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METROLOGY LABORATORY REQUIREMENTS FOR THIRD-GENERATION SYNCHROTRON RADIATION SOURCES*

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Metrology Laboratory Requirements for Third-Generation Synchrotron Radiation Sources

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ABSTRACT

New third-generation synchrotron radiation sources that are now, or will soon, come on line will need to decide how to handle the testing of optical components delivered for use in their beam lines. In many cases it is desirable to establish an in-house metrology laboratory to do the work. We review the history behind the formation of the Optical Metrology Laboratory at Brookhaven National Laboratory and the rationale for its continued existence. We offer suggestions to those who may be contemplating setting up similar facilities, based on our experiences over the past two decades.

KEYWORDS: Optical metrology, mirrors, synchrotron radiation, surface finish, surface figure, roughness, surface profile, facilities

MOTIVATION

Manufacturing tolerances for optical components used in synchrotron radiation (SR) beam lines are extremely stringent. In order to preserve the intrinsic brightness of third generation SR sources, mirrors are required to have surface finishes better than 5 Å RMS and surface slope errors not greater than 1 μrad RMS over the entire 1 meter or more length of the surface. In addition, radius of curvature tolerances require 1% or less error in surfaces that have hundreds of meters to several kilometers curvature. The required error bar for such a measurement is on the order of a few nanometers[1], which is at or beyond the capabilities of most optical shop testing techniques. The cylindrical shape of most grazing incidence mirrors also makes them nearly impossible to test by conventional means. Rather specialized expertise is necessary to make meaningful measurements on cylindrical aspheres.

In order to fulfill these stringent requirements, careful consideration needs to be given to the entire optics manufacturing process: the material selection, the manufacturing procedure, inspection in the shop and at the user's laboratory, deformation during installation, distortion during high heat load operation, etc. Problems in any one of these areas could influence the final surface figure significantly and affect the performance of the beam line. Accurate alignment of beam line components is also very important for achieving high monochromator resolution, for obtaining high intensity on the sample, and for producing the smallest possible focal spot. To insure a successful outcome, these precise and sophisticated procedures require instruments and expertise available from a well-equipped optical metrology laboratory.

Presently a number of new third generation synchrotron radiation facilities are in the commissioning stages, or are still in the planning and under construction stages. Surface figure distortion by high heat loads on cooled mirrors is a serious problem in the design of third-generation sources. An in-situ method of measuring the shape of these optical components has been shown to be effective in diagnosing heat-load related problems[2, 3].

A major question that most new SR source facilities face is the necessity of establishing an in-house metrology laboratory. Should an investment be made in the required resources to build up a metrology capability? What are the required resources? What are the benefits to be derived from establishing a metrology laboratory? We have been asked to comment on these questions recently, so we thought it would be a worthwhile exercise to try to answer these questions based on the years of experience we have gained during the operation of optical metrology laboratories at Brookhaven National Laboratory and at ELETTRA in Trieste.

HISTORICAL PERSPECTIVE

Over the past 2 decades or so, since the NSLS has been operational and ELETTRA in Trieste has come on line, mirror specifications for SR mirrors have usually always exceeded the measurement capability of many optics suppliers and of most SR laboratories who do not have sufficiently accurate test instrumentation. For example, during the first phase of ELETTRA construction, we found that more than 50% of the optical components that we tested were out of specification. Inspection of delivered parts in an optical metrology laboratory before installation in the beam line is absolutely necessary.

Similar experiences occurred also at the NSLS. During the late '70s and early '80s when the National Synchrotron Light Source was in its final construction phase, the major concern was to get mirrors made with sufficient smoothness to minimize scattered light and preserve the intrinsic source brightness. The unconventional design of grazing incidence optical systems required the use of far off-axis aspheric mirrors -- cylinders, toroids, ellipsoids and paraboloids -- that were extremely difficult to polish to a smooth finish. To insure that mirrors and optical systems would be able to meet the stringent requirements imposed by the synchrotron beam, Brookhaven established an optical metrology laboratory in 1983.

Fortunately, at about this time, a commercial instrument was developed that revolutionized surface roughness measurement technology[4]. The micro phase-measuring interferometer (micro PMI) enabled quick and accurate measurement of surface roughness with sub-Ångstrom level accuracy on parts of any size or shape. We acquired one of these instruments and immediately began providing manufacturers with feedback that allowed them to improve the quality of the surfaces provided to us[5, 6]. Since we were pushing the micro PMI beyond the limits of its intended use, we also established a research effort, in collaboration with E.L. Church, to understand the performance of the micro PMI and to validate the link between surface roughness measurements and actual performance of a mirror in a SR beam line[7-12]. This has been, and continues to be, a very fruitful collaboration.

In the early days of the NSLS, the thinking was to design some new beam lines and monochromators based around the new mirror fabrication technology of single-point diamond-turning (SPDT)13. SPDT manufacturing methods could produce very precise, highly aspheric surfaces quickly and easily. The only drawback was that the metal surfaces needed to be post-polished to remove the residual diamond turning grooves before they would be smooth enough for use in soft x-ray beam lines. Despite the successful efforts to produce low Ångstrom-level surface roughnesses on these aspheres, we quickly realized that the polishing process effectively destroyed the precise figure that was originally applied to the surface by the precision machining process. We also realized that most of the conventionally-polished large cylindrical mirrors in use at the NSLS had large slope errors that broadened the image and seriously compromised the intrinsic source brightness. Figure measurement techniques for SR mirrors were extremely crude at this time[14–16]. There were no commercial instruments capable of measuring grazing incidence aspheres with the required accuracy, so the final product was seldom within the desired range of specification for both surface roughness and figure error. After finding a effective solution to the surface finish measurement problem, we then turned our attention to the figure measurement problem.

In the early '80s, a surface profiling technique was developed by von Bieren, the pencil-beam interferometer, that was ideally suited for the measurement of long cylindrical aspheres[17, 18]. A development effort was started at BNL to apply this technique, and an instrument incorporating an improved version of the original pencil-beam interferometer was developed, which we called the Long Trace Profiler (LTP)[19-21]. The LTP is optimized for measuring the figure and slope errors on meter-long aspheres that have a long radius of curvature in the axial direction. It can handle surfaces with a total slope change of 10 mrads with better than 1 μrad repeatability. Despite the limited angular acceptance range, the LTP can handle about 99% of all mirrors used in grazing incidence optical systems. As with the micro PMI, we provided feedback to manufacturers and saw a gradual improvement in the quality of SR mirrors, not only for the NSLS, but for all SR facilities for which the mirrors were destined. Fig. 1 illustrates a typical case of the improvement possible with the correct metrology. The current version of the LTP, the LTP II, has now become the *de facto* standard in SR mirror figure metrology in most places around the world.

Table I -- World-Wide Synchrotron Radiation Sources
(after the Wisconsin SRC WWW homepage)

Facility	Location
USA	
ALS	Berkeley, CA
APS	Argonne, IL
CAMD	Baton Rouge, LA
CHESS	Ithaca, NY
DFELL	Durham, NC
NC STAR	Raleigh, NC
NSLS I	Upton, NY
NSLS II	Upton, NY
SRC	Stoughton, WI
SSRL	Stanford, CA
SURF II	Gaithersburg, MD
Brazil	
LNLS-1	Campinas
LNLS-2	
British	
DIAMOND	Daresbury
SINBAD	Daresbury
SRS	Daresbury
Canada	
CLS/CISR	London, Ontario
China PRC	
BSRF	Beijing
NSRL	Hefei
SSRF	Shanghai
China ROC-Taiwan	
SRRC	Hsinchu
Denmark	
ASTRID	Aarhus
France	
ERSF	Grenoble
DCI	Orsay
SOLEIL	Orsay
SuperACO	Orsay
Germany	
ANKA	Karlsruhe
BESSY I	Berlin
BESSY II	Berlin
DELTA	Dortmund
DORIS III	Hamburg
ELSA	Bonn
PETRA II	Hamburg
ROSY	Dresden
India	
INDUS-I	Indore
INDUS-II	Indore
Italy	
DAFNE	Frascati
ELETTRA	Trieste
Japan	
Accumulator Ring	Tsukuba
AURORA	Kusatsu
HBLS	Kashiwa
HISOR	Hiroshima
Kansai SR	Osaka
KSR	Kyoto
Nano-hana	Ichihara
NIJI II	Tsukuba
NIJI III	Tsukuba
NIJI IV	Tsukuba
Photon Factory	Tsukuba
SPring-8	Nishi Harima
SOR-Ring	Tokyo
Subaru	Nishi Harima
TLS	Sendai
UVSOR	Okasaki
Korea	
Pohang Light Source	Pohang
Netherlands	
AmPS	Amsterdam
EUTERPE	Eindhoven
Russia	
Siberia I	Moscow
Siberia II	Moscow
Siberia-SM	Novosibirsk
TNK	Zelenograd
VEPP-2M / 3 /4	Novosibirsk
Spain	
Catalonia SR Lab	Barcelona
Sweden	
MAX I / MAX II	Lund
Switzerland	
SLS	Villigen

A large part of our work in the metrology laboratory deals with educating people who have a stake in SR mirror manufacture, design, or use. This is a continuing process. New users and designers need to learn how to specify unconventional parts. Most new entrants into the fabrication industry tend to go through the same growth phases. Because procurement budgets are usually very limited, most users try to get their optics from small shops that are generally less expensive than big-name optical fabricators. New manufacturers invariably start by producing rather poor quality, unacceptable products but eventually learn how to achieve the required surface finishes. Small shops generally don't have the resources to buy expensive metrology equipment, so we provide both the measurement service and the education to interpret the measurement results. Seemingly insignificant details in an RFQ can result in enormous cost escalation. We provide the educational resources to users and designers who want to know how to communicate with manufacturers and vice versa.

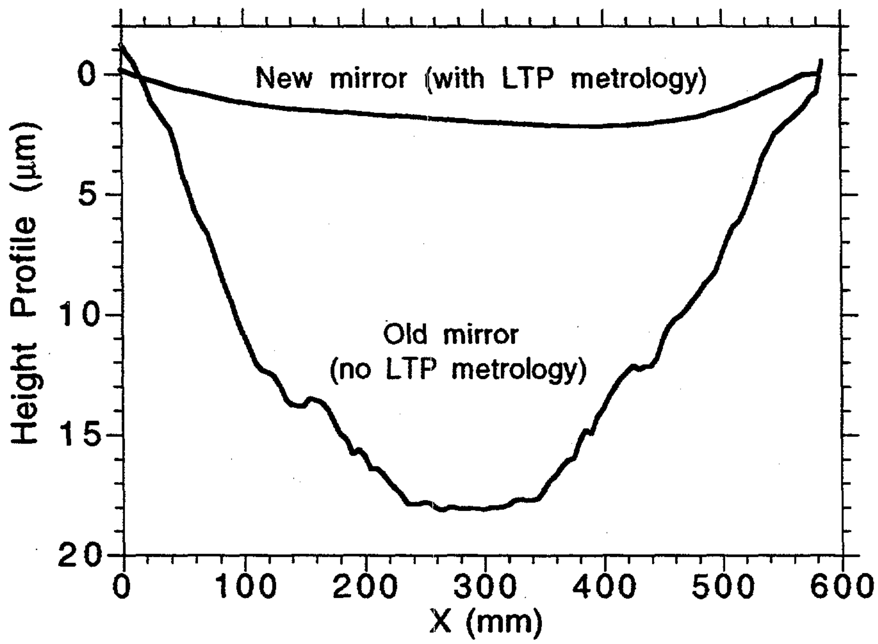

Fig. 1 -- Example of surface profile measurements made on an old SR cylinder mirror before LTP technology was available and on a newer, improved replacement mirror made after feedback was provided to the manufacturer. The improvement in overall flatness and mid-spatial frequncy ripple is obvious.

THE PRESENT

A list of all current SR sources throughout the world, taken from the Wisconsin SRC WWW site, that are operational, under construction, or planned is shown in Table I[22]. Each one of these sources has, or will have, dozens of beam lines, each requiring a set of optical components. Some of these will be mirrors, some will be crystals. We are concerned here only with the metrology of mirrors, since the surface figure and finish requirements for crystals are significantly different from mirrors. The potential need for synchrotron-specific metrology capability is readily apparent. Table II lists those facilities with dedicated optical metrology laboratories in existence or in planning and the approximate staffing level of each. The facilities information in the list is what is currently known to the authors. If we have missed any, or are providing inaccurate information, our apologies. This information is provided to assist in planning for new facilities.

Table II -- SR facilities with dedicated optical metrology laboratories.

Facility Location	Staff	Equipment
BNL NSLS USA	3	LTP I, WYKO NCP-1000 with Micromap upgrade, WYKO SIRIS 630, AFM
LBNL ALS USA	2	LTP II, WYKO NCP-1000 with Micromap upgrade, Zygo GPI XP, AFM
ESRF France	3	WYKO TOPO 2D/3D, LTPII (ESRF), WYKO SIRIS 6000, Zeiss wavefront tester, R&D beam line
ELETTRA Italy	2	LTP II, ZYGO Mark IV, Micromap 512
ANL APS USA	1	LTP II, In-situ LTP, WYKO TOPO 2D/3D, WYKO SIRIS 6000
BESSY II Germany	1	LTP II, Micromap, AFM
SRRC Taiwan	1	LTP II (on order)
SSRF Shanghai		(in planning stage)
SPring8 Japan	?	R&D beamlines,?

WORK PERFORMED BY AN OPTICAL METROLOGY LABORATORY

The expertise available in the metrology laboratory is useful in performing a number of different functions. In order to justify the need for a metrology laboratory separate from other operational facilities, we have compiled a list of some of the major tasks that we have been involved with in the past and at present:

1. Check figure and finish quality before installing optics into beamlines
   Roughness, radius of curvature, slope error
2. Bent mirror and adaptive optics testing -- calibrate bender, preset radius, debug bender design.
3. In-situ mirror distortion measurements under high heat load conditions.
4. Installation of optical components into beamlines.
5. Provide assistance for beam line alignment to improve resolution, intensity, and image size.
6. Provide a sheltered environment for off-line equipment assembly and alignment.
7. Monitor surface figure during assembly to check for deformation.
8. Test components for damage after exposure to SR beam.
9. Maintain a stock of components and equipment for experiment bread boarding by users.
10. Development of new test methods and instruments to solve unforeseen user problems.
11. Provide guidance and expertise in optical component selection and specification.
12. Provide oversight and advice in mirror procurement process.
13. Conduct research on new techniques and materials for problem solutions.
14. Development of standards for measurement techniques and analysis methods and for instrument calibration.
15. Interpret test results from other sources.
16. Educate manufacturers and users in the special needs of SR optics.

RECOMMENDED EQUIPMENT AND COSTS

For those contemplating establishing a new metrology facility, one of the most important considerations is the cost to provide the necessary resources to do the required tasks listed above. Based on our experiences, our recommendations for a suggested complement of instruments for a functional metrology laboratory at a SR facility are listed in Table III. Instrument costs are only rough estimates based on today's prices for typical instruments. Actual costs will vary according to desired features and customized installation details.

Table III -- Suggested instrument complement for a SR metrology laboratory

Instrument	Cost
Micro PMI surface roughness measurement instrument:	$60,000 -140,000
Conventional interferometer	$50,000 - 100,000
Figure and slope error profiling instrument	$100,000-135,000
2 Optical tables (1.5mx3m)	$10,000
1 granite table	$5,000
Microscope, Nomarski	$5,000
Autocollimator	$10,000
Theodolite and level	$20,000
Stepping motor or DC motor and controller	$15,000
Desktop computer/controller	$10,000
Miscellaneous mechanical and optical components, translation stages, and lasers	$50,000
Best-guess Total	$350,000 - 500,000

One of the most difficult things to do in the metrology lab is to set up a test configuration and make sure that all of the components are at the same height along the same center line. This may seem like a trivial consideration, but the effort involved in finding the proper mounting components can be very frustrating and time consuming unless careful thought has gone into procuring a compatible set of miscellaneous hardware. Two optical tables are listed above. These are required to support the interferometric measuring instruments and provide space to set up breadboard tests. A granite table is recommended for the LTP installation.

Miscellaneous items that are especially useful include an alignment cube and a plane parallel. The alignment cube has faces that are at 90° angles to each other within a 1 or 2 arc second tolerance. The plane parallel is a thick piece of high quality glass with its two faces polished parallel to each other with a 1 arc second tolerance. Accurate penta prisms are also useful for locating items orthogonal to a given direction. Some of the instruments will need to be modified to handle full-sized SR mirrors. In particular, the micro PMI instrument usually has a sample stage that is designed for small, lightweight pieces. A major modification will usually be required to enable the sample stage to support meter-long, heavy, full size mirrors. Careful consideration must be given to the mechanical stability of the stage to minimize vibration.

Absent from the list is an atomic force microscope (AFM). The micro PMI provides coverage over the relevant surface spatial period range, between 3 mm and 1 micron, that affects x-ray scatter from grazing incidence optics. The AFM is, however, useful for assessing the quality of substrates and mirrors with multilayer coatings that are to be used at normal incidence, and in measuring the quality of diffraction grating grooves. These are not routine measurements at most SR facilities, so the need for an AFM will depend on the extent to which measurements like these will be performed. We have a special stand-alone AFM scanner head available for use in our laboratory that can be placed anywhere on a full-sized mirror surface.

ENVIRONMENTAL CONSIDERATIONS

Precision metrology can not be accomplished without a controlled thermal environment. Most optical interferometers are extremely sensitive to temperature changes and thermal gradients. A temperature change of 0.1°C between two arms in a typical interferometer that are each 100mm long will produce an optical path difference of about 200 nm. This is about one-third of a wavelength of light and is a significant error source when precision and accuracy at the level of 1/100 of a wavelength is required. For slope-measuring devices, such as the LTP, temperature gradients that produce a tilt of one end of the air bearing beam relative to the other have the potential to introduce slope error artifacts into the measurement. A temperature difference of 0.1°C between the two end supports of an LTP will produce a tilt of about 0.5 μrad, which is a significant error source when attempting to measure absolute radius of curvature in kilometer-radius surfaces that have only a 20 μrad total change in slope. Temperature and humidity fluctuations destroy measurement repeatability, and without repeatability, one cannot hope to achieve accuracy in measurement.

Recommended guidelines for minimum environmental control in a SR metrology laboratory are as follows:

1. Cleanliness class: 1000 (better) - 10,000
2. Temperature fluctuations over 24 hours:
    a). LTP: ± 0.1°C
    b). Roughness test : 1-2°C
    c). Interferometer: ± 0.1°C
3. Vibration isolation: use active air isolation supports and/or massive optical tables.
4. Air turbulence: minimize, but maintain sufficient mixing.
5. Minimize acoustic vibration coupling from air handling systems.
6. Separate enclosures for each instrument.

These conditions are the minimum necessary for accurate and reliable measurements and can be improved as conditions and resources permit. We use a separate air conditioner unit to provide the ± 0.1°C temperature stability in the vicinity of the LTP in our lab.

SUMMARY

We have tattempted to justify the usefulness of having an in-house metrology capability at a SR facility and have offered some insights into how we arrived at our current position. We hope this document is useful for those engaged in planning for the future. One thing that we have found over the years is that our business has never declined: there always seems to be a need for the same kinds of measurement and the continual education of new users in the field.

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DISCLAIMER

The opinions expressed in this paper are solely those of the authors and should not in any way be construed as an official endorsement of any commercial product by the United States Government or any of its offices or agencies.

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