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Air Convection Noise of Pencil-beam Interferometer for Long Trace Profiler

Valeriy V. Yashchuk[a], Steven C. Irick[a], Alastair A. MacDowell[a], Wayne R. McKinney[a], and Peter Z. Takacs[b]

a) Lawrence Berkeley National Laboratory, Berkeley, California, 94720
b) Brookhaven National Laboratory, Upton, New York, 11973

vvyashchuk@lbl.gov

Outline

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- ***Introduction***
  - → *LTP performance and environmental conditions*
- ***Motivation***
  - → *Environmental conditions must be improved first!*
  - → *The improvement must be functional and cost effective*
- ***Laser beam pointing stability and air convection***
  - → *Experimental set-up and data processing*
  - → *Air convection flow stimulated with resistive heater*
  - → *Effect of air convection on laser pointing*
  - → *Effect of air blowing on air convection noise*
- ***Air convection and PSD measurements with the LTP***
  - → *Air-blowing against air-convection noise in the LTP reference channel*
  - → *Relation between PSD of a slope trace and corresponding height distribution*
- ***Conclusions and Acknowledgements***

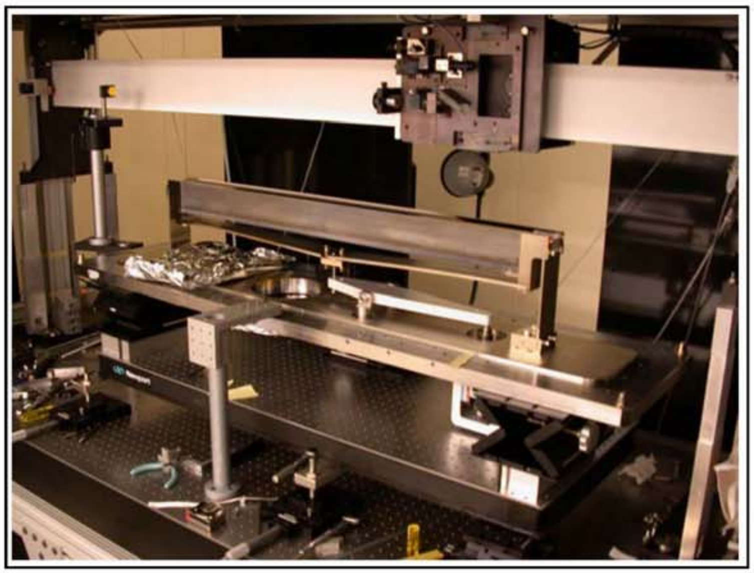
"...In truth, the gold standard is already a barbarous relic..."

John Maynard Keynes, *Monetary Reform* (1924)

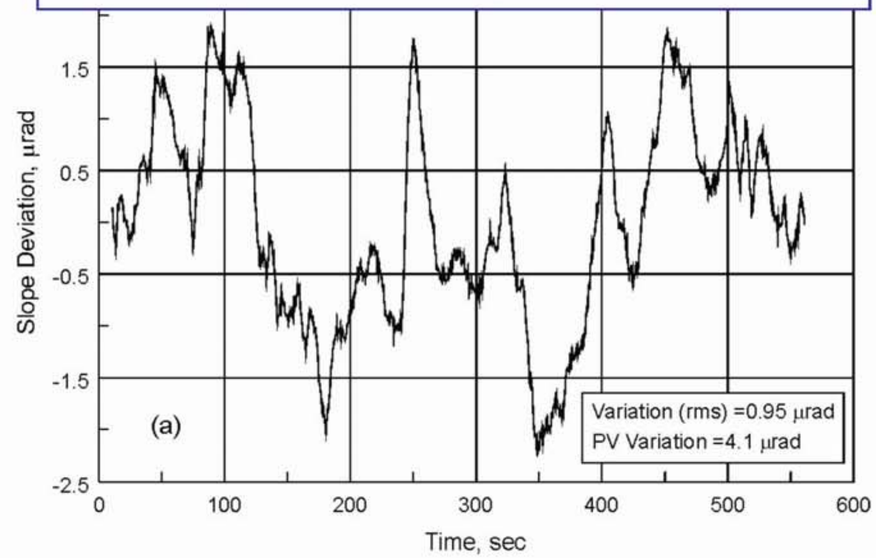
Air-convection is due to temperature gradients inside the hutch (~20 mK);

Air-convection correlates with air-density fluctuation along optical paths

Air-density fluctuation causes pointing instability of the laser beam



Air-convection noise in the LTP reference channel



Environmental conditions must be improved first!

Straightforward ways for improvement:

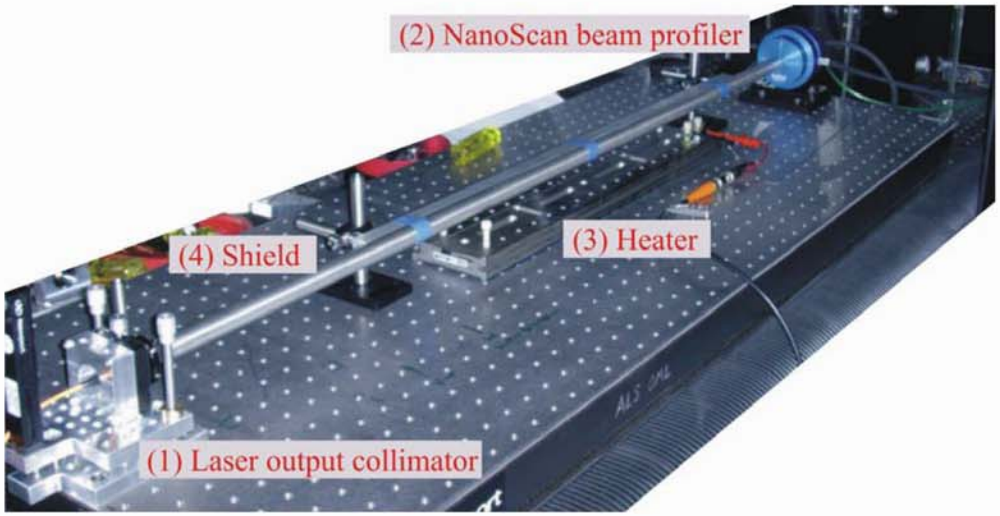
- **Vacuum or helium atmosphere ($$$)**
- **Carefully sealing the LTP hutch and the lab +**
- **Temperature stabilization on the level of ~ 1 mK ($$$)**

(similar to BESSY and PTB)

Non-straightforward way?

Our goal: to develop an effective way to suppress air-convection noise

Set-up for measurement of laser pointing stability and data processing

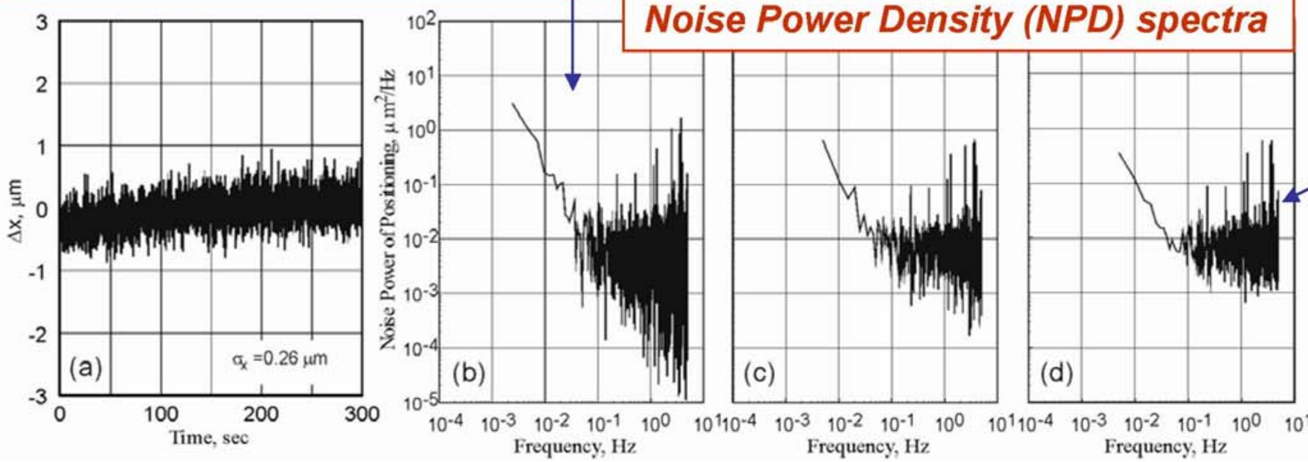


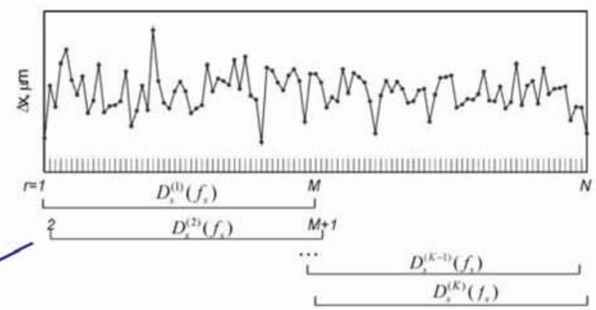
- Melles Griot fiber-coupled diode laser (1) (635 nm; 3 mW; ~0.8 mm FWHM spot);
- NanoScan beam profiler (2) as a beam positioning detector with $\leq 0.1\,\mu m/\sqrt{Hz}$ accuracy.
- Resistive heater (3) to stimulate air convection (one rectangular loop, 12-in × 2-in, of stainless steel wire (0.009-in diam.; 17.4 Ohm resistance).
- Stainless steel tube (¾-in outer diameter, 0.04-in wall thickness, 1m length) to shield the beam against air-convection perturbations (4).
- The baseline of the set-up is 1050 mm, then:

$$\sim 0.1\,\mu rad/\sqrt{Hz}$$

$$D_s(f_s) = \Delta t \cdot \left| Fourier(P_r(t_r)) \right|^2 = \frac{\Delta t}{N} \left| \sum_{r=1}^{N} P_r(t_r) \cdot \exp\{2\pi i (r-1)(s-1)/N\} \right|^2$$

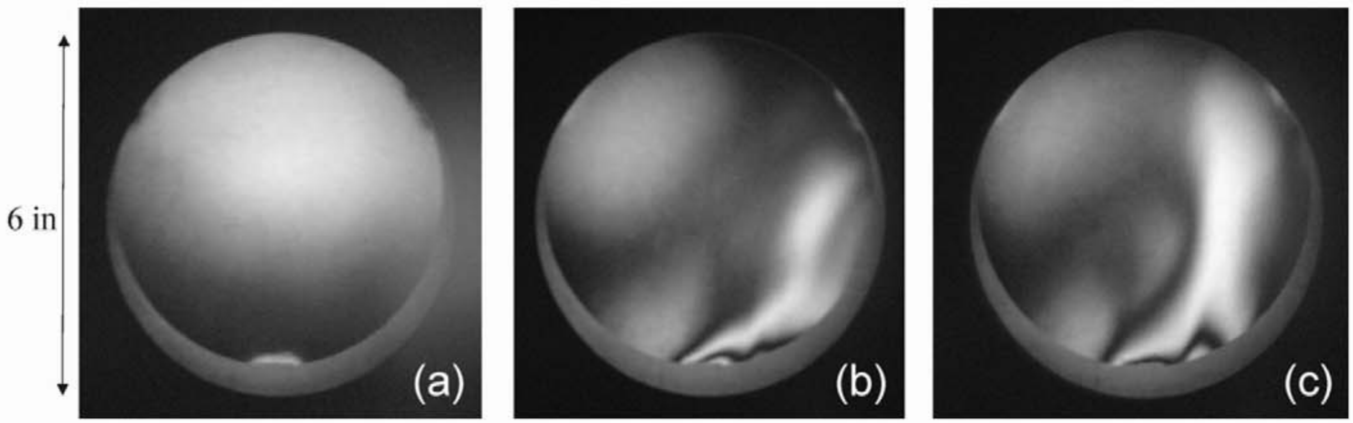
Noise Power Density (NPD) spectra



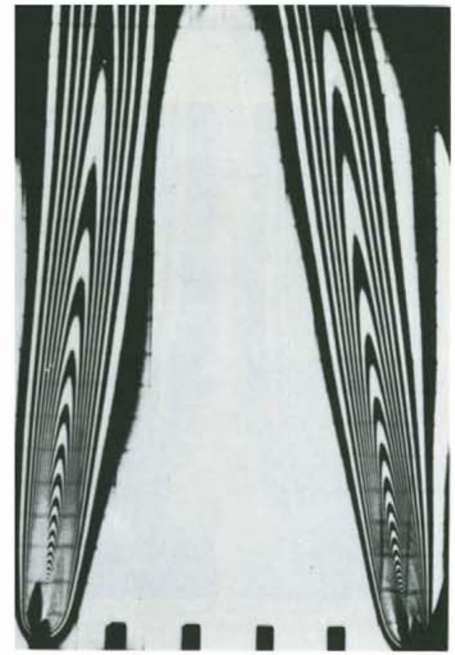


W. H. Press, S. A. Teukolsky, W. T. Vetterling, B. P. Flannery, *Numerical Recipes in C++: The Art of Scientific Computing* (Second Ed., Cambrige Univ. Press, Cambridge, 2003).

Air convection stimulated with resistive heater



The interferograms obtained with the ZYGO GPI interferometer available at the OML. (a) - the image of a flat etalon with unpowered heater. (b) and (c) – the interferograms obtained when the wire heater produces approximately 1 W resistive heat.

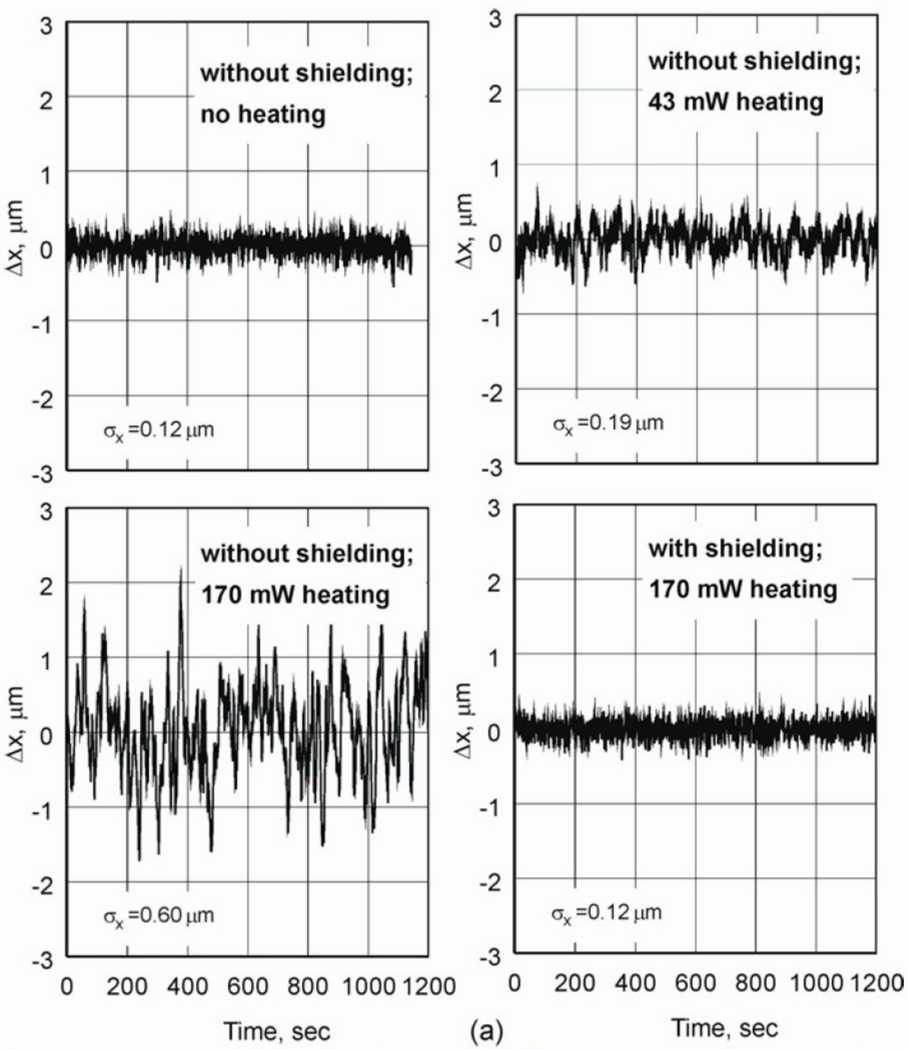


Interferometric image of air convection stimulated with a two-wire resistive heater made of two Nichrome wires 18 cm long and separated by 7.2 cm. The interferogram was recorded with a Mach-Zehnder interferometer.

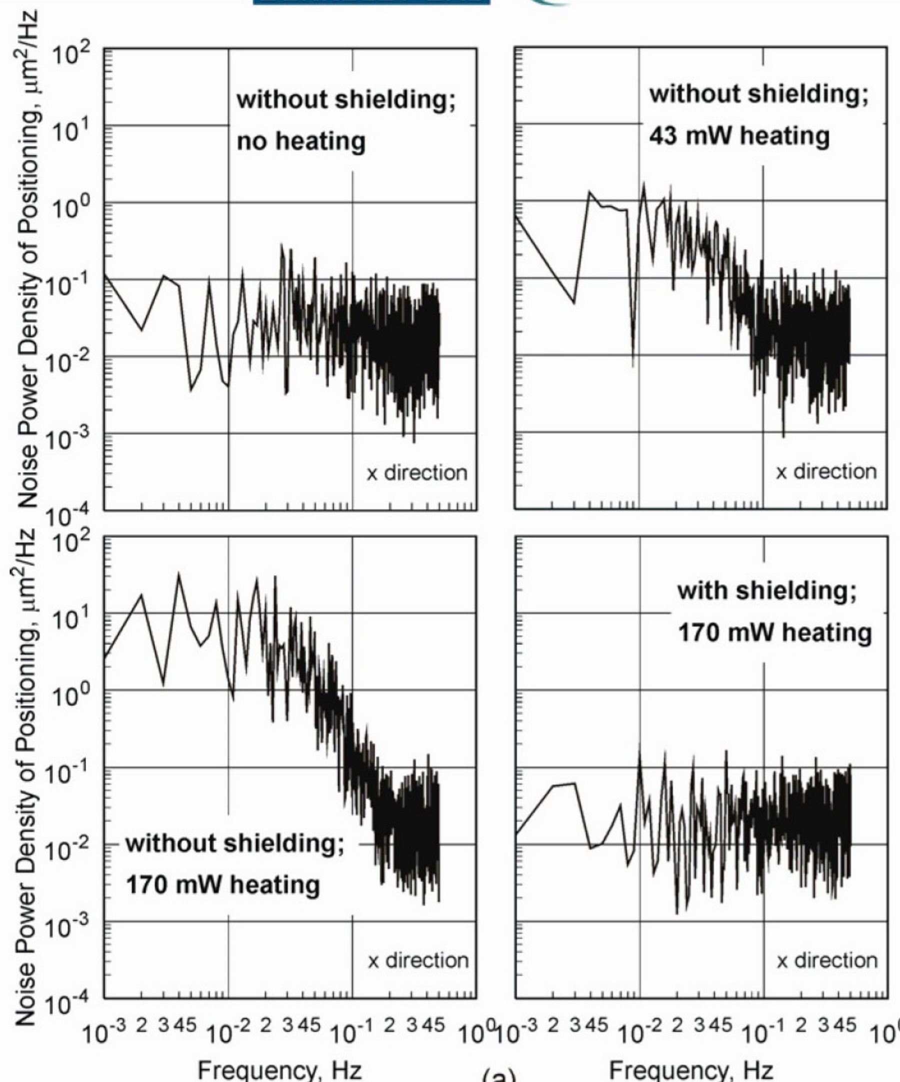
The picture is adapted from:
L. Pera and B. Gebhard, Laminar Plume Interactions, Journal of Fluid Mechanics 88(2), 461-463 (1975).

Effect of air convection on laser beam pointing

in the horizontal direction



Temporal dependence of pointing instability in the horizontal direction measured at different power applied to the resistive heater.



Noise power density spectra calculated from the data of the beam-position-variation in the horizontal direction.

The measurements were performed at the 5 Hz profiler scanning frequency with averaging over 5 successive position measurements.

Effect of air convection on laser beam pointing

in the vertical direction

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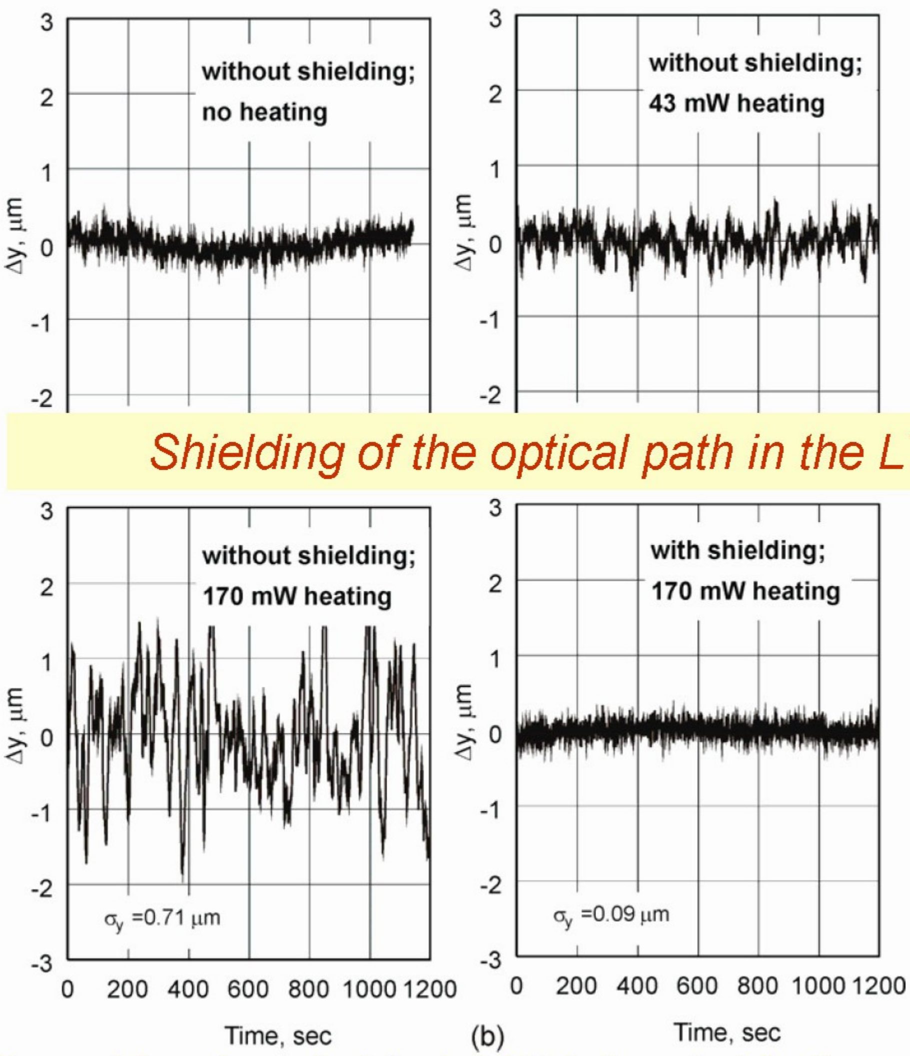
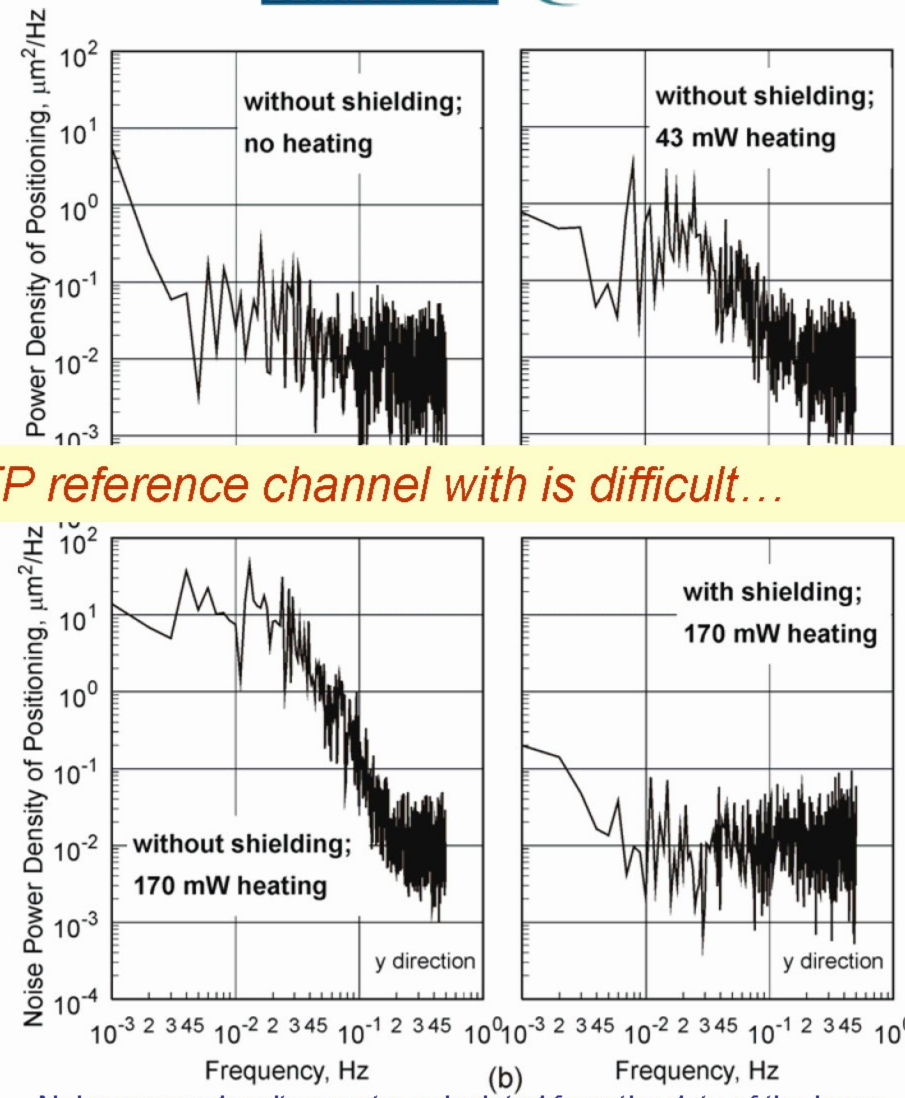




Shielding of the optical path in the LTP reference channel with is difficult…

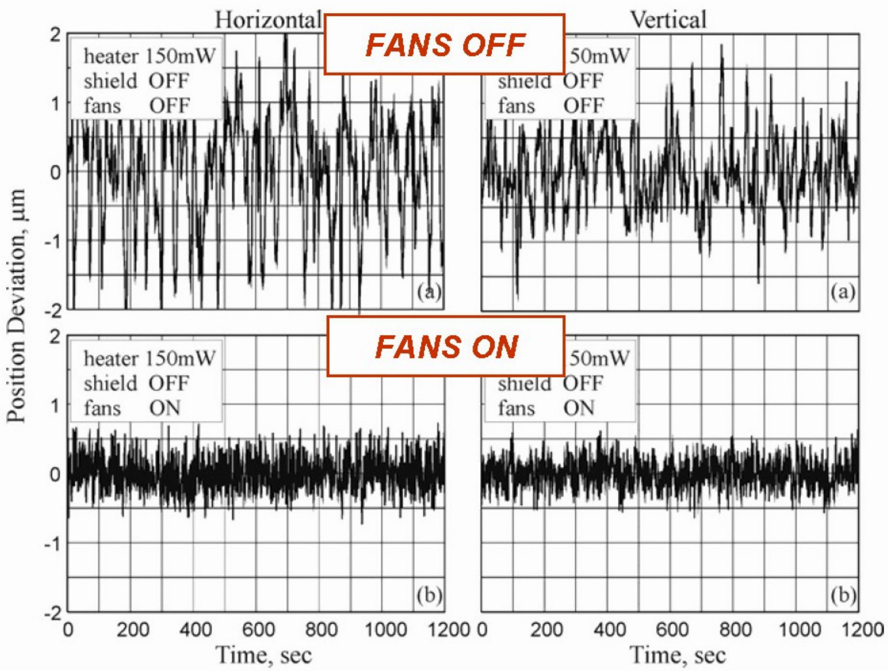
Temporal dependence of pointing instability in the vertical direction measured at different power applied to the resistive heater.

Noise power density spectra calculated from the data of the beam-position-variation in the vertical direction.

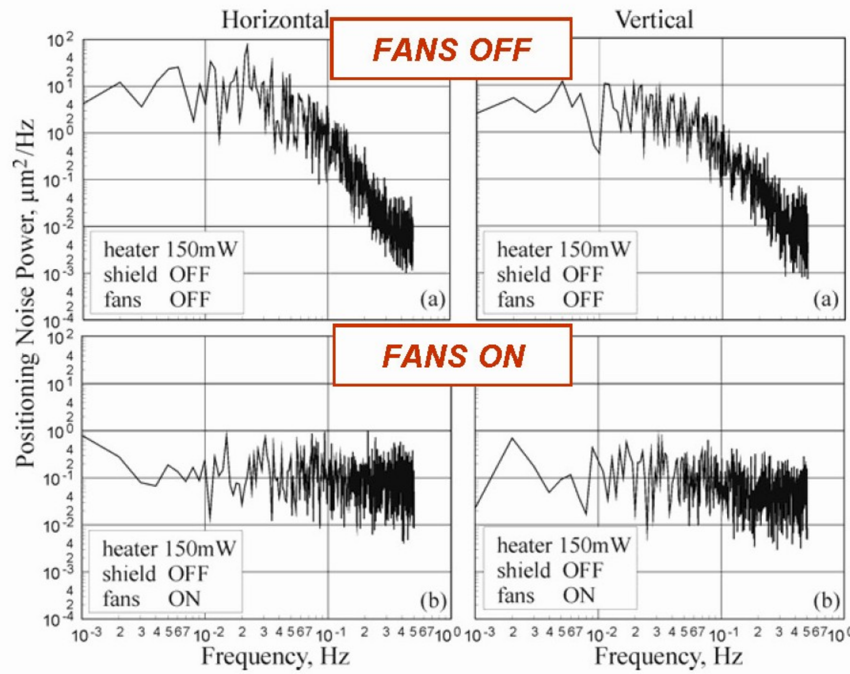
The measurements were performed at the 5 Hz profiler scanning frequency with averaging over 5 successive position measurements.

Effect of air blowing on air convection noise

- ***Experimental arrangement used for investigation of air-blowing effects on laser pointing stability.***
- ***The air blowing system consists of 10 low-noise computer fans assembled along the 1050-mm long optical path.***
- ***Air blowing suppresses the pointing variation from 0.8 μrad to 0.26 μrad (rms).***

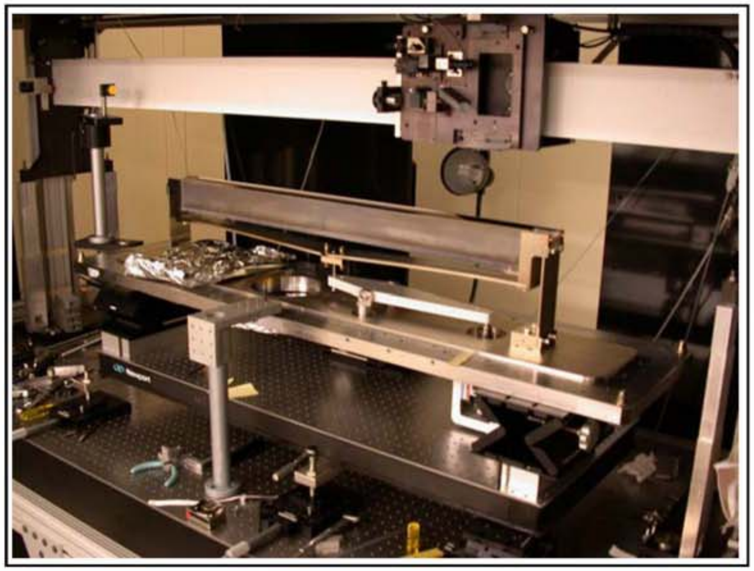


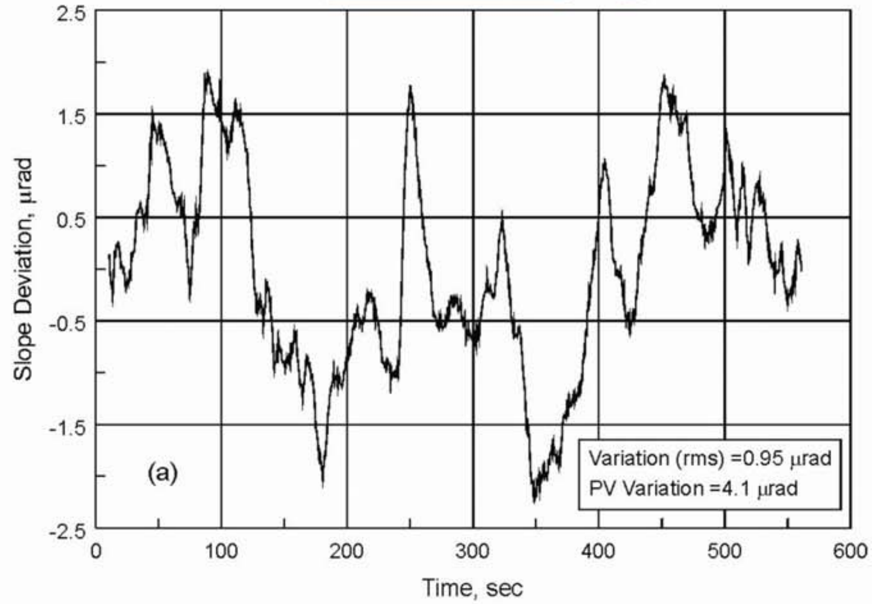
Temporal variation of laser beam position measured with the profiler at 1050 mm from the collimator at 150 mW power supplied to the heater.



Noise power density spectra calculated from the data of the beam-position-variations measured at 150 mW heater power.

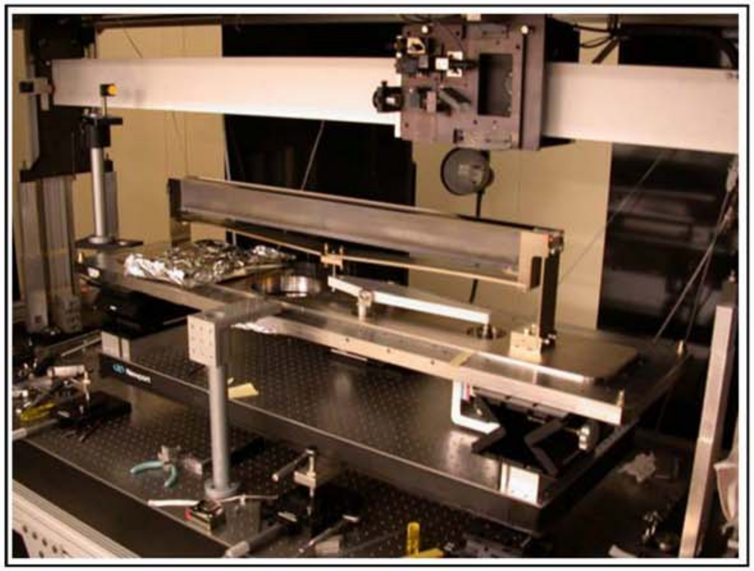
Air-convection noise in the LTP reference channel

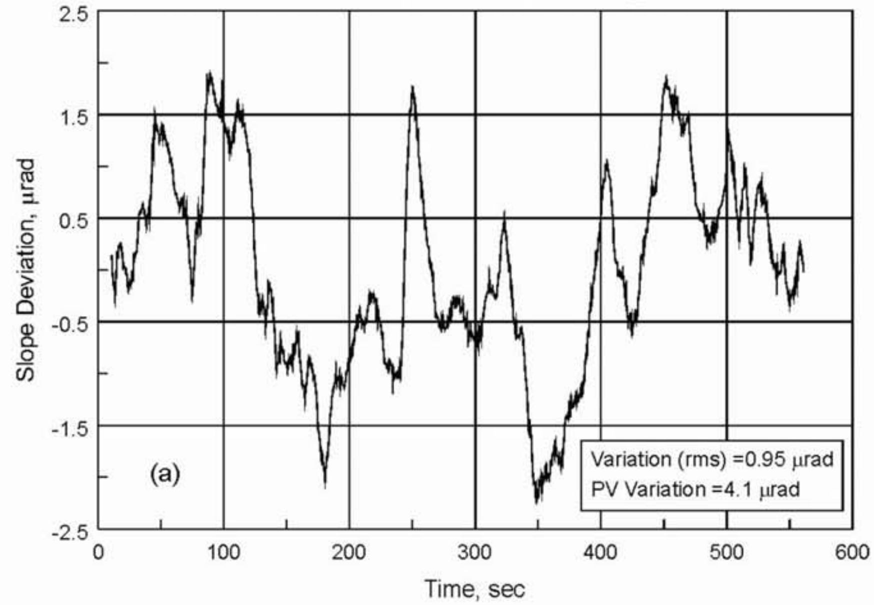


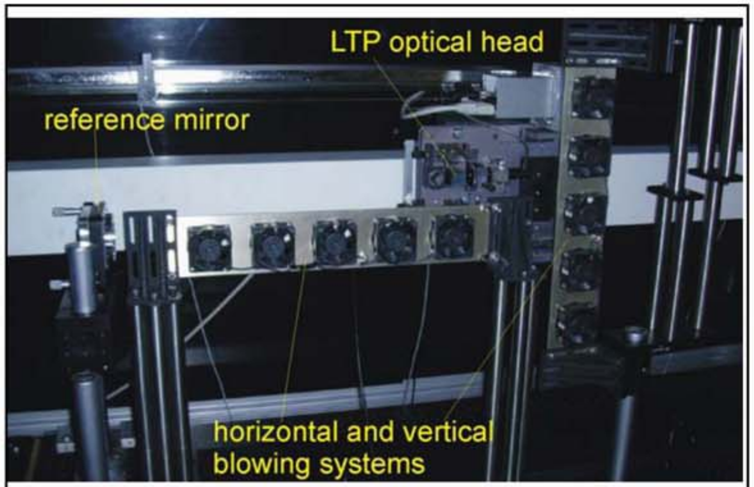


Air-blowing against

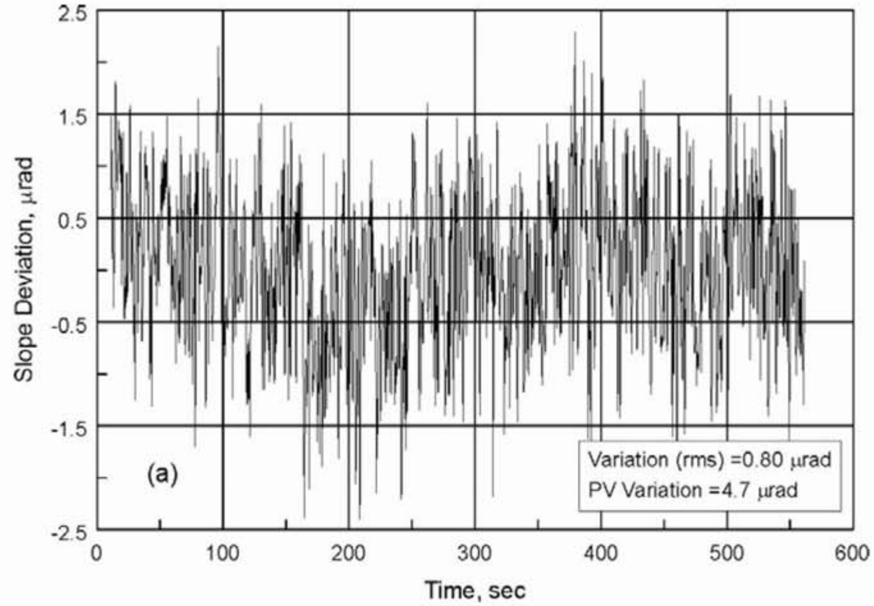
Air-convection noise in the LTP reference channel





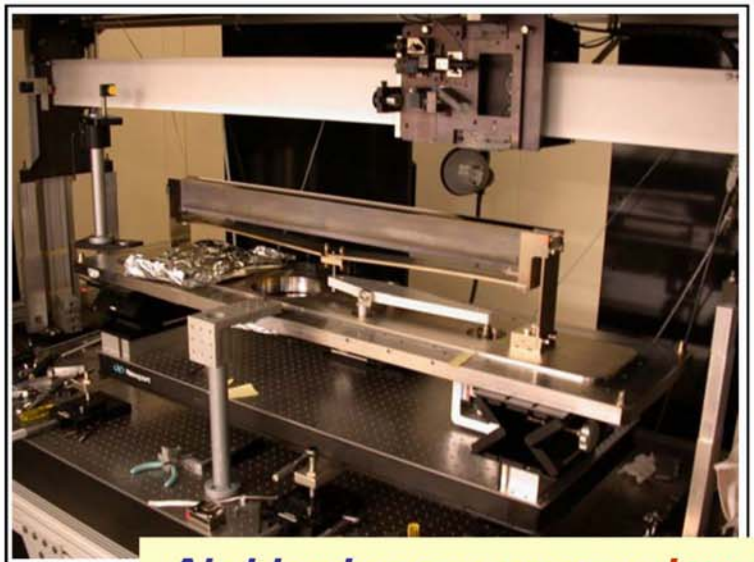


Set-up for measurement of air-convection noise in the LTP reference channel



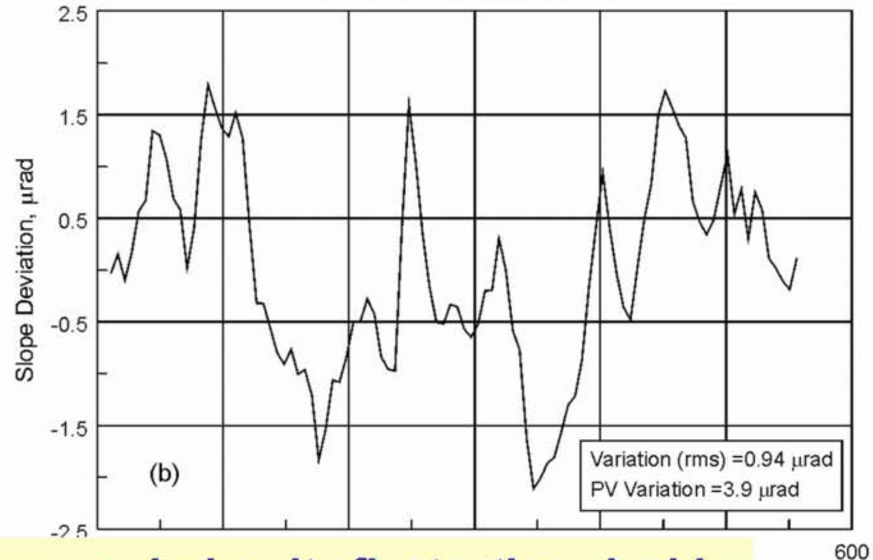
Air-blowing against

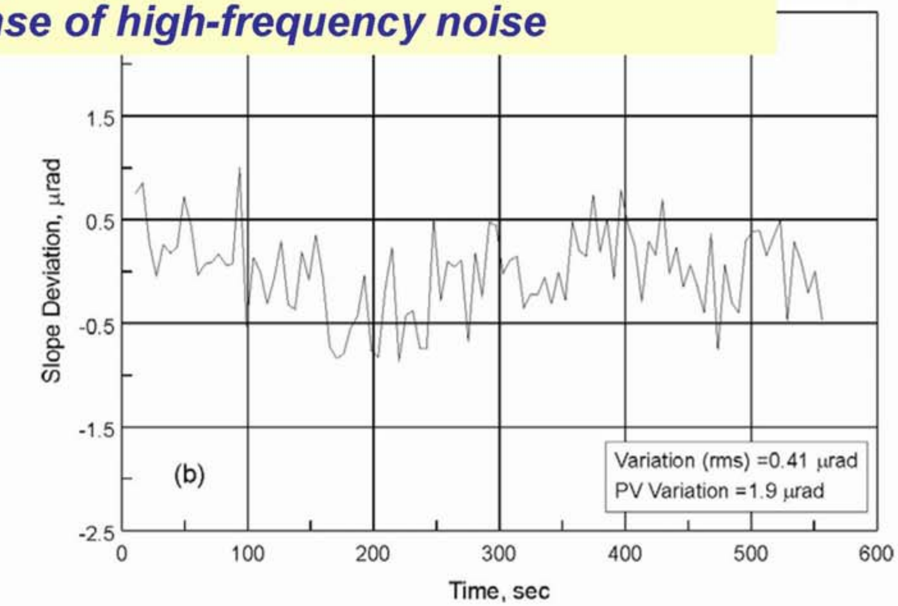
Air-convection noise in the LTP reference channel



Set-up for measurement of air-convection noise in the LTP reference channel

Air-blowing suppresses low-frequency air density fluctuations inside the hutch at the expense of high-frequency noise

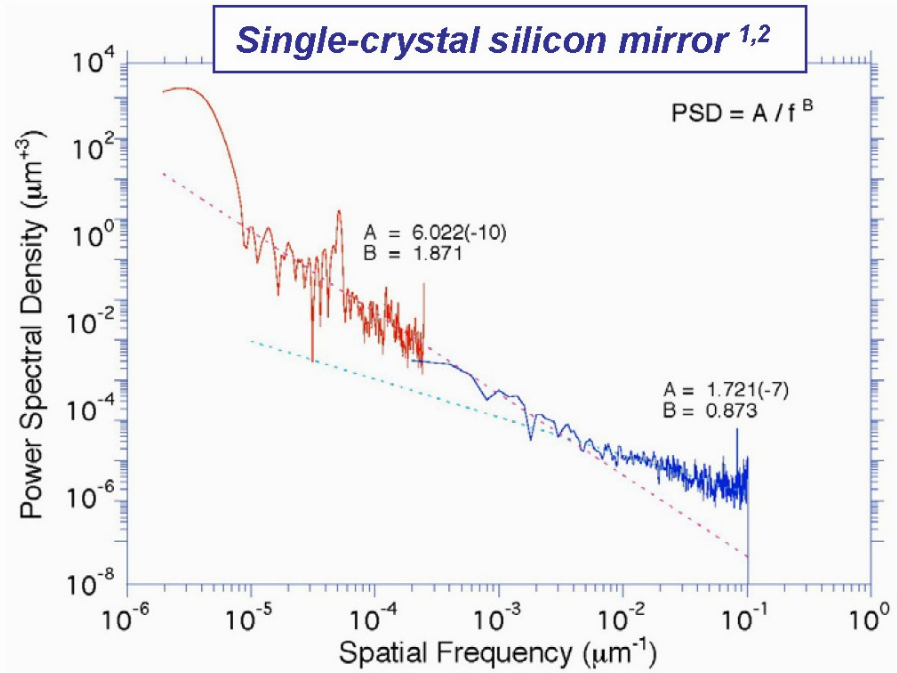


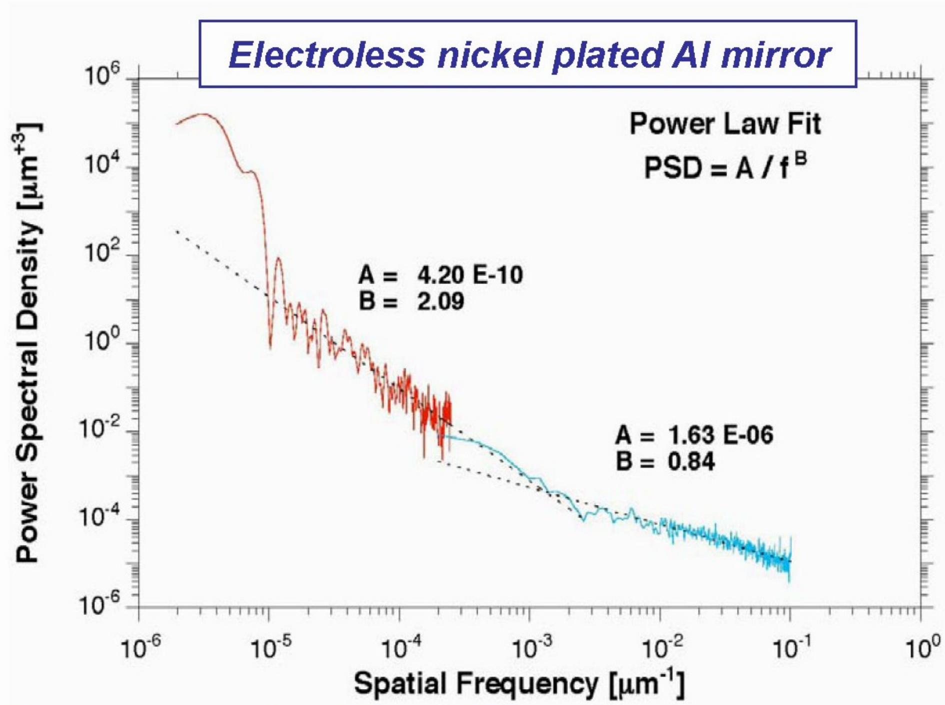


After filtering with averaging over 10 sequential points

PSD measurements at lower frequencies

Tangential 1D PSD spectra obtained with the LTP and the MicroMap™ interferometric microscope (BNL).





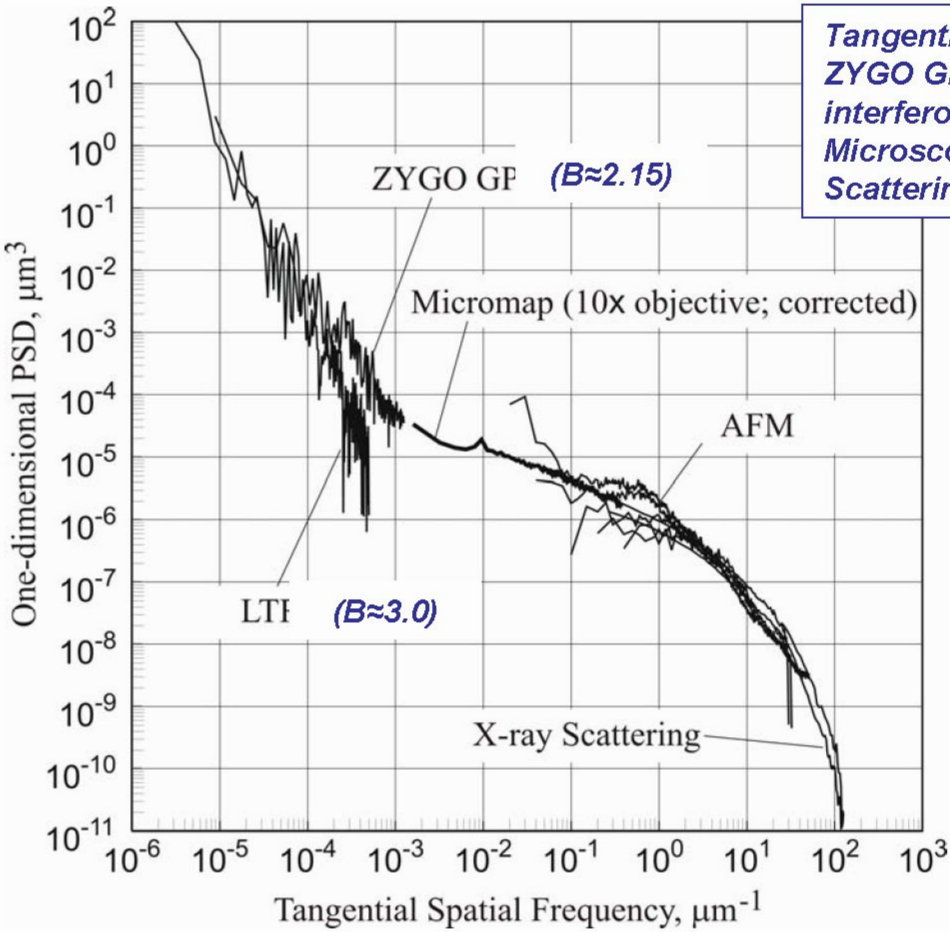
The straight lines are the best fitted inverse-power-law ('fractal') functions.

*Both mirrors were made in the late 1980s or early 90's. Each mirror exhibits a 2-component inverse-power-law spectrum. This is probably typical behavior for a polished surface of this size. It **can** occur as a result of the normal polishing process, where the surface starts out as a rough surface and then becomes smoother by knocking down the high frequency end of the spectrum faster than the low end. However. It also **can** be due to instrumental noise and/or data processing (detrending, windowing).*

[1] E. L. Church and P. Z. Takacs, *Specification of glancing- and normal-incidence X-ray mirrors,* Optical Eng. 34,(2), 353-60 (1995).

[2] E. L. Church and P. Z. Takacs, *Specification of surface figure and finish in terms of system performance,* App. Optics 32(19), 3344-531 (1993).

Should we believe in the PSD measurements at lower frequencies?



Tangential 1D PSD spectra obtained with the ZYGO GPI interferometer, the LTP, the Micromap™ interferometric microscope, the Atomic Force Microscope, and the CXRO Reflectometry and Scattering experimental facility[1].

The mirror is somewhat smoother than both of the mirrors shown in the previous viewgraph, especially in the spatial period range around 10^{-3} μm, as it should be for a modern mirror. However, the index of inverse-power-law approximation at the lower spatial frequencies is still larger than 2.

Do the systematically high values of the index reflect a real property of polished surfaces?

Does the break point between the two spectral fits just coincidentally fall right at the overlap of the two instrumental regions?

Or, perhaps, there are some principal problems of measurements at the lower spatial frequencies?

[1] V. V. Yashchuk, S. C. Irick, E. M. Gullikson, M. R. Howells, A. A. MacDowell, W. R. McKinney, F. Salmassi, T. Warwick, *Cross-check of different techniques for two-dimensional power spectral density measurements of X-ray optics*, SPIE Conference on Advances in Metrology for X-Ray and EUV Optics, SPIE Proceedings 5921, pp. 59210G-1-12 (San Diego, California, USA, 2-3 August 2005).

Height PSD from the slope data must be considered *carefully*

Derivative theorem of the Fourier transform:

If $F(u)$ *is the Fourier transform of function* $h(x)$,

then $\dfrac{\partial h(x)}{\partial x}$ *has the Fourier transform* $i\,2\pi\,u\,F(u)$.

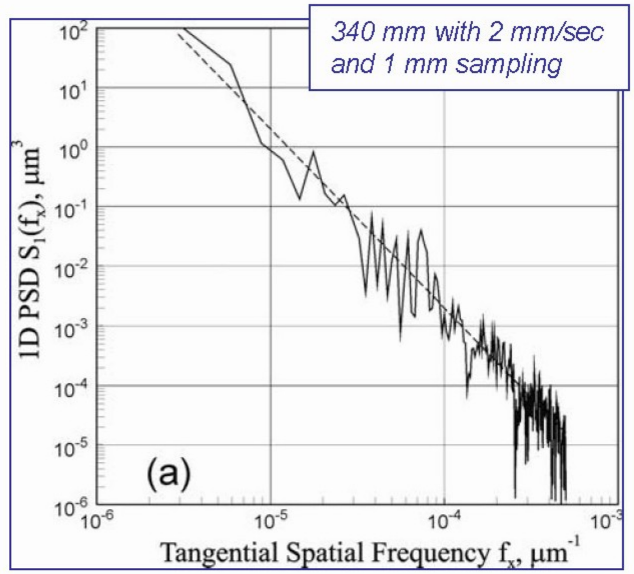
Therefore,

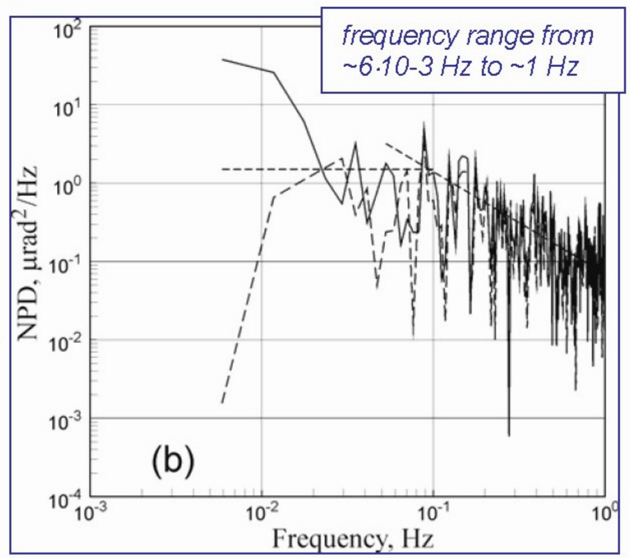
if PSD of the surface height variation $h(x)$ *is approximated with an inverse-power-law function* $\dfrac{S(1)}{u^B}$, *then the PSD of the slope variation* $\alpha(x) \equiv \dfrac{\partial h(x)}{\partial x}$ *has to be described with a power-law function:*

$$4\pi^2 u^2 \frac{S(1)}{u^B} \propto \frac{1}{u^{B-2}}.$$

Then,

PSDs of the surface slope variations measured with the LTPs have white-noise-like or close to (frequency)$^{-1}$-like spectra





(a) ***PSD spectrum a stainless steel mirror measured with the LTP.*** *The dashed line shows a fractal approximation with a power index equal to 3.*

(b) ***The same PSD measurement presented as a dependence of the slope NPD on sampling frequency.*** *The dashed lines depict the characteristic behavior of the NPD spectra due to air convection: a linear slope at higher frequencies and a white-spectral noise at lower frequencies.*

Conclusions

✓ *The effect of air convection on laser-beam pointing noise has been investigated.*

✓ *It has been shown that the NPD spectra due to air convection have a very characteristic form.*

In the range of frequencies from ~0.05 Hz to ~0.5 Hz, the spectra can be modeled with an inverse-power-law function. Depending on the intensity of air convection that is controlled with a resistive heater of 40 to 170 mW along a one-meter-long optical path, the power index lies between 1 and 3 at the overall rms noise from ~0.2 to ~1 μrad.

✓ *A high efficiency of the developed air-blowing technique based on a set of PC fans to suppress the air convection noise of the laser beam pointing has been experimentally verified.*

Air-blowing leads to a white-noise-like spectrum. The spectrum is the result of a tradeoff: when the fans are turned on the noise in the low frequency part of the spectrum goes down at the expense of an increase in the high frequency end of the spectrum.

✓ *A significant perturbation of the LTP measurements due to air convection effects has been demonstrated.*

✓ *The air-blowing technique developed and based on PC fans allows a significant suppression of the noise in the LTP reference channel at lower frequencies.*

✓ *Similarity of X-ray mirror PSD distributions measured with the LTP and NPD spectra due to air convection suggests a significant effect of air convection on LTP measurements.*

Acknowledgements

For extremely useful discussions, the authors are grateful to

Eugene Church
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Tony Warwick

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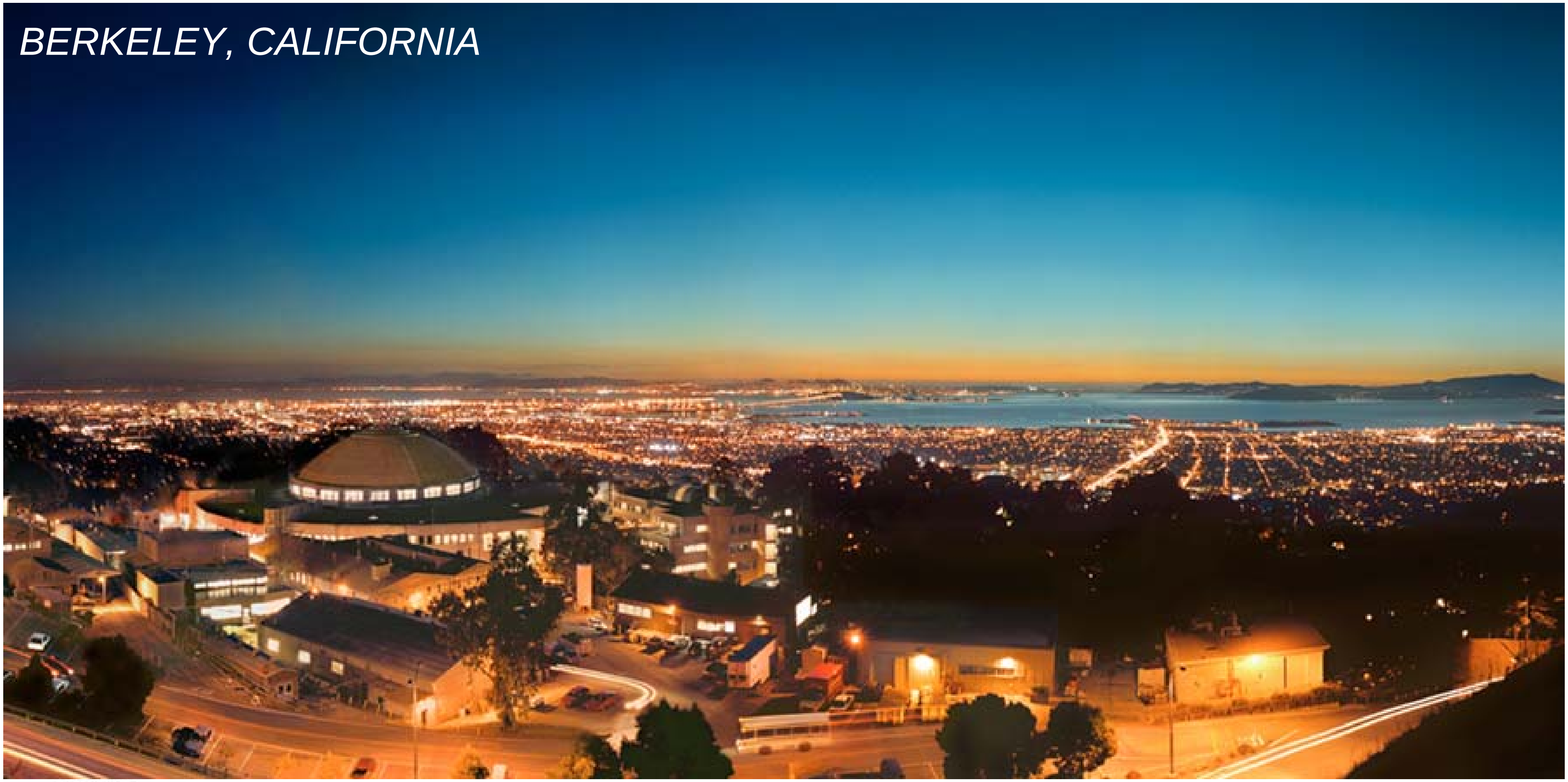
THANKS!



OPTICAL METROLOGY LABORATORY
EXPERIMENTAL SYSTEMS GROUP
ADVANCED LIGHT SOURCE
LAWRENCE BERKELEY NATIONAL LABORATORY

vvyashchuk@lbl.gov