Metrology of X-ray Optics
In Pursuit of Perfection

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BROOKHAVEN NATIONAL LABORATORY

a passion for discovery

U.S. DEPARTMENT OF ENERGY | Office of Science

MEADOW 2013 Workshop, ICTP Trieste, Italy
28-30 October 2013

Roadmap

- One man's journey in pursuit of the perfect surface
  - A retrospective on how profilometry has improved the state-of-the-art of fabrication of SR optics over the past 30+ years.

- Brief history of x-ray optics
- Surface finish metrology
- Surface figure metrology

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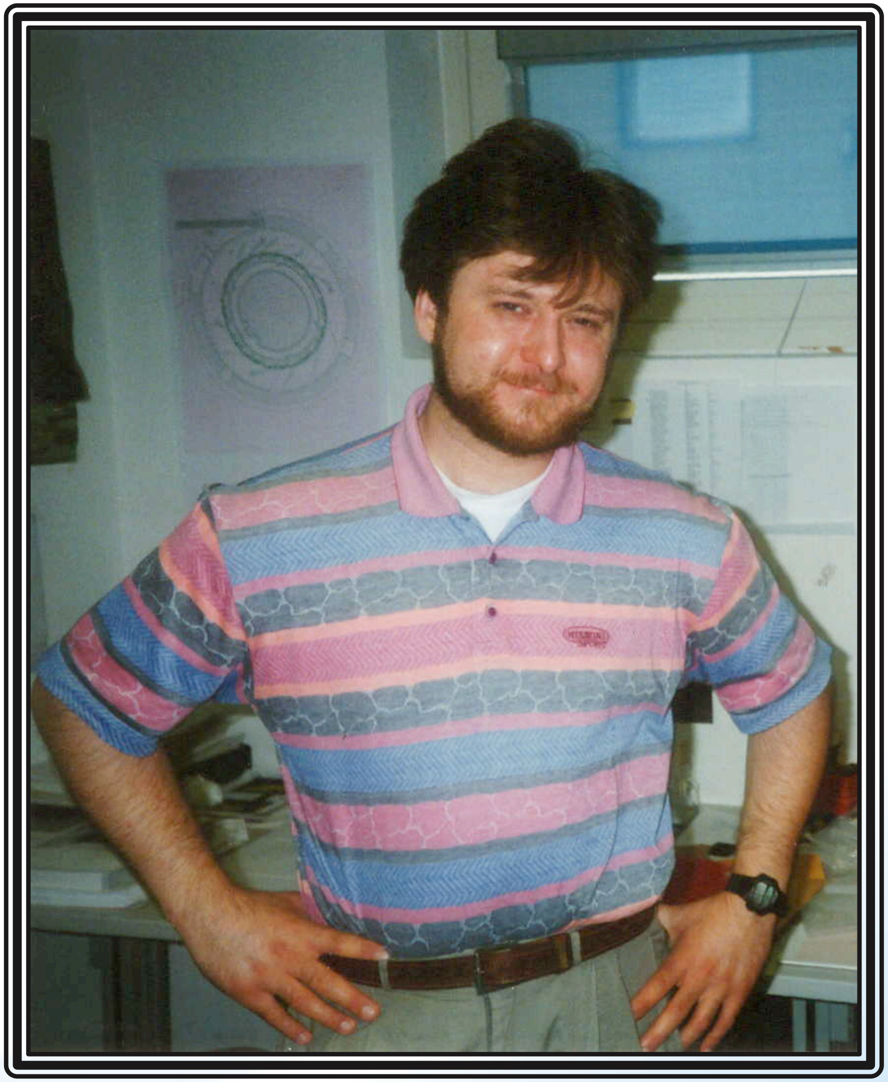
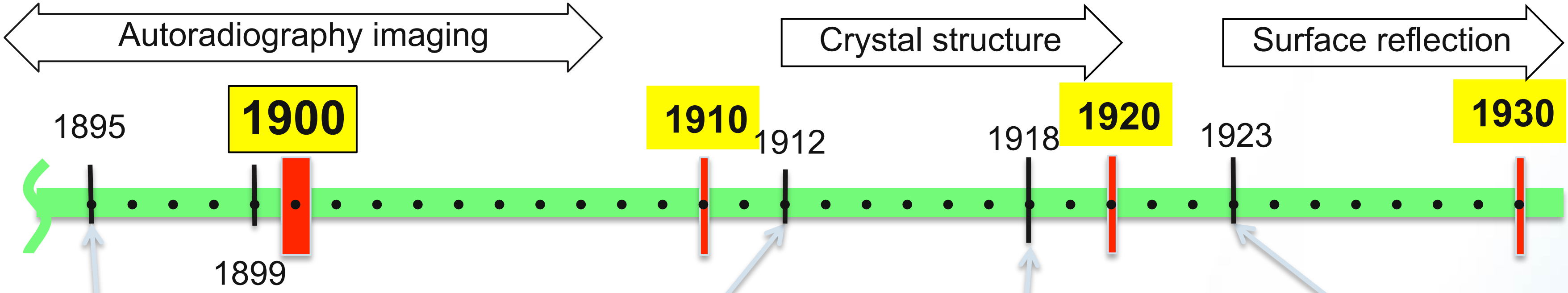
Giovanni Sostero – friend and colleague



Reflective x-ray optics

BRIEF HISTORICAL INTRODUCTION

Brief history of significant events in x-ray science



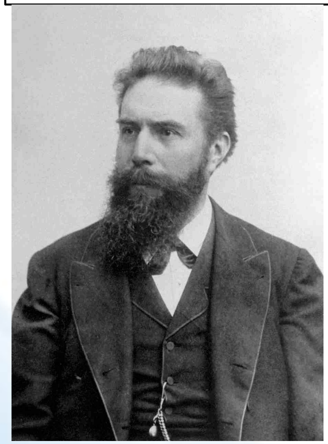
X-rays are electromagnetic waves (Haga&Wind)

Röntgen discovers x-rays

Diffraction from crystals

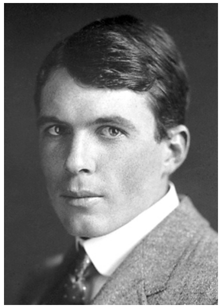
Recognizes measurements as total external reflection

Total external reflection demonstrated

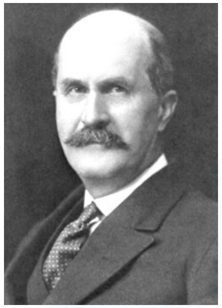


Wilhelm Conrad Röntgen (1845-1923)

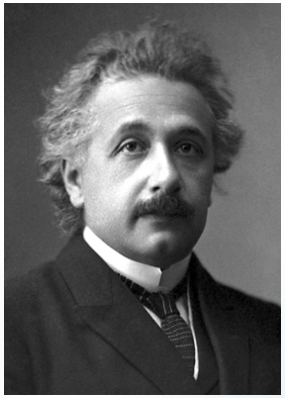
Max von Laue (1879-1960)



W. H. Bragg (1862-1942)



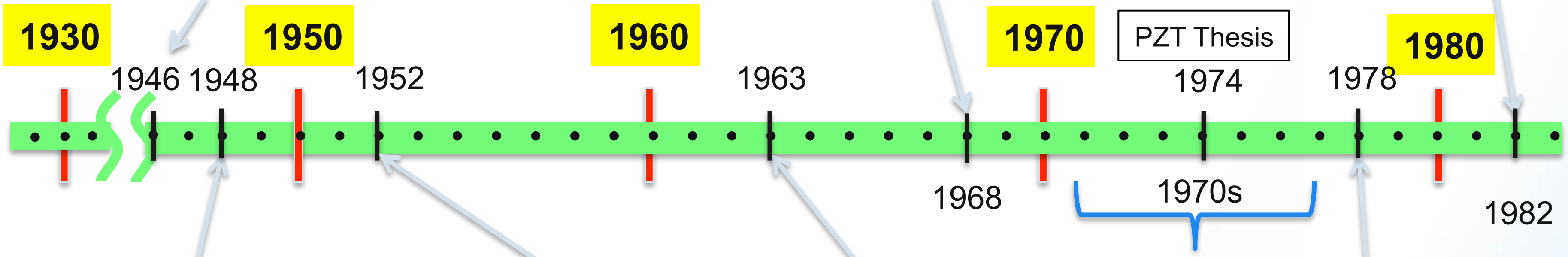
W. L. Bragg (1890-1971)



A. Einstein (1879-1955)

Arthur Holly Compton (1892-1962)

A brief history – cont.



First observation of synchrotron light at GE

Tantalus - First dedicated synchrotron light source

NSLS-I

PZT Thesis

KB mirrors for imaging

Wölter microscope designs

Wölter telescope on sounding rocket for solar x-rays

Wolter and KB astronomical telescopes on sounding rockets

HEAO-B (Einstein) First satellite imaging telescope

ROSAT 1990

XMM (Newton) AXAF (Chandra) 1999

Formation of Optical Images by X-Rays

Paul Kirkpatrick (1894-1992)

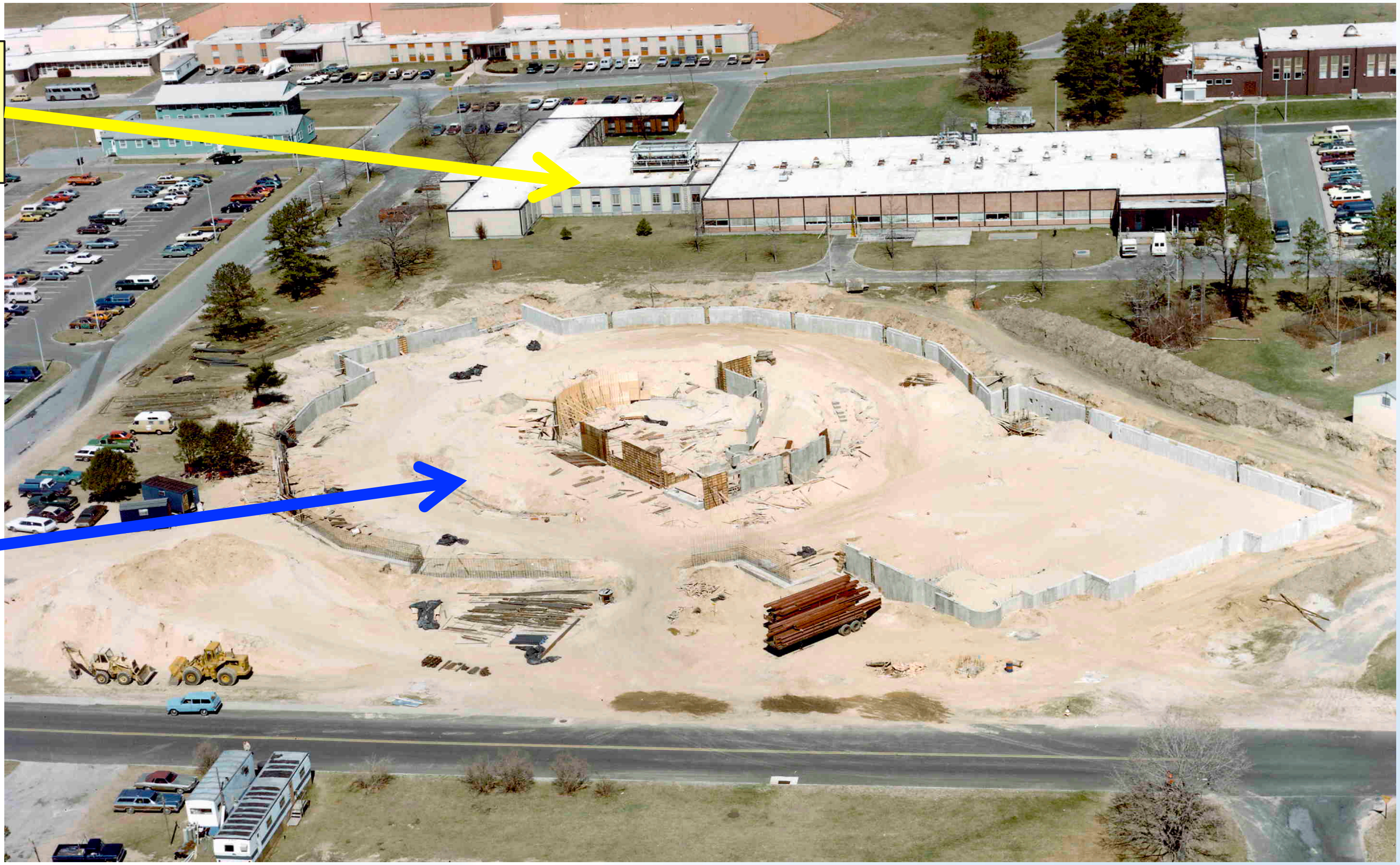
AIP Emilio Segre Visual Archives, Physics Today Collection

Albert V Baez (1912-2007)

Hans Wölter (1911-1978)

Riccardo Giacconi

Brookhaven National Lab: 1979



Instrumentation Division

NSLS-I

The problem with x-ray mirrors

Excellent review article by Aschenbach (1985)

Refers to comments by Ehrenfeld (1949):

> "The study of surfaces by x-ray reflection is of interest by itself, but it may not be easy to improve optical surfaces to such an extent as to reduce appreciably the stray light near an x-ray optical focus."

Scattered light was the limiting factor in making VUV monochromators work in early synchrotron beam lines in the late 1970's

B Aschenbach, "X-ray Telescopes", Rep. Prog. Phys. **48**, 579-629 (1985).

W. Ehrenberg, "X-Ray Optics: Imperfections of Optical Flats and Their Effect on the Reflection of X-Rays", JOSA **39,** 746-751 (1949)

Immediate problem – make surfaces smoother

SURFACE FINISH

Surface profiler technology – pre-1980

- Analog electronics (!)
- Strip chart recorder output
- RC filters

FIGURE 62 – The first Talysurf instrument

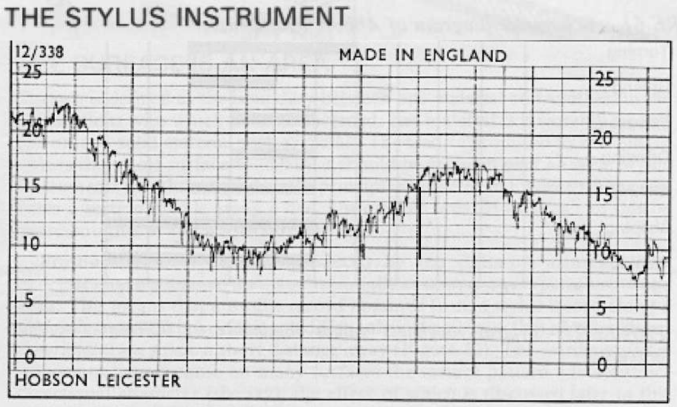


FIGURE 10 – Typical profile graph

FIGURE 21 – The author is bewildered by a profile graph which is a simple enlargement of the surface cross-section

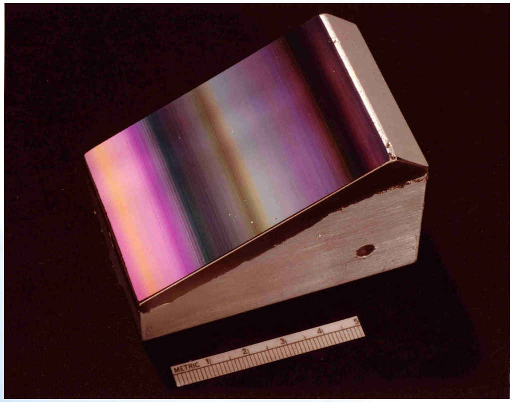
"Exploring Surface Texture", by H. Dagnall M.A., Rank Taylor Hobson (1980)

NSLS Plane Grating Monochromator – c.a. 1981

- Malcolm Howells novel design – utilized 5 off-axis paraboloids.
- How to polish? How to measure roughness on aspheres? How to analyze roughness?
    - ➢ TIS and Talystep profiler
- TIS measured at China Lake by Jean Bennett: σ = 3.4Å
- Talystep at NIST: σ = 32.3 Å

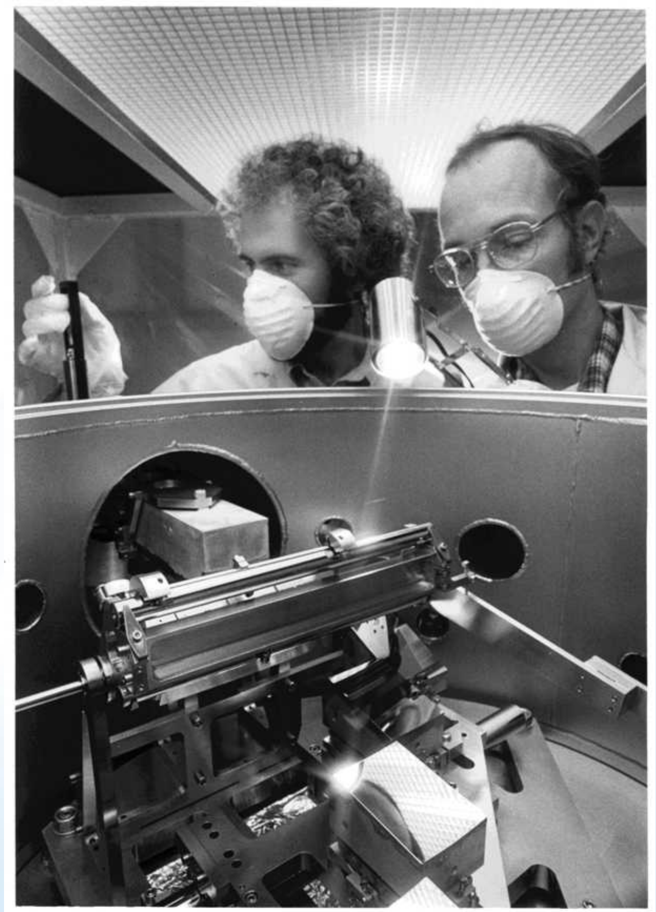
WHY SUCH A DIFFERENCE????

Diffraction rainbow from diamond turning grooves



Off-axis paraboloids

PZT with Mike Kelly



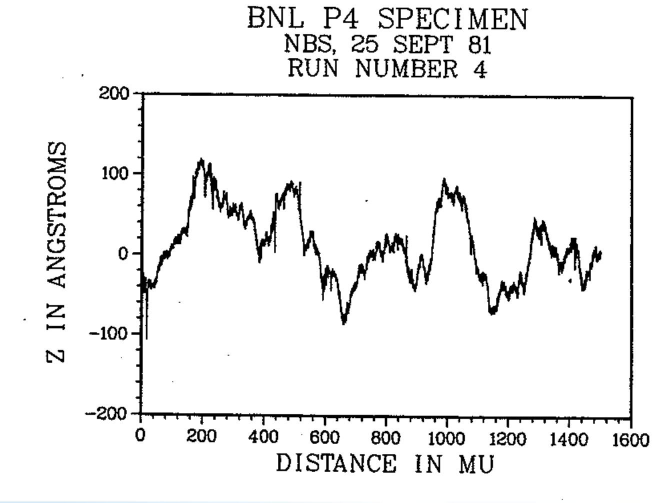
Collaboration with E.L. Church – Frequency Footprints

"It is Procrustean to make a direct comparison with stylus and TIS measurements"

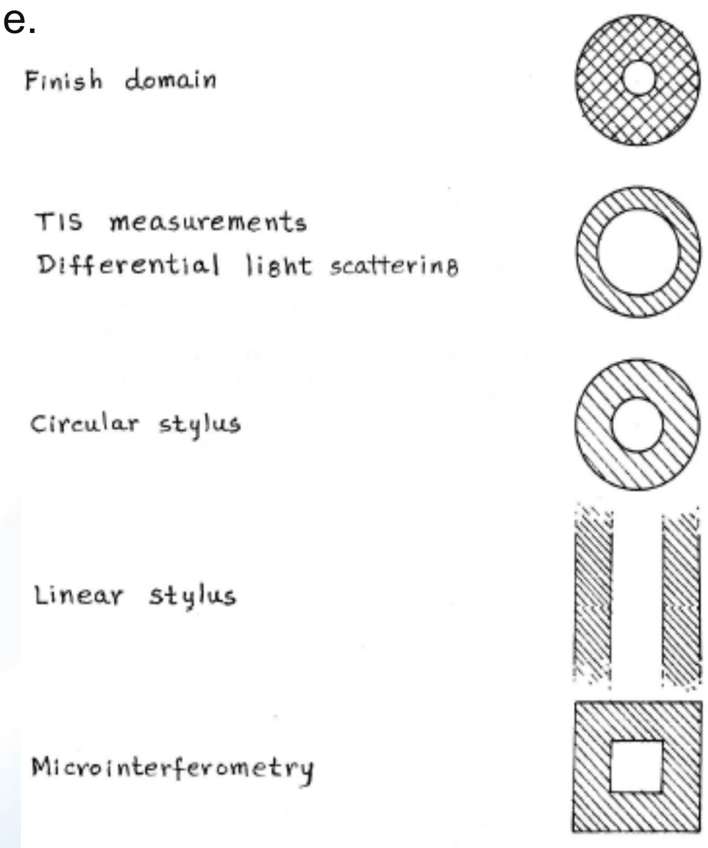
- Instruments are sensitive to different spatial frequency domains.
- Comparing apples to oranges.
- Need to insure that spatial frequency ranges coincide.

E. L. Church, "The precision measurement and characterization of surface finish", Proc. SPIE **429**, pp. 86-95, (1983)

Spatial Period range [μm]	(Hi freq) Short per 2 – 12	(Low freq) Long per 12-500	Full range 2-500	
Stylus	3.68	32.0	32.3	Å
TIS	3.4			Å



E. L. Church, M. R. Howells, and T. V. Vorburger, "Spectral analysis of the finish of diamond-turned mirror surfaces", in Proc. SPIE **315**, pp. 202-218 (1981).



Power Spectral Density - PSD

- **Periodogram** estimator (one-sided) of profile PSD function:

$$S_1\left(f_n\right) = 2\frac{D}{N}\underbrace{\left|\sum_{m=0}^{N-1}\exp\left[i2\pi mn / N\right]\cdot W(m)\cdot \tilde{Z}(mD)\right|}_{\text{DFT}}^2 K(m)$$

$$f_n \equiv \frac{n}{ND} = \frac{n}{L} = n\cdot f_1 \qquad n = 1,\ldots,\frac{N}{2}$$

where $\tilde{Z}$ is the **detrended** profile

W is the Window function

K is a book-keeping factor for one-sided FT

This explicit form of the PSD function insures that Parseval's theorem is satisfied:

$$\left\langle \frac{1}{N}\sum \tilde{Z}_n^2 \right\rangle = \left\langle \frac{1}{ND}\sum S_1\left(f_m\right)\right\rangle$$

=> over the Ensemble Average

E. L. Church and P. Z. Takacs, "Chapter 8 - Surface Scattering," in *Handbook of Optics*. Vol. I, M. Bass, ed., 3rd ed: McGraw-Hill, 2009.

SR optics surface finish considerations

- Need for fast, non-contact, visible light method for characterizing surface finish.
- Observation: The spatial frequency range that affects near-angle scatter at x-ray wavelengths at grazing incidence is the same as for visible light at normal incidence => *the "grazing incidence forgiveness factor"*
  - 1 micron to 1 millimeter spatial periods
- So take advantage of visible light to quantify roughness that affects scattered light at x-ray wavelengths.
  - Want to be able to measure the surface quality of full size optics BEFORE they are installed in a SR beam line.
- TIS only sensitive to a very small spatial period range: 2 - 12 microns.
  - Very small frequency footprint
- Stylus profilers damage delicate SR coated surfaces.
  - Difficult to handle large full-size optics with Talystep
- Enter: the **OPTICAL PROFILER**

Surface profiler technology, after 1980

- WYKO NCP-1000 Digital Optical Profiler
- Invented by Chris Koliopolous (1981)

C. L. KoliopouIos. “Interferometric OpticaI Phase Measurement Techniques,” Ph.D. Dissertation, U. Arizona (1981).

- Microscope-based, non-contact
- Perfectly suited for SR optics
- Computer controlled
- Easy to use

E.L. "Gene" Church - Signal processing guru & mentor

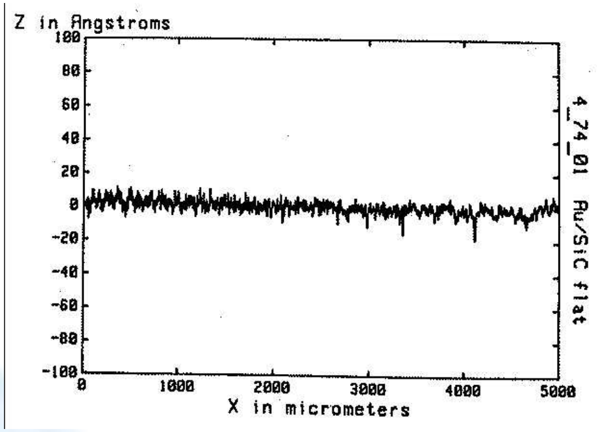
Malcolm Howells connected with Gene at a 1979 SPIE x-ray optics workshop in Huntsville.

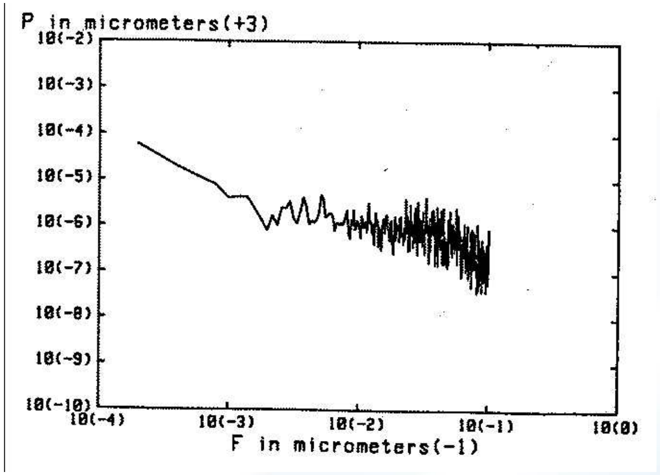
- Measurements are useless, unless you understand how the instrument works.
- Keen interest in understanding how the optical profiler works.
- Pushed the NCP-1000 beyond the limits for which it was designed.
- Analysis of profile data in frequency domain.
- Introduced frequency domain concepts to surface roughness
  - **Power Spectral Density function, PSD**
  - Frequency footprint of instrument
  - Transfer function analysis to correct for high frequency MTF attenuation.
  - Bandwidth-limited statistics

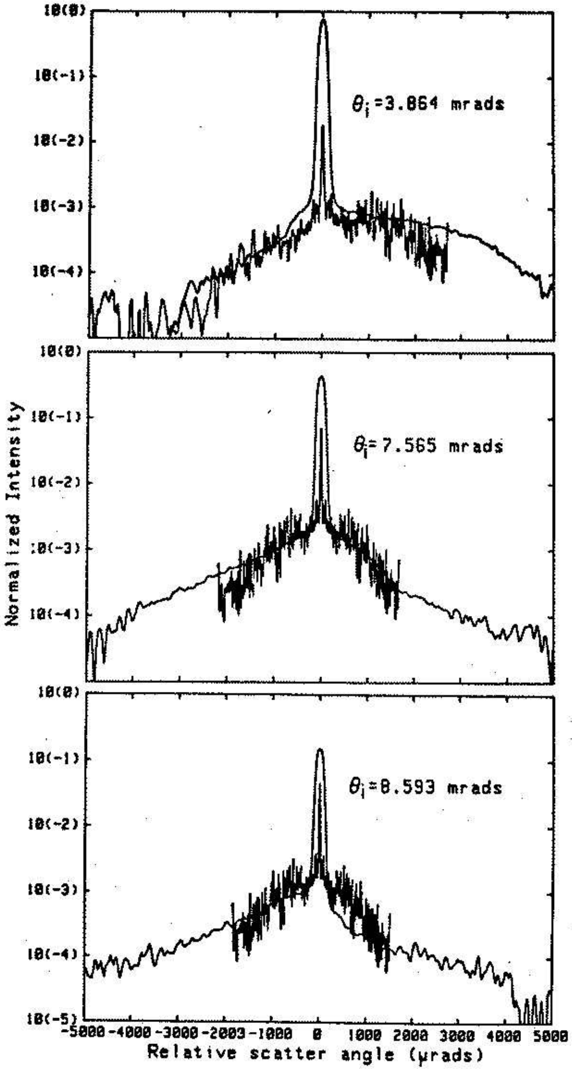
Finish-Function relationship confirmed

- Au-coated SiC flat, σ = 4.74 Å [10μm, 5mm]
- Predict quantitative scattering at 8.9 keV
- Rayleigh-Rice vector perturbation theory (Church)
  - Connects PSD with observed scatter.
- The “Golden Rule” for grazing incidence x-rays

$$\frac{1}{I_i}\left(\frac{dI}{d\theta}\right)_s = 16\pi^2\left(\frac{\sin\theta_i}{\lambda}\right)^3 \cdot R(\theta_i)\cdot K(\theta_i,\theta_s,0,\epsilon)\cdot S(f_x)$$







THEORY PREDICTION AGREES WITH MEASUREMENT

E. L. Church, and P. Z. Takacs, "Subsurface and volume scattering from smooth surfaces", Proc. SPIE 1165, pp. 31-41, (1989)

However…..

- There are subtleties involved in the proper calculation of the PSD:

DETRENDING

WINDOWING

SYSTEM TRANSFER FUNCTION

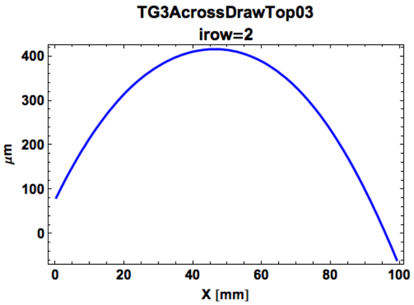
- Gene Church provided the mathematical foundation.

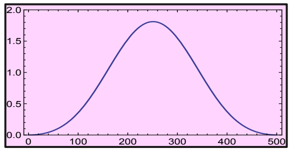
DETRENDING & WINDOW function effects

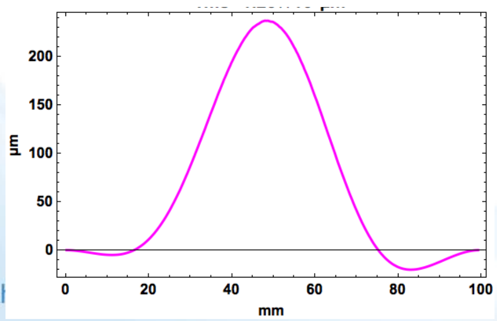
- Window function tapers profile endpoints to 0. Minimizes spurious power introduced into Discrete FT by edge discontinuities.
- Distorts actual profile, but preserves ensemble average of random statistics.

Blackman window

$$W(n) = \sqrt{\frac{2}{1523}}\left[21 - 25\cos\left(\frac{2\pi(n-1)}{N}\right) + 4\cos\left(\frac{4\pi(n-1)}{N}\right)\right]$$

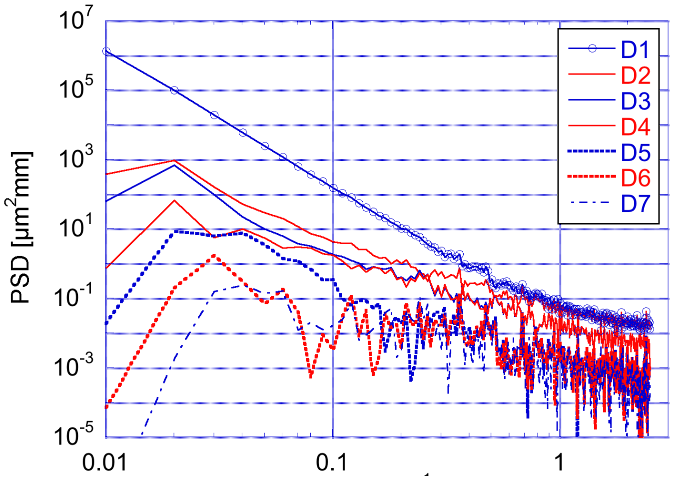




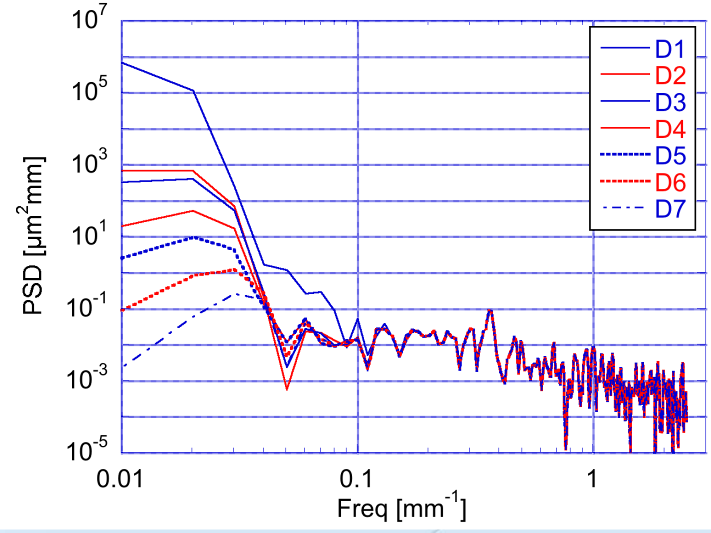


Detrend with No window

PSD

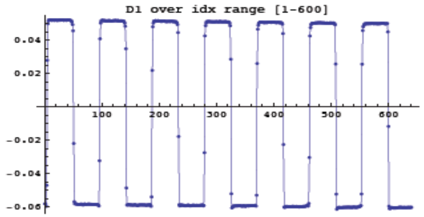


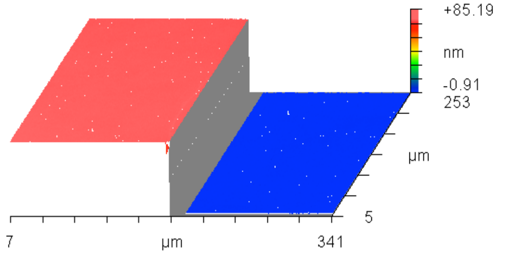
Detrend with Window



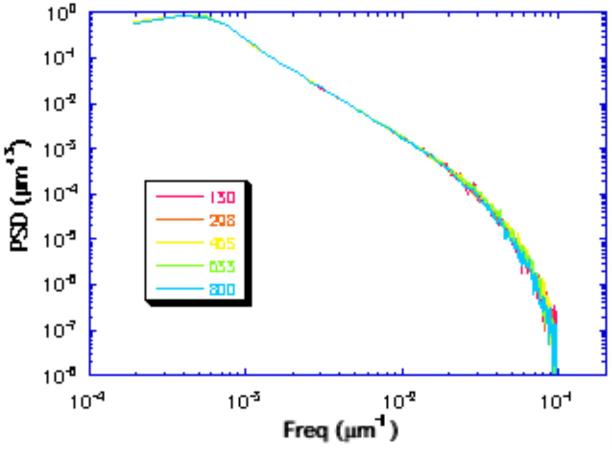
Transfer Function - Step Height Standard

- Need to characterize transfer function of profilers.
- Pixel sampling, MTF attenuation at high frequencies distort PSD.
- Single sharp step has a mathematically precise $1/f^2$ spectrum.
- Etch sharp step in Si(110) surface with bar patterns for AFM calibration.
- Single material – no phase shift ambiguities
- Use step for optical profiler and scatterometer, bars for AFM and stylus profilers.
- CROSS CALIBRATE fundamentally different instruments.

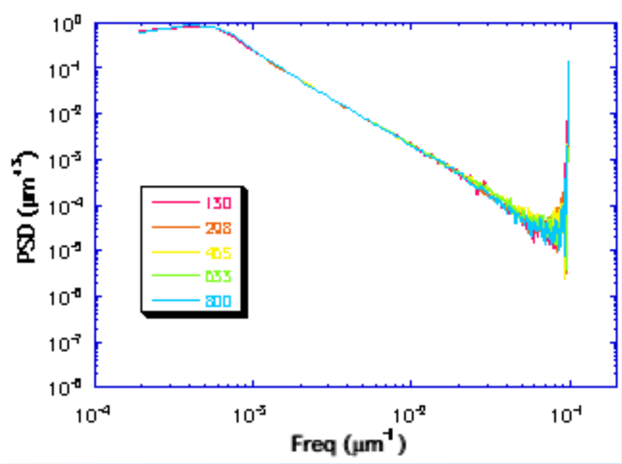




Raw data PSD



"Restored" with inverse filter



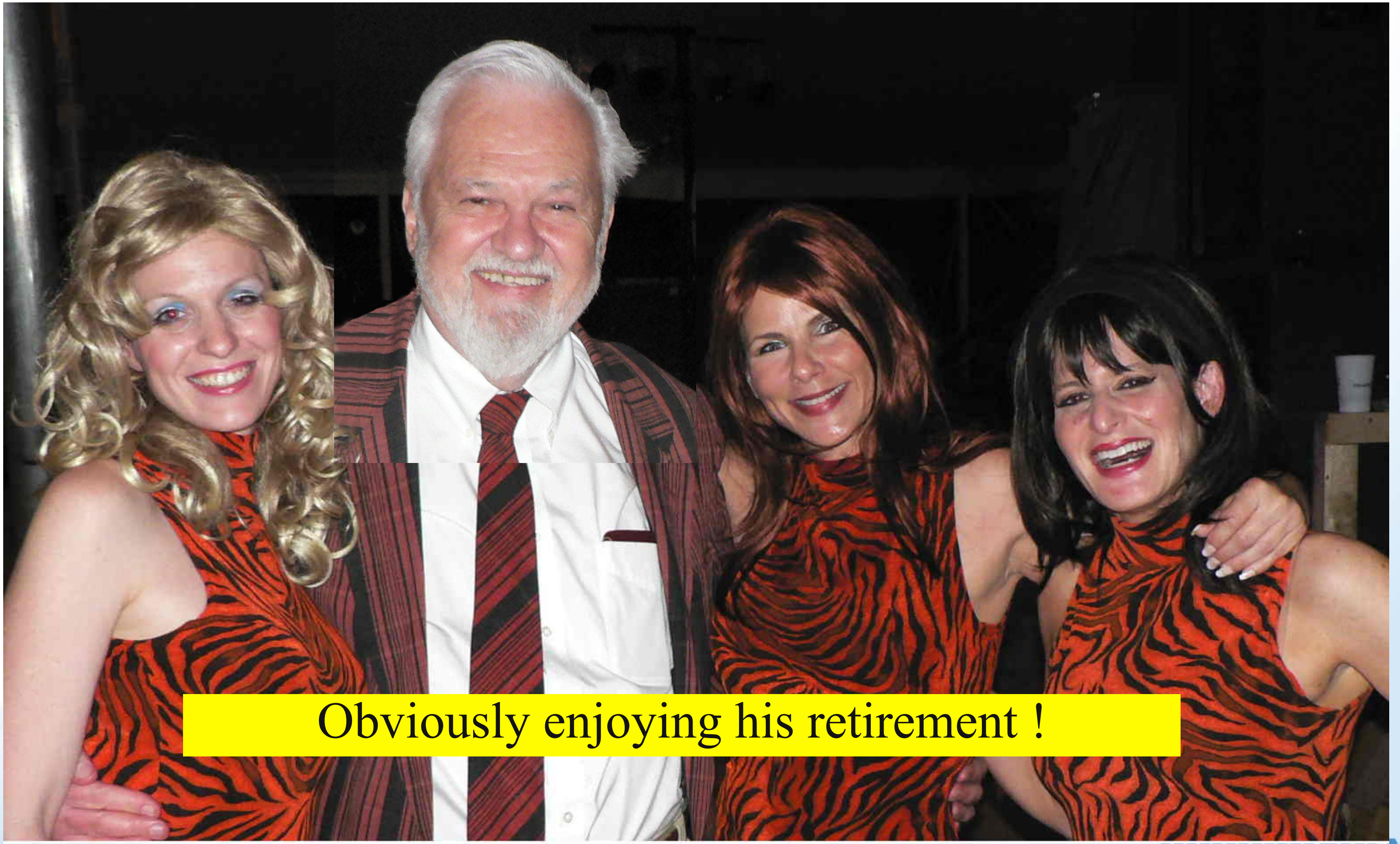
Next generation standard artifact developed in collaboration with Yashchuk utilizing a binary pseudorandom array (BPRA) for 2D area profilers.

Surface finish “finish”

- Optical profilers are used extensively now for measurements of surface roughness on optical surfaces.
    - Talystep stylus-type profilers are hard to use, risk of surface damage.
    - AFM instruments now provide quasi non-contact measurements over very high frequency bandwidth.
- Profiler instrument limitations are understood.
    - Bandwidth limits are now understood.
    - Many commercial instruments still do not implement detrending and windowing properly in analysis software.
    - Standard artifacts make instrument limitations vislble.
- Surfaces are smoother, polishing technology has advanced significantly.
- Everything you want to know about surface roughness is in:

E. L. Church and P. Z. Takacs, "Chapter 8 - Surface Scattering," in *Handbook of Optics*. vol. I, M. Bass, Ed., 3rd ed: McGraw-Hill, 2009.

E. L. “Gene” Church - retired but still active at 88



Obviously enjoying his retirement !

Finish problem "solved", now address:

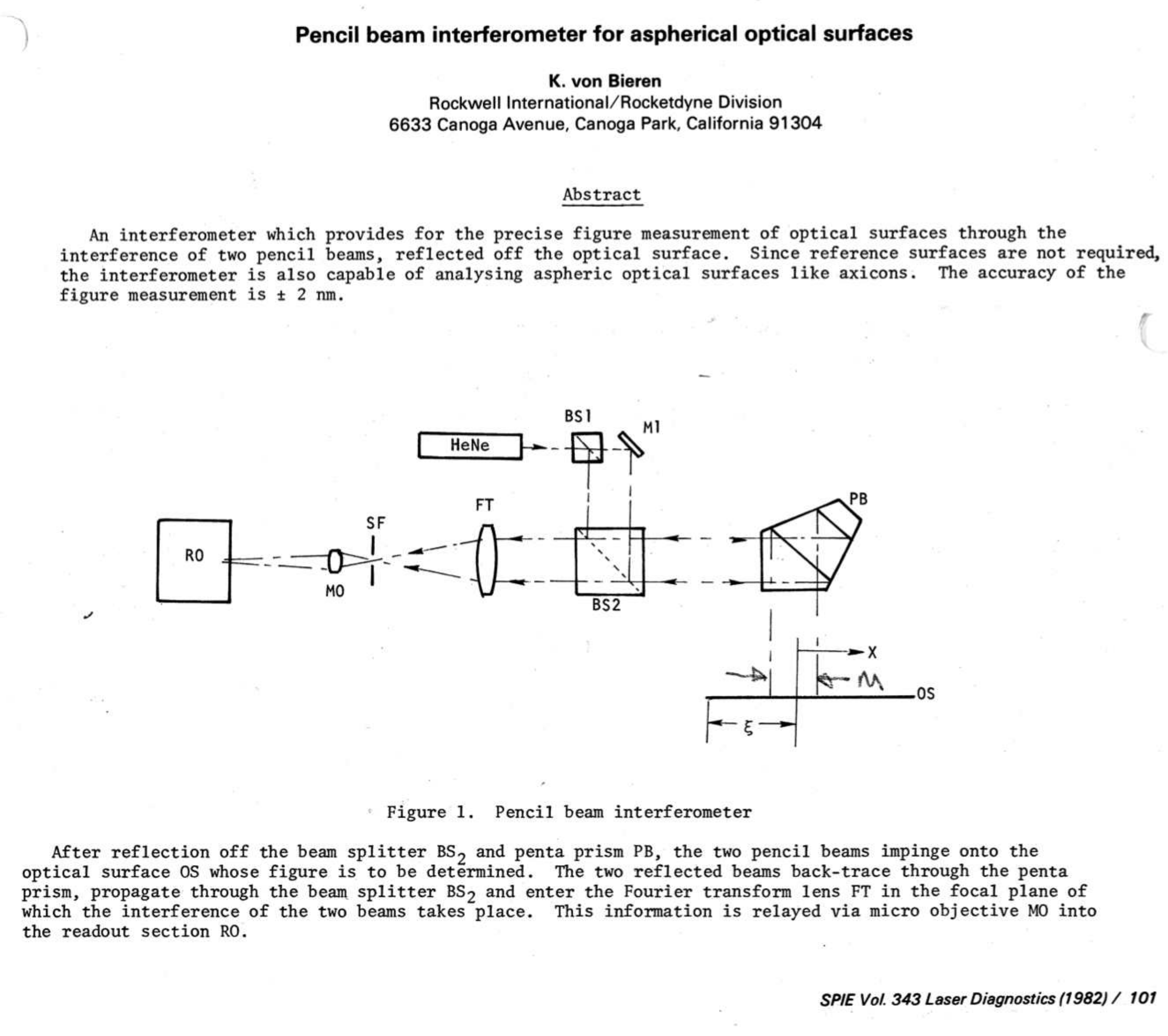
SURFACE FIGURE

Requirements for SR mirror metrology in 1980s

- Need for versatile instrument that can measure the shape of meter-long cylindrical aspheres with kilometer tangential curvatures.
- Visible light method required.
- Use of null lenses is not allowed.
  - NSLS can't afford special lens for each different mirror.
- Must be fast, easy to set up and use.
- Inexpensive to build.
- Measure slope error directly.
  - This is what matters for incoherent x-rays. They are basically bullets that reflect off of the local slope of the surface.
- Provide accuracy to measure state-of-the-art 1-2 arcsec slope errors (!)
  - This is 1980's: 2nd generation SR machines were new.

8:1 SiC ellipsoid
ca.1985

von Bieren: Pencil Beam Interferometer, 1982



Pencil beam interferometer for aspherical optical surfaces

K. von Bieren
Rockwell International/Rocketdyne Division
6633 Canoga Avenue, Canoga Park, California 91304

Abstract

An interferometer which provides for the precise figure measurement of optical surfaces through the interference of two pencil beams, reflected off the optical surface. Since reference surfaces are not required, the interferometer is also capable of analysing aspheric optical surfaces like axicons. The accuracy of the figure measurement is ± 2 nm.

Figure 1. Pencil beam interferometer

After reflection off the beam splitter BS_2 and penta prism PB, the two pencil beams impinge onto the optical surface OS whose figure is to be determined. The two reflected beams back-trace through the penta prism, propagate through the beam splitter BS_2 and enter the Fourier transform lens FT in the focal plane of which the interference of the two beams takes place. This information is relayed via micro objective MO into the readout section RO.

SPIE Vol. 343 Laser Diagnostics (1982) / 101

Scanning laser profiler concept - 1984

- Discussions with Rocketdyne over PBI
  - Cost too much to build for us
- Let's build it ourselves (M. Howells encouragement)

- Use a scanning laser profiler, modeled on the von Bieren pencil beam interferometer, for long, narrow SR optics.
  - Perfectly suited for long radius SR mirrors.
- Precision motion with air bearing slide.
- Measure and correct slide error with autocollimator.
- Unlimited depth of focus - easy alignment of SUT (surface under test)
- Measure SLOPE directly. This is what affects image quality in 2nd generation SR machines.

The Long Trace Profiler (LTP) is born

Timeline for LTP Development at BNL - to 2000

State-of-the-art
SR mirror quality

NSLS construction & commissioning

1980

– NSLS PGM paraboloids ordered from Y-12 SPDT facility (M. Howells).

1981 --

How to test for surface finish and figure???

5µrad

1982 --

1983 --

– Doing time at TRW => von Bieren Rocketdyne PBI profilometer for aspheric optics.

1984 --

-- Discussions with Rocketdyne about Pencil Beam Interferometer

1985

– RFQ from BNL for "Long-Trace Surface Profiling Instrument"

1986 --

– Design/Construction of in-house BNL LTP-I system (P. Takacs ,S. Qian, W.Liu, R. DeBiasse)
Software development (E.L.Church, Kate Feng)

1987 --

1988 --

-- Nov 5-6, 1987 – First LTP scans with breadboard Reticon array detector (J. Colbert)
7/88 - AUI Patent rights waived to Takacs and Qian

1989 --

-- LTP II project with LBL (Irick & McKinney), Cont Opt. (M. Grindel, C. Bresloff), and Baker Eng. (N. Lien)

1990

12/89 - Patent granted to Takacs and Qian

1991 --

4/91 - LTP II delivered to LBL by CO

1992 --

9/92 – Patent assigned back to AUI

1993 --

-- CRADA between BNL and CO for LTP II commercialization

1µrad

1994 --

1995

-- CRADA with CO for ISLTP development (K. Randall, APS)
CO SBIR from NASA for VSLTP development (Haizhang Li)

1996 --

1997 --

2/97 - Shinan returns to BNL from Trieste

1998 --

1999 --

0.5µrad

2000

-- Grindel retires, CO closes, LTP to Ocean Optics

Timeline (cont.)

2000
2001 --
2002 --
2003 --
2004 --
2005
2006 --
2007 --
2008 --
2009 --
2010
2011 --
2012 --

Grindel retires, CO closes, LTP to Ocean Optics
-- LTP-IV & V CRADA with OOI (Roy Walters, Jeremy Rose)

0.5µrad

← Portable LTP (Qian)

← Multi-Function LTP (Qian)

Ocean Optics drops LTP, patent expires.

0.2µrad

OSMP project begins (Yashchuk, Idir, Assoufid)

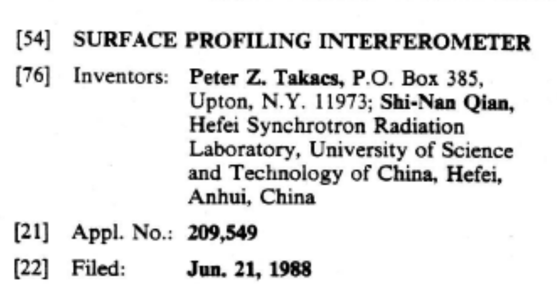
0.1µrad

??? nrad

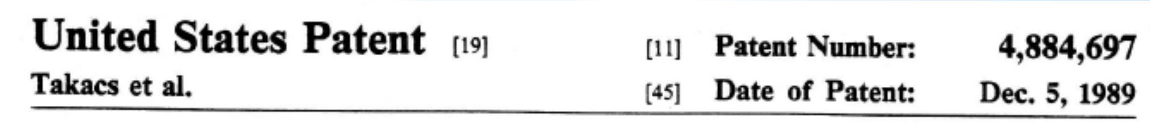
Original LTP I, 1988

Controlled by HP216 desktop computer BASIC program

Optical design:
Shinan Qian
Mechanical design:
Shinan Qian
Wuming Liu
Software, motion control:
Takacs
System commissioning:
Bob DeBiasse



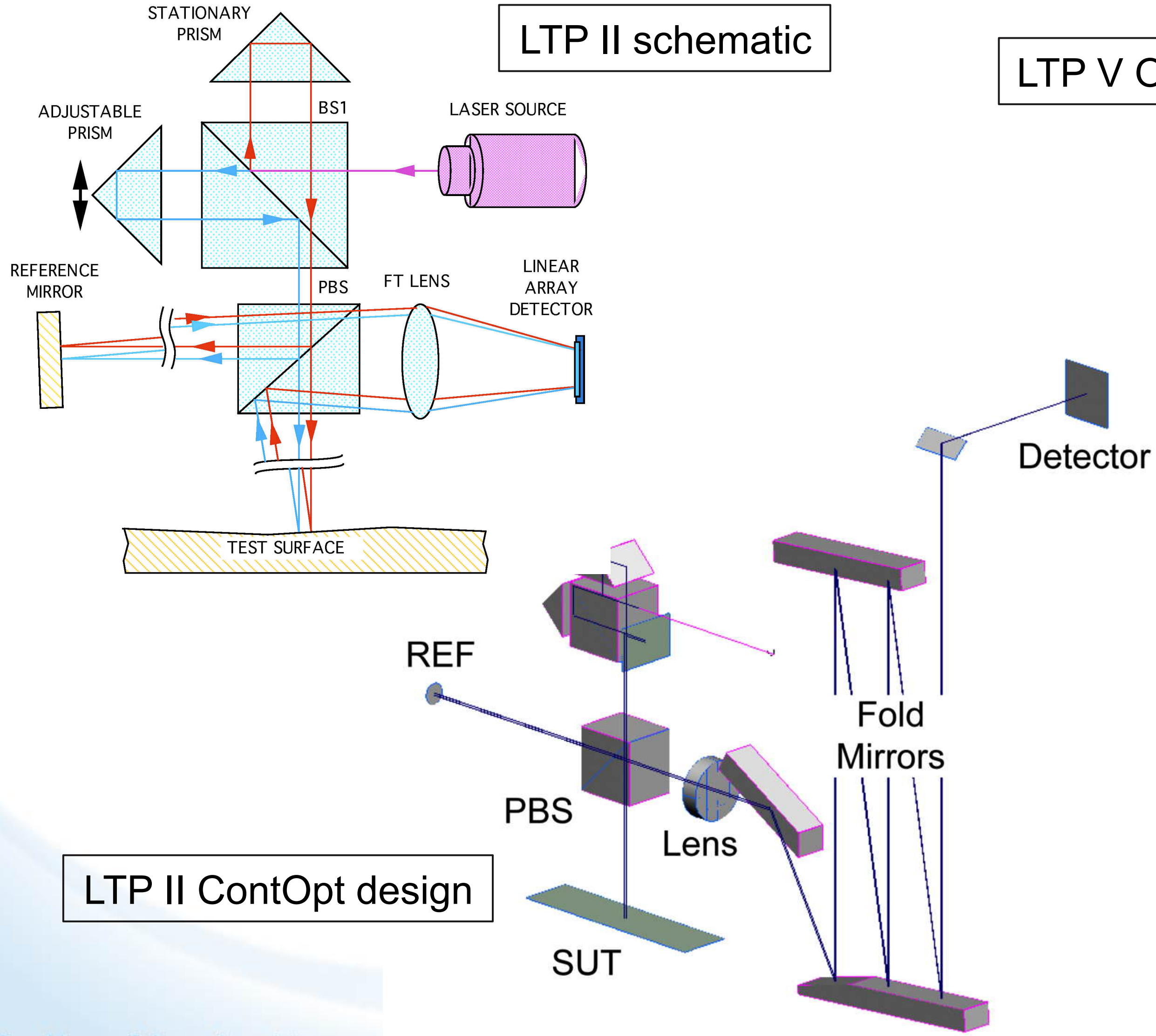
[54] **SURFACE PROFILING INTERFEROMETER**
[76] Inventors: **Peter Z. Takacs**, P.O. Box 385, Upton, N.Y. 11973; **Shi-Nan Qian**, Hefei Synchrotron Radiation Laboratory, University of Science and Technology of China, Hefei, Anhui, China
[21] Appl. No.: **209,549**
[22] Filed: **Jun. 21, 1988**



United States Patent [19]
Takacs et al.
[11] **Patent Number: 4,884,697**
[45] **Date of Patent: Dec. 5, 1989**

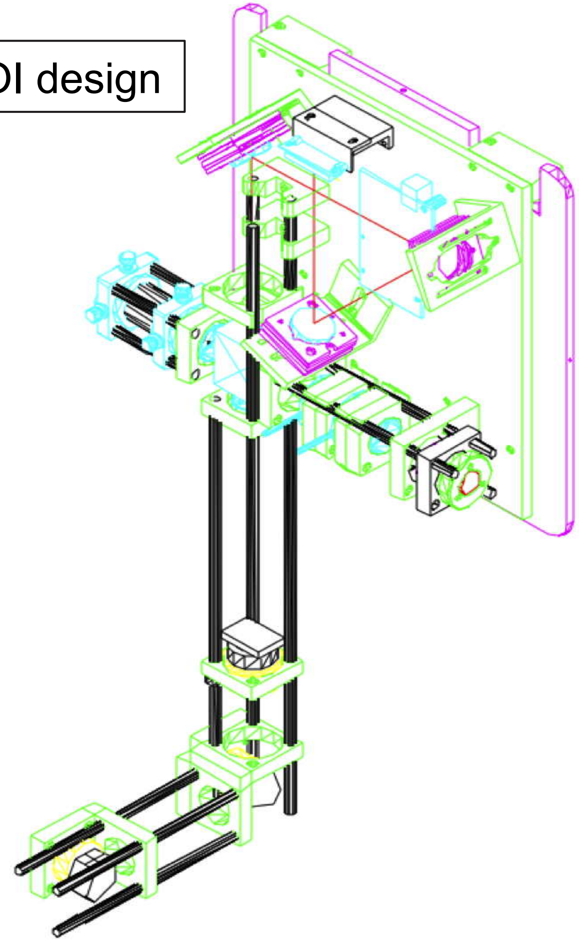
LTP Optical Design Evolution

LTP II schematic



LTP II ContOpt design

LTP V OOI design



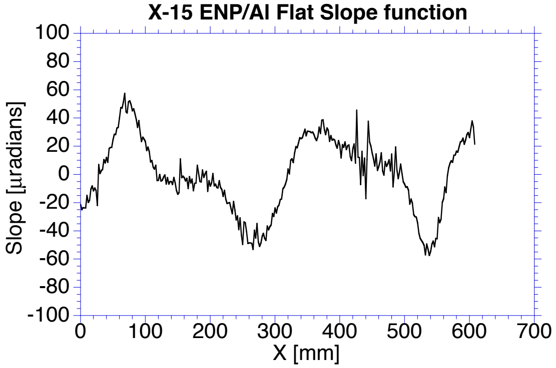
Long Trace Profiler capabilities

- The LTP enabled slope profile measurements on cylindrical aspheres and flats up to 1 meter long with a 1 mm sampling period.
- Measurements in any orientation: face up, face down, sideways.
- Surfaces can be concave or convex: x-ray telescope mandrels and shells.
- Versatile, no custom null optics required.
- Fast, easy mirror setup - no focusing required.
- Adaptable optical system - optical head mounted on moving air bearing, or stationary with a moving penta prism, or multiple heads for multi-function measurements.
- Many collaborators contributed to numerous innovations and improvements .

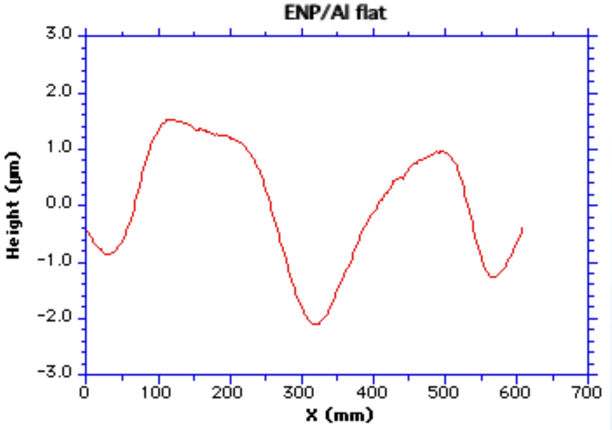
Profile measurement example – WYKO & LTP

X15 ENP/Al flat by Diamond Electro Optics (1989)

LTP measurement

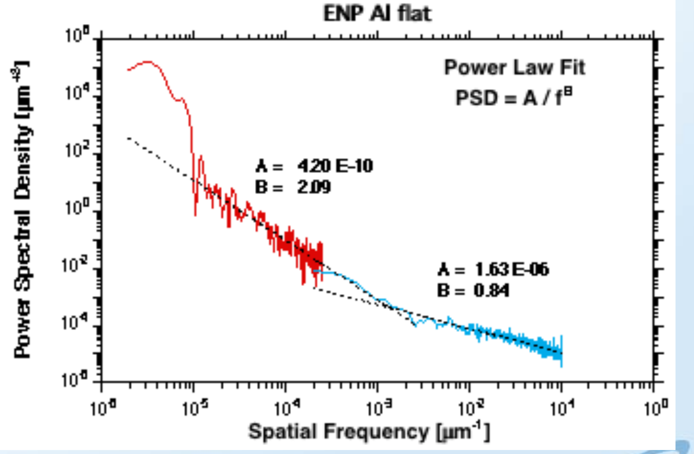


SLOPE
to
HEIGHT

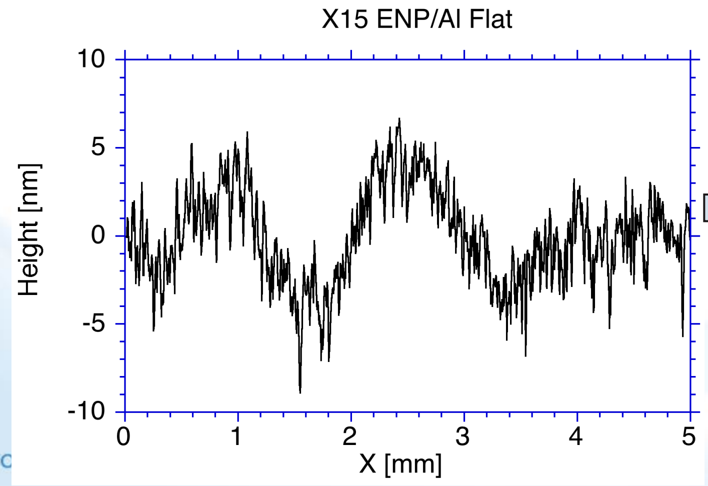


ANALYZE LTP FIGURE DATA EXACTLY THE SAME AS ROUGHNESS DATA

PSD



WYKO measurement

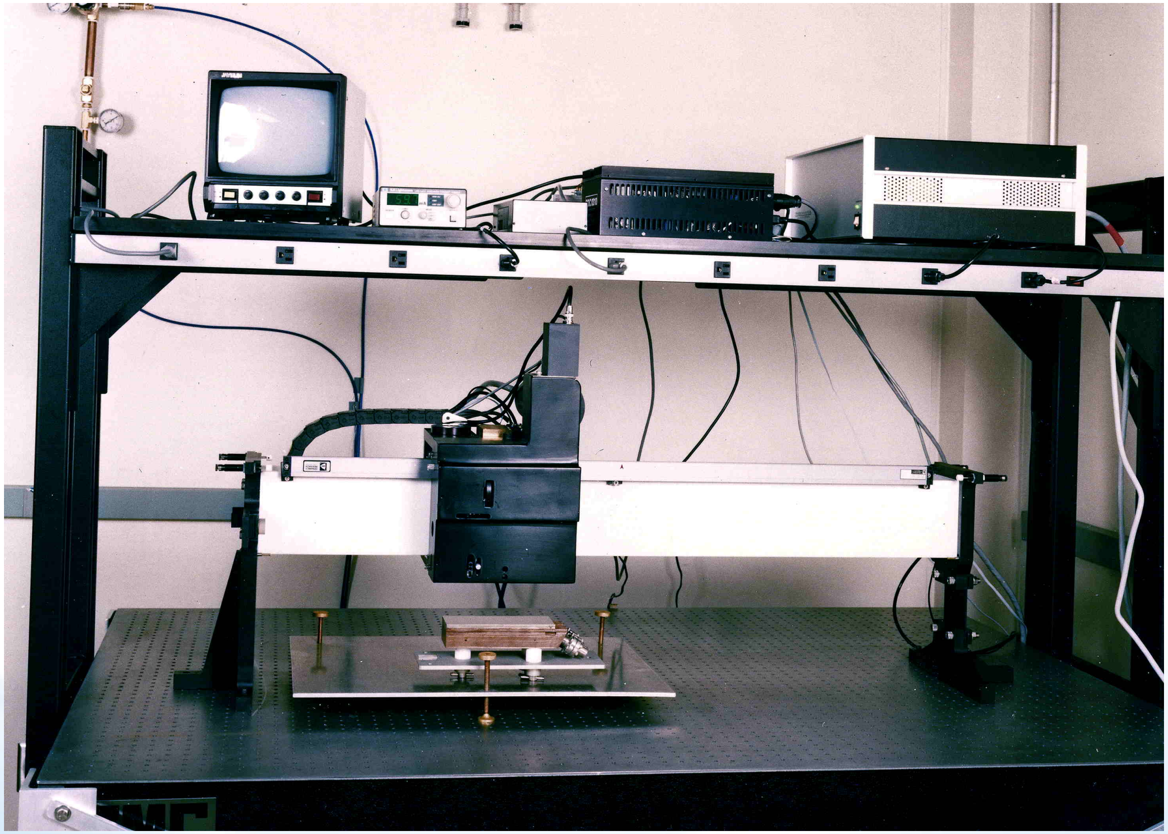


PSD

The LTP II Collaboration

- The LTP is a result of a collaborative effort of many people around the world.
- LBL, BNL, Continental Optical – project to build commercial version.

Original LTP II delivered to LBL ALS - 1991



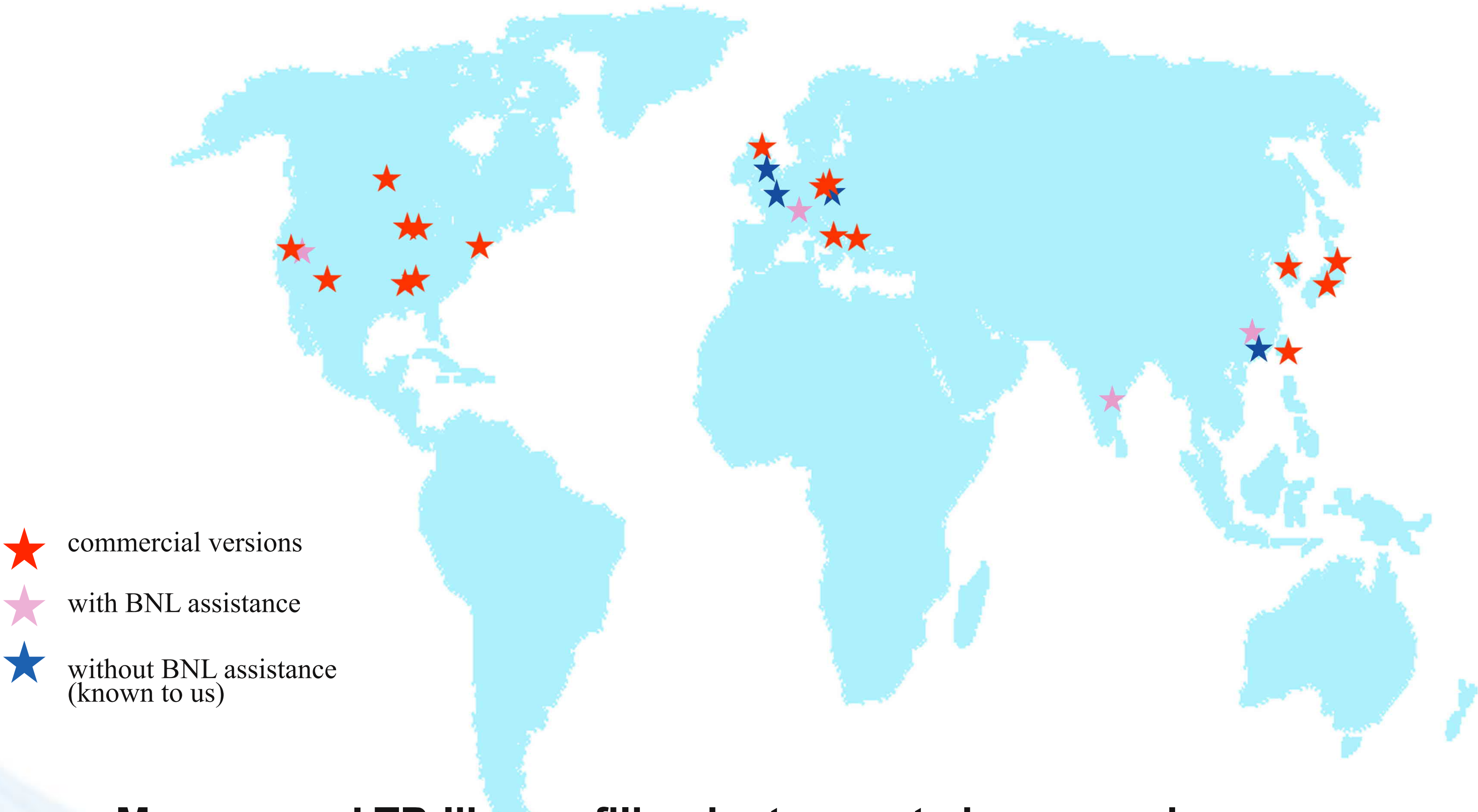
Steve Irick

LTP II collaboration innovations

- Continental Optical Corp. (Manfred Grindel) recognized the importance of the LTP for his company to compete in SR mirror business.
- Mechanical system design by Neil Lien, Baker Engineering.
  - Brushless DC direct drive motor.
  - Wilbanks (CoorsTek) precision ceramic air bearing beam.
- ∗ Internal REF beam (Irick&McKinney)
- Dual array camera - keeps REF beam on-axis
- Dove prism in REF arm, both mechanical and thermal errors are phased correctly. (C. Bresloff)
- Fiber optics laser delivery system
  - Initial method: polarization-preserving fiber
  - Later method: unpolarized fiber
- Penta Prism scanning - optical head stationary (S. Qian)
- ISLTP - In-situ LTP for on-beamline optics
- VSLTP - vertical scan for x-ray telescope mirrors (Haizhang Li)

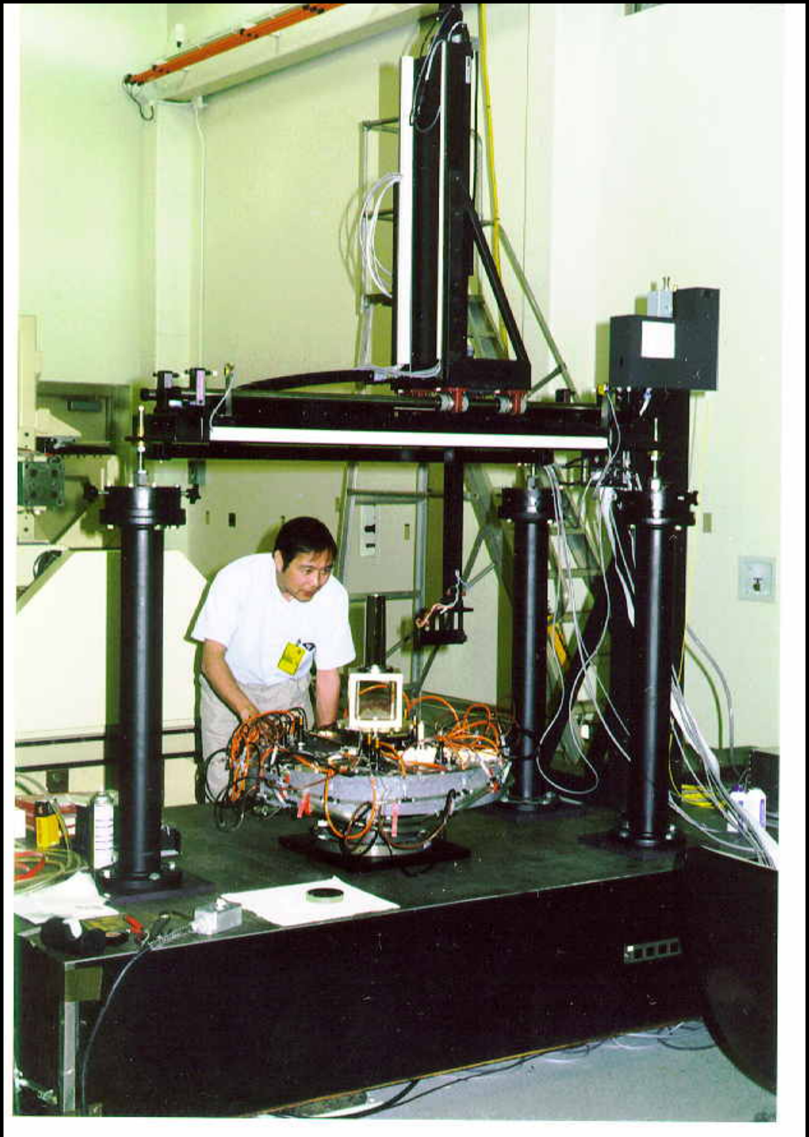
Worldwide installations of LTPs 1989-2009

Every commercial version of the LTP was a custom design



Many more LTP-like profiling instruments have now been developed by many other groups not shown here.

VSLTP at NASA MSFC for X-ray Telescopes



- LTP II penta prism scan design
- Designed for full vertical and azimuthal scans on complete Wolter telescope optics
- 3 axis motorized motions
  - Vertical scan axis
  - Horizontal probe positioning
  - Rotary stage for azimuthal scans
- Internal optical head actuators for remote control adjustment
  - Intensity polarizer rotation
  - Balance HW plate rotation
  - Dove prism linear slide for beam rotation
- Risley prism rotator on probe arm for beam direction steering

Profilometry beyond the LTP V

Most SR facilities now have a metrology lab for insuring that mirrors perform as designed. Most have some sort of figure-profiling machine because slope profilometry has proven to be invaluable for producing SR mirrors.

Most labs have modified the basic LTP design to improve on it. Innovations in optical design and analysis methods have pushed the accuracy well below the 100nrad level. Heiner Lammert made significant advances with the NOM machine. He combined a precision autocollimator with an LTP optical head to enable sub-nm measurement precision. He demonstrated the importance of precise environmental control. SPring8 has taken this environmental control to the next level in their most recent LTP development.

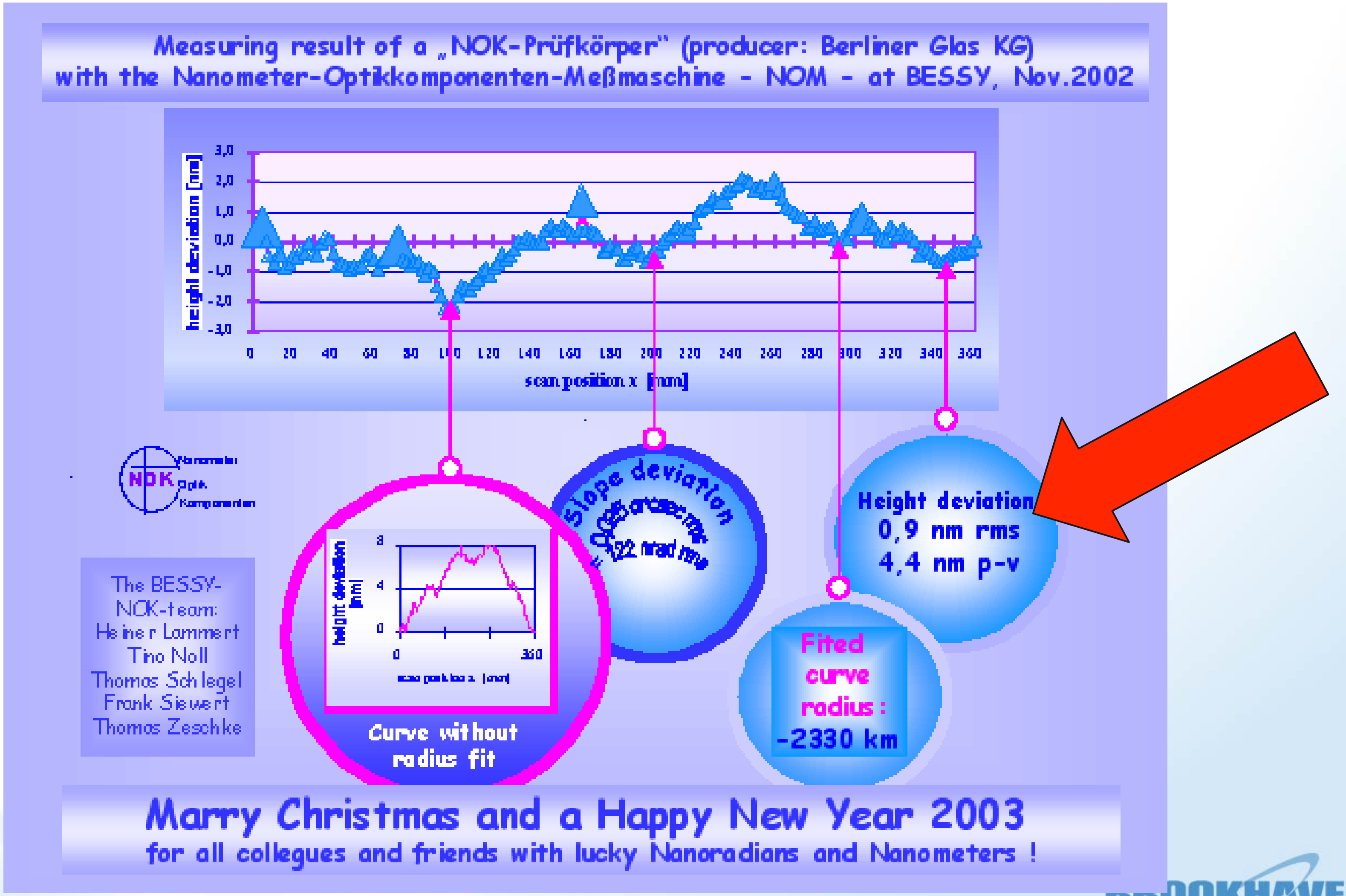
Yashchuk has developed sophisticated measurement and analysis techniques to reduce slow drift errors to improve absolute accuracy. Along with Idir and Assoufid, they have initiated the Optical Slope Measuring System project, modeled after the NOM, to incorporate environmental stability with automated error-reduction techniques.

Soliel with Imagine Optic have pioneered the use of Shack-Hartmann optics in 2D slope profilometry. Gubarev at NASA MSFC, in collaboration with LBL and BNL, is developing a multi-beam LTP for reducing the time needed to make a single scan.

Profilometry of SR optics continues to evolve and improve.

Heiner Lammert Christmas card – 2002

- Celebrating sub-nm surface error measurement with NOM



Measuring result of a „NOK-Prüfkörper" (producer: Berliner Glas KG)
with the Nanometer-Optikkomponenten-Meßmaschine - NOM - at BESSY, Nov.2002

The BESSY-
NOK-team:
Heiner Lammert
Tino Noll
Thomas Schlegel
Frank Siewert
Thomas Zeschke

Curve without
radius fit

Slope deviation
± 0,025 arcsec rms
± 122 nrad rms

Height deviation
0,9 nm rms
4,4 nm p-v

Fited
curve
radius :
-2330 km

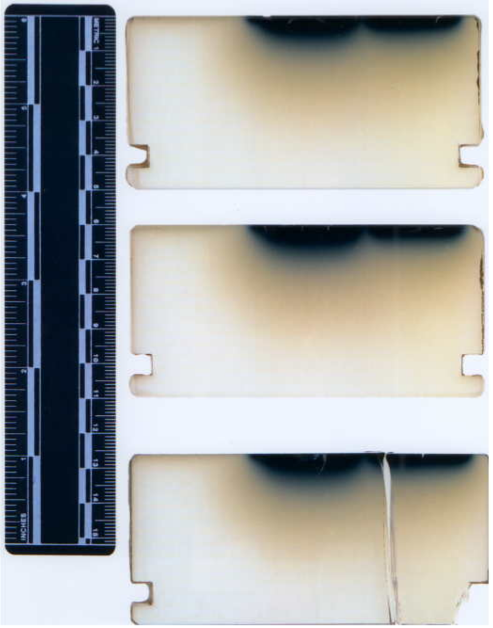
Marry Christmas and a Happy New Year 2003
for all collegues and friends with lucky Nanoradians and Nanometers !

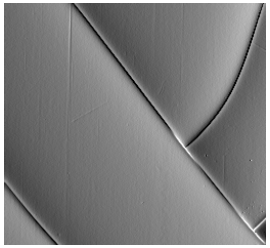
Metrology beyond profilometry

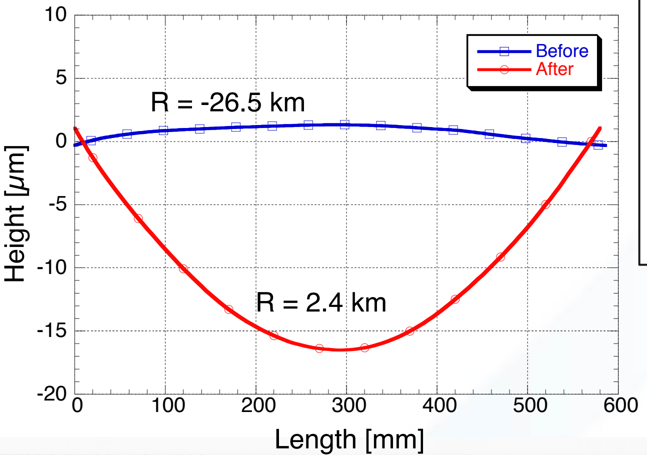
- Some optical shops use grazing incidence interferometry to measure long flats and near-flat spheres and aspheres. Dedicated setups, not very versatile.
- Stitching interferometry methods, such as RADSI technique developed by Mimura, et al. at Osaka. This has enabled production of coherence-preserving optics.
- Scanning Shack-Hartmann wavefront sensors are now providing sub-100nrad measurement accuracy on 2D surfaces.
- At-wavelength metrology – Phase-retrieval demonstrated by Souvorov at SPring8 and advanced by Yumoto, et al. is used to produce nearly-perfect imaging optics. Talbot grating interferometry developed by Weitkamp is able to measure x-ray wavefront distortions that map into surface slope errors of less than 100nrad with a lateral resolution of 1mm.
- At-wavelength metrology is the *only way to measure imperfections in multilayer-coated surfaces*. Visible light profilometry does not probe below the surface.
- Excellent reviews of various SR optics metrology in the current issue of *Synchrotron Radiation News,* edited by Valeriy Yashchuk.

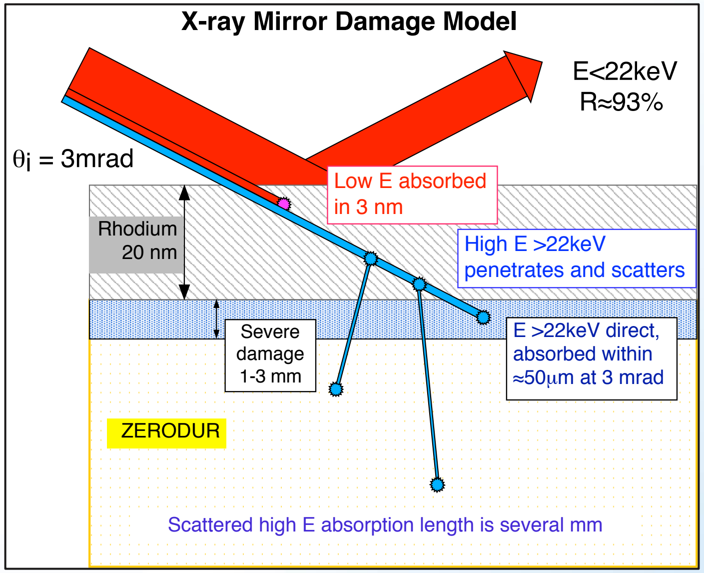
Forensic Metrology

- Investigate why mirrors are not working – they are “dead”.
- Damage from long-term x-ray exposure
- Slumping, stress, and fracture









X-ray Mirror Damage Model

E<22keV
R≈93%

θi = 3mrad

Low E absorbed
in 3 nm

Rhodium
20 nm

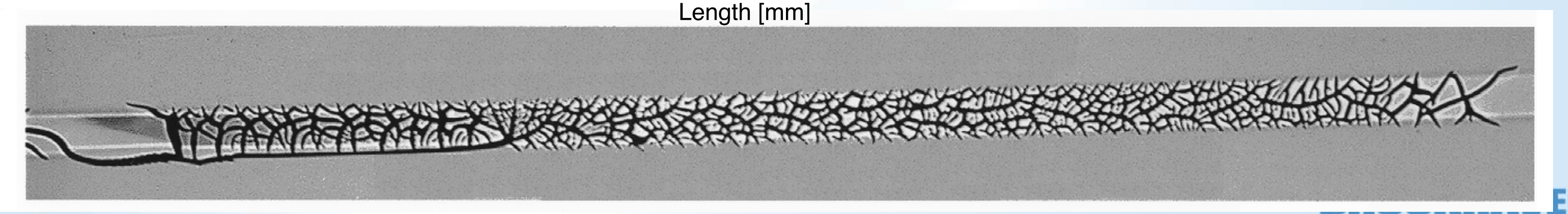
High E >22keV
penetrates and scatters

Severe
damage
1-3 mm

E >22keV direct,
absorbed within
≈50μm at 3 mrad

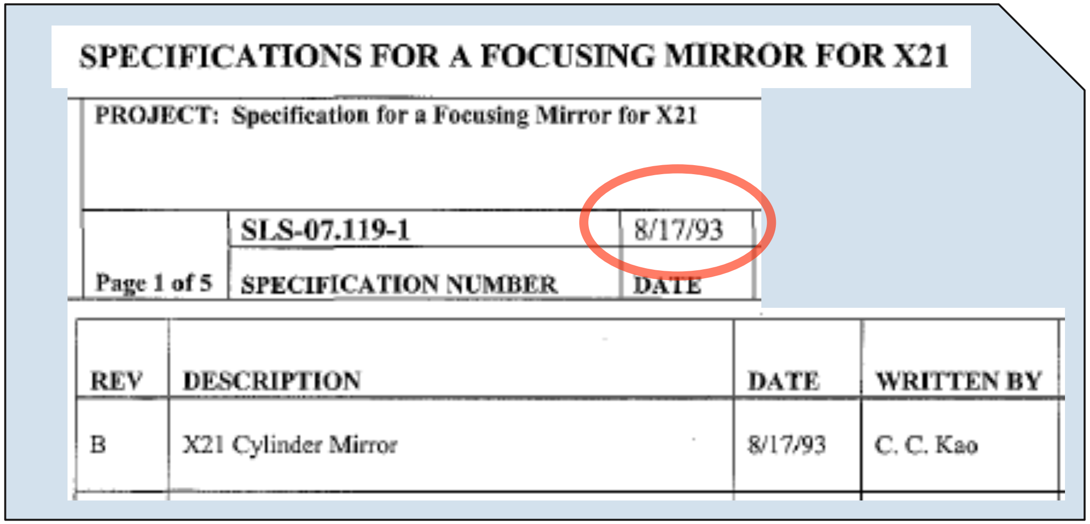
ZERODUR

Scattered high E absorption length is several mm



Archaeo-metrology

NSLS user wants to know about mirror currently in beamline.
Sends me a copy of the original specification - FROM 1993 !

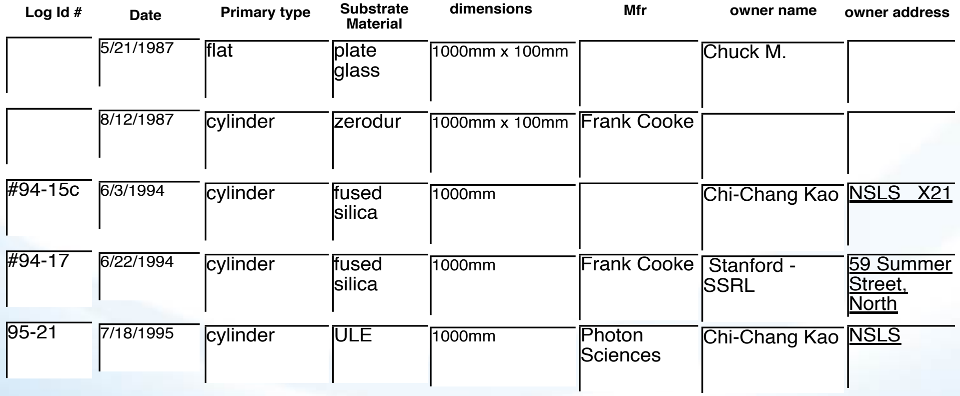


SPECIFICATIONS FOR A FOCUSING MIRROR FOR X21

PROJECT: Specification for a Focusing Mirror for X21		
Page 1 of 5	SLS-07.119-1 SPECIFICATION NUMBER	8/17/93 DATE

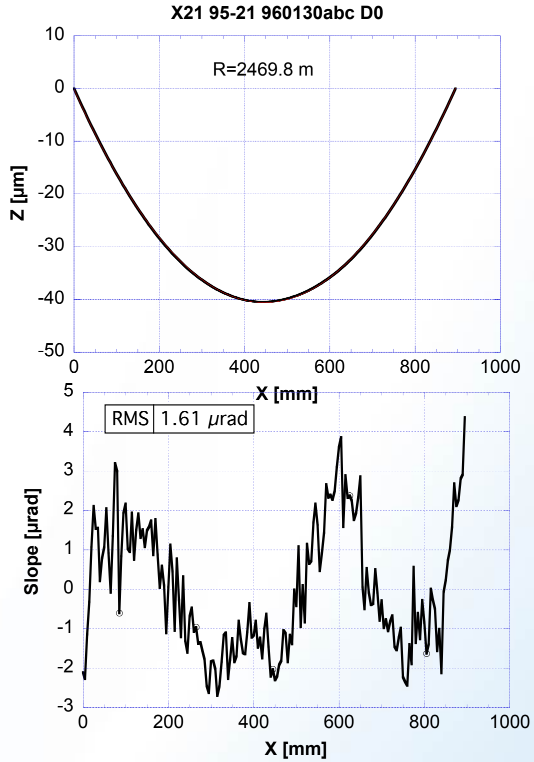
REV	DESCRIPTION	DATE	WRITTEN BY
B	X21 Cylinder Mirror	8/17/93	C. C. Kao

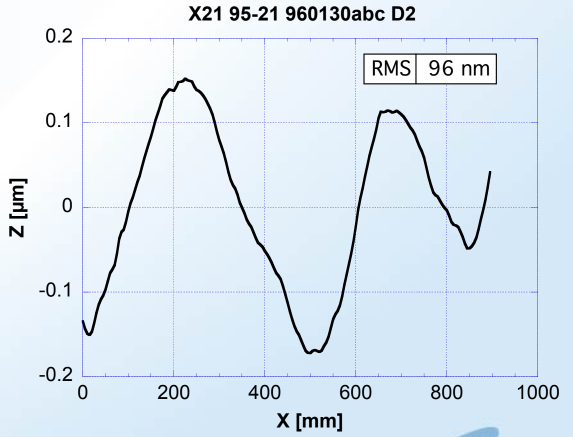
Search database for "1000mm"



Log Id #	Date	Primary type	Substrate Material	dimensions	Mfr	owner name	owner address
	5/21/1987	flat	plate glass	1000mm x 100mm		Chuck M.	
	8/12/1987	cylinder	zerodur	1000mm x 100mm	Frank Cooke		
#94-15c	6/3/1994	cylinder	fused silica	1000mm		Chi-Chang Kao	NSLS X21
#94-17	6/22/1994	cylinder	fused silica	1000mm	Frank Cooke	Stanford - SSRL	59 Summer Street, North
95-21	7/18/1995	cylinder	ULE	1000mm	Photon Sciences	Chi-Chang Kao	NSLS

Data from 1994 ULE mirror





Final thoughts

I was fortunate to be in the right place at the right time to be able to pursue an idea. For this I am indebted to my supervisor, Veljko Radeka, who had the foresight and trust to allow his staff to pursue whatever research directions that interested them.

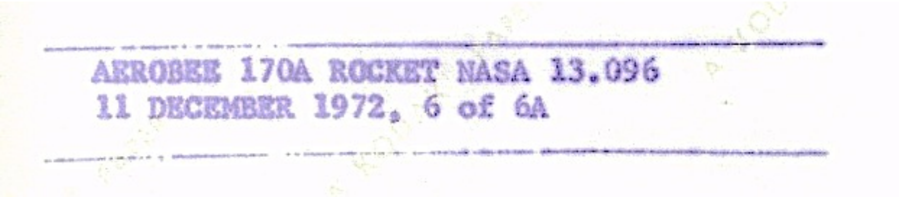
SR metrology is a collaborative effort. Many people, some already acknowledged, have made significant contributions to the development of surface profilometry for surface figure and finish measurement. We introduced the concept of “slope error” and "spatial frequency" into the vocabulary of optical fabrication.

At the risk of omitting anyone, I will not attempt to enumerate all those individuals and groups who are now advancing the state-of-the-art in SR mirror metrology into the nanoradian range. You know who you are. I applaud your efforts and pass the torch. I did the easy work: your job is much more difficult. I salute you.

And it is with great sadness that I note that Giovanni Sostero is not here to continue in this quest for perfection. We miss him.

FINIS

My career is launched



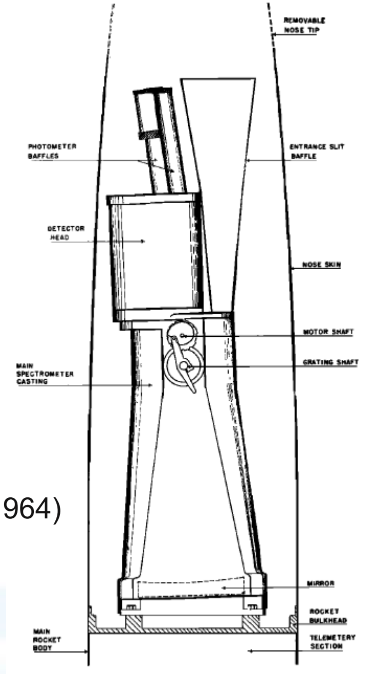
AEROBEE 170A ROCKET NASA 13.096
11 DECEMBER 1972, 6 of 6A

Takacs, P. Z.,

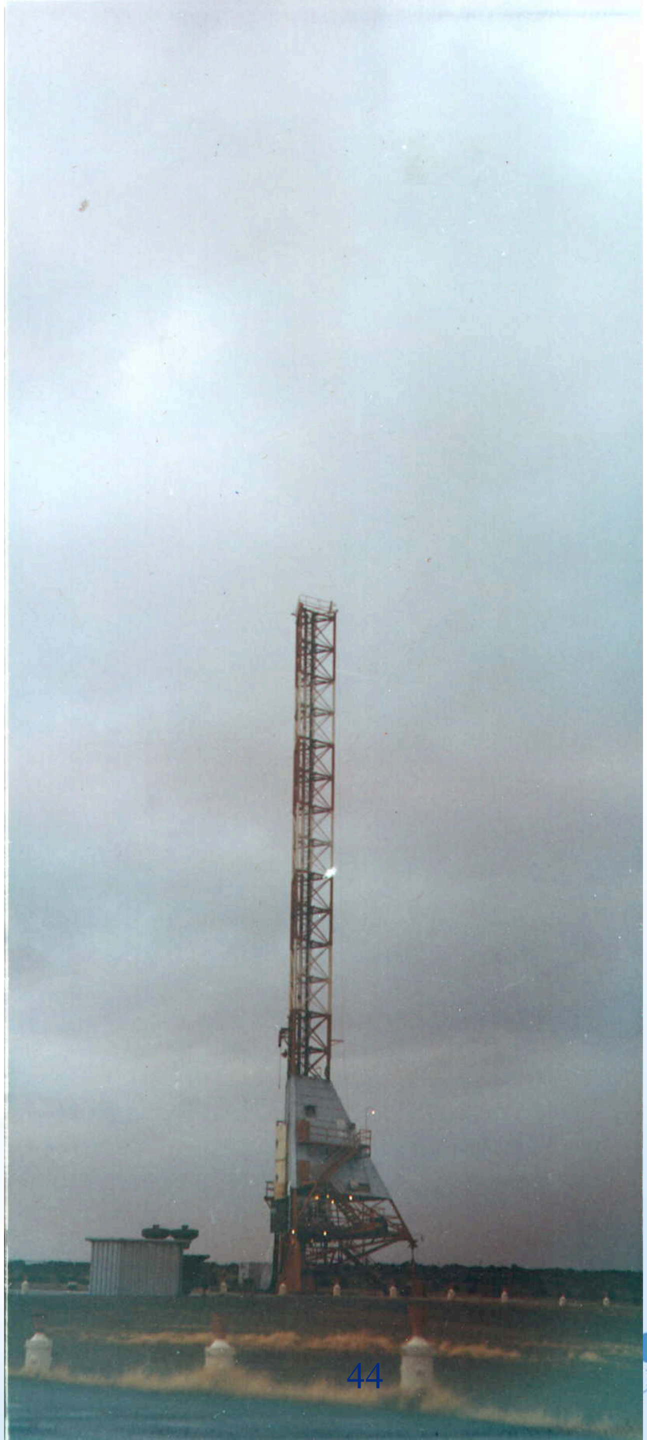
"Far ultraviolet atomic and molecular nitrogen emissions in the day airglow",

Ph.D. thesis, Johns Hopkins Univ., Baltimore, Md., 1975.

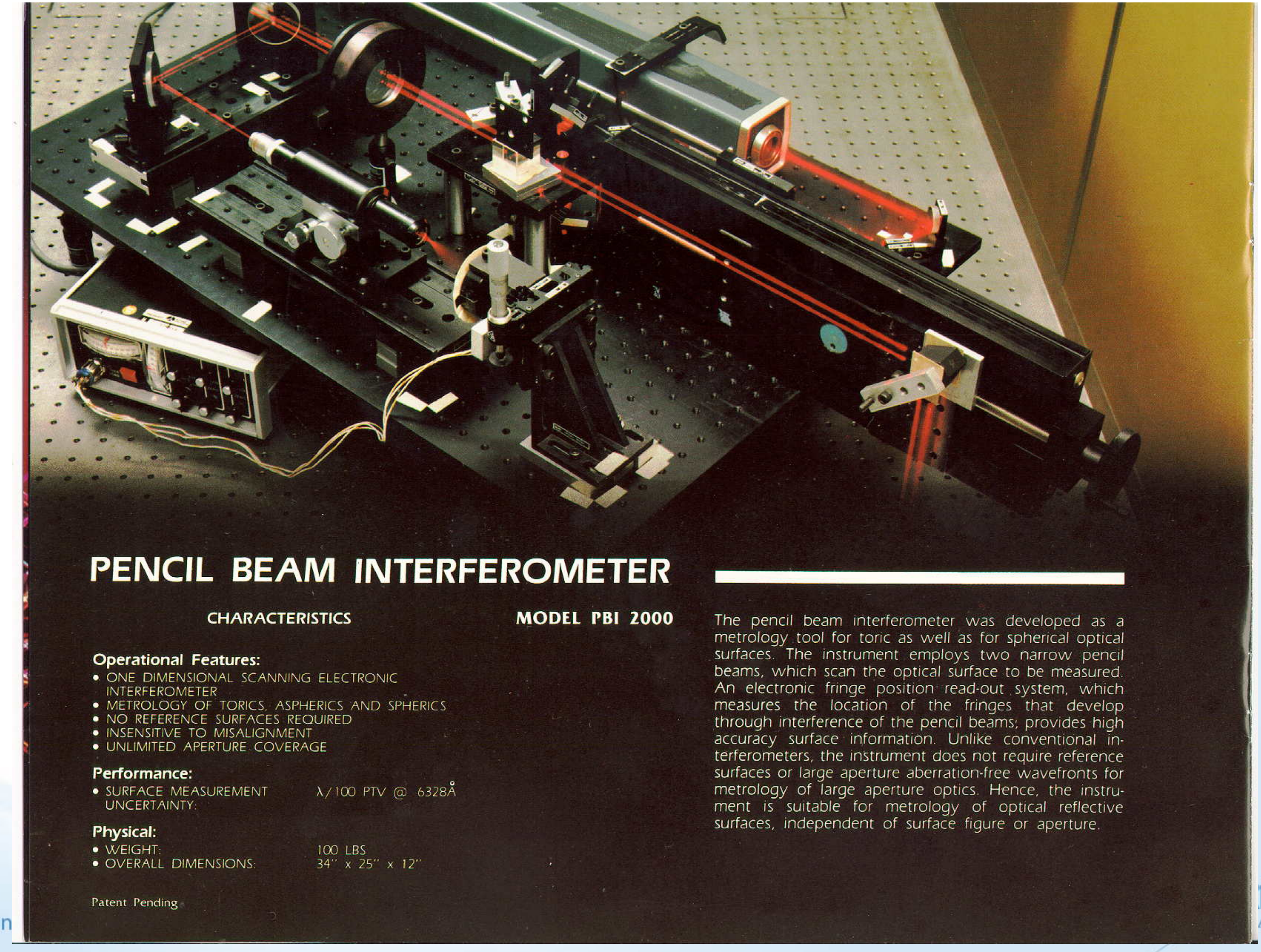
Ebert-Fastie
¼ m FUV
spectrometer



Fastie, Crosswhite & Heath, JGR **69**, (1964)



Rocketdyne version of PBI, 1983



PENCIL BEAM INTERFEROMETER

CHARACTERISTICS **MODEL PBI 2000**

Operational Features:

- ONE DIMENSIONAL SCANNING ELECTRONIC INTERFEROMETER
- METROLOGY OF TORICS, ASPHERICS AND SPHERICS
- NO REFERENCE SURFACES REQUIRED
- INSENSITIVE TO MISALIGNMENT
- UNLIMITED APERTURE COVERAGE

Performance:

• SURFACE MEASUREMENT UNCERTAINTY:	$\lambda/100$ PTV @ 6328Å

Physical:

• WEIGHT:	100 LBS
• OVERALL DIMENSIONS:	34" x 25" x 12"

Patent Pending

The pencil beam interferometer was developed as a metrology tool for toric as well as for spherical optical surfaces. The instrument employs two narrow pencil beams, which scan the optical surface to be measured. An electronic fringe position read-out system, which measures the location of the fringes that develop through interference of the pencil beams; provides high accuracy surface information. Unlike conventional interferometers, the instrument does not require reference surfaces or large aperture aberration-free wavefronts for metrology of large aperture optics. Hence, the instrument is suitable for metrology of optical reflective surfaces, independent of surface figure or aperture.

Bandwidth-limited statistics from PSD

- Once you have the PSD, $S(f_n)$, you can calculate bandwidth-limited statistics very easily:

$$Rq\left(f_{lo}, f_{hi}\right) = \sqrt{\frac{1}{ND}\sum_{f_{lo}}^{f_{hi}} S\left(f_i\right)}$$

where $ND = L$ is the total profile length

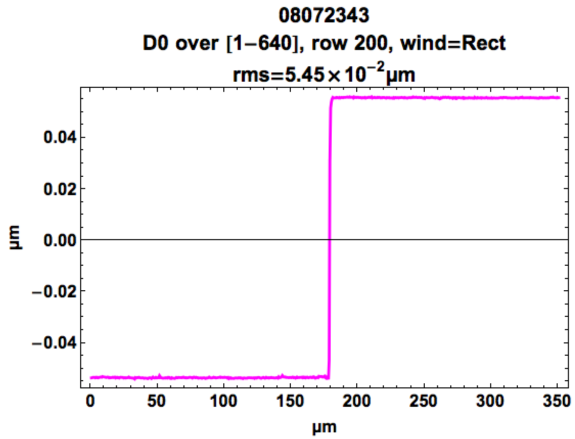
and $\frac{1}{ND} = \frac{1}{L} \equiv f_1$ => fundamental freq is inverse of total length.

f_{lo}, f_{hi} are integer multiples of f_1 (harmonics of fundamental)

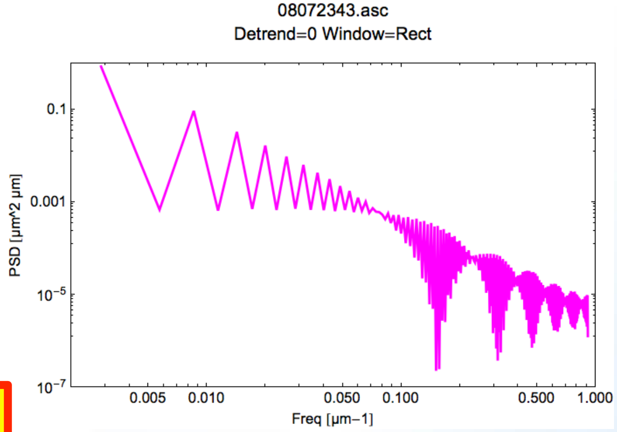
- Be sure PSD has been corrected for instrumental effects, i.e. MTF rolloff, pixel sampling size, aliasing, stylus tip radius, etc.

PSD of Step - apply Window function

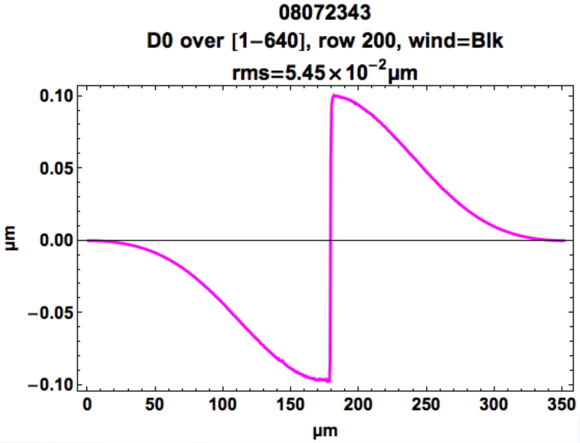
- PSD of step should be $1/f^2$ straight line.
- Roll off at high freq measures departure from ideal system transfer function


08072343
D0 over [1–640], row 200, wind=Rect
rms=5.45×10^{-2}µm

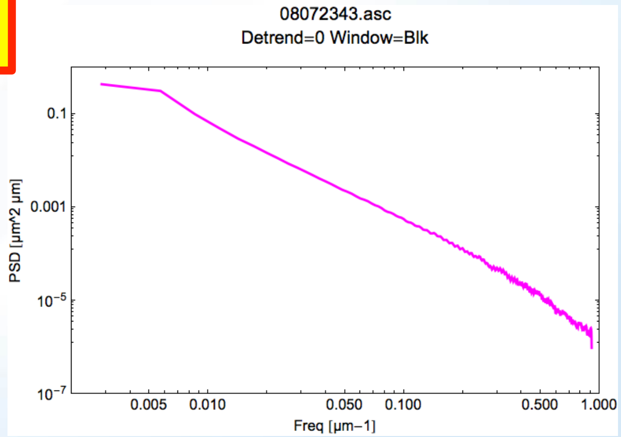
No Window


08072343.asc
Detrend=0 Window=Rect

Without window, edge effects completely swamp the true system response.


08072343
D0 over [1–640], row 200, wind=Blk
rms=5.45×10^{-2}µm

Blackman Window


08072343.asc
Detrend=0 Window=Blk

The problem with SR mirrors - figure

- Very difficult to measure shape of far off-axis aspheres, such as toroids, ellopsoids, and cylinders by conventional optical shop techniques.

R.J Speer (1979) Linnick interferometer at grazing incidence at λ=1216Å for toroidal grating surface. Requires several toroids to set up the test. Very impractical for optical shop.

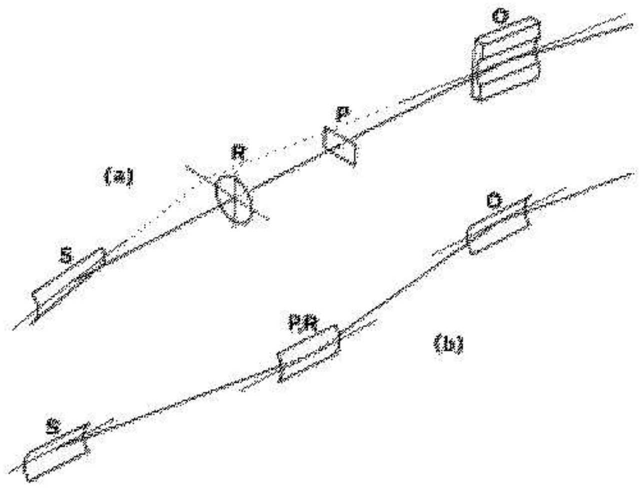


Fig. 7. Grazing incidence systems, conjugate surfaces.

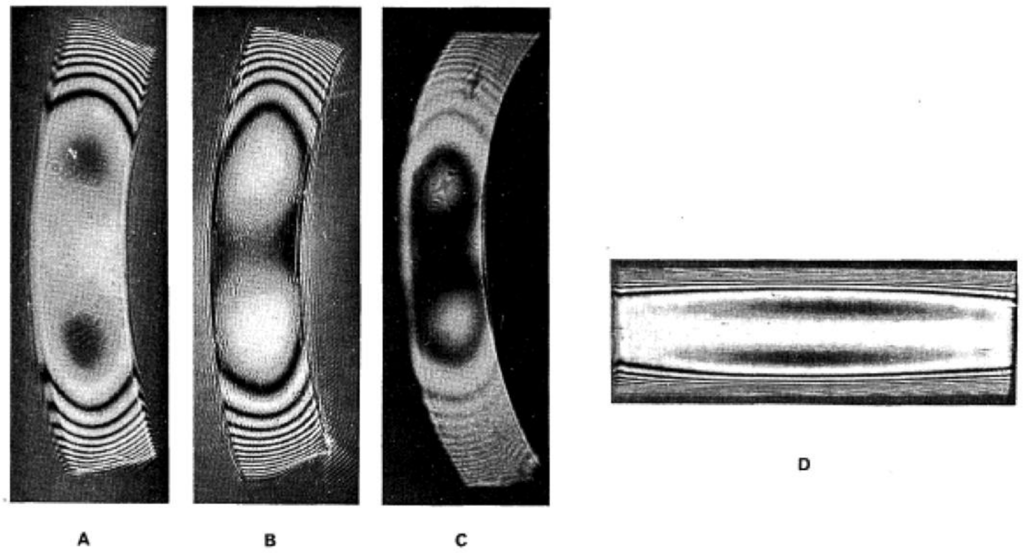


Fig. 11. A comparison of interferograms from three systems. *A*, Transmission scheme, Fig. 6(a); *B*, reflection scheme Fig. 6(d); *C*, reflection all grazing incidence scheme Fig. 6(e) and Fig. 7(b); *D*, interferogram recorded in the correct projection.

R. J. Speer, M. Chrisp, D. Turner, S. Mrowka, and K. Tregidgo, “Grazing incidence interferometry: the use of the Linnik interferometer for testing image-forming reflection systems,” Applied Optics, vol. **18**(12), 2003-2012 (1979).

R&D 100 Award for LTP II - 1993

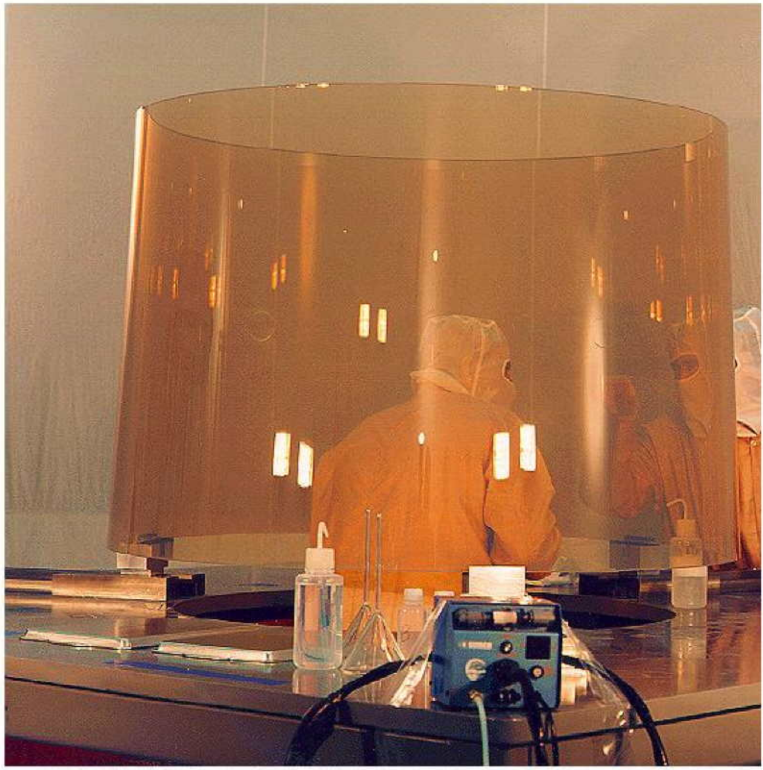
E.L. "Gene" Church

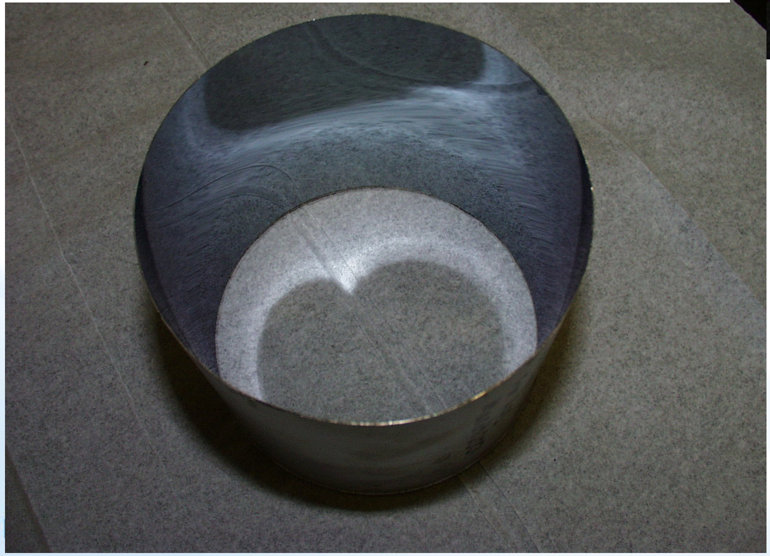
Steve Irick

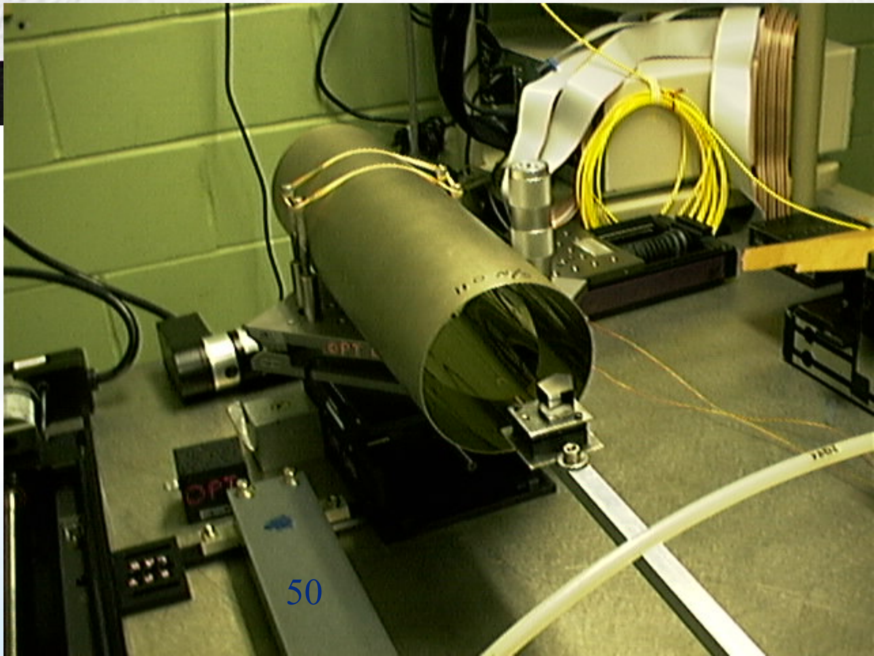
Shinan Qian

Manfred Grindel

PZT

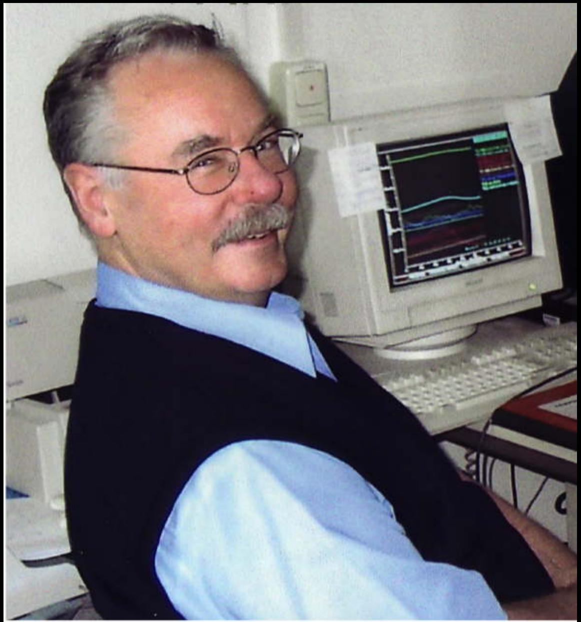




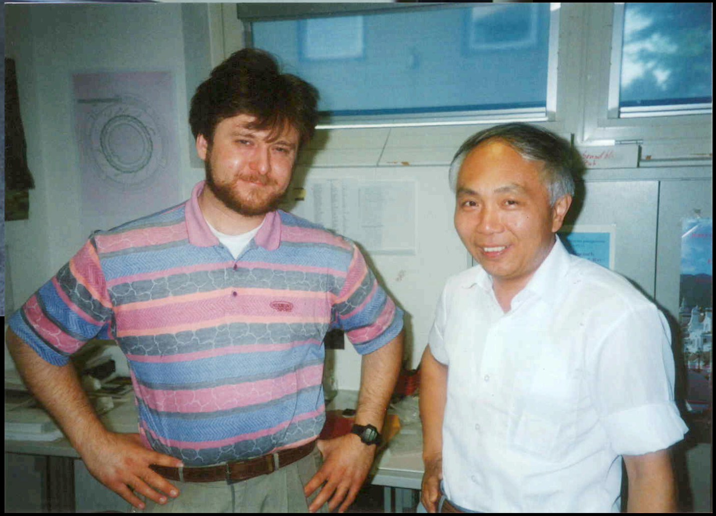


LTP IV on BESSY NOM measuring machine

Designed by Heiner Lammert, Metrologist *par excellence*

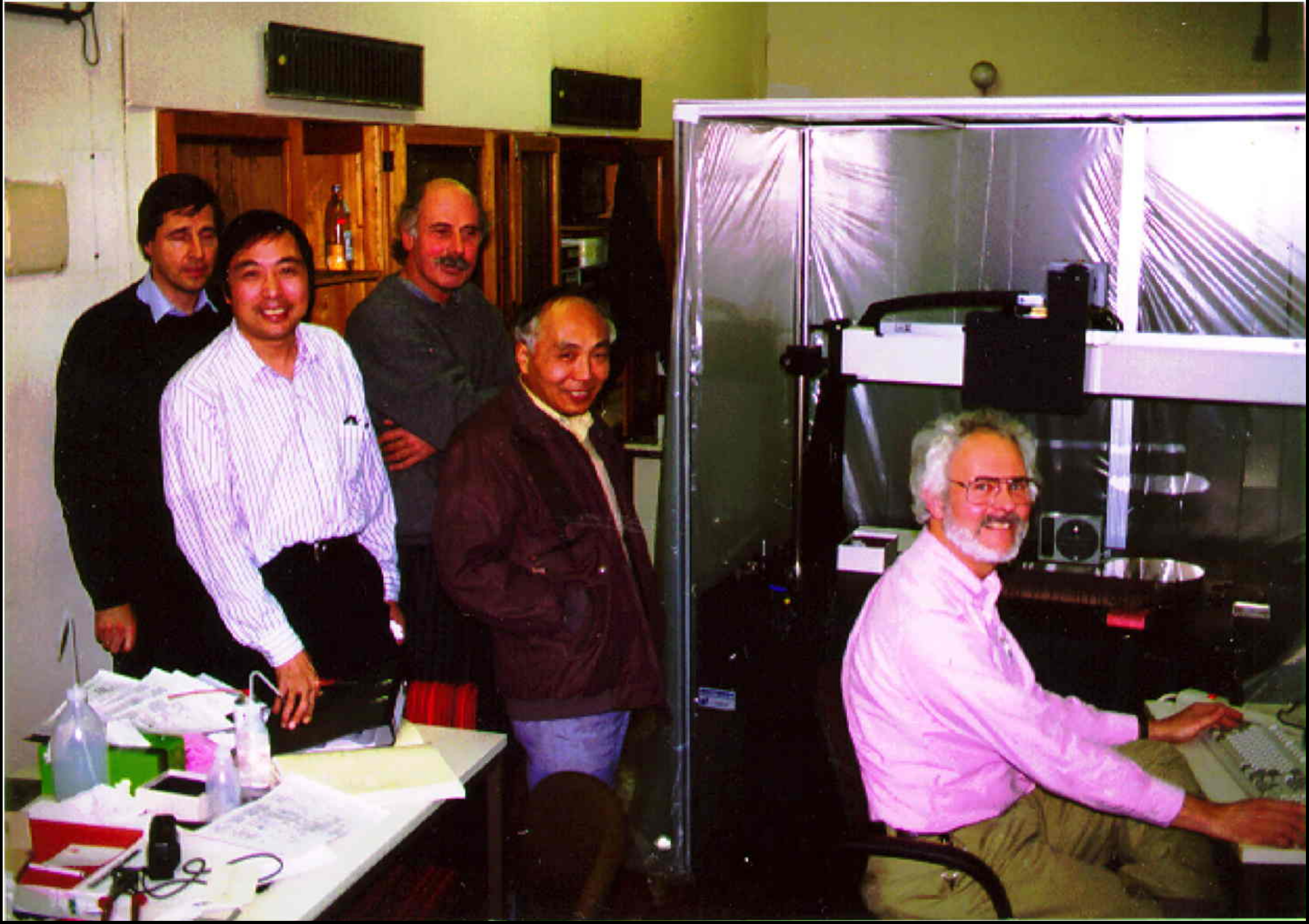


LTP II ELETTRA Trieste

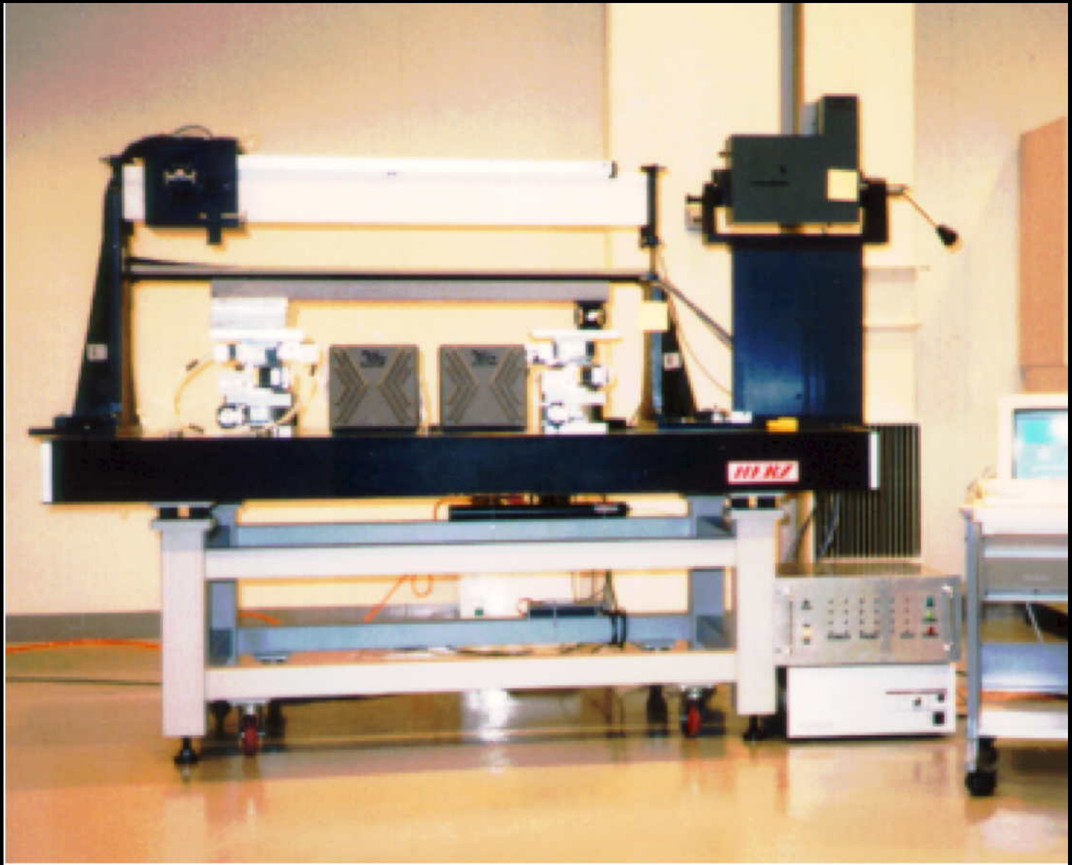


- Penta prism scan version
- Optimized for horizontal beam deflection

LTP II at BESSY I

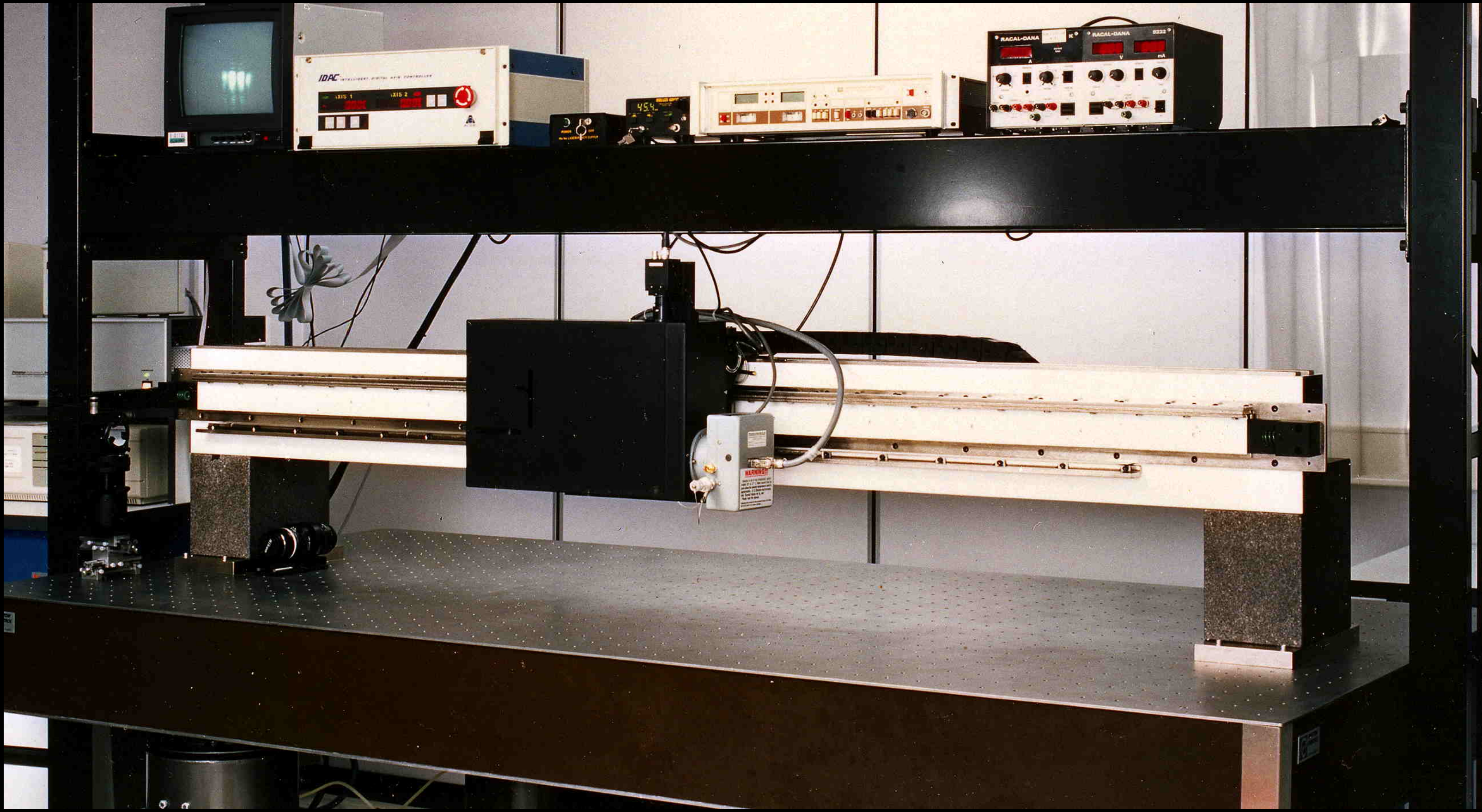


LTP II at SPring8 Japan



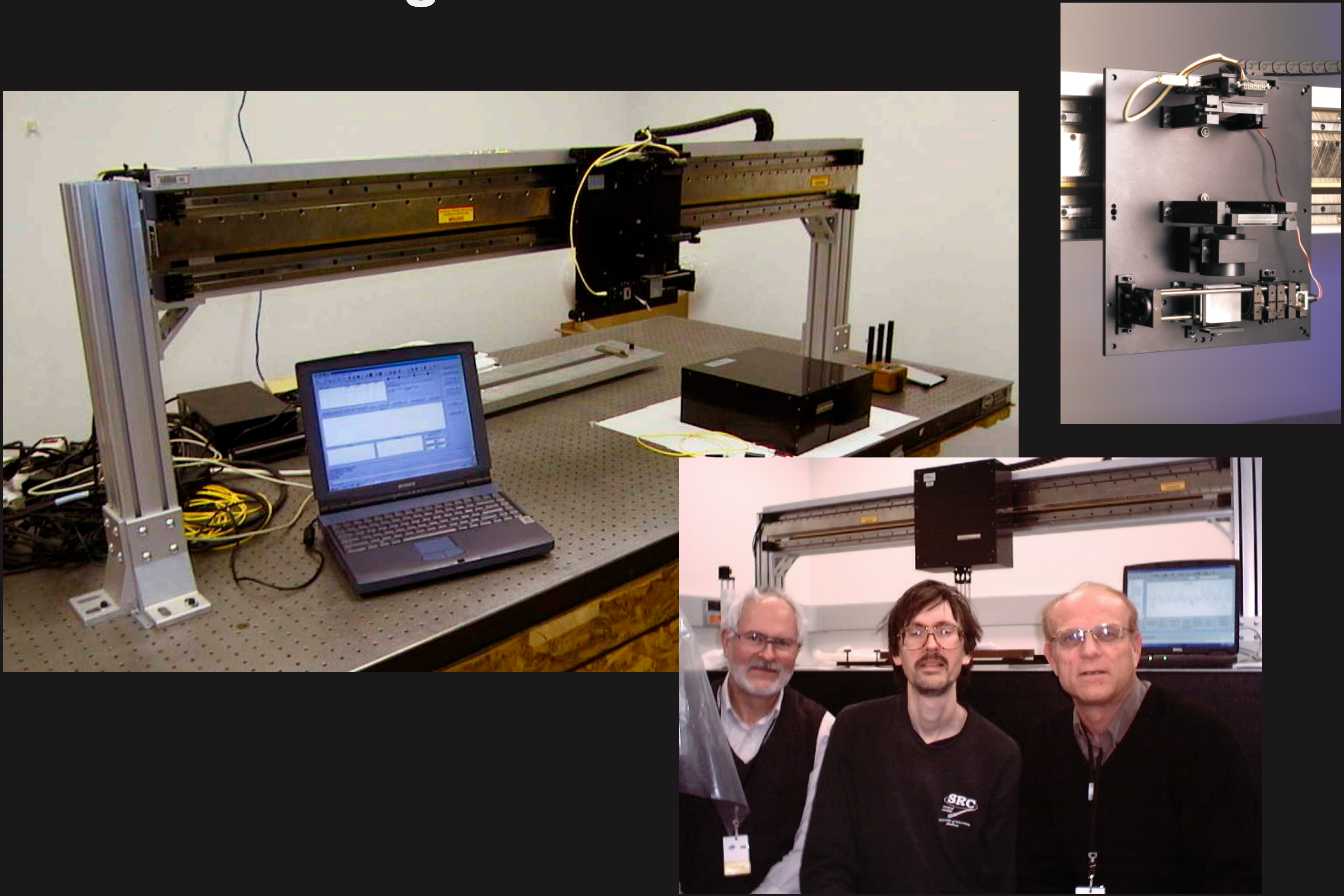
- 2 meter travel length
- Side-mounted optical head
    - Penta prism scans
- Head rotates for sideways measurements

LTP at ESRF - original version

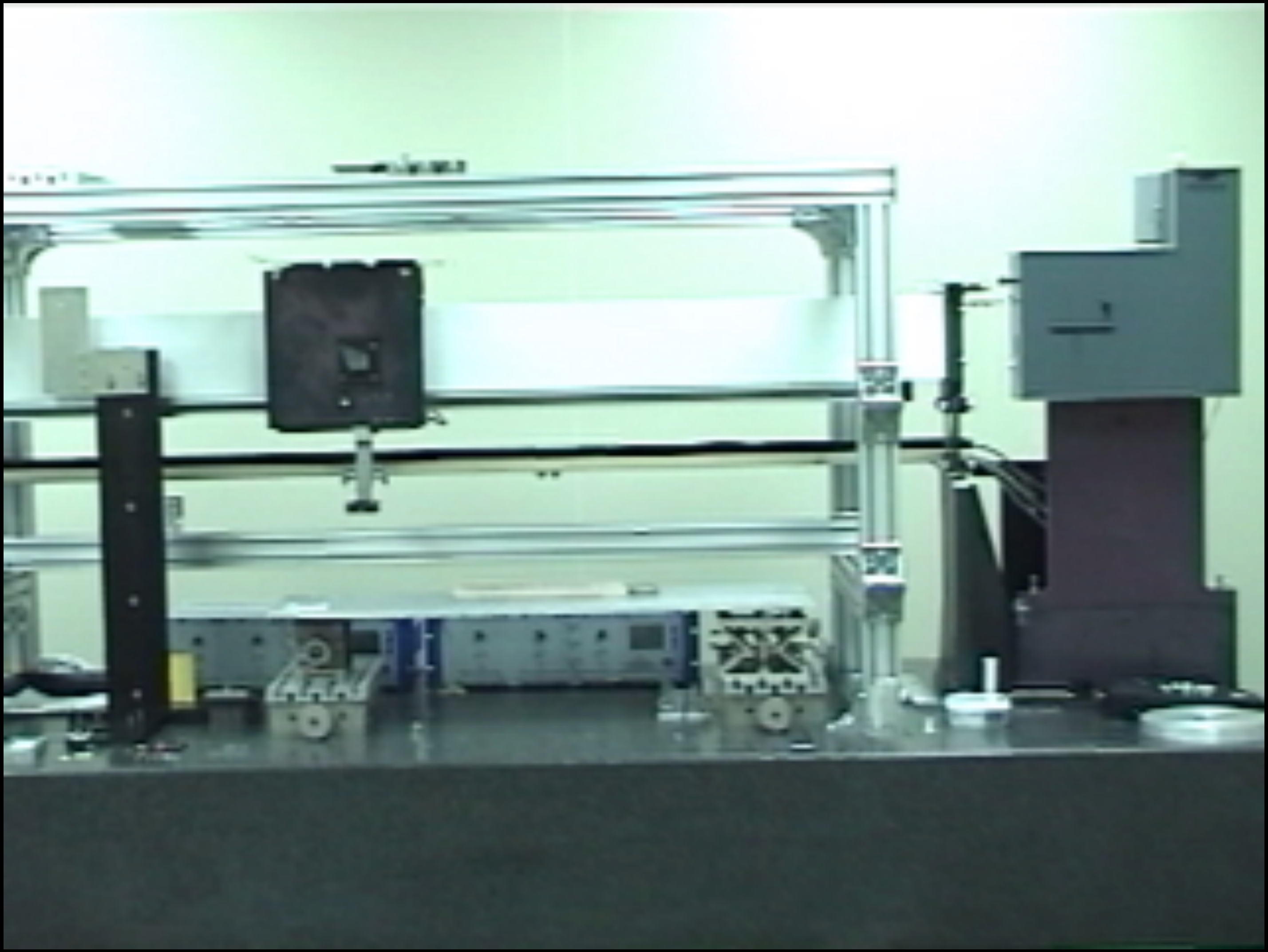


- Modified LTP II design
- Made in-house by ESRF with design from BNL
- Anorad air bearing and linear motor

Canadian Light Source – LTP IV



LTP II SSRC Taiwan



LTP II* at Crystal Scientific, UK

- Retrofit of OOI detector and motor controller to existing LTP
- Original unit “homemade” by Beamline Technologies Corp., A. Lunt

Penta-prism scan method.

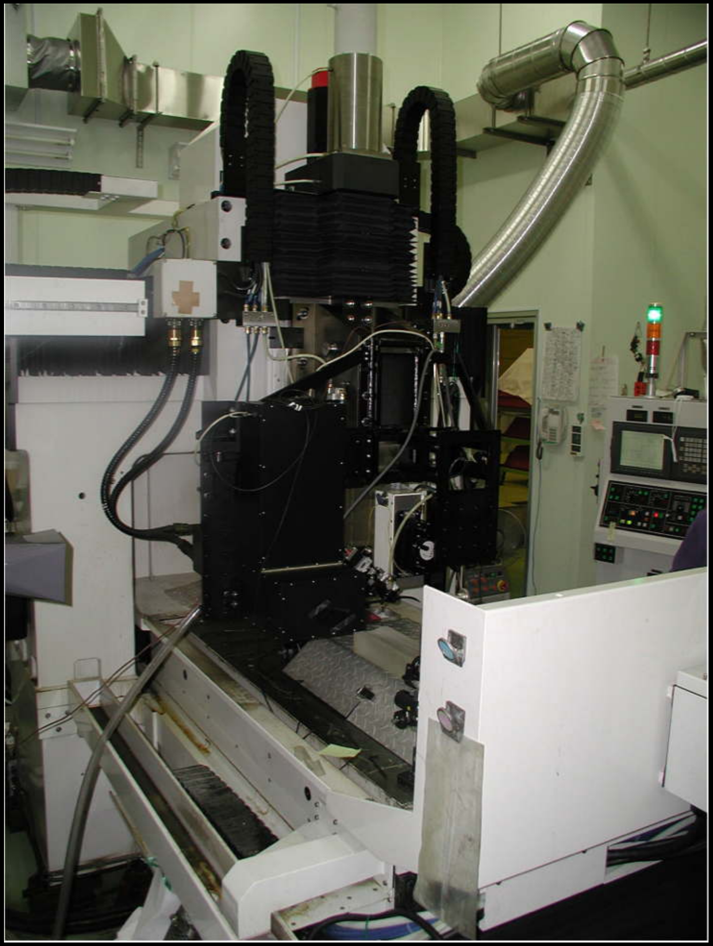
Slide mounted under beam -
  - Roller bearings not preloaded.
  - Too much yaw and roll error

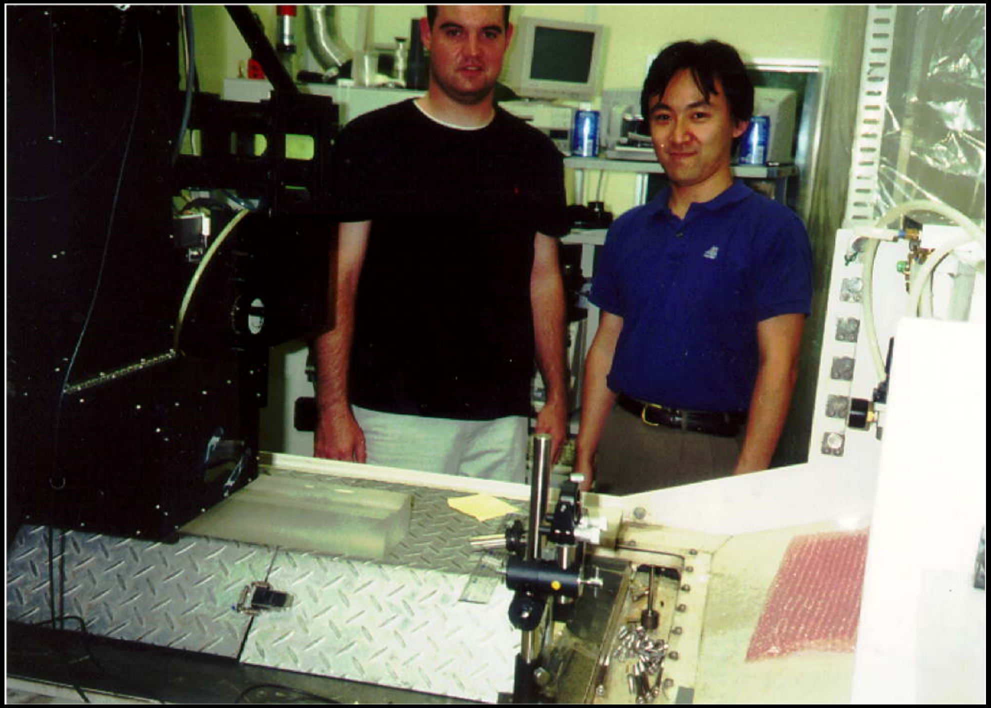
Opt head attached to inside of leg -
  - Extra steering mirrors req’d.

Detector mounted on table top -
  - Not connected directly to optics board.

Recent modifications -
  - Use OOI detector and motor controller.
  - Air bearing from New Way.

OOI LTP IV on ELID grinding machine at RIKEN





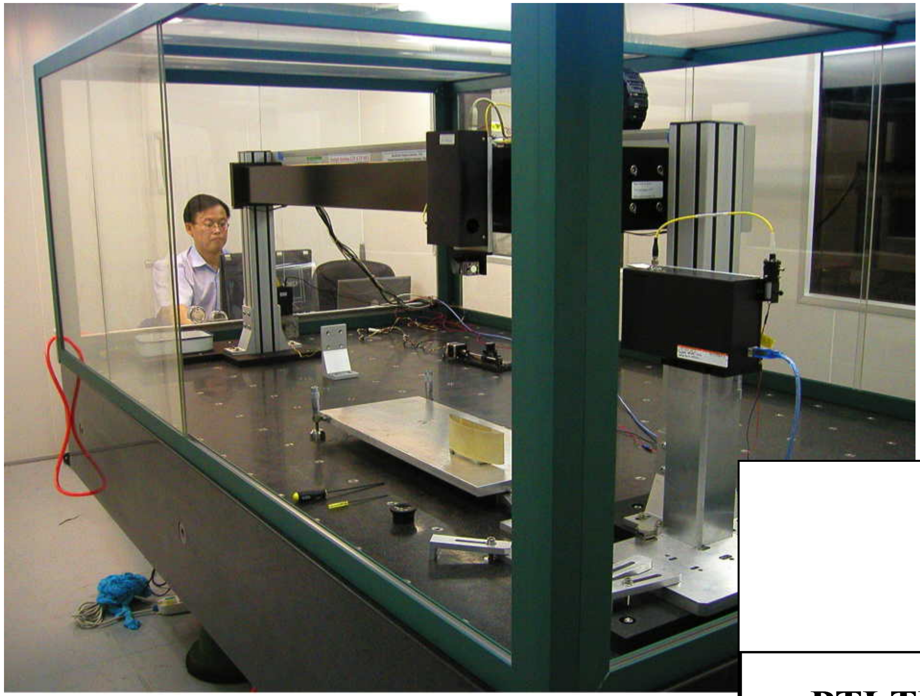
Compact PTLTP developments - BNL

- The Portable LTP (PTLTP) was developed for comparisons and in-situ testing (S. Qian)
- Optical head, laptop, control system, and compact slide can be packaged into one laptop bag for comparison measurements worldwide.
- Has led to a family of compact and special purpose LTP designs.

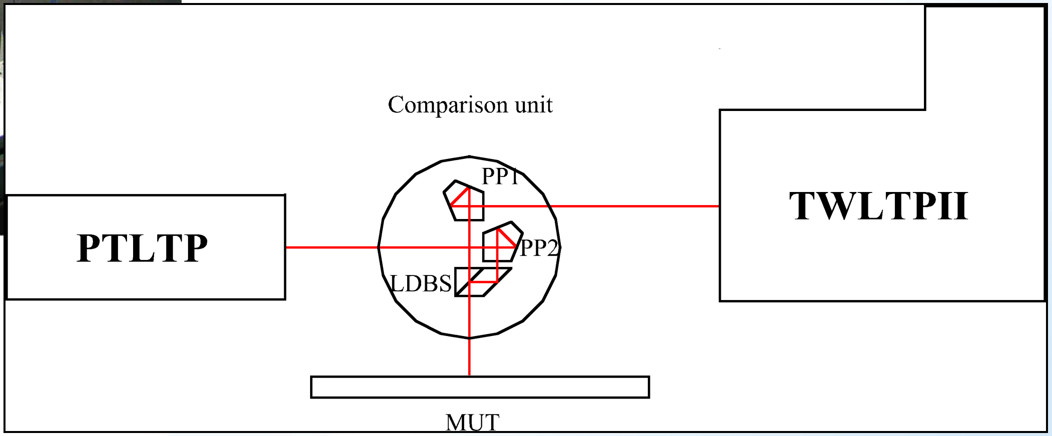
Qian, S., Takacs, P., Sostero, G., and Cocco, D., *Portable long trace profiler: Concept and solution*, Rev. Sci. Instrum. 72(8), p. 3198-3204 (2001).

Really compact PTLTP

Multiple Function LTP (LTP-MF) - BNL



- Multiple Function LTP (LTP-MF) for NSRL, China, in 2005.
- Operate as: LTP, PPLTP, In-situ LTP, with double optical heads and non-tilted reference method to increase accuracy.



- Qian, S., Wang, Q., Hong, Y., and Takacs, P., "Multiple functions Long Trace Profiler (LTP-MF) for National Synchrotron Radiation Laboratory of China", Proc. SPIE 5921, San Diego, CA: 2005.
- Qian, S.N. and Takacs, P., Design of multiple-function long trace profiler, Optical Engineering 46(4), (2007).