

LAB 1: CLEANING OPTICS AND DATA ANALYSIS

The educational labs associated with this course have several objectives:

- 1) To demonstrate the optical principles discussed in class.
- 2) To learn how to clearly and accurately summarize and communicate the experimental procedure and results.
- 3) To become familiar with basic data handling and analysis.
- 4) To learn common optical methods and procedures which are routinely used in the research lab.
- 5) To learn the safe and proper handling of basic equipment.

The topics to be covered in Lab #1 are as follows:

- Introduction to the lab
- Safety
- Proper handling of equipment
- Data reduction and analysis
- Lab write-ups
- Grading
- Measurement scales
- Cleaning optical elements

INTRODUCTION TO THE LAB

The lab part of this course is only an introduction to the broad subject of optics. You will construct many optical instruments, and see many phenomena demonstrated. Remember that some of these instruments have undergone hundreds of years of development and one can devote a lifetime to the study of some of the phenomena you will see. The tips on safety and equipment handling are general guidelines applicable in many situations, but are not all encompassing. Common sense and careful thinking go a long way towards safety in any kind of laboratory.

The most important point to remember about these labs is that your understanding of the optical principles is far more important than obtaining accurate data or results. Too many students in too many labs feel pressured to obtain the "right answer" to an experiment. What they fail to remember is that experiments at this level are designed so that most anyone can obtain the "right answer." The most challenging and useful part to any lab is to be able to understand how and why the "right answer" was obtained. The success of this understanding should be your primary goal in these labs.

Sometimes the "right answer" may not be obtained, either because of small errors or even large ones. Many students feel a sense of failure at this point, a sense that the experiment did not work. If you can understand where the errors came from, and can calculate how large they are, the experiment will have worked. You will have learned more about the "right answer" than if you had gotten it the first time, patted yourself on the back, and had quickly gone on to the next experiment.

The second most important point about these labs is that being able to explain and calculate your experimental errors is more important than obtaining the "right answer." Make it your goal to understand the errors or uncertainties associated with any number you measure, report, or read about. As we learn more about data analysis, you will have the necessary math tools to accomplish this.

SAFETY

Obviously, this is first and foremost. Always remember that your actions may affect your colleagues. No general rules can encompass every situation, but here are some general guidelines. The most common potential hazards in an optics lab are light sources and electrical equipment. Light sources can produce immediate or delayed effects. Fortunately, you naturally turn away from dangerously intense sources (the aversion response). So do not continue to stare at lights if it is uncomfortable to do so. Lasers demand special caution since even the low power He-Ne lasers used in this course can have devastating consequences. Never look directly into the beam. This can cause instant, irreversible, permanent, and severe visual damage. Be careful when setting up equipment never to point the laser towards others. More importantly, be aware of any object that is placed in or moved through the

path of a laser beam. If the beam is not blocked, the object may specularly reflect or scatter the laser light into your own eyes or those of a colleague clear across the room. Common objects that are notoriously bad include optical elements (lenses, mirrors, filters, pieces of glass), apertures, lens holders, metal posts, rulers, micrometers, calipers, hands with rings and watches on them, and pens or pencils. Always keep your own head and face clear of a laser beam. If an experiment requires that you look at something close to a laser beam, be aware of just how close the beam is to your own face and eyes. This situation is even more critical for people who wear eyeglasses. Be very careful of a laser beam hitting any part of the eyeglasses or frames and reflecting directly into your eye. The more intense lasers in research labs require additional precautions, and possibly special eye protection. Always familiarize yourself with the specific safety requirements of any equipment you use. Always be aware of where the laser beam is located, and keep your face clear of it. Use the shutter to block the beam whenever the laser is not being used.

Invisible radiation e.g. ultra-violet (UV) and infrared (IR) pose a special threat. Remember that sources which emit safe levels of visible radiation may also produce unsafe levels of IR or UV. Such sources should not be used without appropriate filters. The lab instructor will caution you if this is necessary. We often forget that light sources can also damage skin. While this is not an issue in this lab, anyone working in the optics industry should appreciate the cumulative risks of exposure over years similar to sunburns.

We use a lot of high voltage electrical equipment (usually to run our dangerous light sources). Proper grounding and electrical safety procedures should be followed. This lab does not use any dangerous chemicals, but research labs do. In addition to the health risks, these may pose an environmental hazard. Be sure to learn the proper handling and disposal methods for any chemical you use, especially organic solvents.

PROPER HANDLING OF EQUIPMENT

Student labs are frequently criticized for the imprecise equipment. The criticism is not only irrelevant, but shows a lack of understanding of experimental science. Certainly, precise measurements are required to reject or accept theories. However, the goal of the educational lab is not to validate theory, but to learn the methods by which theories are validated. Measurements with research grade equipment are usually time consuming, and impossible within the time constraints of a course. The cost of duplicating expensive equipment is prohibitive.

The equipment used in this lab is new, and of the highest quality given the purpose for which it is intended. Please treat it appropriately.

Some general guidelines are to be noted:

- Always handle optical elements (lenses, mirrors, etc.) by their edges so as not to leave fingerprints on the surfaces.

- Optical elements should always be placed on soft surfaces to prevent scratches. The bare top of the optical table is not a soft surface! A layer of cotton or tissue will solve the problem.
 - When adjusting optical hardware, use only light pressure to tighten down the screws. This is especially true for the top two screws on the lens holders, the collets for the mounting posts, and the top two screws that hold the lasers in place. Over-tightening screws leaves pit marks on surfaces, burrs on posts, and can often break an optical element.
 - The yellow markings along the side of the optical rails are painted on and can be scratched off rather easily. Be aware of this when placing the carriers on the rails.
 - The instruments used for making measurements of length (micrometers and calipers) are delicate and somewhat fragile. **Do not force them open or closed, and do not drop them!**
 - The tops of the optical tables are precision ground surfaces. Any action that badly scratches or puts a pit in them is to be avoided. Typical examples include dropping heavy objects onto them or even sitting on them (the rivets on most jeans can cause bad scratches.) Treat the tables as well as any other optical element.
 - **NO FOOD OR DRINK ALLOWED IN THE LAB.**
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DATA REDUCTION AND ANALYSIS

This is an entire discipline in its own right, and here we will introduce only a few basic concepts. For a more complete discussion you should consult any one of several standard texts. Two excellent introductory texts are listed as references at the end of this section. (Taylor, 1982 and Benivington, 1969)

An underlying fact in all experimental science is that it is impossible to measure anything perfectly. Given enough time and money, measurement errors can usually be reduced to extremely small values. However, this is a luxury that most real-life situations do not warrant. One of the goals of an engineer should be to know how to use data analysis to calculate errors and know when they are small enough to accomplish the job at hand. One of the challenges in science and engineering is to know how to modify an experiment as economically as possible in order to reduce the experimental errors.

There are two types of errors in measurements -- **SYSTEMATIC** and **RANDOM**. Systematic errors are repeatable and introduce a fixed bias into the result. For instance, a ruler incorrectly machined will give erroneous (but consistently erroneous) results. Random errors change with each measurement and are best analyzed statistically. They are introduced by noise in the system being measured or by some variability in the data-taking

process itself. When using a ruler, for example, random errors are introduced by having to interpolate between the smallest markings.

Two terms are used to describe a set of measurements -- **PRECISION** and **ACCURACY**. The term precision deals with the reproducibility of a measurement. The more reproducible a measurement is, the more precise it is. However, a measurement may be reproducible but still quite different from the actual value of the physical parameter being measured. It is the term accuracy which describes how close a measurement (or average of a set of measurements) is to the actual or true value being measured. **Note that precision is affected by random errors, and accuracy is affected by systematic errors.** Quite often precision and accuracy are used interchangeably and therefore incorrectly. Make it a goal of this semester to learn the correct use for the two terms.

The assumption is made in most experimental situations that repeated measurements of the same physical parameter are independent and uncorrelated. In other words, one measurement does not affect the next one. The result of this is that random errors inherent in the process cause the data to follow a Gaussian distribution. The following figure shows the Gaussian distribution. (For this course, just remember that the Gaussian function is the standard, or normal, bell-shaped curve often associated with grades done "on the curve.") Said another way, if you take repeated measurements of the same physical parameter and make a histogram plot of the number of times you measure a particular value (y-axis) vs. the value itself (x-axis), you will approach a Gaussian distribution as the number of samples becomes large. The true, or mean, value of the distribution (the average of all values in the data set) occurs at the center, or peak of the curve as shown in Fig. 1.1.

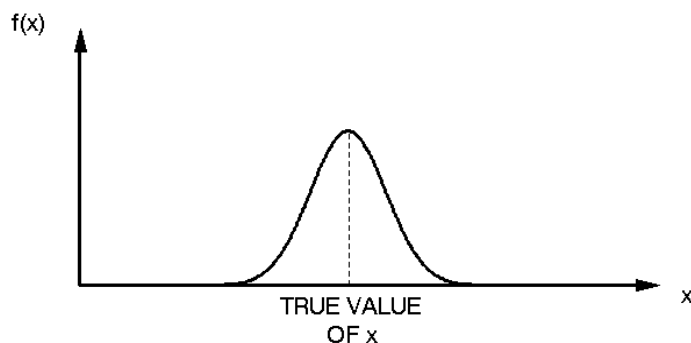


Figure 1.1. The limiting distribution for a measurement subject to random errors. The curve is Gaussian and centered on the true value of x .

The width of the curve is most easily described by a geometrical interpretation known as the **full width at half maximum**, or **FWHM**. This is the width of the Gaussian

curve at a value equal to one-half its maximum height. The following Fig. 1.2 shows the meaning of FWHM.

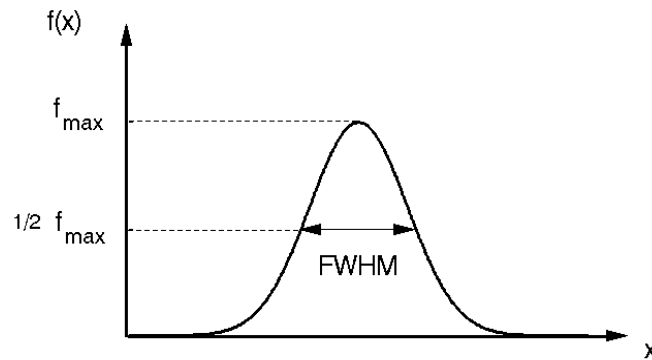


Figure 1.2. Full width at half maximum FWHM.

Another measure of the width of a Gaussian distribution is given by twice the sample standard deviation, commonly written as σ . The value of σ represents the uncertainty in the individual measurements in the data set. It can be shown that the sample standard deviation is related to the FWHM by the following relation:

$$\text{FWHM} = 2.35 \sigma$$

In other words, the width of the Gaussian is given by twice the sample standard deviation is (narrower) than the full width, at half maximum. As it turns out, the sample standard deviation σ has a much more useful statistical interpretation than does the FWHM. The width of two σ is the range of data over which 68% of the values fall about the mean. Stated another way, we can be 68% confident that a subsequent measurement will fall within $\pm 1\sigma$ of the mean.

The relationship between sample standard deviation and the precision in a set of measurements can now be better understood. A large sample standard deviation corresponds to a large spread in data values about the mean, and therefore low precision in the measurements. The uncertainty that another measurement will fall close to the mean is quite low. Conversely, a small sample standard deviation corresponds to a narrow spread in data values about the mean, and implies high precision in the measurements. Any subsequent measurement is much more likely to fall closer to the mean value.

The following Fig. 1.3 demonstrates this, as well as the concept of accuracy.

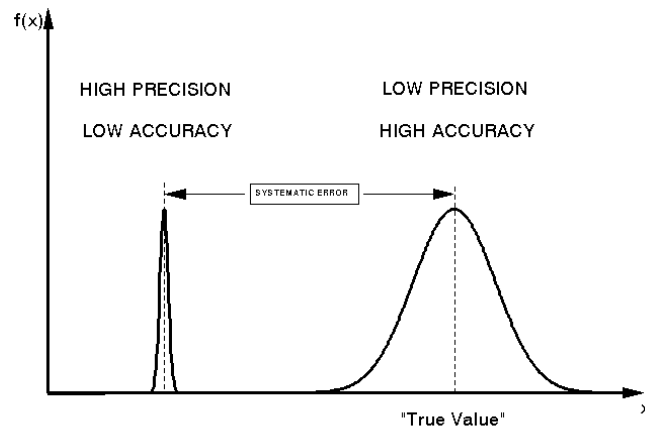


Figure 1.3 Precision vs. accuracy in measured data.

Another statistic which needs discussion is the standard deviation of the mean, $\sigma_{\bar{x}}$. This is a number which describes the uncertainty in knowing the true value of the mean. As such, it is more useful than σ itself. It is related simply to the sample standard deviation σ by a

factor of, $\frac{1}{\sqrt{N}}$, $\sigma_{\bar{x}} = \frac{\sigma}{\sqrt{N}}$, where N is the total number of measurements taken. Note that in

order to reduce the uncertainty in the average of a set of data by a factor of 10, one has to increase the number of measurements by a factor of 100

ANY MEASURED VALUE QUOTED IN THIS COURSE SHOULD BE GIVEN AS THE MEAN OF A DATA SET \pm ONE STANDARD DEVIATION OF THE MEAN.

$$\bar{x} \pm \sigma_{\bar{x}}$$

To this point, we have discussed how to calculate the error or uncertainty in a single set of data. For one physical parameter being measured, the uncertainty is given simply by the standard deviation of the mean. However, many physical quantities of interest are calculated with a mathematical function (equation) using experimentally measured parameters.

The question still to be answered is how does one calculate the uncertainty in the (calculated) physical quantity, given the uncertainties in each of the measured physical parameters?

A simple example is the measurement of the area of a rectangle. One doesn't actually measure the area directly, but instead calculates it based on two measurements of distance (length and width). Based on our previous discussion, the numbers used for the length and width should be the mean of an entire set of data taken for each parameter. The uncertainty in the length and the width would be the standard deviation of the mean in each case. How then does one calculate the uncertainty, or error, in the area itself?

The answer to this lies in a fundamental theorem of Calculus. The value of a function in any small region around a given point in parameter space may be calculated using a Taylor Series expansion. The uncertainty in each of the parameters is taken to be the standard deviation of the mean from a set of measured data for that parameter. Assuming each of these standard deviations (errors) to be small, (an assumption always made), only the first (linear) terms in the Taylor Series need to be kept. The general equation for calculating the errors in a quantity (function) containing n measured parameters is:

$$\Delta f = \sqrt{\left(\frac{\partial f}{\partial x_1} \sigma_{\bar{x}_1}\right)^2 + \left(\frac{\partial f}{\partial x_2} \sigma_{\bar{x}_2}\right)^2 + \dots + \left(\frac{\partial f}{\partial x_n} \sigma_{\bar{x}_n}\right)^2} \quad (1.1)$$

where f is a function of the parameters x_1, x_2, \dots, x_n , Δf is the calculated error in the physical quantity of interest, the $\frac{\partial f}{\partial x_i}$'s are partial derivatives and the $\sigma_{\bar{x}_i}$'s are the standard deviation of the mean for each parameter. The numerical value used for each parameter is the mean of its measured data set. Note that for one measured parameter, $n=1$, the expression reduces to the familiar definition of a derivative in one-dimension:

$$\Delta f = \left| \frac{df}{dx} \right| \Delta x \quad (1.2)$$

where Δx is the same as $\sigma_{\bar{x}}$ the standard deviation of the mean. For the one-dimensional case, the following Fig. 1.4 may help illustrate how the error in the measured parameter affects the error in the calculated quantity through the definition of the derivative, given above.

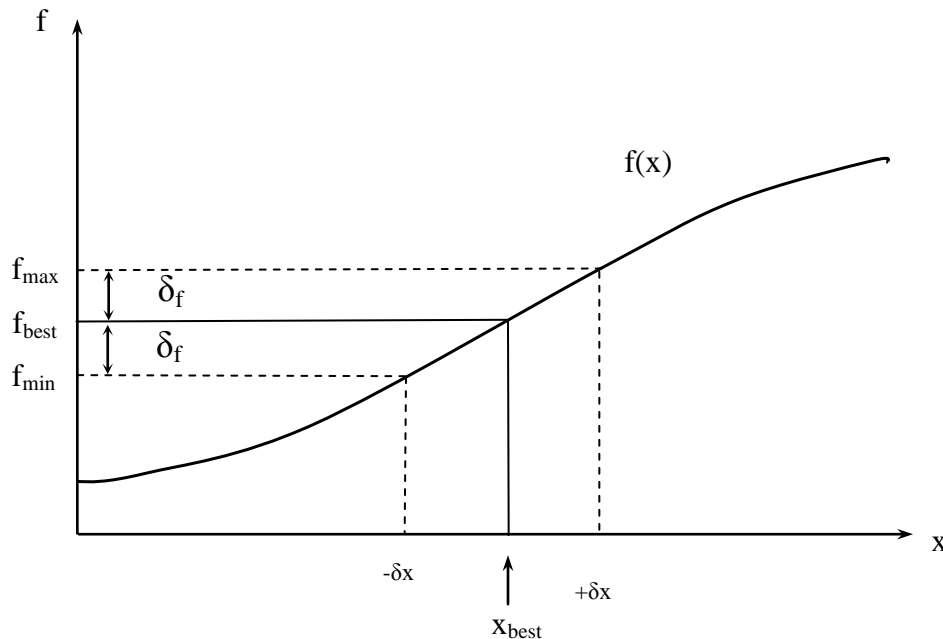


Figure 1.4. Graph of a generalized function $f(x)$. If x is measured as $x_{\text{best}} \pm \delta x$, the output, or result, is quoted as $f_{\text{best}} \pm \delta f$

As a final comment, the absolute value signs are used so as to always contribute a positive value to the overall error. Also, the square root of the sum of the squares, or root-sum-square (RSS) in equation (1.1), is a consequence of the fact that the errors are taken to be random and independent. RSS is sometimes referred to as adding in quadrature, vs. simple algebraic addition. The justification for this will not be given here, but RSS addition of errors should always be used in this course.

We are now in a position (finally!) to calculate the error in the area of our rectangle. Applying equation (1.1) gives:

$$A = L \cdot W \quad (1.3)$$

$$\Delta A = \sqrt{(L \cdot \sigma_w)^2 + (W \cdot \sigma_L)^2} \quad (1.4)$$

As a numerical example, assume that you made 10 measurements of the length L , and 6 measurements of the width W , (the lab ended early . . . remember this is only an example). The scatter in the data resulted from having to interpolate between the smallest markings on your ruler, which are in mm.

DATA POINT #	LENGTH [mm]	WIDTH [mm]
1	14.9	3.2
2	14.8	2.9
3	14.9	3.1
4	15.0	3.2
5	14.8	3.0
6	15.1	2.8
7	14.9	
8	14.8	
9	15.1	
10	14.7	
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	$\bar{L} = 14.9$	$\bar{W} = 3.0$
	$\sigma_{\bar{L}} = 0.1$	$\sigma_{\bar{W}} = 0.2$

The means and standard deviation of the means were calculated using equations (1.5) and (1.8). **Note that we rounded off to the tenth decimal place.** Using equation (1.4) to calculate the error in the area gives:

$$\begin{aligned}\Delta A &= \pm \sqrt{[(14.9)(0.2)]^2 + [(3.0)(0.1)]^2} \\ &= \pm 3.0 \text{mm}^2\end{aligned}$$

Finally, the complete answer is given as:

$$A = 44.7 \pm 3.0 \text{mm}^2$$

Note the proper use of rounding and significant figures as stated in the next section.

SUMMARY OF EQUATIONS AND RULES FOR DATA ANALYSIS

ROUNDING NUMBERS: Round any number to its least significant digit by considering the next least significant digit. If this number is between 0 and 4, leave the least significant digit as is. If this number is between 5 and 9, round the least significant digit up.

SIGNIFICANT FIGURES: The number of significant figures in a measured value should coincide with one half of the smallest resolvable unit in the measurement, if possible. (If you are using a ruler with the smallest markings being in mm, estimate and quote each value to within $\pm \frac{1}{2}$ mm. If you are reading a digital voltmeter that has 3 digits, estimate and quote each value to within the decimal place of the 3rd digit.)

ERROR ANALYSIS: Unless directed otherwise, **ERROR ANALYSIS FOR THIS LAB SHOULD BE DONE USING THE STANDARD DEVIATION OF THE MEAN.** The errors calculated through the use of the standard deviation of the mean and the Taylor series expansion are not strictly equivalent. For small errors, (which we will assume), they should be very comparable in magnitude. The use of the standard deviation of the mean will, in general, be quite adequate for purposes of this lab and is much easier to calculate than use of a Taylor series.

Mean:

$$\bar{x} = \frac{\sum_{i=1}^N x_i}{N} \quad (1.5)$$

where N = the number of measurements

Sample Variance:

$$\sigma^2 = \frac{\sum_{i=1}^N (x_i - \bar{x})^2}{N - 1} \quad (1.6)$$

Sample Standard Deviation: σ (square root of sample variance)

$$\sigma = \sqrt{\frac{\sum_{i=1}^N (x_i - \bar{x})^2}{N - 1}} \quad (1.7)$$

Standard Deviation of the Mean:

$$\sigma_{\bar{x}} = \frac{\sigma}{\sqrt{N}} \quad (1.8)$$

Propagation of errors is handled by the following formulae (assuming the errors are random, i.e. independent and uncorrelated). These equations are derived as special cases by applying the general form of the Taylor Series, equation (1.1):

1) Addition and Subtraction

$$f = x + y + z \quad (1.9)$$

$$\Delta f = \sqrt{(\Delta x)^2 + (\Delta y)^2 + (\Delta z)^2} \quad (1.10)$$

2) Multiplication and Division

$$f = \frac{xy}{z} \quad (1.11)$$

$$\frac{\Delta f}{|f|} = \sqrt{\left(\frac{\Delta x}{x}\right)^2 + \left(\frac{\Delta y}{y}\right)^2 + \left(\frac{\Delta z}{z}\right)^2} \quad (1.12)$$

3) Powers

$$f = x^n \quad (1.13)$$

$$\frac{\Delta f}{f} = \left| \frac{n \cdot \Delta x}{x} \right| \quad (1.14)$$

References:

J. R. Taylor, *An Introduction to Error Analysis*, Oxford University Press, 1982.

P. R. Bevington, *Data Reduction and Error Analysis for the Physical Sciences*, McGraw-Hill, 1969.

LAB WRITE-UPS

The purposes of the lab report are for you to demonstrate that you (1) actually did the lab, (2) understand the procedures involved, (3) understand the theory behind each experiment, and (4) understand how to properly calculate the numerical results and associated experimental errors. In order to make the reports easier to write, the following guideline should be used:

- Name
- Lab# / Lab Title
- Lab Day (Tue., am/pm Wed., pm Thur., am/pm)
- Experiment Name
- SUMMARY OF EXPERIMENT
 - brief summary of the objective of the experiment
 - brief summary of the procedure used (just the highlights)
 - brief summary of appropriate theory

(The SUMMARY should be done in one or two paragraphs...no more than 1/2 page)!

- Raw Data (present in organized tables)
- Equation(s) used to analyze the data
- Calculated results (present in tables when appropriate)
- Graphs or Plots (include as specified by the lab handout or the instructor)
- Error Analysis (include as specified by the lab handout or the instructor)
- Answers to all questions in the lab manual.

NOTE: All questions will be marked with an asterisk *.

Repeat back *to Experiment Name* for other experiments in the lab handout.

The write-ups should NOT be lengthy. It is important to summarize the experiment as *concisely* as possible, without simply repeating words in the lab handout. A brief example of a write up for the minimum angle of deviation part of Lab #3 is included on the next page. Be sure to answer all questions in the handout. In this age of computers, you may wish to use a word processor in doing your write-ups. For that matter, you may wish to use a form or boiler plate to help outline each write-up. That's OK, as long as the words and data are your own and you answer all questions. By the way, use of pen and paper is perfectly acceptable (*don't use pencil*). The point of the write-up is to communicate (legibly) your understanding of the optics learned, not to write a publication-ready article.

THE WRITE-UPS ARE DUE ONE WEEK AFTER THE LAB SESSION, AND ARE TO BE TURNED IN AT THE BEGINNING OF THE FOLLOWING LAB.

SAMPLE LAB WRITE-UP

Serious Student

Lab #3--Refractive Index and Snell's Law

Friday lab

Minimum Angle of Deviation

SUMMARY: This experiment provides an accurate method of measuring the index of refraction of a glass. Of the various methods studied, this one is the most accurate. It involves the use of a spectrometer and a glass sample in the form of a prism. The spectrometer is used to measure the apex angle of the prism as well as the angles of incidence and deviation. Experimentally, the minimum angle of deviation is found by rotating the prism (changing the angle of incidence) and observing when the deviation angle is at a minimum. Vernier scales on the spectrometer were used to measure the angles to an accuracy of 1 arc min. An equation is derived which relates the index of refraction of the glass to the angles of incidence and deviation. At minimum angle of deviation, the equation reduces to a simpler form used to calculate the index at the red spectral line of an argon source. A complete error analysis is given.

DATA: Four measurements of the prism angle, A , and five measurements of the minimum angle of deviation, D , for the red argon line were performed. The calculated average value of the prism angle was used for all calculations of n , the index of refraction.

TRIAL #	A	D	$n (\bar{A} = 60^\circ 0')$
1	$60^\circ 2'$	$37^\circ 11'$	1.5000
2	$59^\circ 58'$	$37^\circ 14'$	1.5006
3	$60^\circ 5'$	$37^\circ 08'$	1.4995
4	$60^\circ 9'$	$37^\circ 10'$	1.4998
5		$37^\circ 09'$	1.4996
Average	$60^\circ 0'$	$37^\circ 10'$	1.4999
$\sigma_{\bar{x}}$	$0^\circ 5'$	$0^\circ 2'$	0.0004

The error in refractive index may also be calculated using a Taylor series expansion. Using the following equations:

$$\text{at minimum angle: } n = \sin[(D_{\min} + A)/2] / \sin(A/2)$$

after taking the derivative:

$$\Delta n = \left[\left| \frac{\sin\left(\frac{A}{2}\right) \cos\left(\frac{A + D_{\min}}{2}\right) - \sin\left(\frac{A + D_{\min}}{2}\right) \cos\left(\frac{A}{2}\right)}{2 \sin^2\left(\frac{A}{2}\right)} \right|^2 \cdot |\Delta A|^2 + \left| \frac{\cos\left(\frac{A + D_{\min}}{2}\right)}{2 \sin\left(\frac{A}{2}\right)} \right|^2 \cdot |\Delta D_{\min}|^2 \right]^{1/2}$$

Using $\bar{A} = 60^\circ 0'$, $\bar{D} = 37^\circ 10'$, $\sigma_{\bar{A}} = 0^\circ 5'$, and $\sigma_{\bar{D}} = 0^\circ 2'$ gives: $\Delta n = 0.0005$

The final answer is: $n = 1.4999 \pm 0.0005$

GRADING

The grading will attempt to reflect your level of understanding of the optical principles presented in the lab. The SUMMARY section will be only a very small part of the grade, although it is a required part of the write-up. Most of the grade will come from the data analysis and questions. Each lab will be graded based on a raw point score that will vary from lab to lab. This allows for a finer "resolution" of the grading on the more lengthy labs.

EACH LAB SCORE WILL BE NORMALIZED TO A 100 POINT SCALE.

MEASUREMENT SCALES

An important lab skill required throughout this course is the ability to make measurements with micrometers, calipers, and angular scales. The ability to read a vernier scale is also required. This section is an introduction to the use of these measuring instruments.

We begin by reviewing the units of measurement most commonly used in this and other scientific labs. Almost all of our measurements of length will be done in metric units. The fundamental metric unit of length is the meter [m], slightly longer than 39 inches. While all of your calculations involving length may be done in units of meters [m], you will find

it much more convenient to use the smaller divisions of the meter, namely millimeters [mm], centimeters [cm], or micrometers or microns [μm]. The relationship between these units is based on factors of 10, as follows:

	<i>1 meter [m]</i>	<i>= 1 meter</i>
10 (10^1)	decimeters [dm]	= 1 meter
100 (10^2)	centimeters [cm]	= 1 meter
1000 (10^3)	millimeters [mm]	= 1 meter
1,000,000 (10^6)	micrometers [μm]	= 1 meter
1,000,000,000 (10^9)	nanometers [nm]	= 1 meter
1,000,000,000,000 (10^{12})	picometers [pm]	= 1 meter
1,000,000,000,000,000 (10^{15})	femtometers [fm]	= 1 meter

NOTE: Any of these prefixes may be used with the units of time [seconds] or volume [liters] in the same manner.

The most practical units of use for this lab are millimeters, centimeters, micrometers (microns), and nanometers. To convert from the English system of inches and feet to the metric system, the following conversion factor is the easiest to remember and work with:

$$\mathbf{1 \text{ INCH} = 2.54 \text{ CM}}$$

Another important unit used in this lab (and in OPTI 226) is that for measuring angles. The most common unit of angle is the degree [$^\circ$], defined with the fact that there are 360 degrees included in a full circle. Note that 360 degrees are also equal to 2π , or 6.283185 radians, the radian being another unit of angle. Confirm for yourself that 1 radian is equal to 57.295779 degrees.

* How many degrees is $\pi/2$?

The unit of a degree is broken down into smaller units of angle termed minutes ['] and seconds ["]. There are 60 minutes in one degree, and one minute contains 60 seconds. The following relationships will be used throughout the labs:

2π radians	=	1 complete circle
360 degrees	=	1 complete circle
1 degree	=	1 degree
60 minutes	=	1 degree
3600 seconds	=	1 degree
60 seconds	=	1 minute

Optical Rails

The optical rails you will use for most of the experiments function as a ruler marked in millimeters, mm. Notice that each of the carriers that slide along the rail have a cut-out portion along one end, with a vertical marking in the middle. This marking is coincident with the center of the carrier and the lens or aperture holders on the carrier itself. Estimate these readings to within $\pm \frac{1}{2}$ mm.

Calipers

The calipers contained in the red measuring kit are basically a refined steel rule. Properly termed slide calipers, they operate by sliding a movable jaw along a steel rule marked in 0.1" increments. A dial calibrated in units of 0.001" is coupled to the movement through a rack and pinion gearing arrangement. Movement of the jaw through 0.1" moves the dial through 100 divisions, or one complete revolution. The final reading is the sum of the reading of the steel rule and the dial.

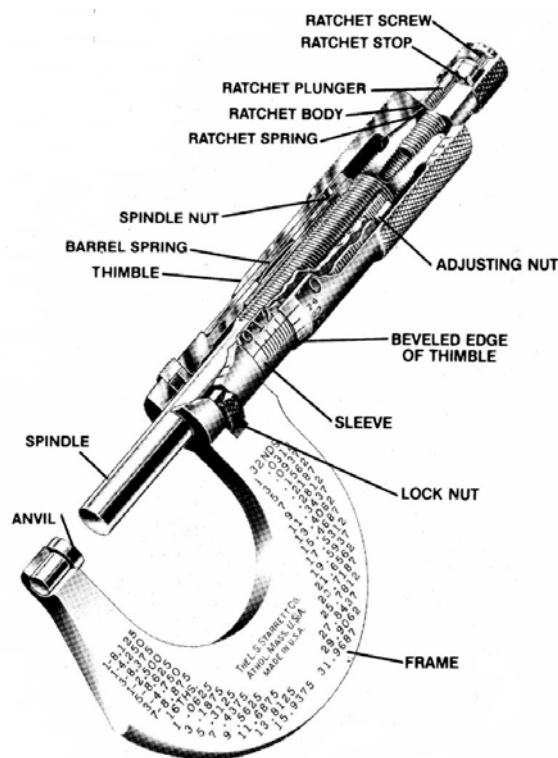
Hold the calipers in your right hand along the length of the steel rule, with your right thumb resting on the knurled knob thus supporting most of the weight. With your left hand, loosen the locking screw at the top right of the dial. Open the jaws by rotating the knurled knob with your right thumb. Run your hand along the inside of the lower jaws to make sure they are clean. Gently close the jaws and make sure the dial reads 0. If not, loosen the bottom screw, grasp the outside of the dial and rotate it until the pointer is at 0, then gently tighten the bottom screw.

These calipers are capable of measuring up to 6.000" in length, outside-diameter (O.D.), or inside-diameter (I.D.). The lower jaws are used for measuring length as well as O.D. The upper jaws are used for measuring the I.D. of round material such as pipe or tubing. Notice how the distances between the upper and lower jaws is the same because the right side of each jaw moves on the same carriage.

Micrometers

The micrometers in the kit and on the optical translation stages are used to measure length. A good discussion of the micrometer is found in a booklet published by The L.S. Starrett Co., *Tools & Rules for Precision Measuring*. Portions of this booklet are reprinted here, with permission from The L.S. Starrett Co.

Figure 1.5. Construction of a micrometer.



(Photo used with written permission from The L.S. Starrett Co.)

NOTE: NEVER FORCE THE SPINDLE AGAINST THE WORK PIECE OR ANVIL. ALWAYS USE THE LIGHTEST PRESSURE NEEDED TO JUST ENSURE CONTACT.

"The micrometer caliper consists of a highly accurate ground screw or spindle which is rotated in a fixed nut, thus opening or closing the distance between two measuring faces on the ends of the anvil and spindle. A piece of work is measured by placing it between the anvil and spindle faces and rotating the spindle by means of the thimble until anvil and spindle both contact the work. The desired work dimension is then found from the

micrometer reading indicated by the graduations on the sleeve and thimble (as described in the following sections)."

At this point, look at the micrometers in the kit and on the translation stage. Notice the differences in markings on the sleeves and thimbles. Reading each micrometer is slightly different, and will be covered in the next two sections.

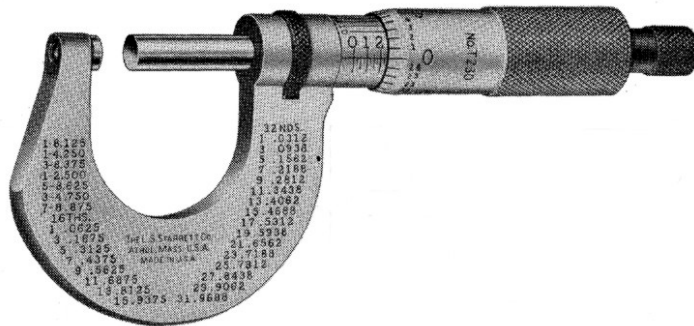


Figure 1.6. English-reading micrometer with a vernier scale.
(Photo used with written permission from The L.S. Starrett Co.)

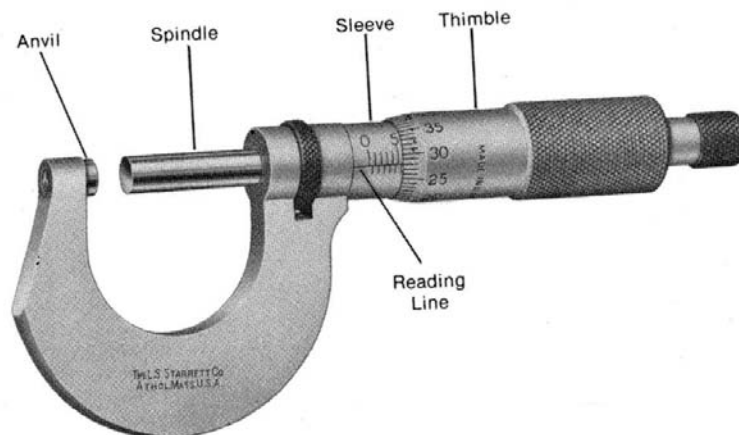


Figure 1.7. Metric-reading micrometer with a vernier scale.
(Photo used with written permission from The L.S. Starrett Co.)

How to Read a Micrometer Graduated in Ten-Thousandths of an Inch (.0001") --(from our kits)

"Since the pitch of the screw thread on the spindle is $1/40$ ", or 40 threads per inch, one complete revolution of the thimble advances the spindle face toward or away from the anvil face precisely $1/40$ or 0.025 inches.

The reading line on the sleeve is divided into 40 equal parts by vertical lines that correspond to the number of threads on the spindle. Therefore, each vertical line designates $1/40$ or 0.025 inches and every fourth line which is longer than the others designates hundreds of thousandths. For example: the line marked "1" represents 0.100 ", the line marked "2" represents 0.200 ", and the line marked "3" represents 0.300 ", etc.

The beveled edge of the thimble is divided into 25 equal parts with each line representing 0.001 " and every line numbered consecutively. Rotating the thimble from one of these lines to the next moves the spindle longitudinally $1/25$ of 0.025 " or 0.001 inches; rotating two divisions represents 0.002 ", etc. Twenty-five divisions indicate a complete revolution, 0.025 or $1/40$ of an inch.

To read the micrometer in thousandths, multiply the number of vertical divisions visible on the sleeve by 0.025 ", and to this add the number of thousandths indicated by the line on the thimble which coincides with the reading line on the sleeve."

Example A: [WITHOUT the vernier]

Refer to the illustration below and your own micrometer.

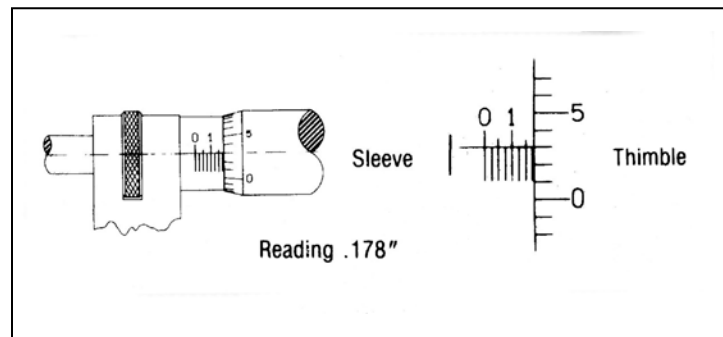


Figure 1.8. Using an English-reading micrometer.
(Drawing used with written permission from The L.S. Starrett Co.)

The "1" line on the sleeve is visible, representing 0.100 "

There are 3 additional lines visible, each representing 0.025 "

$$3 \times 0.025" =0.075"$$

Line "3" on the thimble coincides with the reading line on the sleeve, each line representing 0.001 "

$$3 \times 0.001" =0.003"$$

(the reading line is the first horizontal line on the vernier scale, marked "0")

The micrometer reading is the total of these readings **0.178 "**

Example B: [WITHOUT the vernier]

Refer to the illustration below and your own micrometer.

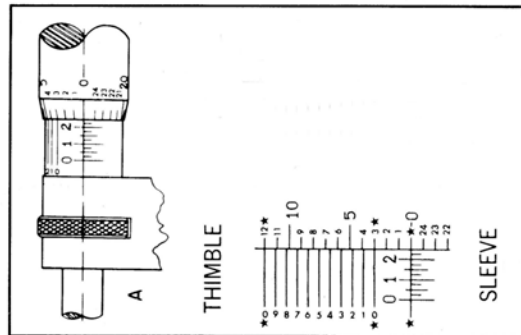


Figure 1.9. Using an English-reading micrometer.
(Drawing used with written permission from The L.S. Starrett Co.)

The "2" line on the sleeve is visible, representing0.200"

There are two additional lines visible, each representing 0.025"

$$2 \times 0.025'' = \dots\dots\dots 0.050''$$

Line "0" on the thimble coincides with the reading line on the sleeve,

$$\text{representing} \dots\dots\dots 0.000''$$

The "0" lines on the vernier coincide with lines on the thimble, representing0.000"

The micrometer reading is**0.250"**

Micrometers graduated in ten-thousandths of an inch are used like micrometers graduated in thousandths as just described, except that an additional reading in ten-thousandths which is obtained from a vernier is added to the thousandths reading. (It is interesting to note that the vernier scale was invented in 1631 by Pierre Vernier and is in effect a combination of rulers.)

The vernier consists of ten divisions on the sleeve which occupy the same space as nine divisions on the thimble. (Prove this to yourself. Unlock the micrometer thimble by moving the lever counterclockwise. Rotate the thimble until the "0" matches the "0" on the spindle reading line. Note the two numbers that match at the other end of the vernier scale.) Therefore, the difference between the width of one of the ten spaces on the vernier and one of the nine spaces on the thimble is one-tenth of a division on the thimble, or one-tenth of one-thousandth, which is one ten-thousandth. To read the micrometer to the ten-thousandths digit, first obtain the thousandths reading, then see which of the lines on the vernier coincides with a line on the thimble. If it is the line marked "1" add one ten-thousandth, if it the line

marked "2" add two ten-thousandths, if it is the line marked "3" add three ten-thousandths, etc.

Example C: [WITH the vernier]

Refer to the illustration below and your own micrometer.

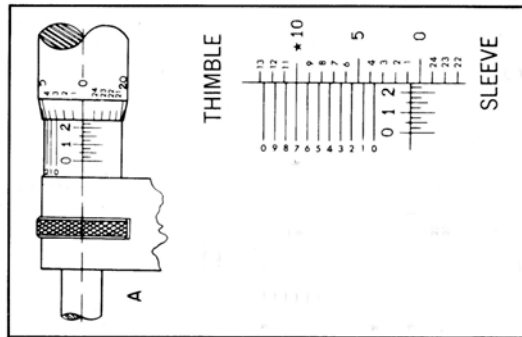


Figure 1.10. Using an English-reading micrometer.
(Drawing used with written permission from The L.S. Starrett Co.)

The "2" line on the sleeve is visible, representing0.200"

There are two additional lines visible, each representing 0.025"
 $2 \times 0.025'' = \dots\dots\dots 0.050''$

The reading line on the sleeve lies between the "0" and "1" on the thimble indicating ten-thousandths of an inch are also to be added as read from the vernier:

The "7" line on the vernier coincides with a line on the thimble, representing
 $7 \times 0.0001'' = \dots\dots\dots 0.0007''$

The micrometer reading is **0.2507''**

How to Read a Micrometer Graduated in Two-Thousandths of a Millimeter
(0.002 mm) -- (on our translation stages)

“Since the pitch of the spindle screw is one-half millimeter (0.5 mm), one revolution of the thimble advances the spindle toward or away from the anvil the same 0.5 mm distance.

The reading line on the sleeve is graduated in millimeters (1.0 mm) with every fifth millimeter being numbered from 0 to 25. Each millimeter is also divided in half (0.5 mm), and it requires two revolutions of the thimble to advance the spindle 1.0 mm.

The beveled edge of the thimble is graduated in 50 divisions, every fifth line being numbered from 0 to 50. Since one revolution of the thimble advances or withdraws the spindle 0.5 mm, each thimble graduation equals $1/50$ of 0.5 mm or 0.01 mm (10 microns). Thus two thimble graduations equal 0.02 mm (20 microns); three graduations equal 0.03 mm (30 microns), etc.

To read the micrometer, add the number of millimeters and half-millimeters visible on the sleeve to the number of hundredths of a millimeter indicated by the thimble graduation which coincides with the reading line on the sleeve.”

Example D: [WITHOUT the vernier]

Refer to the illustration below and your own micrometer.

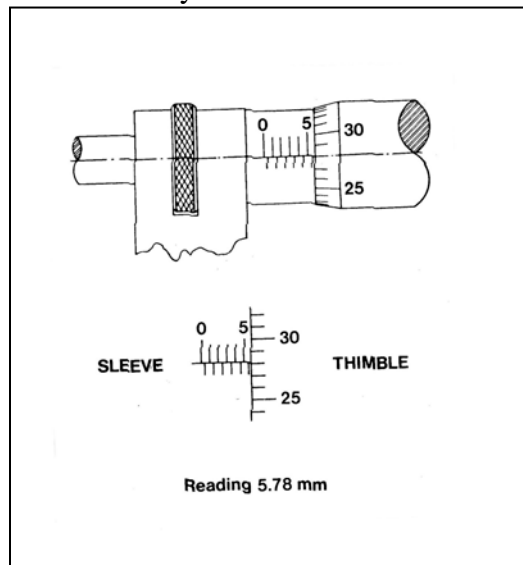


Figure 1.11. Using a metric-reading micrometer.
(Drawing used with written permission from The L.S. Starrett Co.)

The 5 mm sleeve graduation is visible 5.00 mm
 One additional 0.5 mm line is visible on the sleeve 0.50 mm
 Line 28 on the thimble coincides with the reading line on the sleeve, so
 $28 \times 0.01 \text{ mm} = \dots\dots\dots 0.28 \text{ mm}$
 The micrometer reading is **5.78 mm**

Metric vernier micrometers are used like those graduated in hundredths of a millimeter (0.01 mm), except that an additional reading in two-thousandths of a millimeter (0.002 mm) is obtained from a vernier scale on the sleeve.

The vernier consists of five divisions each of which equals one-fifth of a thimble division--1/5 of 0.01 mm or 0.002 mm.

To read the micrometer, obtain a reading to 0.01 mm in the manner just discussed. Then see which line on the vernier coincides with a line on the thimble. If it is the line marked 2, add 0.002 mm; if it is the line marked 4, add 0.004 mm, etc.

Example E: [WITH the vernier]

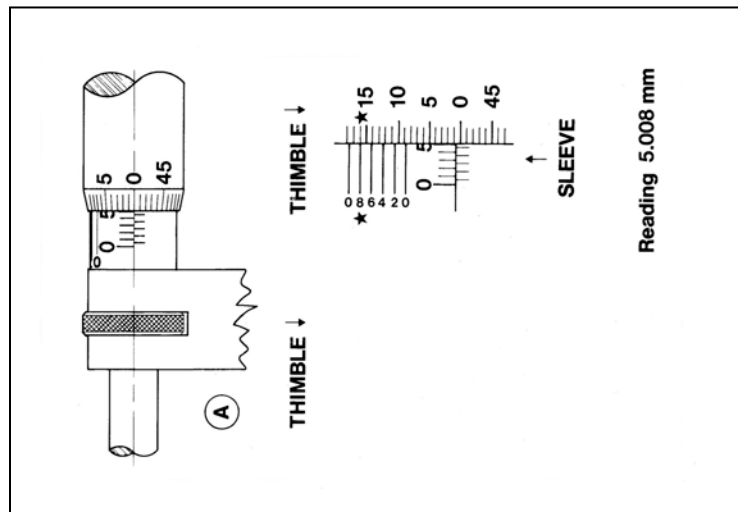


Figure 1.12. Using a metric-reading micrometer.
(Drawing used with written from The L.S. Starrett Co.)

The 5 mm sleeve graduation is visible 5.000 mm

No additional lines on the sleeve are visible 0.000 mm

Line "0" on the thimble lies below the reading line on the sleeve, indicating that a vernier reading must be added.

Line 8 on the vernier coincides with a line on the thimble 0.008 mm

The micrometer reading is **5.008 mm**

CLEANING OPTICAL ELEMENTS

The cleaning of optical elements (lenses, mirrors, filters, windows, beamsplitters, etc.) is both an art and a science. In the past few years, it has become much more of a science because of the demand for ultra-clean surfaces used in state-of-the-art optical systems (ref. Bennett 1990). The following information is presented as general guidelines that any optical engineer should be familiar with. Regardless of the cost of the optical element, one rule should always be followed: treat all optical surfaces with great care and attention. Good habits in handling low-cost optics will pay off when you are required to handle very expensive components.

Optical surfaces may be categorized in two general ways: Hard vs. Soft and Coated vs. Uncoated. The following table gives examples of both:

UNCOATED SURFACES

- | | |
|------|---|
| HARD | <ul style="list-style-type: none"> • most glasses used for lenses in visible light • glass substrates used for mirrors • colored glass filters • glass and sapphire windows |
| SOFT | <ul style="list-style-type: none"> • most glasses and materials used for infrared lenses (Si, Ge, NaCl, CsI, etc.) • sheet plastic filter material (Wratten filters) • plastic optics (lenses, Fresnel lenses) • copper or aluminum mirrors |

COATED SURFACES

- | | |
|------|---|
| HARD | <ul style="list-style-type: none"> • MgF on lenses (purple tint on your camera lenses) • SiO overcoat used on mirrors |
| SOFT | <ul style="list-style-type: none"> • bare Al, Ag, or Au coatings on mirrors • GRATINGS!! • patterns deposited on glass substrates (Ronchi rulings, reticles, etc.) • photographic film • holograms |

One of the most basic rules in cleaning optics is simple and direct: **DON'T CLEAN A SURFACE IF IT DOESN'T NEED CLEANING!** The obvious question, then, is how does one know when a surface is dirty enough to need cleaning? Fingerprints and heavy layers of dust are easy to spot, but mono-layers of molecular contaminants are much more difficult. Furthermore, the need for cleaning a surface may depend on where the contamination is located. A single fingerprint on the edge of a 60" mirror is a much different situation than the same fingerprint located in the center of a 2" camera lens. The general answer to when an optic needs cleaning depends on the situation, time, and cost involved.

HOW TO TEST FOR CLEANLINESS

The starting point in all of this is to identify the degree to which the surface is contaminated. Qualitatively, the most useful way to test for cleanliness is to look at the surface visually, with your own eyes. Use a high intensity light source and look along the surface at high angles, near grazing incidence. A flashlight in a darkened room works well for this. By looking in the direction of forward-scatter (along the surface into the light), one can spot contaminants quite readily. It is useful to note that the human eye can easily resolve 10 micron particles on a smooth optical surface using this technique! Although the laser is a source of high-intensity light, looking into the direction of forward scatter (almost directly back into the laser itself) is a dangerous practice. As it turns out, the flashlight actually works better and is much safer.

To measure surface contamination quantitatively, one measures the Bidirectional Reflectance Distribution Function (BRDF) of the surface on an instrument designed for making BRDF measurements (Brooks, 1982). BRDF is generally accepted as the correct means of measuring and describing the amount of light scattered from a surface. The amount of scatter can then be related to the level of surface contamination.

In practice, it is usually sufficient to qualitatively look at a surface to determine its level of cleanliness. The visual technique described above is easy to do, requires no fancy equipment, and is quite sensitive. It becomes more useful and even somewhat quantitative the more one uses it. On the other hand, if you have a need to assess the cleanliness of an expensive super-polished surface, measuring its BRDF may be warranted.

References:

- Bennett, Jean M., "When is a Surface Clean?" *Optics & Photonics News*, Vol.1, No.6, June 1990 (pp.29-32).
- Brooks, L. D., *Microprocessor-Based Instrumentation for BSDF Measurements from Visible to FIR*, OSC Dissertation, 1982.

GENERAL GUIDELINES

The following section lists some general guidelines for cleaning optics. Keep in mind that all situations are different, and require different approaches. These guidelines should serve as a good starting point:

- Clean an optic only if absolutely necessary.
- Start with the method of cleaning that is least likely to damage the surface (gentle stream of air from an air bulb, for example).
- Clean an optic only to the degree of cleanliness needed. (not every optic needs ultrasonic cleaning!)
- If you are uncertain about the consequences of a cleaning method, check first.
- Use lint-free cotton or talc-free surgical gloves when handling optics.
- Handle an optic by the edges or backside only.
- Test the cleaning method on the smallest area possible on the optic, at the edge.
- Remove fingerprints from an optic as soon as possible since the acid in skin oil can quickly begin to etch a surface.
- Blow off dust and particles from a surface before cleaning. Don't scrape this grit around on the surface when cleaning.
- Use the least amount of pressure needed when contacting the surface. The **drag method**, described below, uses the least pressure.
- The swab or tissue used must be cleaner than the surface being cleaned. Use a fresh swab or tissue for each step of cleaning.
- Do not allow a solvent to "puddle" on the surface. Small amounts of contaminant are left after the puddle evaporates and the contaminant actually increases in concentration in the area left by the puddle.
- Don't immerse or flush mounted optics in a solvent, as the solvent may dissolve an adhesive or coating used in the optics mount, or holder.

GENERAL CLEANING PROCEDURES

This next section discusses cleaning procedures, listed in order of minimal to most effective, and at the same time safest to most potentially damaging.

Air Cleaning

The advantage of using air or some type of dry gas (nitrogen) is that it avoids making physical contact with the surface being cleaned. In all following cases, make sure the air or gas is pure and not contaminated with oils.

(1) Rubber Squeeze Bulb

- cheap
- be careful not to touch the surface with the motion of the bulb!
- no contaminating oils in the air blown out

(2) Canned Air -- (Dust Off is one trade name)

- use only at glancing incidence (point the nozzle along the surface)
- GO EASY!! A full force from the nozzle can actually imprint particles into a soft surface or even knock the optic right out of your hand.
- make sure the can is designed for optical use (oil-free)

(3) Compressed Air -- (air line in a typical lab)

- usually contains oil contaminants
- make sure that an in-line filter is used to remove the oils
- there is MUCH force behind the air stream . . . GO EASY!

Brush Cleaning

(1) Camel's Hair Brush

- go easy with light pressure
- can be combined with a rubber squeeze bulb
- an antistatic lens brush, or an antistatic gun may be needed to remove charged dust particles

Solvent Cleaning

Solvent cleaning is generally used only for uncoated or unmounted optics. For the best cleaning, use distilled and deionized water and/or Reagent Grade solvents. If costs permit, use Spectroscopic Grade solvents. Always pour a small amount of the solvent into a clean jar or beaker in which to dip your swab or tissue. **NEVER** place a contaminated swab or tissue into a bottle of clean solvent. In all of the following cases, don't allow the solvent to puddle and dry on the surface.

(1) Flush or Immerse the Optic

- the simplest method to use
- the least efficient method to use (it may take hours for the solvent to remove the contamination with simple immersion)
- dry the optic in distilled water followed with an ethanol rinse

(2) Tissue Drag Method

- wet the surface and tissue with solvent, then gently drag the tissue across the surface, from one edge to the other
- use only the amount of solvent needed so the solvent quickly evaporates along the trailing edge of the tissue (no puddling)
- use overlapping paths across the surface of the optic
- the only forces acting against the surface are the liquid surface tension and gravity

(3) Swab the Optic

- use clean Q-tips dipped in solvent
- use only light pressure
- start at the edge first on a very small area
- roll the Q-tip as you move it across the surface so as to pick the contamination up off the surface

Adhesive Films

Adhesive films are usually used to protect and clean optical surfaces. Known by names such as Strip-Coat or Opti-Coat, these solutions are really collodions that remain flexible when dry. They are applied by pouring, dipping, or spraying, and work by trapping and retaining dirt particles in the dried film. Use a layer that is neither too thick nor too thin--a thick layer wastes material and may not dry properly, and too thin of a layer may tear apart when the coating is removed.

- use a small piece of Scotch tape to remove the film--press the tape along one edge of the film, and carefully lift up across the surface
- a film that is too thin may tear during this process, leaving islands of film in the middle of the optic--careful use of the tape is required at this point!
- *these films are known to leave a thin organic layer or plasticizer on the surface. DO NOT USE these films on super-polished surfaces!*

(The layer of plasticizer itself may act as a contaminant, causing a higher degree of scattered light from the surface. For ordinary optical surfaces, this probably doesn't matter.)

Finally, some guidelines may be given as to which cleaning methods should be used with the type of surface to be cleaned. Keep in mind that any unique situation may arise for which special precautions may be necessary. The following table organizes the general guidelines.

SURFACE TYPE	CLEANING METHODS
UNCOATED--Hard	(1) air cleaning (2) soap and water cleaning, followed with an alcohol rinse (most glasses) If deposits remain: * organic (fingerprints, oils) use alcohol * inorganic (silicone grease) use acetone
UNCOATED--Soft	(1) GENTLE air cleaning (rubber squeeze bulb) NO SURFACE CONTACT (bare Al,Au,Ag) NO SOLVENTS (GRATINGS)
COATED--Hard	(same as for uncoated hard surfaces)
COATED--Soft	(1) air cleaning (2) APPROVED solvent cleaning

NOTE: Most coatings can take alcohol or acetone, but **CHECK INFORMATION ABOUT THE COATING FIRST.** Use a Q-tip with the solvent to first test the outside edge of the coating. Mirrors can have either hard or soft coatings. It is preferable not to use soap and water on mirrors.

LAB EXERCISES

MICROMETERS

A comparison is often made between the diameter of an optical fiber and a human hair. Although this exercise is simple and quick, it demonstrates measurement skills and data analysis. The end result is both useful and interesting.

- (1) Use the micrometers to measure the diameter of one of your own hairs. (It is easier if you remove it from your head first!)
- (2) Take 5 readings (using the vernier to read the 0.0001" 's digit).
- (3) Calculate the mean and standard deviation of the mean for these 5 numbers.
- (4) Calculate the mean and standard deviation of the mean of all data taken by persons in your lab group.
- (5) Comment on the results.
- (6) CAREFULLY measure the diameter of the glass optical fiber 5 times.
- (7) Calculate the mean and standard deviation of the mean for these 5 numbers.
- (8) Convert your answers from steps (4) and (8) to microns, stating the errors properly.
- (9) Comment on how the two objects compare in size.

CLEANING OPTICS

The following exercises are designed as an introduction to the art and science of cleaning optics. No numbers are involved--make use of visual observations and describe what you see. Each person is to clean the following optics, in the order listed, using the steps outlined below:

Plane mirror	(dust and fingerprints)
Plane glass plate	(dust and fingerprints)
Plane mirror	(unknown contamination)
Plane glass plate	(unknown contamination)
Concave mirror	(dust) lint drag

- (1) Use the illumination test to determine how dirty the surfaces are. Look both in the forward and backscatter directions. Are there dust or dirt particles that are seen in one direction but not the other? Describe what you see. Repeat this step after each of the following cleaning steps, to ascertain how well you've cleaned the surface.
- (2) Use the air bulb to remove as much of the dust as possible.
- (3) Practice the tissue drag technique using the thick glass plate. Use a single piece of lens tissue and alcohol. Drape the tissue paper on top of the plate, so most of the tissue paper hangs off the back edge. Squirt a couple of drops of alcohol on the tissue paper, along the back edge. Slowly and at a uniform rate, pull the tissue paper forward until it moves free of the plate. Pull the tissue paper forwards at a rate such that no alcohol is left on the plate. Practice so as not to allow the alcohol to puddle on the surface. If this happens, describe what you see after the alcohol evaporates (basically, it leaves a concentrated "ring" of contamination at the front edge of the plate).

Clean the optics using the following methods:

Plane mirror	Tissue Drag technique
Plane glass plate	Tissue Drag technique
Concave mirror	Q-tip "roll" technique
Eyepiece	Q-tip "roll" technique

Clean the Plane glass plate (unknown contamination, slide marked with a "black dot"):

- (1) Soak the optic in soap and water followed by a water/alcohol rinse. For purposes of this lab, let the optic soak for 5 minutes or so.
- (2) Use the tissue drag technique with alcohol to clean the entire surface.
 - * Did that remove the contamination?
- (3) Use the Q-tips and alcohol to further clean along the contamination.
 - * Did this remove the contamination?
 - * What do you think the mystery contamination on the glass plate is?