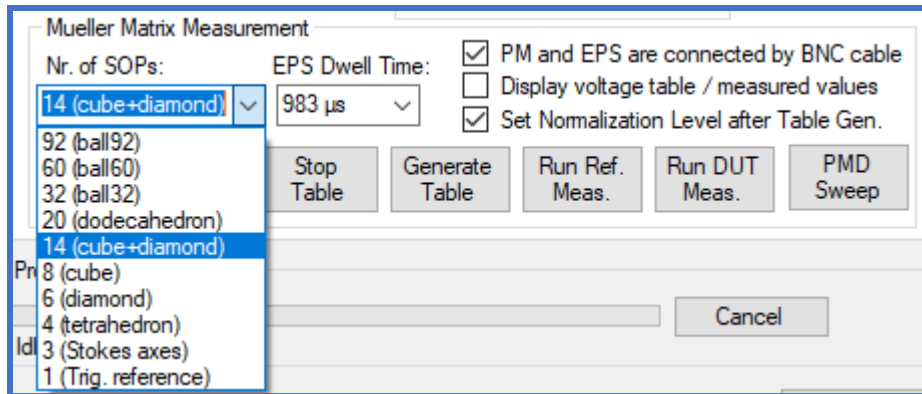
If PDL is measured by *Extinction Method*, the polarization scrambler/transformer is driven to obtain the polarization states where minimum and maximum transmissions are reached. From minimum and maximum transmission, PDL can be calculated.



Starting at "0", all 16 electrode voltages are modified subsequently. After measuring the optical power at maximum and minimum transmission, the calculated PDL will be displayed.

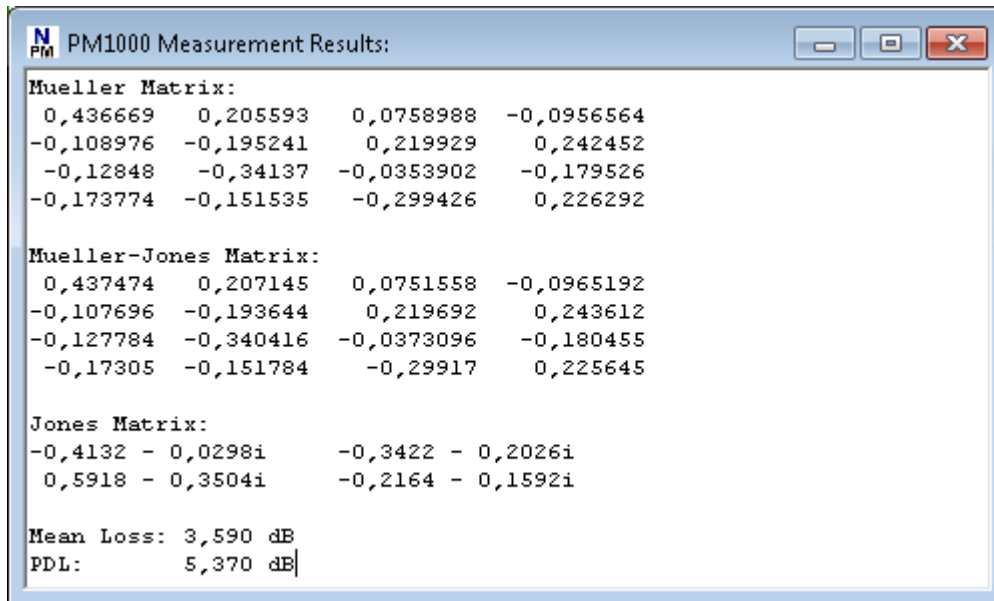
Mueller matrix measurement

PDL can also be calculated from the Mueller matrix of a DUT. To measure the Mueller matrix of a DUT, first a minimum of 4 voltage sets that lead to a predefined polarization state have to be found. Examples for most suitable polarization sets are the corners of tetrahedrons, diamonds, cubes and other polyhedrons. The GUI allows to choose between 1, 3, 4, 6, 8, 14, 20, 32, 60 and 92 polarization states, where “4” corresponds to 4 corners of a tetrahedron, “6” corresponds to the 6 normal vectors on the surface of a cube, “8” corresponds to the 8 corners of this cube, “14” is a combination of these two, and “20” corresponds to the corners of a dodecahedron. The selection of “1” or “3” is not suitable for measuring the Mueller matrix.



The EPS1000 will cyclically apply the selected number of SOPs (up to 92) to the DUT, with a dwell time in each state between 1.28 μs and 983 μs . In the above configuration, one Mueller matrix takes 14 times 983 μs , so 13.76 ms. If one needs to shorten the measurement time, for example during a fast laser sweep, one can reduce the number of SOPs and select a shorter dwell time. The fastest possible Mueller measurement takes 4 times 1.28 μs , so 5.12 μs .

If one or two optional optical switches are available, the checkboxes “*Switch 1 (Ref/DUT)*” and “*Switch 2 (Forw/Backw)*” can be checked/unchecked instead of reconnecting patchcord and DUT. With a patchcord connected between EPS1000 and polarimeter instead of the DUT (or the optional optical switch set to REF state), the GUI searches for the corresponding number of voltage sets after you have clicked on *Generate Table*. The reference measurement is performed right after the voltage sets are found. For this, the GUI switches to the non-normalized normalization mode. The reference measurement can be repeated at a later time by clicking *Run Ref. Meas.* After the DUT has been connected again (or the optional optical switch set to DUT state), the DUT measurement can be started with the *Run DUT Meas.* button. In order to get appropriate results, the input polarization to the EPS1000 must not change between Reference and DUT measurement. After the DUT measurement has finished, the Mueller matrix and the calculated PDL are displayed.



Aligning the scrambler output to specific polarizations

If “3 (Stokes axes)” is selected from the dropdown list of target SOPs, the GUI will create a voltage table which switches between horizontal ([1 0 0]), vertical ([0 1 0]) and right-circular ([0 0 1]) polarization. If “1 (Trig. Reference)” is selected, the GUI will align the polarization to the reference SOP defined in the “Internal Trigger” / “SOP Event” tab. Apart from selecting one SOP from the dropdown list, any vector can be typed into the textbox in the format “0.00; 0.00; 0.00”. The reference SOP will be normalized to “1”, e.g. if you type [1;1;1] it will be stored as [0.58; 0.58; 0.58]. In addition, you can set the current SOP as reference by pressing *Set Cur. SOP* or invert any current reference SOP by pressing *Set Opp. SOP*.



Please note that this reference SOP serves also as target SOP for the optional digital feedback signal output used for the tracking option of EP1000.

If you want to keep the generated voltage table for later usage, press “Disconnect” in the “Device Test” tab of the PM1000 GUI to disconnect from the scrambler. Then open the EPS1000 GUI, connect to the scrambler and click “Save File” in the “Synchronous/Triggered Scrambling” tab of the EPS1000 GUI. This way one can create several files that allow switching to desired polarizations by loading the corresponding file into the EPS1000 GUI. Please note that these files are only valid as long as the input polarization to the scrambler is preserved.

Synchronizing Polarimeter and Scrambler

If PM1000 and EPS1000 are connected by a BNC cable, SOP switching and SOP recording can be synchronized. In this case, the dwell time at each input SOP is reduced from about 1 s to 1 ms, which dramatically reduces measurement time.

Delaying the external trigger signal input:

Caused by internal processing, Stokes parameter signals reach the PM1000 memory with a delay of about 0.8 μ s. This means that if polarization changes and external trigger signal occur simultaneously, the source of the recorded sample lies 0.8 μ s in the past. The PM1000 can compensate the Stokes parameter time lag by delaying the trigger signal internally. If synchronism is required, the user should set $TAU=80$ and $CLKEXP=0$ in the *Triggering / Gating* tab to achieve a trigger signal delay of 0.8 μ s.

During Mueller matrix measurement with synchronized PM1000 and EPS1000 in contrast, the Stokes parameter time lag is helpful: As the EPS1000 will indicate a polarization change at the beginning of each cycle with a rising edge of the trigger signal, the PM1000 will store a sample from the time the polarization was stable, 0.8 μ s in the past. Any delay of the DUT will be added to the Stokes parameter time lag. Very long DUT delays or very short cycles can cause the PM1000 to sample in an unstable region of a cycle, e.g. in the first half of the cycle. In this case the trigger should be delayed to compensate the delay of the DUT.

Since firmware 1.0.3.1, the delay can be defined by $TAU * 2^{CLKEXP} * 10$ ns, where TAU is between 13 and 524 and $CLKEXP$ is between 0 and 15. The minimum value 13 of TAU is caused by a fundamental processing delay of the trigger signal. $CLKEXP$ causes an undersampling of the trigger input. The undersampling can increase the uncertainty of the sampling point within the cycle. Hence it is recommended to make use of the full range of TAU and let $CLKEXP$ be as small as possible.

Determining the DUT delay with synchronized PM1000 and EPS1000:

The delay of the DUT can be determined by recording a polarization event synchronous to the external trigger input using the *trigger event recording* function of the PM1000. The button *Configure for Delay Meas.* in the *Device Test* tab will load a suitable voltage table with 100 ms cycle time to the EPS1000. In the *Memory* tab, enable *Trigger-Event Recording*, press *Start Recording* and open the oscilloscope window after the measurement has been completed. By using a suitable ATE value and the zoom function of the oscilloscope view, the time difference between trigger event (the center of the figure as long as not shifted) and SOP event can be determined. Change the delay in the *Triggering / Gating* tab and repeat the measurement until the DUT delay is compensated. It is recommended to leave a small (positive) safety margin between trigger and SOP event, for example 0.5 μ s at a cycle time of 1 ms. The adjusted trigger delay will be applied during the DUT measurement of a Mueller matrix measurement. The adjusted values will be ignored in the reference measurement since most commonly a patch cord is used as the DUT and the delay will be close to zero.

Wavelength Sweep

The polarimeter GUI can measure, store and evaluate Mueller matrices obtained during a wavelength sweep and calculate the differential group delay (DGD) of the device under test (DUT). Since the sweep consist of discrete frequency steps, measurement range depends on step size. With 50 GHz frequency steps, maximum unambiguous DGD measurement is limited (by Nyquist's theorem) to $1/(2 * 50 \text{ GHz}) = 10 \text{ ps}$. If larger DGD is to be measured, smaller frequency steps must be chosen. On the other side of the range, with a maximum frequency difference of $88 * 50 \text{ GHz} = 4.4 \text{ THz}$, mean DGDs of 12 fs have been measured with a standard deviation of $\leq 3 \text{ fs}$ in experiments.

The screenshot shows the 'Wavelength Sweep' window with the following settings:

- Use Calibration File
- Limit PMD Evaluation Range
- Startchannel: 1
- No. of channels combined: 2
- No. of PMD values (0=all): 0
- Novoptel LU1000, connected by USB or LAN
- Device: LU1000-CC-FP-L-D 24
- Buttons: Disconnect, USB Refresh...
- LU1000 Properties:**
 - LU1000-CC-FP-L-D 24
 - Device Firmware Version: 1.0.1.5
 - 2 Laser(s) installed.
 - Laser 1:
 - Min. Frequency: 191,70 THz
 - Max. Frequency: 196,10 THz
 - Grid Spacing: 050,00 GHz
 - Max. Channel Nr.: 89
 - Laser 2:
 - Min. Frequency: 191,70 THz
 - Max. Frequency: 196,10 THz
- Sweep Settings:**
 - Laser Nr.: 1
 - First Channel: 1
 - Last Channel: 89
 - Channel Step: 1
 - Pause Time [s]: 0,05
 - Automatic switch Ref. /DUT at each Freq.
 - Buttons: Run Ref. Sweep, Run DUT Sweep
- Other laser, controlled by user
 - Laser with blanking between steps
 - Laser with step trigger out
 - Frequency, Start [THz]: 191,70
 - Step [GHz]: 50,00
 - Wavelength, Start [nm]: 1520,00
 - Step [nm]: 0,100
 - Channels: 801
 - Stopfreq.: 198.00 THz (1620.00 nm)
 - Buttons: Rec. Ref. Sweep, Rec. DUT Sweep
- Buttons: Save Data to File, Close

Sweep with Novoptel LU1000:

If a Novoptel laser unit LU1000 is connected by USB to the same PC, it can be controlled by the polarimeter GUI during the wavelength sweep. After the GUI connects to the LU1000, it displays the laser module capabilities and sets the sweep settings to cover the maximum possible wavelength range. The pause time (here: 50 ms) during the channel switching also depends on the laser module type and has to be checked against the laser module data sheet by the user.

There are two possibilities to perform the sweep(s):

- a) One sweep of the reference path (button *Run Ref. Sweep*), then switching to the DUT path with the switch control on the polarimeter main window, then one sweep of the DUT path (button *Run DUT Sweep*). One reference sweep can be used for several subsequent DUT sweeps.
- b) One combined sweep, during which the optical switch is automatically toggled at each frequency to measure both reference and DUT. This means more frequent switching. Switch lifetime is defined by the manufacturer as $>10^7$ cycles.

Saving measurement data:

After the DUT sweep (or the combined sweep in above case b)) the calculated DGD value will be displayed. For further analysis, the obtained data can be saved to a text file in Matlab format. The saved data contains

- current laser frequency,
- Mueller matrix,
- Mueller-Jones matrix,
- Jones matrix,
- mean loss and
- PDL

for each wavelength during the sweep.

Sweep with other laser, controlled by user:

If no LU1000 is available, the sweep can be performed by any other laser that meets one of the conditions a), b) below. Start frequency/wavelength, step size and number of frequencies/wavelengths have to be defined before the sweep.

- a) While switching from one channel to the next, the output power must drop significantly (by >10 dB) for at least 2 Milliseconds. This way, the GUI can indicate a number of laser pulses corresponding to the different wavelengths in the measured data. If the number of detected pulses differs from the set value, a warning will be displayed after the measurement. The user must set the laser to a channel >1 before the sweep, so that the switching to channel 1 upon starting the sweep can be recognized by the associated intensity dip. The width of the laser pulses must exceed the measurement time for one Mueller matrix. E.g. if the *Nr. of SOPs* for each measurement is set to *14 (cube+diamond)* with dwell time 1 ms in the main window, each Mueller matrix measurement takes $14 * 1$ ms, and so the laser pulse width should be >14 ms + intensity dip time. To start the reference measurement, click *Ext. Ref Sweep*. Then manually start the sweep of the laser. After the laser finished the sweep, stop the measurement with the *cancel* button at the bottom of the polarimeter main window.

- b) The laser provides a rising edge in a LVCMOS33 trigger signal after each sweep step. This trigger signal must be applied at the BNC jack labeled “Laser” at the rear panel. Ensure that the laser step time exceeds the Mueller matrix measurement time. To start the reference measurement, click *Ext. Ref Sweep*. Then manually start the sweep of the laser. The progress of the measurement will be shown on the progress bar in the main window. If no progress is reported, check BNC connection between laser and PM1000. After the specified number of Mueller matrixes have been measured, the process will stop.

To measure the DUT, switch the paths and repeat above steps except that you now click *Ext. DUT Sweep*. Saving data and using calibration files is the same as with LU1000. Combined sweeps of Ref. + DUT are not possible here.

Limit PMD Evaluation Range:

The PMD (DGD) value displayed in the GUI and written in to the data file is normally obtained by evaluating the full frequency range of the laser sweep.

The frequency range can be limited by activating the checkbox *Limit PMD Evaluation Range*. It is possible to

- Exclude some channels from the evaluation: For example, if you set *Startchannel* to “3”, channels 1 and 2 will be excluded from evaluation.
- Limit the number of channels per PMD value: For example, if you set *No. of channels combined* to “2”, PMD will be calculated by only using the frequency difference between two neighbor channels. If 89 channels are in evaluation, you will get 88 PMD values.
- Limit the number of PMD values: From the 88 PMD values in the above example, you can discard the last 8 if you set the *No. of PMD values* to 80. If set to 0, all possible PMD values will be calculated depending on *Startchannel* and *No. of channels combined*.

Using calibration files:

Sometimes one wants to determine the changes in a DUT, for instance by repositioning of a patchcord or applying a voltage to a photonic circuit. Let us define DUT1 and DUT0 to be the DUT with and without change, respectively. It is straightforward to measure DUT0 as the reference and DUT1 as the DUT. The result is DUT1 “-” DUT0. We put the minus sign in quotation marks “-” because in reality the calculation involves no subtraction. This works well. However, over extended time the polarization states generated by the EPS1000 may drift. In such cases, for measurements over extended time, the following is helpful:

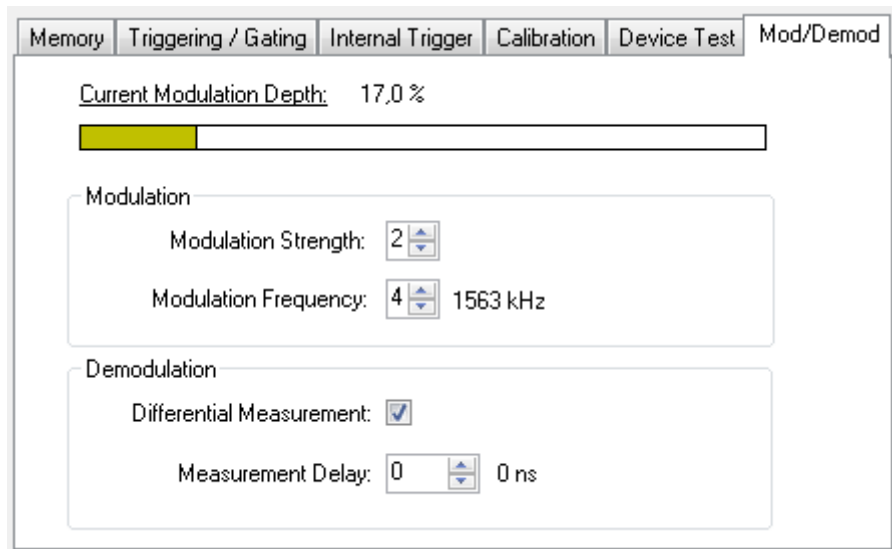
- 1) Sweep with the reference path: The internal reference path, which we call REF0 at this time, is measured as the reference.
- 2) Sweep with the DUT path: The external DUT0 is measured as the DUT.
- 3) The result is DUT0 “-” REF0. Save the measurement data to a file.

- 4) Activate *Use Calibration File* and select the formerly saved file in the upcoming dialogue. In the time elapsed since the measurements DUT0, REF0, the polarization states of the EPS1000 may have drifted, or may have been searched anew. This does not matter significantly.
- 5) Sweep with the reference path: The internal reference path, which we call REF1 at this time, is measured as the reference.
- 6) Sweep with the DUT path: The external DUT1 is measured as the DUT.
- 7) The displayed result will be $(DUT1 \text{ “-“ } REF1) \text{ “-“ } (DUT0 \text{ “-“ } REF0) = (DUT1 \text{ “-“ } DUT0) \text{ “-“ } (REF1 \text{ “-“ } REF0)$, i.e., DUT change “minus” reference change.

The measurements can be verified with, say, a patchcord as DUT. If it is left unchanged all the time, $DUT1 \text{ “-“ } DUT0$ and $(DUT1 \text{ “-“ } REF1) \text{ “-“ } (DUT0 \text{ “-“ } REF0)$ both yield a Mueller matrix very close to identity. But if a lot of time has elapsed between measurements DUT0, DUT1, then $(DUT1 \text{ “-“ } REF1) \text{ “-“ } (DUT0 \text{ “-“ } REF0)$ (with REF0 measured together with DUT0, and REF1 together with DUT1) will generally be closer to the identity matrix than $DUT1 \text{ “-“ } DUT0$.

Laser Modulation / Demodulation

The PM1000 can optionally be equipped with a second BNC output for intensity modulation of a laser. This output has to be connected to the modulation input of a Novoptel LU1000 laser unit with intensity modulation option. The PM1000 synchronously demodulates the laser signal during sampling, which is also known as lock-in detection. The lock-in detection is superior when measuring a signal with superimposed low-frequency disturbance/noise, by shifting the measurement to a frequency where no or just little disturbance/noise is present. Namely, unwanted optical signals which do not carry this laser modulation will be suppressed.



Modulation:

Two parameters determine the modulation signal. *Modulation Strength* is a measure for the modulation signal amplitude and can be selected between 0 (no modulation) and 4 (highest modulation amplitude). The *Modulation Frequency* is determined by an integer number between 2 (6.25 MHz) and 8 (98 kHz), i.e. each integer step halves the modulation frequency. A graphical bar and a numeric value in percent show the resulting modulation depth of the laser signal at the top of the window. The modulation depth depends on the two selected parameters, but also on output power and modulation efficiency of the laser and the sensitivity mode of the PM1000. The higher the laser power, the lower is the resulting modulation depth (in percent).

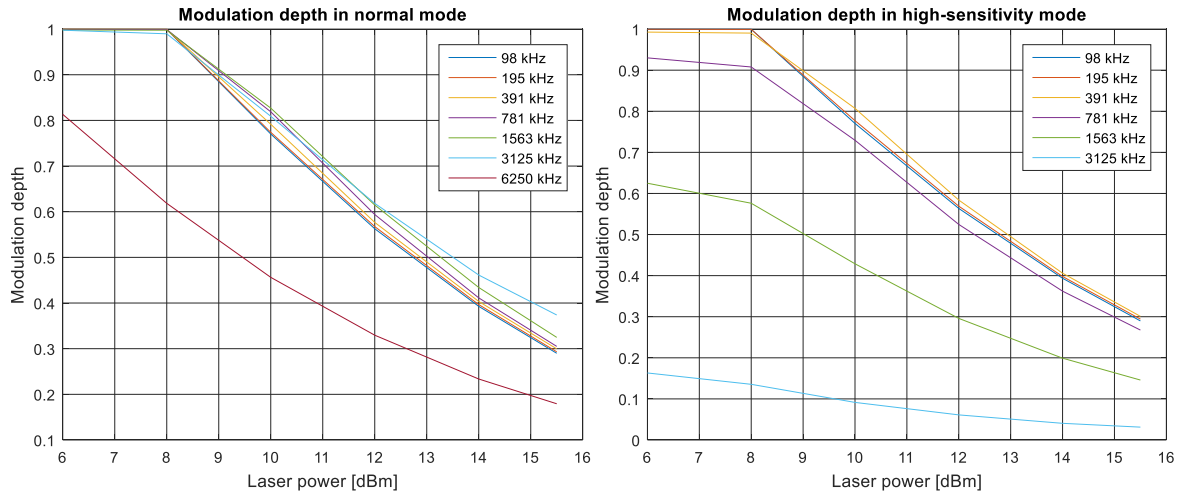


Fig. 2: Modulation depth depending on laser output power, modulation strength = 4

It is recommended to operate with modulation depths of about 50%. Larger modulation depths can cause mode hops or slow response. Current modulation (in mA) and optical power modulation (in mW) inside the LU1000 is proportional to modulation strength. So, for a given modulation strength, modulation depth is low at high mean powers and high at low mean powers. Furthermore, associated FM is on the order of 100 MHz and decreases with increasing modulation frequency.

Fig. 3 shows that with an output power of about +13 dBm, a 50% modulation depth is reached for modulation frequencies 98 kHz ... 1563 kHz. This is the recommended usage. In the high-sensitivity range with limited bandwidth, response is significantly reduced already at 3125 kHz. In the normal mode response is significantly reduced only at 6250 kHz, due to the laser's modulation bandwidth.

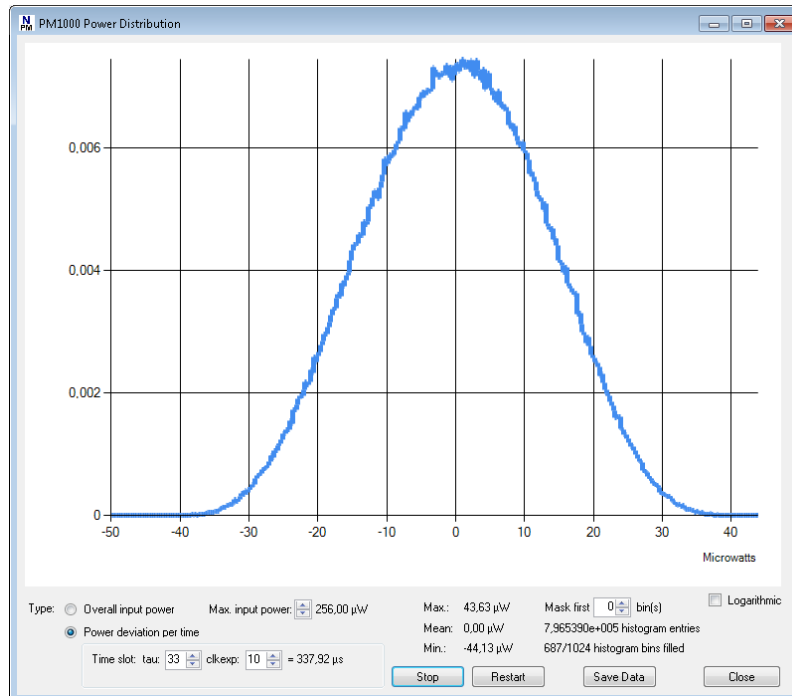
Demodulation:

The checkbox *Differential Measurement* enables the demodulation. When activated, the signal is averaged over quarters of the modulation period. The PM1000 takes the signal difference between 2nd and 4th quarter of the modulation period to generate the demodulated measurement signal. Please note that in this mode, the stored and displayed signal power depends on the modulation depth and can therefore be lower than the actual or mean input power.

Successful demodulation depends on the signal delay between the source modulation and the optical input signal of the PM1000. When measuring Mueller matrices or PDL, also the DUT can add extra delay. This gets more important at higher modulation frequencies. The user can take into account increased signal delay by setting the additional *Measurement Delay* in steps of 10 ns until the current modulation depth reaches a maximum. For Mueller matrices or PDL measurements, the user may have to set different delays for reference and DUT measurement.

Input Power Histograms

The polarimeter can accumulate the actual input power value in a histogram. The GUI configures, reads and displays the histogram.



If desired, the user can switch to “Power deviation per time”, where only the difference between the actual power value and a delayed power value is put into the histogram. The delay time can be determined by the values tau and clkexp and can be calculated by $T_d = 10 \text{ ns} \cdot \tau \cdot 2^{\text{clkexp}}$.

A new value is put into the histogram every 20 ns if clkexp is 0 or 1. For other values of clkexp, the period is $10 \text{ ns} \cdot 2^{\text{clkexp}}$.

The histogram data can be saved to a text file.

SOP Speed Histograms

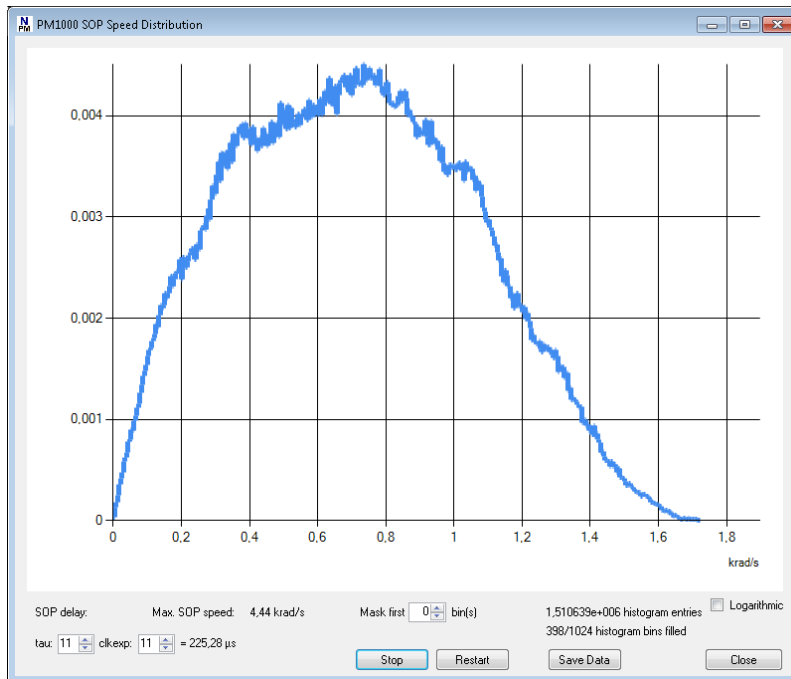
The polarimeter can calculate the momentary SOP speed and accumulate the values in a histogram. For this purpose, the current SOP is compared with a delayed copy of an earlier SOP. Again, the delay T_d is calculated by $T_d = 10 \text{ ns} \cdot \tau \cdot 2^{\text{clkexp}}$.

If a large SOP arc exceeds the histogram range, it is put into the last histogram bin with number 1024. If bin number 1024 is filled during a measurement, the user should decrease the delay time so that the future SOP arcs become smaller and match the histogram range.

A new value is put into the histogram every 20 ns if clkexp is 0 or 1. For other values of clkexp, the period is $10 \text{ ns} \cdot 2^{\text{clkexp}}$.

The histogram data can be saved to a text file.

In the logarithmic plot, the y-axis gives the count readings of the histogram bins. In the linear plot, the y-axis is normalized to the sum of all count readings.



Using Matlab to analyze stored data

As described in the sections above, the GUI allows storing the measured data in form of text or binary files. These files can be opened for further investigation by Matlab or other programs in an easy way. Since version 2.0.0.0 of the GUI, timestamps are included in the files for each SOP.

The files start with a header that contains the measurement meta data. The header of text files is formatted in such a way that it can directly be evaluated by Matlab after the hash (“#”) signs are removed:

```
# Timestamp='2021/07/09 12:49:07.657688360';
# Timestamp_Win='2021/07/09 12:49:07.657665360';
# ATE=7;
# SamplePeriod_ns=1280;
# ME=10;
# Data1Name='Power';
# PowerLeftShift=4;
# Normalization=1;
# NonNormPowRef=1000;
# TriggerGatingReg=1;
# CyclicRecording=1;
# PreTriggerSamples=0.125;
# TriggerSource='SOP 19.56 krad/s';
# SOPTriggerConfiguration=799;
# SOPTriggerThreshold=655;
# SOPTriggerPowerThreshold=1;
# POWTriggerReference=1000;
# POWTriggerThreshold=100;
```

In binary files, the length of the header is given by the variable *headerlength*, which itself stands at the beginning of the header. It is at least 256. This means that the first 256 bytes of the file (or more, if *headerlength* is larger) represent text in ASCII format which should be evaluated to get the measurement metadata. The measurement data starts after the header at byte 256 (if header bytes are counted from 0 to 255), i.e. byte 257 in total. The variable *Timestamp* is a timestamp at the last sample of the measurement data. This time counting inside the PM1000 is synchronized with the host PC at the beginning of the recording with an uncertainty of about 1 ms. This timestamp can be used to calculate the trigger moment when the duration of post-trigger data sampling is subtracted. *ATE*, *ME* and *Normalization* refer to the selected settings of the same name. *SamplePeriod_ns* is the sample period in nanoseconds, derived from *ATE*. *Data1Name* is either “Power” or “DOP”, depending on the data selection for the Stokes parameter S_0 . When “Power” is selected, the value *PowerLeftShift* determines the amount of fractional bits in the data of S_0 . For example, if “PowerLeftShift=4”, a value S_0 of 17520 in the file corresponds to an input power of $17520 \cdot 2^{-4} = 1095$ Microwatts.

In the “Non-normalization” mode, the Stokes parameters S_1 to S_3 are only normalized to the specified power reference, given in the variable *NonNormPowRef*.

TriggerGatingReg is the content of register (512+92) which defines the triggering and gating conditions.

When the PM1000 is in cyclic (triggered) recording mode (*CyclicRecording*=1), *PreTriggerSamples* states the relative amount of pre-trigger samples in the data. *TriggerSource* reveals the actual trigger event, either “SOP”, “POW” or “EXT”, notwithstanding the fact that more than one trigger source may have been configured in the tab “Triggering / Gating”. “POW” and “EXT” are followed by the trigger threshold.

TriggerConfiguration refers to the trigger signal configuration register (512+86) and *TriggerThreshold* is the value of the trigger threshold register (512+91). *SOPTriggerPowerThreshold* is the power in Microwatts, under which the SOP trigger would be blocked.

POWTriggerReference and *POWTriggerThreshold* give the power reference and power threshold for the power event trigger signal.

In contrast to binary files, the byte length of the header in text files is not specified. Hence the variable *headerlength* is missing. Instead, all lines of the header begin with a hash sign to distinguish header from subsequent measurement data.

The measurement data in text files are comma-separated values that also allow opening the file in Excel for instance. The binary files cannot be opened by Excel. If files were saved in binary format by mistake, they can be opened in the GUI's oscilloscope window and saved again, this time in text format.

The following Matlab or GNU Octave (www.octave.org) function `pm1000plot.m` opens a file and plots the contained data. This function is available at <https://www.novoptel.de/Home/Downloads/pm1000plot.m> or <https://www.novoptel.eu/Home/Downloads/pm1000plot.m>. Since standard browsers open .m files as text files, simply save the file `pm1000plot.m` from within the browser.

```
% This is to plot the Stokes parameters loaded from a Novoptel PM1000 polarimeter
% supports GUI version 2.0.0.0, with Timestamps
% Copyright 2020 Benjamin Koch, Novoptel GmbH

% Usage: pm1000plot(filename, withtimestamps);
% filename can for instance be 'myrecord.txt' (text file) or 'myrecord.bin' (binary file).
% For GUI >=2.0.0.0, firmware >=1.0.6.0, the records contain timestamps.
% To accomodate this, withtimestamps is chosen as 1 or, if dropped, is chosen as 1 by default.
% Examples: pm1000plot('myrecord.txt'); pm1000plot('myrecord.bin');
%           pm1000plot('myrecord.txt',1); pm1000plot('myrecord.bin',1);
% For GUI <2.0.0.0, there are no timestamps, and one sets withtimestamps as 0.
% Examples: pm1000plot('myrecord.txt',0); pm1000plot('myrecord.bin',0);

function pm1000plot(filename, withtimestamps)

if (nargin<2) || isempty(withtimestamps)
    withtimestamps=1;
end

% open the data file
FID=fopen(filename);

if sum(filename(end-3:end)=='\.bin')==4, % this is a binary file

    % get the header length (mimimum 256 bytes)
    C=fread(FID, 256, 'uint8');
    headerstrings=strsplit(char(transpose(C)), char(13));
    try eval(char(headerstrings(1)))
    catch err
        disp(sprintf('ERROR: Unknown command: %s', char(headerstrings(1))));
        pause
    end

    % get the full header with meta data
    fseek(FID, 0, 'bof');
    C=fread(FID, headerlength, 'uint8');
    headerstrings=strsplit(char(transpose(C)), char(13));
    size_headerstrings=size(headerstrings);
    nlines=size_headerstrings(2);

    % load information from meta data
    if nlines>2,
        for ii=2:nlines-1
```

```

        try eval(char(headerstrings(ii)))
        catch err
            disp(sprintf('ERROR: Unknown command: %s', char(headerstrings(ii))));
            pause
        end
    end;
end;

% get the data after the header
fseek(FID, headerlength, 'bof');
C=fread(FID, 'uint16');

if withtimestamps,
    % get the timestamps and stokes parameters
    TS_N = reshape(C, 8, floor(length(C)/8));

    % get the timestamps, referred to the first sample
    Timestamp_ns = uint64(TS_N(4,:)*2^48) + uint64(TS_N(3,:)*2^32) ...
        + uint64(TS_N(2,:)*2^16) + uint64(TS_N(1,:));
    Timestamp_ns = Timestamp_ns - Timestamp_ns(1);

    % restore the Stokes parameters
    N=TS_N(5:8,:);
else
    N = reshape(C, 4, floor(length(C)/4));
    Timestamp_ns = (1:length(N))*SamplePeriod_ns;
end;

else % this is text file

    % get the meta data
    C=textscan(FID, '#%s', 'Delimiter', '@');

    % load information from meta data
    if length(C{1})>0,
        for ii = 1:length(C{1}),
            try eval(C{1}{ii})
            catch err
                disp(sprintf('ERROR: Unknown command: %s', C{1}{ii}));
            end
        end
    end

    if withtimestamps,
        % get the timestamps and stokes parameters
        NN=textscan(FID, '%f %f %f %f %f', 'Delimiter', ',');

        clear Timestamp_ns;
        Timestamp_ns(1,:)=NN{1};

        % restore the Stokes parameters
        clear N
        for ii=2:5,
            N(ii-1,:)=NN{ii};
        end;
    else
        % get the stokes parameters
        NN=textscan(FID, '%f %f %f %f', 'Delimiter', ',');

        % restore the Stokes parameters
        clear N
        for ii=1:4,
            N(ii,:)=NN{ii};
        end;

        Timestamp_ns = (1:length(N))*SamplePeriod_ns;
    end

end;

% close the data file
fclose(FID);

```

```
% remove offset from Stokes parameters 1..3
N(2:4,:) = N(2:4,:) - 2^15;
S = N / 2^15;

% plot the data
figure;
x = Timestamp_ns; %X-axis in Nanoseconds
plot(x, S(1,:), 'k', x, S(2,:), 'r', x, S(3,:), 'b', ...
      x, S(4,:), 'g');
legend(DataName, 'Stokes 1', 'Stokes 2', 'Stokes 3');
xlabel('Nanoseconds');
grid on;
```

Operation of the instrument using register access

The polarimeter is controlled by reading from and writing to internal control registers, see chapter “register description”.

Access the USB driver

The USB driver has to be installed on your system and the instrument needs to be connected using a USB cable.

Support for Matlab

Matlab needs a header file like *ftd2xx.h* from FTDI to access the USB 2.0 driver directly. Novoptel provides the header version *matftd2xx.h*, in which the data types are modified to become compatible with current Matlab versions.

You will find help about communicating to a driver at

<http://www.mathworks.com/help/techdoc/ref/loadlibrary.html>

The different functions of the driver can be seen from the header file. Information about each function is provided at <http://www.ftdichip.com/Support/Knowledgebase/index.html>

To avoid accessing the driver with Matlab directly, Novoptel provides precompiled MEX files for basic read and write functions. Examples of Matlab communication scripts are included in Matlab_USB_Support_Files.zip, which can be downloaded from

https://www.novoptel.de/Home/Downloads_en.php and
https://www.novoptel.eu/Home/Downloads_en.php.

USB 2.0 Settings

The following settings have to be applied within Matlab (or other programs) to enable USB communication:

Baud Rate	230400 baud
Word Length	8 Bits
Stop Bits	1 Bit
Parity	0 Bit

To speed up sequential read and write operations, we further recommend the following setting:

USB Latency Timer	2 ms
--------------------------	------

USB 2.0 Transfer protocol

The instrument is controlled by reading from and writing to USB registers. The register address line is 12 bits wide, while each register stores 16 bits. All communication is initiated by the USB host, e.g. the Matlab program.

Writing to a register uses a 9 byte data packet. Each byte represents an ASCII-coded character. The packet starts with the ASCII-character “W” and ends with the ASCII-code for *carriage return*.

Send *write data* packet

„W“	A(2)	A(1)	A(0)	D(3)	D(2)	D(1)	D(0)	^CR
-----	------	------	------	------	------	------	------	-----

The 12 bit register address A is sent using 3 bytes, each containing the ASCII-character of the hexadecimal numbers 0 to F which represents the 4 bit nibble. The character of the most significant nibble is sent first. The 16 bit data, which should be written into the register, is sent with 4 bytes using the same coding as the register address.

Reading data from a register requires the host to send a *request data* packet to the instrument. The packet starts with the ASCII-character “R”, followed by the register address coded the same way as in *write data* packets.

Send *request data* packet

„R“	A(2)	A(1)	A(0)	„0“	„0“	„0“	„0“	^CR
-----	------	------	------	-----	-----	-----	-----	-----

After receiving the *request data* packet, the instrument sends the requested data packet to the host:

D(3)	D(2)	D(1)	D(0)	CR
------	------	------	------	----

Burst transfer

To increase transfer speed, consecutive addresses of an internal memory can be transferred at once. Additional packets are defined for this purpose:

Send *Set burst address register* packet

„X“	„0“	„0“	„0“	D(3)	D(2)	D(1)	D(0)	^CR
-----	-----	-----	-----	------	------	------	------	-----

The data D is the address of the register that will be incremented during burst transfer. In most cases, this register will represent the read address of a memory.

Send *Set start value* packet

„X“	„0“	„0“	„1“	D(3)	D(2)	D(1)	D(0)	^CR
-----	-----	-----	-----	------	------	------	------	-----

The data D is the start value of the counting.

Send *Set stop value* packet

„X“	„0“	„0“	„2“	D(3)	D(2)	D(1)	D(0)	^CR
-----	-----	-----	-----	------	------	------	------	-----

The data D is the stop value of the counting

Send *Set read address* packet

„X“	„0“	„0“	„3“	D(3)	D(2)	D(1)	D(0)	^CR
-----	-----	-----	-----	------	------	------	------	-----

The data D is the address of a register that contains the data to be sent during burst transfer. In most cases, this register will represent the data output of a memory. After sending this packet, burst transfer will start. Beginning with the start value, the address register will be incremented until it reaches the stop value. After every step, the data appearing in the read address register will be transferred to the host.

SDRAM data transfer

To increase transmission speed when reading from the SDRAM of the PM1000, parts of the SDRAM can be transferred in a single packet. The SDRAM part is defined by the start address and the number of addresses to be transferred. Since the start address is 26 bit wide, it requires 2 registers for definition. One SDRAM address contains one SOP (4 Stokes parameters * 16 bit = 64 bit). Since the buffer size is 2^{16} bytes, the packet size is limited to 2^{13} SOPs. The data transfer sequence is as follows:

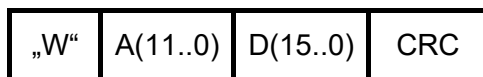
- write lower 16 bits of start address into register number 512+105
- write upper 10 bits of start address into register number 512+106
- write number of addresses to be transferred into register number 512+107
- write "39293" into register number 512+104 (this triggers the transfer)
- wait for buffer to be filled, then read the buffer

USB 3.0 Transfer protocol

The protocol of the USB 3.0 interface differs from USB 2.0. CRC words and ACK packets ensure correct data transfer. The word size is 16 bit instead of 8 bit.

Write data packet

Writing to a register via USB 3.0 requires a 4 word (1 word = 16 bit) data packet. The packet starts again with the ASCII-code 0x57 (for "W"), but here as a 16 bit word instead of a byte.



The 12 bit register address is sent in the second word, followed by the 16 bit register data in another word. The packet is completed by a cyclic redundancy check (CRC) word. The CRC value can be calculated by the following c-code lines, assuming the array data_p contains the write data packet:

```

crc = 0xFFFF;
length = 3;
while (length--)
{
    crc = (crc<<1) | (crc>>15); // cyclic shift of crc
    crc ^= *data_p++;          // xor with data
}

```

After the PM1000 has received the write data packet, it sends an acknowledgement (ACK) packet:



At least the first word of the ACK packet should be checked by the transmission script. If CRC_OK equals 52428, the PM1000 has received a packet with correct CRC word. The rest

of the packet are command (CMD, = "W" in this case), register address and register data as in the write data packet sent to the PM1000.

Request data packet

„R“	A(11..0)	0	CRC
-----	----------	---	-----

After receiving the *request data* packet, the instrument sends the requested data packet to the host:

FIFO_LENGTH	PM_CRC	D(15..0)	FIFO_CRC
-------------	--------	----------	----------

FIFO_LENGTH and FIFO_CRC are for SDRAM data transfer and can be ignored here. D(15..0) is the data read from the register. PM_CRC is the CRC calculated from the request packet and the register data word. It can be calculated with the following c-code lines:

```
crc = crc_req; // crc as sent in the request packet
crc = (crc<<1) | (crc>>15); // cyclic shift of crc
crc ^= data; // xor with received data word
```

SDRAM data transfer

The USB 3.0 interface also supports SDRAM data transfer. The buffer sizes is smaller (4096 bytes), which limits the number of SOPs/addresses per packet to 512. Up to the triggering of the data transfer ("39293" to register 512+104), the packet sequence is the same as in the USB 2.0 case. After the transfer triggering, one must continuously read an arbitrary register and check the FIFO_LENGTH packet until its value reaches the requested number of SOPs. Then, the interface has to be switched into the FIFO mode by the following packet:

„F“	0	0	CRC
-----	---	---	-----

This packet will not be acknowledged. Instead, the requested number of SOPs can now be read from the interface. The SOP data can be verified by calculating the CRC over the complete packet and compare it with FIFO_CRC of the last request data packet.

TCP/IP (LAN) Communication

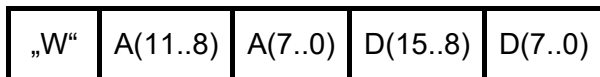
The user can set the IP address, gateway and subnet mask via the front buttons. After the next power-up, the PM1000 will open a TCP/IP socket using the entered settings and wait for a connection.

TCP/IP Settings

Port: 5025
Input buffer: 16384 Bytes

Write data packet

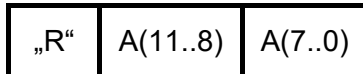
In contrast to USB 2.0 communication, writing to a register via TCP/IP requires only a 5 byte data packet. The packet starts with the ASCII-code 0x57 (for "W").



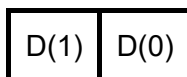
The 12 bit register address is sent first in two bytes, followed by the 16 bit register data in another two bytes.

Reading data over TCP/IP requires the program to send a *request data* packet of 3 bytes to the instrument. The packet starts with the ASCII-code 0x52 (for "R"), followed by the register address coded the same way as in *write data* packets.

Request data packet



After receiving the *request data* packet, the instrument sends the requested data packet to the host:



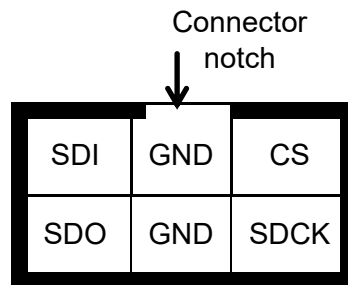
SDRAM data transfer

The SDRAM data transfer sequence is identical to the USB 2.0 case, except for the following:

- The buffer size is 16384 bytes
- The trigger code is "39294" instead of "39293"

SPI Communication

All internal registers can also be accessed by SPI. The SPI interface allows communication with much lower latency than USB. The SPI connector at the backside of the device provides the following connection:



Transmission starts with falling edge of CS and ends with rising edge of CS. After falling edge of CS, the command is transmitted. SDI is sampled with rising edge of SCK. Maximum SCK frequency is 500 kHz. Command and data word length is 16 bit each. MSB of command and data word is sent first, LSB last. If a valid *register read* (RDREG) command is received, the SDO output register shifts with falling edge of SCK to transmit the requested data word. Otherwise SDO remains in high impedance state. Data transfer to the device continues directly after transmitting a *register write* (WRREG) command.

Serial interface (SPI) commands

Command	Code	Data	Function
RDREG	0XXXh	OUT	Read register XXXh (see section <i>Register description</i>)
WRREG	1XXXh	IN	Write register XXXh (see section <i>Register description</i>)

Serial interface (SPI) timing

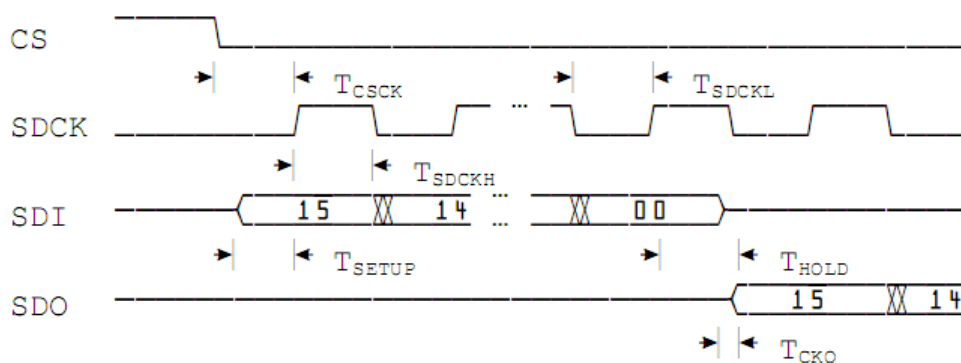


Fig. 3: Timing of SPI port.

Symbol	Description	Min	Max	Units
T_{CSCK}	CS low to SDCK high	120	–	ns
T_{CKCS}	SDCK low to CS high	120	–	ns
T_{SDCKL}	SDCKL low time	1	–	μ s
T_{SDCKH}	SDCKL high time	1	–	μ s

T _{SETUP}	SDI egde to SDCK high (setup time)	30	–	ns
T _{HOLD}	SDCK to SDI edge (hold time)	30	–	ns
T _{CKO}	SDCK edge to stable SDO	–	100	ns

Operation of the instrument using other programs

The USB vendor <http://www.ftdichip.com/Support/Knowledgebase/index.html> provides examples for USB access using other programs, for example LabVIEW®. A rudimentary example of a LabVIEW-VI (virtual instrument) is available from Novoptel upon request.

Firmware upgrade

Via the JTAG port the user can upgrade the firmware, if ever needed.

The schematic and timing of the JTAG port correspond to that detailed in Spartan-6 FPGA Configuration User Guide UG380 (v2.6) June 20, 2014 from Xilinx (www.xilinx.com).

Acronyms

ATE	Averaging time exponent
DOP	Degree of polarization
DUT	Device under test
DVI	Digital visual interface
FPGA	Field-programmable gate array
GUI	Graphical user interface
HDMI	High definition multimedia interface
LAN	Local Area Network
LSB	Least significant bit
JTAG	Joint test action group
ME	Memory exponent
MSB	Most significant bit
PC	Personal computer
PDL	Polarization-dependent loss
PMD	Polarization mode dispersion
PPS	Pulse per second
SOP	State of polarization
SPI	Serial peripheral interface
USB	Universal serial bus