Profilometry of X-ray Optics: Current Progress

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10 April 2002
Long Trace Profiler

LTP II Optical Head

Intensity Fringes on Detector
LTP II - Optical Model

- Manufactured by Continental Optical Corp. 1991-1999 under license from BNL
- $F = 1250$ mm, Surface Angular Range = $\pm5$ mrad
Brief History of the LTP

- 1985 - Begin original design
- 11/87 - LTP I with GPIB detector and stepping motor, **HP BASIC**
- 12/91 - LTP II for LBL from Continental Optical
  - ISA bus PI detector and brushless DC servo motor, **C and LabWindows CVI, DOS**
- 4/94 - 2/98 - CRADA, SBIR with Continental Optical for NASA VSLTP
  - C++ version
- 9/97 - In Situ LTP at Advanced Photon Source
  - 8 bit camera (**DOS**)
- 1/00 - LTP I changed to **HT BASIC on WinNT PC**
- 1/01 - LTP I changed to **LabVIEW**, Dalsa camera&frame grabber
- 6/01 - CRADA with Ocean Optics
  - ELID machine project at RIKEN, Tokyo: OOI detector, **C++ software**
- 11/01 - Portable LTP at SPring8: Cronin camera, motor on parallel port
- 12/01 - Ocean Optics CRADA, Opt head for BESSY
What’s New?

- Switch from Continental Optical to Ocean Optics
  - C++ unified software
  - USB interface for detector and motor
  - Eliminate air bearing - use linear motor stage, lightweight, compact
- Special optical head for BESSY
- RIKEN ELID grinding machine optical head
- In situ measurement with PTLTP at SPring8 and Taiwan
- XEUS mirror metrology proposal
- LTP II upgrades
- Develop standards for long radius measurement
- Investigate systematic error sources that prevent <1.0 µrad accuracy
## LTP Installations Worldwide

<table>
<thead>
<tr>
<th>Location</th>
<th>LTP Version</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brookhaven National Laboratory Upton, NY USA</td>
<td>4</td>
<td>LTP I, LTP III, ISLTP, PTLTP</td>
</tr>
<tr>
<td>Lawrence Berkeley Laboratory Berkeley, CA USA</td>
<td>1</td>
<td>LTP II</td>
</tr>
<tr>
<td>NASA Marshall Space Flight Center Huntsville, AL USA</td>
<td>2</td>
<td>LTP II, VSLTP</td>
</tr>
<tr>
<td>Argonne National Laboratory Argonne, IL USA</td>
<td>1</td>
<td>LTP II</td>
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<tr>
<td>University of Chicago Chicago, IL USA</td>
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<td>LTP II</td>
</tr>
<tr>
<td>InSynch, Inc Albuquerque, NM USA</td>
<td>1</td>
<td>LTP II</td>
</tr>
<tr>
<td>Ocean Optics, Inc. Winter Park, FL USA</td>
<td>1</td>
<td>LTP IV</td>
</tr>
<tr>
<td>Sincrotrone Trieste Trieste, Italy</td>
<td>2</td>
<td>PTLTP, ISLTP</td>
</tr>
<tr>
<td>European Synchrotron Radiation Facility Grenoble, France</td>
<td>1</td>
<td>LTP II modified</td>
</tr>
<tr>
<td>BESSY II Berlin, Germany</td>
<td>2</td>
<td>LTP II, LTP III</td>
</tr>
<tr>
<td>Synchrotron Radiation Research Center Hsinchu, Taiwan</td>
<td>1</td>
<td>LTP II</td>
</tr>
<tr>
<td>SPring-8, Japan Synchrotron Radiation Research Institute, Hyogo, Japan</td>
<td>1</td>
<td>LTP II</td>
</tr>
<tr>
<td>RIKEN Institute Tokyo, Japan</td>
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<td>LTP III</td>
</tr>
<tr>
<td>Osservatorio Astronomico di Brera Merate, Italy</td>
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<td>LTP II</td>
</tr>
<tr>
<td>Pohang Accelerator Laboratory Pohang, Korea</td>
<td>1</td>
<td>LTP II</td>
</tr>
<tr>
<td>Crystal Scientific Alnwick, England</td>
<td>1</td>
<td>LTP II *</td>
</tr>
</tbody>
</table>
VSLTP at NASA MSFC

- X-ray telescope cylinders and mandrels to 1 m diameter
- SBIR with Continental Optical, design by T. Oversluizen
RIKEN ELID Optical Head

- **ELID** ultra precision grinding machine
  - “electrolytic in-process dressing” of cutting tool
  - produces ready-to-polish cylindrical optics in glass, Si, SiC
- Need for on-machine metrology for final fabrication stages
- Collaboration with BNL (design, optics board) and Ocean Optics (fabrication, detector, software)
- Interface ContOpt software with ELID motion control system
  - field installation by OOI software engineer
- Added 3D surface map capability with beam-steering mirror
- Problem with cylinder lens installation - rework system
ELID Ultra Precision Grinding Machine

Sketch with LTP optical head installed
ELID LTP Optical Head

• Uses existing optics board
• Off-the-shelf parts for lens bench
• Incorporates OOI detector

Kinematic mount for installation on machine
ELID LTP Data
Analysis code based on VSLTP 3D surface analysis

CYL11.raw - fix W parameter to compute correct angle. Now scan up full width of cyl.
HGT from D1 slp
Portable LTP - PTLTP

- Compact optical head design
- Uses monolithic SBS beamsplitter for exceptional stability
- Basis for current Ocean Optics standard unit
- Use for *in situ* measurements of mirrors under actual operating conditions
- Designed for “before-after” measurements, not for absolute accuracy
- Collaboration with SPring8 - distortion of cooled grating in soft x-ray beam line
- Adaptable to different translation stages
BESSY Optical Head

- For German NOK project (Nanometer Optikkomponenten)
  - Optical head for ultra-precision metrology of optics for x-ray lithography
- Requirement for 10nm absolute accuracy over 1.2 meter length.
- Need <30nrad slope error accuracy
  - Stringent performance on lens design
  - Low distortion F-θ lens
- Model various configurations with ZEMAX and OptiCAD
  - Moving optical head -> better lens performance
  - Fixed optical head, penta prism scan -> less mechanical error
BESSY Optical Head Design

- Scanning penta prism, fixed optical head
  - difficult lens problem
- 3 SUT ranges: 1750mm, 1150mm, 550mm
- Max surface angle: ±6.6mrad
- Minimize distortion over all ranges and angles
OptiCAD Raytrace of BESSY LTP

• Fixed optical head, moving penta prism
• 3 element lens design gives 100nrad performance
• Fixed head requires larger size optics -> more errors
• Moving head design - can get <2nrad distortion

Max slope error | Allowed distortion limit
-----------------|------------------------
1 μrad           | 0.0167 %
100 nrad         | 0.0017 %
30 nrad          | 0.0005 %
BESSY LTP
Uses Microbench parts
XEUS X-ray Telescope Metrology

- Collaboration with O. Citterio at Osservatorio Astromonica di Brera, Milano, Eimeldingen, OOI
- Measure Wolter telescope segments: 1.2 to 10 meters in diameter
- Nested thin foil segments, 1m x 1m square, vertical orientation
- Scan up from table top, not down from bridge structure
  - more compact system
- Scan close to surface or along symmetry axis???
- Require 100 nm accuracy with 3D full-surface map
- Difficulty is azimuthal scan accuracy
  - requires including mechanical tolerances in measurement loop.
- Proposal due later in 2002
$r = g(z_0)$

Conicoid symmetry axis

Vertical Scan Axis

$\Phi_0$

$Z_{pn}$

$Z_{0n}$

$D(z)$

$\theta_0 = n \delta \theta$

$R(z)$

$R-D$

$x_0$

$y$

$x$

$y$

$z$

$z$

$5$

$4$

$3$

$2$

$1$

$0$

$5040$

$5020$

$5000$

$4980$

$4960$

$4940$

$-66$

$-65$

$-64$

$-63$
3 axis stage by Eimeldingen
Can be used in near or far configuration
LTP III

- Replaced original LTP I in Metrology Lab
- Dalsa camera, frame grabber, Nikon lenses, same GPIB motor controller
- LabVIEW control and analysis program
- Versatile, custom configuration for any mirror geometry
  - Face up, face down, sideways
- Thermal sensitivity
  - Replace NBS with SBS or phase plate
- Systematic errors at the microradian level
X12B - SESO cylinder mirror, face down
X26C Mirror bender calibration

R from D1 on slopes relative to 9e @ 0 half-steps

X26C bender R vs. motor steps
Stability vs. Beam-splitting Optics

Produce phase shift of $\lambda/2$ between beams

NBS w/Porro prisms (separate pieces)

SBS (monolithic)

Phase Plate

Standard LTP

Compact LTP
Qian patent pending

Z. Li, et al
Tsinghua University
LTP III Stability Scan - 7 hours

BNL LTP III optical head with $\Delta T=0.2^\circ C$

Very sensitive to temperature and humidity fluctuations.
Improve BNL LTP III Stability

Using SBS monolithic beamsplitter

Using phase plate
Systematic error effects

- Difficult to achieve accuracy below 1 µrad in LTP III
- Lack of repeatability in long-radius measurements
- Suspect glass inhomogeneity problems in lenses and PBS
- Modify LTP III structure to “open architecture” system -
  \[\Rightarrow \text{LTPIIIa}\]
  - Use of Microbench parts
  - Allows for rapid reconfiguration

- Use external laser source for LTPIIIa tests
LTP IIIa
“Open” architecture
LTPIIIa w/External Laser - Single Direct Beam

- Remove all glass between laser and detector.
- Scan carriage at 0.2 mm steps.
- Shift absolute position by ~10mm between scans.
- 2nd order polynomial fit to peak of Gaussian beam.

2 sets of scans, average of 16 scans in each set.

Shift second scan by 0.6mm to align starting points.
External laser test - results

- See microradian-level errors in residuals between adjacent points.
- Independent of measurement location of carriage
  - Not caused by encoder position error or lead screw error
- Must be internal to Dalsa detector chip?
- Multiple reflections in cover glass?
- Investigate effect of smaller beam size.
- Possible solutions-
  - Lookup table for position correction
  - Replace Dalsa camera with OOI USB detector.
    - Requires major software change to C++ code.
    - Change motor controller
LTP II upgrades

- Original Princeton Instruments detector obsolete - dual array no longer made by Reticon
- ISA bus interfaces for detector and motor controller obsolete
- USB interface with OOI detector, motor controller
- Increase surface slope range from 10 mrad to 30 or 60 mrad
- Requires decrease in focal length and change in folding mirror board

Design criteria
- Keep detector in current location
- Keep current PBS aperture - 30mm
- Single lens and single folding mirror

- What range of acceptance angles are possible with current geometry?
Original LTP II
EFL = 1250 mm
Aperture angle = 20 mrad
EFL = 415 mm
θ = 60 mrad
EFL = 285 mm
θ = 87.6 mrad
EFL = 165.3 mm
θ = 150 mrad
LTP II Upgrade

ZEMAX lens design distortion results

<table>
<thead>
<tr>
<th>Design acceptance</th>
<th>F-θ max distortion</th>
<th>Absolute surface distortion</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>D = 100mm</td>
<td>D = 80mm</td>
</tr>
<tr>
<td>60 mrad</td>
<td>&lt;0.0001%</td>
<td>0.002%</td>
</tr>
<tr>
<td>87.6 mrad</td>
<td>0.076%</td>
<td>0.059%</td>
</tr>
<tr>
<td>150 mrad</td>
<td>3.25%</td>
<td>2.80%</td>
</tr>
<tr>
<td>150 mrad 2-lens</td>
<td>0.27%</td>
<td>0.246%</td>
</tr>
<tr>
<td>150 mrad 3-lens</td>
<td>0.0224%</td>
<td>1.12%</td>
</tr>
</tbody>
</table>
Acknowledgments

• Photo credits-
  – Dieter Schneider and Toshi Karasawa, AVANCE

• Phase plate fabrication
  – John Warren and Don Elliott

• Shop work
  – Richard Ryder and Bill King
Design projects
   RIKEN ELID head
   BESSY NOK project head
   VLTP for Citterio
   LTP II upgrades
   Portable LTP - OOI detector
   Compact Optical Head
   SPring8 In Situ LTP project

LTP Improvements
   Super Stable Beamsplitter
   Phase Plate beamsplitter
   OOI commercial version - no air bearing

LTP I upgrade
   LTP III w/Nikon lenses, Dalsa camera, LabView control and analysis software
   LTP IIIa - open architecture

Investigations
   Absolute accuracy in long R measurement
   Systematic errors at <1 microradian