Nano-Roughness Scatterometer
Product Requirements Document
Sydor Optics

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Document Number 00001

Revisions Level	Date
E	12-11-2015

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Authentication Block

Rev	Description	Date	Authorization
A	Initial PRD	10-26-2015	AQA
B	PRD Revision 1: Clarified 1 minute per side, not per part. Narrowed temperature and humidity operation range. Clarified “Standard Shop floor environment”. Clarified other specifications. Added sections: Current Method for testing, Resources Available, Current List of Experiments, Design Description, Bill of Materials, Timeline	11-17-2015	AQA
C	Formatting, Table of Contents	11/25/2015	AQA
D	Customer info, Roles, UV regulatory issues, Added specification table, system block diagram Developed Testing Protocol Expanded BoM	12/6/2015	AQA
E	Edited system block diagram; Updated BoM Created Initial Photon Budget Calculation	12/11/15	AQA

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The Surface Nano-Roughness Instrument is a customer driven product. As such, its design inputs were derived from interactions with Sydor Optics and our faculty adviser Wayne H. Knox, as well as Per Adamson.

Vision:

The customer would ultimately like to develop an instrument which can quantitatively distinguish between laser grade and standard grade optical flats with an accuracy of greater than 99 percent correlation. This measurement should be able to be performed in under 1 minute per side of each flat. The instrument should be production robust. We are responsible for developing working instrument with a user-friendly interface.

Customer Information:

Sydor Optics is a local Rochester optics manufacturing company. Sydor Optics is the global leader in custom flat optics fabrication.

Team Roles:

Alex Anderson: Project Manager, system design, CAD
Tyler Berryman: Customer Liaison; Matlab Interface
Jiajian He: Document Handler, Matlab Interface
Zhiqi Wang: Scribe, Testing Lead

Environment:

As an industrial measuring instrument, it needs to operate in the following environment:

Temperature

Expected to operate in room temperature

65-75 °F (18.3-23.9°C) – operation range

Relative Humidity

40-60%

- It will operate in a standard shop floor environment. This means there may be air currents, and there may be some dust in the air.
- Must operate in full ambient light
- It will operate under standard 110V outlet power.
- The surfaces of the instrument in contact with the samples should be easily cleanable.

Regulatory Issues:

Probably an ANSI 3b laser. Depends on the laser we use in the instrument.

UV Exposure (if a UV LED is used):

- OSHA:
    - The American Conference of Governmental Industrial Hygienists (ACGIH), a non-governmental organization, has established allowable employee threshold limit recommendations (TLVs) for direct ocular and skin exposures to ultraviolet radiation. The values are published in the annual Threshold Limit Values for Chemical Substances and Physical Agents & Biological Exposure Indices. If you need a copy of the suggested allowable exposure limits to UV, please contact ACGIH directly.
    - There are no OSHA-mandated employee exposure limits to ultraviolet radiation.
    - https://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=INTERPRETATIONS&p_id=24755

- University of Rochester Medical Center: Ultraviolet Light Safety Guidelines

Band	Wavelength	Primary Visual Hazard	Other Visual Hazards	Other Hazards
UV-A	315-400nm	Cataracts of lens		Skin cancer, retinal burns
UV-B	280-315nm	Corneal Injuries	Cataracts of lens, photokeratitis	Erythema, skin cancer
UV-C	100-280nm	Corneal Injuies	Photokeratitis	Erythema, skin cancer

- “There is no Occupational Safety and Health Administration (OSHA) standard for exposure to ultraviolet light, but the National Institute for Occupational Safety and Health (NIOSH) recommends that the time of exposure to an intensity of 100 microwatts per square centimeter at wavelength 254 nanometers not exceed 1 minute. When averaged over an eight-hour work day, this value is 0.2 microwatts per square centimeter.”
- https://www.safety.rochester.edu/ih/uvlight.html

Fitness for use:

The system will:

- Distinguish between laser grade and standard grade optical flats
- Align and measure samples in less than 1 minute per side of an optical flat. Does not need to automatically flip sample over to test other side.
- Accommodate 200 mm diameter optical flats, with thicknesses of 1-10 mm
- Accommodate pentangle and rectangle optical flats of size smaller than 200 mm diameter
- Measure surface at least 2 locations per side (a line scan would be acceptable)
- Capable of measuring samples composed of fused silica (Corning 7980) or borofloat (Schott)
- Results should have a greater than 99% correlation with current method.
- Fits on countertop: roughly 3ft x 4ft x 2-3ft
- Should be production robust: Doesn't require frequent recalibration. Requires low maintenance. Relatively insensitive to vibration. Standard shop floor environment

User Interface

- User-friendly; should walk user through measurement process
- Report whether sample is "laser grade" or "standard grade"
- Display graphical representation
- Report a quantitative measure of surface roughness/scattering

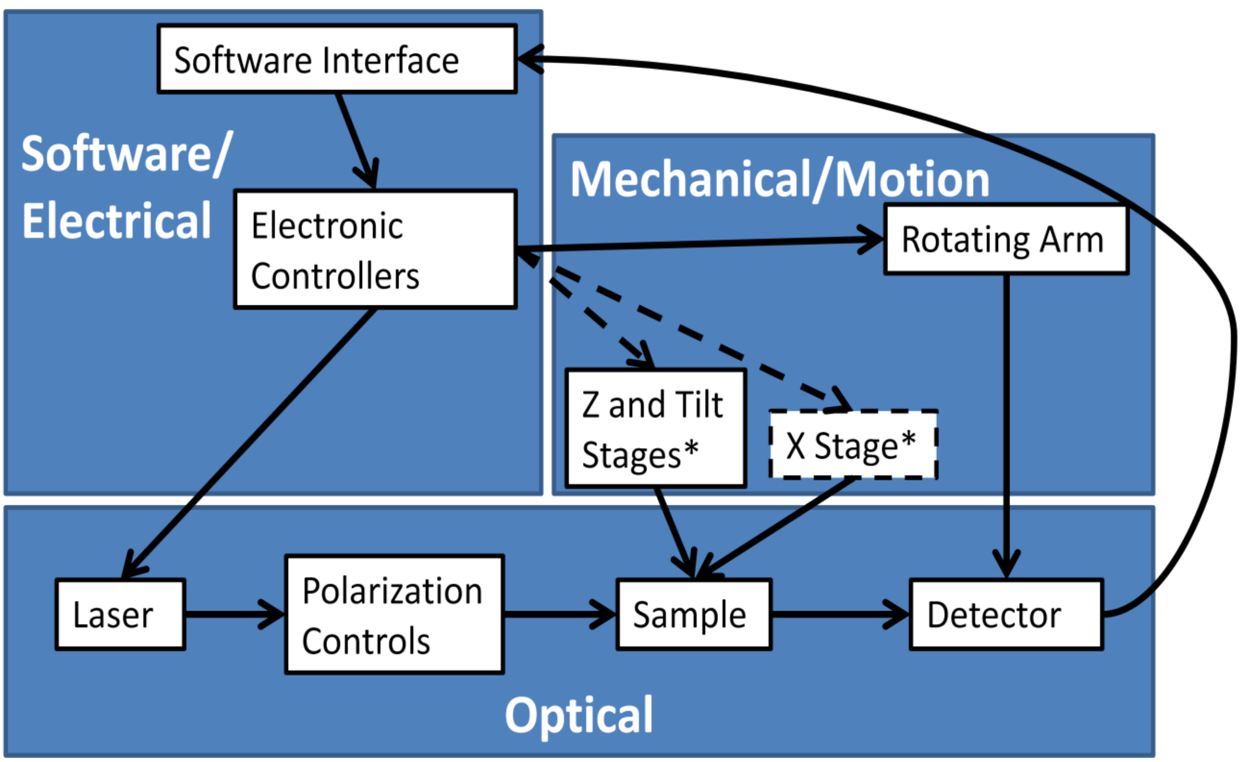
It is desirable that:

- Measurements taken at several points along surface
- Accommodate optical flats up to 13 inches in diameter
- Costs in the range of $5000. (No specific budget given)
- Capable of measuring samples composed of Bk7
- Automated alignment of optics of different thicknesses
- Automated alignment for different materials
- Automated movement of sample for measuring different points on sample
- The laser in use is eye-safe
- Laptop or tablet for user interface is desirable

Specification Table

	Required	Desired
Maximum Sample Diameter	≤200 mm	≤13” = 330.2 mm
Sample Thickness	1-10 mm	
Measurement and Processing Time	< 1 minute/side	
Roughness Sensitivity	Sensitive to 1-2 Å rms roughness	
Device Size	< 3x4x2 ft	
Detector Wavelength Sensitivity (for prototype only)	400 – 633 nm	300 – 633 nm

System Block Diagram:



Dashed lines indicate optional components or links. The dashed arrows from electronic controllers to the mechanical stages indicates that these stages could be operated manually rather than being automated. Because the X-stage is within a dashed box, the entire stage could be removed if desired. (This would result in the sample being moved by hand.)

Project Scope:

We are responsible for developing working instrument with a user-friendly interface. We are not responsible for creating optical samples for testing; Sydor will provide test samples.

A fully operational device will be delivered to Sydor Optics along with a user guide by the end of April.

Intellectual Resources:

Adviser: Professor Knox, for expertise in Scatterometry

No expectation of additional requirements of intellectual resources

Software: Matlab, CAD (Creo)

Appendix A: Current Method for Testing Optical Flats:

The sample is wiped clean then placed and aligned in the NewView white light interferometer with a 20x objective. The NewView averages 5 measurements at a location on the surface of the sample. This measurement is saved as an xyz file and exported into their customer's custom Matlab "black box" software to analyze whether or not the flat is standard quality or laser quality. Two spots are measured on each side of the sample; one spot is approximately in the middle of the sample and the second spot is located nearer to the edge of the sample. This method is considered their "gold standard" and is their only way to evaluate whether a sample is laser or standard grade; our method must have better than 99% correlation with this method.

By Sydor's approximations, the laser grade materials should have a surface roughness of less than 5 Å, a peak to valley roughness of 50-60 Å. The quality depends on surface texture and laser grade optical flats should cause minimal diffraction of light.

Appendix B: Resources Available

Sydor will provide optical flats of standard and laser grade quality for testing.

Sydor will provide a budget on the order of $5000 to purchase parts for the instrument.

Sydor will provide a laptop to run the user interface.

Professor Knox will provide a HeNe laser for testing purposes.

Professor Knox can provide a 405nm laser pointer for testing purposes, but a laser pointer must be purchased for the final product.

Professor Knox will provide space in his lab for us to build our prototype.

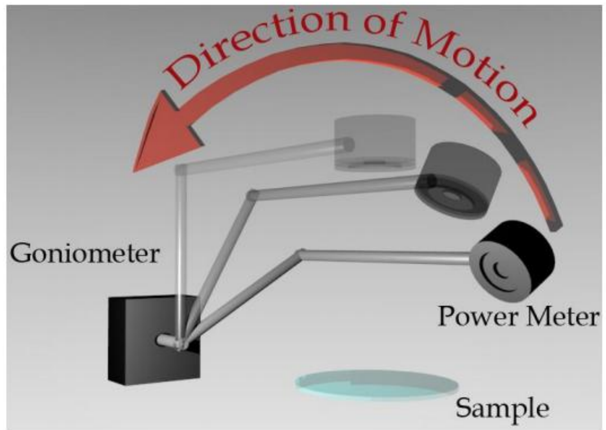
Appendix C: Testing Protocol

- Assess the polarization properties of each source
  - Aim laser directly at photodetector through linear polarizer. Measure power at detector at 5° increments of polarizer. If linear, the minimum power should be approximately 0, and the maximum power should be equal to the power measured when the polarizer is removed. If not linear, calculate the ellipticity of the polarization and verify calculation using a QWP to linearize the polarization.
- To compare light sources: for each source, compare scattered light:
  - Along arc through Brewster's angle
  - Along arc offset from Brewster's angle
- Measure at discreet points: How many data points along the surface are required for an accurate surface characterization
- Possibly test a UV LED: use a pinhole to limit to beam of light
- Comparison of what needs to be changed for Fused Silica vs Borofloat
  - Check the sensitivity of the device to the angle of the sample—is there a decrease in performance if the angle of laser at the sample is a couple degrees away from the Brewster's angle? Can both materials be set at the same angle?

Appendix D: Design Description

A scatterometer is designed to measure the angular scattering intensity distribution of sample surface over the desired angular range. Based on the theory that the amount of scattered power in the angular light distribution would vary proportionally with surface roughness, the roughness level of optics surface could be determined by comparing the intensity profiles of scattered light for different surfaces.

Building on the work of last year's team, we will use a reflection geometry with the sample at Brewster's angle to reduce the measured power at the central peak. With the input beam p-polarized, this will eliminate the specular reflection, and the measured signal will consist only of scattered light. A goniometer with a power meter on the end of a mechanical arm will rotate over a range of angles to measure the scattering power from the surface.



Ivanov, T, Westover, S, Huang, D. Surface Roughness Inspector: Design Description Document, 2015. (The DDD from last year's group.)

Feidenhansl, N. A. *et al.* Comparison of optical methods for surface roughness characterization. *Measurement Science and Technology* **26,** 085208 (2015).

Hakko, M., Kiire, T., Barada, D., Yatagai, T. & Hayasaki, Y. Shape estimation of diffractive optical elements using high-dynamic range scatterometry. *Applied Optics* **54,** 4255 (2015).

Appendix E: Preliminary Concept CAD Models

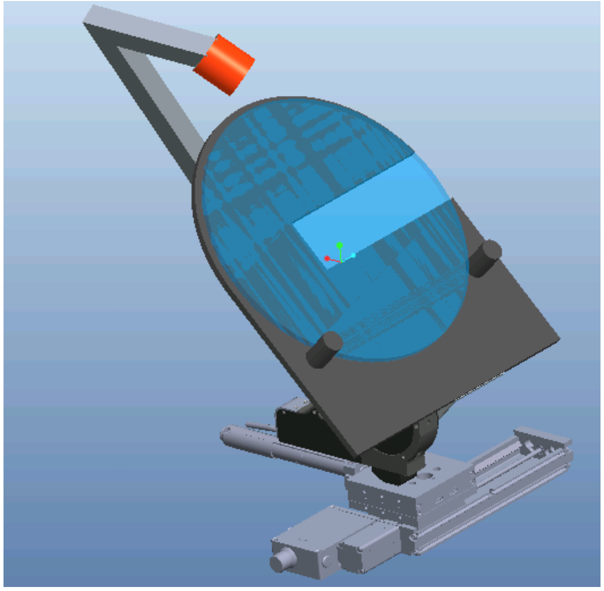


Figure 1: Polarized laser beam comes in from the right. Strikes sample within slotted area of mount. Beam dump mounted would be mounted behind the sample to attenuate the transmitted beam. The arm and detector (orange) should have clearance for the sample to translate 100mm laterally. The bottom mount moves laterally 100mm to enable measurements across the sample. The second translation mount moves the sample parallel to the beam to adjust for samples of varying thicknesses. The rotation mount on top of the 2 translation mounts allows the sample to be rotated to the Brewster's angle. The arm may be mounted in front or behind the sample.

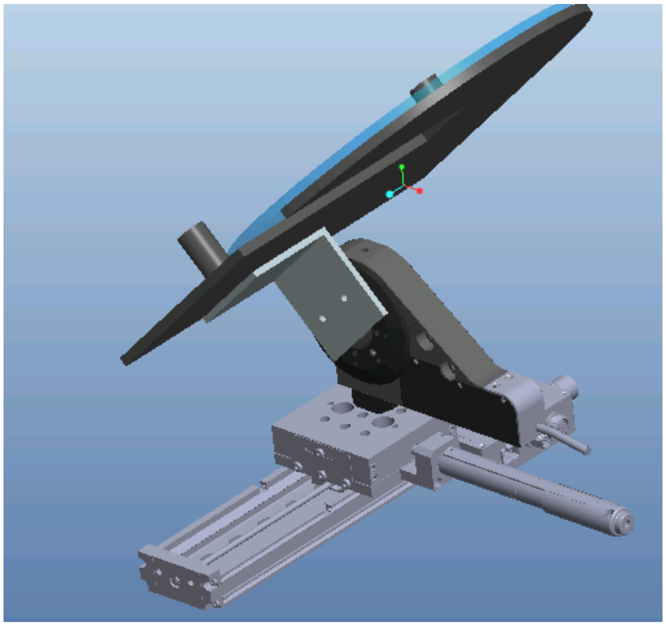


Figure 2: Sample mount concept is a flat plate with 2 standoffs to hold sample in place. The plate is mounted to the rotation stage with an angle bracket. *Note that actual mounting (hardware, alignment of holes in platforms, etc) is omitted for this preliminary drawing.*

Appendix F: Torque Calculation

Matlab used to estimate max expected torque.

Assumptions (very conservative estimates):

- Newport detector used; mass is approximately 140 g
- Rotation axis of arm will be horizontal
- Arm will have 2 segments
    - First segment (upper arm): normal to rotation axis
    - Second Segment (forearm): parallel to rotation axis
- 2 Aluminum rods, 12.7mm diameter, will be used for the both segments of arm
- Sample-arm clearance
    - Detector must be scanned 180° over widest part of 200mm sample
    - Sample must be able to be moved to measure center and near the edge (~100mm lateral shift)

These assumptions drove the lengths for each part of the arm; the upper arm was length was set to 210 mm, and the forearm was set to 100 mm.

Max Torque in this configuration would be when the arm is at the extremes of its motion (the upper arm is pointing horizontal).

Calculated Maximum torque: 0.502 N*m

Using a Safety Factor of 2, (which also accounts for any fasteners not considered here): 1 N*m

Appendix G: Bill of Materials

*Items are currently motorized and can be replaced with cheaper manual stages, the computer would indicate where to set the stage.
**Item can be eliminated if desired for price savings
***Cheaper model available with lower specifications.

Equipment	Company	Part Number	Purpose	Unit Price	Number needed	Total Price	*
50mW 405 nm Blue Laser Pointer	Laser Pointer Pro	HK-E00219	Laser Source	$7.00	1	$7.00	
5mW 405 nm Violet Laser Pointer	Laser Pointer Pro	88007294	Laser Source	$7.49	1	$7.49	
High Power LEDs - Single Color Ultraviolet	Mouser Electronics	897-LZ400U600	UV LED Source (pending analysis to confirm power and angular spectrum are appropriate)	121.9	1	$121.90	**
24" x 24" x 0.5" Optical Breadboard	Thorlabs	MB2424	Mount the device	$483	1	$483	
25.4mm Diameter Linear Polarizer	Edmund Optics	85-919	Polarize the laser	$30.00	1	$30.00	
25.4mm Polarizer Holder	Edmund Optics	84-348	Hold the polarizer	$39.00	1	$39.00	
1"D 405 nm Mounted Half-wave Plate	Thorlabs	WPMH05M-405	Rotate the polarization	$234.60	1	$234.60	
Adjustable Lens Mount (0.28" - 1.80" D)	Thorlabs	LH1	Mount for the half-wave plate	$39.50	1	$39.50	
Motorized Rotary Stage with Controller	Zaber	X-RSW60A-KX13A	Motor, controller, power supply for the Arm	$2,058.00	1	$2,058.00	
Motorized Rotation Stage/Mount and Controller	ThorLabs	PRM1Z8E	Rotate sample to Brewster's angle to account for samples of different materials	1340	1	$1,340.00	*
Motorized Linear Stage, 100mm	Zaber	X-LSM100B-KX11A	Translate sample to measure at different points along sample	2089	1	$2,089.00	**

Equipment	**Company**	**Part Number**	**Purpose**	**Unit Price**	**Number needed**	**Total Price**	*****
Motorized Linear Stage, 12mm	ThorLabs	MT1-Z8	Align sample to allow for variation in thickness	810	1	$810.00	*
Tcube motor controller	ThorLabs	TDC001		613	1	$613.00	*
Tcube Power Supply	ThorLabs	TPS001		25.8	1	$25.80	*
200-1100 nm UV Silicon Detector	Newport	918D-UV-OD3R	Detector sensitive from UV through visible spectrum	$715.00	1	$715.00	
High Performance Power Meter	Newport	1936-R	Power Meter must detect ranges down to 10 pW	$2,948.00	1	$2,948.00	***
200 nm - 3um Beam Dump	Thorlabs	BT-600	Recollect stray beam / prevent backscattering	$229.50	1	$229.50	
100 kHz lock-in amplifier	SRS	SR830	Improve S/N ratio and reduce ambient light sensitivity	$4,950.00	1	$4,950.00	***, **
M6 *10 Stainless Steel Cap Screw 25mm pack of 25	Thorlabs	SH6MS25	Screws used for mount	$9.50	1	$9.50	
Ø12.7 mm Optical Post SS, M4 Setscrew, M6 Tap, L = 100 mm, 5 Pack	Thorlabs	TR100/M-P5	Posts used for mount	$26.42	2	$52.84	
Swivel Base Adapter	Thorlabs	UPHA	Posts Mount	$19.90	6	$119.40	
Adapter with Internal M6 x 1.0 Threads and External M4 x 0.7 Threaded Stud	Thorlabs	AS6M4M	M6 M4 Converter	$4.10	2	$8.20	
Additional assorted Mounting Hardware (To be determined)	TBD			$200.00	1	$200.00	
Black Cardboard/ Light Tight material	TBD		For Light Tight Box for Device	$10.00	1	$10.00	
					Total	**$17,130.73**	

Appendix H: Potential Savings in Bill of Materials

Below is a table of components that can either be replaced with cheaper, manual components, or entirely eliminated to reduce the cost of the system.

Purpose	Manual vs. Auto	Equipment	Company	Part Number	Unit Price	Number needed	Total Price
Rotate sample to Brewster's angle to account for samples of different materials	Auto	Motorized Rotation Stage/Mount and Controller	ThorLabs	PRM1Z8E	$1,340.00	1	$1,340.00
	Manual	Manual Rotation Stage	ThorLabs	PRM05	$160.00	1	$160.00
						Savings	**$1,180.00**
Purpose	**Manual vs. Auto**	**Equipment**	**Company**	**Part Number**	**Unit Price**	**Number needed**	**Total Price**
Translate sample to measure at different points along sample	Auto	Motorized Linear Stage, 100mm	Zaber	X-LSM100B-KX11A	$2,089.00	1	$2,089.00
						Savings	**$2,089.00**
Purpose	**Manual vs. Auto**	**Equipment**	**Company**	**Part Number**	**Unit Price**	**Number needed**	**Total Price**
Align sample to allow for variation in thickness	Auto	Motorized Linear Stage, 12mm	ThorLabs	MT1-Z8	$810.00	1	$810.00
		Tcube motor controller	ThorLabs	TDC001	$613.00	1	$613.00
		Tcube Power Supply	ThorLabs	TPS001	$25.80	1	$25.80
	Manual	Manual Single-axis 1/2" Translation Stage	ThorLabs	MT1	$286.00	1	$286.00
						Savings	**$1,162.80**
Purpose	**Manual vs. Auto**	**Equipment**	**Company**	**Part Number**	**Unit Price**	**Number needed**	**Total Price**
Improve S/N ratio and reduce ambient light sensitivity	N/A	100 kHz lock-in amplifiers	SRS	SR830	$4,950.00	1	$4,950.00
						Savings	**$4,950.00**

Appendix I: Initial Photon Budget Analysis

To calculate the total integrated scatter from a surface, I used the equation below, where R_q is the rms roughness of the surface, R_0 is the theoretical reflection on the surface, and θ is the incident angle of the light on the surface. The Fresnel reflection for R_0 was calculated at normal incidence to allow an approximation of the scatter because our polarized beam of light would have no theoretical reflection. (This indicates that this equation may not be a good approximation for our setup, so we will continue research on this area).

$$TIS_{BP}(R_q) = R_0 \left[1 - e^{-\left(\frac{4\pi R_q \cos\theta_i}{\lambda}\right)^2}\right]$$

"Optical Scattering and Surface Roughness." Eckhardt Optics LLC. Web. 10 Dec. 2015. <http://eckop.com/optical-scatter-2/optical-scattering-versus-surface-roughness/>.

	Value	units
n_air	1	
n_material	1.4696	
Brewster's angle (angle of incidence)	55.8	degrees
wavelength	4.05E-07	m
area of detector	0.0001	m2
length of detector arm	0.21	m
Fresnel Reflectance (normal)	0.036	
RMS Roughness	1.00E-09	m
Theoretical Total Integrated Scatter	-1.10E-05	%
Solid Angle of detector (normal orientation)	0.0023	Str
Input Power	0.005	W

We have not yet determined the intensity distribution of the scattered light. The distribution scattered light may be a cosine squared distribution, or possibly normally distributed, but this will be determined experimentally with data from the scatterometer. The table below uses the approximations of the first table to estimate the power at the detector for various angles from normal, assuming a cosine squared distribution.

Angle	Detector Power (W)
0	1.15E-06
15	1.07E-06
30	8.62E-07
45	5.74E-07
60	2.87E-07
75	7.70E-08
90	0

Appendix J: Timeline

By 11/25	• Investigate if an LED is needed
	  ○ how much power do we need
	  ○ Specifics on which wavelength and power we need
	• Create a list of experiments for next semester
	  ○ Look into how sensitive angle measurement is.
	    ▪ Needs research to ensure rotational stage is precise enough
	• Rough CAD model 1st draft
	• Research scatterometry methods (continue)
	• Compile BoM, including prices
	  ○ Ask Zack whether they would prefer the ease of use of a Lock-in amplifier or if they would prioritize cost
	• Determine: methods for holding the sample

By 12/7	Finalize BoM, send to Sydor for approval/revisions
12/11	Final PRD due; order materials
January	• Assembly and troubleshooting • Goal to have functioning instrument • Ensure GUI works
February	• HeNe vs 405nm testing • See *Testing Protocol* section • Determine how to scan across part or measure at 2 locations
March	• Automate moving Z-stage to compensate for sample thicknesses • Verify best method from February works with Borofloat glass ○ Check if we can use a average of Brewster's angle for both glasses • Make any necessary changes to GUI
April	• Overflow from previous months • Final testing/touch ups • "Try to break the system"