REVIEW OF
LIGO BAFFLE DESIGN
AND
LIGHT SCATTERING IN BEAM TUBE

6-7 JANUARY 1995

LIGO-G950079-00-R

REVIEW of LIGO BAFFLE DESIGN AND LIGHT SCATTERING IN BEAM TUBE

January 6 and morning of January 7, 1995
Room 114 East Bridge, Caltech, Pasadena, CA

Final Agenda
Begin Each Morning at 9:00AM
Indicated Times Include Discussion

PRELIMINARIES:

9:00 Overview of Issues --- Kip Thorne
(20min)

9:20 The Present Baffle and Beam Tube Designs
(40min)
LIGO --- Larry Jones
VIRGO --- Jean-Yves Vinet
GEO --- Walter Winkler

ISSUES UNDERLYING SCATTERING CALCULATIONS [brief presentations by some or all of the indicated people, followed by a general discussion]:

10:00 Mirror Irregularities and Light Scattering from Mirrors:
(45min) Measurements; Theory; 1/\theta^2 Approximation for dP/d\Omega;
Reciprocity Relation for Scattering Out of and Into Main Beam
--- Rai Weiss
--- Jean-Yves Vinet
--- Walter Winkler
--- Eanna Flanagan [Reciprocity Relation]

10:45 Surface Roughness, Specular Reflectivity, BRDF & Scattering Cross
(45min) Sections for beam-tube materials [small incidence angle] and for
candidate baffle materials [large incidence angle]:
measurements and theory
--- Rai Weiss
--- Bob Breault
--- Jean-Yves Vinet
--- Walter Winkler
--- Hal Bennett???
--- Eanna Flanagan

11:30 Beam Tube and Baffle Vibrations
(45min)
--- Larry Jones [seismic spectra at LIGO sites]
--- Mike Gamble [normal mode analysis of LIGO beam tube]
--- Eanna Flanagan [phase noise put onto scattered light that scatters or diffracts off vibrating baffles and scatters or reflects off vibrating walls]
--- Jean-Yves Vinet
--- Walter Winkler

12:15 Photodetector Spatial Inhomogeneities, and the Unimportance??
(15min) of Recombination of Scattered Light Into the Main Beam at the
Photodetector Compared to Recombination at a Cavity Mirror
--- Rai Weiss
--- Kip Thorne

12:30 Lunch

SATURDAY MORNING

9:00 (30min) Special Scattering Noise Effects for Special Interferometer Configurations:

Delay Lines
--- Walter Winkler

Dual Recycled Interferometers
--- Kip Thorne

9:30 (30min) Scattering Noise and its Control in Instrumentation Chambers

---Jean-Yves Vinet
---Rai Weiss
---Walter Winkler

CONCLUSIONS:

10:00 (2hours) Is the present LIGO baffle design adequate? optimal?
What changes should be considered?
What further studies should be done before freezing the design?

12:00 Finish

SCATTERING CALCULATIONS:

1:30 Overview of the Calculations and Final Answers for the
(60min) Gravitational-Wave Noise h(f) from the Dominant Scattering Paths

LIGO --- Kip Thorne
VIRGO --- Jean-Yves Vinet
GEO --- Walter Winkler

Details of scattering calculations assuming Full Decoherence. Each scattering path will be discussed individually and fully before turning to the next one. Some or all of the following people to make presentations on each issue...

--- Bob Breault
--- Rai Weiss
--- Eanna Flanagan
--- Kip Thorne
--- Jean-Yves Vinet
--- Walter Winkler

2:30 Specular Reflection from One End of the Tube to the Other,
(30min) Evading All Baffles

3:00 Backscatter off Baffles
(30min)

3:30 Backscatter off Near Wall
(20min)

3:50 Backscatter off Objects at Far End of Vacuum System
(15min)

4:05 Diffraction Aided Reflection
(5min)

4:10 Diffraction off Baffles; Coherent Scattering Effects
(60min) and their Control; Mechanisms of Decoherence

5:10 Reflection off Baffle Edges
(5:15)

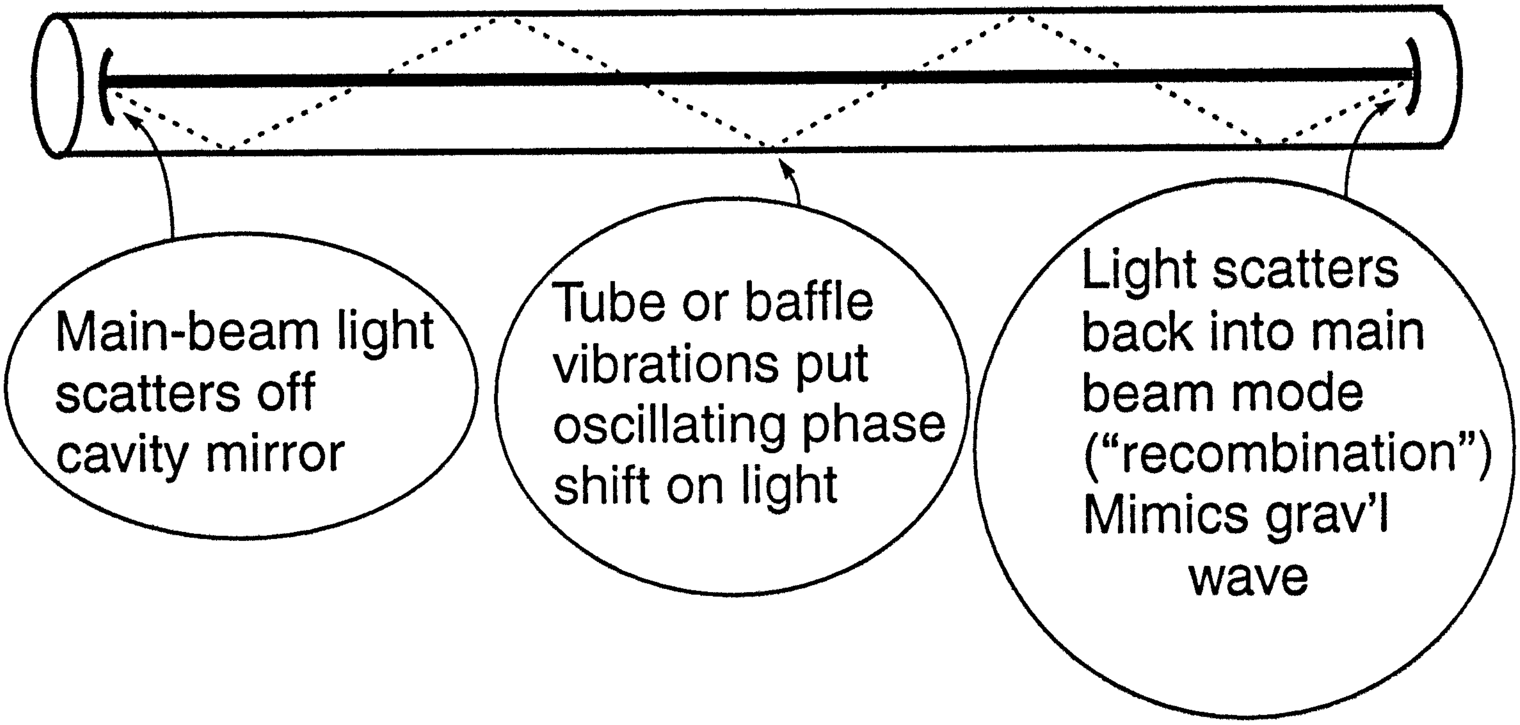
LIGO BAFFLE REVIEW

Caltech, 6 & 7 January 1995

OVERVIEW OF ISSUES

Kip Thorne

PHYSICAL ORIGIN OF SCATTERING NOISE



Main-beam light scatters off cavity mirror

Tube or baffle vibrations put oscillating phase shift on light

Light scatters back into main beam mode ("recombination") Mimics grav'l wave

- Differs from usual light-scattering noise by the essential role of the fluctuating phase shift

- DC scattered light is NOT a problem

AGENDA

Philosophy of organization

By issue, with short presentations by several people + discussion

Walk through;
changes since preliminary

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Indicated Times Are the Earliest Each Item is Likely to Occur;
up to 90 minutes of slippage are possible

Chair: Stan Whitcomb

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12:00 Finish

MY GUESS AT BOTTOM LINE OF MEETING

- We are not ready to freeze baffle design
- We will probably want to make a number of changes in the baffle design
- We need further measurements and further calculations based on those measurements, before finalizing the design changes

SOME SUGGESTIONS FOR BAFFLE CHANGES

1. Change design goal
   from "SQL for 1 ton test mass",
   to "0.1 SQL for 1 ton"
   = "0.03 SQL for 100kg"
2. Change baffle material
   from beam-tube steel ($dP/d\Omega = 0.01$)
   to Martin black or other material
   with $dP/d\Omega = 0.001$
3. Baffle the first 100 meters of beam tube (it is now bare)
4. Remove unneeded baffles from central regions of beam tube
5. Randomize the heights of baffle serration peaks and valleys by 0.5mm

LIGO BAFFLE REVIEW

Caltech, 6 & 7 January 1995

OVERVIEW OF SCATTERING NOISE CALCULATIONS, ANSWERS, AND IMPLICATIONS [LIGO]

Kip Thorne

HISTORY OF CALCULATIONS & METHODS
LIGO

- Kip, 88/89 -- Analytic:
  phase coherent paraxial optics;
  phase incoherent intensity analysis

- BRO + Weiss & Whitcomb, 91/92 --
  Monte Carlo ray propagation
  + phase noise

- Vinet found two serious errors in Kip's analytic analysis & correspondingly in phase noise part of BRO + WW, 93 & 94

- Eanna Flanagan & Kip, 94 --
  Analytic; complete reanalysis:
  phase coherent paraxial optics;
  phase incoherent intensity analysis

QUANTUM NOISE & BAFFLING GOAL

STANDARD QUANTUM LIMIT

$$\tilde{h}_{SQL} = \left(\frac{8\hbar}{\underset{\uparrow 1\,\text{ton}}{m}(2\pi f L)^2} \right)^{1/2} = \frac{4\times10^{-24}}{\sqrt{Hz}} \; \frac{10\,Hz}{f}$$

OLD GOAL:

Keep $\tilde{h}_{SCATT} < \tilde{h}_{\underset{1\,ton}{SQL}}$ @ $10\,Hz < f < 100\,Hz$

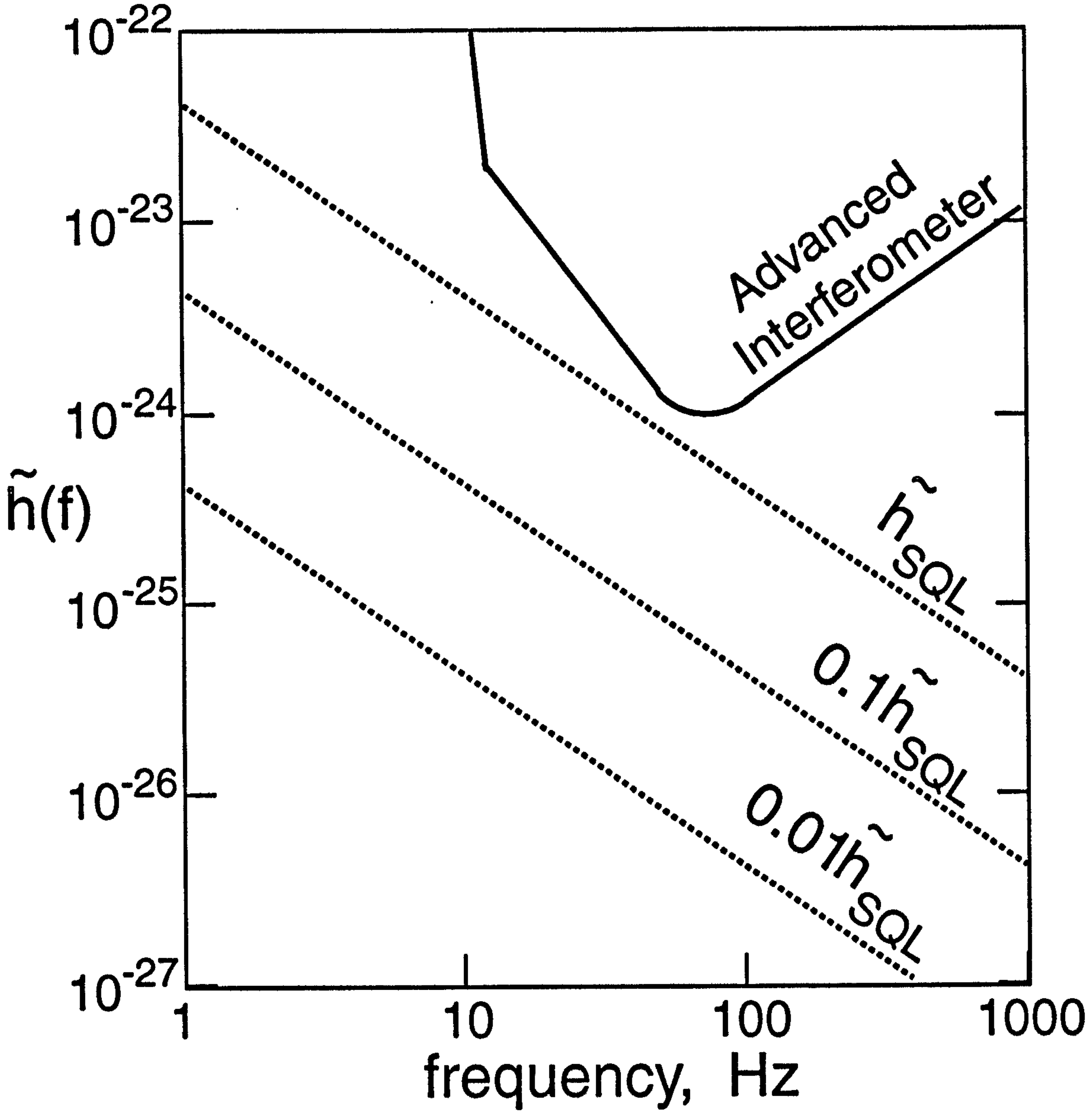
(keep best estimate below $0.1\,\tilde{h}_{SQL}$
.... factor 10 for uncertainties)

BUT:

10 to 30 years after LIGO begins operations, hope for say factor 10 of QND @ say $m = 100\,kg$ ⇒ detector noise @ $\tilde{h} = \frac{1}{3} \times \tilde{h}_{\underset{1\,ton}{SQL}}$

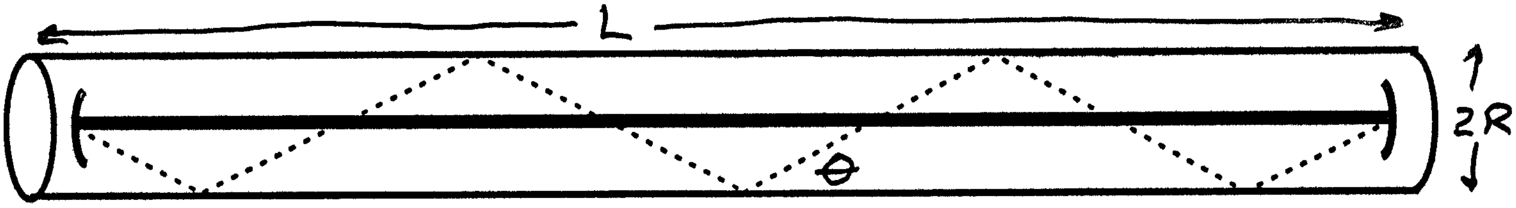
⇒ SUGGESTED NEW GOAL

$$\boxed{\text{Keep } \tilde{h}_{SCATT} < 0.1\,\tilde{h}_{\underset{1\,ton}{SQL}} \text{ @ } 10\,Hz < f < 100\,Hz}$$



10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
$\tilde{h}(f)$
1
10
100
1000
frequency, Hz
Advanced Interferometer
$\tilde{h}_{SQL}$
$0.1\tilde{h}_{SQL}$
$0.01\tilde{h}_{SQL}$

REFLECTION / FORWARD SCATTERING



Avoiding baffles

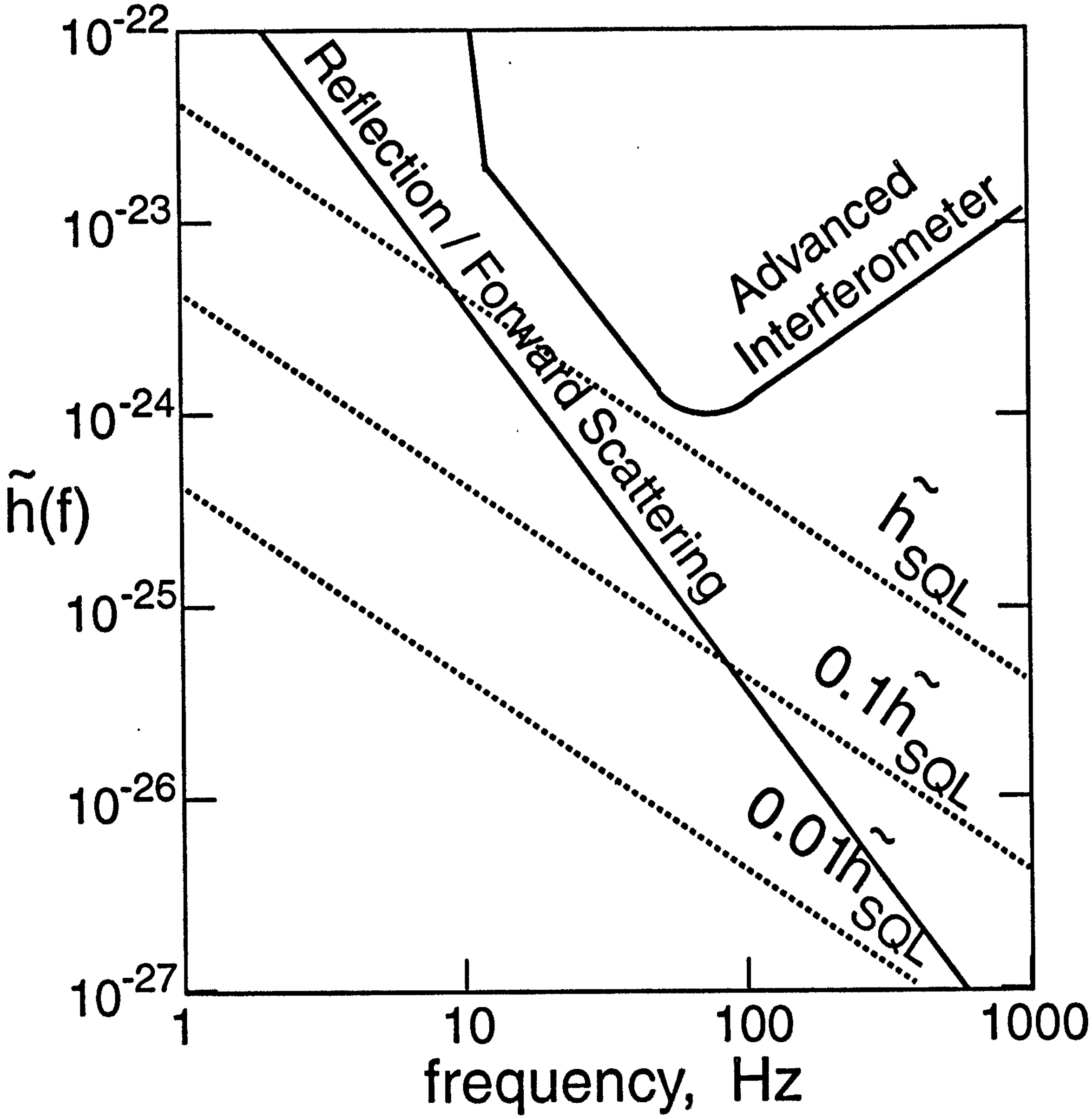
$$\tilde{h}_{refl} = \alpha \sqrt{2 \underset{\substack{\uparrow \\ \text{Attenuation}}}{\mathcal{R}(\theta)} \underset{\substack{\uparrow \\ \text{coherent} \\ \text{magnification} \\ \cdots 2\ ?}}{\mathcal{M}(\theta)}} \frac{\lambda}{\sqrt{LR}} \frac{\overset{\text{Beam tube transfer function}}{\bar{A}(f)}\, \tilde{\xi}_s(f)}{R} \sqrt{\Delta\theta}$$

$$= \overbrace{3.4\times10^{-24}}^{\simeq \tilde{h}_{SQL}} \left(\frac{10\,Hz}{f}\right)^2 \sqrt{\mathcal{R}(\theta)} \sqrt{\mathcal{M}(\theta)/2} \left(\frac{\Delta\theta}{0.01}\right)^{1/2} \times \frac{\tilde{\xi}_s}{10^{-7}(f/10\,Hz)^2}$$

ISSUES:

- Rai complete measurements of forward scattering
- Redo analysis of attenuation down pipe, and noise from this process, for various baffle configurations

Proposal: Baffle the presently bare 1st 100 m of wall after gate valve

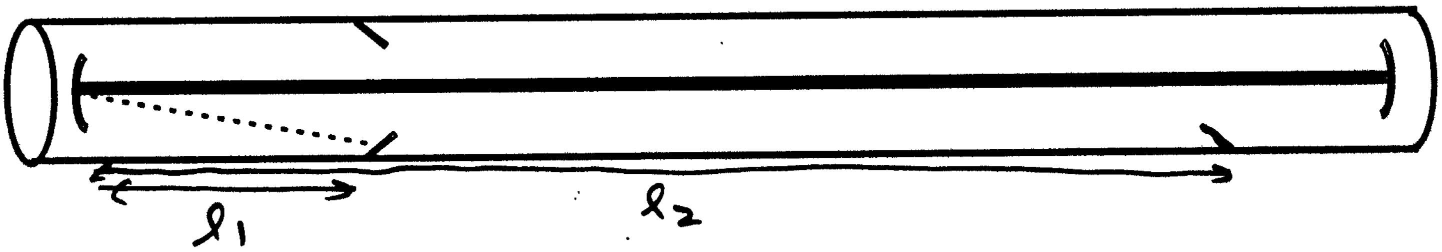


$\Delta\theta = 0.01 = 0.5°$

$\bar{A}(f) = 0$ No vibrational amplification of beam tube

$\mathcal{R}(\theta) = 0$ No attenuation down tube

BAFFLE BACKSCATTER



$$\tilde{h}_{bb} = \left[4\pi\alpha^2\beta \ln\left(\frac{l_1}{l_2}\right) J_0 \right]^{1/2} \bar{A}(f) \, \frac{\lambda}{R} \, \frac{\tilde{\xi}_s(f)}{L}$$

β ← baffle $dP/d\Omega$

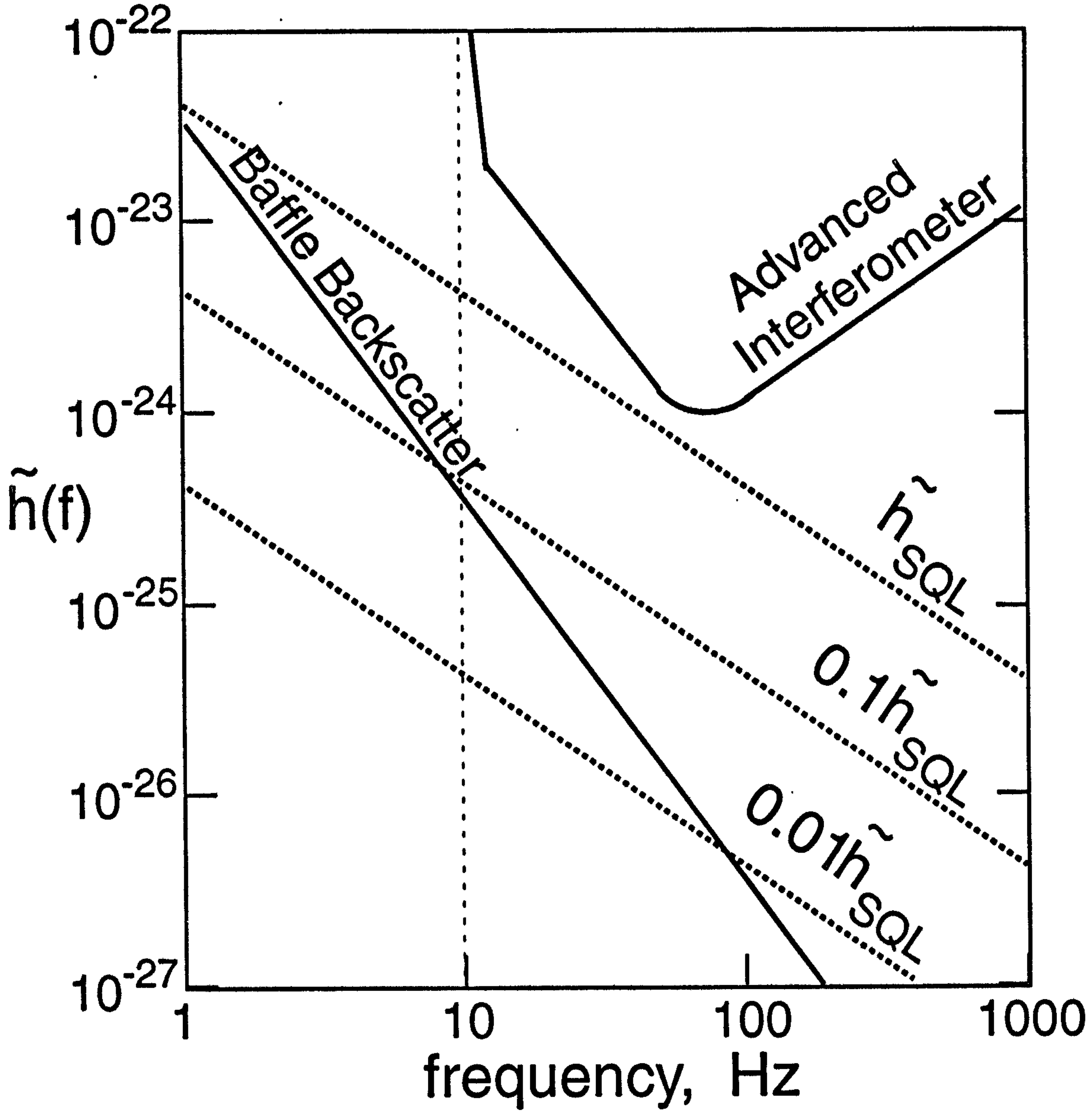
J_0 ← 1 for centered mirrors
4 for 20 cm from wall

$$= \frac{3\times10^{-25}}{\sqrt{Hz}} \left(\frac{10\,Hz}{f}\right)^2 \boxed{\left(\frac{\beta}{0.01}\right)^{1/2}} \sqrt{\frac{J_0}{4}} \sqrt{\frac{\ln(l_1/l_2)}{\ln(4km/120m)}}$$

$$\times \frac{\alpha}{10^{-6}} \, \bar{A}(f) \, \frac{\tilde{\xi}_s}{10^{-7}\,cm/\sqrt{Hz}\,(f/10\,Hz)^2}$$

J_0 ← Scales approx.

$$\propto \frac{1}{\left(\text{distance to wall}\right)}$$



$\beta = 0.01$ [Baffle BRDF]

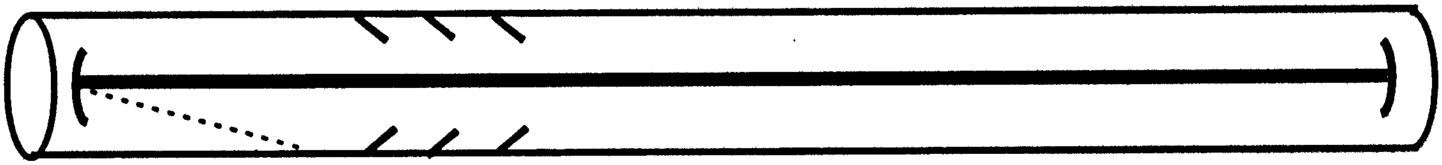
beam 20 cm from wall

NO vibrational amplification by tube, $\bar{A} = 1$

PROPOSAL:

Change baffle material to Martin Black or something else with $\beta = 10^{-3}$

NEAR-WALL BACKSCATTER

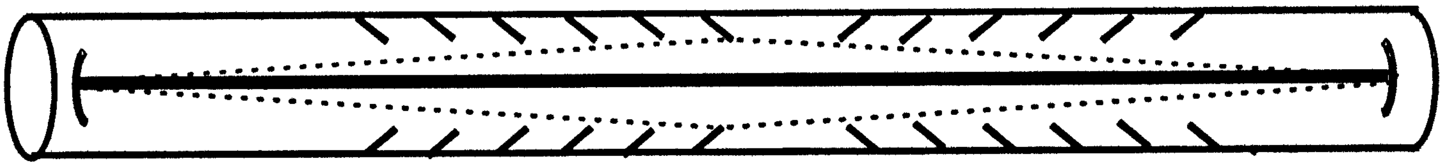


With same wall backscatter β as for baffles
(β =0.01; Rai's recent measurement),
noise from near wall is same as from baffles.
If change baffle material to β=0.001, then

Recommendation:
Baffle the near wall with material of β=0.001

(Recall: may want to baffle near wall anyway
to reduce reflection/forward scattering noise)

BAFFLE DIFFRACTION



- Coherence worries for centered mirrors:
  Eanna & Kip have done phase coherent, paraxial optics calculation

- For unserrated, perfectly round baffles, circularly symmetric baffle vibrations, circularly symmetric mirrors centered in beam tube [extreme phase coherence]

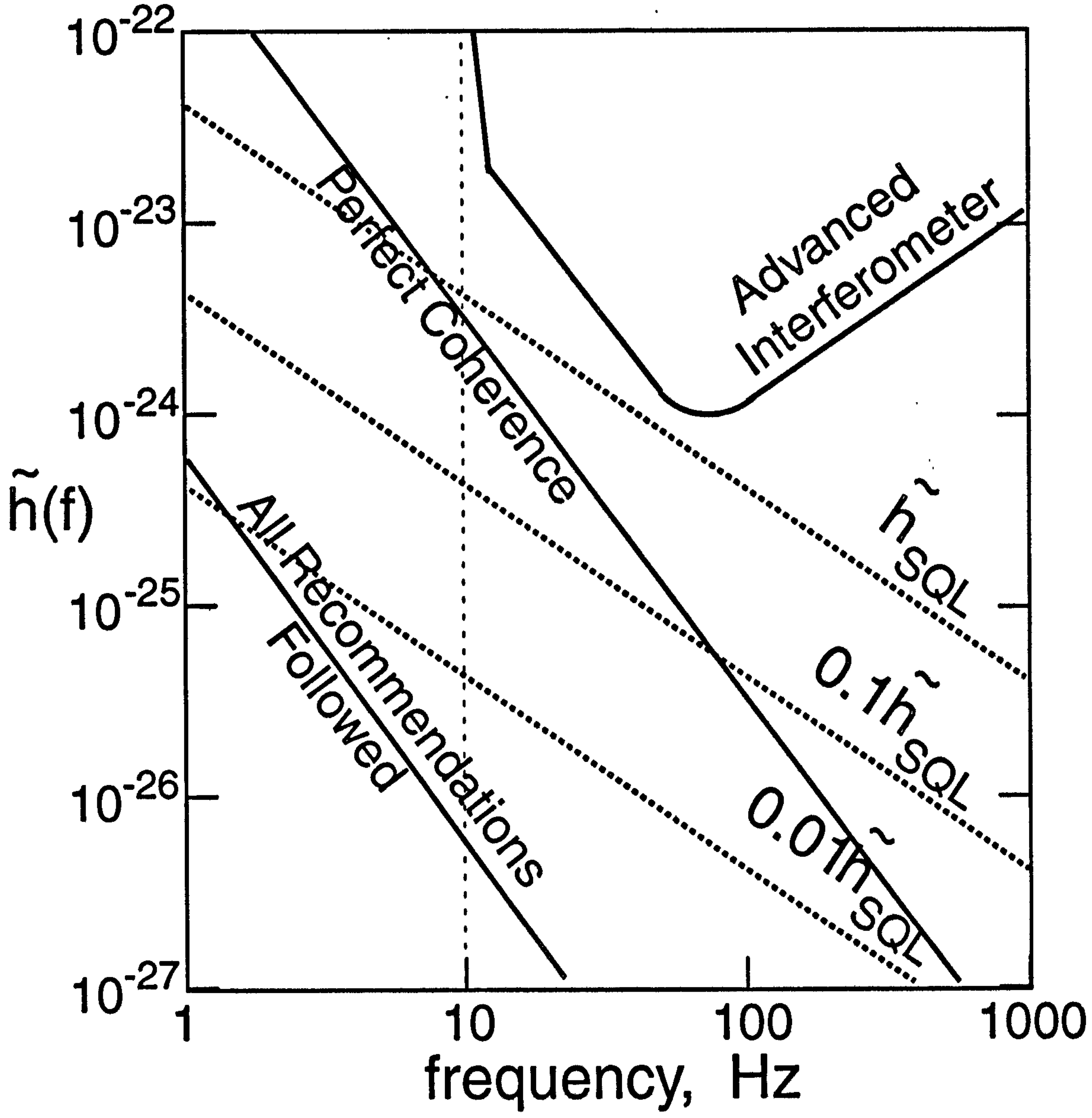
$$\tilde{h} = \frac{\alpha \lambda \bar{A}(f) \tilde{\xi}_s(f)}{L R} \sqrt{N_B}$$

↖ number of baffles

$$= \frac{3.1 \times 10^{-24}\ \mathrm{Hz}^{-1/2}}{(f/10\,\mathrm{Hz})^2} \left(\frac{N_B}{220}\right)^{1/2} \bar{A} \; \frac{\tilde{\xi}_s}{10^{-7}\,\mathrm{cm}/\sqrt{\mathrm{Hz}}\ (f/10\,\mathrm{Hz})^2}$$

- To reduce noise:
  Remove unnecessary baffles [recommendation]
  Serrate baffles [already planned]
  Randomize heights of serration peaks and valleys by 0.5mm (breaks coherence!) [recommendation]

BAFFLE DIFFRACTION
Centered Baffles



$\bar{A}(f) = 1$ [no amplification by beam tube vibrations]

BAFFLE DIFFRACTION
Very Off-Center Baffles

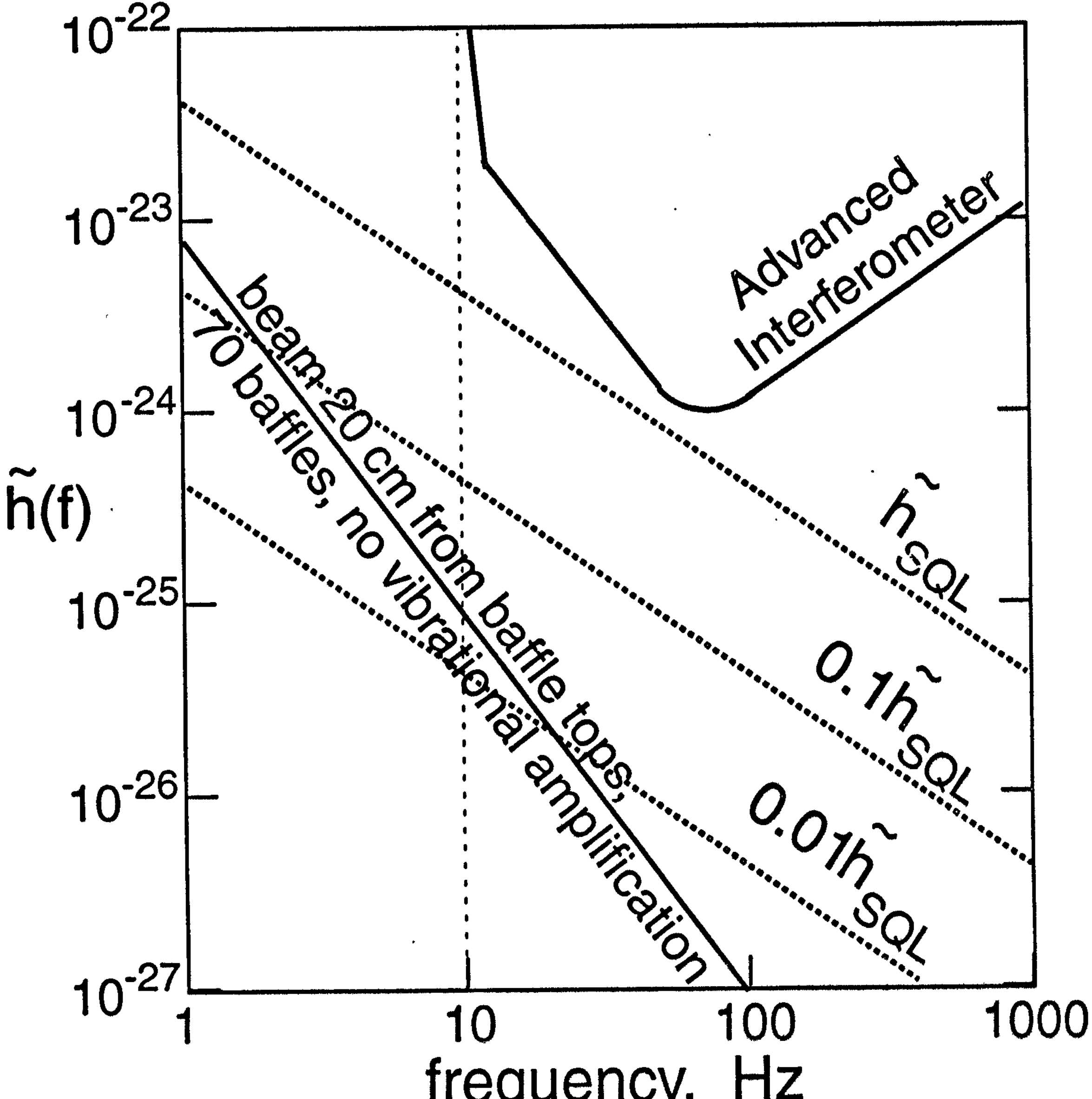
- Baffles serrations neither help nor hurt the noise; Fresnel zone pattern at baffle automatically destroys coherence

$$\tilde{h} = \frac{\alpha}{\sqrt{3}}\,\frac{\sqrt{2L}}{4\pi R}\,\frac{2\bar{A}\,\tilde{\xi}_s}{LR}\,\sqrt{2N_B}\,\frac{R^2}{y_0^2}$$

Distance to baffle tops

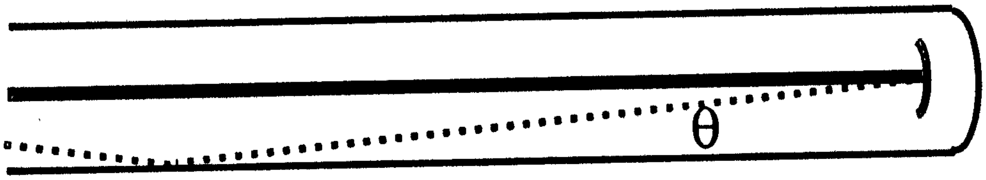
$$= \frac{1\times10^{-25}\ \mathrm{Hz}^{-1/2}}{(f/10\,\mathrm{Hz})^2}\left(\frac{N_B}{70}\right)^{1/2}\left(\frac{20\,\mathrm{cm}}{y_0}\right)^2\frac{\tilde{\xi}_s\ \ \bar{A}}{10^{-7}\,\mathrm{cm}/\sqrt{\mathrm{Hz}}\,(f/10)^2}$$

↑ Get rid of 2/3 of baffles

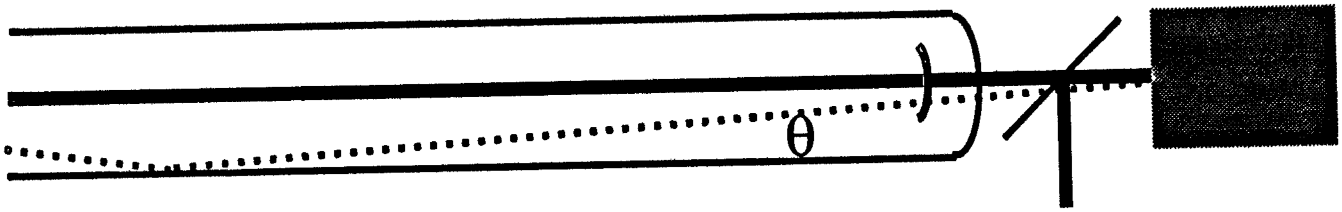


PHOTODIODE RECOMBINATION

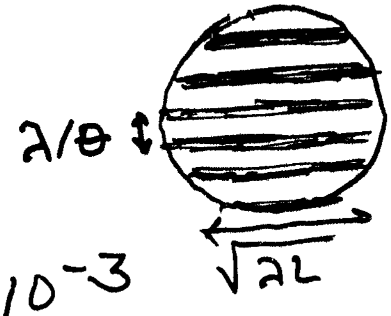
CAVITY RECOMBINATION



PHOTODIODE RECOMBINATION



$$\sigma_{CAVITY} = \lambda^2 \overset{\frac{dP}{d\Omega}}{\boxed{\frac{\alpha}{\theta^2}}}$$



$$\sigma_{P.D.} = \frac{\lambda L}{B^2} \, \frac{\sqrt{\lambda/L}}{\theta} \left[\overset{\sim 10^{-3}}{\eta_{rms}} (\nu = \underbrace{\theta/\lambda}_{\frac{10}{cm} \text{ to } \frac{300}{cm}}) \right]^2$$

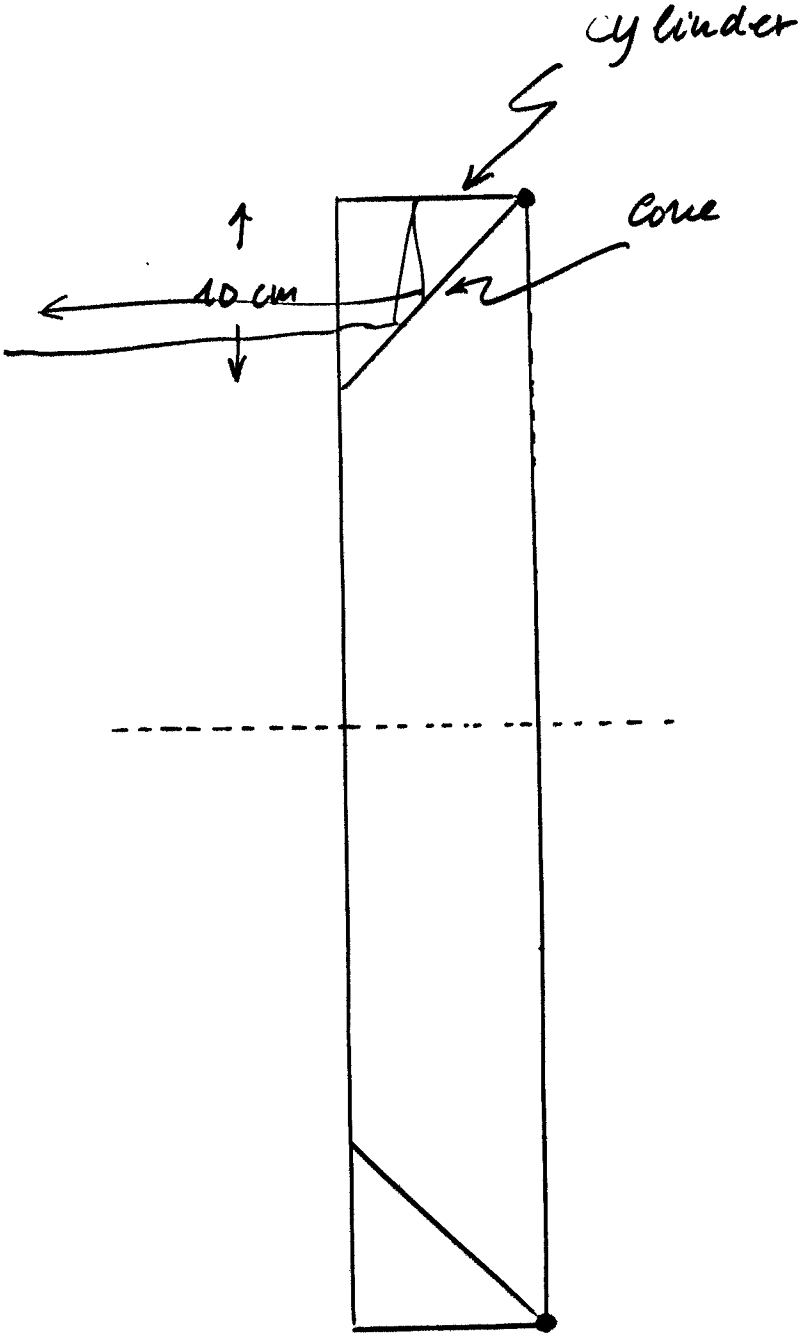
$$\frac{\sigma_{P.D.}}{\sigma_{CAVITY}} = \frac{\sqrt{L/\lambda}}{\alpha B^2} \theta (\eta_{rms})^2 \sim 10^{-3} \frac{\theta/10^{-3}}{(B/100)^2}$$

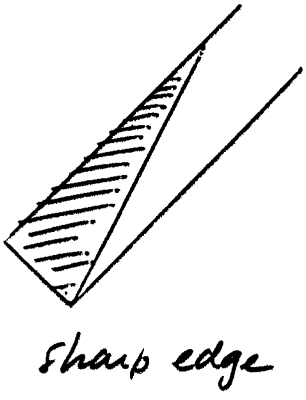
[If P.D. recombination <u>were</u> important, remove with output mode cleaner

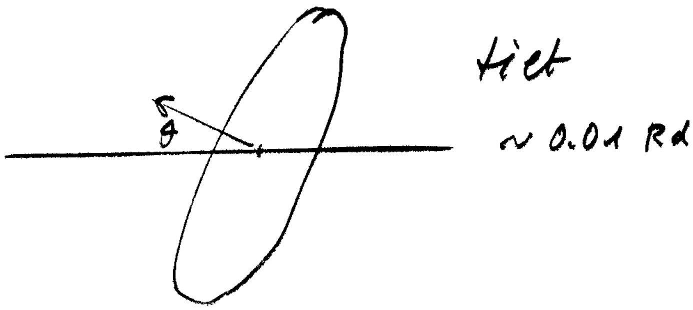
VIRGO BAFFES & TUBE

- JEAN-YVES VINET

Structure in two pieces







2') Baffles design

The baffles are traps. They must have
- * a low reflection rate
- * a low scattering rate

Solution presently under study : main ideas

- baffles made out of glass plates
  → low diffusion, comparable to mirrors

- very low transmission through the glass by using a dark type
  either ATHERMAL (Schott-Desag-Germany)
  or PROTAN (Corning-Sicover-France)

  $T \leq 10^{-7}$

- low intrinsic reflection coefficient by antireflective coating $\sim 5 10^{-3}$ at 45°
  10^{-3} normal incidence

  → "cheap" coating deposited by bath

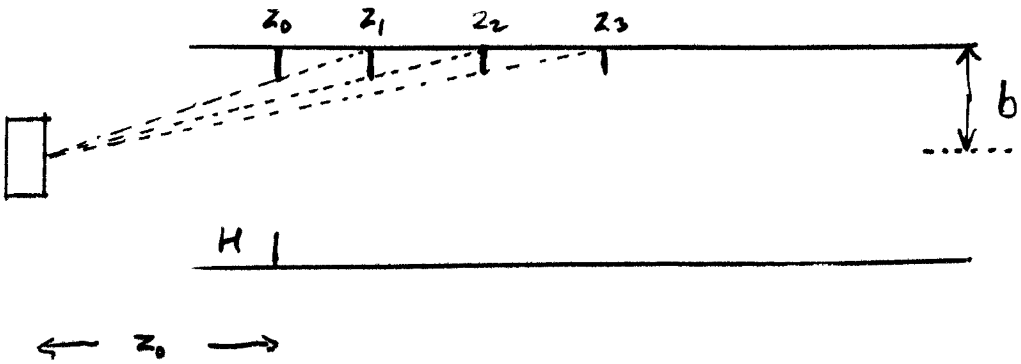
- trap structure to enhance absorption by multiple reflections

- Avoid effects due to coherence of the field directly reflected by the edges to the emitting mirror
  - machining to get sharp edges ~ 100μm

Baffles Design

1°) General principle : Baffles locations

Hide the tube to mirror by covering the whole solid angle by <u>traps</u>



Once chosen $\left\{\begin{array}{l}\text{the Height } H\\ \text{the 1st baffle abscissa } z_0\end{array}\right.$

we have $z_n = z_0 \left[\frac{1}{1-H/b}\right]^{n-1} = z_0\, p^{n-1}$

$b = 0.6$

$H = 0.1$ for having a 1 m free ϕ

$z_0 = 6\,m$

1st family until the middle of the pipe

2d family : symmetrical / middle

The ratio will be chosen smaller than $\frac{1}{1-H/b}$ to make the shadows overlapping

1.15 instead of 1.2 ⇒ ~ 80 baffles/arm

Schedule

- Tests will be completed at the end of January 95
- Edition of 2 Final Design reports for the "Tube Technical Advisory Group" TTAG
- TTAG gives recommendations and advice concerning
  - * costs
  - * security
  - * France Italy equilibrium
  - * technology
  - * reliability

→ March 95

- The Management Staff decides : April 95

VIRGO tube design
present status

Tests in progress for 2 types of tube

1) Straight tube with stiffener rings
1.20 m diameter   5 mm thick

50 m Prototype at Pisa

outgasing ~ $3 \cdot 10^{-12}$ [mbar ℓ cm^{-2} s^{-1}]
with regular 304L stainless steel
$\leq 10^{-14}$
with 400° baked in air complete tube

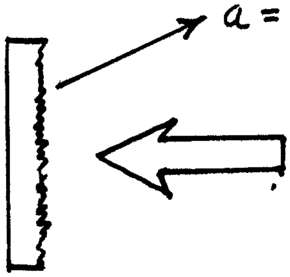
2) Corrugated tube
90 mm wavelength
25 mm peak to peak

1.20 m diameter   2 mm thick

4 x 7.50 m modules at Orsay

outgasing
$3 \cdot 10^{-12}$ regular 304L ss
$8 \cdot 10^{-14}$ with 950°C
baked in vacuum plates

Scattering off a mirror



$$a = e^{ipx} e^{iqy}$$

$$A = \sqrt{P}\, \varphi_{00}(x,y) = \sqrt{P} \sqrt{\frac{2}{\pi W^2}}\, e^{-\frac{x^2+y^2}{W^2}}$$

Rough surface : $R(x,y) = e^{2ikf(x,y)}$

$f(x,y)$: Stochastic process
$$\begin{cases} \langle f \rangle = 0 \\ \langle f^2 \rangle = \sigma^2 \\ \langle f(x+\xi, y+\eta) \cdot f(x,y) \rangle = C(\xi,\eta) \cdot \sigma^2 \end{cases}$$

1) Coupling between the gaussian beam and any plane wave:

$$|\langle A, a \rangle|^2 = P\, |\tilde{\varphi}_{00}|^2 (p,q) = P \cdot 2\pi W^2 e^{-2\theta^2/\theta_g^2}$$

$$\theta_g = \lambda/\pi W_0$$

maximum coupling

$$|\langle A, a \rangle|^2_{max} = P\, 2\pi W^2$$

2) Coupling between the gaussian beam reflected by the mirror and the plane wave

$$|\langle RA, a \rangle|^2 = P\,(1 - 4k^2\sigma^2)\, |\tilde{\varphi}_{00}|^2 (p,q)$$

$$+ P \cdot \boxed{4k^2\sigma^2}\, \frac{1}{4\pi^2} \int dp'dq' |\tilde{\varphi}_{00}|^2 (p',q')\, \tilde{C}(p-p', q-q')$$

ε losses

spectral density of the beam

spectral density of the surface

If $\theta \gg \theta_g$ $\quad |\langle RA, a \rangle|^2 \simeq \varepsilon P\, \tilde{C}(p,q)$

3) Integrated scattered power

$$\frac{1}{4\pi^2}\int |\langle RA, a\rangle|^2 \, dp\, dq = \varepsilon P = P_{sc} \qquad \left[\frac{1}{4\pi^2}\int dp\,dq\, \tilde{C}(p,q) = C(0,0) = 1 \right]$$

$$\Rightarrow \quad \frac{1}{4\pi^2} |\langle RA, a\rangle|^2 = \frac{dP_{sc}}{dp\,dq}$$

with $dp\,dq = k^2 \sin\theta \, d\theta \, d\varphi$

$$|\langle RA, a\rangle|^2 = \lambda^2 \frac{dP_{sc}}{d\Omega}$$ differential cross-section

4) Efficiency of coupling with a direction (p,q):

$$r(\theta,\varphi) = \frac{|\langle RA, a\rangle|^2}{|\langle A, a\rangle|^2} = \frac{\pi}{2}\,\varepsilon\,\theta_g^2 \; \frac{1}{P_{sc}} \frac{dP_{sc}}{d\Omega}$$

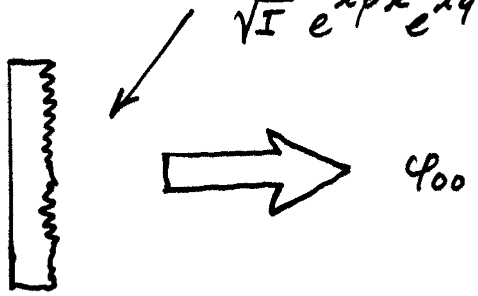
If (isotropy) $\frac{1}{P_{sc}}\frac{dP_{sc}}{d\Omega} = \frac{1}{2\pi} p(\theta)$

$$\boxed{r(\theta) = \frac{1}{4}\,\varepsilon\,\theta_g^2 \, p(\theta)}$$

Recombination process on a mirror

$$\sqrt{I}\, e^{ipx} e^{iqy} = A$$

$$\begin{cases} p = k \sin\theta \cos\varphi \\ q = k \sin\theta \sin\varphi \end{cases}$$



Rough surface $f(x,y)$ $\qquad R(x,y) = e^{2ikf(x,y)}$

1) Direct coupling

$$|\langle A, \varphi_{00} \rangle|^2 = I \left| \tilde{\varphi}_{00}(p,q) \right|^2 = 2\pi w^2 I\, e^{-2\theta^2/\theta_g^2}$$

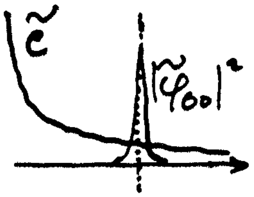
when $p = q = 0$: $|\langle A, \varphi_{00} \rangle|^2_{max} = 2\pi w^2 I$

2) Coupling via the surface

$$|\langle RA, \varphi_{00} \rangle|^2 = (1 - 4k^2\sigma^2) I\, |\tilde{\varphi}_{00}|^2 (p,q)$$

$$+ 4k^2\sigma^2 I\, \frac{1}{4\pi^2} \int dp'\, dq'\, |\tilde{\varphi}_{00}|^2 (p',q')\, \tilde{C}(p-p', q-q')$$

for $\theta \gg \theta_g$



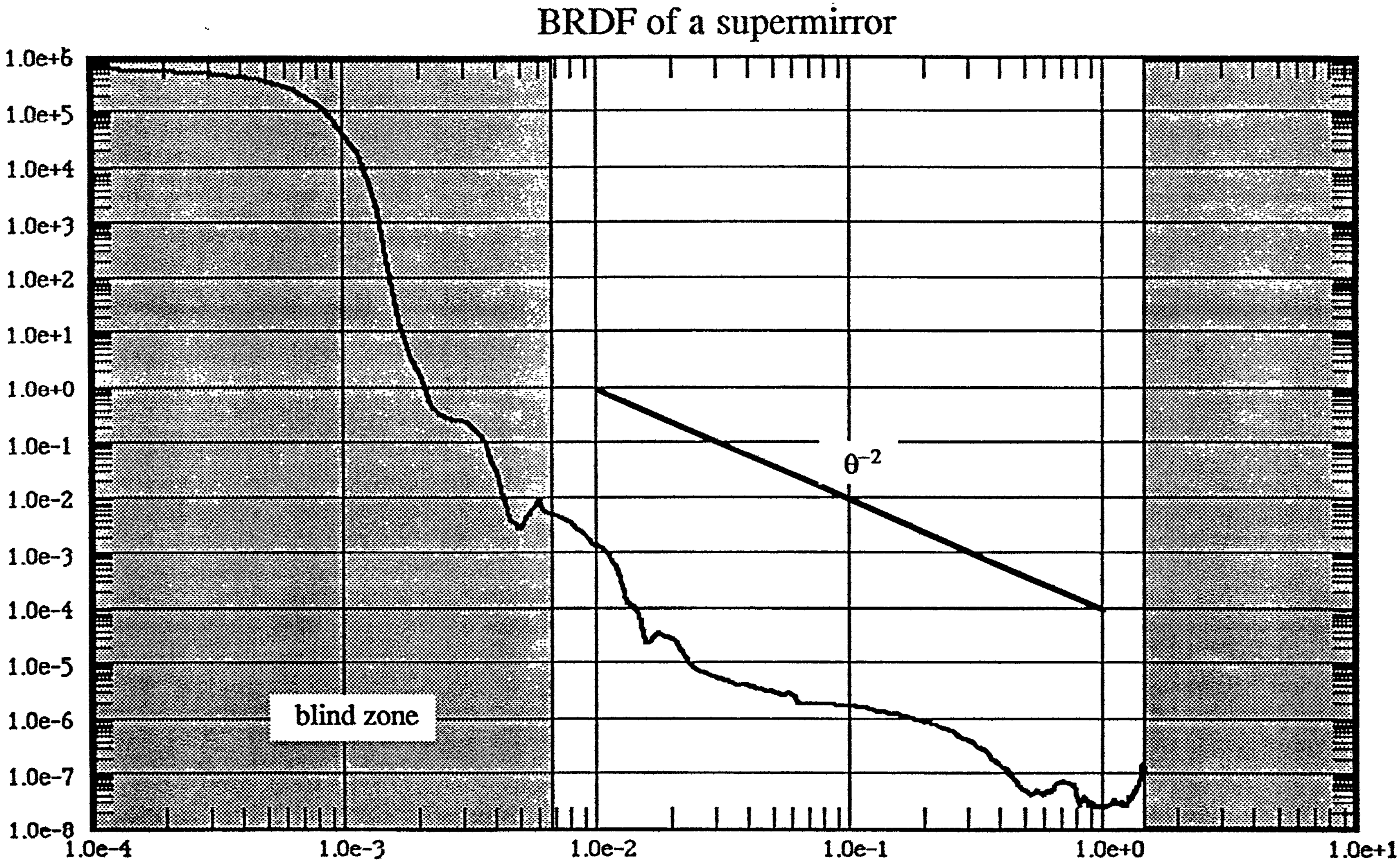
$$|\langle RA, \varphi_{00} \rangle|^2 \simeq \varepsilon I\, \tilde{C}(p,q)$$

$$\simeq \varepsilon I \lambda^2 \frac{1}{P_{sc}} \frac{dP_{sc}}{d\Omega}$$

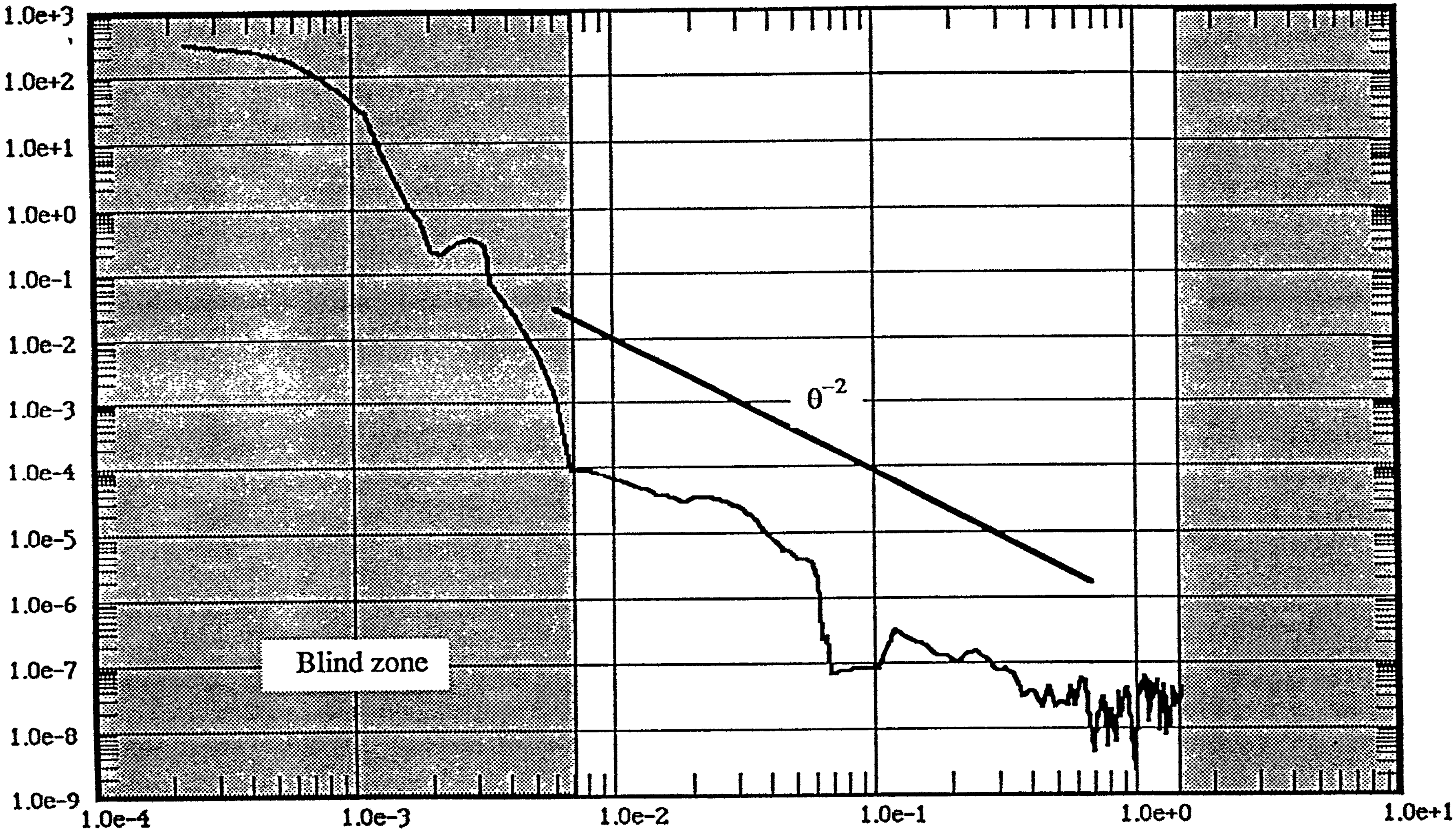
3) Recombination efficiency

$$r(\theta,\varphi) = \frac{|\langle RA, \varphi_{00} \rangle|^2}{|\langle A, \varphi_{00} \rangle|^2} = \frac{\pi}{2} \varepsilon\, \theta_g^2\, \frac{1}{P_{sc}} \frac{dP_{sc}}{d\Omega}$$

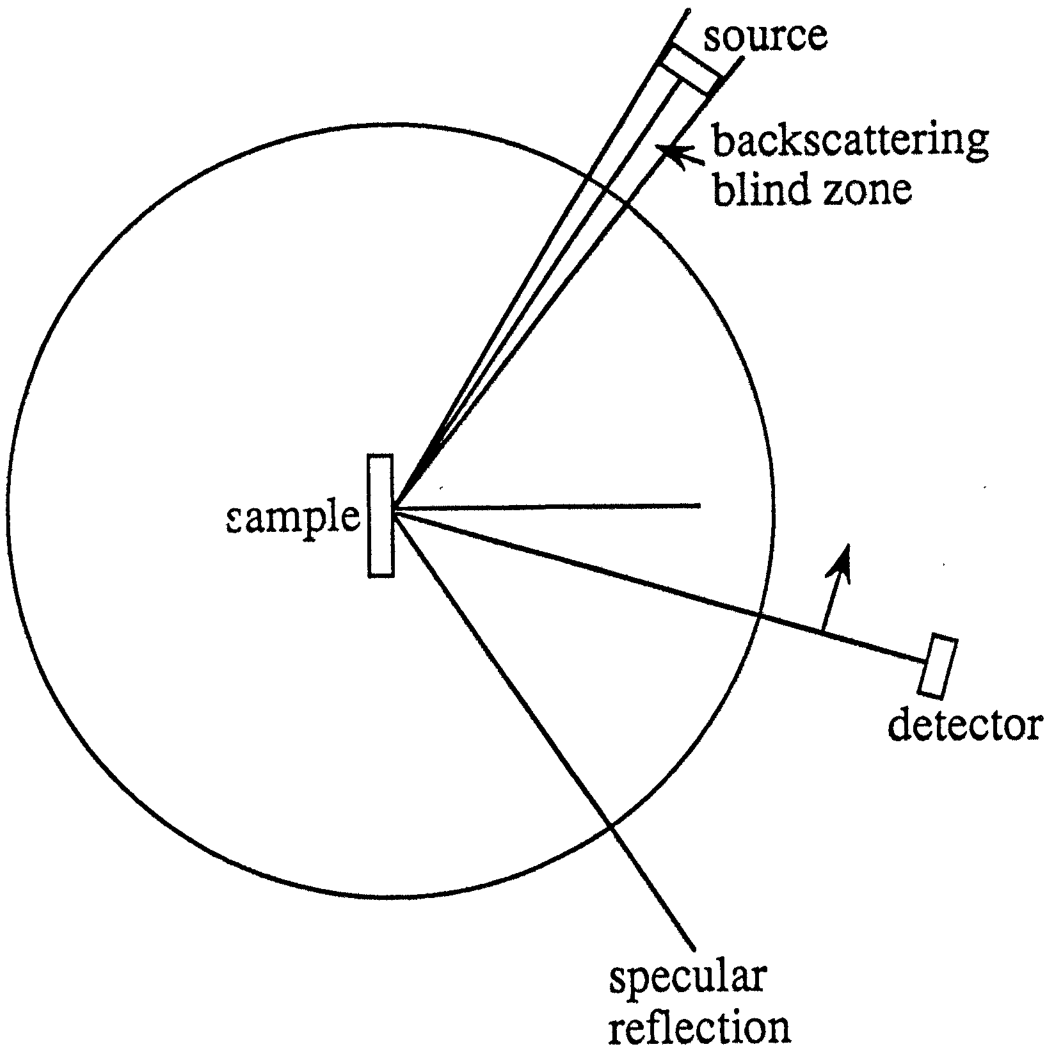
Isotropic : $\boxed{r(\theta) = \frac{1}{4} \varepsilon\, \theta_g^2\; p(\theta)}$

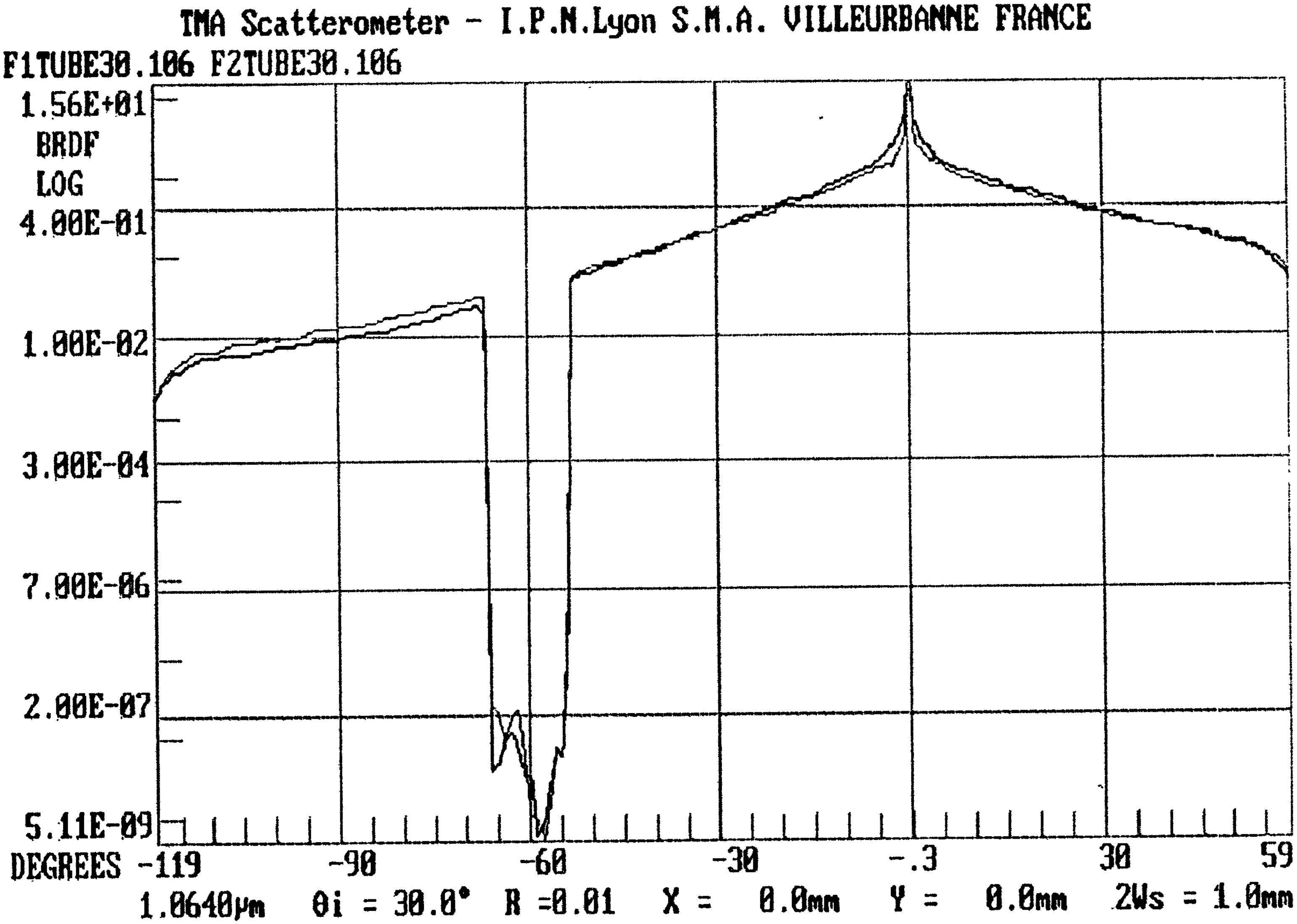

BRDF of a supermirror
1.0e+6
1.0e+5
1.0e+4
1.0e+3
1.0e+2
1.0e+1
1.0e+0
1.0e-1
1.0e-2
1.0e-3
1.0e-4
1.0e-5
1.0e-6
1.0e-7
1.0e-8
1.0e-4
1.0e-3
1.0e-2
1.0e-1
1.0e+0
1.0e+1
θ^-2
blind zone

BRDF of a PMS substrate

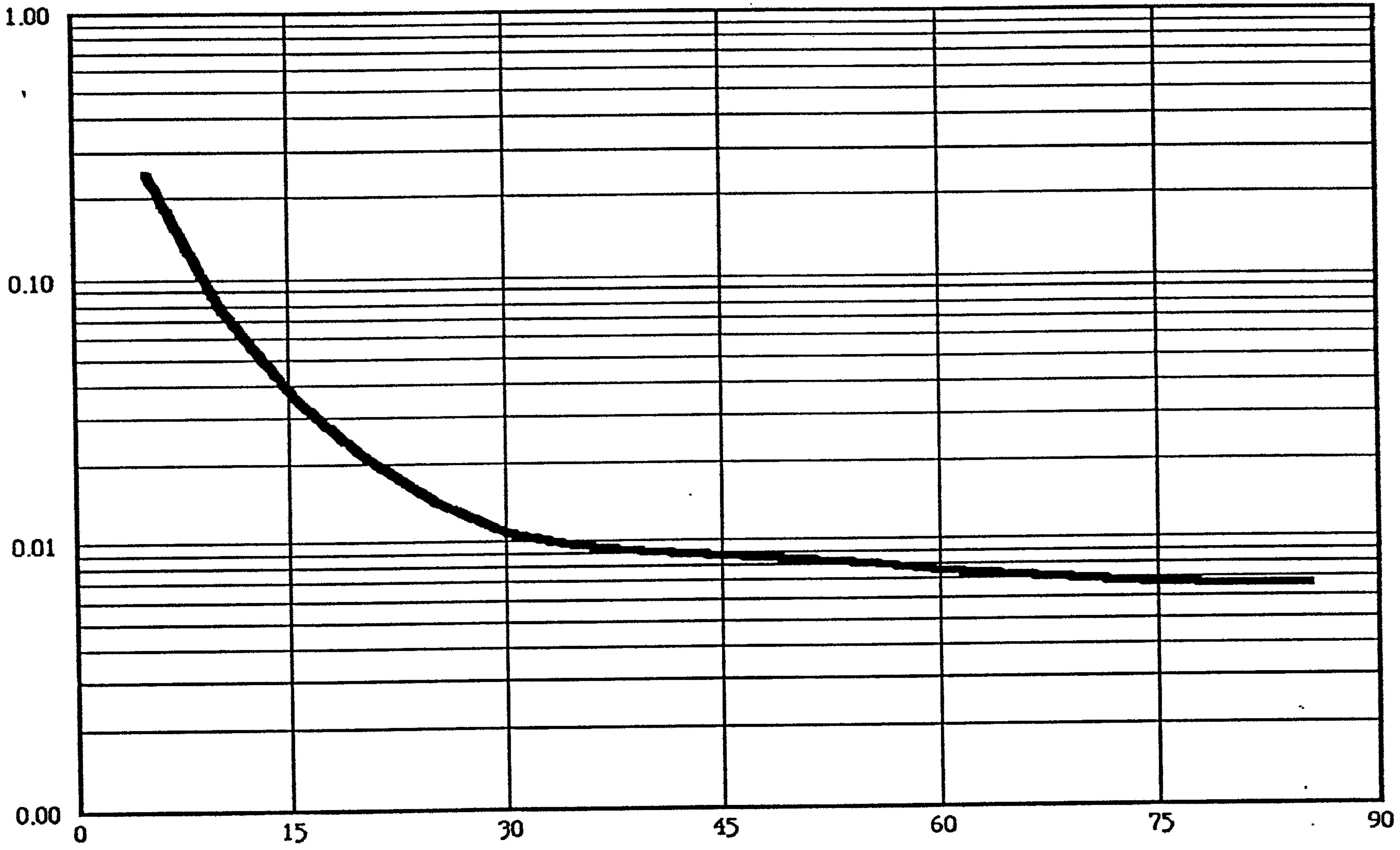


SCATTEROMETER

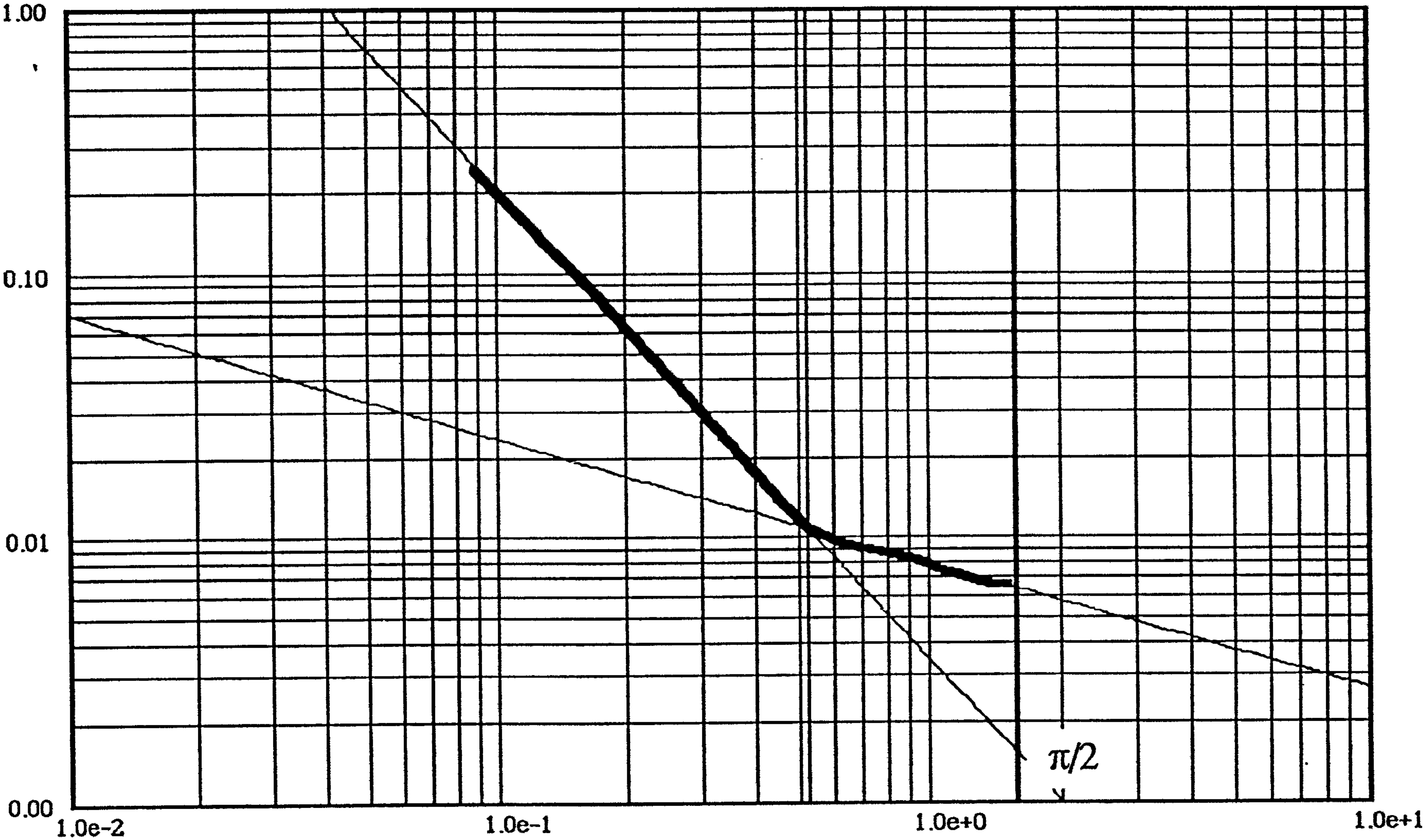


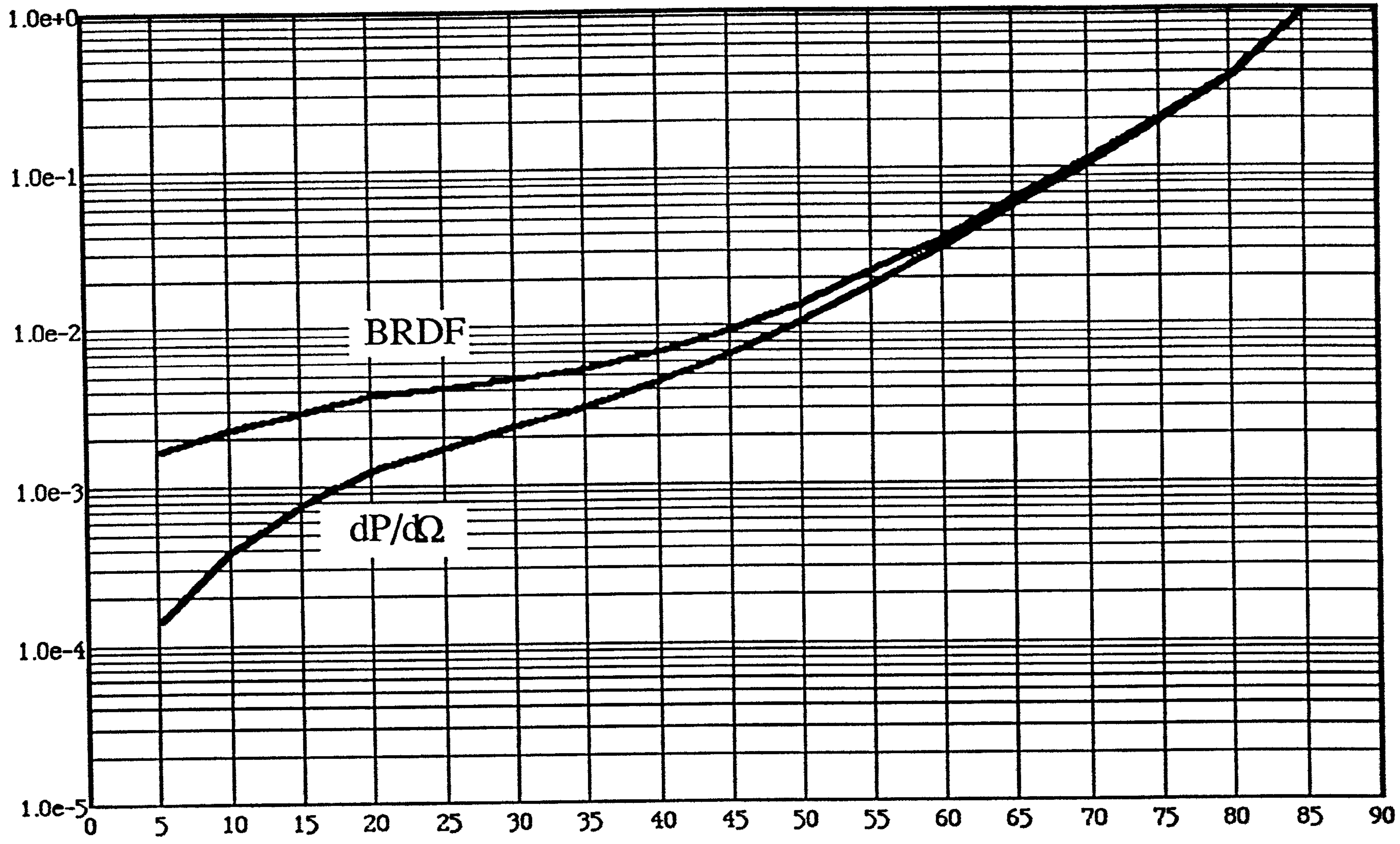

TMA Scatterometer - I.P.N.Lyon S.M.A. VILLEURBANNE FRANCE
F1TUBE30.106 F2TUBE30.106
1.56E+01
BRDF
LOG
4.00E-01
1.00E-02
3.00E-04
7.00E-06
2.00E-07
5.11E-09
DEGREES -119
-90
-60
-30
-.3
30
59
1.0640µm θi = 30.0° R =0.01 X = 0.0mm Y = 0.0mm 2Ws = 1.0mm

Reflectivity of a 304 L Stainless steel sample



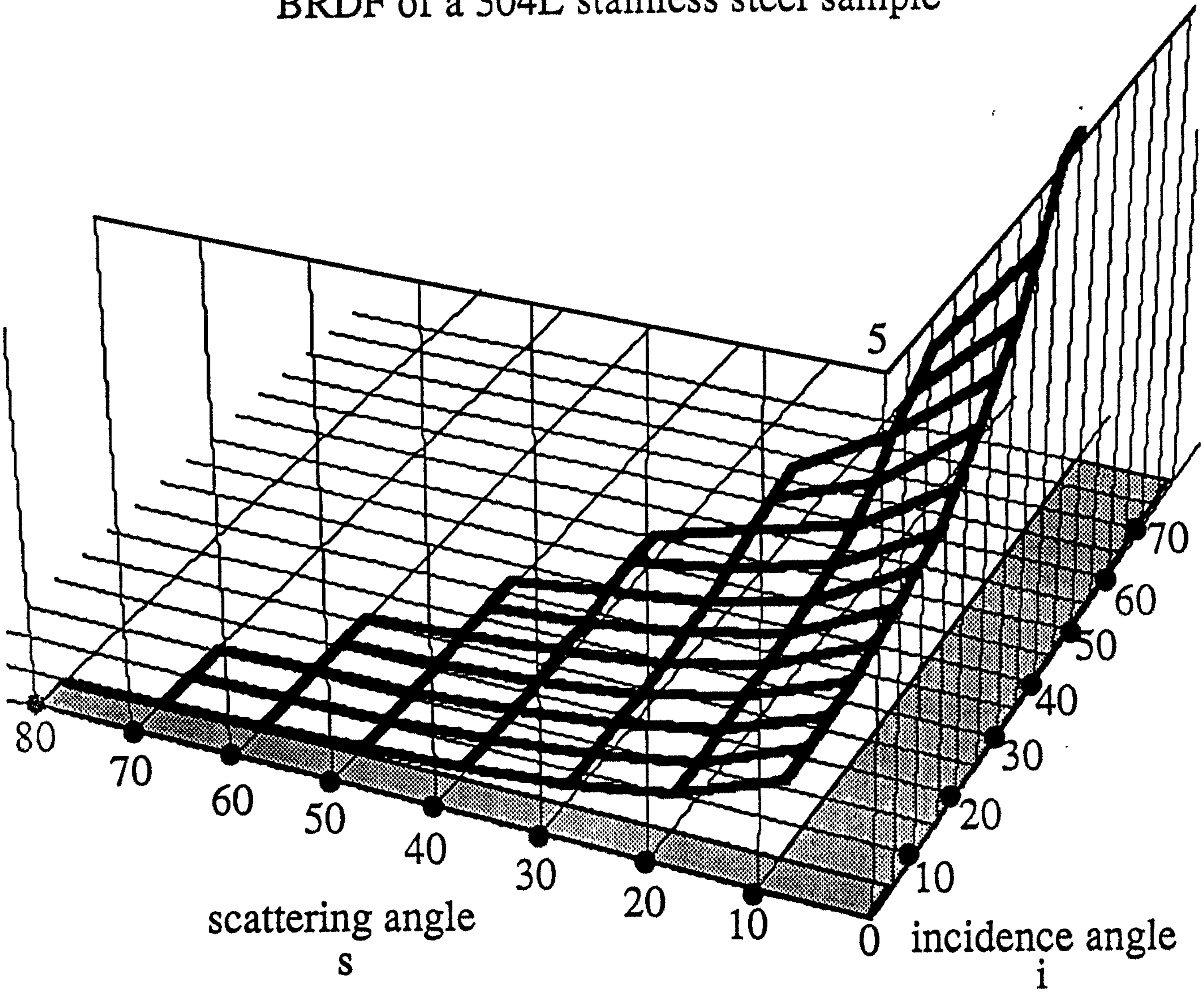
Reflectivity of a 304L stainless steel sample

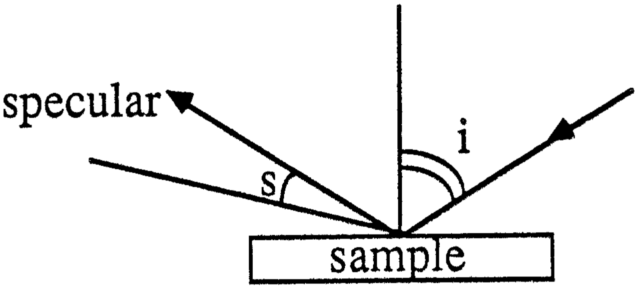




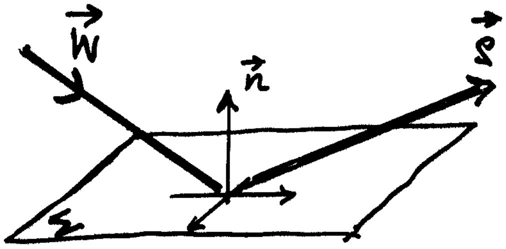
Backscattering from a 304L stainless steel sample

BRDF of a 304L stainless steel sample





Modulation by moving surfaces



Coupling of two waves by interaction with a material surface

Surface of equation $\quad z = f(x,y)$

Displacement : $\quad \vec{X}(t) = [\,\xi(t),\, \eta(t),\, \zeta(t)\,]$

New equation:
$$\begin{cases} x' = x + \xi \\ y' = y + \eta \\ z' = z + \zeta \end{cases} \qquad z = \zeta + f(x-\xi,\, y-\eta)$$

Coupling coefficient between
$$\begin{cases} A = e^{ik\vec{w}\cdot\vec{r}} \\ B = e^{ik\vec{s}\cdot\vec{r}} \end{cases}$$

$\int$ over the surface:
$$\langle A,B\rangle = \int dx\,dy\, e^{-ik(W_1-S_1)x}\, e^{-ik(W_2-S_2)y}\, e^{-ik(W_3-S_3)[\zeta + f(x-\xi,\, y-\eta)]}$$

Change the coordinates
$$\langle A,B\rangle = e^{-ik(\vec{W}-\vec{S})\cdot\vec{X}} \langle A,B\rangle_0$$

where $\quad \langle A,B\rangle_0 = \int dx\,dy\, e^{-ik(W_1-S_1)x}\, e^{-ik(W_2-S_2)y}\, e^{-ik(W_3-S_3)f(x,y)}$

⇨ phase modulation $\qquad \phi(t) \equiv (\vec{W}-\vec{S})\cdot\vec{X}(t)$

Spectral density $\qquad \vec{X}(f) = \vec{e}\ X(f)$

⇒ Spectral density of phase noise

$$\phi(f) = e \ X(f)$$

$$e = (\vec{w} - \vec{s}) \cdot \vec{e}$$

Special cases

1) Specular reflection $\vec{s} = \vec{w} - 2(\vec{w} \cdot \vec{n})\vec{n}$

$$\Rightarrow \quad e = 2(\vec{w} \cdot \vec{n})(\vec{n} \cdot \vec{e})$$

$$\underline{e = 2 \cos \theta_{inc} \ e_n}$$

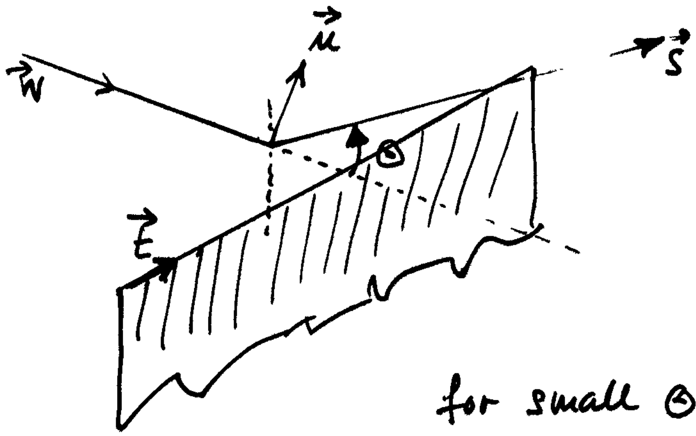
2) Scattering $\underline{e = (\vec{w} - \vec{s}) \cdot \vec{e}}$

3) Backscattering $\vec{s} = -\vec{w}$

$$\underline{e = 2 \vec{w} \cdot \vec{e}} = 2 e_{\parallel}$$

4) Diffraction by an edge

$$\vec{u} = \vec{w} \times \vec{t}$$



$$\vec{s} = \cos\Theta \ \vec{w} + \sin\Theta \ \vec{u}$$

$$e = (1 - \cos\Theta) \vec{w} \cdot \vec{e} - \sin\Theta \ \vec{u} \cdot \vec{e}$$

for small Θ

$$\underline{e \simeq \Theta \ e_{\perp}}$$

{ Central part of the interferometer
{ Instrumentation chambers

* Analytical calculations are difficult (no simple shape, no symmetry)

→ This is the main point for the efficiency of a Monte Carlo code

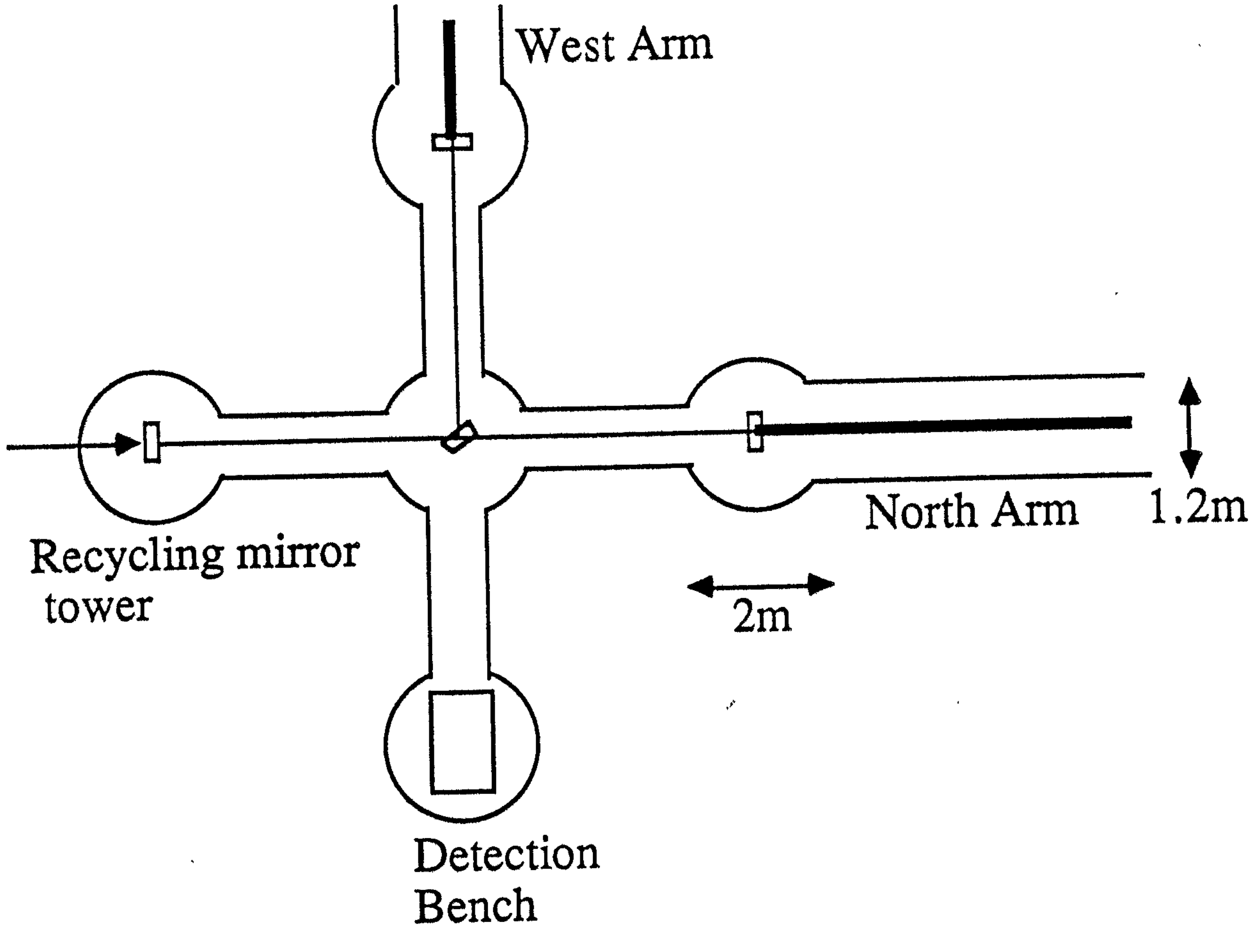
→ Must include a realistic model of scattering by walls

* Light scattered by mirrors is less dangerous than inside the cavities

- Factor of $1/F$
- wider angles ⇔ smaller recombination efficiency
- no recombination on the recycling mirror nor on 1 face of the splitter

* Spurious reflections inside the splitter are worrying. We have to develop special traps

VIRGO Central Area



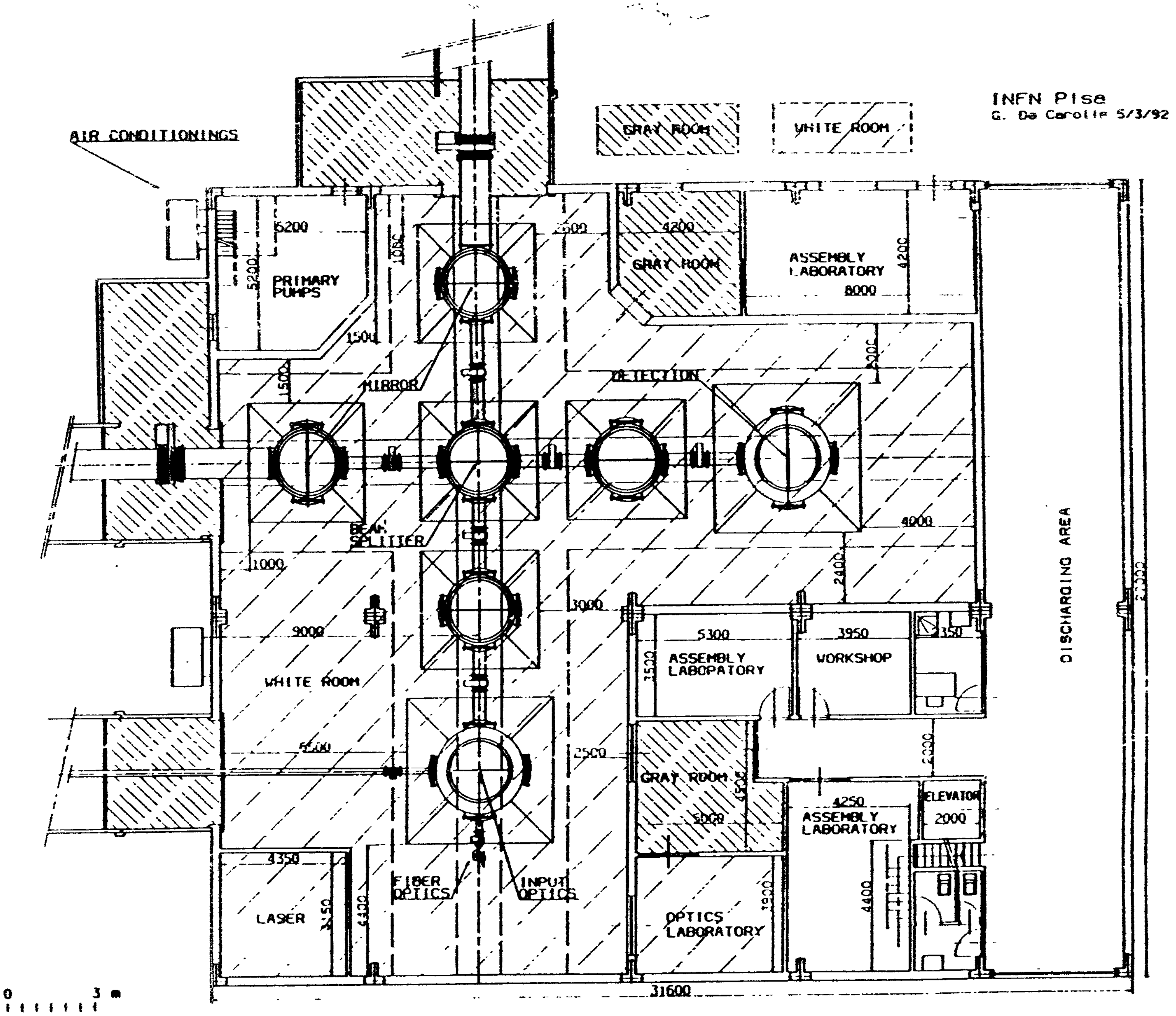

AIR CONDITIONINGS
GRAY ROOM
WHITE ROOM
INFN Pise
G. Da Carolis 5/3/92
5200
5200
PRIMARY PUMPS
1050
1500
1500
MIRROR
2500
4200
GRAY ROOM
ASSEMBLY LABORATORY
8000
4200
4200
DETECTION
BEAM SPLITTER
1000
4000
2400
3000
9000
WHITE ROOM
5300
ASSEMBLY LABORATORY
1530
3950
WORKSHOP
1350
DISCHARGING AREA
23000
6500
2500
GRAY ROOM
4500
5000
2300
4250
ASSEMBLY LABORATORY
ELEVATOR
2000
4350
LASER
3150
4400
FIBER OPTICS
INPUT OPTICS
OPTICS LABORATORY
1900
4400
31600
0
3 m

Fig. 5a

Present status of our effort in scattered light calculations
(VIRGO)

Background : • We study at Orsay the baffle system (V. Brisson)

• We develop at Pisa A. Monte Carlo code (S. Braccini) for evaluation of the noise especially in the central part (Instrumentation Chambers)

Three specific domains of work

Coding
1) develop and upgrade the code
- description of a complex structure
- realistic models for reflection - scattering by stainless steel
- correct summation of modulation effects

general principles
2) Study of the link between the particle picture and the wave picture

3) Analytical calculations

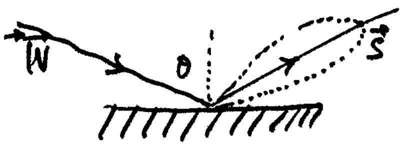
Present understanding of general principles

1) Photon (particle) picture

1.1 emission

use of the BRDF as a probability distribution

1.2 Interaction with walls or baffles



1) rate of
- absorption
- specular reflection
- scattering

versus θ

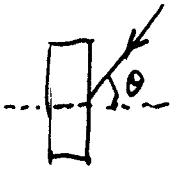
2) BRDF of the material

local modulation : $(\vec{W}-\vec{S})\cdot\vec{e} = \delta$

update of previous modulation status

$$\Delta^2 = \Delta^2 + \delta^2$$

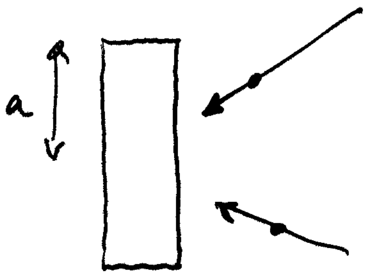
1.3 Recombination at a mirror



summation of all arriving photons

- weighted by their recombination probability $r(\theta) = \frac{1}{4}\theta_g^2\ p(\theta)$
- weighted by their global modulation rate Δ^2

need some theory



incoming flux of M photons/s on a surface of area $S = \pi a^2$

→ Each photon is associated to a plane wave of amplitude $A = 1/\sqrt{\pi a^2}$

k_{th} photon: $$A\, e^{i \sin\theta_k \cos\varphi_k x + i \sin\theta_k \sin\varphi_k y} \cdot e^{i\phi_k}$$

where ϕ_k: random d.c. part + modulation

Amplitude generated by the recombination process in the TEM_{00} mode:

$$\delta W = \sqrt{2\pi w^2} \sum_{k=1}^{M} A \underbrace{\sqrt{r(\theta_k)}}_{\text{recombination efficiency}} e^{i\phi_k}$$

Amplitude of the main beam

$W_0 = \sqrt{P}$ P: stored power (10kW)

Phase change: $$\delta\phi = \mathrm{Im}\left[\frac{\delta W}{W_0}\right]$$

$$= \frac{A\sqrt{2\pi w^2}}{\sqrt{P_0}} \sum_{k=1}^{M} \sqrt{r(\theta_k)} \sin\phi_k$$

Variance: $$\langle\delta\phi^2\rangle = \frac{1}{N} \frac{w^2}{2a^2}\, \varepsilon\, \theta_g^2 \sum_{k=1}^{M} p(\theta_k)\, n_k^2$$

$N \equiv$ number of photons/unit of time in the main beam

$n_k^2 \equiv \langle \sin^2\phi_k \rangle$

Introduce M_S: number of scattered photons

$$\langle\delta\phi^2\rangle = \frac{1}{\ } \frac{M_S}{\ } \left(\frac{\lambda}{\ }\right)^2 \varepsilon\, \frac{1}{\ } \sum^{n} p(\theta_k)\, n^2$$

with $h(f) = \frac{\lambda}{4\pi L}\phi(f)$

$$h^2(f) = \frac{1}{32\pi^4}\,\varepsilon^2\left(\frac{\lambda}{L}\right)^2\left(\frac{\lambda}{a}\right)^2\frac{1}{m_S}\sum_k p(\theta_k)\,\eta_k^2(f)$$

Evaluation of $\eta_k(f)$

$$\sin\phi_k = \sin\Big[\underset{\substack{\uparrow\\ \text{dc random}}}{\phi_{0k}} + \sum_{i=1}^{\nu_k} e_{ik}\,\varphi_{ik}\Big]$$

cumulated modulation

ν_k : number of interactions with vibrating objects

- Case of small cumulated modulation

$$\eta_k^2(f) = \langle \sin^2\phi_k \rangle = \frac{1}{2}\sum_{i=1}^{\nu_k} e_{ik}^2\,\varphi_{ik}^2(f)$$

$$= \frac{1}{2}\,\varphi^2(f)\cdot\sum_{i=1}^{\nu_k} e_{ik}^2$$

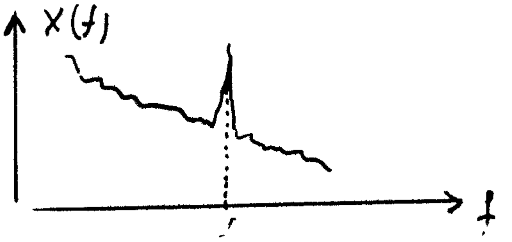
$$\varphi^2(f) = \frac{2\pi X(f)}{\lambda}$$

$X(f)$: spectral density of displacement of the wall

$$X(f) \simeq \frac{\delta}{f^2} \qquad \delta = 10^{-6}\ \text{m Hz}^{3/2}$$

$$\boxed{h(f) = \frac{\varepsilon}{4\pi}\,\frac{\delta}{f^2}\,\frac{\lambda}{La}\sqrt{\frac{1}{m_S}\sum_{k=1}^{m} p(\theta_k)\,e_{ik}^2}}$$

- Case of large cumulated modulation



$$\sin \phi_k \sim \sin\left(\phi_{0k} + \sin 2\pi f_0 t \sqrt{\sum e_{ik}^2} \cdot \frac{2\pi x_0}{\lambda}\right)$$

$$\sim \sum_p J_p \left[\underbrace{\frac{2\pi x_0}{\lambda} \sqrt{\sum e_{ik}^2}}_{z} \right] e^{ip \cdot 2\pi f_0 t + \alpha_p}$$

$J_p(z)$ negligible for $p > |z|$ →

$$\begin{cases} n_k^2(f) \lesssim \dfrac{1}{\left[\dfrac{2\pi x_0}{\lambda} \left(\sum e_{ik}^2\right)^{\frac{1}{2}}\right]^2 f_0} & \text{for } 0 \leq f \leq f_0 \\[2ex] = 0 & \text{for } f \geqslant f_0 \end{cases}$$

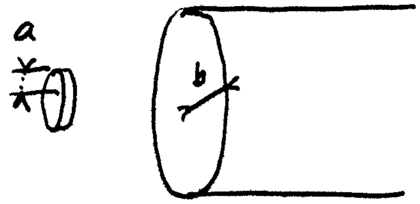
2/ Comparison with Kip's formulas

Example of backscattering

$$h^2(f) = \frac{1}{32\pi^4} \varepsilon^2 \left(\frac{\lambda}{L}\frac{\lambda}{a}\right)^2 \frac{1}{n_S} \sum_{k=1}^{n} p(\theta_k)\eta_k^2(f)$$

for a distributed source

$$\sum p(\theta_k)\eta_k^2(f) \equiv \overbrace{\int \underbrace{n_S\, p(\theta)\,\theta\, d\theta}_{\text{photons reaching the element of backscatt. source}} \cdot \underbrace{p_{BS}(\theta)\frac{\pi a^2}{d^2}}_{\text{returning to the mirror}} \; p(\theta)\,\eta_k^2(\theta)}^{\updownarrow}$$



$$= n_S \frac{\pi a^2}{b^2} \int p(\theta)^2\, P_{BS}(\theta)\, \eta^2(\theta)\, \theta^3 d\theta \qquad \left(\frac{b^2}{d^2} \equiv \theta^2\right)$$

$$\Rightarrow h^2(f) = \frac{1}{32\pi^3} \varepsilon^2 \left(\frac{\lambda}{L}\right)^2 \left(\frac{\lambda}{b}\right)^2 \int p(\theta)^2 P_{BS}(\theta)\, \eta^2(\theta)\, \theta^3 d\theta$$

$$= \frac{\pi}{2}\left(\frac{\lambda}{4\pi L}\right)^2\left(\frac{\lambda}{b}\right)^2 \int \Big[\underbrace{\frac{\varepsilon}{2\pi}\, p(\theta)}_{\frac{dP}{d\Omega}}\Big]^2 P_{BS}(\theta)\, \eta^2(f,\theta)\, \theta^3 d\theta$$

$$= \frac{1}{16}\left(\frac{\lambda}{4\pi L}\right)^2\left(\frac{\lambda}{b}\right)^2 \int \left[\frac{dP(\theta)}{d\Omega}\right]^2 P_{BS}(\theta)\, \eta^2(f,\theta)\, 8\pi\theta^3 d\theta$$

For 2 mirrors, a factor of 1/8 with respect to Kip?

GEO BAFFLES

WALTER WINKLER

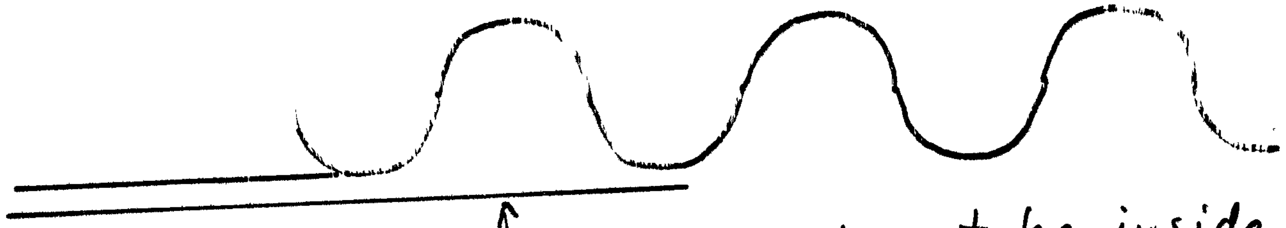
Backscatter from baffles

$$\sigma^2 = \underset{\substack{\uparrow \\ \text{input} \\ \downarrow}}{f(\vartheta_1)} \underbrace{\frac{2\pi r H}{\Delta l^2}}_{d\Omega} \underset{\substack{\uparrow \\ \text{baffle}}}{f(\vartheta)} \frac{\pi w^2}{(\Delta l)^2} f'(\vartheta_1) \frac{\pi w^2}{l^2}$$

$$= f(\vartheta_1) \underset{\substack{\uparrow \\ \gtrsim 10^{-6}}}{f'(\vartheta_1)} \underset{\substack{\uparrow \\ 10^{-2}}}{f(\vartheta)} \; 2 \cdot 10^{-16} \left[\frac{r}{0.3} \frac{H}{3 \cdot 10^{-2}} \left(\frac{w}{2 \cdot 10^{-2}}\right)^4 \underset{\uparrow}{\left(\frac{6}{\Delta l}\right)^4} \left(\frac{600}{l}\right)^2 \right]$$

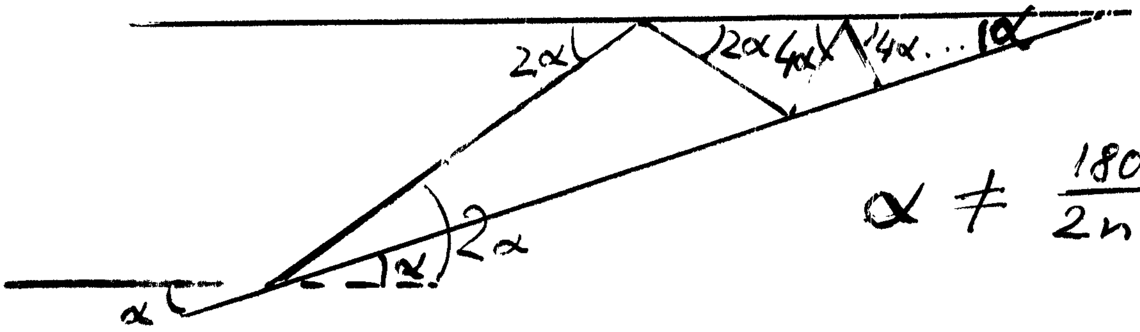
Distance to first baffle: large

Straight tube at the end (near mirrors)

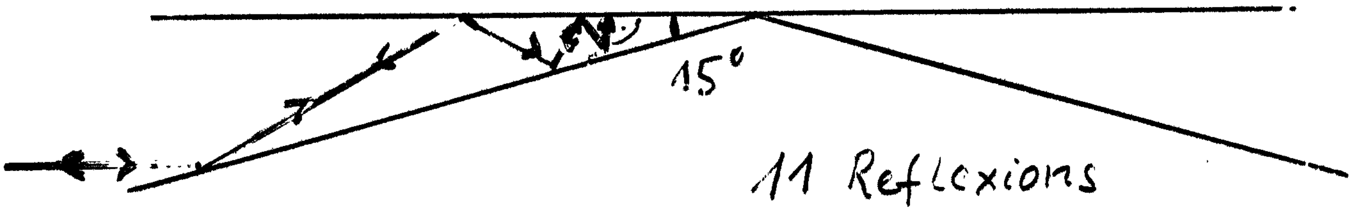


↑ may be: extra tube inside, ~2 … 3 m long, smooth, low scattering

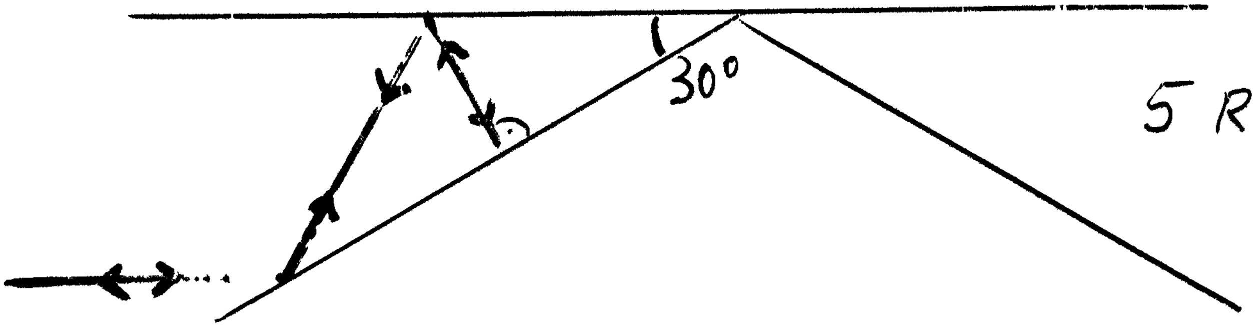
Baffles



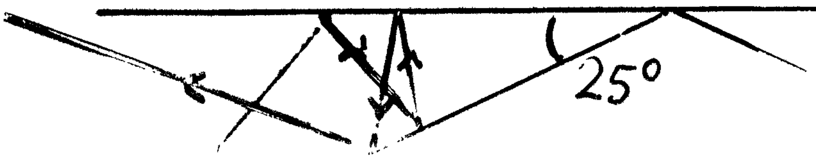
$$\alpha \neq \frac{180°}{2n}$$



11 Reflexions



5 Reflexions



5 Reflexions

GE0600 13
3.12.94

Baffles

For Reflex: baffles act like a mirror: tilt of input beam tilts "reflected" beam in opposite direction, by the **Same** angle, if number of reflections odd.

For even number of reflections: tilt by same angle in same direction.

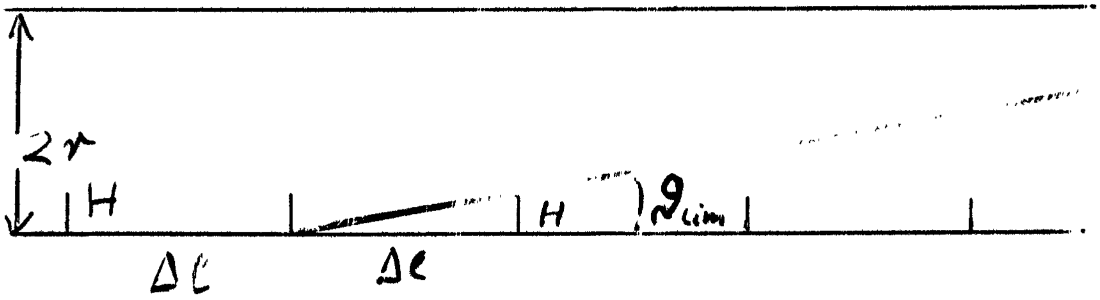
1) Aquadag

2) Anodizing

3) SiO_2 / Inconel layers

⑩

Baffles



How far can one see the tube?

$$\vartheta_{lim} = \frac{H}{\Delta l} = \frac{2r}{D} \curvearrowright D = 2r\,\frac{\Delta l}{H}$$

↷ H big, Δl small (many and high baffles)

H = 3 cm: reduces 60 cm ∅ → 54 cm ∅

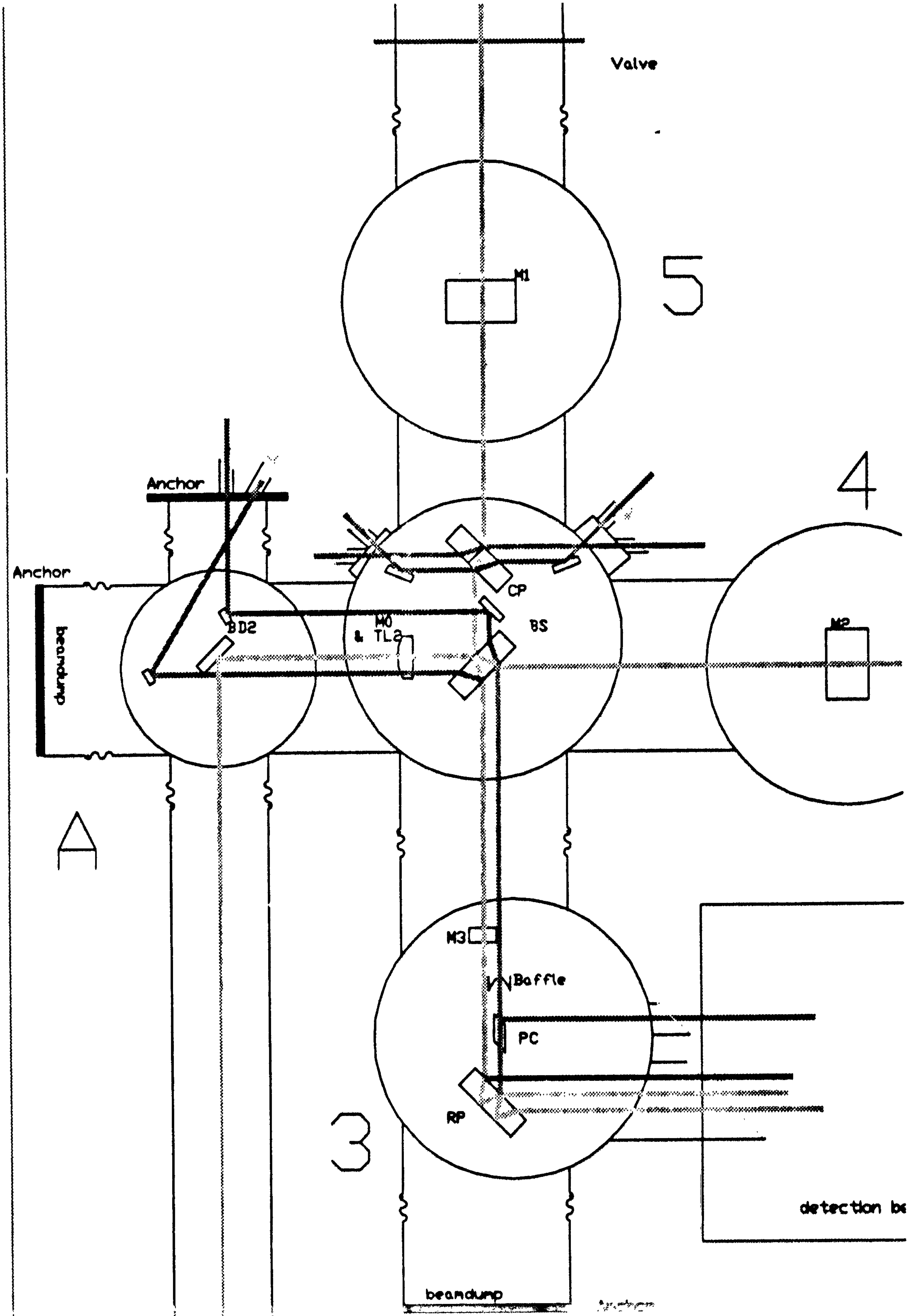
See far end for

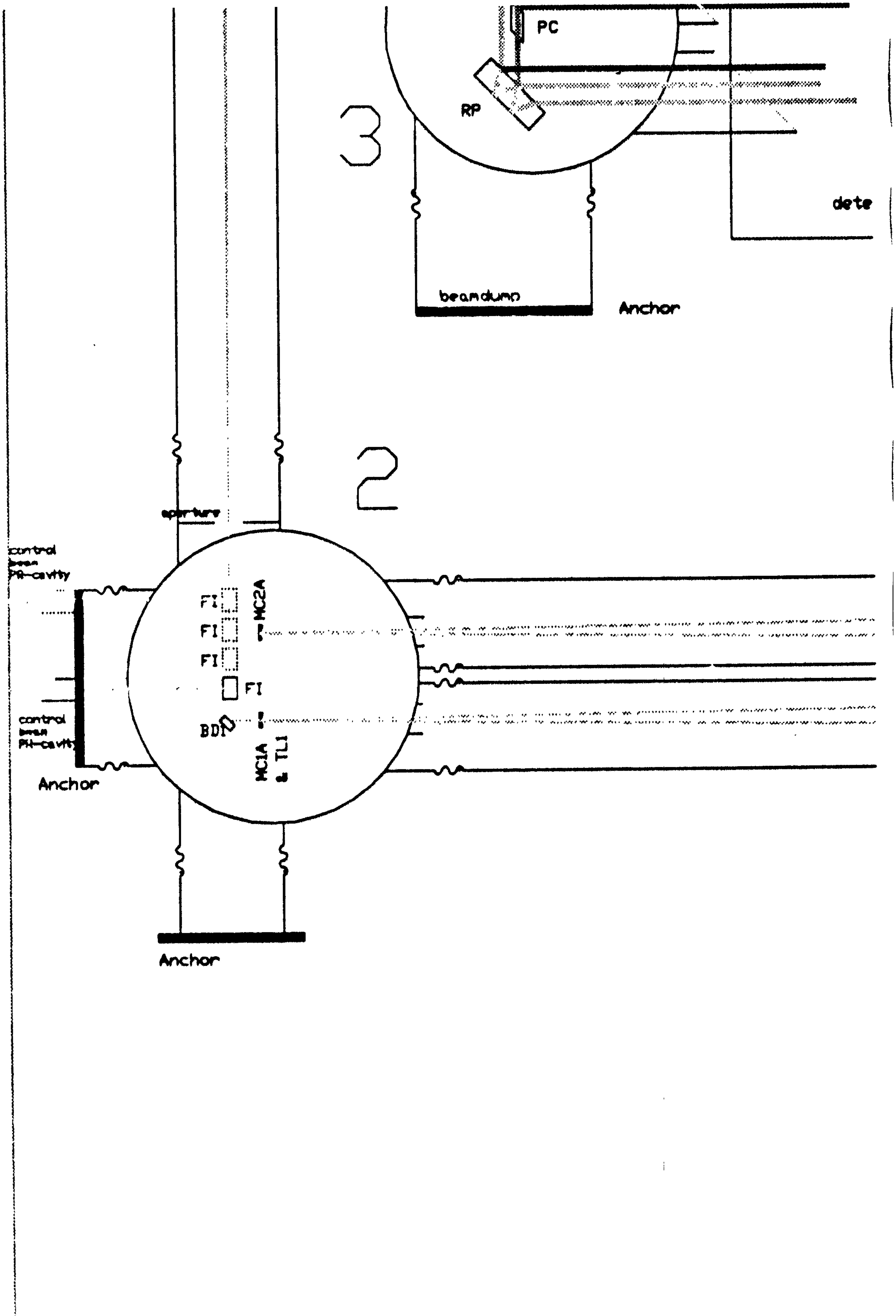
$$D = l = 2r\,\frac{\Delta l_{lim}}{H} \curvearrowright \Delta l_{lim} = \frac{H}{2r}\,l = \frac{3\cdot 10^{-2}}{0.6}\,600\,m$$

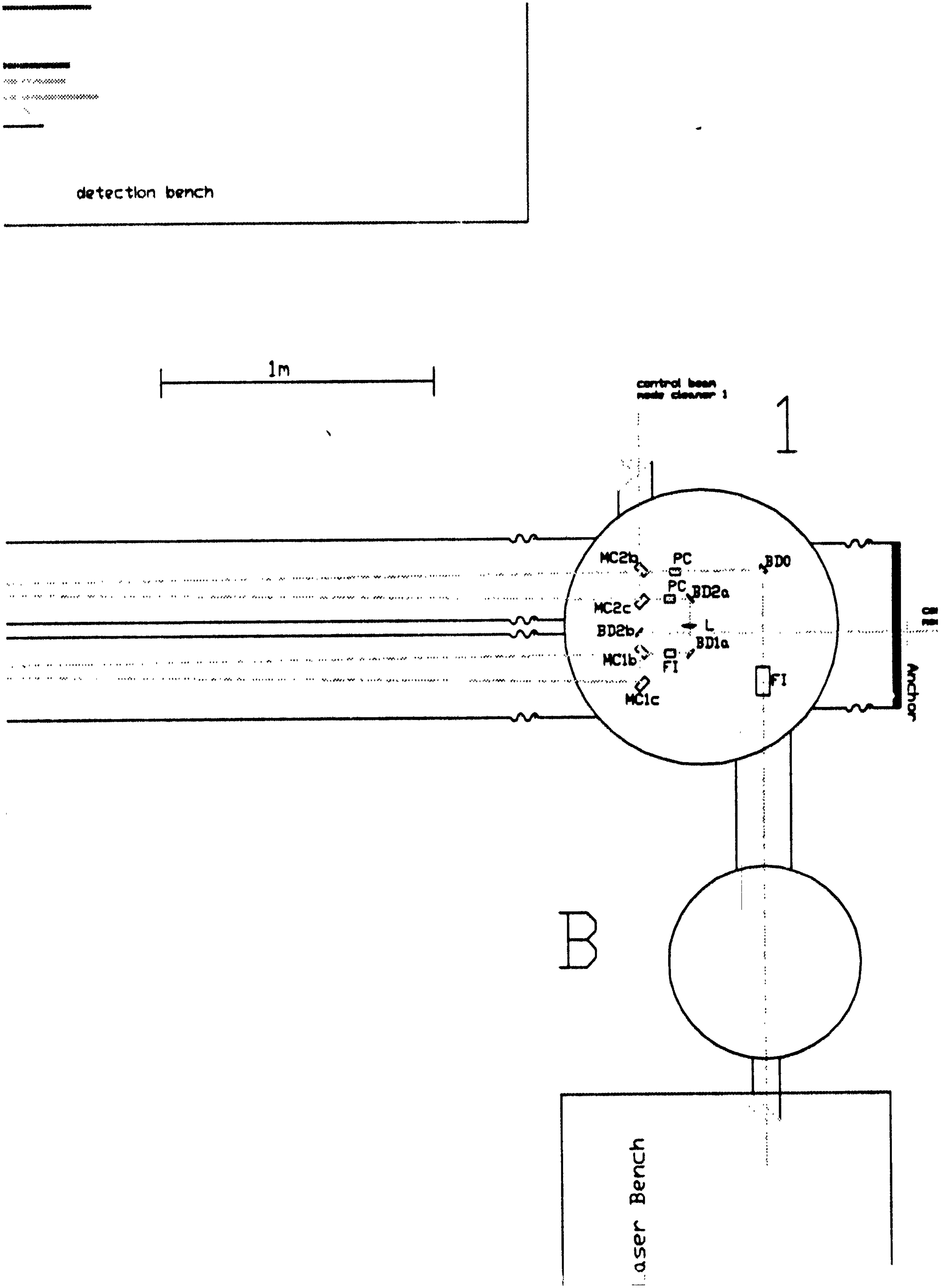
$$\Delta l_{lim} = 30\,m$$

↷ 3 cm baffles each 30 m ↷ one can still see the far end

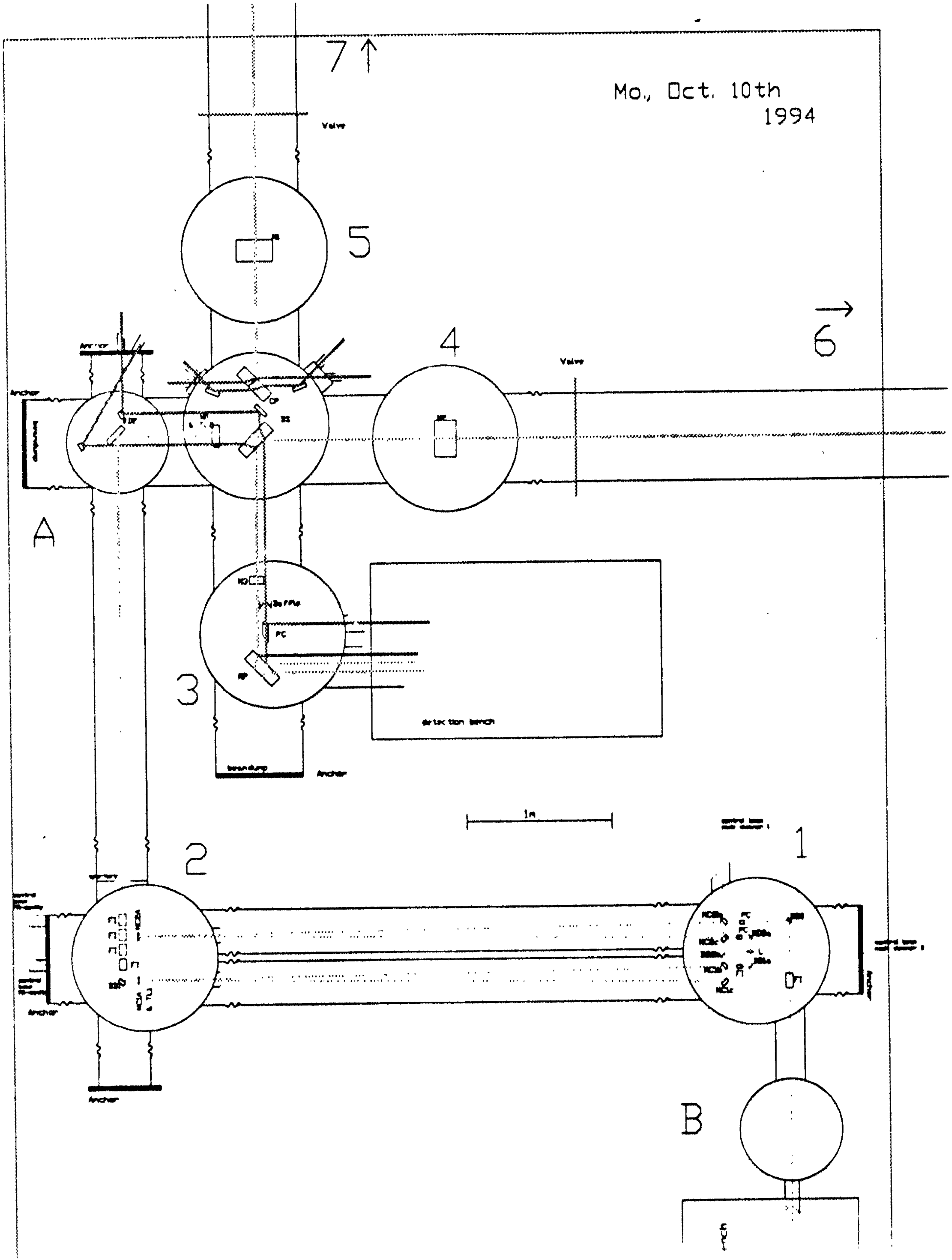
↷ either higher or more baffles


Valve
5
M1
4
Anchor
Anchor
beamdump
BD2
M0
& TL2
CP
BS
M2
A
M3
Baffle
PC
RP
3
detection be
beamdump
Anchor


PC
RP
3
dete
beamdump
Anchor
2
aperture
control
beam
PR-cavity
FI
FI
FI
FI
MC2A
BD
control
beam
PR-cavity
MC1A
& TL1
Anchor
Anchor

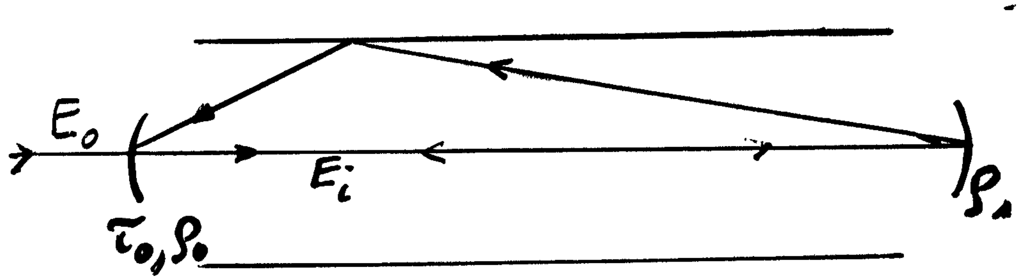


detection bench
1m
control beam
mode cleaner 1
1
MC2b
PC
BD0
PC
BD2a
MC2c
BD2b
L
BD1a
MC1b
FI
FI
MC1c
Anchor
B
aser Bench



Mo., Oct. 10th
1994

Cavities



$$E_i = E_0 \Big[\tau_0 + \tau_0 \rho_1 \rho_0 e^{i\vartheta} + \tau_0 \rho_1 \sigma_1 \rho_0 e^{i\phi} + \tau_0 \rho_0 (\rho_1 e^{i\vartheta} + \sigma_1 \rho_1 e^{i\phi})(\rho_1 \rho_0 e^{i\vartheta} + \sigma_1 \rho_0 \rho_1 e^{i\phi}) + \dots \Big]$$

$$\frac{E_i}{E_0} = \tau_0 \Big[1 + \rho_0 \rho_1 (e^{i\vartheta} + \sigma_1 e^{i\phi}) + \rho_0 \rho_1 (e^{i\vartheta} + \sigma_1 e^{i\phi}) \times \rho_0 \rho_1 (e^{i\vartheta} + \sigma_1 e^{i\phi}) + \dots \Big]$$

$$= \frac{\tau_0}{1 - \rho_0 \rho_1 (e^{i\vartheta} + \sigma_1 e^{i\phi})}$$

Expansion around $\vartheta_0 = 0 \bmod 2\pi$

strongest influence of $\delta\phi$ at $\phi_0 = 0 \bmod \pi$

$$\rightsquigarrow \frac{E_i}{E_0} \approx \frac{\tau_0}{1 - \rho_0 \rho_1 (1 + i\delta\vartheta + \sigma_1 + i\sigma_1 \delta\phi)}$$

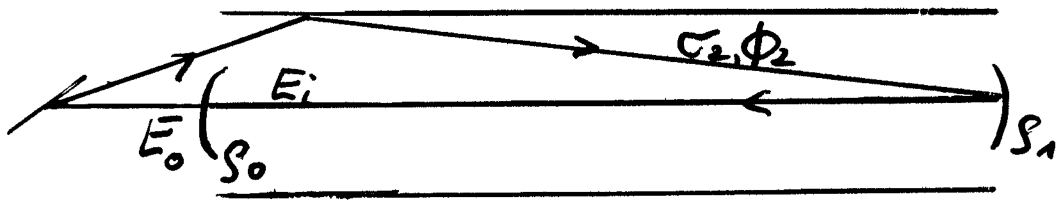
$$\rightsquigarrow \sigma_1 \delta\phi \overset{!}{<} \delta\vartheta$$

$$\sigma_1 2\pi \frac{\delta L_s}{\lambda} < 4\pi \frac{l}{\lambda} h$$

$$\delta L_s = 2\, \delta x_{ground} \mathbb{P}$$

$$\boxed{\sigma_1 \delta x_{ground} \mathbb{P} < l h}$$

Scattering at beamsplitter less critical



$$E_i = E_0 \tau_0 \left[1 + \rho_0\rho_1 e^{i\vartheta} + (\rho_0\rho_1)^2 e^{i2\vartheta} + \dots \text{(main beam)}\right]$$

$$+ E_0 \sigma_2 \left[\rho_0 e^{i\phi_2} + \rho_1 \rho_0^2 e^{i(\phi_2+\vartheta)} + \rho_1^2 \rho_0^3 e^{i(\phi_2+2\vartheta)} + \dots \text{(stray-light)}\right]$$

$$= E_0 (\tau_0 + \sigma_2 \rho_0 e^{i\phi_2})(1 + \rho_0\rho_1 e^{i\vartheta} + (\rho_0\rho_1)^2 e^{2i\vartheta} + \dots)$$

$$= E_0 \frac{\tau_0 + \rho_0 \sigma_2 e^{i\phi_2}}{1 - \rho_0\rho_1 e^{i\vartheta}}$$

Signal ≡ Imaginary part

$$\frac{E_i}{E_0} = \frac{(\tau_0 + \rho_0\sigma_2 e^{i\phi_2})(1 - \rho_0\rho_1 e^{-i\vartheta})}{|1 - \rho_0\rho_1 e^{i\vartheta}|^2}$$

$$= \frac{(\tau_0 + \rho_0\sigma_2\cos\phi_2 + i\rho_0\sigma_2\sin\phi_2)(1 - \rho_0\rho_1\cos\vartheta + i\rho_0\rho_1\sin\vartheta)}{|1 - \rho_0\rho_1 e^{i\vartheta}|^2}$$

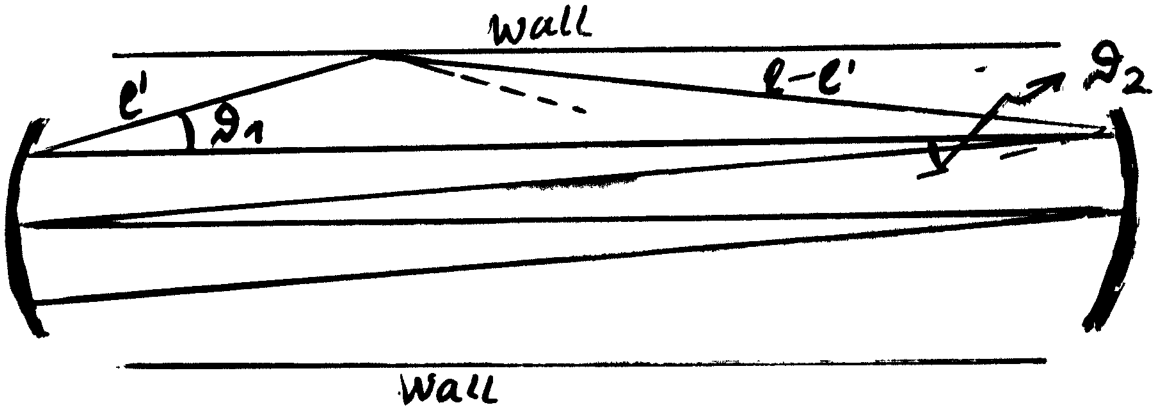
$\vartheta \approx 0, \ \phi_2 \ll 1 \qquad \rho_0(1-\rho_0\rho_1)\sigma_2 \sin\phi_2 \overset{!}{<} (\tau_0 + \rho_0\sigma_2)\rho_0\rho_1 \sin\vartheta$

$\sigma_2 \ll \tau_0 \qquad \rho_0^2 + \tau_0^2 = 1$

$$\curvearrowright \ \sigma_2 \, \delta x_{ground} \, \mathbb{P} \overset{!}{<} \frac{4}{\tau_0} \ell h$$

Jan 95

Delay-line /walls



$$\delta L_s^2 = \underbrace{\left(\frac{N}{2} f(\vartheta_1) \frac{dF_1}{l'^2}\right)}_{\text{"source"-mirror /wall}} \underbrace{\left(f(\vartheta) \frac{\pi w^2}{(l-l')^2} \cdot \frac{N}{2}\right)}_{\text{wall-"target" mirror}} \underbrace{\left(f(\vartheta_2) \frac{\pi w^2}{l^2}\right)}_{\text{back into light-mode to next mirror}} \mathbb{P}^2 \delta x_{ground}^2$$

$\delta L = N \delta l$ $\quad$ l = mirror separation

$h \approx \frac{\delta L}{L} = \frac{\delta l}{l}$

$\delta L_s \overset{!}{<} \delta L_{GW}$

$\curvearrowright \; \frac{1}{4} \sigma_1 \delta x_{ground} \mathbb{P} \overset{!}{<} l h$

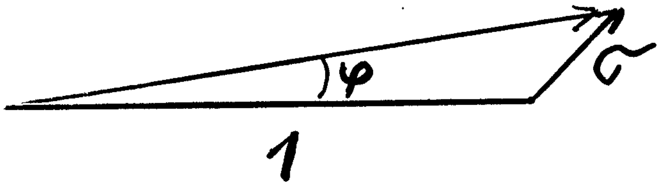
Scattering "inside" delay-line

1) Measurement (1979 and following years)

$$\Delta\phi = \omega\tau = \omega\frac{\Delta L}{c}$$

$$\dot{\omega}\frac{\Delta L}{c} = \Delta\dot{\phi} = \omega_r$$

a) Measure ω_r ↷ ΔL

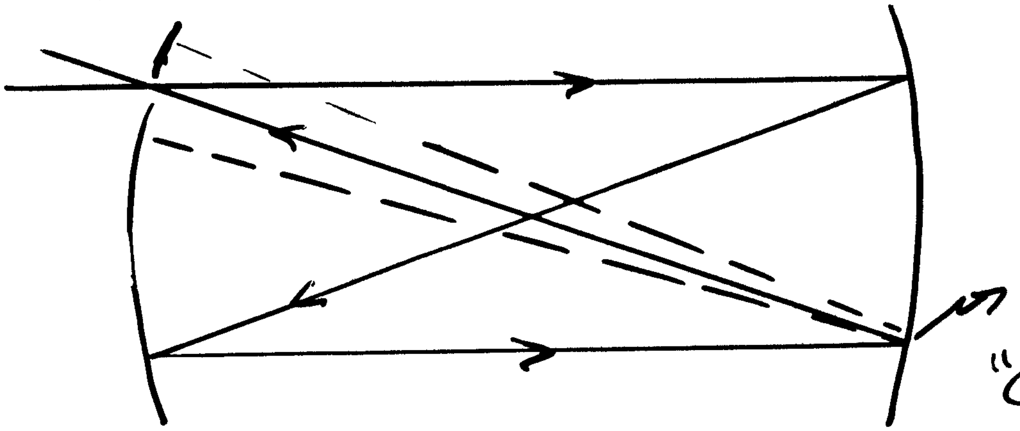


b) Measure amplitude of φ ↷ σ

Results: a) $\Delta L = nL$ ↷ "coupling hole"

b) $\Delta L = 2n\ell$ ↷ "neighbours"

Coupling hole:



scattering "cone" around main beam

at later reflections: backscatter into main beam

Scattering inside delay line

"Neighbours": Tails of beam (produced by scattering process) fall onto area of neighbouring reflection spots; scattering of these tails into mode of the main beam, reflected regularly at neighbouring spot gives contributions

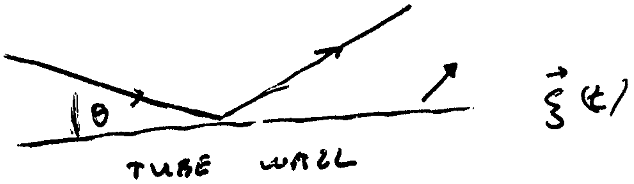
Measurement of $f(\vartheta)$ $\left(\frac{\delta P}{P} = f(\vartheta)\, d\Omega\right)$ and calculation of σ's agreed very well with measured values of σ's.

Eannas

January 6-7, 1995

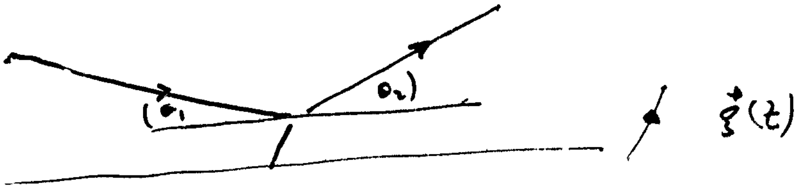
PHASE NOISE FROM BACKSCATTER / DIFFRACTION / SPECULAR REFLECTION.

SPECULAR REFLECTION



BACKSCATTER

BAFFLE DIFFRACTION



IN EACH CASE $\Psi_{final} = \Psi_0 \, e^{i\Phi(t)}$

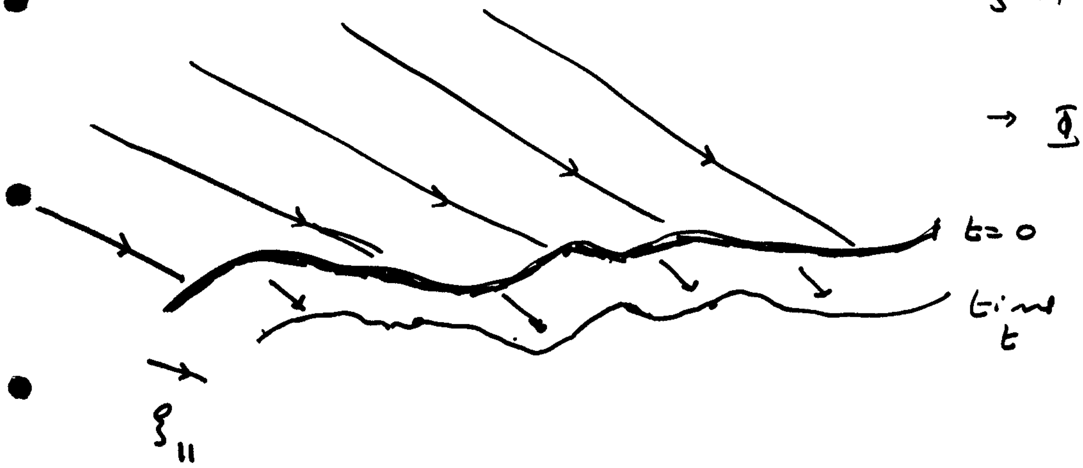
$$\check{\Phi}(f) = \begin{cases} \frac{4\pi}{\lambda} \, \theta \, \check{\xi}(f)_{vert} & \text{REFLECTION} \\ \frac{4\pi}{\lambda} \, \check{\xi}(f)_{\parallel} & \text{BACKSCATTER} \\ \frac{2\pi(\theta_1+\theta_2)}{\lambda} \check{\xi}(f)_{vert} & \text{DIFFRACTION} \end{cases}$$

- NO DEPENDENCE ON FLUCTUATIONS IN WALL TILT.

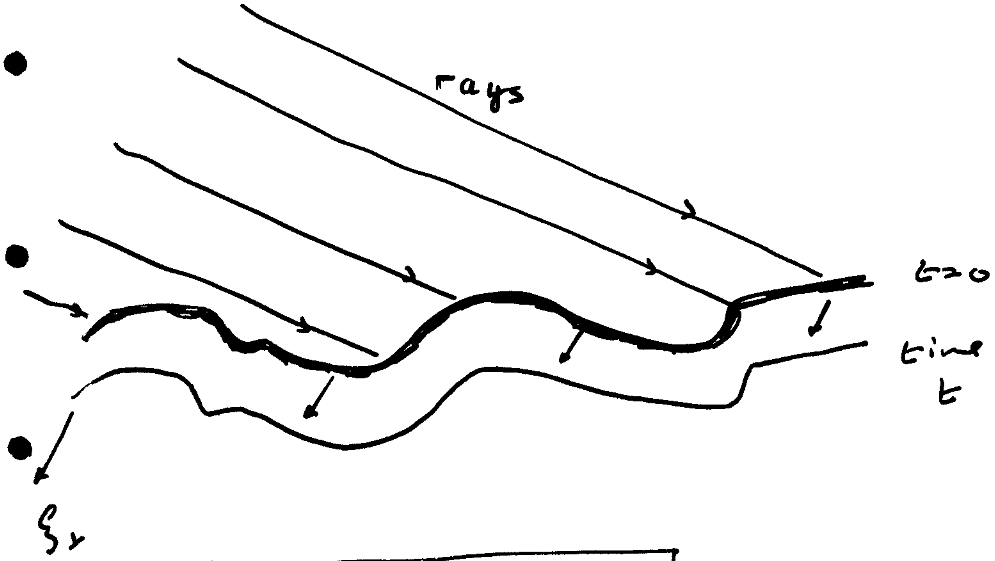
BACKSCATTER

$$\vec{\xi}(t) = \vec{\xi}_\parallel(t) + \vec{\xi}_\perp(t)$$

$$\rightarrow \Phi(t) = \Phi_\parallel(t) + \Phi_\perp(t)$$

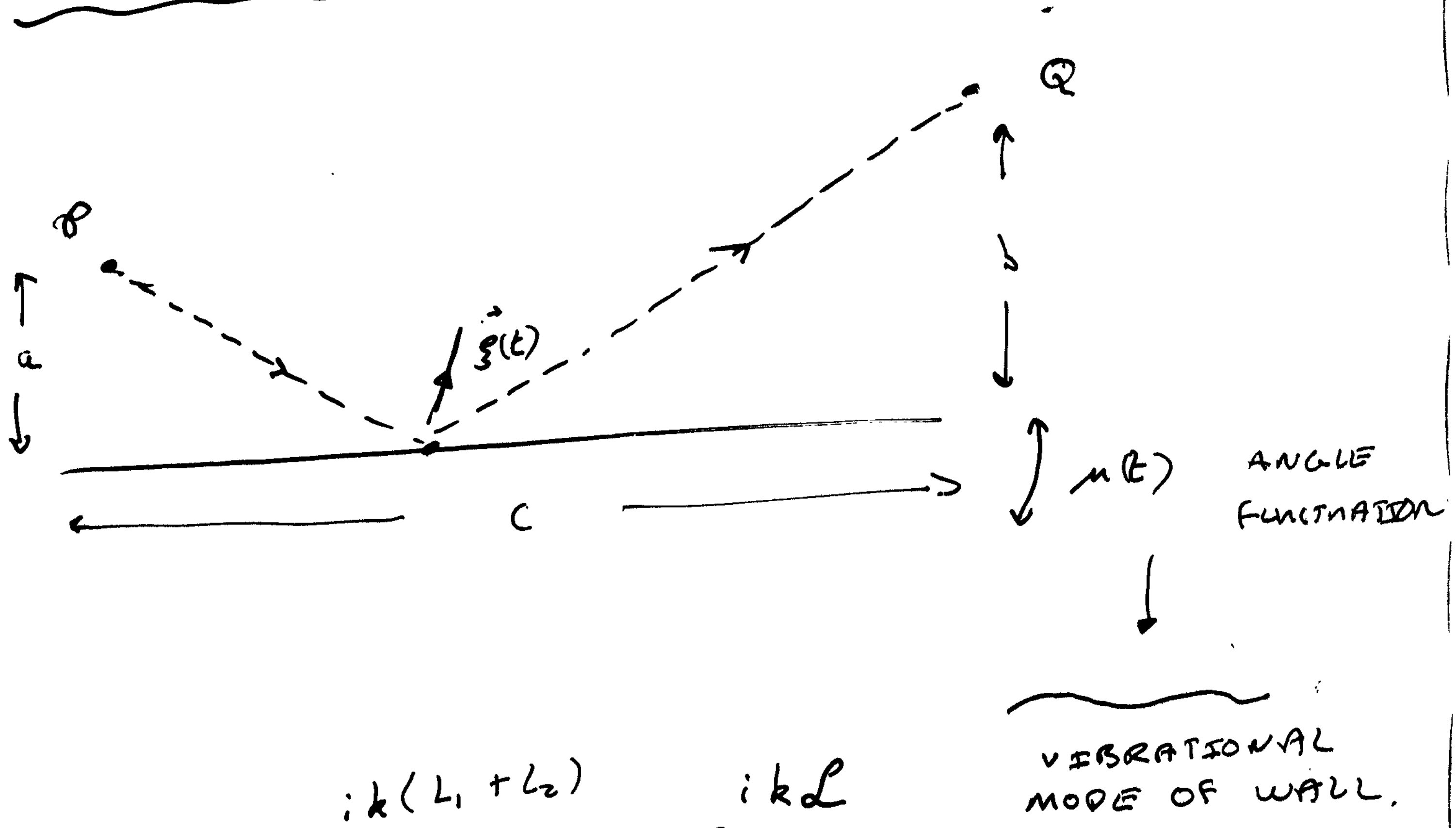


$$\boxed{\Phi_\parallel = 2k\xi_\parallel = \frac{4\pi}{\lambda}\xi_\parallel}$$



$$\boxed{\Phi_\perp \lesssim \frac{\xi_\perp}{\sqrt{\lambda r}}}$$

SPECULAR REFLECTION



$$G(P,Q) \propto \frac{e^{ik(L_1+L_2)}}{L_1+L_2} = \frac{e^{ik\mathcal{L}}}{\mathcal{L}}$$

$$\delta\Phi = k\,\delta\mathcal{L}$$

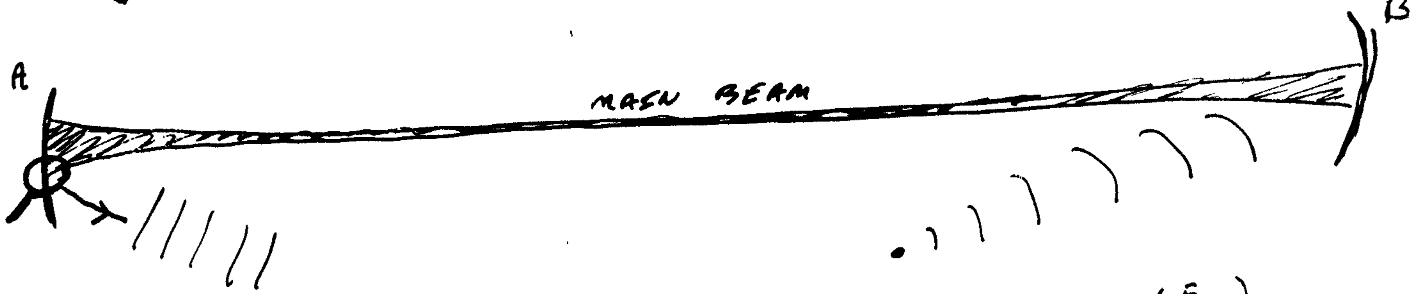
$$\delta\mathcal{L} = \underbrace{\frac{2(a+b)}{c}\,\vec{\xi}(t)}_{\text{DOMINANT}} + \frac{c}{2}\left[-1 + \frac{(a-b)^2}{(a+b)^2}\right]\mu(t)^2 + O(\xi^2, \mu^3)$$

NEGLIGIBLE (VINET + BRISSON)

RECIPROCITY RELATION | "ANTENNA THEOREM"

LIGHT SCATTERING OUT OF MAIN BEAM AT MIRROR A

LIGHT SCATTERING BACK INTO MAIN BEAM AT MIRROR B



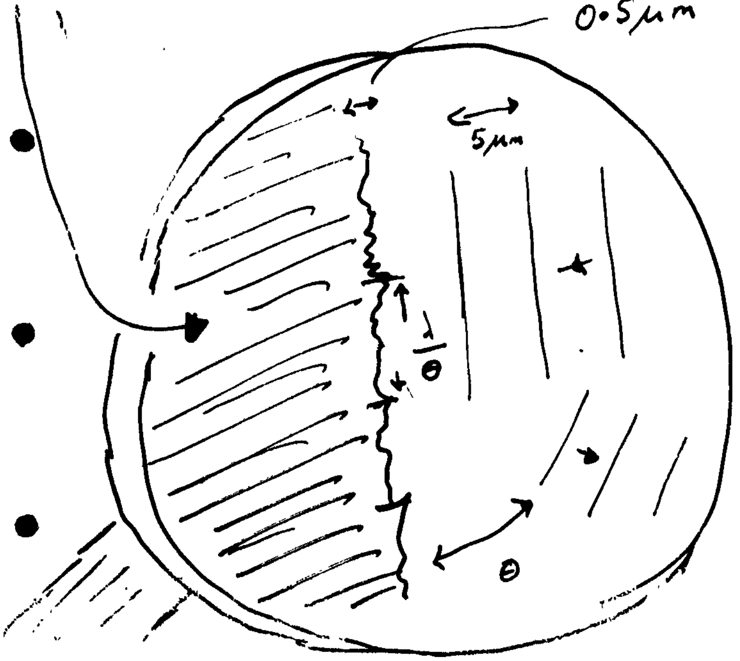
$$\frac{dE}{dt\, d\Omega_{ms}} = \frac{dP}{d\Omega_{ms}}(\underset{\sim}{\theta})\, I_{mb}$$

$$\left[= \frac{\alpha}{\theta^2}\, I_{mb} \right]$$

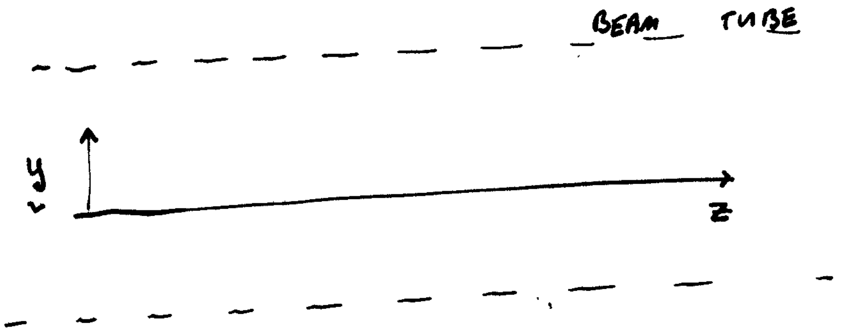
$$\left(\frac{dE}{dt}\right)_{\substack{\text{back}\\ \text{into}\\ \text{main}\\ \text{beam}}} = \left(\frac{dE}{dt\, dA}\right)_{\text{incident}} \sigma_{ms}(\underset{\sim}{\theta})$$

$$\boxed{\sigma_{ms} = \lambda^2 \frac{dP}{d\Omega_{ms}}}$$

- PROCESSES RELATED BY TIME REVERSAL INVARIANCE
- DOES NOT DEPEND ON $\boxed{\sigma << \lambda}$



PROOF



Ⓐ

$$\psi(\vec{y}, z) = \underbrace{\int d^2y'}_{\text{integral over mirror}} \underbrace{\sqrt{I_{mb}}\ \hat{\psi}_{00}(\vec{y}')}_{\text{main beam incident field}} \underbrace{e^{i\varphi(\vec{y}')}}_{\text{small phase shift due to mirror roughness}} \underbrace{\left\{ \frac{-ik}{2\pi z} e^{ikz} e^{ik\frac{(\vec{y}-\vec{y}')^2}{2z}} \right\}}_{\text{Paraxial propogation}}$$

Field after reflection off mirror

$$\frac{dP}{d\Omega_{ms}} = \frac{1}{I_{ms}} |\psi(\vec{y}, z)|^2 z^2$$

Ⓑ

$$\psi_{inc}(\vec{y}') = \sqrt{\frac{dE}{dt\, dA}}\ e^{ik(\vec{y}-\vec{y}')^2/2z}$$

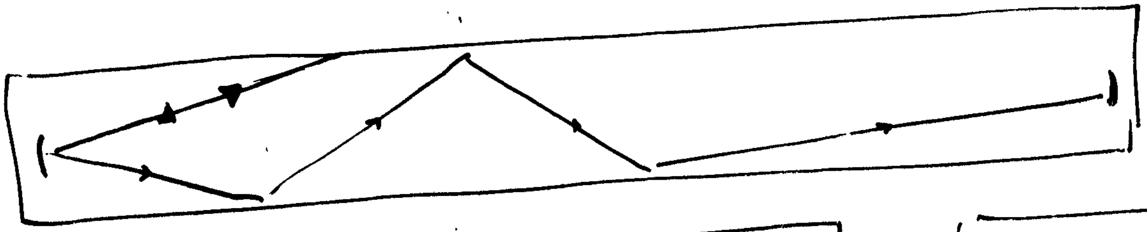
Incident field coming from $(\vec{y}, z)$ to receiving mirror

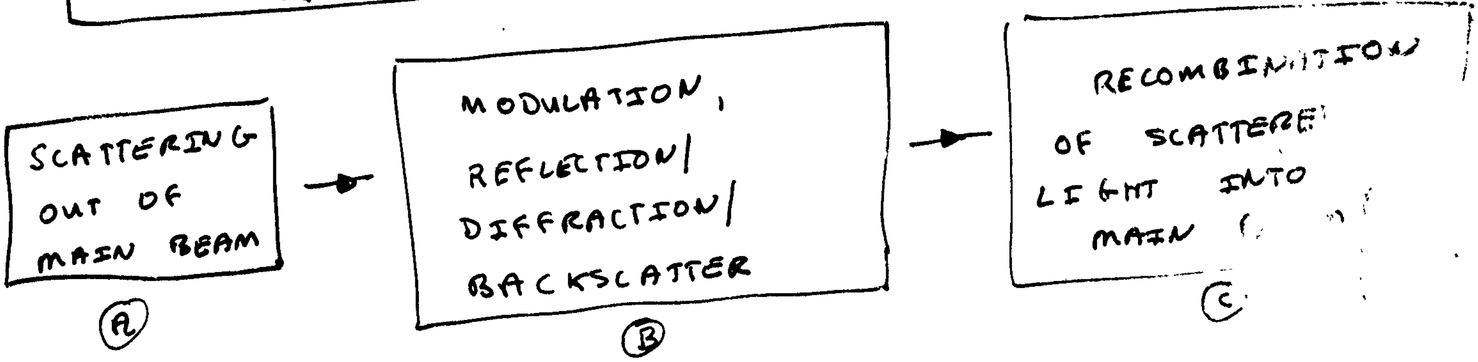
$$\sigma_{ms} = \frac{1}{dE/dt\,dA} \left| \underbrace{\int d^2y'}_{\text{integral over receiving mirror}} \psi_{inc}(\vec{y}')\ e^{i\varphi(\vec{y}')} \underbrace{\hat{\psi}_{00}(\vec{y}')}_{\text{normalized eigenfunction for TEM00 mode.}} \right|^2$$

DERIVATION OF GRAVITATIONAL WAVE NOISE

– FOUNDATIONS

- THE FOLLOWING INTENSITY ANALYSIS ASSUMES LIGHT IS INCOHERENT

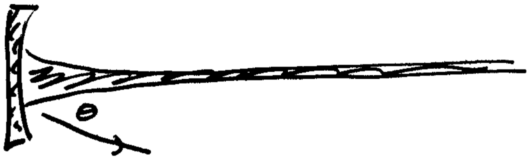




- KEEP TRACK OF (i) ENERGY
  (ii) PHASE MODULATION

  AT EACH STAGE.

Ⓐ SCATTERING OUT OF MAIN BEAM

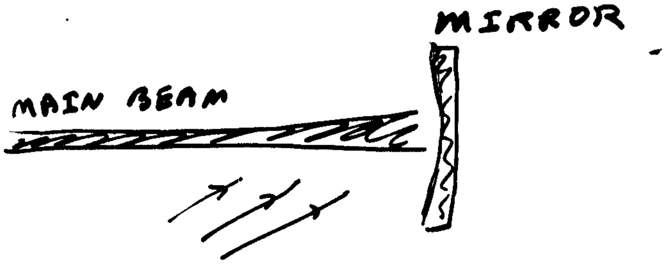


$$\left(\frac{dE}{dt\,d\Omega}\right)_{\text{scattered}}(\underset{\sim}{\theta}) = \underbrace{\left(\frac{dP}{d\Omega_{ms}}\right)(\underset{\sim}{\theta})}_{\frac{\alpha}{\theta^2}} I_{mb}$$

$\alpha = 10^{-6}$

$$\boxed{\left(\frac{dE}{dt\,dA}\right)_{\substack{\text{distance}\\ r}} = \frac{1}{r^2}\,\frac{\alpha}{\theta^2}\,I_{mb}.}$$

ⓒ RECOMBINATION



Some incident scattered light with energy

$$\left(\frac{dE}{dt}\right)_{rec} = \sigma_{ms} \left(\frac{dE}{dt\,dA}\right)_{incident}$$

and phase noise $\Phi(t)$

- MAIN BEAM FIELD Ψ_{mb} IS AUGMENTED BY

$$\boxed{\frac{\delta \Psi_{mb}}{\Psi_{mb}} = \sqrt{\frac{1}{I_{mb}} \left(\frac{dE}{dt}\right)_{rec}} \left[\cos \Phi(t) + i \sin \Phi(t) \right]}$$

- A GRAVITATIONAL WAVE $h(t)$ PRODUCES

$$\frac{\delta \Psi_{mb}}{\Psi_{mb}} = e^{2ikL\,h(t)} - 1 \simeq 2ikL\,h(t)$$

$L = 4$ km

$k = \frac{2\pi}{5} \ldots$

COMBINING

$$\Rightarrow \boxed{\tilde{h}(f)^2 = \frac{1}{I_{mb}} \left(\frac{\lambda}{4\pi L}\right)^2 \sigma_{ms}(\underset{\sim}{\theta}) \times \left(\frac{dE}{dt\,dA}\right)_{inc} \tilde{S}(f)^2}$$

WHERE $\tilde{S}(t) = \sin[\Phi(t)] \simeq \Phi(t)$ [illegible].

OR

$$\boxed{\tilde{h}(f)^2 = \frac{1}{I_{mb}}\left(\frac{\lambda}{4\pi L}\right)^2 \underbrace{\int d^2\Omega_{rm}} \left[\frac{dE}{dt\,dA\,d^2\Omega}(\underline{\theta}) \quad \tilde{\Phi}(f)^2\right]}$$

integral over
incident direction
$\underline{\theta}$ at recombining
mirror

- NO FACTOR OF B !

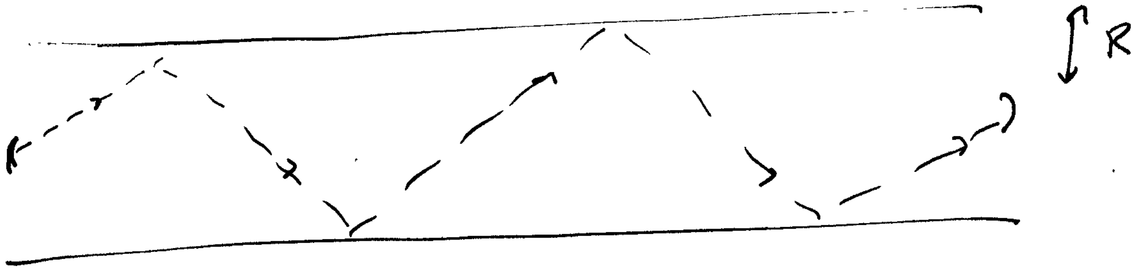
(JEAN - YVES VINET,
BRISSON).

• SPECULAR REFLECTION

- BAFFLES DESIGNED TO ELIMINATE RAYS WITH $\theta \le \theta_0 \simeq 0.01$ RADIANS

- HERE WE CALCULATE NOISE FROM LIGHT @ $\theta \ge \theta_0$.

- THIS ANALYSIS NOW KNOWN TO BE INVALID BECAUSE OF NEW SCATTERING MEASUREMENTS BY WEISS.



KEY INGREDIENTS

- LIGHT UNDERGOS $N = \frac{L\theta}{2R}$ BOUNCES

$$\Rightarrow \tilde{\Phi}(f)^2 = N\,\tilde{\Phi}(f)^2_{1\,\text{bounce}} = \frac{L\theta}{2R}\left(\frac{4\pi\lambda}{\theta}\right)^2 \tilde{\xi}(f)^2$$

- $\frac{dE}{dt\,d\theta}$ PRESERVED DOWN MIRROR.

- ENERGY DENSITY IS UNIFORM ON RECEIVING PLANE

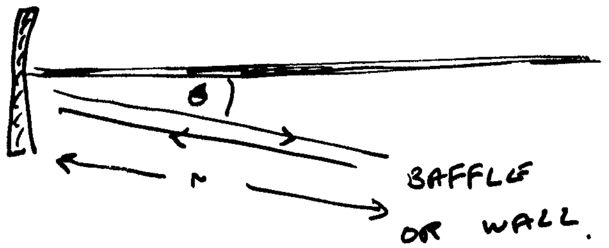
$$\Rightarrow \left(\frac{dE}{dA\, dt\, d^2\Omega}\right)_{rec} = \frac{1}{\pi R^2}\left(\frac{dE}{dt\, d^2\Omega}\right)_{rec}$$

COMBINE TO GET

$$\boxed{\check{h}(f) = \alpha \sqrt{2\, A(\theta)\, m(\theta)}\ \frac{\lambda}{\sqrt{LR}}\ \frac{\overset{\text{CAN BE AS LARGE AS 10.}}{\overset{\downarrow}{\hat{A}(f)}}\ \check{\xi}_1(f)}{R}\ \sqrt{\Delta\theta}}$$

$$= \frac{2.4\times10^{-24}}{Hz^{\frac{1}{2}}}\left(\frac{10Hz}{f}\right)^2 \sqrt{A(\theta)\, m(\theta)}\ \hat{A}(f)\sqrt{\frac{\Delta\theta}{0.01}}$$

BACKSCATTER



$$\frac{1}{\delta\Omega_{ms}}\left(\frac{dE}{dt}\right)_{\text{back to main beam}} = \sigma_{ms} \times \overbrace{\frac{dP}{d\Omega_{bs}} \times \underbrace{\frac{1}{r^2}\frac{dP}{d\Omega_{ms}} I_{mb}}_{\left(\frac{dE}{dt\,dA}\right)_{out}}}^{\left(\frac{dE}{dt\,dA}\right)_{rec}}$$

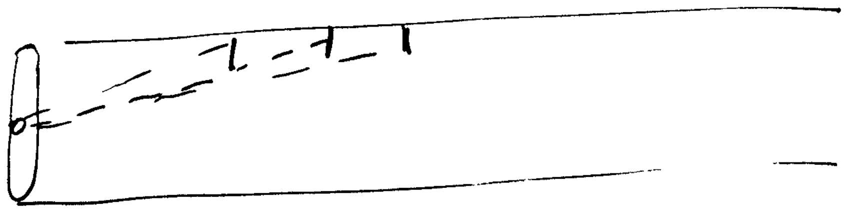
$$\Rightarrow \boxed{\delta\check{h}(f)^2 = \left(\frac{\lambda^2}{4\pi r L}\right)^2 \underbrace{\left(\frac{dP}{d\Omega_{ms}}\right)^2}_{\left(\frac{\alpha}{\theta^2}\right)^2} \left(\frac{dP}{d\Omega_{bs}}\right) \underbrace{\tilde{S}(f)^2}_{\frac{1}{2}\tilde{\Phi}(f)^2} \delta\Omega_{ms}}$$

FOR ALL BACKSCATTER PROCESSES

BAFFLE BACKSCATTER.

$$\theta_{bs} \neq \theta$$

$$\check{h}(f)^2 = \frac{1}{2}\left(\frac{\lambda^2}{4\pi R L}\right)^2 \int_{\theta_1}^{\theta_2} d\theta \left(\frac{\alpha}{\theta^2}\right)^2 \underbrace{\frac{dP}{d\Omega_{bs}}}_{\beta = 10^{-2}} (\theta_{bs}) \underbrace{\tilde{\Phi}(f;\theta)^2}_{\left[\frac{4\pi}{\lambda} A(f) \xi_s(f)\right]^2} 8\pi \theta^3 \, d\theta$$



- "COMPLETE SHADOWING" ⇒ RESULTING NOISE <u>INDEPENDENT</u> OF DETAILS OF BAFFLE SPACING ETC.

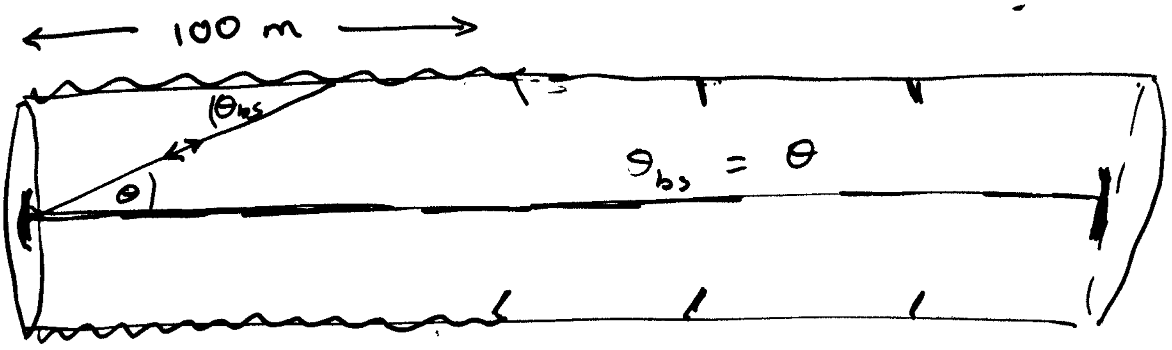
$$\tilde{h}(f) = \left[4\pi \alpha^2 \beta \ln\left(\frac{l_2}{l_1}\right) J_0(\rho)\right]^{\frac{1}{2}} \bar{A}(f) \frac{\lambda}{R} \frac{\tilde{\xi}_s(f)}{L}$$

$$= \frac{3\times10^{-25}}{\sqrt{Hz}} \left(\frac{10\,Hz}{f}\right)^2 \bar{A}(f) \frac{\sqrt{J_0(\rho)}}{2} \left(\frac{\beta}{10^{-2}}\right)^{\frac{1}{2}} \left[\frac{\ln(l_2/l_1)}{\ln(4000/120)}\right]^{\frac{1}{2}}$$

$$\left(\frac{\alpha}{10^{-6}}\right) \tilde{\xi}_s(f) \Big/ \left[10^{-7}\, cm \cdot Hz^{-\frac{1}{2}} (f/10\,Hz)^{-2}\right]$$

$$\simeq 0.8\, \tilde{h}_{goal}$$

BARE WALL BACKSCATTER



$$\tilde{h}(f)^2 = \left(\frac{\lambda^2}{4\pi R L}\right)^2 \int_{\theta_1}^{\theta_2} d\theta \left(\frac{\alpha^2}{\theta^2}\right)^2 \underbrace{\frac{dP}{d\Omega_{bs}}(\theta)}_{\begin{cases} \boxed{\beta \simeq 10^{-2}} \\ \text{OR } \beta\,\theta \end{cases}} \underbrace{\tilde{\Phi}(f)^2}_{\left[\frac{4\pi}{\lambda} A(f)\, \tilde{\xi}_s(f)\right]^2} 4\pi\theta^2\, d\theta$$

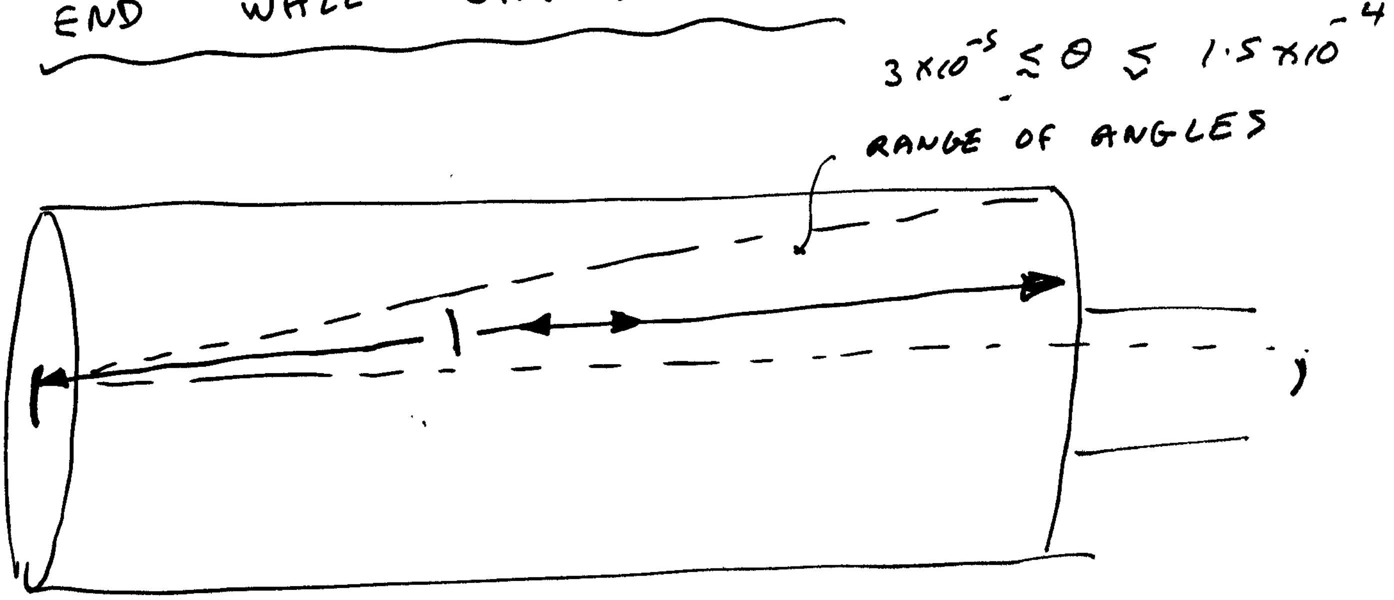
$$= \frac{3\times10^{-25}}{\sqrt{Hz}} \left(\frac{10\,Hz}{f}\right)^2 \tilde{A}(f) \frac{\sqrt{J_0(\rho)}}{2} \left(\frac{\beta}{10^{-2}}\right)^{\frac{1}{2}} \left(\frac{\alpha}{10^{-6}}\right)$$

"PESSIMISTIC CASE"

$$\underbrace{\left[\frac{\ln(l_2/l_1)}{\ln(120m/2m)}\right]^{\frac{1}{2}}}_{\text{ONLY FACTOR WHICH DIFFERS FROM BAFFLE BACKSCATTER}} \frac{\tilde{\xi}_s(f)}{10^{-7}\,cm\,Hz^{-\frac{1}{2}}\,(f/10Hz)^2}$$

$$\simeq 0.8\, \tilde{h}_{goal}$$

END WALL BACKSCATTER



- ASSUME $\frac{dP}{d\Omega_{bs}} = \beta = 0.01$

- $\frac{dP}{d\Omega_{ms}} = \frac{\alpha}{\theta^2}$ VALID AT SMALL ANGLES

- HORIZONTAL VIBRATIONS $\tilde{\xi}(f) = A(f)\,\tilde{\xi}_s(f)$

$$\Rightarrow \tilde{h}(f) = \frac{3\times10^{-25}}{\text{Hz}^{\frac{1}{2}}}\left(\frac{10\,\text{Hz}}{f}\right)^2\left(\frac{\alpha}{10^{-6}}\right)\left(\frac{\beta}{10^{-2}}\right)^{\frac{1}{2}}\tilde{A}(f)\left(\frac{12\,\text{cm}}{R_{mirror}}\right)$$

COHERENCE EFFECTS

- THE FUNDAMENTAL FORMULA OBTAINED FROM AN INTENSITY ANALYSIS IS

$$\check{h}(f)|^2 = \frac{1}{I_{mb}}\left(\frac{\lambda}{4\pi L}\right)^2 \int d^2\Omega_{rm}(\underset{\sim}{\theta})\, \frac{dE}{dt\,dA\,d^2\Omega}(\underset{\sim}{\theta})\, \check{\Phi}(f;\underset{\sim}{\theta}))^2$$

- THE SAME FORMULA IS OBTAINED FROM AMPLITUDE **IF** LIGHT INCIDENT FROM DIRECTIONS SEPARATED BY

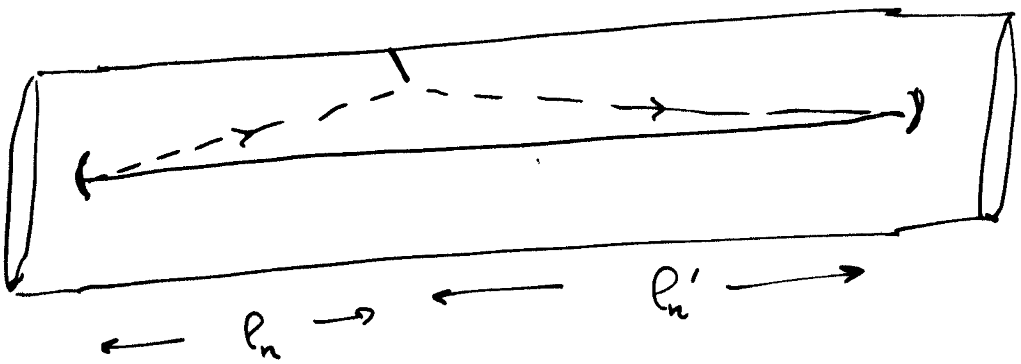
$$\Delta\theta \gtrsim \theta_{\substack{main\\beam}} = \frac{\sqrt{\lambda L}}{L}$$

IS PHASE INCOHERENT

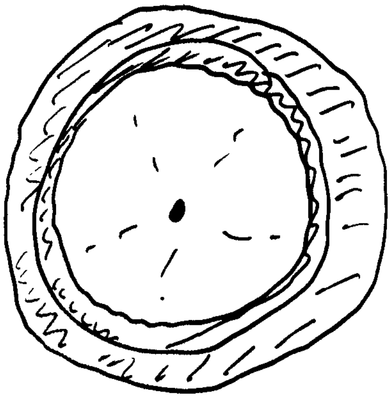
- 2 POSSIBLE MECHANISMS OF DECOHERENCE

- TO CHECK COHERENCE EFFECTS WE NEED TO DO A FULL AMPLITUDE ANALYSIS FOR EACH TYPE OF NOISE

BAFFLE DIFFRACTION - DANGER



. BAFFLE SEEN FACE ON



▨ Region where most of the diffracted light is coming from.

- THERE IS A DANGER OF PHASE COHERENCE ALL THE WAY AROUND THE EDGE
  (NOISE FROM DIFFERENT BAFFLES WILL BE INCOHERENT)

EFFECTS THAT MITIGATE COHERENCE

① BAFFLE MOTIONS INCOHERENT

② FRESNEL FRINGE PATTERN FOR OFF CENTERED MIRRORS

③ NON AXISYMMETRY OF MIRRORS – 'LASER SPECKLE'

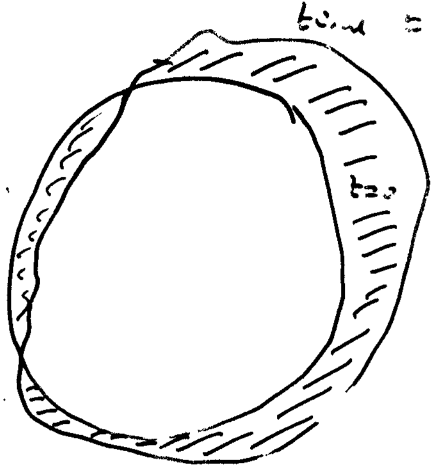
④ SERRATIONS ON BAFFLES.

⑤ COHERENCE OF DC PORTION OF LIGHT IS UNIMPORTANT.

BAFFLE DIFFRACTION

A. COHERENT ANALYSIS

Baffle seen face on



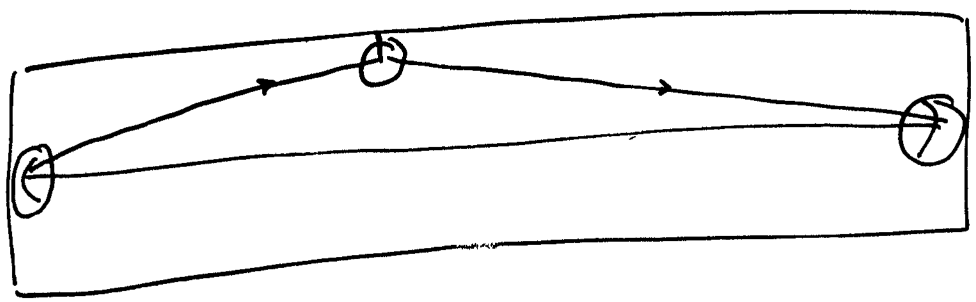
▨ Area Opened up

▧ Area closed off

• DO NOT SEPARATELY ANALYSE { ENERGY / PHASE MODULATION OF SCATTERED LIGHT

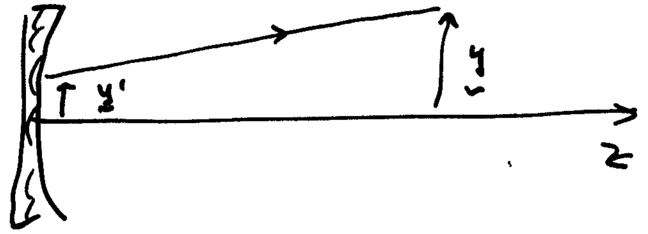
$$\Psi_0 e^{i\Phi(t)} \simeq \Psi_0 + \underbrace{i\Psi_0\Phi(t)}$$

Look at spectrum of fluctuating part of wave field.



3 integrals in expression for h(t).

AMPLITUDE DESCRIPTION OF SCATTERING OFF MIRROR



$$\Psi_{scatt}(\underset{\sim}{y}, z) = \int d^2\underset{\sim}{y}' \, \underbrace{\frac{e^{-ik}}{2\pi z} \, e^{ikz} \, e^{ik\frac{(\vec{y}-\vec{y}')^2}{2z}}}_{\text{STANDARD PARAXIAL PROPOGATOR}} \; \underbrace{\hat{\psi}_{00}(\vec{y}') \sqrt{I_{mb}}}_{\text{main beam field}}$$

$$\times \underbrace{e^{2ikN(\vec{y}')}}_{\text{mirror imperfections}}$$

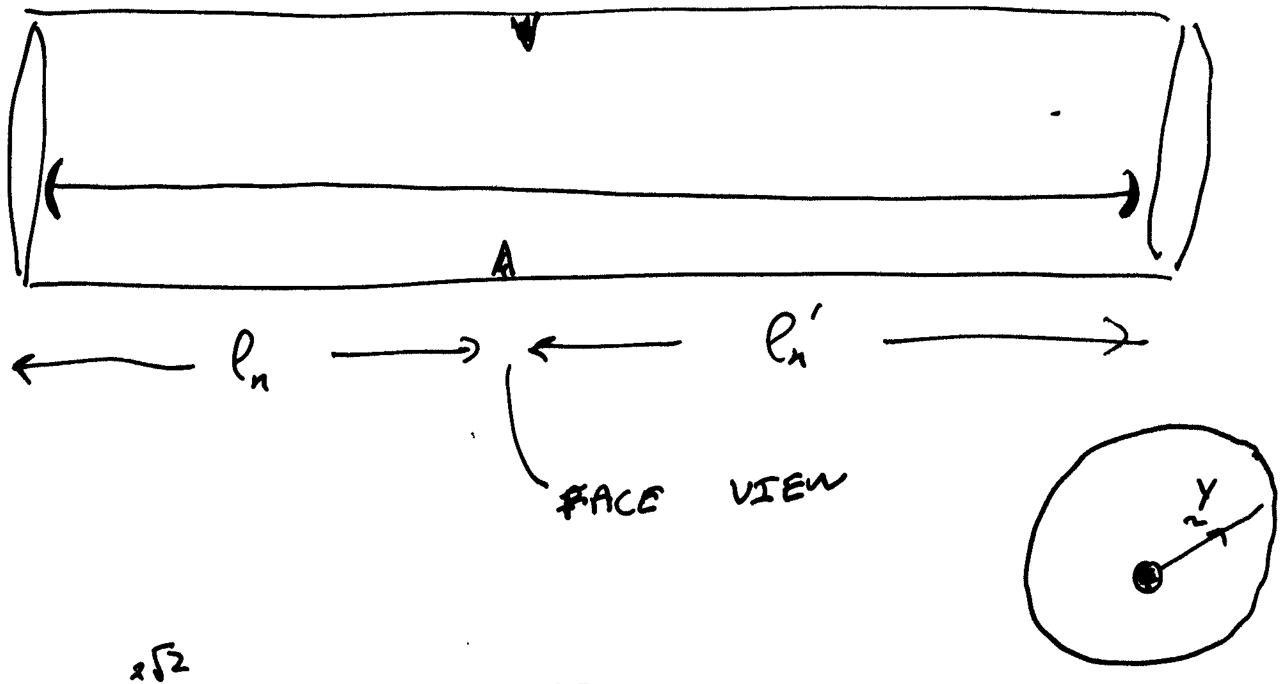
$$= \frac{1}{z} e^{ikz} \, e^{ik\frac{y^2}{2z}} \sqrt{\frac{dP}{d\Omega_{ms}}\left(\frac{\underset{\sim}{y}}{z}\right)} \; \underbrace{f_{sm}(\underset{\sim}{y}, z)}_{\text{THE EXTRA INFO GIVEN BY AMPLITUDE ANALYSIS}}$$

FLUCTUATING FUNCTION

RMS = UNITY

VARIES ON SCALES

$\sim \sqrt{\lambda z}$



$$h(t) = \sum_{mir}^{\overset{2\sqrt{2}}{\uparrow}} \underbrace{\sum_{n=1}^{N_b}{}'}_{\text{sum over baffles}} \int_0^{2\pi} \underbrace{R\, \xi_s(\varphi)\, d\varphi}_{\int d^2A} \quad \underbrace{\frac{\lambda}{4\pi L}}_{\text{conversion factor}}$$

$$\underbrace{\left[\frac{\sqrt{\alpha}}{Y_n} f_{sm}(\underset{\sim}{Y}_n)\, e^{i\frac{k Y_n^2}{2\ell_n}} \right]}_{\text{field arriving at battle}} \left[\frac{\sqrt{\alpha}}{Y_n} f_{rm}(\underset{\sim}{Y}_n)\, e^{i\frac{k \underset{\sim}{Y}_n^2}{2\ell_n'}} \right]$$

ANSWERS

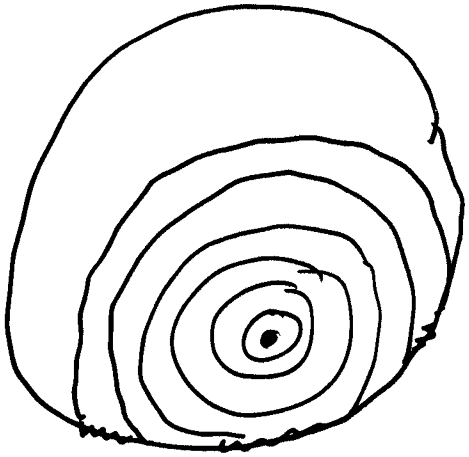
Ⓐ WORST CASE - FULL COHERENCE, CENTERED MIRRORS

$$\check{h}(f) = \frac{\alpha \lambda \bar{A}(f) \tilde{\xi}(f)}{L R} \sqrt{N_b}$$

$$= \frac{3 \times 10^{-24}}{\sqrt{Hz}} \bar{A}(f) \left(\frac{N_B}{220} \right)^{\frac{1}{2}}$$

$$= 8 \times \tilde{\check{h}}_{goal} \quad !$$

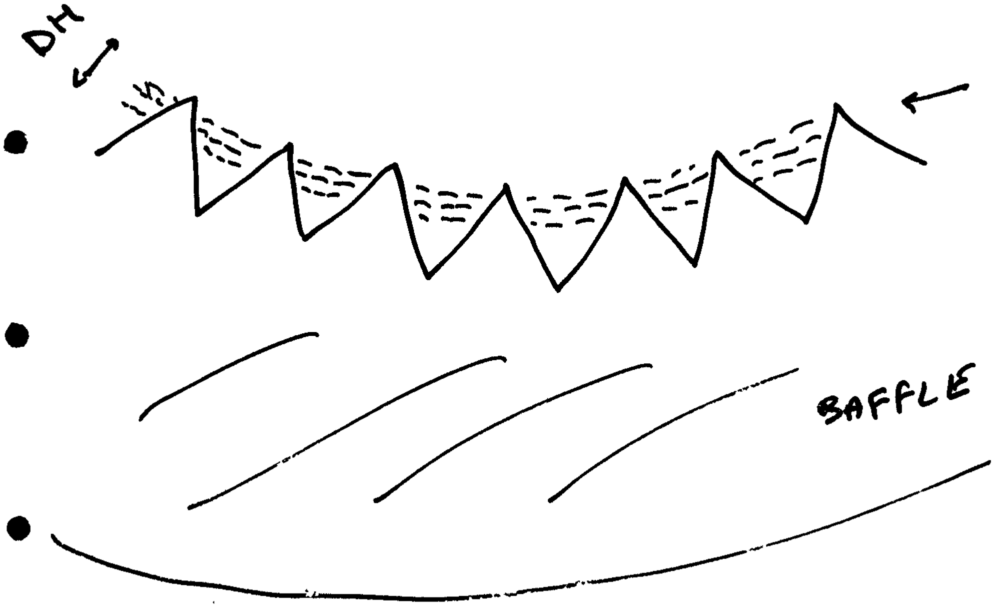
③ OFF-CENTERED MIRRORS ARE PROTECTED BY FRESNEL-FRINGE PATTERN



$$\check{h}_{diff}(f) = \sqrt{\frac{2}{3}}\ \frac{\alpha\sqrt{\lambda L}}{4\pi R}\ \frac{\lambda \bar{A}\, \tilde{\xi}_s}{L R}\ \sqrt{N_b}\ G(\rho)$$

$$= \frac{2\times10^{-25}}{\sqrt{Hz}} \left(\frac{f}{10Hz}\right)^{-2} \underbrace{\left(\frac{N_B}{220}\right)^{\frac{1}{2}}}_{\text{can improve by Factor of } \sqrt{2}} \ \frac{G(\rho)}{11}$$

ⓒ CENTERED BEAM, REGULAR SERRATIONS



Extend through many Fresnel zones.

- FIND

$$\boxed{\tilde{h}(f) = \tilde{\ell}(f)_{\text{worst case}} \times \frac{\sqrt{2}}{8\pi}\left(\frac{\lambda L}{R\,DH}\right)\sqrt{\frac{1}{N_b}\sum_{n=1}^{N_b}\beta_n^2}}$$

$$\beta_n = \frac{4\ell(L-\ell)}{L^2}$$

$$0.1 \leq \beta_n \leq 1.$$

$$= \frac{2 \times 10^{-25}}{\sqrt{Hz}} \underbrace{\sqrt{\frac{N_B}{220}}} \left(\frac{2mm}{\Delta H}\right) \bar{A}$$

CAN BE REDUCED BY $\sqrt{\frac{1}{5}}$ BY REMOVING BAFFLES

- RANDOMIZING THE SERRATIONS HELPS

REGULAR SERRATIONS

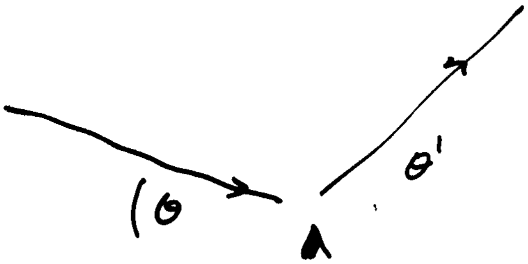
$$\int d\varphi = \underbrace{\sum_{\text{serrations}}}_{\text{still add in phase.}} \underbrace{\int_{1\,\text{serration}} d\varphi}_{\text{reduced by serrating}}$$

- $\check{h}(f)$ GOES DOWN BY

$$\sqrt{\frac{\sigma_B}{2\pi R}} \sim \sqrt{\frac{\sqrt{\frac{1}{4}\lambda L}}{2\pi R}} \simeq \frac{1}{12} \;!$$

σ_B = lengthscale over which serrations loose coherence.

AGREEMENT WITH INTENSITY ANALYSIS



$$\left(\frac{dE}{dt}\right)_{diff} = \left(\frac{dE}{dt\,dA}\right)_{in} \Delta x \; \Delta\theta' \; \underbrace{\frac{\lambda}{4\pi^2}\,\frac{1}{(\theta+\theta')}}_{\text{diffraction cross section.}}$$

- INTENSITY ANALYSIS PREDICTS THE SAME ANSWER AS FOR OFF CENTERED BEAMS IN ORDER OF MAGNITUDE

– ASSUME $\frac{dE}{dt\,dA}$ UNIFORM ON RECEIVING PLANE

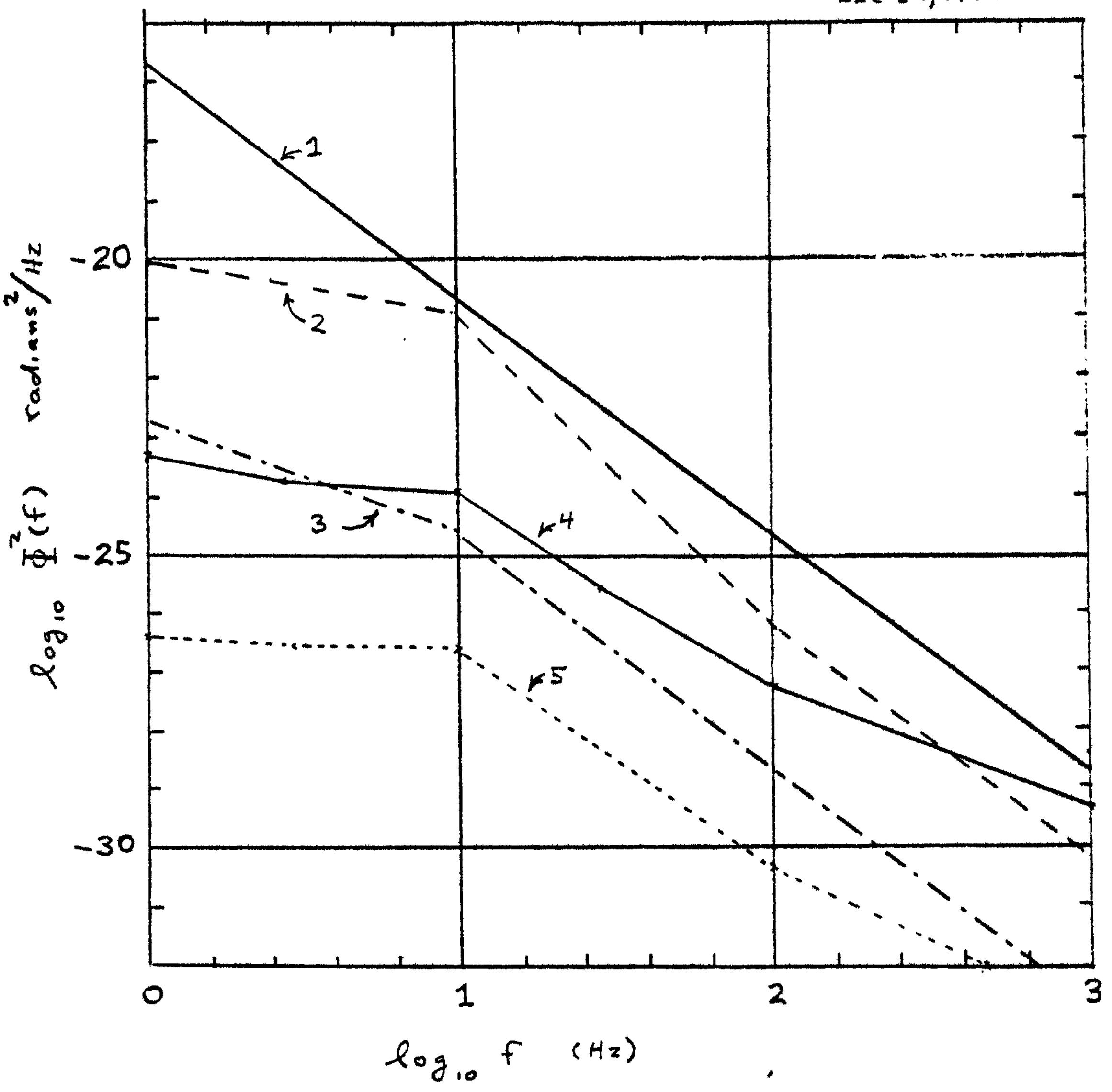
– $\check{h}(f) \propto \frac{\lambda^{3/2}}{R^2 L}$

RAI WEISS

CALCULATIONS OF

SCATTERING NOISE

DEC 29, 1994



PHASE NOISE FROM BRO STRAY LIGHT ANALYSIS

1 $^1/_{10}$ (AMPLITUDE) SQL 10^6 gms 4 Km

2 ALL PATHS, CAVITY MIRROR RECOMBINATION $f_0 = 10$ Hz

3 NO BACKSCATTER PATHS, CAVITY RECOMBINATION $f_0 = 10$ Hz

4 ALL PATHS, DETECTOR RECOMBINATION

5 NO BACKSCATTER PATHS, DETECTOR RECOMB.

$\left.\begin{matrix} 4 \\ 5 \end{matrix}\right\} \frac{\sigma_{SENS}}{SENS} \sim 10^{-3}$

BAFFLE AND STEEL SURFACE DIFFERENTIAL SCATTERING

$$\frac{\frac{dP_{SCAT}(\theta)}{d\Omega}}{P_{INC}} = 1.25 \times 10^{-2} \cos\theta \quad sr^{-1}$$

THE PHASE NOISE ANALYSIS FROM BREAULT STRAY LIGHT ANALYSIS

R. Weiss December 29, 1994

The stray light analysis was carried out by Breault Research Organization (BRO) based on a simplified model of the LIGO beam tubes and baffles. The phase noise analysis, using the results of the BRO study, was done by the LIGO project.

BRO Analysis:

In broad outline the original analysis used:

1. A simplified geometry of the LIGO tubes and baffles with one optical cavity

2. The optical beam was placed near the tube center

3. Baffles had a uniform 12 meter spacing with a radial height of 6cm high in the shape of a 45 degree isosceles triangle. The baffles were serrated at the top edge with a depth and period of 3mm.

4. The closest baffle to a mirror was 100 meters.

5. The differential scattering of the tube and the baffles was approximated by a Lambertian distribution

$$\frac{dP_{\text{scat}}(\theta)}{d\Omega}/P\text{inc} \;=\; 0.1\,\cos(\theta) \;\; \text{sr}^{-1}$$

6. The BRO diffraction model for baffles with serrated edges was used.

7. An effective reflectivity of the tube and baffle combinations was used in 10 discrete sections of the system.

8. The cavity mirror scattering (and subsequent recombination in the phase noise estimate) used a differential scattering

$$\frac{dP_{\text{scat}}(\theta)}{d\Omega}/P_{\text{inc}} \;=\; \frac{1\times10^{-6}}{\theta^2} \;\; \text{sr}^{-1}$$

9. The stray light propagation used ASAP a "directed" Monte Carlo method to gain sensitivity (requires experience and forethought to get the correct normalization).

10. The stray light intensity and brightness was estimated in maps at the tube ends.

11. The path history was given for each entry in the map.

    Number, location and type of encounter/entry

    Backscatter, forward scatter or specular reflection

Phase noise power estimate

The program broscat1a.f was used, the introduction to the program is given below.

Program calculates the phase noise from the individual paths in the BRO scattering analysis. It calculates the maximum, average and minimum phase noise for each of the trajectories given in the BRO path history tables and also uses both recombination at the final mirror with mode filtering or recombination at a nonuniform photodetector. The estimate is made at 7 frequencies of the ground noise 1,3,10,30,100,300,1000 Hz.It uses the notation of the BRO layout.

The seperate regions of the calculation are:

Region 1 = input mirror

Region 2 = 100 meters of wall at input mirror

Region 3 = Position of first baffle at 100 meters

Region 4 = 307 baffles and wall 100 to 1400 meters from input mirror

Region 5 = 307 baffles and wall 1400 to 2700 meters from input mirror

Region 6 = 307 baffles and wall 2700 to 4000 meters from input mirror

Region 7 = Position of baffle at 4000 meters

Region 8 = 100 meters of wall between 4000 to 4100 meters from input mirror

Region 9 = Output mirror

Region 10 = Reference plane inside the cavity at the input mirror

The amplitude spectral density of position noise on a tube wall or baffle is assumed to be isotropic and given by

x(f) = 10**-7 $1 \leq$ f $\leq$ 10 Hz cm/sqrt(Hz)
= 10**-5 / f**2 f $\geq$ 10 Hz

The amplitude of the angular fluctuation noise at the walls is

mu(f) = 6 x 10**-9/f f $\geq$ 10 Hz radians/sqrt(Hz)

The angular fluctuations include a Q of ten for the undamped tube modes. The spectrum is also used illegitimately for f $\leq$ 10 Hz

The phase noise is summed in power with three different cases

Case 1 Forward scattering:

phi**2(f,theta) = (4*pi*theta*x(f)/lambda)**2

Case 2 Back scattering:

phi**2(f,theta) = (4*pi*x(f)/lambda)**2

Case 3 Specular reflection:

phi**2(f,theta,al) = (4*pi*theta*(bl-2*al)*mu(f)/lambda)**2

where al is the distance of the specular reflection center from one end of the tube and bl is the distance between the reference plane and the origin of the ray to be specularly reflected.

New information after the initial estimation

The backscattering of the candidate steel for the beam tubes at 45 degrees incidence is smaller than that assumed in the BRO model by about a factor of 8. (This is about to be altered again based on the December 1994 measurements on the qualification test beam tube)

The spatial uniformity of the photodiode sensitivity, initially assumed to have an rms of 0.1 was measured to have an rms of 0.001. This makes photodetector recombination a less important process.

Vinet discovered an error in the calculations we had made in the estimate of the scattered field in the cavity. He asserted, and we agree, that the cavity field build up of the scattered field must be included in estimating the phase noise. This has increased the phase noise by cavity mirror recombination.

The original phase noise power estimates included only the phase noise contribution from one mirror, these have to be increased by a factor of 4 to account for the four cavity mirrors.

The enclosed figure shows the most recent version of the scattered phase noise budget including the above corrections.

The recombination probabilities are:

For an unapodized beam and a non-uniform photodetector, case 1:

Prec(theta) = ((1-eta)**2/2*theta)*sqrt(lambda/L)

For an apodized beam (mode filterered), case 2:

Prec(theta) = (2*alpha/theta**2)*(lambda/L)

The calculation is done by summing the phase contribution from each step in the BRO history of a single path . The BRO normalized intensity for a specific path is the fractional power scattered to the reference plane already integrated over the specified area at the reference plane and over the solid angle subtended at the reference plane of all rays associated with that particular path.

The specified area should really depend on the recombination process, I will use the waist area for both apodized and unapodized estimates.

The calculation consists of

sum phase noise**2 = sum(over all paths in list)* BRO(intensity) *Prec(theta last contact with tube before reference plane)*sum(phase noise**2)of BRO described path

This is done for the 7 frequencies and for three cases the max, average and minimum determined from the minimum, average and maximum angle associated with rays coming from the BRO regions.

Initial results

Baffle backscattering dominates the phase noise budget

Estimated phase noise for cavity recombination lies below 1/10 (amplitude) standard quantum limit associated with a 1 ton mass. The cavity storage time is adjusted to be $\tau = \frac{1}{4\pi f}$ to convert to a phase noise.

Iterations of the numerical analysis

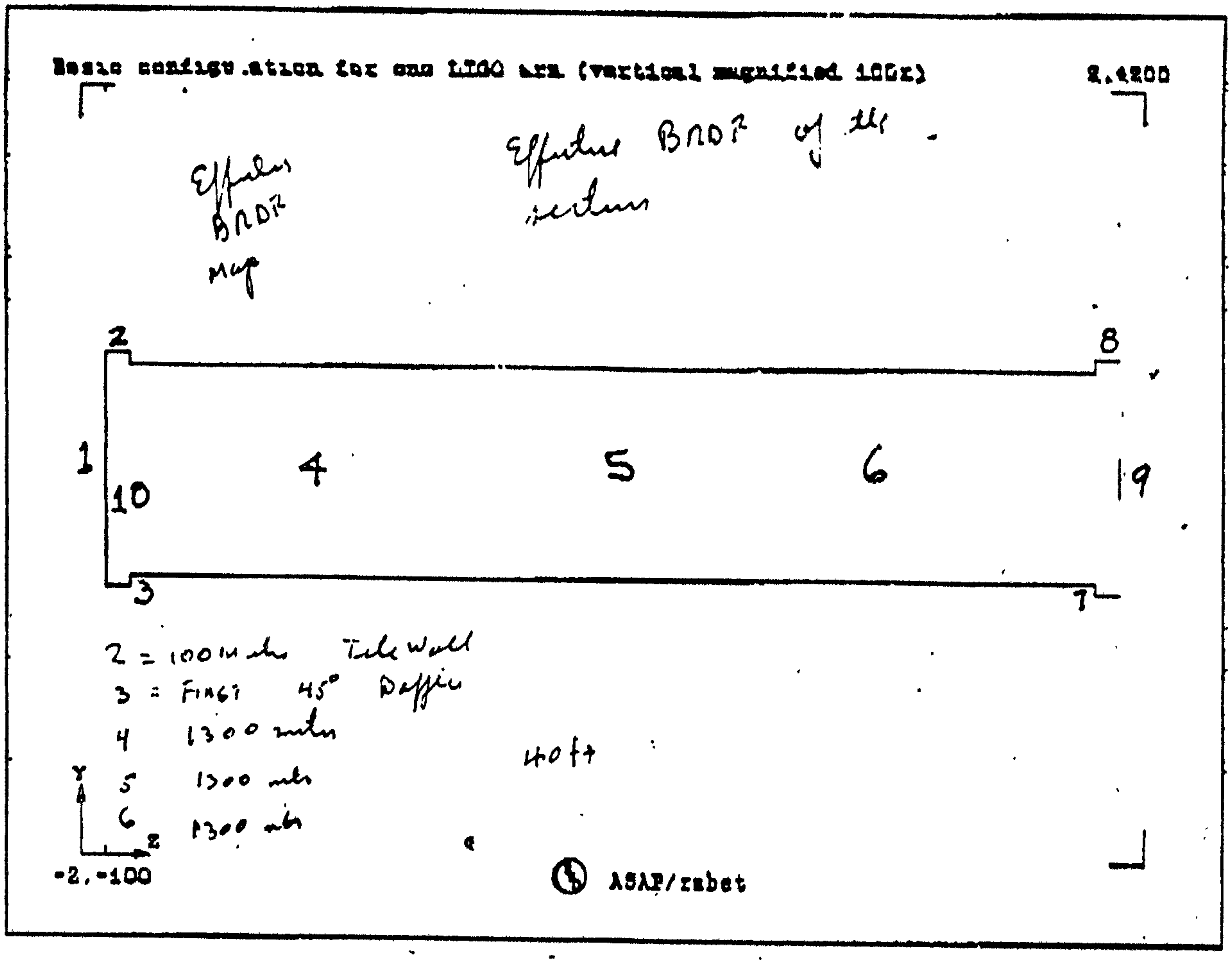
a) The tube and baffle surface roughness was varied $\sigma = 2.5$, 5.0, 7.5 μ

b) The beam was moved 30cm from the tube center.

c) The first baffle was placed at 10 and 30 meters from the nearest mirror.

d) An unprejudiced Monte Carlo analysis was run in the 100 meters nearest the mirror.

Changes in the phase noise power estimates were less than a factor 4 for any of these iterations. The changes can be understood by analytic methods.



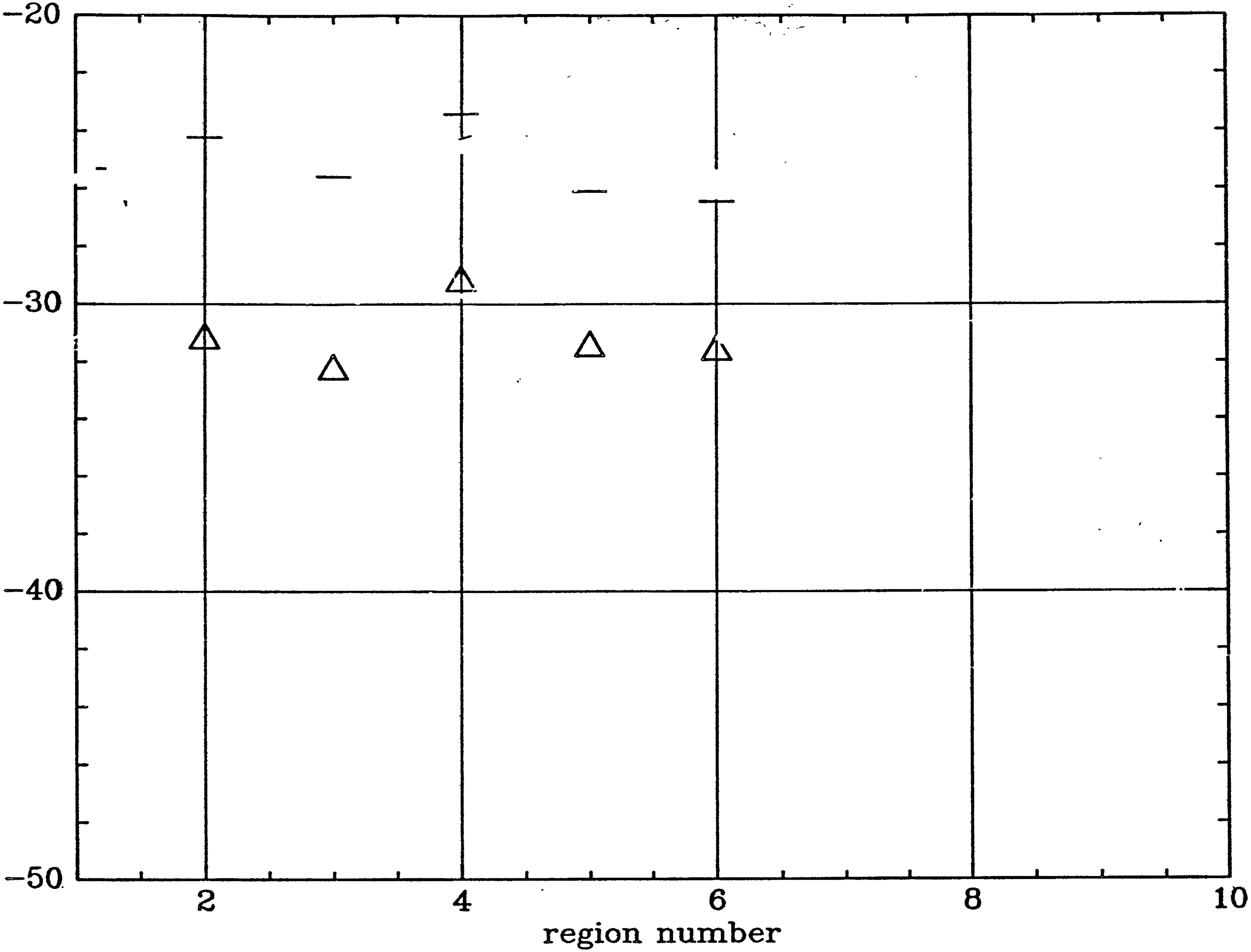
The basic configuration analyzed in this report is a single 4 kilometer arm with all mirrors on axis and no mid-station mirrors. A plot of the computer model of this configuration is shown above with the vertical direction magnified 100 times in order to show more detail. Each distinct surface in the model is called an "object" and is given a unique number and name as listed in the following table :

```
OBJECT numbers/names:
  1=FIRST MIRROR              2=FIRST TUBE WALL          3=FIRST BAFFLE
  4=FIRST BAFFLE SET          5=CENTER BAFFLE SET        6=END BAFFLE SET
  7=END BAFFLE                8=END TUBE WALL            9=END MIRROR
 10=REFERENCE
```

The baffled tube was divided into five sections, separate 100 meter sections at each end and three 1300 meter sections in between. Only the first and last baffles nearest the mirrors were modelled directly. The effects of the other 300 or so baffles were simulated by an effective "scattering" from these 3 objects. None the of the mirror chambers are shown since early on they were found to be insignificant.

phase noise by region of last scat. dash=unapod. triang.. = apod.

bro2a.dat : Mon Apr 6 09:23:04 1992

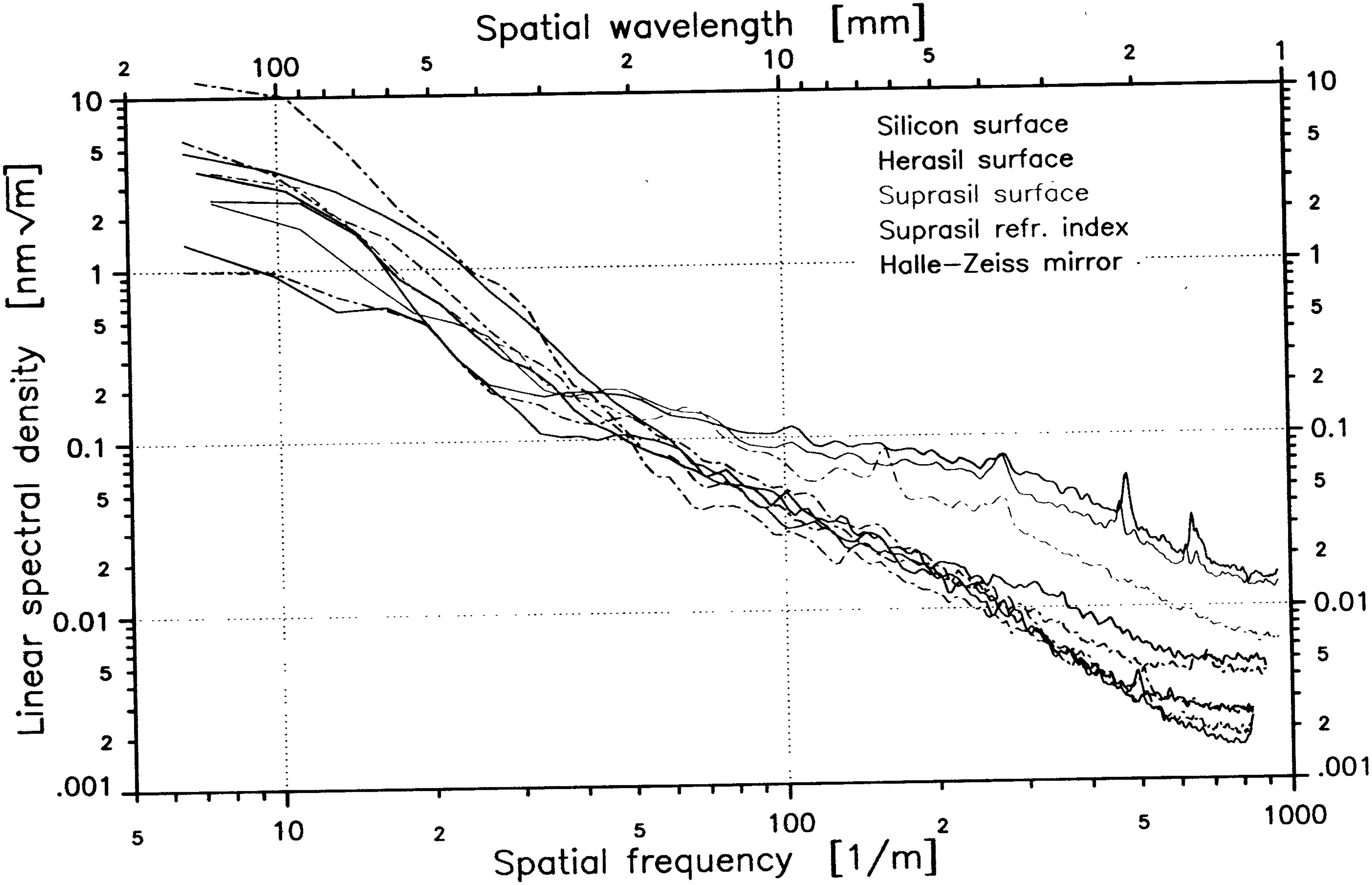


Mirror Properties

Walter Winkler

Roland Schilling, MPQ Garching, 29.11.94 14:52:48

Spectrum of optical path variations



Angular distribution of scatter

The **scattered field** ψ_{scat} (w/o the 00-mode) can be calculated as

$$\psi_{\text{scat}} = \psi_{\text{d}} - a_{00}\psi_{00}\,.$$

Conversion to **angular space** by 2-dim Fourier transformation:

$$\psi^{\text{a}}(\vartheta_x, \vartheta_y) = \text{FT}\Big(\psi_{\text{scat}}(x, y)\Big)\,.$$

The **scattering function** $f(\vartheta)$ is given by averaging over the azimuthal dependence of ψ^a:

$$f(\vartheta) = \frac{1}{2\pi}\int_0^{2\pi} \psi^{\text{a}}(\vartheta, \varphi)\, d\varphi\,.$$

Relation between scattering angle ϑ and spatial wavelength Λ, depending on the light wavelength λ, is given by $\vartheta = \lambda/\Lambda$.

$\Longrightarrow$ Minimum angle $\vartheta_{\text{min}} = \frac{\lambda}{D} \approx 5\,\mu\text{rad}$,

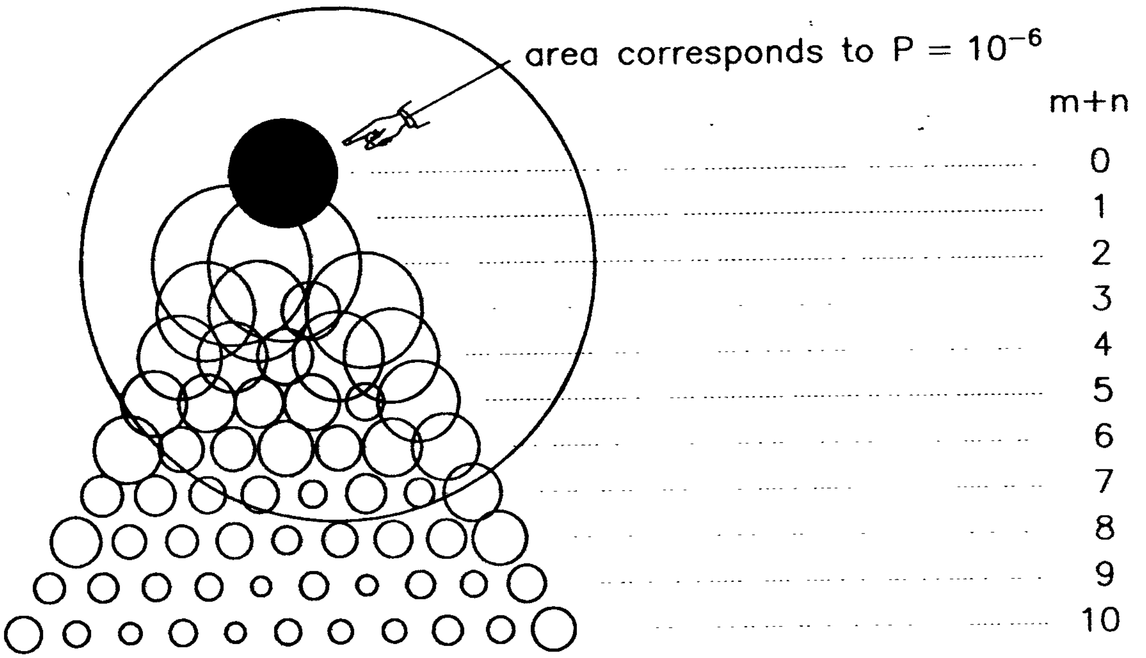
maximum angle $\vartheta_{\text{max}} = \vartheta_{\text{min}}\frac{N}{2} \approx 1\,\text{mrad}$,

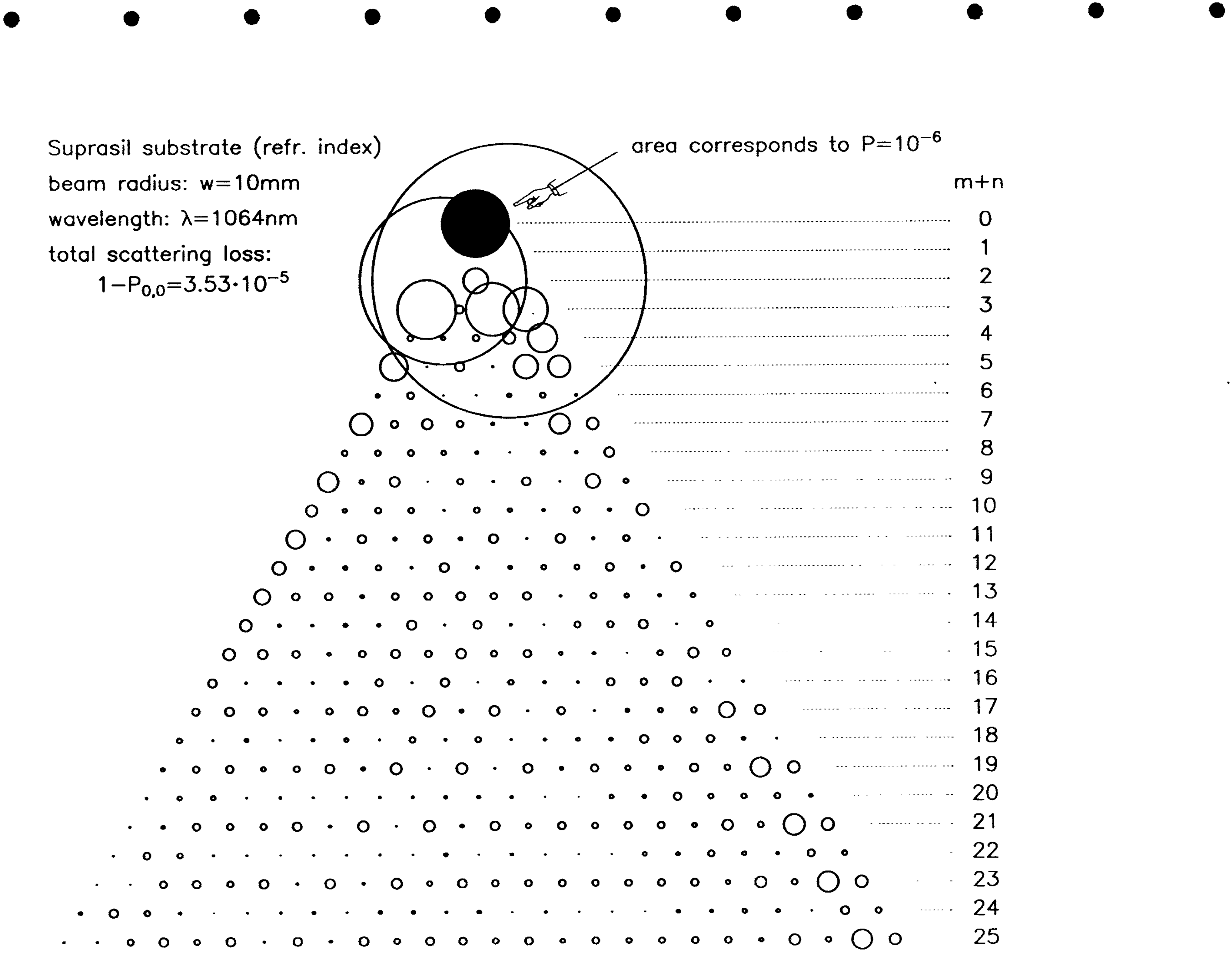
with D = diameter of the component and N = number of data points in one dimension.

Roland Schilling, MPQ Garching, 29.11.94 17:52:39

Suprasil refr. index

beam radius: $w = 10.0$ mm
wavelength: $\lambda = 1064$ nm
total scattering loss:
$1-P_{0,0} = 7.03 \cdot 10^{-5}$




Suprasil substrate (refr. index)
beam radius: w=10mm
wavelength: λ=1064nm
total scattering loss:
$1-P_{0,0}=3.53\cdot10^{-5}$
area corresponds to $P=10^{-6}$
m+n
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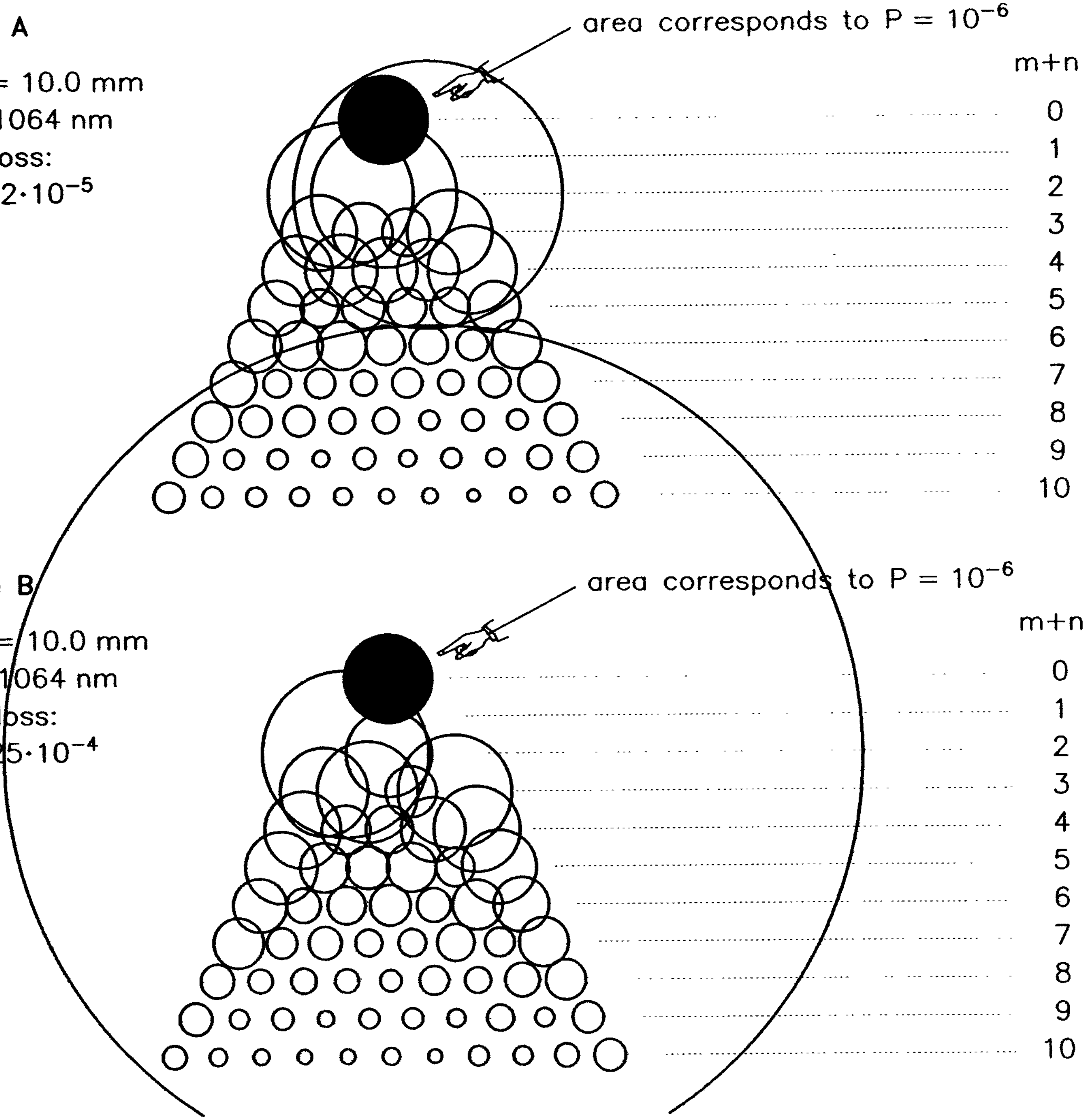
Roland Schilling, MPQ Garching, 01.12.94 10:14:01

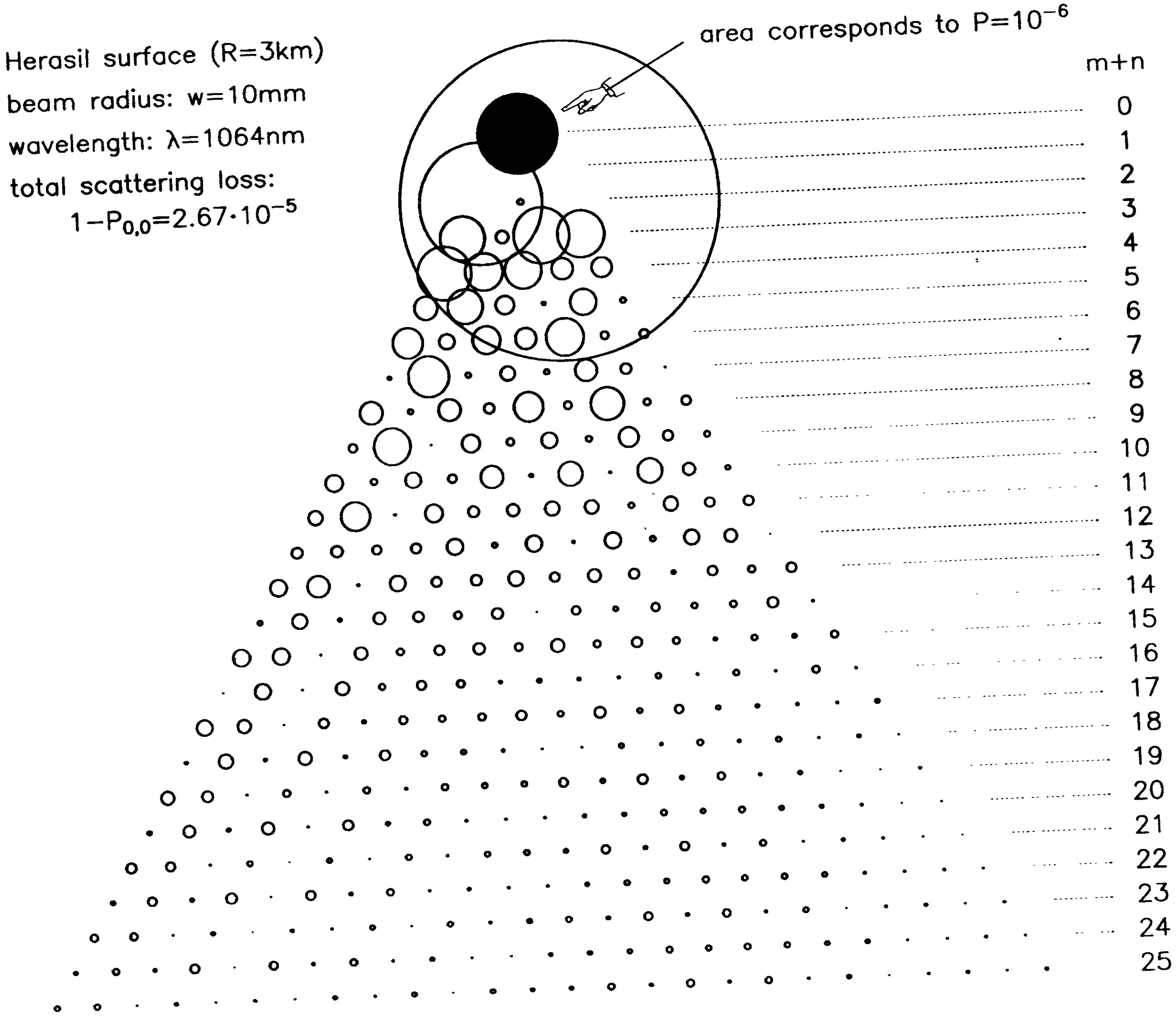
Suprasil surface A

beam radius: w = 10.0 mm
wavelength: λ = 1064 nm
total scattering loss:
$1-P_{0,0} = 4.72 \cdot 10^{-5}$

Suprasil surface B

beam radius: w = 10.0 mm
wavelength: λ = 1064 nm
total scattering loss:
$1-P_{0,0} = 1.25 \cdot 10^{-4}$




Herasil surface (R=3km)
beam radius: w=10mm
wavelength: λ=1064nm
total scattering loss:
$1-P_{0,0}=2.67\cdot10^{-5}$
area corresponds to $P=10^{-6}$
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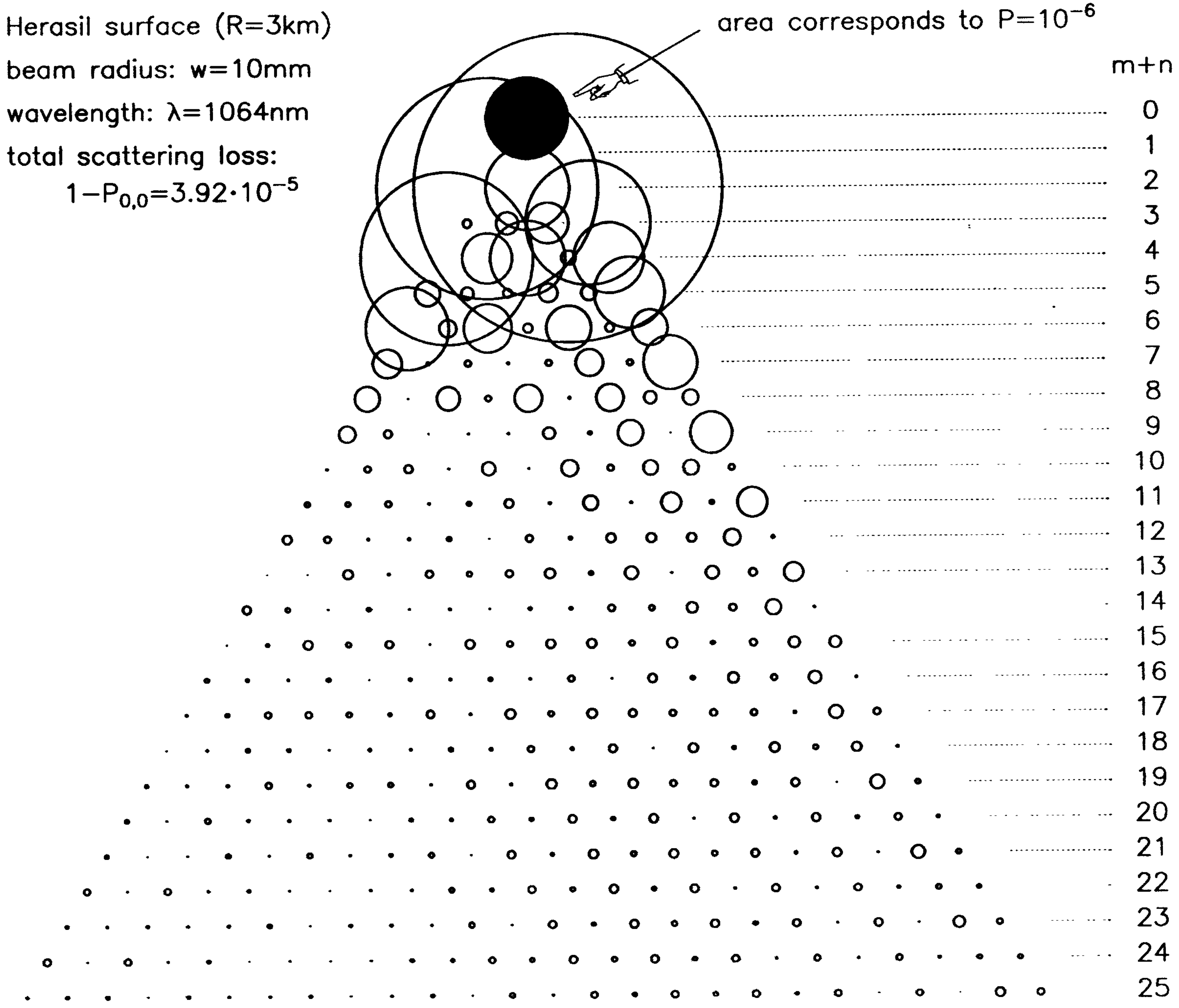
Herasil surface (R=3km)
beam radius: w=10mm
wavelength: λ=1064nm
total scattering loss:
1−$P_{0,0}$=3.92·10^{-5}
area corresponds to P=10^{-6}
m+n
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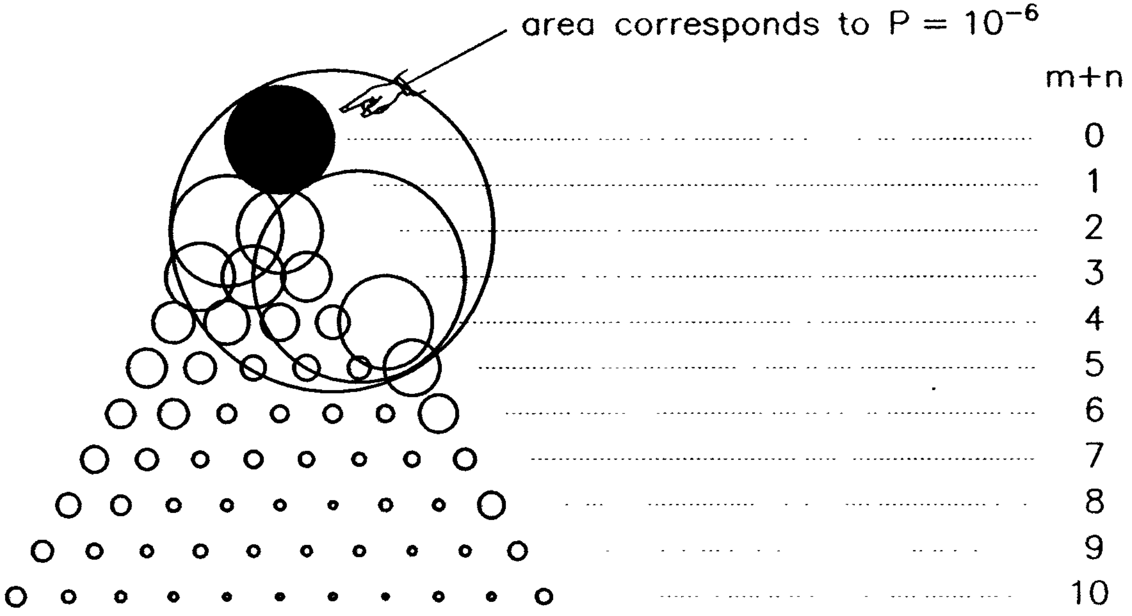
Roland Schilling, MPQ Garching, 01.12.94 10:42:10

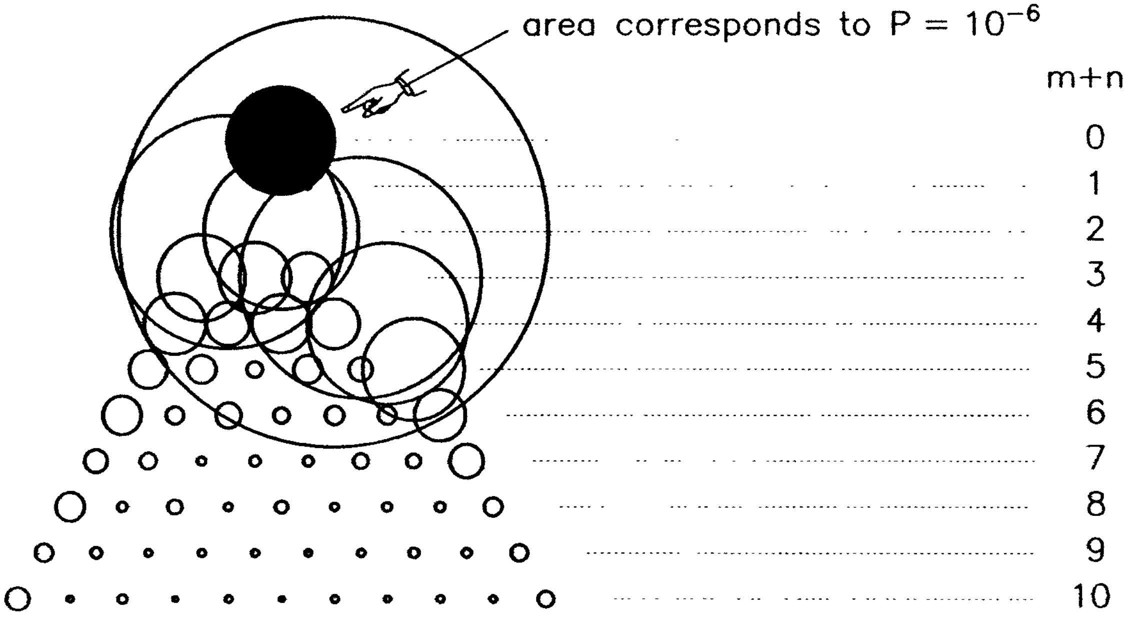
Silicon sample 1i

beam radius: w = 10.0 mm
wavelength: $\lambda = 1064$ nm
total scattering loss:
$1-P_{0,0} = 1.99\cdot10^{-5}$



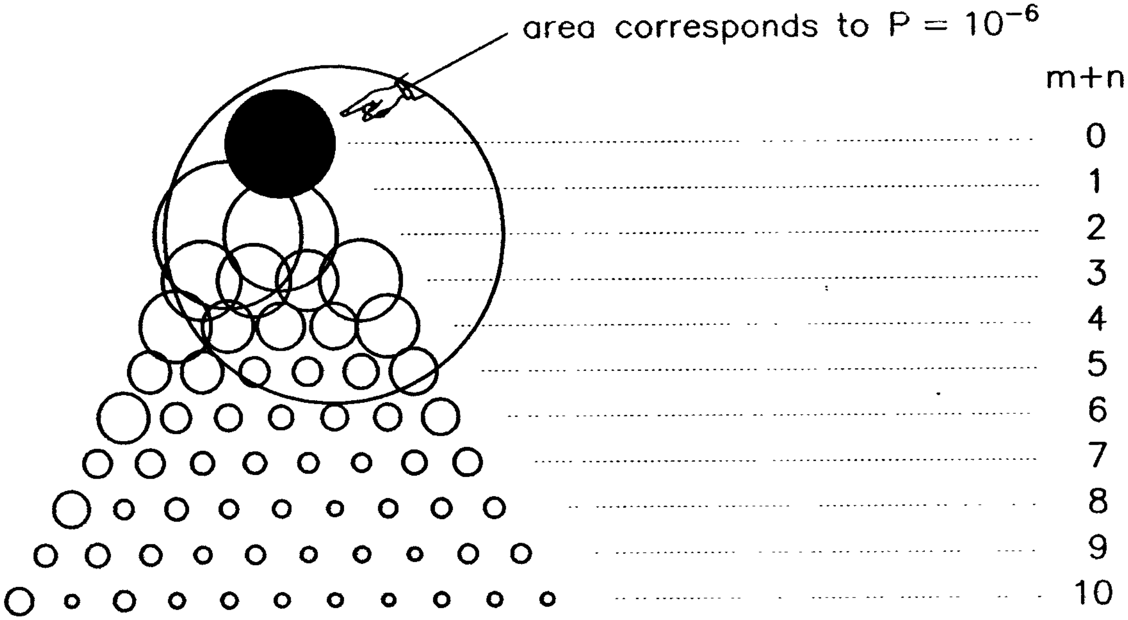
Silicon sample 2i

beam radius: w = 10.0 mm
wavelength: $\lambda = 1064$ nm
total scattering loss:
$1-P_{0,0} = 3.62\cdot10^{-5}$



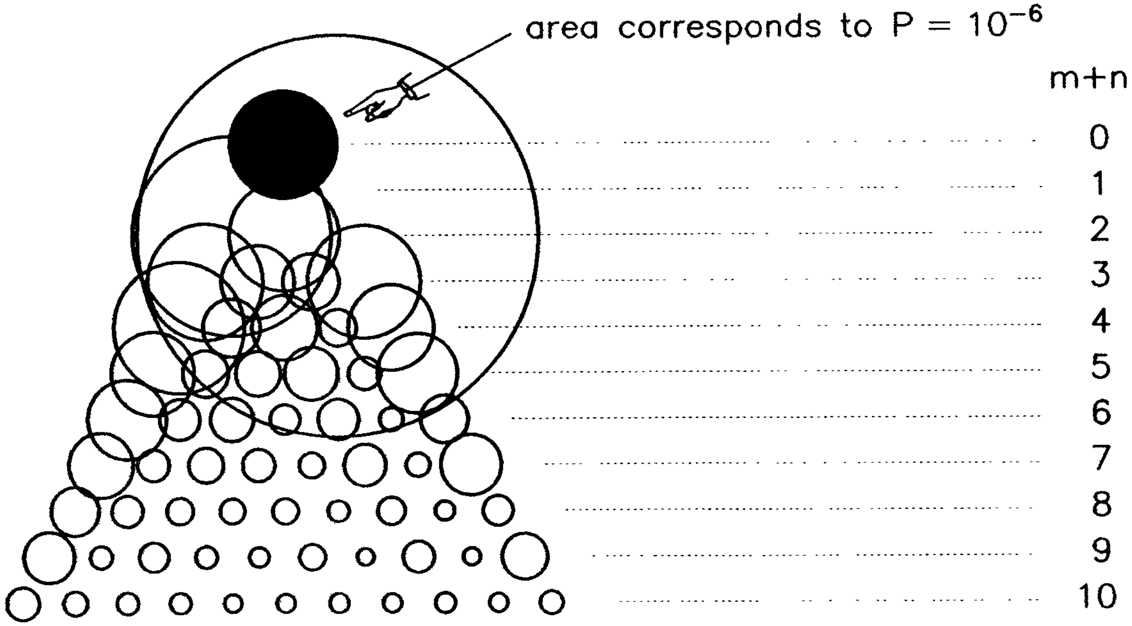
Herasil sample 1

beam radius: w = 10.0 mm
wavelength: $\lambda = 1064$ nm
total scattering loss:
$1-P_{0,0} = 2.14\cdot 10^{-5}$



Herasil sample 2

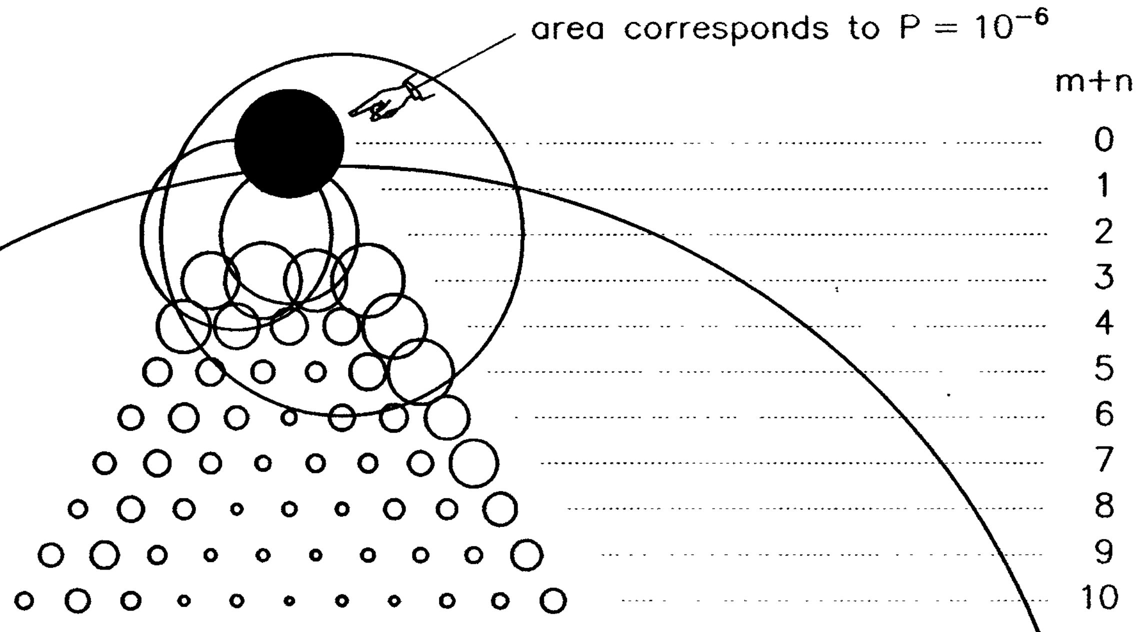
beam radius: w = 10.0 mm
wavelength: $\lambda = 1064$ nm
total scattering loss:
$1-P_{0,0} = 3.58\cdot 10^{-5}$



Roland Schilling, MPQ Garching, 01.12.94 15:46:48

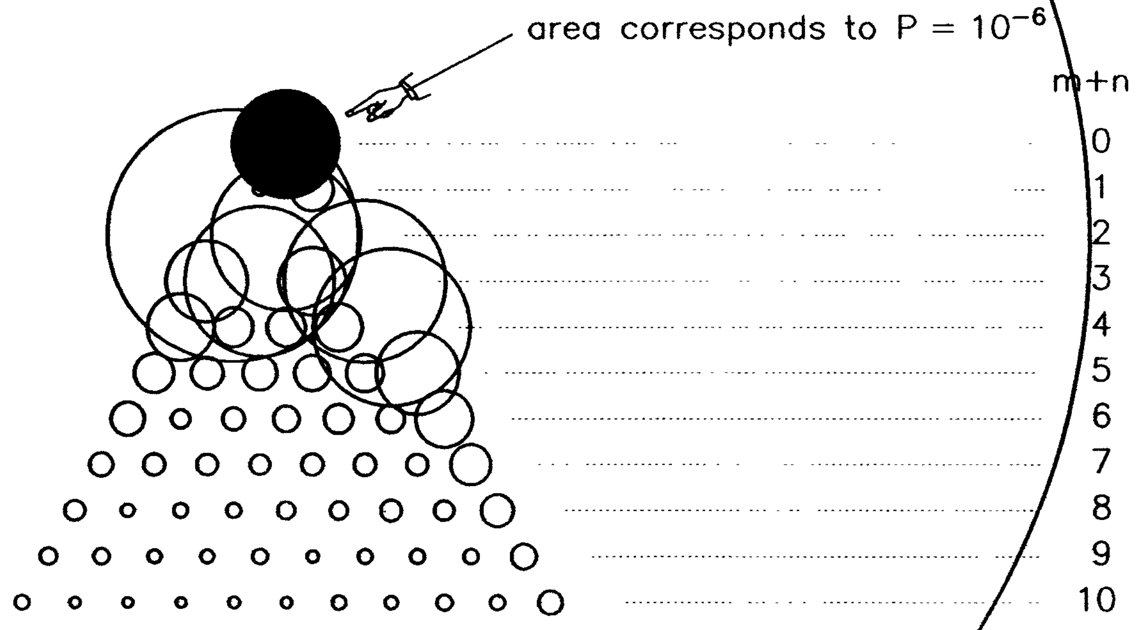
HZ #5 (uncoated)

beam radius: w = 10.0 mm
wavelength: λ = 1064 nm
total scattering loss:
$1-P_{0,0} = 2.41\cdot10^{-5}$



HZ #5 (coated)

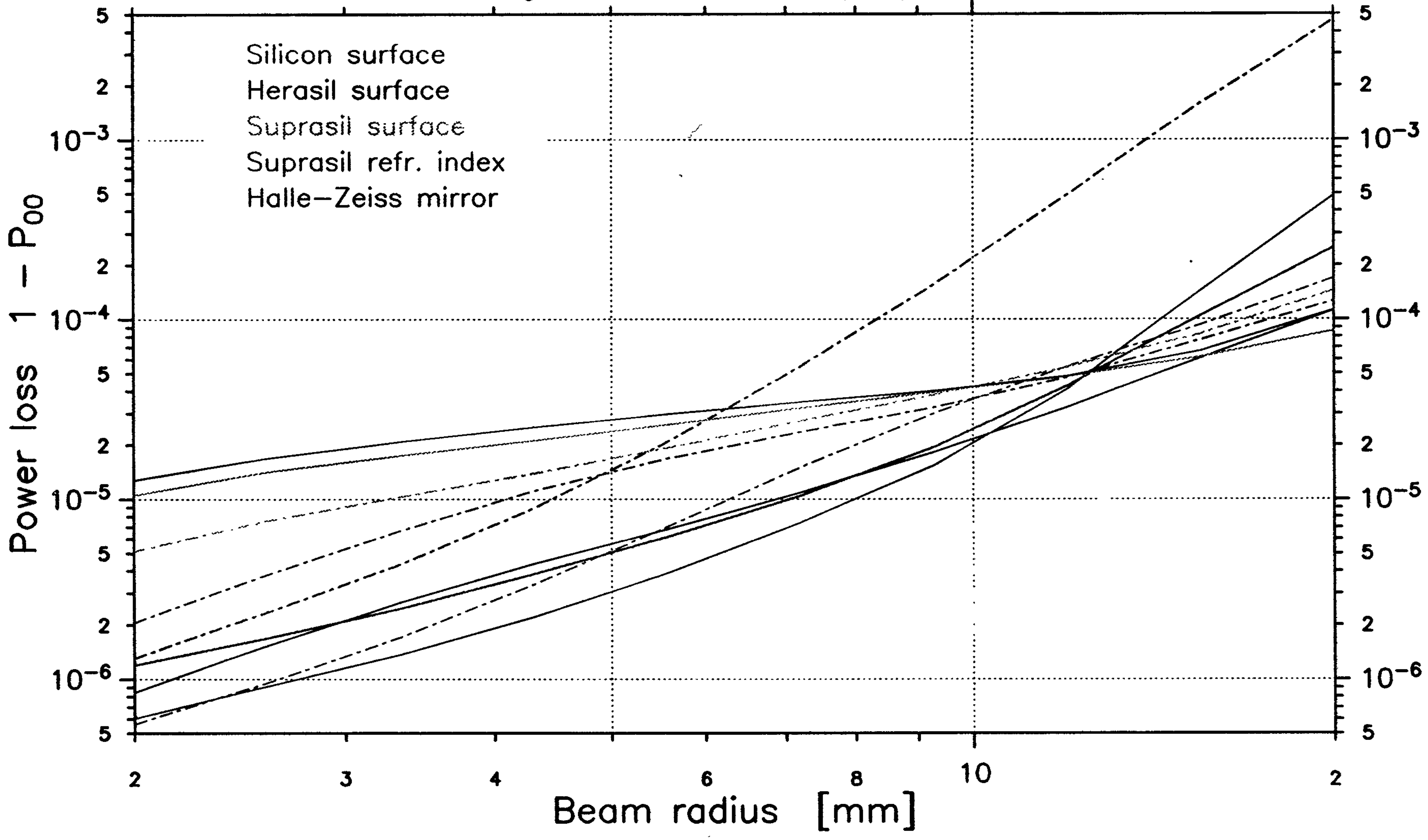
beam radius: w = 10.0 mm
wavelength: λ = 1064 nm
total scattering loss:
$1-P_{0,0} = 2.17\cdot10^{-4}$



Roland Schilling, MPQ Garching, 06.12.94 13:47:18

Total scattering loss

averaged over 20 different spot positions



Power loss due to scattering

The **distorted light field** ψ_d can be described as

$$\psi_{\mathrm{d}}(x, y) = d(x, y) \cdot \psi_{00}(x, y)$$

(incident beam assumed to be pure 00-mode).

The amplitude a_{00} contained in ψ_{d} is given by

$$a_{00} = \iint_{-\infty}^{+\infty} \psi_{\mathrm{d}} \, \psi_{00} \, dx \, dy \, .$$

It depends on the beam radius w of the incident beam.

The power P_{scat} lost from the fundamental mode is

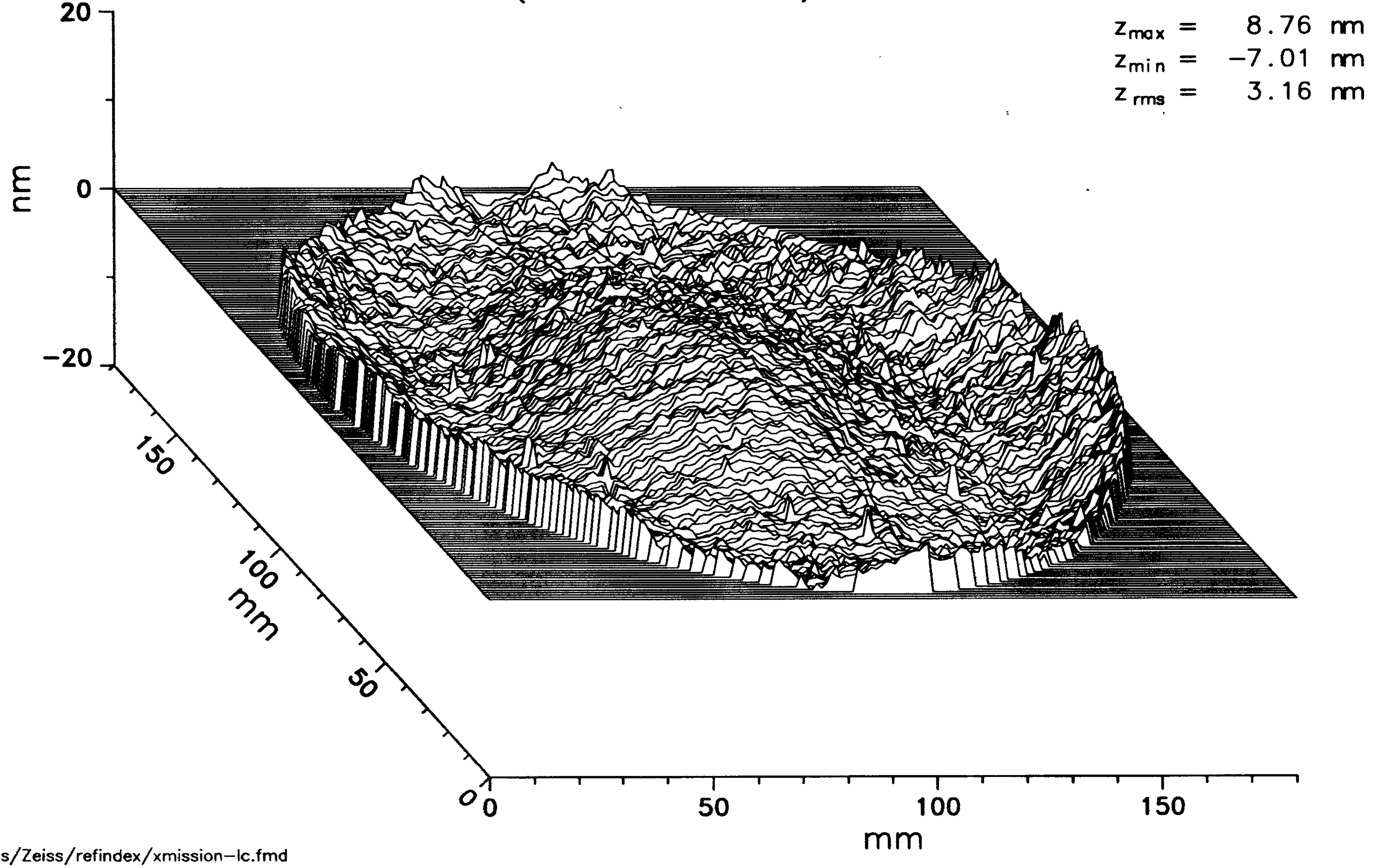
$$P_{\mathrm{scat}} = 1 - a_{00}^2 \, .$$

Conversion into **higher order modes:**

$$a_{mn} = \iint_{-\infty}^{+\infty} \psi_{\mathrm{d}} \, \psi_{mn} \, dx \, dy \, .$$

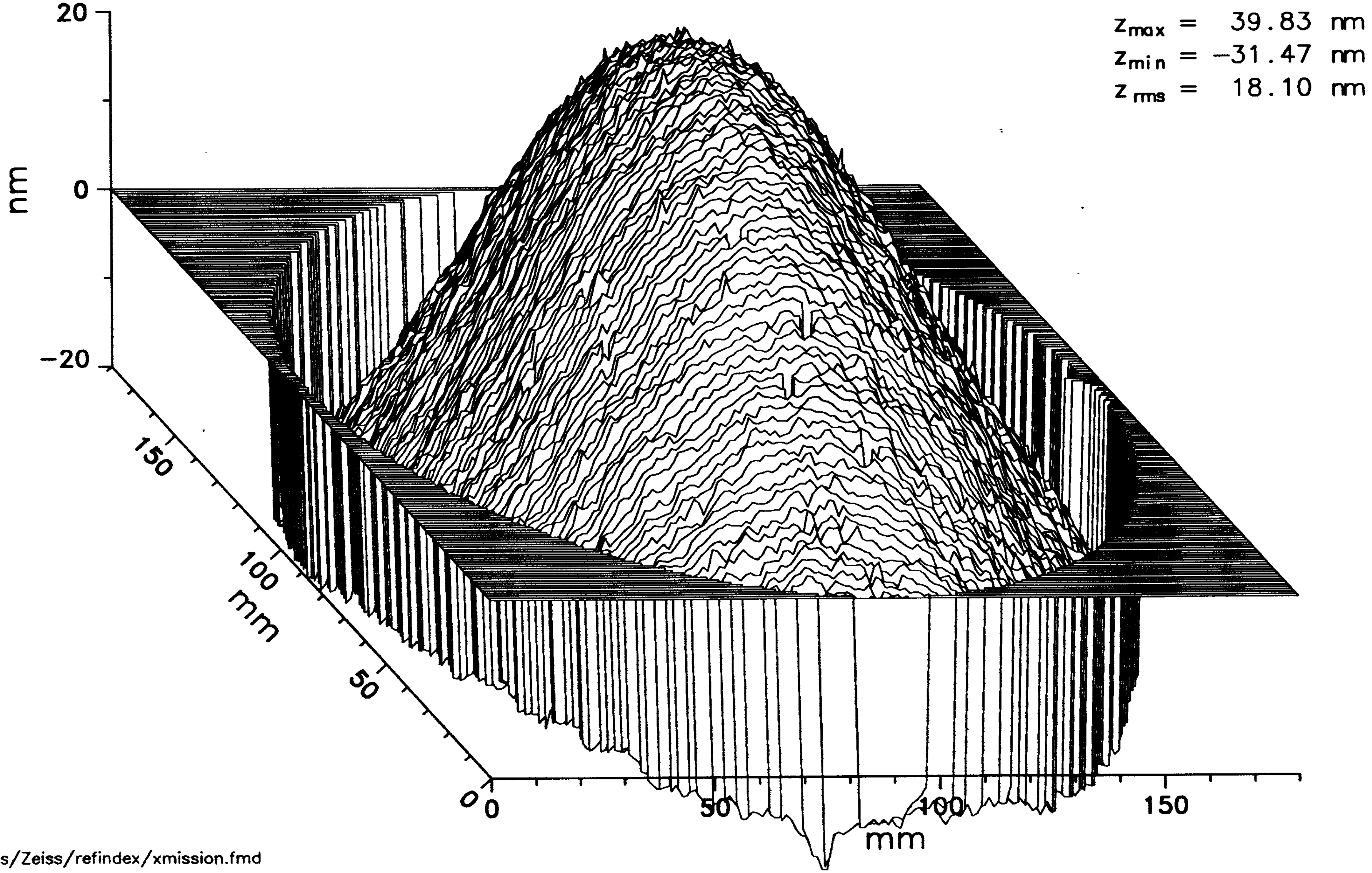
Suprasil substrate: refractive index variations

(lens effect subtracted)

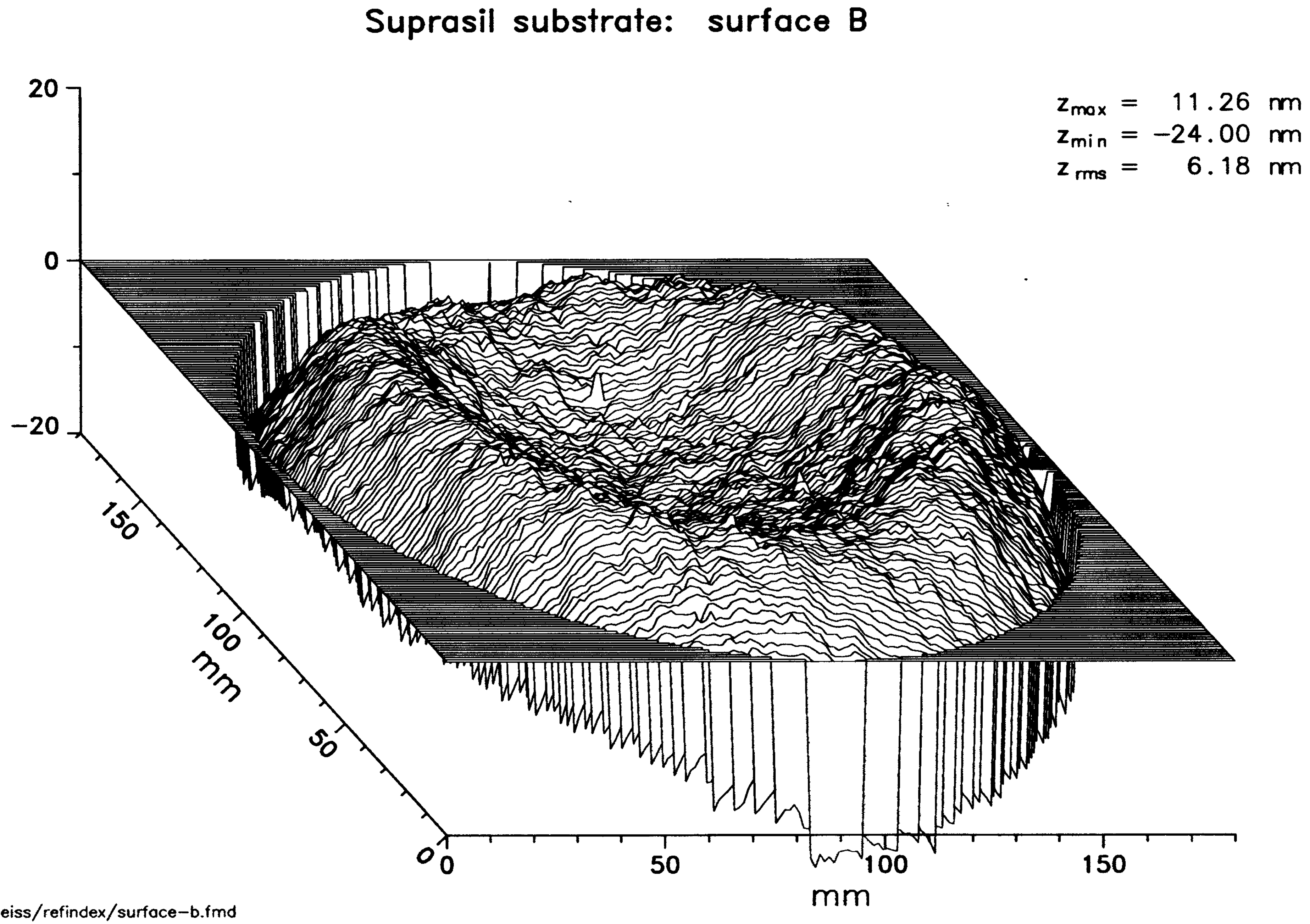


u/ros/Zeiss/refindex/xmission−lc.fmd

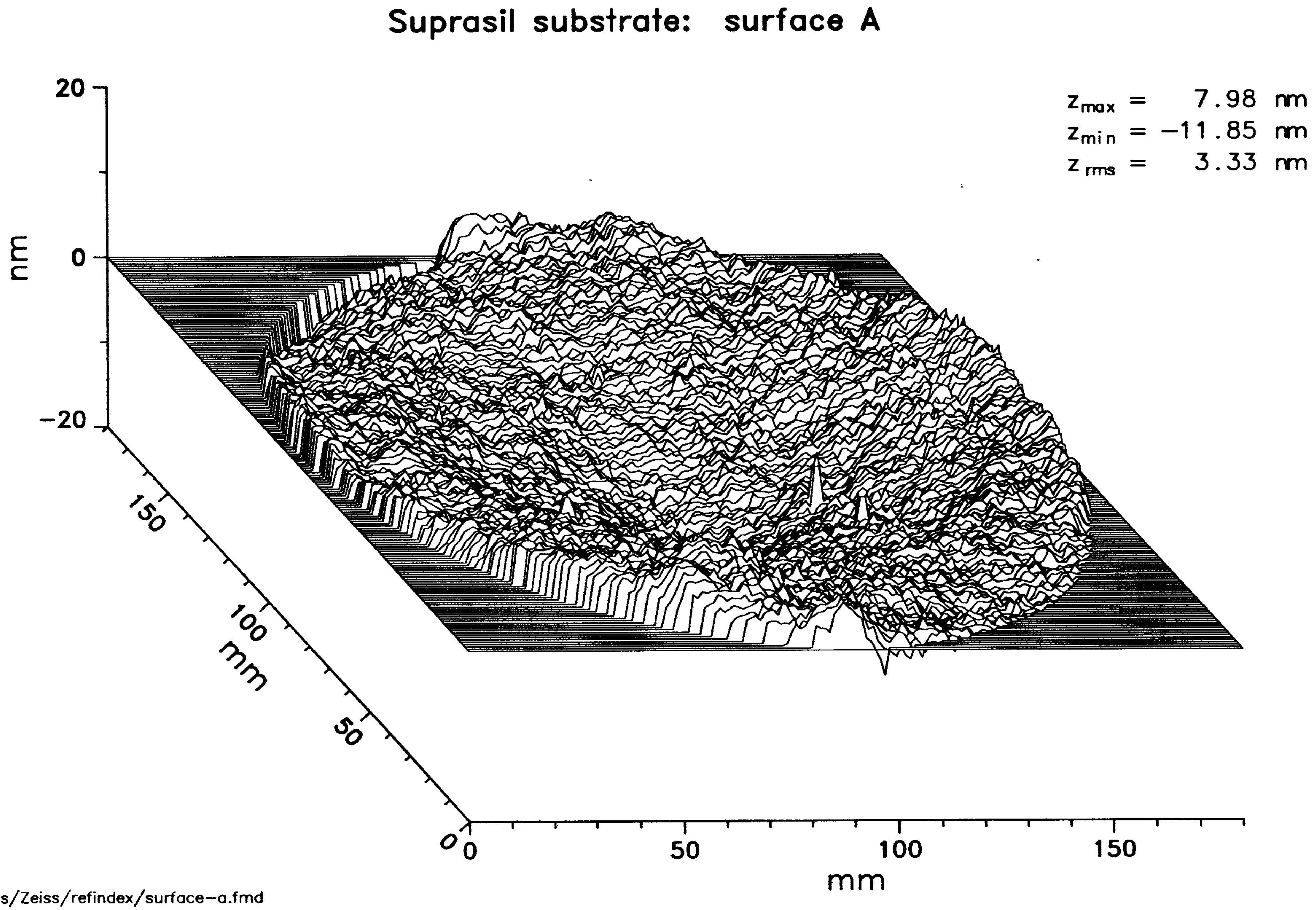
Suprasil substrate: refractive index variations



/u/ros/Zeiss/refindex/xmission.fmd

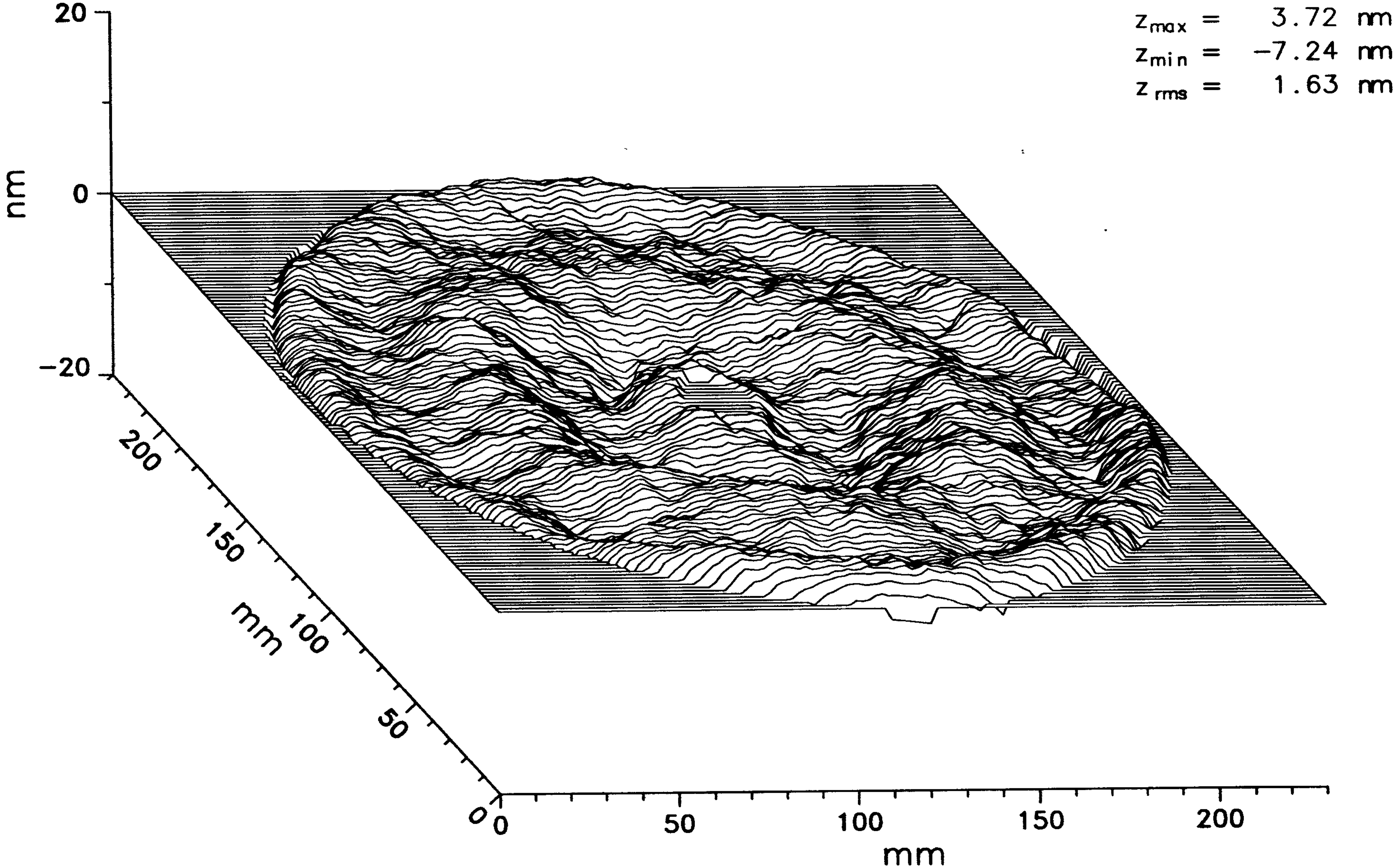


/u/ros/Zeiss/refindex/surface-b.fmd


Suprasil substrate: surface A

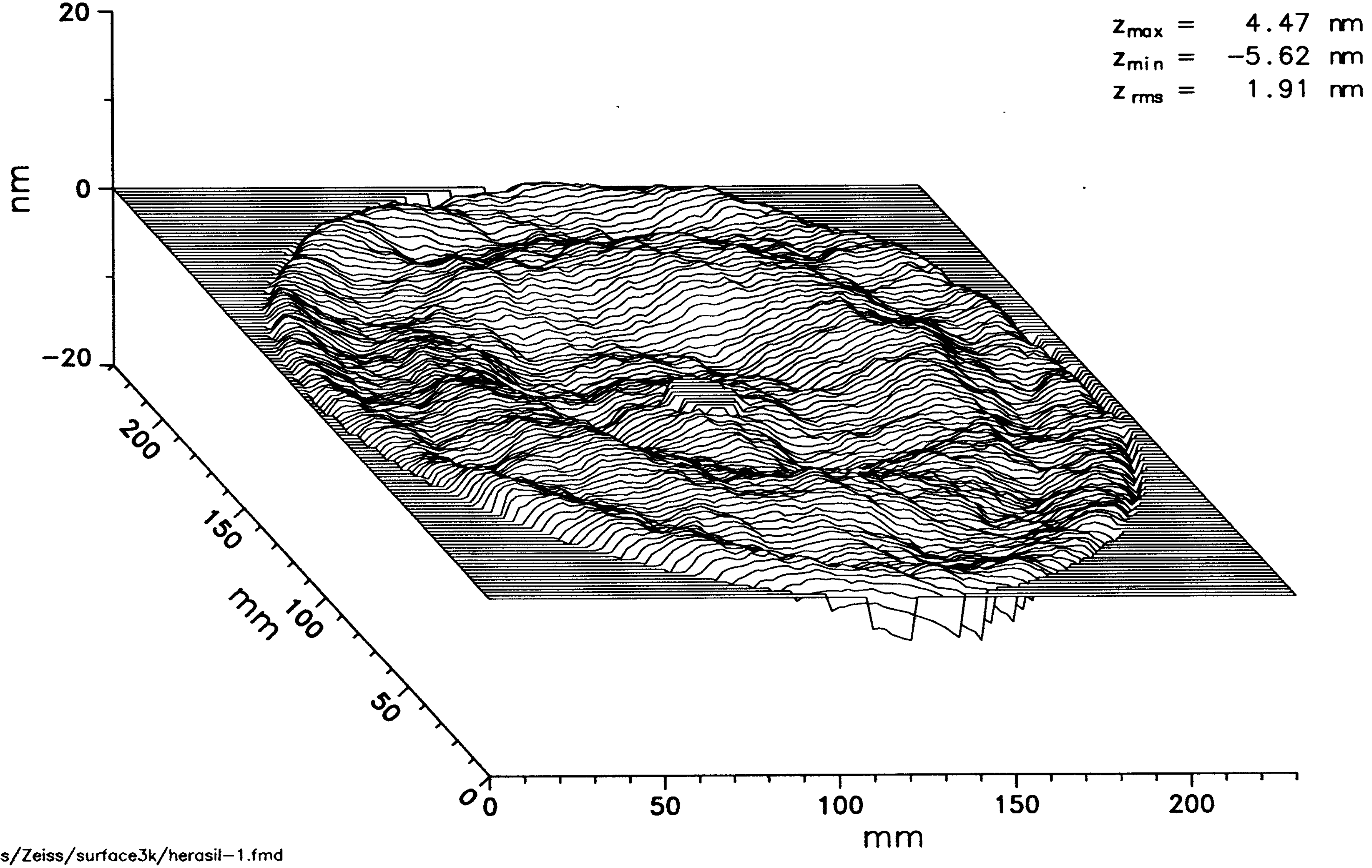
/u/ros/Zeiss/refindex/surface-a.fmd

Herasil substrate: sample 2 (R = 3km)

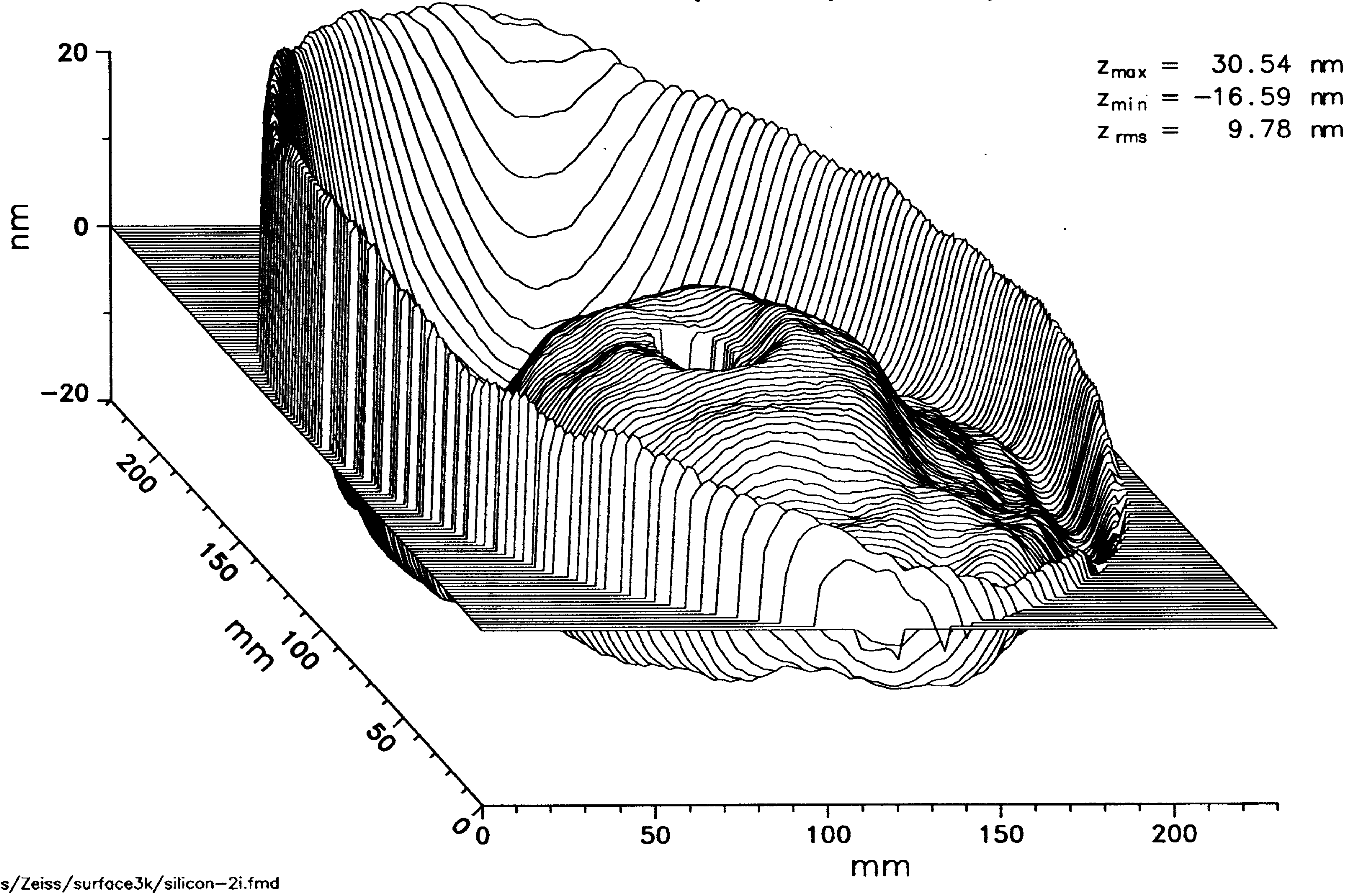


/u/ros/Zeiss/surface3k/herasil-2.fmd

Herasil substrate: sample 1 (R = 3km)



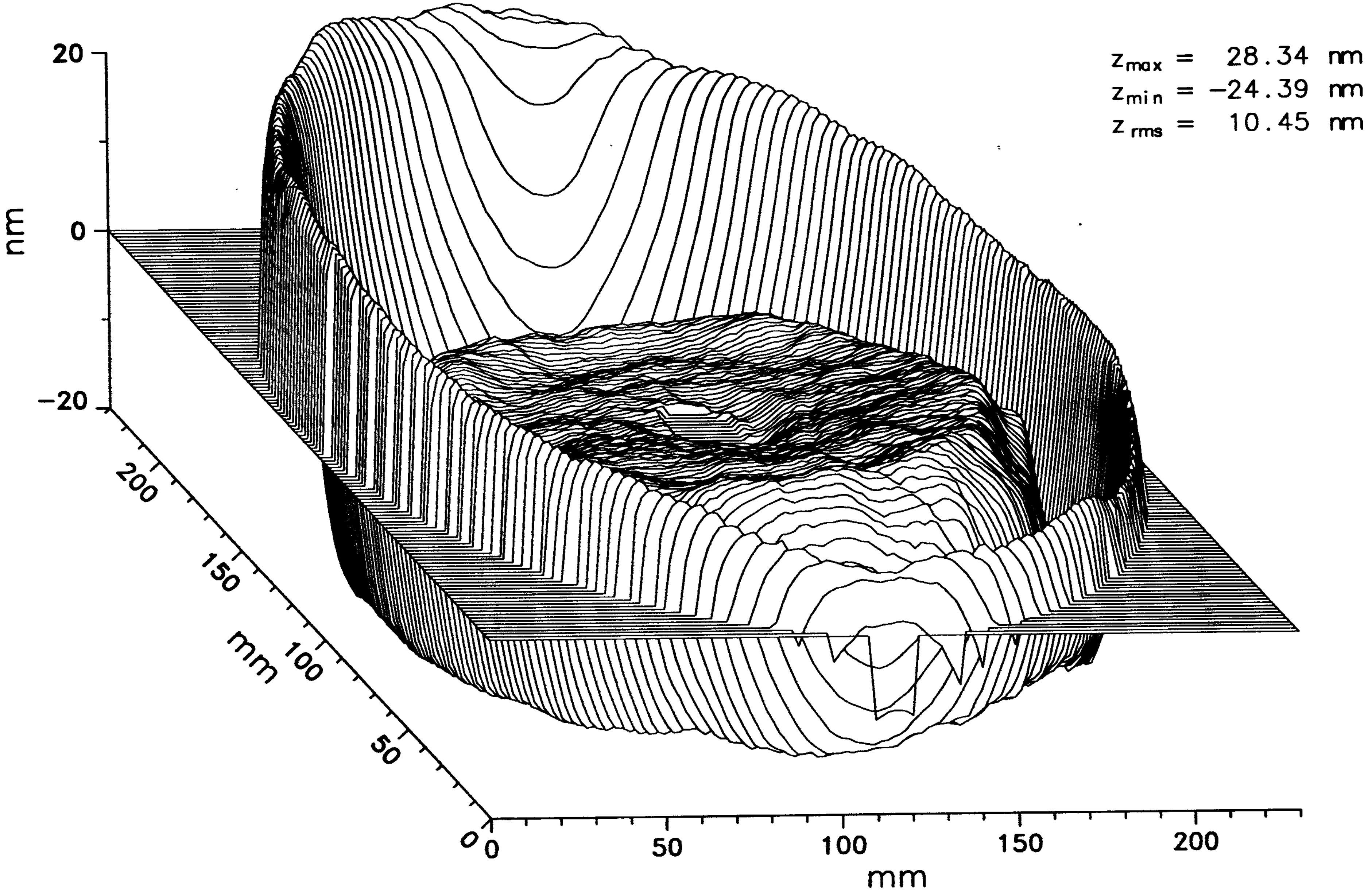
/u/ros/Zeiss/surface3k/herasil−1.fmd



Silicon substrate: sample 2i (R = 3km)

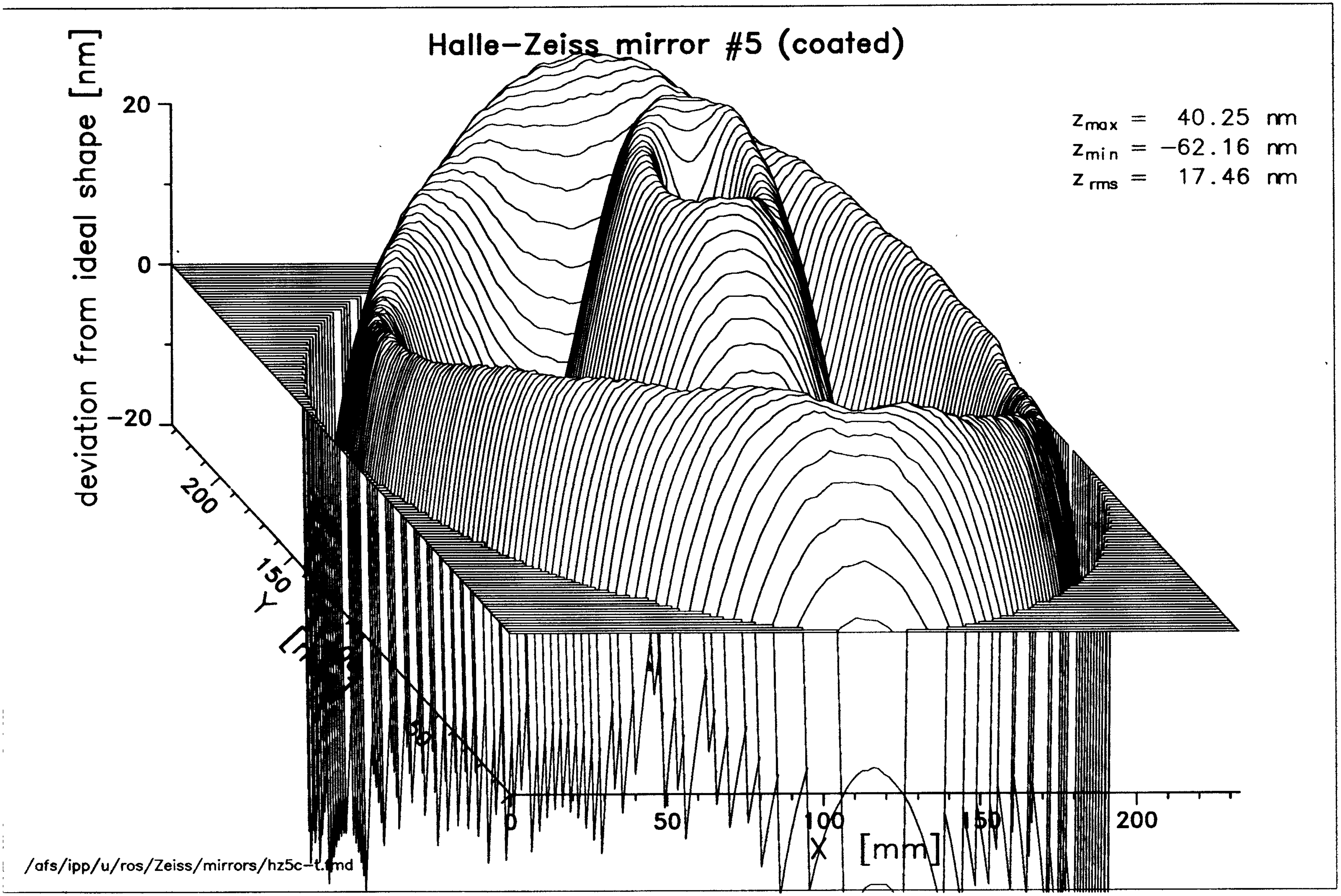
/u/ros/Zeiss/surface3k/silicon−2i.fmd

Silicon substrate: sample 1i (R = 3km)



/u/ros/Zeiss/surface3k/silicon−1i.fmd

Roland Schilling, MPQ Garching, 30.11.94 10:49:26

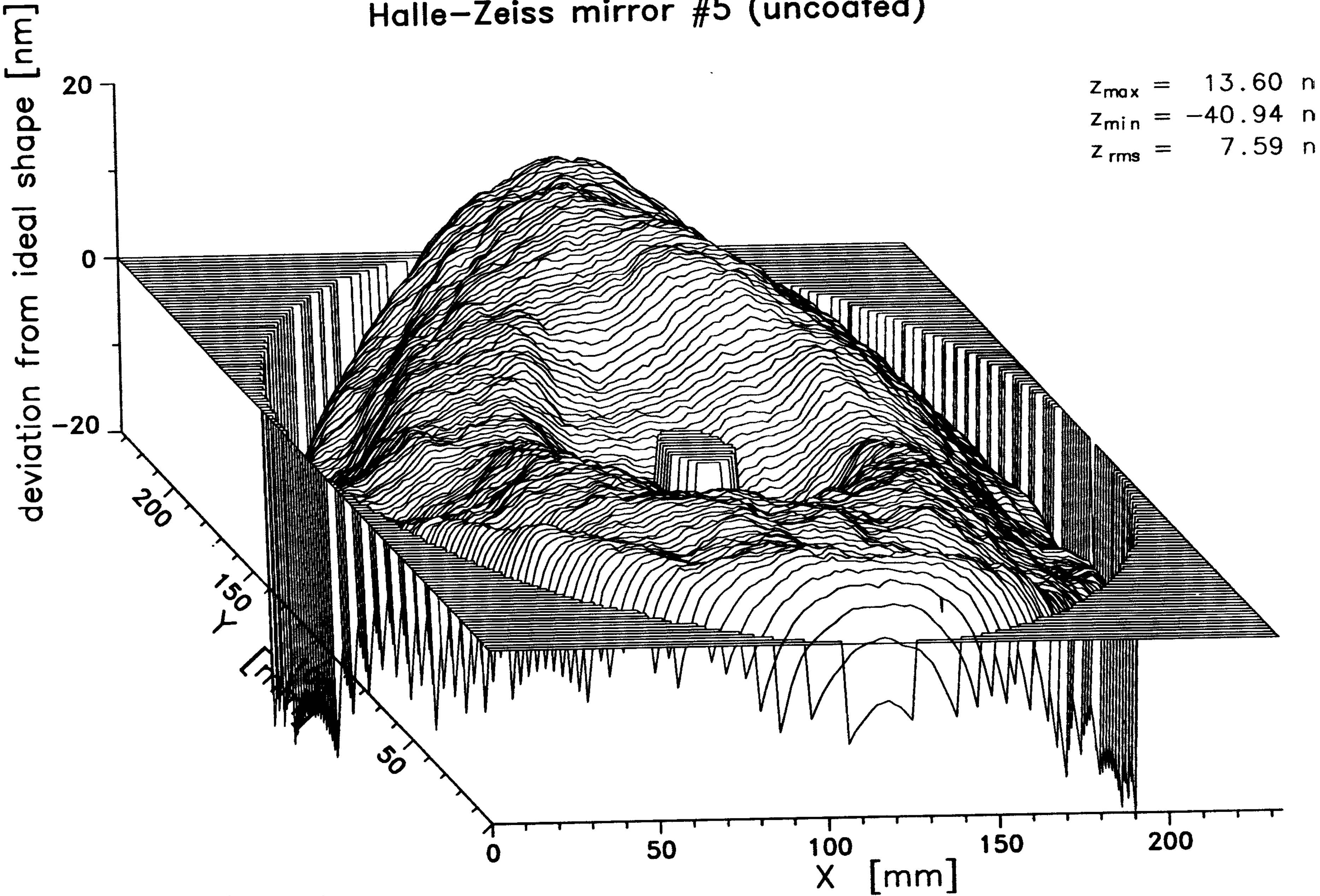


Halle-Zeiss mirror #5 (coated)

/afs/ipp/u/ros/Zeiss/mirrors/hz5c-t.tmd

Roland Schilling, MPQ Garching, 30.11.94 10:51:24

Halle–Zeiss mirror #5 (uncoated)



/afs/ipp/u/ros/Zeiss/mirrors/hz5u–t.fmd

Measurements

All measurements have been performed by **Zeiss**:

Two-dimesional arrays $d(x,y)$ of $N \times N$ data points describing the deviation from the ideal case,

$N = \mathbf{341},\ \mathbf{385}$ or $\mathbf{414}$ (depending on the sample),

covering about **96%** of the full aperture of the samples (i.e. **230** or **180 mm**).

$\Longrightarrow$ Limited spatial resolution of $\approx$ **0.5 mm**

No direct measurements of scatter have been performed,

only simulations of the scatter to be expected from such components (based on the Zeiss measurements).

We will see:

- 3-D plots of the distortion function $d(x,y)$
- Fourier spectra of the distortions
- Power loss due to scattering (for angles $\lessapprox$ **1 mrad**)
- Distribution of scatter into higher-order modes
- Angular distribution of scattering
- The scattering function $f(\vartheta)$
- Scattered power outside a cone of half angle ϑ

Scattering of optical components for gravitational wave detectors

Mainly two effects:

- limitation of power-recycling gain due to scattering losses
- reduction of sensitivity by spurious fake signals

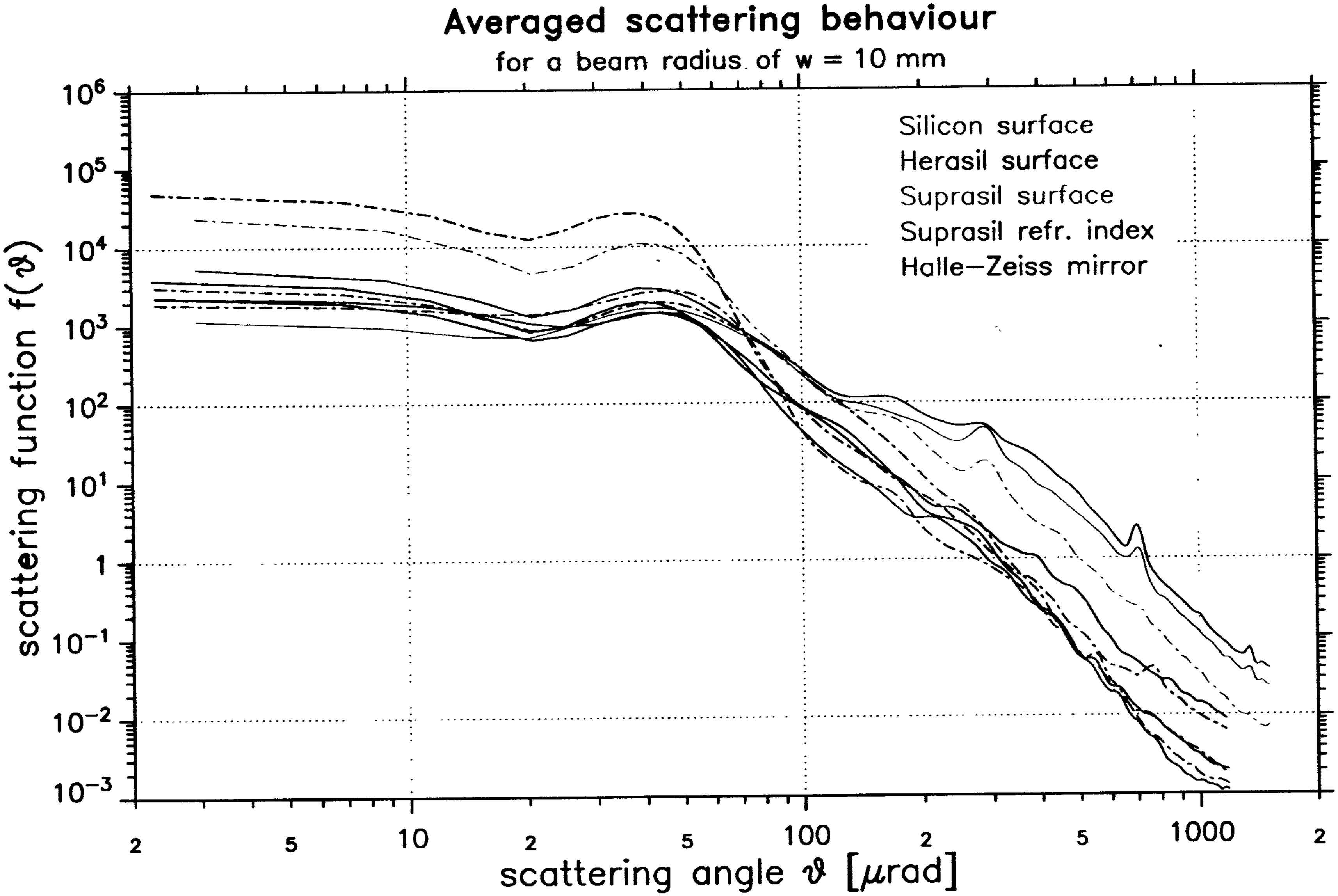
Mainly two origins:

- roughness of optical surfaces
- inhomogeneity of substrates traversed by the light

We have evaluated data measured by Zeiss:

material	number of samples	diameter	thickness	radius of curvature	quality	measurement	possible use
fused silica	1	240 mm	75 mm	31 m / ∞	standard polishing	curved surface uncoated & coated	main mirror
silicon monocrystal	2	240 mm	75 mm	3 km / ∞	best effort polishing	curved surface	main mirror
fused silica Herasil 310	2	240 mm	75 mm	3 km / ∞	best effort polishing	curved surface	main mirror
fused silica Suprasil 311	1	187 mm	32 mm	∞ / ∞	top grade homogeneity	optical path, both surfaces	beam splitter, FP mirror

Roland Schilling, MPQ Garching, 19.12.94 16:45:54



Averaged scattering behaviour

for a beam radius of w = 10 mm

Power loss due to scattering

The **distorted light field** ψ_d can be described as

$$\psi_{\mathrm{d}}(x,y) = d(x,y) \cdot \psi_{00}(x,y)$$

(incident beam assumed to be pure 00-mode).

The amplitude a_{00} contained in ψ_{d} is given by

$$a_{00} = \iint_{-\infty}^{+\infty} \psi_{\mathrm{d}}\, \psi_{00}\, dx\, dy\, .$$

It depends on the beam radius w of the incident beam.

The power P_{scat} lost from the fundamental mode is

$$P_{\mathrm{scat}} = 1 - a_{00}^2\, .$$

Conversion into **higher order modes:**

$$a_{mn} = \iint_{-\infty}^{+\infty} \psi_{\mathrm{d}}\, \psi_{mn}\, dx\, dy\, .$$

Measurements

All measurements have been performed by **Zeiss**:

Two-dimesional arrays $d(x, y)$ of $N \times N$ data points describing the deviation from the ideal case,

$N = \mathbf{341},\ \mathbf{385}$ or $\mathbf{414}$ (depending on the sample),

covering about **96%** of the full aperture of the samples (i.e. **230** or **180 mm**).

$\Longrightarrow$ Limited spatial resolution of $\approx$ **0.5 mm**

No direct measurements of scatter have been performed,

only simulations of the scatter to be expected from such components (based on the Zeiss measurements).

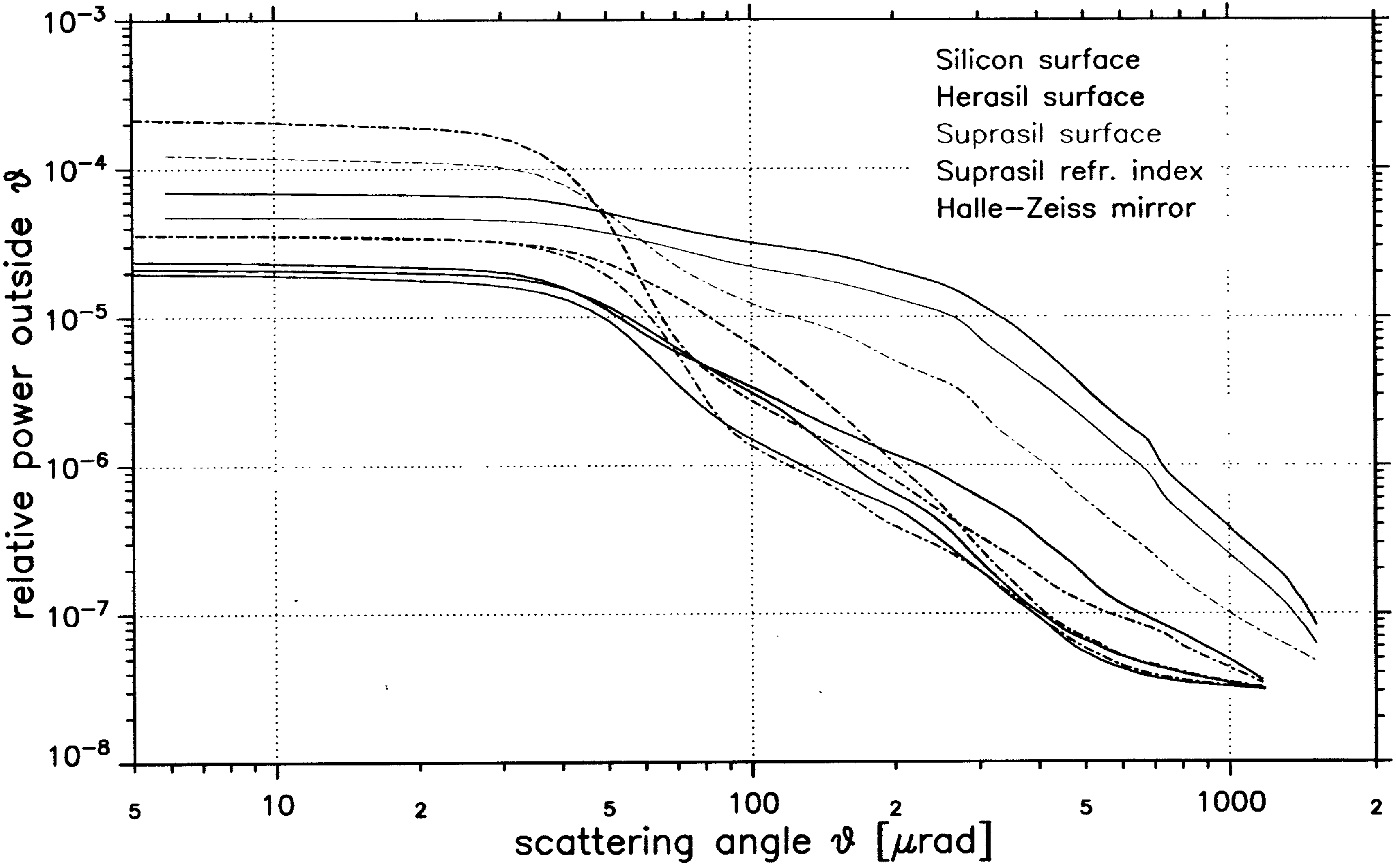
We will see:

- 3-D plots of the distortion function $d(x, y)$
- Fourier spectra of the distortions
- Power loss due to scattering (for angles $\lesssim$ **1 mrad**)
- Distribution of scatter into higher-order modes
- Angular distribution of scattering
- The scattering function $f(\vartheta)$
- Scattered power outside a cone of half angle ϑ

Roland Schilling, MPQ Garching, 19.12.94 16:45:46

Averaged scattering behaviour

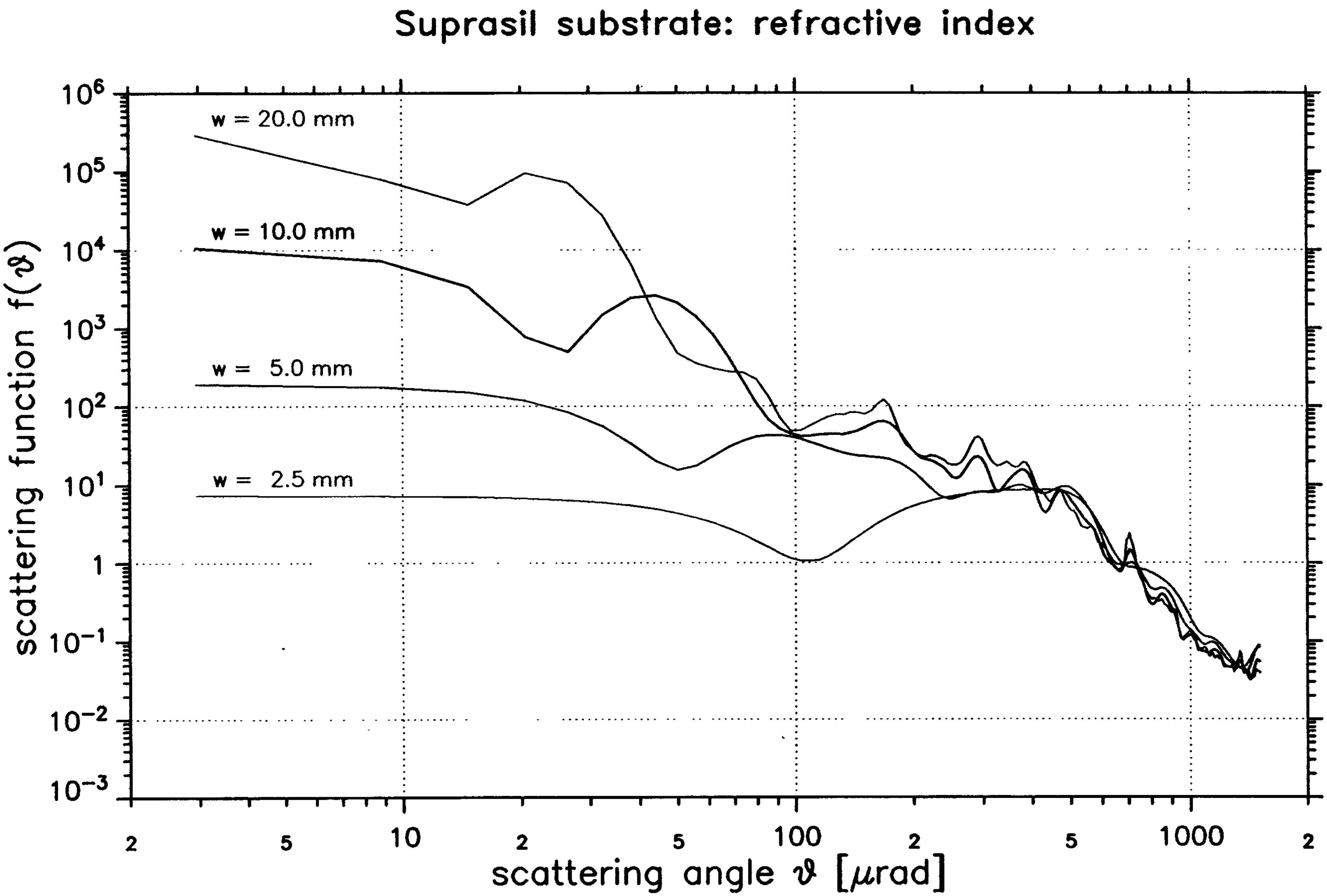
for a beam radius of w = 10 mm



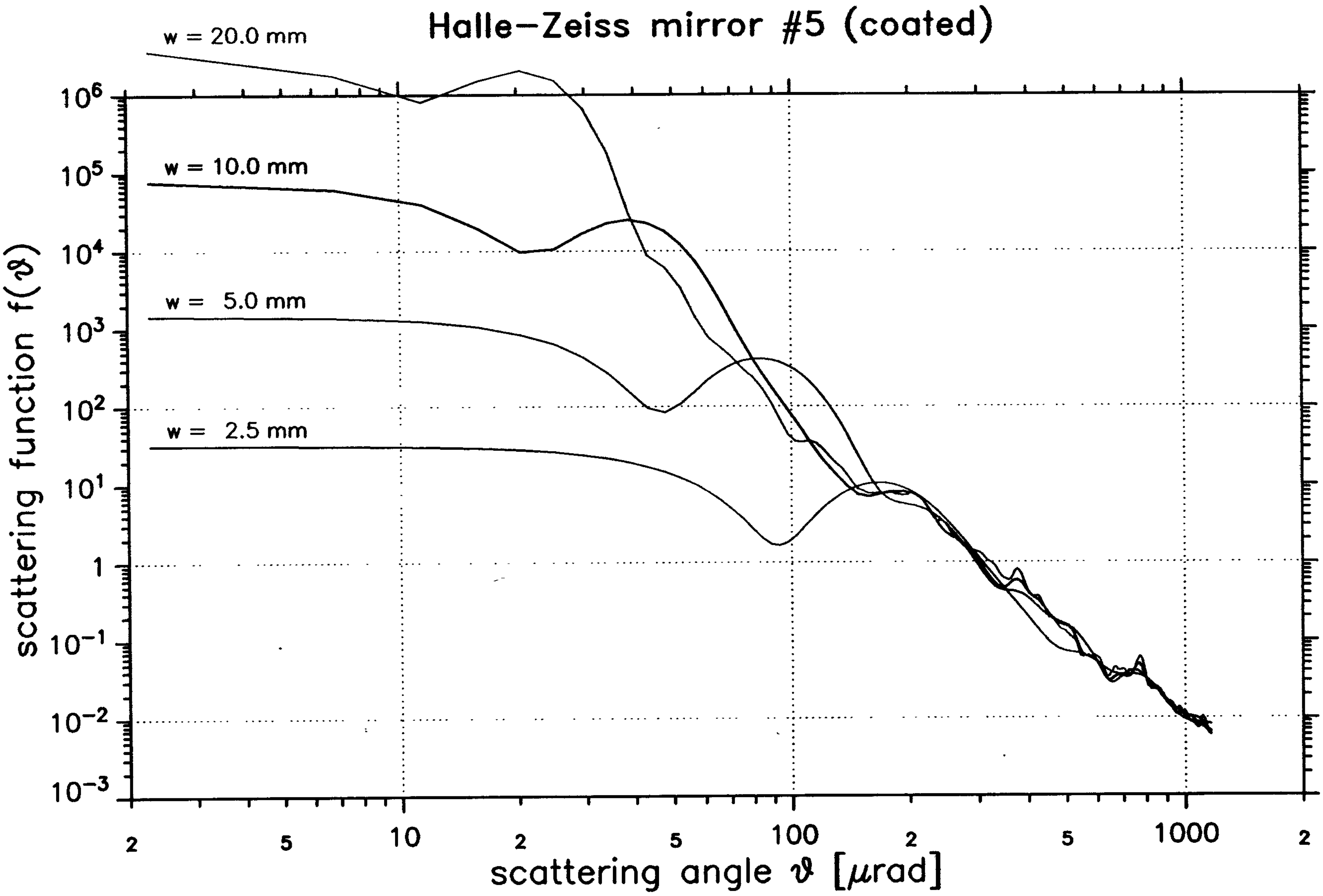
VIRGO
LIGO

GEO 600

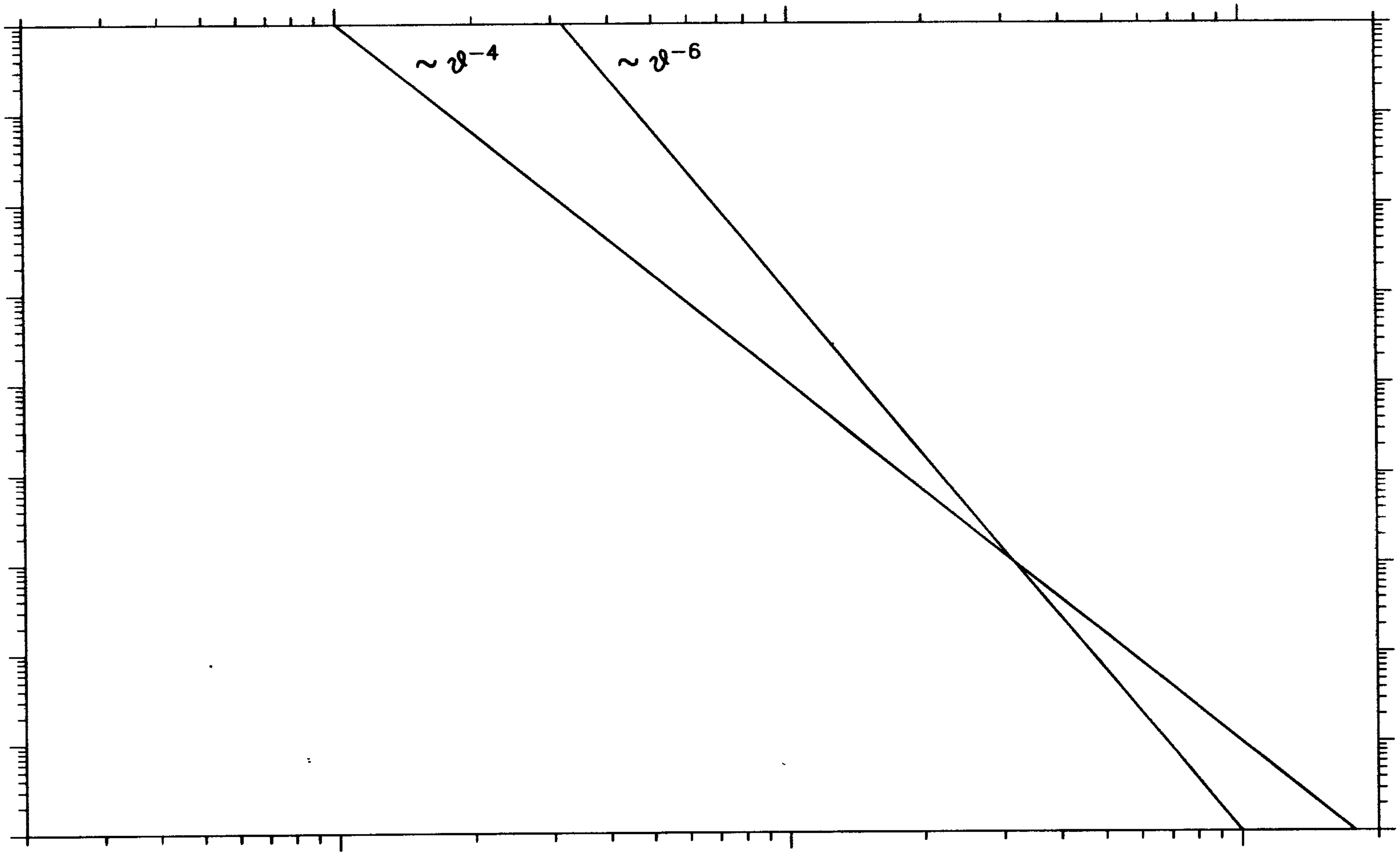
Roland Schilling, MPQ Garching, 30.11.94 17:54:32



Roland Schilling, MPQ Garching, 30.11.94 17:41:47

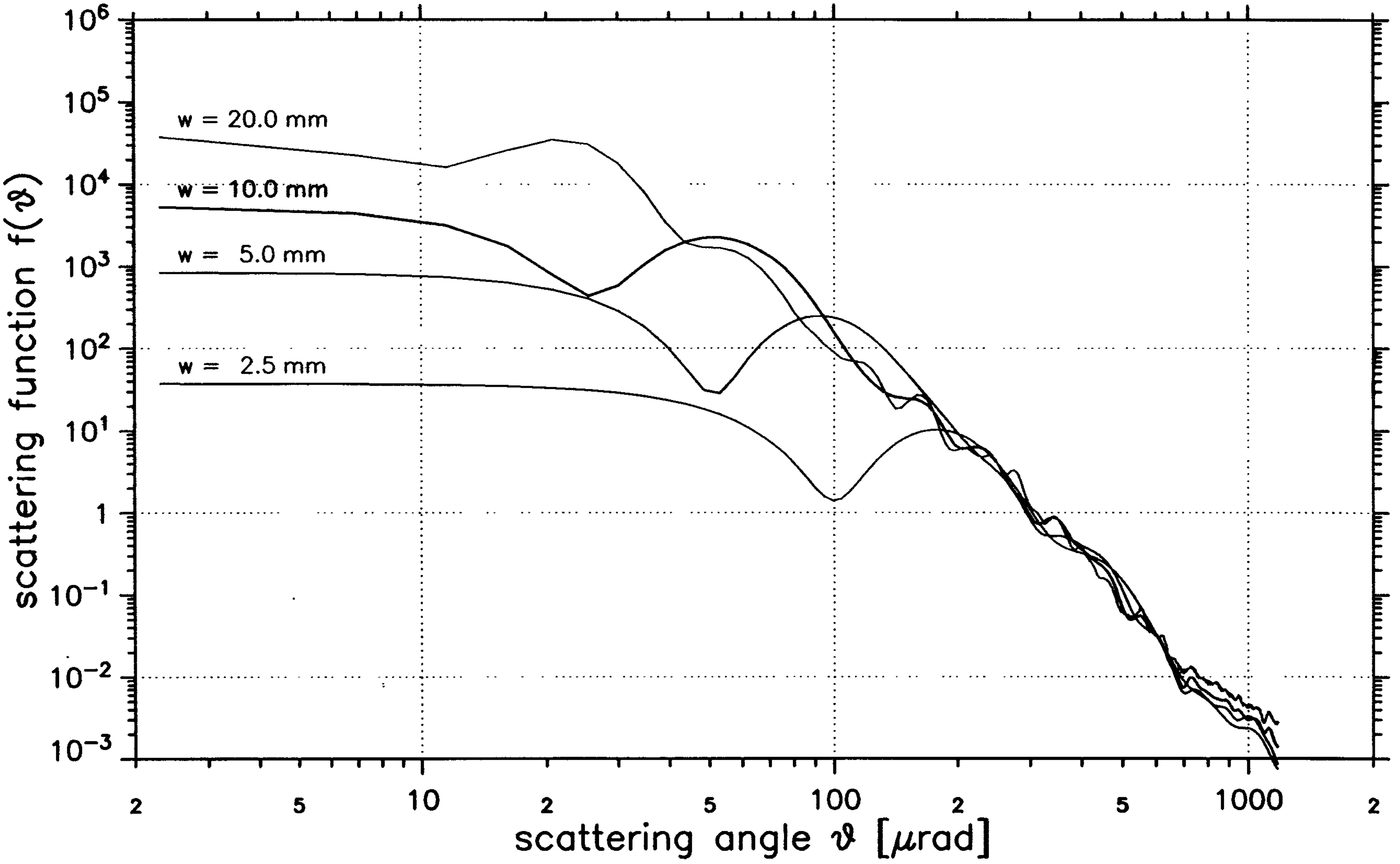


Roland Schilling, MPQ Garching, 29.11.94 15:26:20



Roland Schilling, MPQ Garching, 30.11.94 17:45:09

Herasil surface: sample 2 (R = 3km)



Angular distribution of scatter

The **scattered field** ψ_{scat} (w/o the 00-mode) can be calculated as

$$\psi_{\mathsf{scat}} = \psi_{\mathsf{d}} - a_{00}\psi_{00} \,.$$

Conversion to **angular space** by 2-dim Fourier transformation:

$$\psi^{\mathsf{a}}(\vartheta_x, \vartheta_y) = \mathsf{FT}\Big(\psi_{\mathsf{scat}}(x, y)\Big) \,.$$

The **scattering function** $f(\vartheta)$ is given by averaging over the azimuthal dependence of ψ^a:

$$f(\vartheta) = \frac{1}{2\pi}\int_0^{2\pi} \psi^{\mathsf{a}}(\vartheta, \varphi)\, d\varphi \,.$$

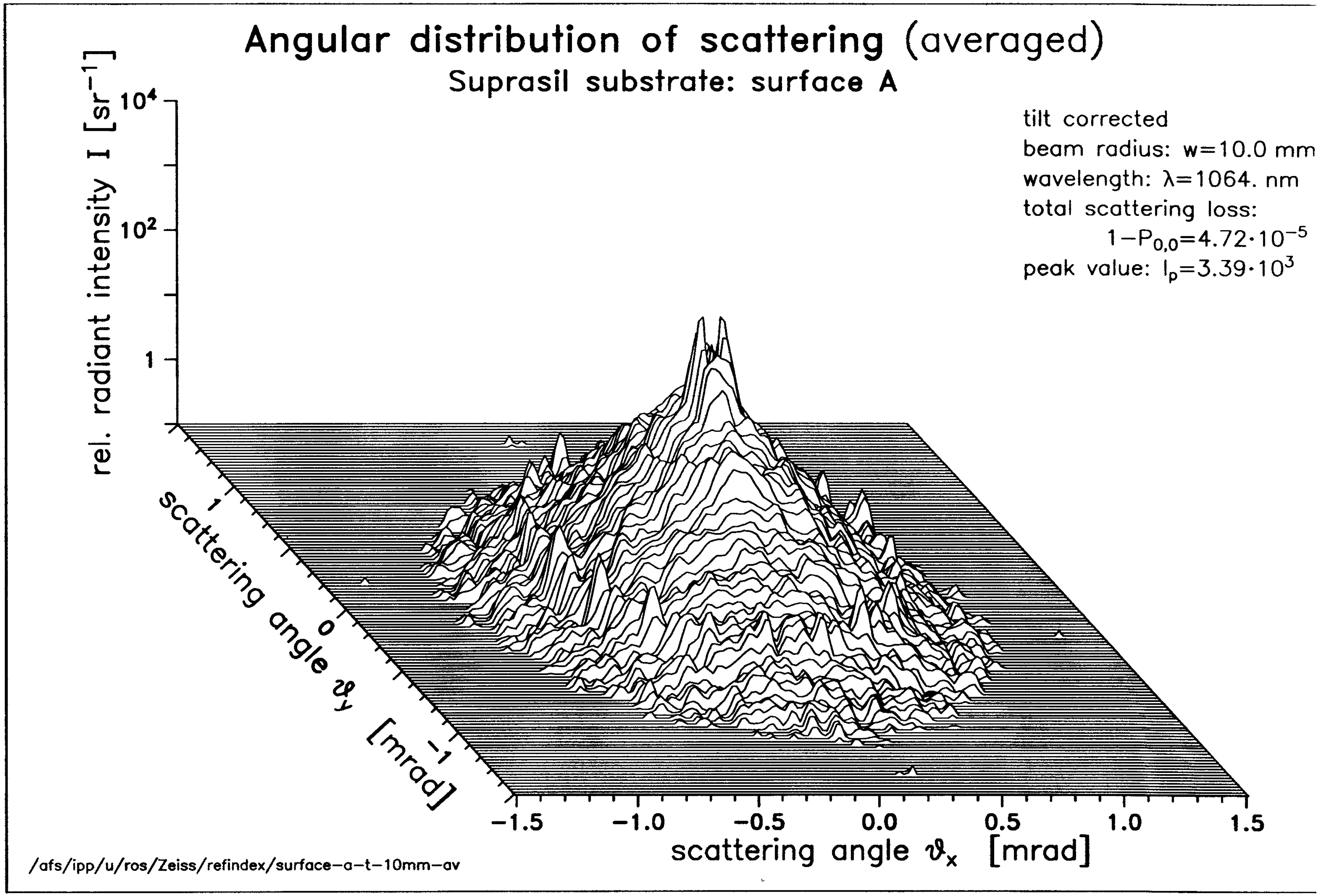
Relation between scattering angle ϑ and spatial wavelength Λ, depending on the light wavelength λ, is given by $\vartheta = \lambda/\Lambda$.

$$\Longrightarrow \text{ Minimum angle } \vartheta_{\mathsf{min}} = \frac{\lambda}{D} \qquad \approx 5\,\mu\mathbf{rad}\,,$$

$$\text{maximum angle } \vartheta_{\mathsf{max}} = \vartheta_{\mathsf{min}}\frac{N}{2} \approx 1\,\mathbf{mrad}\,,$$

with D = diameter of the component and N = number of data points in one dimension.

Roland Schilling, MPQ Garching, 29.11.94 17:52:03



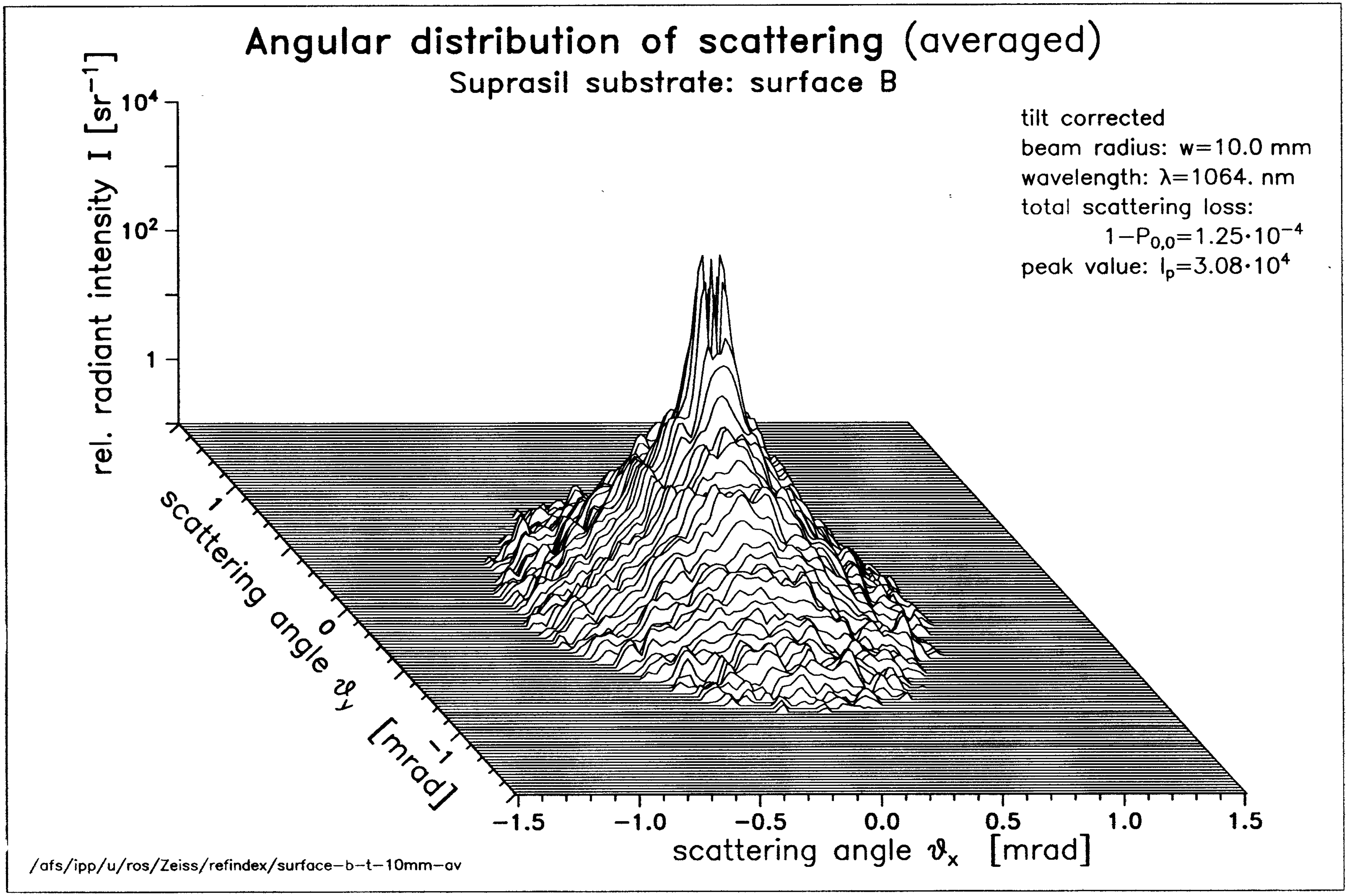
Angular distribution of scattering (averaged)

Suprasil substrate: surface A

tilt corrected
beam radius: w=10.0 mm
wavelength: λ=1064. nm
total scattering loss:
$1-P_{0,0}=4.72\cdot10^{-5}$
peak value: $I_p=3.39\cdot10^{3}$

/afs/ipp/u/ros/Zeiss/refindex/surface−a−t−10mm−av

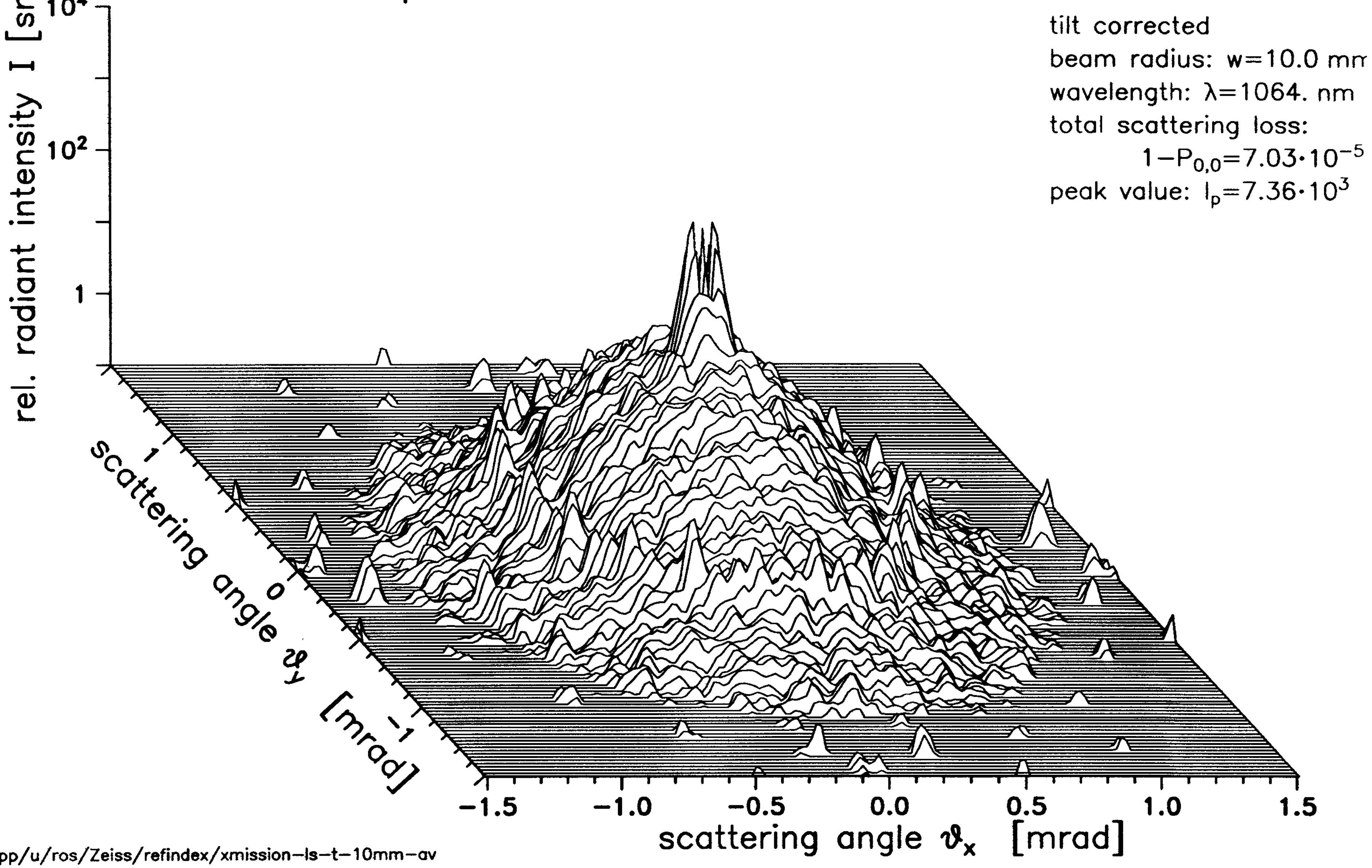
Roland Schilling, MPQ Garching, 29.11.94 17:52:17



Roland Schilling, MPQ Garching, 29.11.94 17:52:33

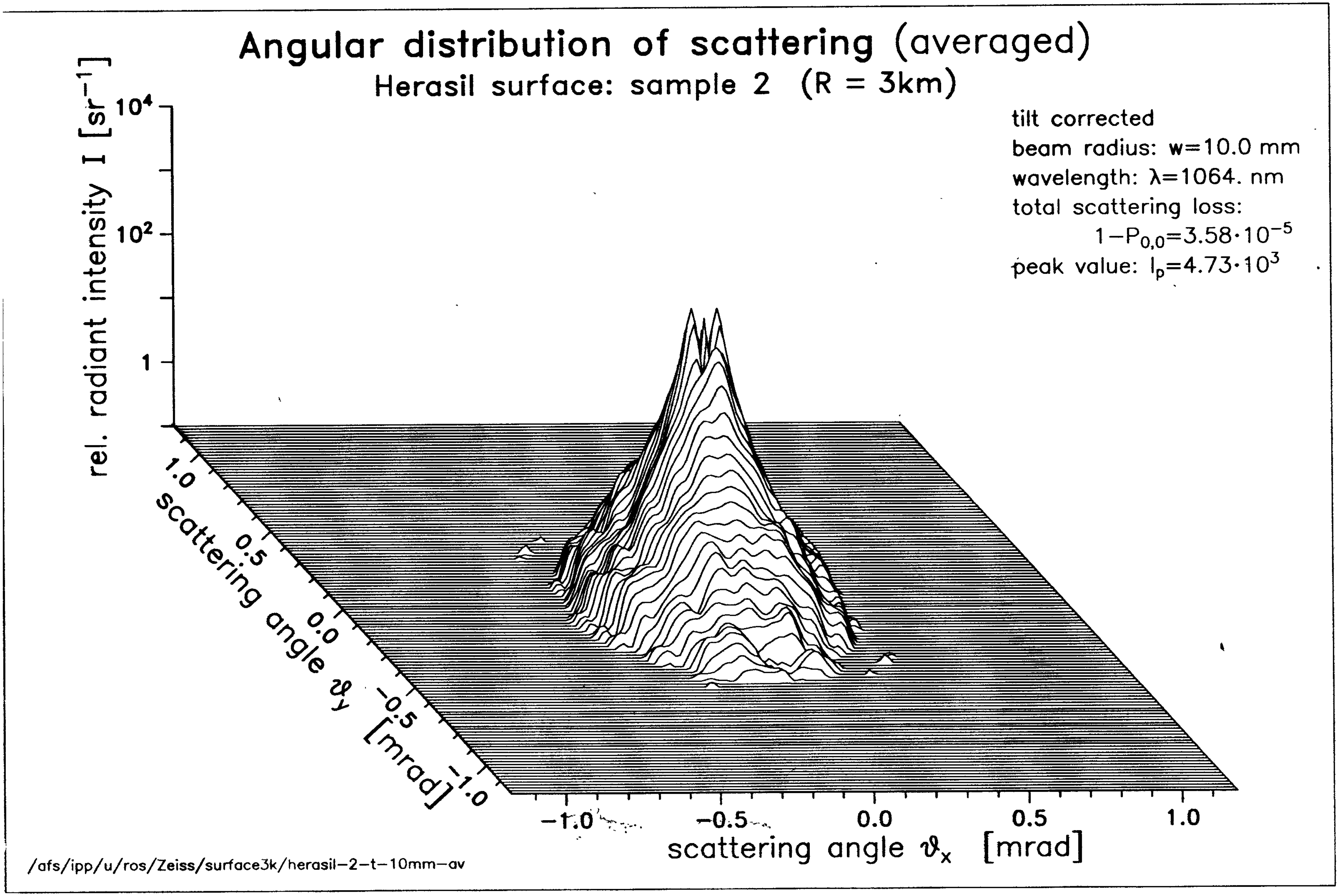
Angular distribution of scattering (averaged)

Suprasil substrate: refractive index

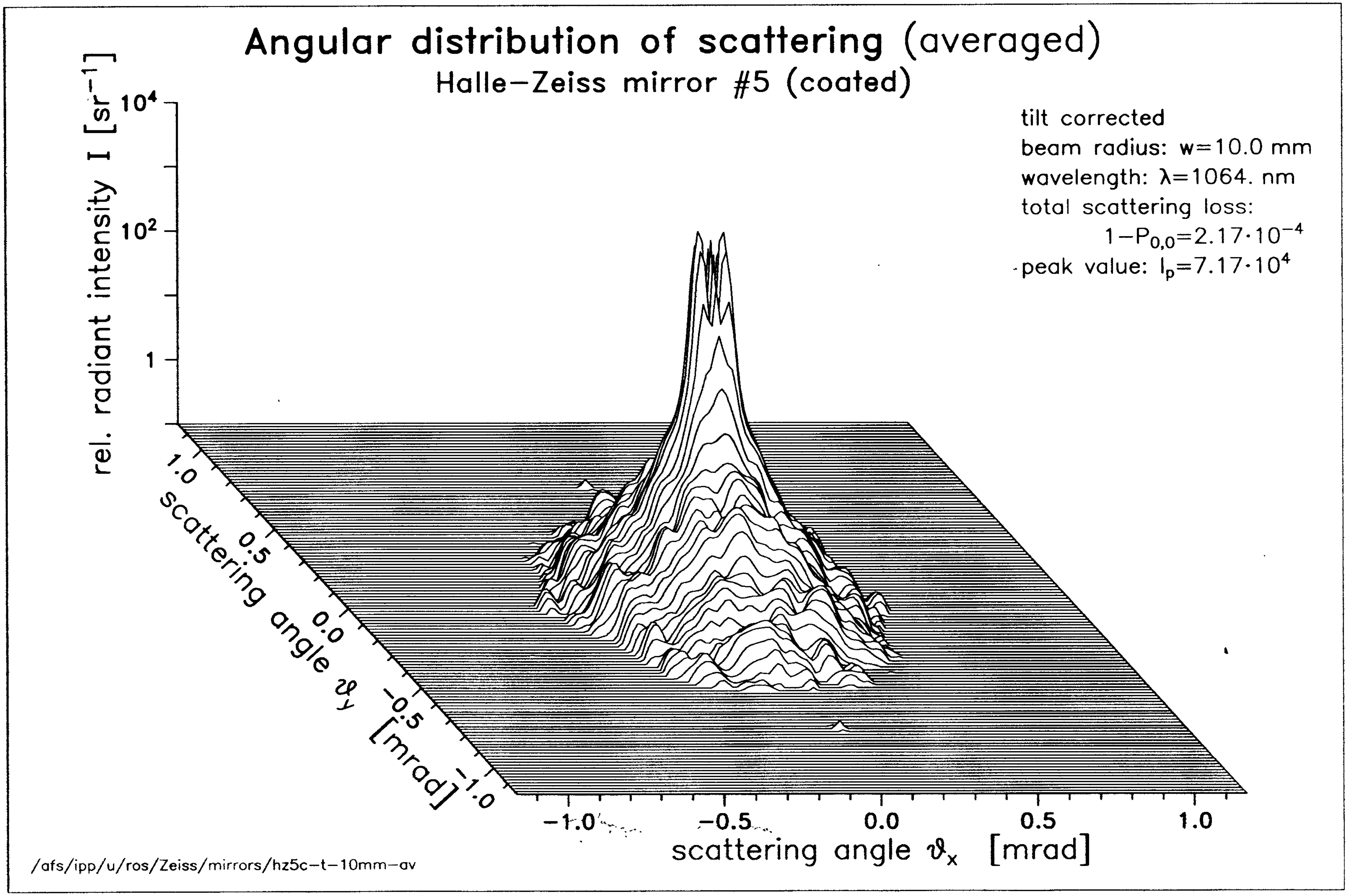


/afs/ipp/u/ros/Zeiss/refindex/xmission-ls-t-10mm-av

Roland Schilling, MPQ Garching, 29.11.94 17:51:22



Roland Schilling, MPQ Garching, 29.11.94 17:50:55



Angular distribution of scattering (averaged)

Halle–Zeiss mirror #5 (coated)

tilt corrected

beam radius: w=10.0 mm

wavelength: λ=1064. nm

total scattering loss:

$1-P_{0,0}=2.17\cdot10^{-4}$

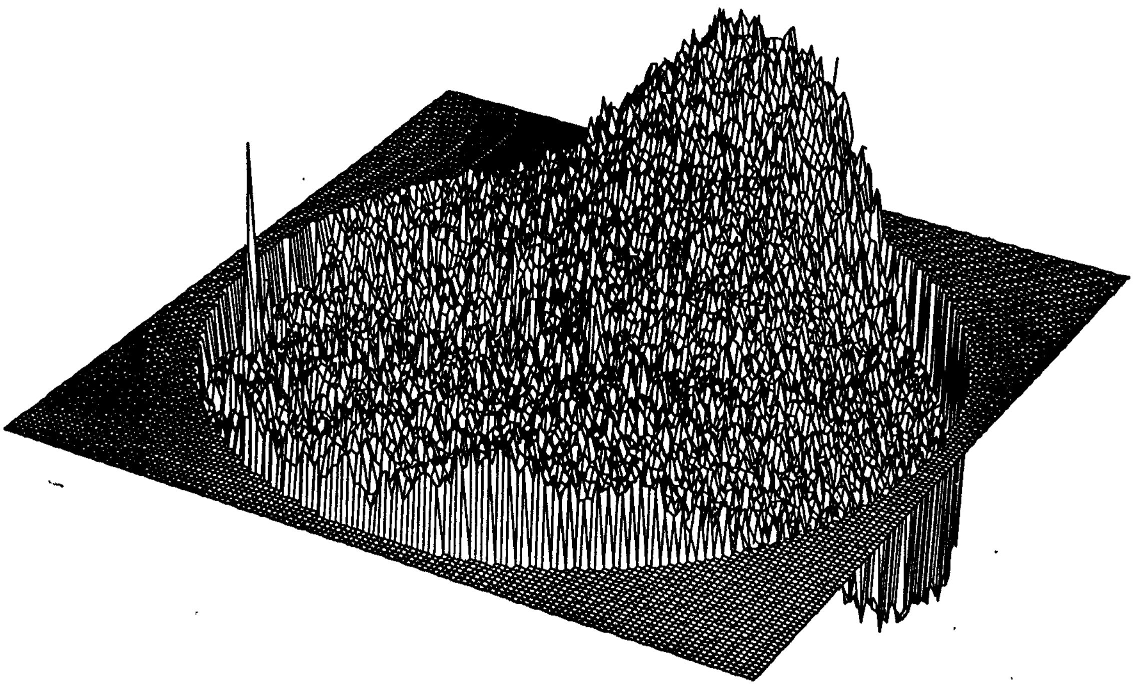
peak value: $I_p=7.17\cdot10^{4}$

/afs/ipp/u/ros/Zeiss/mirrors/hz5c–t–10mm–av

CALFLAT MIRROR MEASUREMENTS

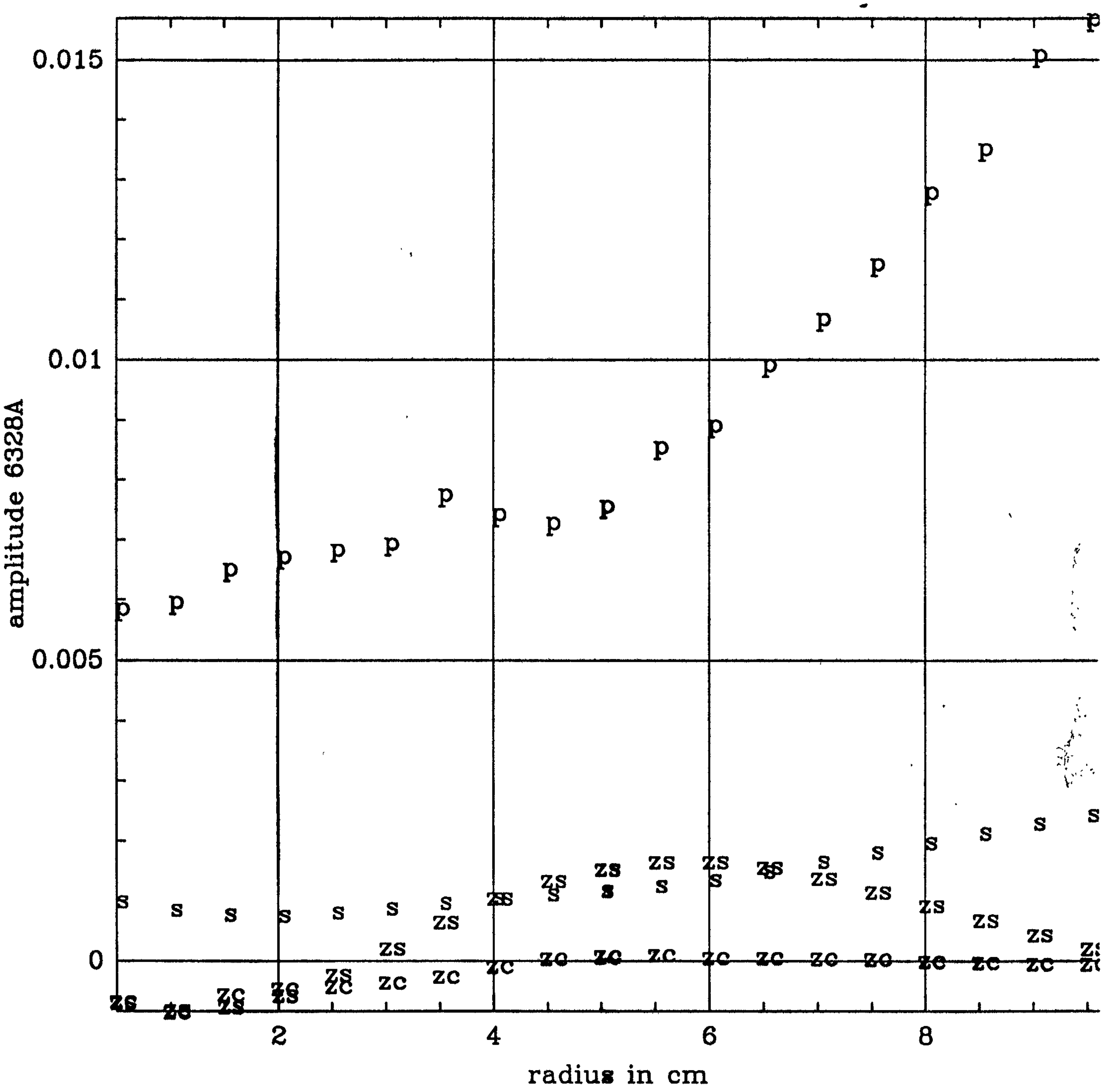
RAI WEISS

calflat3arc.dat : Tue Jun 14 22:47:49 1994



x/y xmin = 0.000E+00 xmax = 2.000E+02 ymin = 0.000E+00 ymax = 2.000E+02

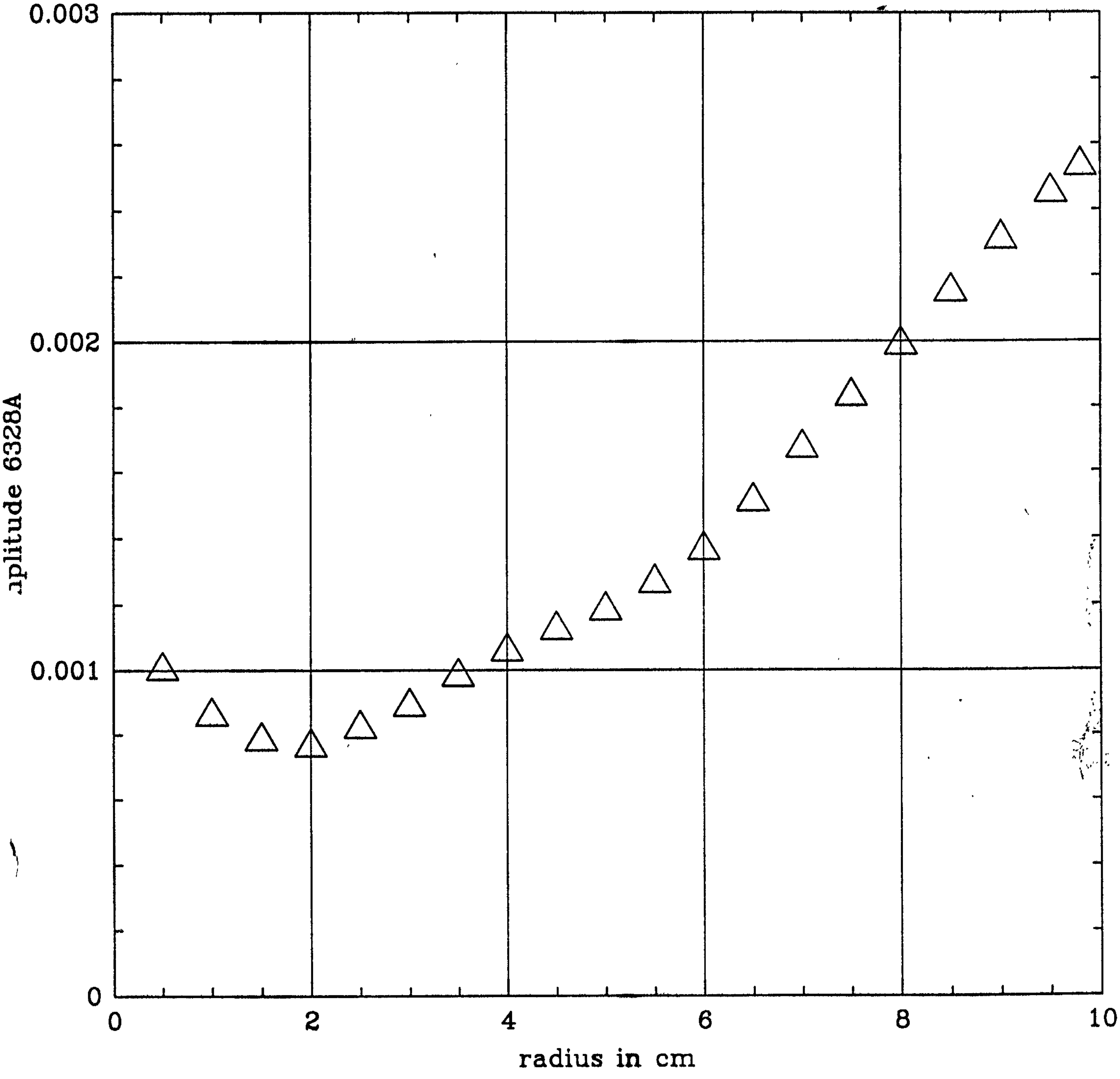
Calflat3arc.f



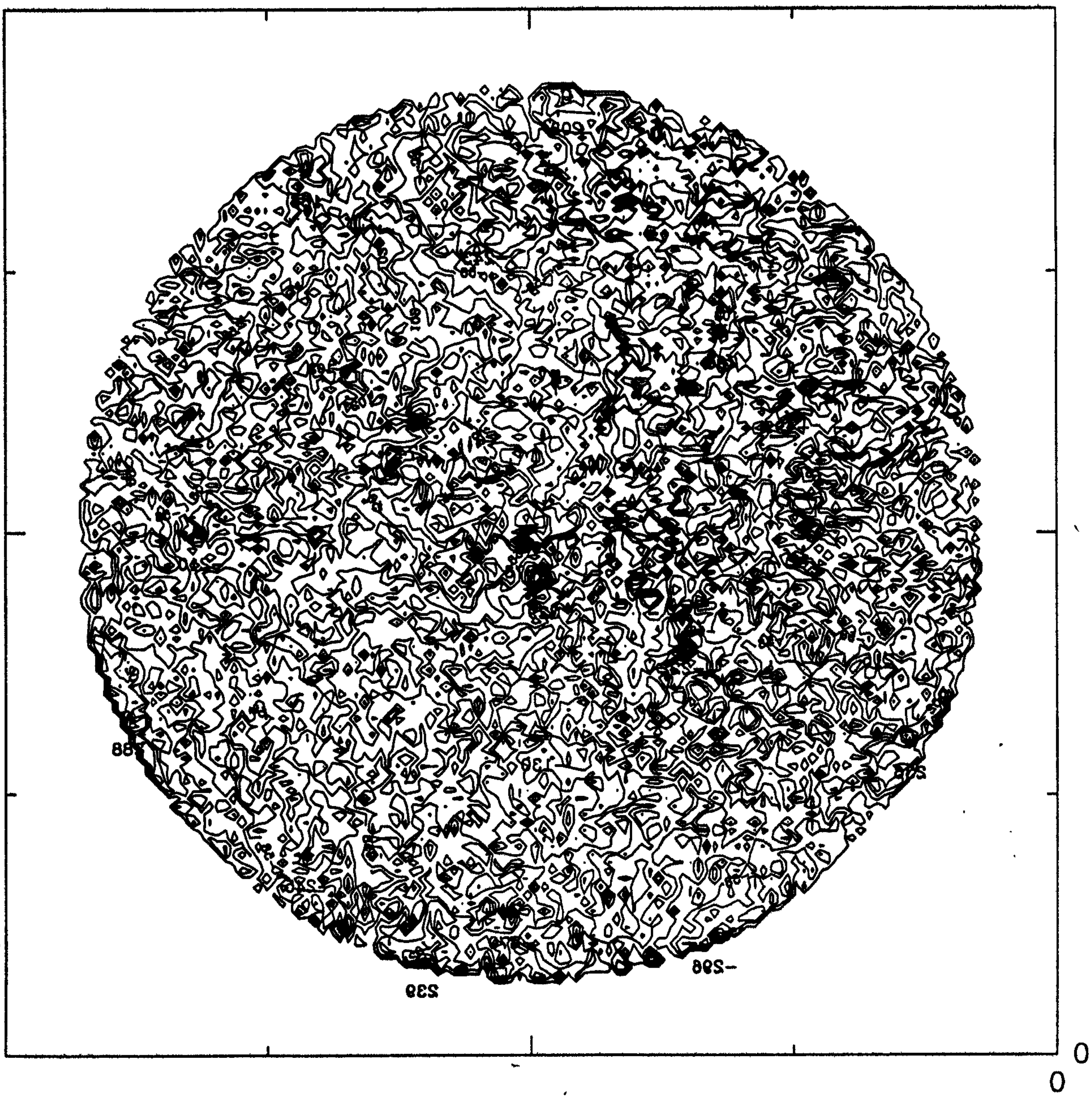
calflatr.dat: radius vs sigma (s), p-p (p), Z11s (zs), Z11c (zc) : Tue Jun 14 22:38:32 1

Calflat

calflatr1.dat : sigma vs radius : Tue Oct 4 11:59:49 1994



junk1.ps : Sun Dec 11 16:11:49 1994



Calflat3a : hol unit

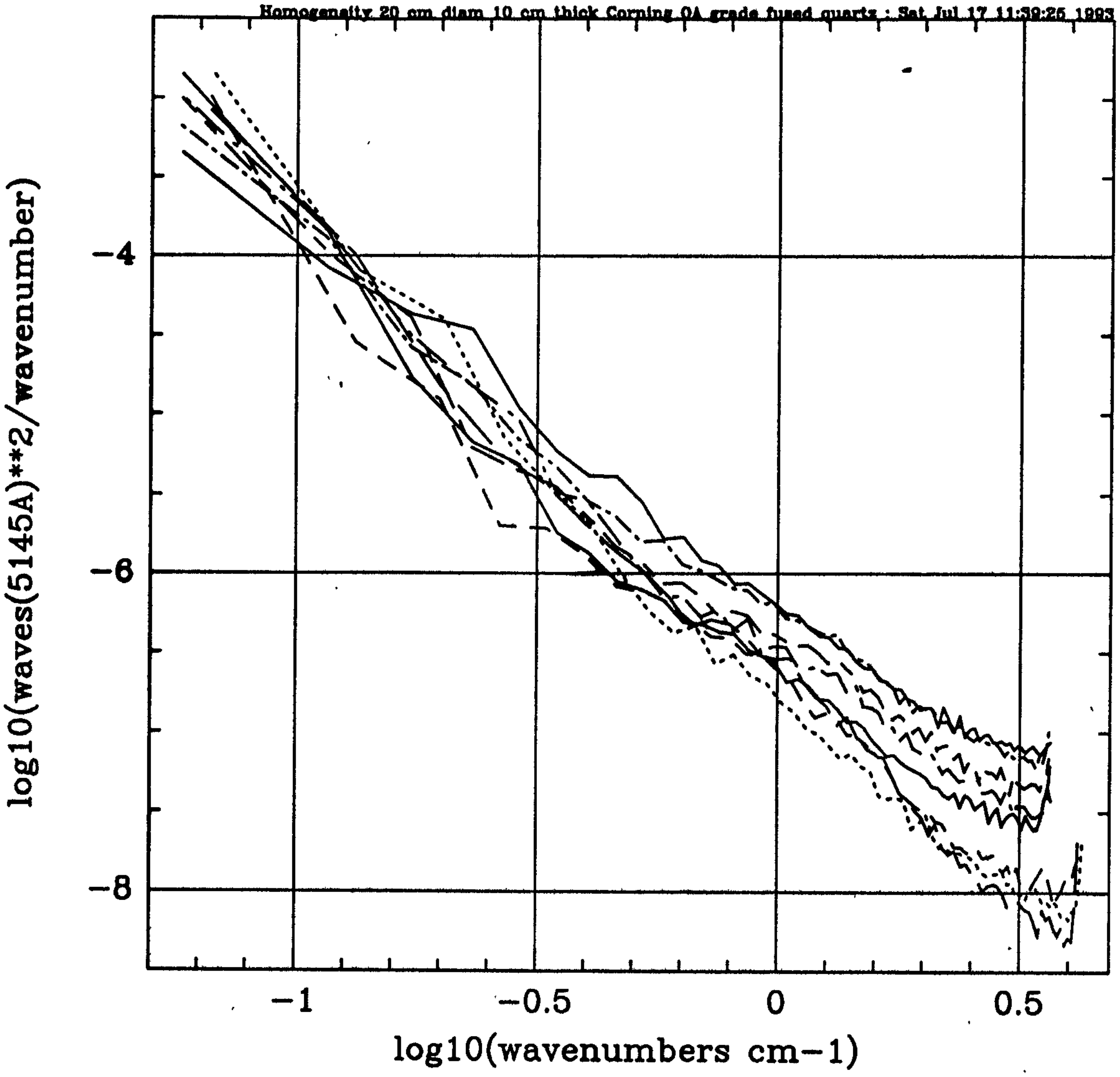
AMPLITUDE λ/(6328)

RADIUS = 8.8 cm

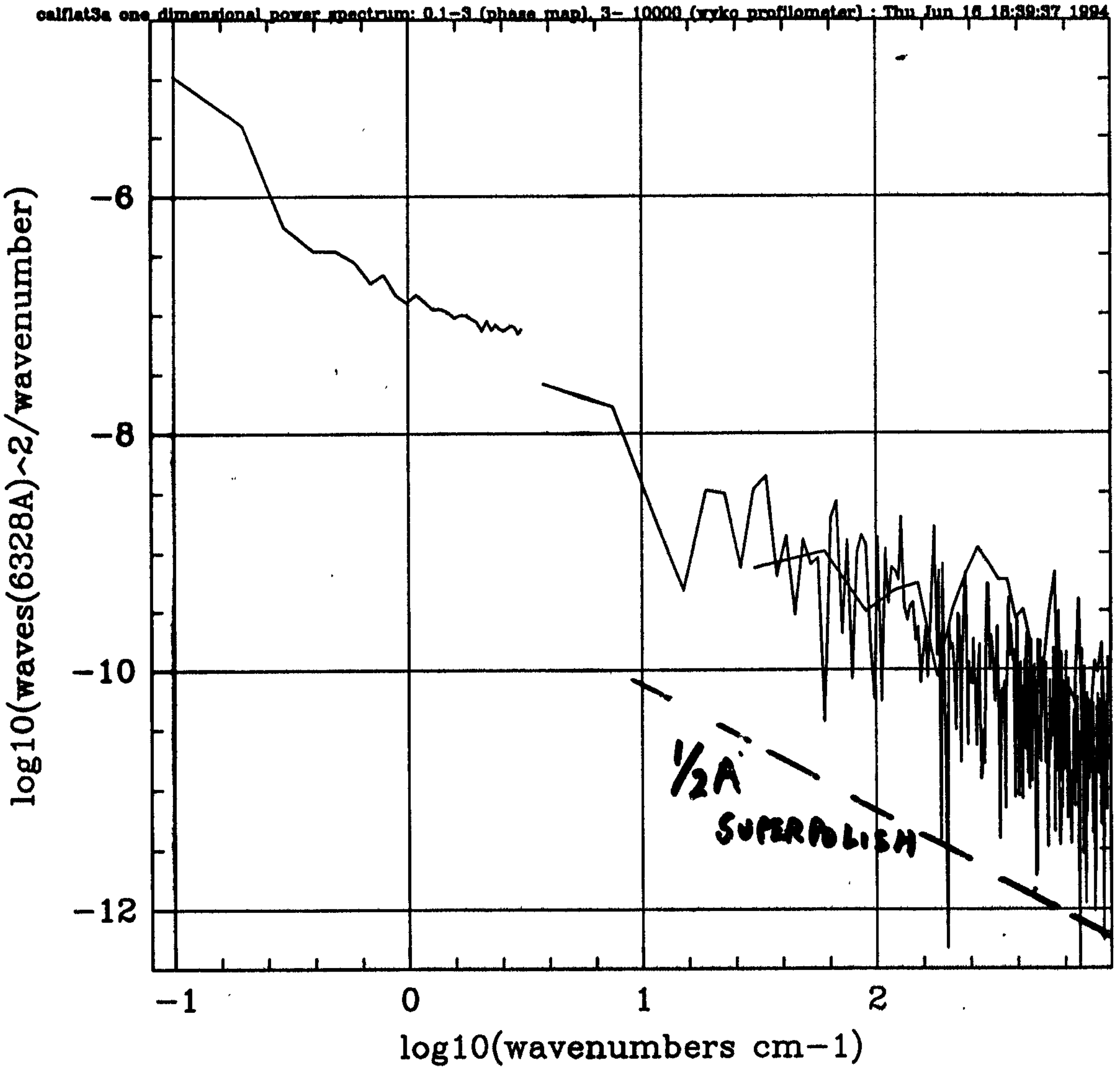
NOTE: HIGH SPOT IN MIDDLE
λ/ 3.78 x 10^-4

n
1, 1
2, 0
2, 2
3, 1
3, 3
4, 0
4, 2

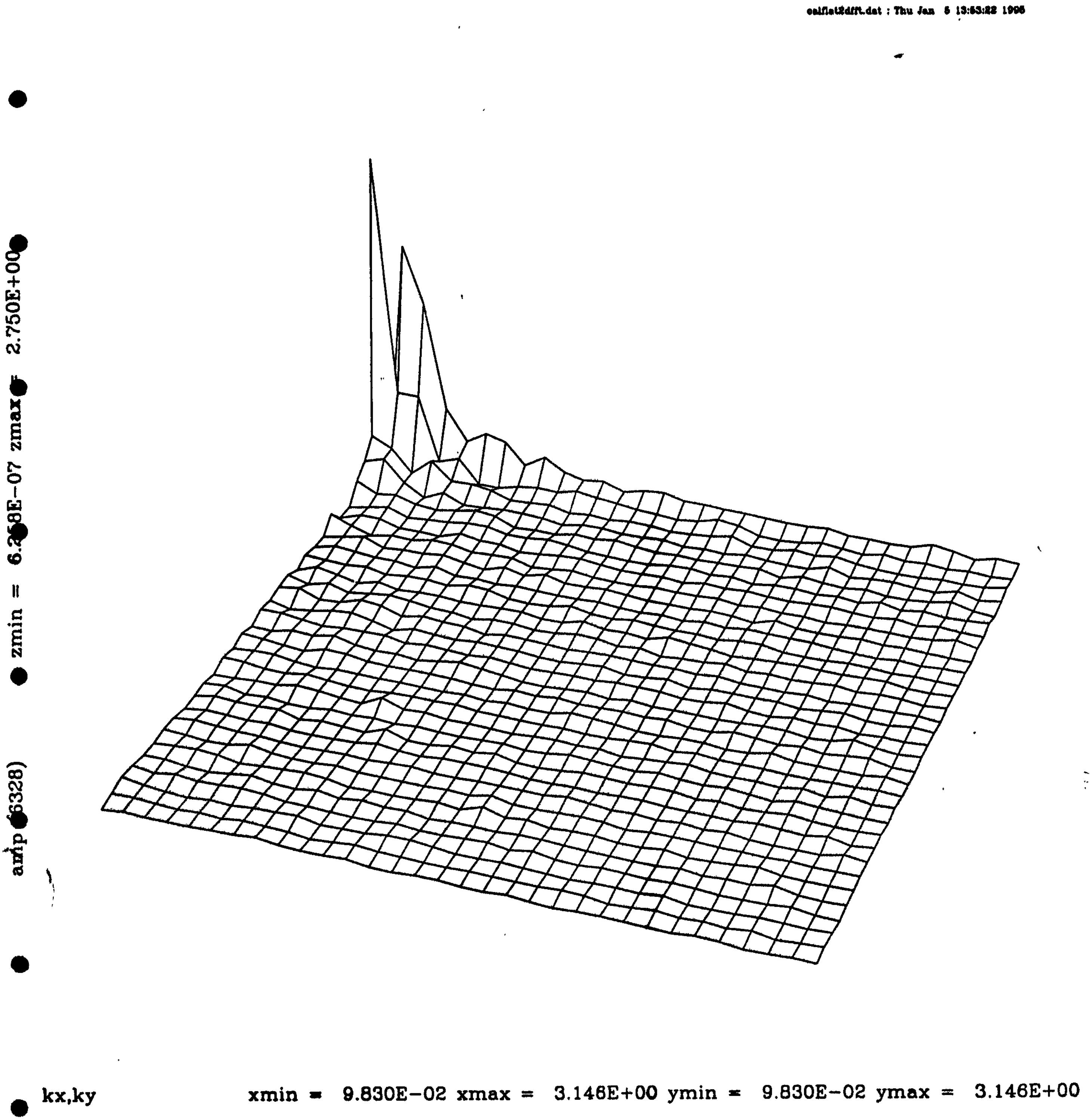
Removed



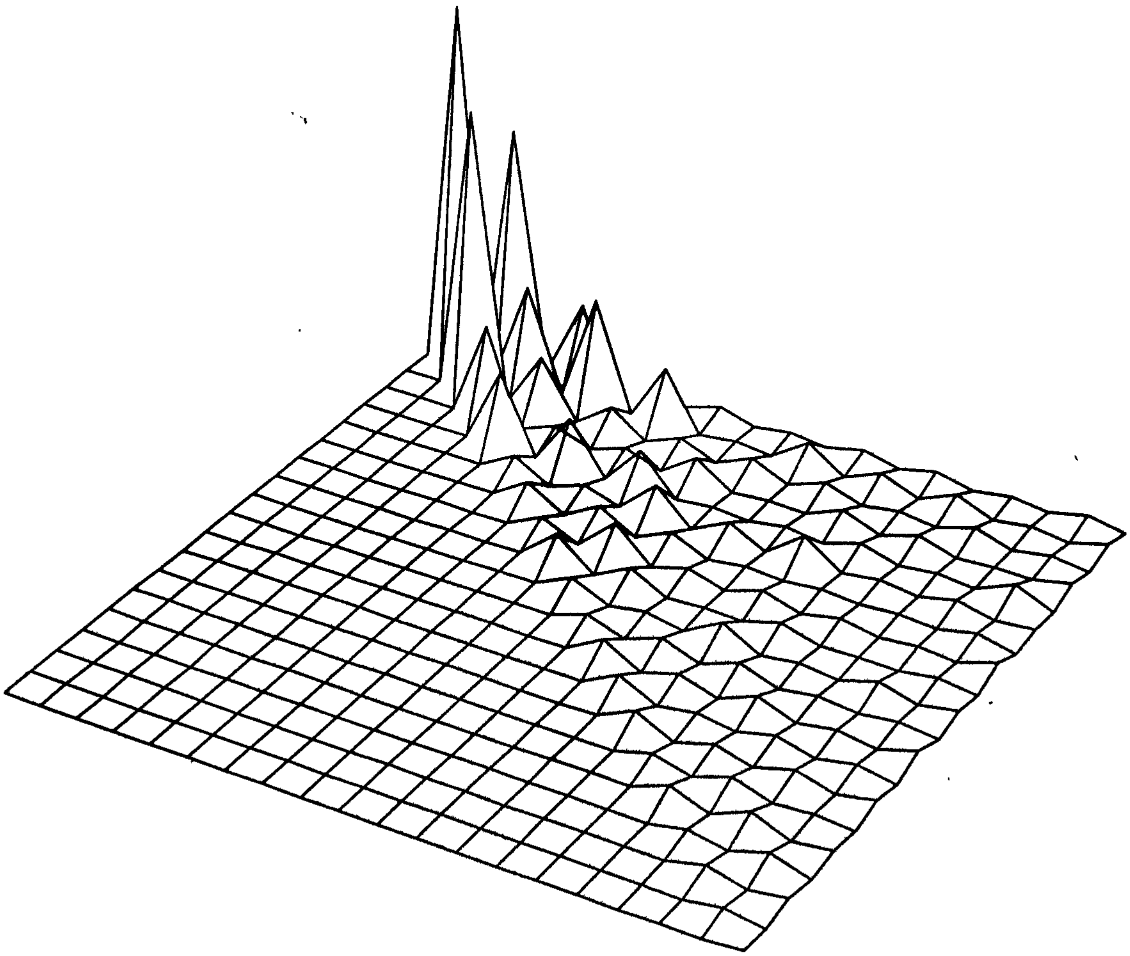
Homogeneity 20 cm diam 10 cm thick Corning 0A grade fused quartz : Sat Jul 17 11:39:25 1993 calflat3a one dimensional power spectrum: 0.1−3 (phase map), 3− 10000 (wyko profilometer) : Thu Jun 16 18:39:37 1994



calflat 3

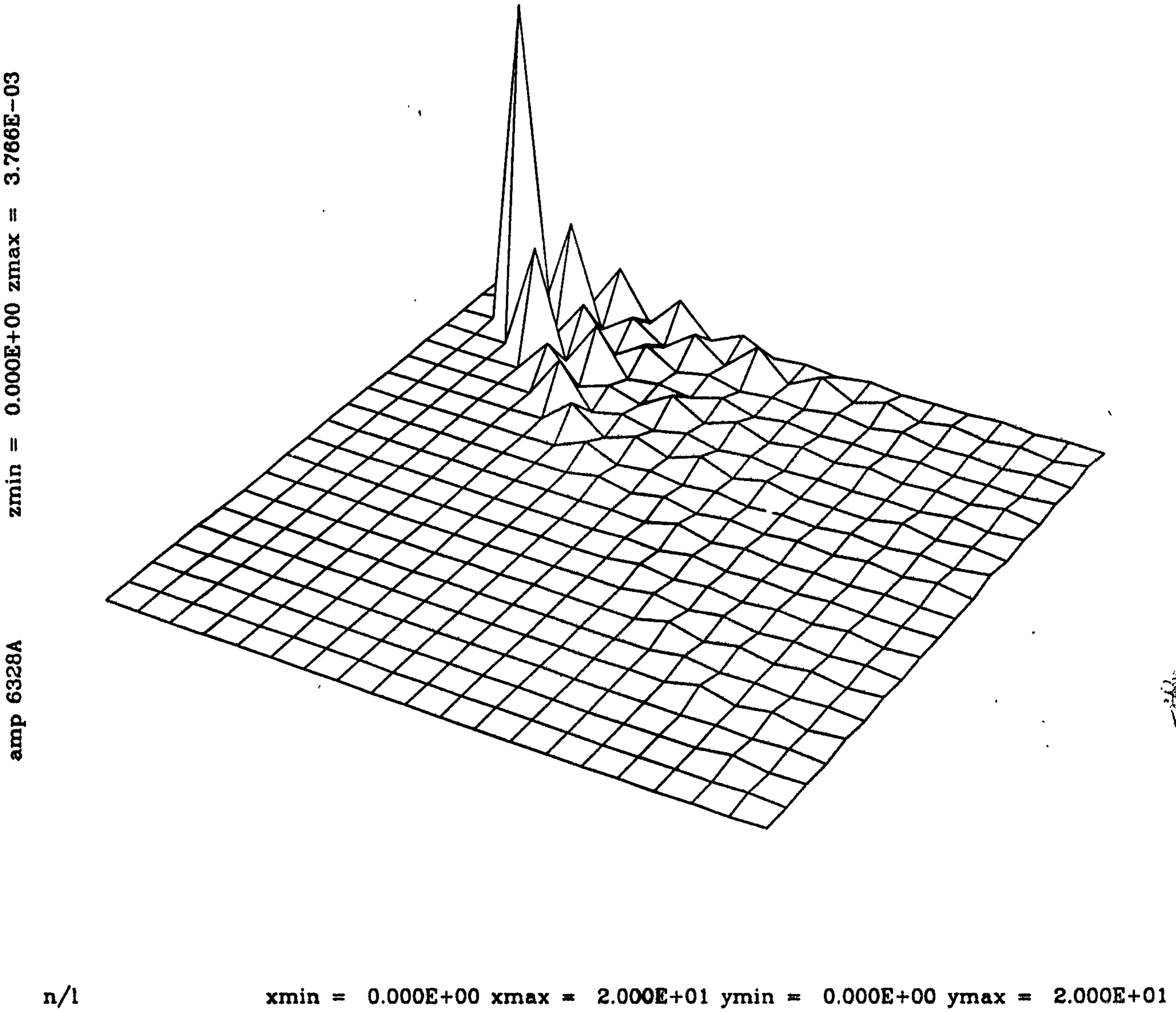

calflat2dfft.dat : Thu Jan 5 13:53:22 1995
amp(6328)
zmin = 6.2[illegible]8E-07 zmax = 2.750E+00
kx,ky
xmin = 9.830E-02 xmax = 3.146E+00 ymin = 9.830E-02 ymax = 3.146E+00

calflatzern3d6,0.dis: ZERNIKE AMPLITUDES 5.0cm radius : Thu Jun 16 21:53:18 1994



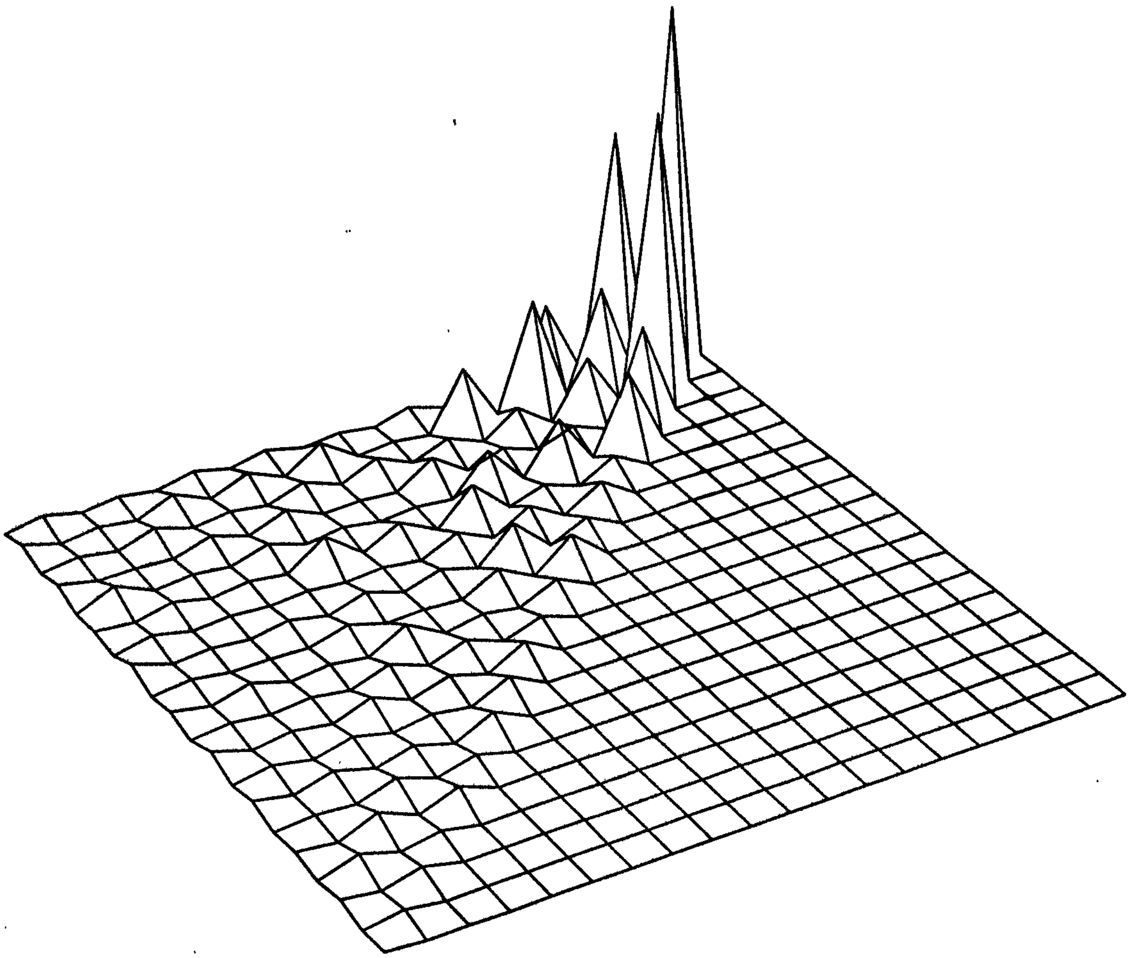
calflatzern3d.

calflatzern3d9.8.dis ZERNIKE AMPLITUDES 9.8cm radius : Thu Jun 16 21:25:14 1994



calflatzern3d9.8.ps

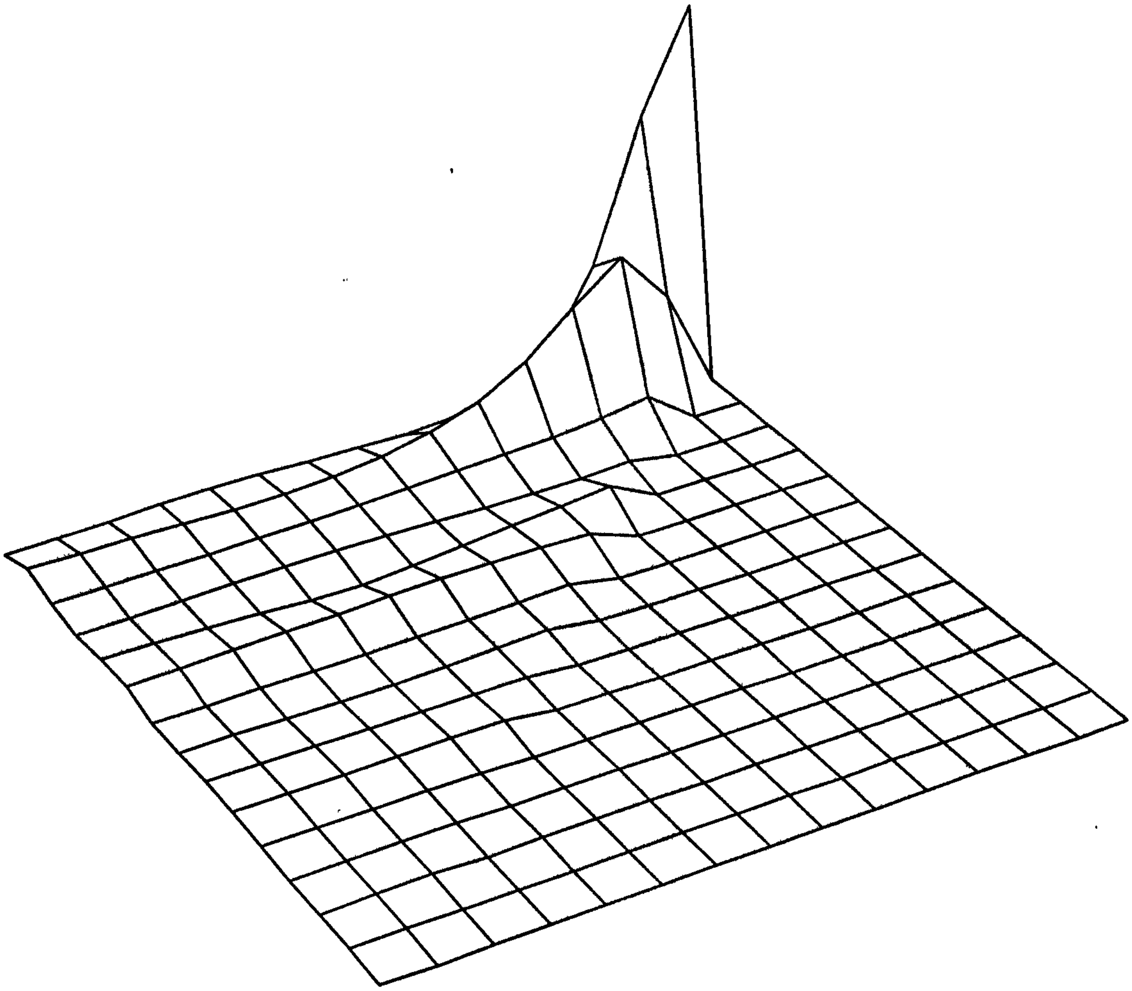
cutflatzern3d6.0.dis: ZERNIKE AMPLITUDES 6.0cm radius : Thu Jun 16 21:53:10 1994



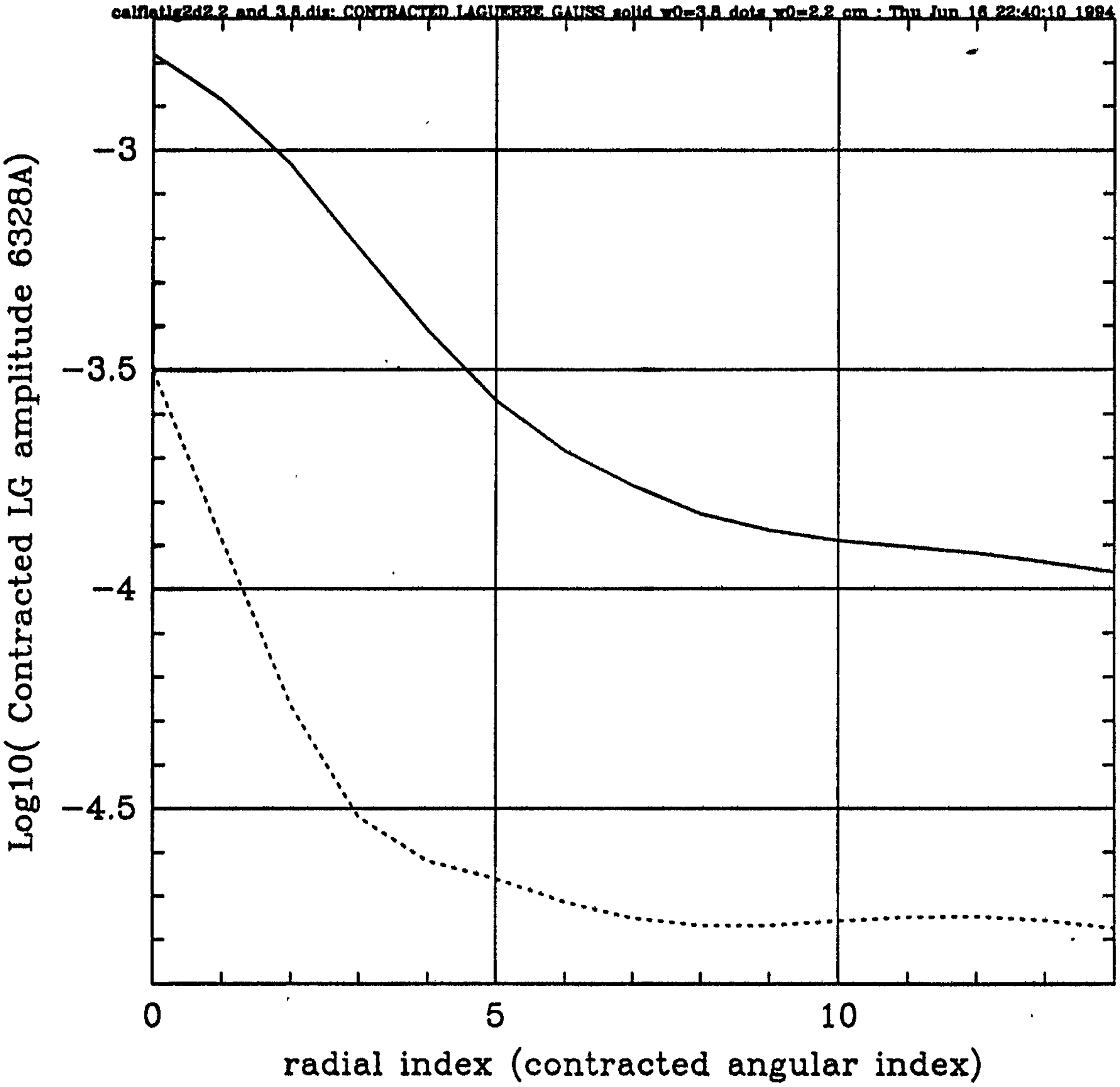
l/n xmin = 0.000E+00 xmax = 2.000E+01 ymin = 0.000E+00 ymax = 2.000E+01

cutflatzern 3d.

[illegible]/g243.8.dis LAGUERRE GAUSS AMPLITUDES w0=3.8 cm : Thu Jun 16 22:18:21 1994



[illegible] 3, 8.95



calflatlg 2,2,3,8 log.ps

Quantity	Values					
RMS in central Surfaces	Zero	Zero	1/900	1/600	1/400	1/200
Imperfect Substrates (y/n)?	no	yes	yes	yes	yes	yes
A	100 ppm	100 ppm	100 ppm	100 ppm	100 ppm	100 ppm
T_Rec_best	2.65%	2.64%	3.25%	4.03%	5.83%	15.9%
T_input	2.99%	2.99%	2.99%	2.99%	2.99%	2.99%
L_asymm_best	.104675 m	.12 m	.122111 m	.135 m	.161555 m	.265838 m
P_laser	2.5 watts	2.5 watts	2.5 watts	2.5 watts	2.5 watts	2.5 watts
Detector Efficiency	.8	.8	.8	.8	.8	.8
P_carr_recyc_cav_00	37.88	37.85	30.758	24.805	17.158	6.305
P_carr_bright_00	36.88	36.86	29.762	23.808	16.149	5.306
P_carr_arm_on_00	2462.5	2460.8	1992.8	1600.2	1095.0	379.60
P_carr_arm_off_00	2462.5	2460.9	1993.7	1601.8	1097.8	383.53
P_carr_dark_00	2.884*10^-25	3.197*10^-12	1.447*10^-6	6.970*10^-6	3.112*10^-5	1.785*10^-4
P_carr_dark_total	2.613*10^-12	2.980*10^-6	1.933*10^-2	3.753*10^-2	6.462*10^-2	0.1122
Carr Contrast Defect	1.42*10^-13	1.62*10^-7	1.298*10^-3	3.146*10^-3	7.957*10^-3	4.109*10^-2
P_sb_bright_00	35.73	23.58	23.85	19.66	13.71	4.827
P_sb_dark_00	0.9846	0.8581	0.9017	0.9137	0.9242	0.9508
P_sb_dark_total	0.9846	0.9082	0.9405	0.9486	0.9560	0.9727
Gamma_best	.00106	.05433	.4671	.5432	.6126	.6882
Absolute Carr Asymm Pow	6.5*10^-9 mW	.0074 mW	43.3 mW	80.7 mW	133 mW	220 mW
Absolute Two-SB Asymm Pow	.00138mW	3.34 mW	242.9 mW	324.9 mW	408 mW	511 mW
h(DC)	4.86*10^-24	5.01*10^-24	6.18*10^-24	7.18*10^-24	9.09*10^-24	1.66*10^-23
h(100Hz)	7.25*10^-24	7.48*10^-24	9.21*10^-24	1.07*10^-23	1.35*10^-23	2.43*10^-23
EQUIV ADDITIONAL LOSS DUE TO MIRROR ROUGHNESS (ppm)		1.12	25.7	56.8	131	565

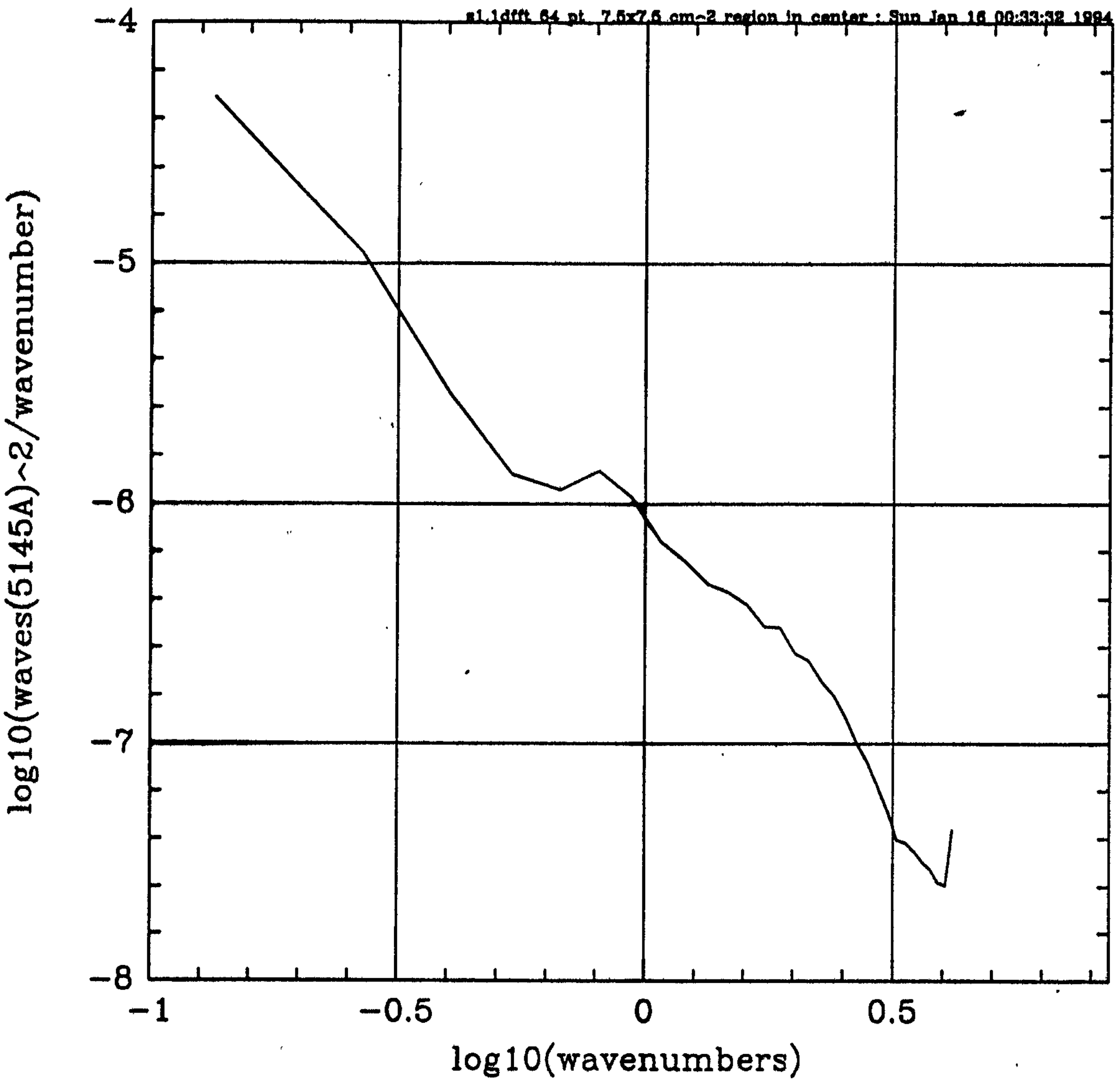
Repeat the h(f) calculations, now using an Output Mode Cleaner (i.e. all non-TEM00 modes aat the asymmetric beamsplitter port are eliminated):

Gamma_best_MC	.00062	.00142	.0454	.0671	.0972	.1491
Absolute Carr Asymm Pow (only TEM00 remains)	7.2*10^-22 mW	8.0*10^-9 mW	.0036 mW	.017 mW	.077 mW	.441 mW
Absolute Two-SB Asymm Pow (only TEM00 remains)	.00047 mW	.0021 mW	2.33 mW	5.14 mW	10.9 mW	26.3 mW
h_MC(DC)	4.86*10^-24	4.87*10^-24	5.42*10^-24	6.07*10^-24	7.39*10^-24	1.30*10^-23
h_MC(100Hz)	7.25*10^-24	7.26*10^-24	8.08*10^-24	9.03*10^-24	1.10*10^-23	1.90*10^-23

Input/Output Data For FFT Simulation Program: Run Data and Results

(All runs below are done with the lambda/400 Calflat surfaces, and the originally faked, non-rescaled substrates.)

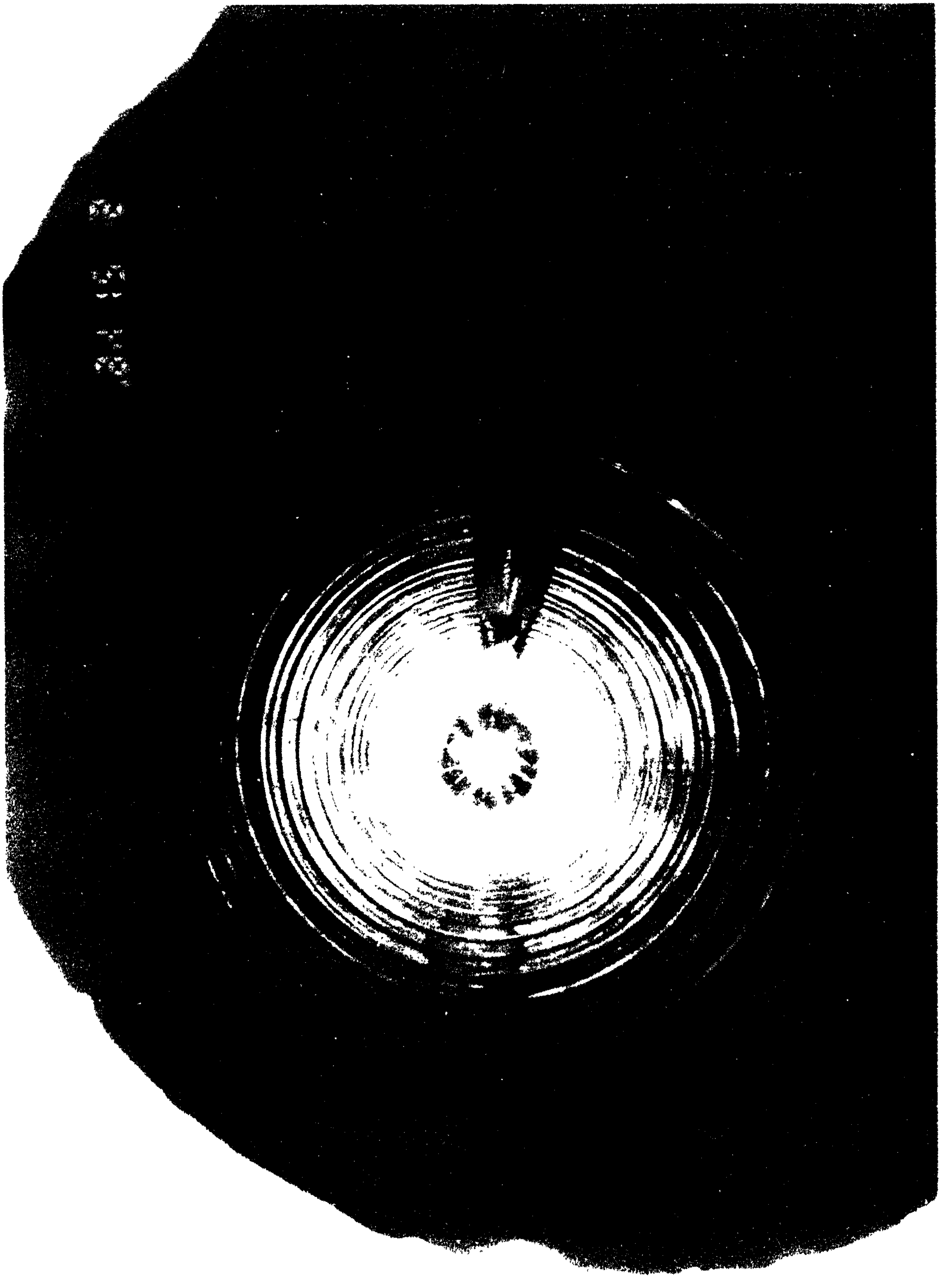
Quantity	Values		
A	50 ppm	100 ppm	150 ppm
RMS in Central Surfaces	1/400	1/400	1/400
T_Rec_best	4.56%	5.83%	7.08%
T_input	2.99%	2.99%	2.99%
L_asymm_best	.145 m	.161555 m	.177 m
P_laser	2 watts	2 watts	2 watts
Gamma_best	.6494	.6126	.5844
P_carr_recyc_cav_00	21.924	17.158	14.113
P_carr_bright_00	20.926	16.149	13.116
P_carr_arm_on_00	1409.3	1095.0	895.32
P_carr_arm_off_00	1412.9	1097.8	897.58
P_carr_dark_00	4.035*10^-5	3.112*10^-5	2.527*10^-5
P_carr_dark_total	8.351*10^-2	6.462*10^-2	5.263*10^-2
Carr Contrast Defect	7.936*10^-3	7.957*10^-3	7.979*10^-3
P_sb_dark_00	0.9076	0.9242	0.9363
P_sb_dark_total	0.9472	0.9560	0.9623
h(DC)	9.193*10^-24	1.02*10^-23	1.103*10^-23
h(150Hz)	1.774*10^-23	1.96*10^-23	2.119*10^-23

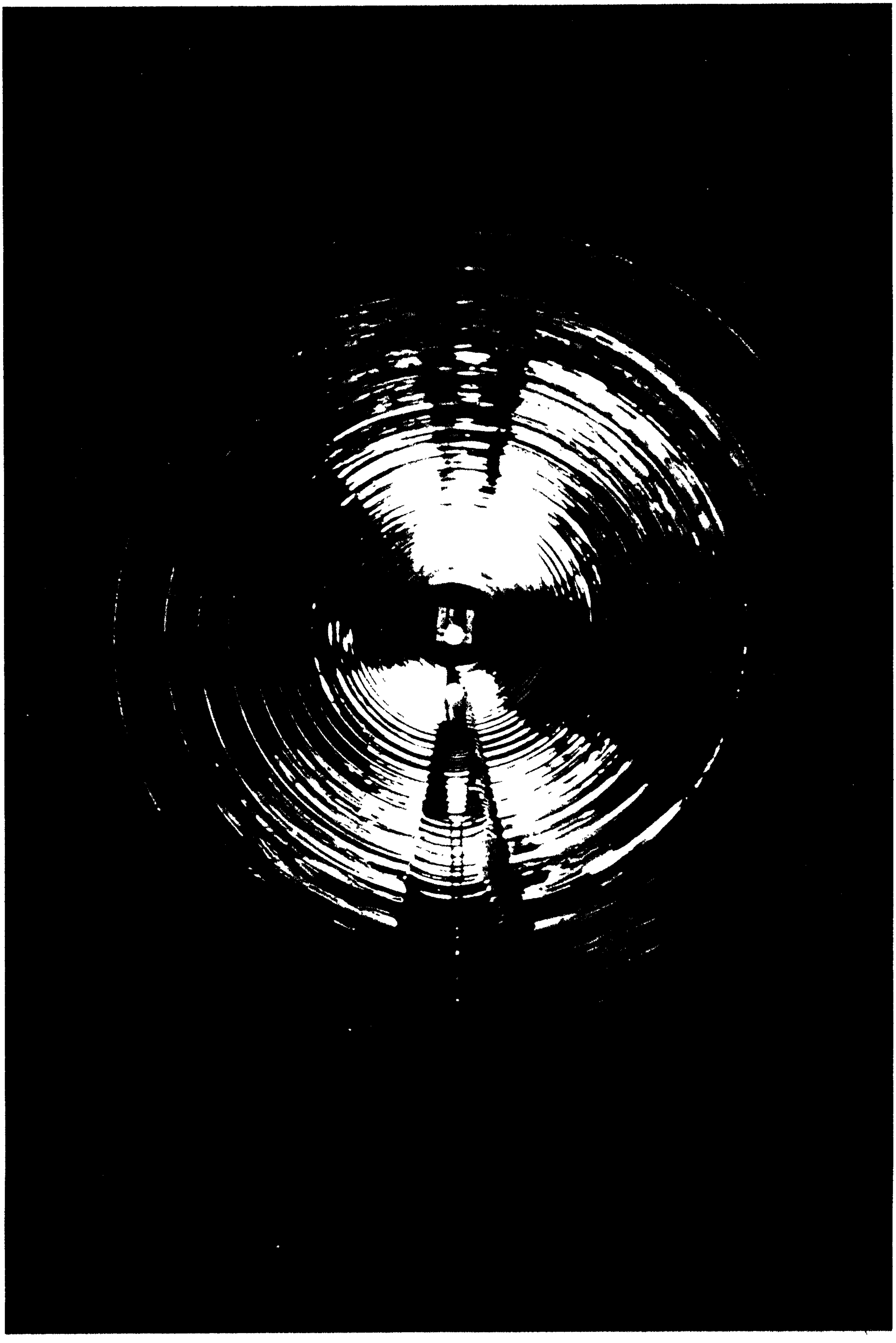

s1.1dfft 64 pt 7.5x7.5 cm~2 region in center : Sun Jan 16 00:33:32 1994
−4
−5
−6
−7
−8
log10(waves(5145A)~2/wavenumber)
−1
−0.5
0
0.5
log10(wavenumbers)

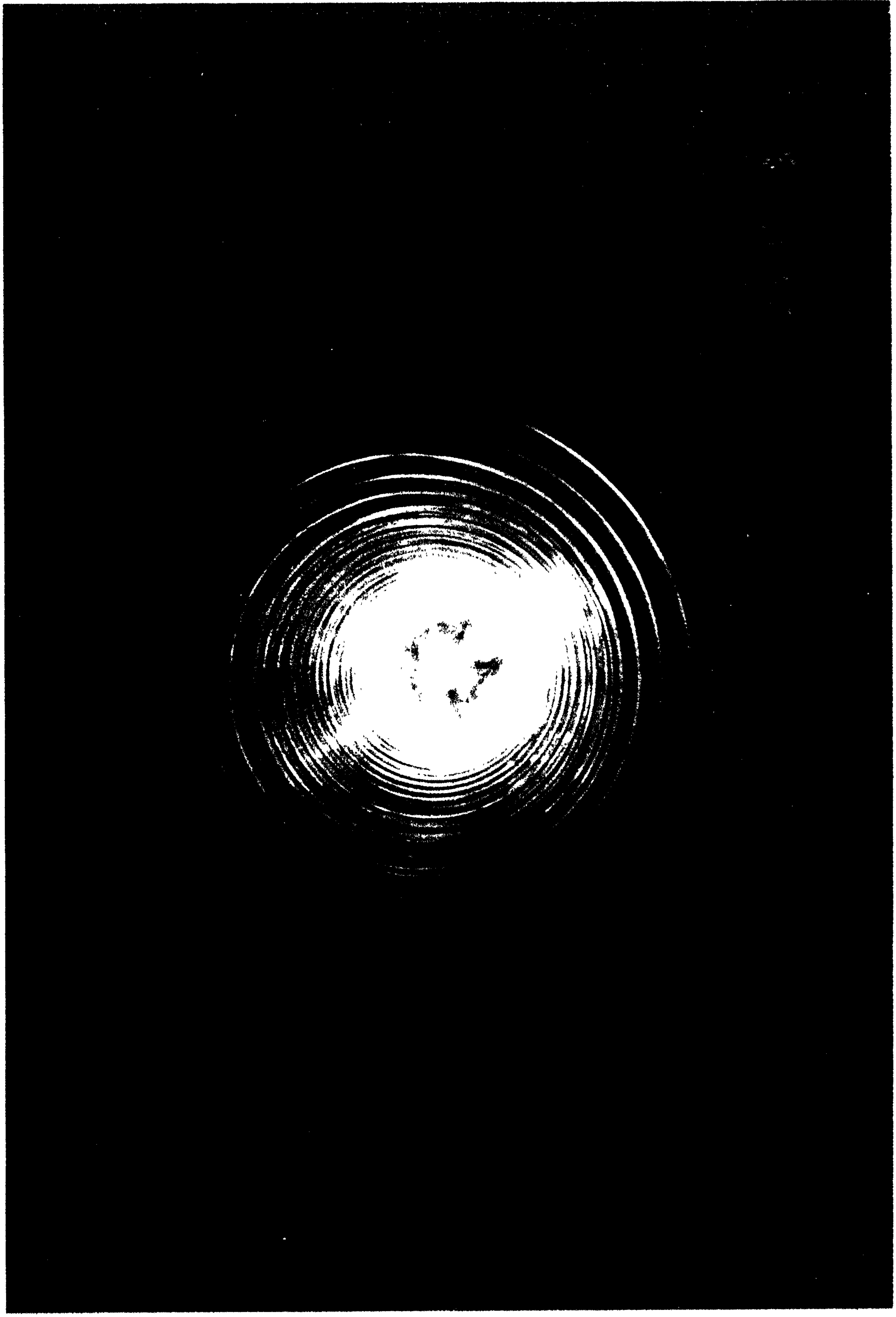
LIGO BEAM TUBE

MEASUREMENTS

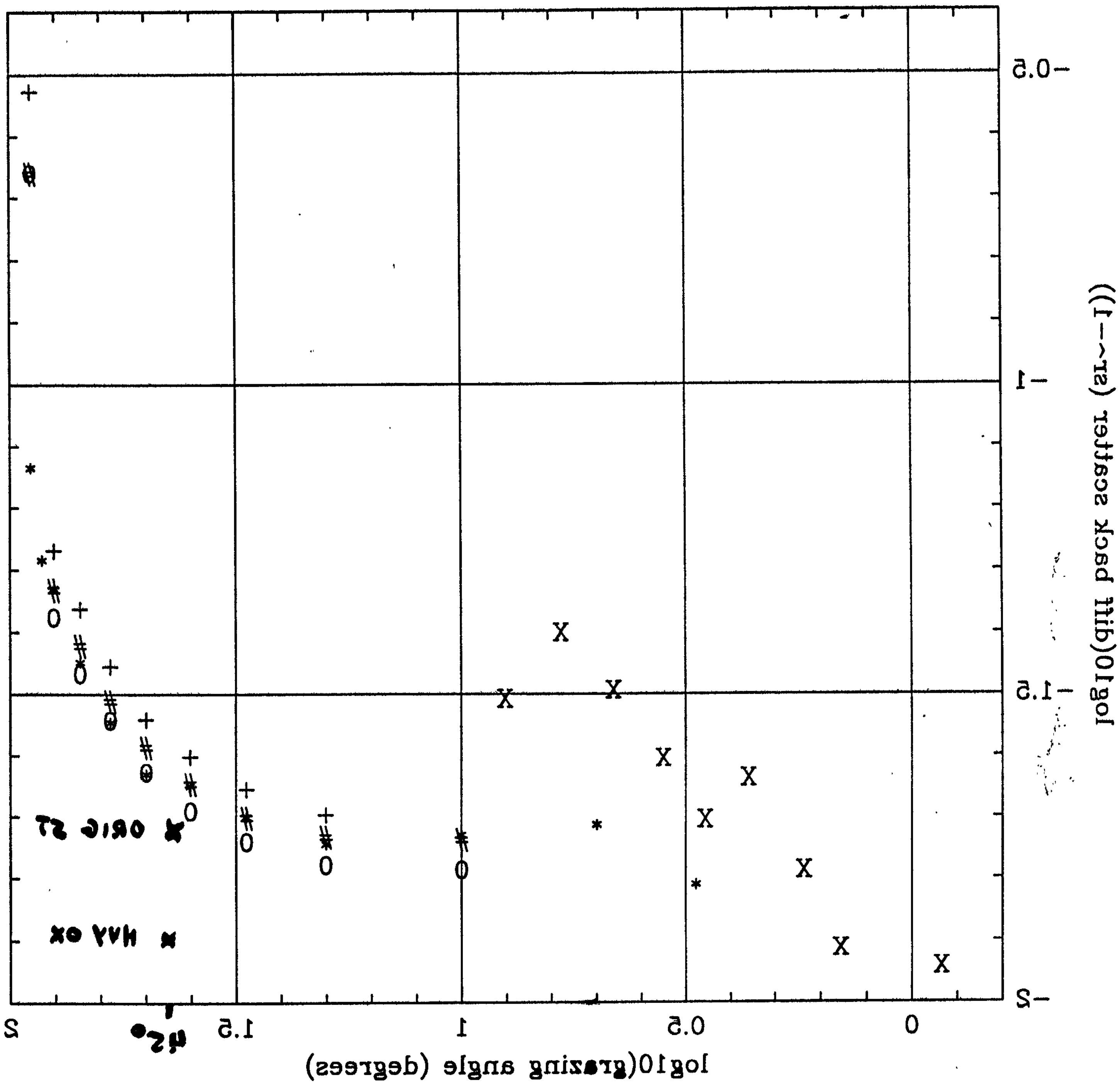
RAI WEISS

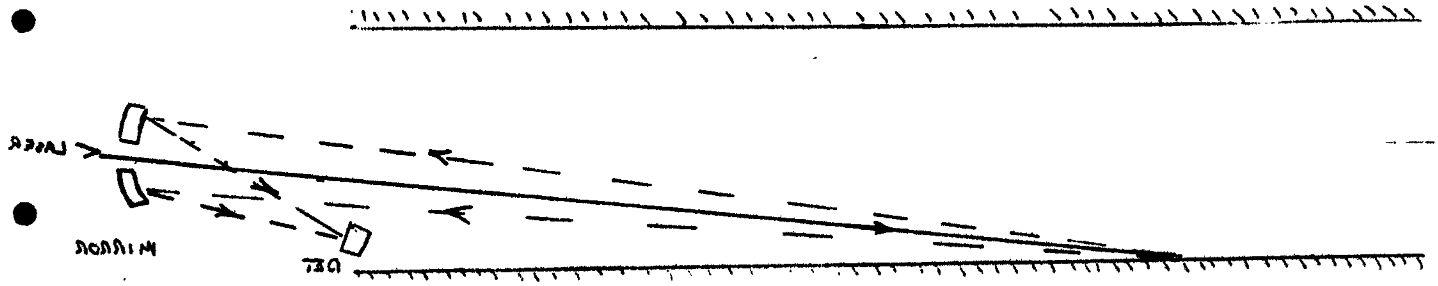






differential back scatter vs grazing angle STEEL:12.5m=*,26m=0,30m=#,36m=+; TUBE = X : Wed Jan 4 00:59:46 1995



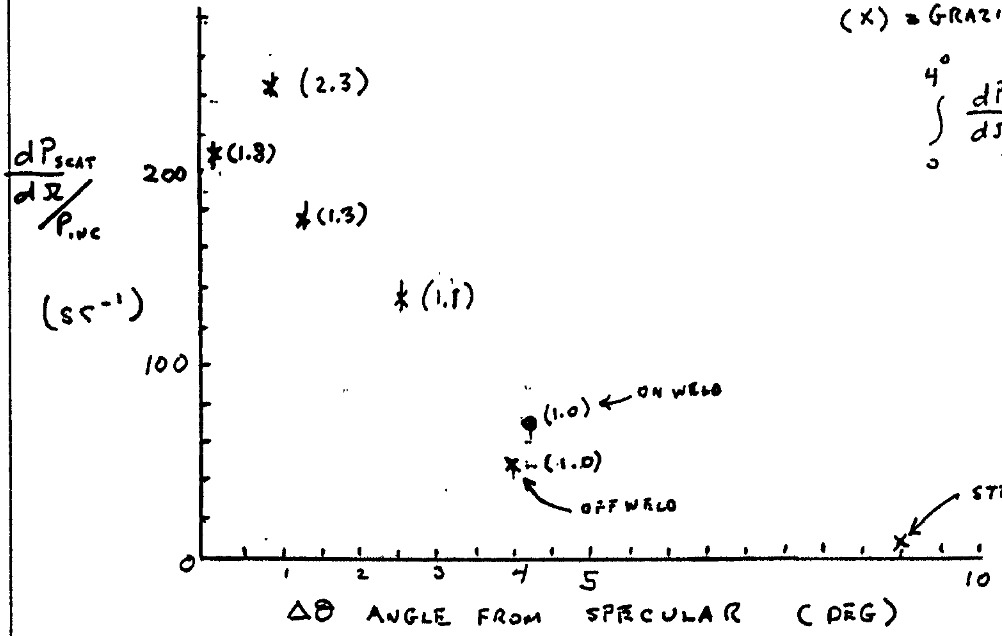


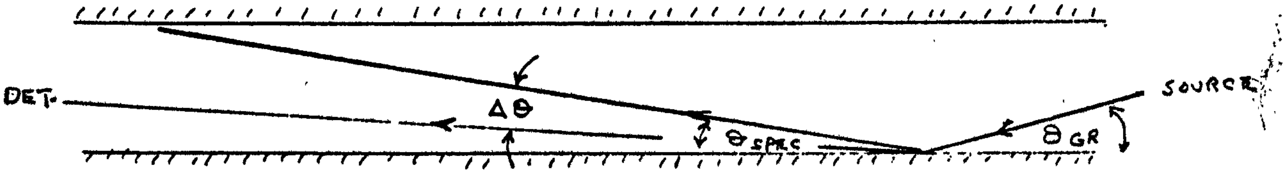
FORWARD SCATTERING FROM BEAM TUBE

PRELIMINARY DATA 1/04/95

(X) = GRAZING ANGLE IN DEGREES

$$\int_0^{4^\circ} \frac{dP_s}{d\Omega} \Big/ P_{inc} \, d\Omega \approx 1 \pm 0.5$$





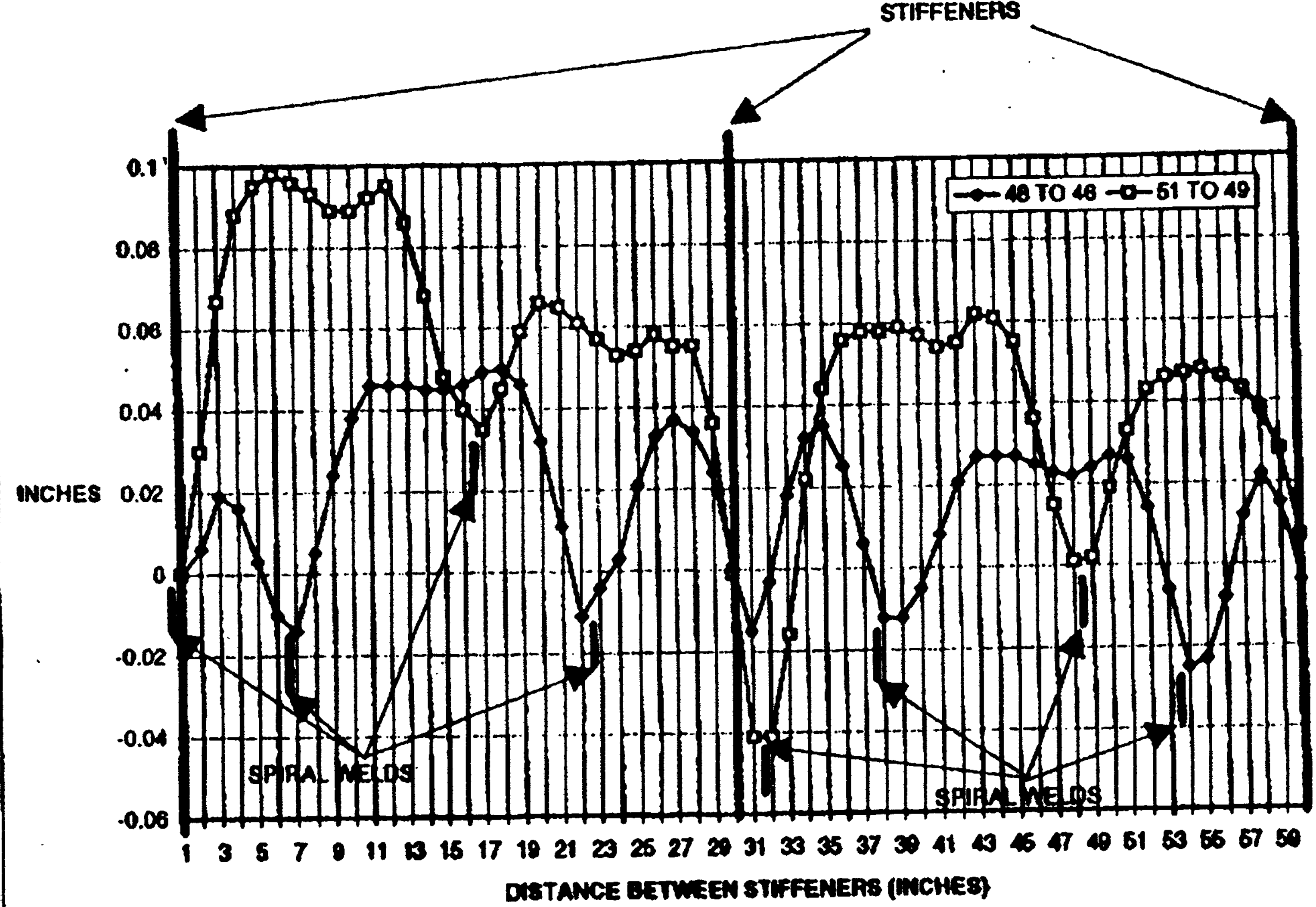
LASER
BEAM DIVERGENCE (FULL ANGLE) 1.65×10^{-3} RADIANS

NEED TO MAKE FURTHER MEASUREMENTS

1) ΔΘ > 5 ON STEEL SAMPLE

2) TOTAL SCATTER

3) LOSS



PROFILE BEAM TUBE SURFACE BETWEEN STIFFENERS

file:brdfmeasurements012493.txt
to: Vacuum group
from: D. Shoemaker and R. Weiss January 24,1993
concerning: Backscatter measurements on steel and Martin black

BACKSCATTER 'APPROX
ITION) REFRCT

We have measured the backscatter of several surfaces at 5145 Angstroms for polarization perpendicular and parallel to the plane of incidence.

The surfaces are:

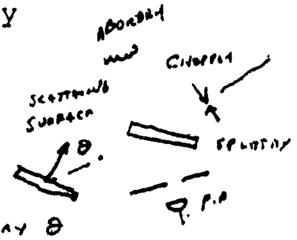
Martin black

"Original"steel used by BRO for stray light study

Heavy oxide steel blue/brown oxide surface

Bead blasted 7511C

Bead blasted 2311C



	5145 Angstroms			6328 Angstroms	6328 Angstroms
	--------NEW MEASUREMENTS-------			BRO MEASUREMENTS	MARTIN DATA
Material	BRDF 1/sr	thetainc degrees	polarization	BRDF 1/sr	BRDF 1/sr
Martin Bl	1.8e-3	0			1.0e-3
Martin Bl		45	unp		1.1e-3
Martin Bl	1.7e-3	45	45		
Martin Bl	2.2e-3	45	perp		
Martin Bl	1.5e-3	45	par		
Original	2->3e-1	0		1.0e-1(adopted value)	
Original	1.7->2e-2	45	45	1.0e-1(adopted value)	
Original	3->3.2e-2	45	perp	1.0e-1(adopted value)	
Original	1.6->1.8e-2	45	par	1.0e-1(adopted value)	
Heavy Ox	3.2->5.5e-2	0		2.7e-2	
Heavy Ox	7.7->9.2e-3	45	45		
Heavy Ox	1.0->1.3e-2	45	perp		
Heavy Ox	1.1->1.4e-2	45	par		
Heavy Ox		45	unp	1.1e-2	
Bead Bl 75	3.0->3.5e-1	0		4.8e-1	
Bead Bl 75	2.1->2.2e-2	45	45		
Bead Bl 75	3.4->3.5e-2	45	perp		
Bead Bl 75	3.3->3.5e-2	45	par		
Bead Bl ?		45	unp	1->3e-2	
Bead Bl 23	2.5->3.2e-1	0			
Bead Bl 23	1.9->2.3e-2	45	45		
Bead Bl 23	3.7->3.9e-2	45	perp		
Bead Bl 23	3.3->3.5e-2	45	par		

Measurement uncertainty in BRDF +- 1e-4 1/sr (due to fluctuation in background subtraction)

Conclusions: Assuming dominant contribution is back scatter.
Phase noise power derived from BRO stray light model to be corrected by multiplying by factor:

Original material	0.17	-	0.2
Heavy Oxide	0.10	-	0.14
Bead Blast 75	0.21	-	0.35
Bead Blast 23	0.19	-	0.39
Martin Black	0.015	-	0.022

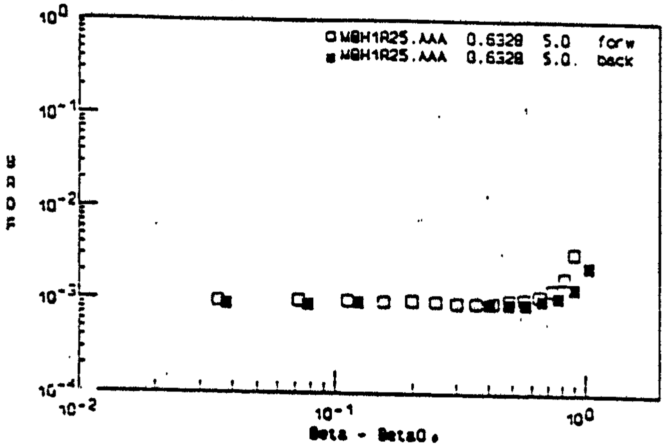


Figure 1. Visible BRDF of Martin Black (5°).

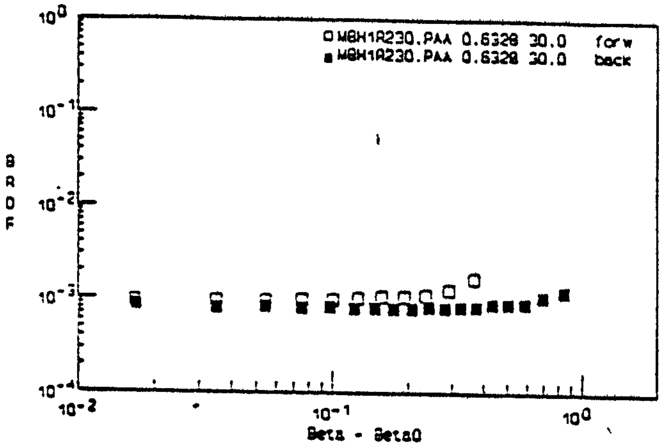


Figure 2. Visible BRDF of Martin Black (30°).

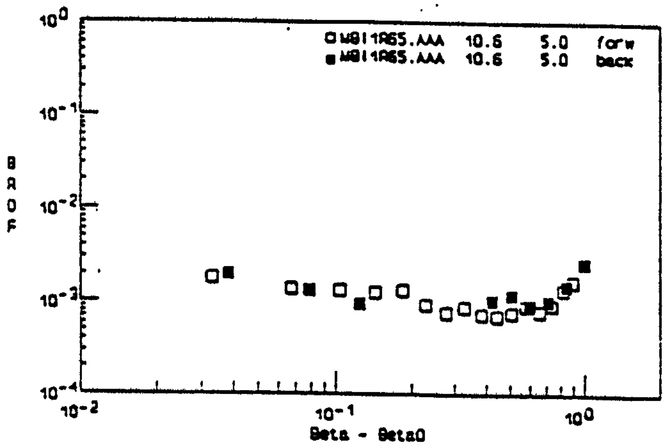


Figure 3. Infrared BRDF of Martin Black (5°).

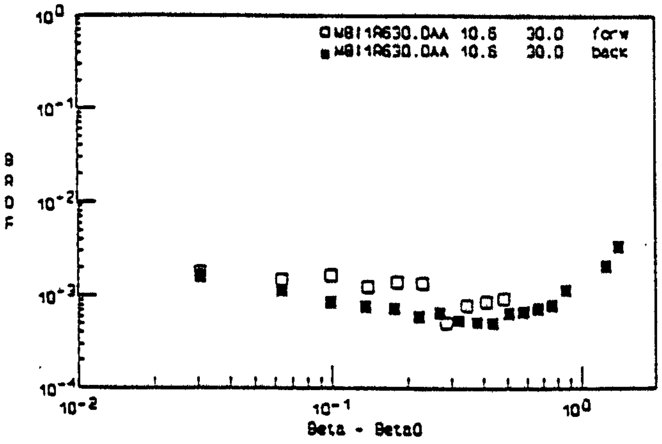
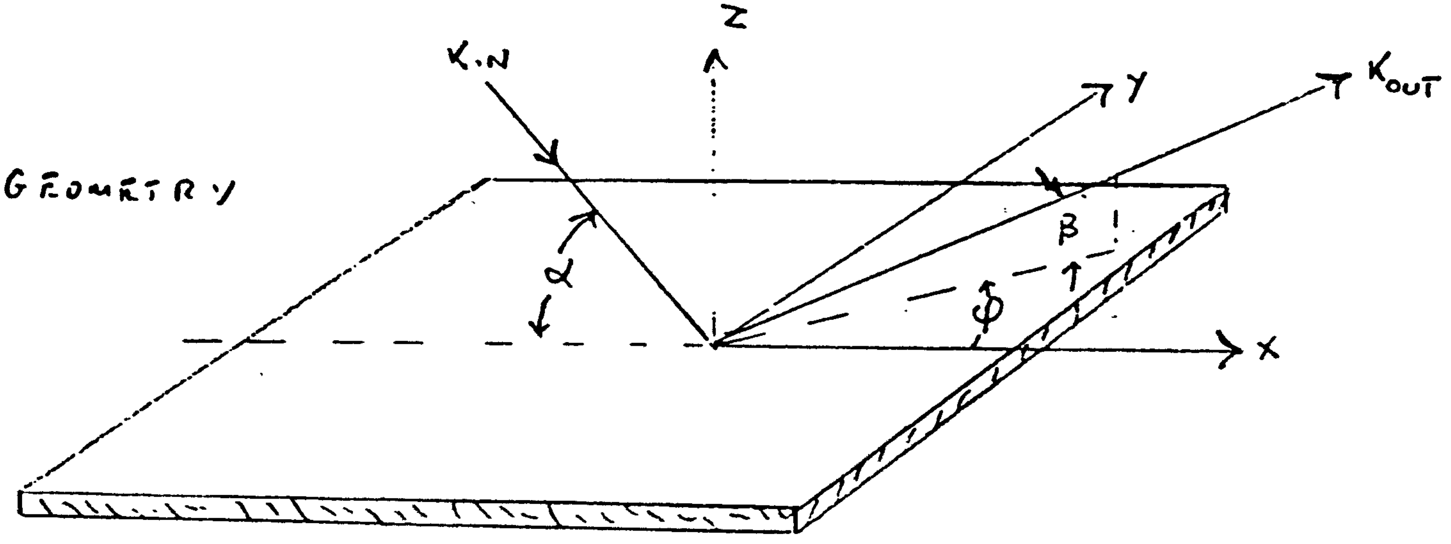
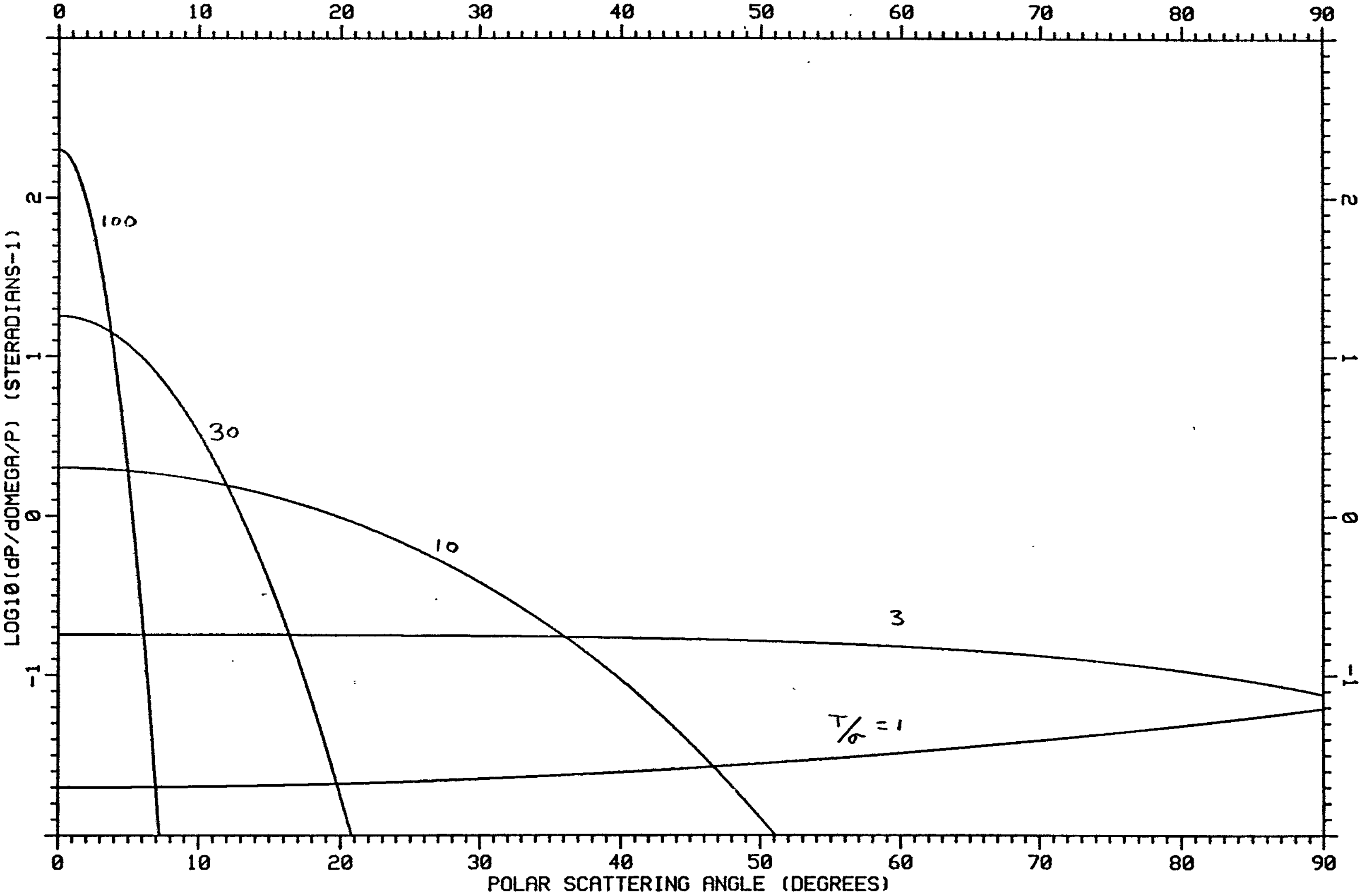


Figure 4. Infrared BRDF of Martin Black (30°).

SCATTERING GEOMETRY





DIFFUSE SCATTERING ALPHA=.01, PHI=0.0 DEGREES

FIGURE 12

file:backscat010495.txt
to: file
from: R. Weiss January 4, 1995
concerning: Apparatus for scattering measurements from steel and beam tube

He-Ne laser with parameters:

lambda = 0.633 microns
power = 1.1 mW
w0 = 2.44 x 10^-2 cm
z0 = 29.5 cm
Nominal beam divergence 1/2 angle = 8.3 x 10^-4 radians

Back scattering collimating system:

mirror diameter = 8.57 cm
hole in mirror = 0.80 cm
focal length = 100 cm
detector distance = 100 cm
Si detector = 0.3 x 0.3 cm^2
Band pass filter at 0.6328 micron
  on resonance transmission = 0.85
  bandwidth = 1.1 x 10^-3 micron

Forward scattering system:

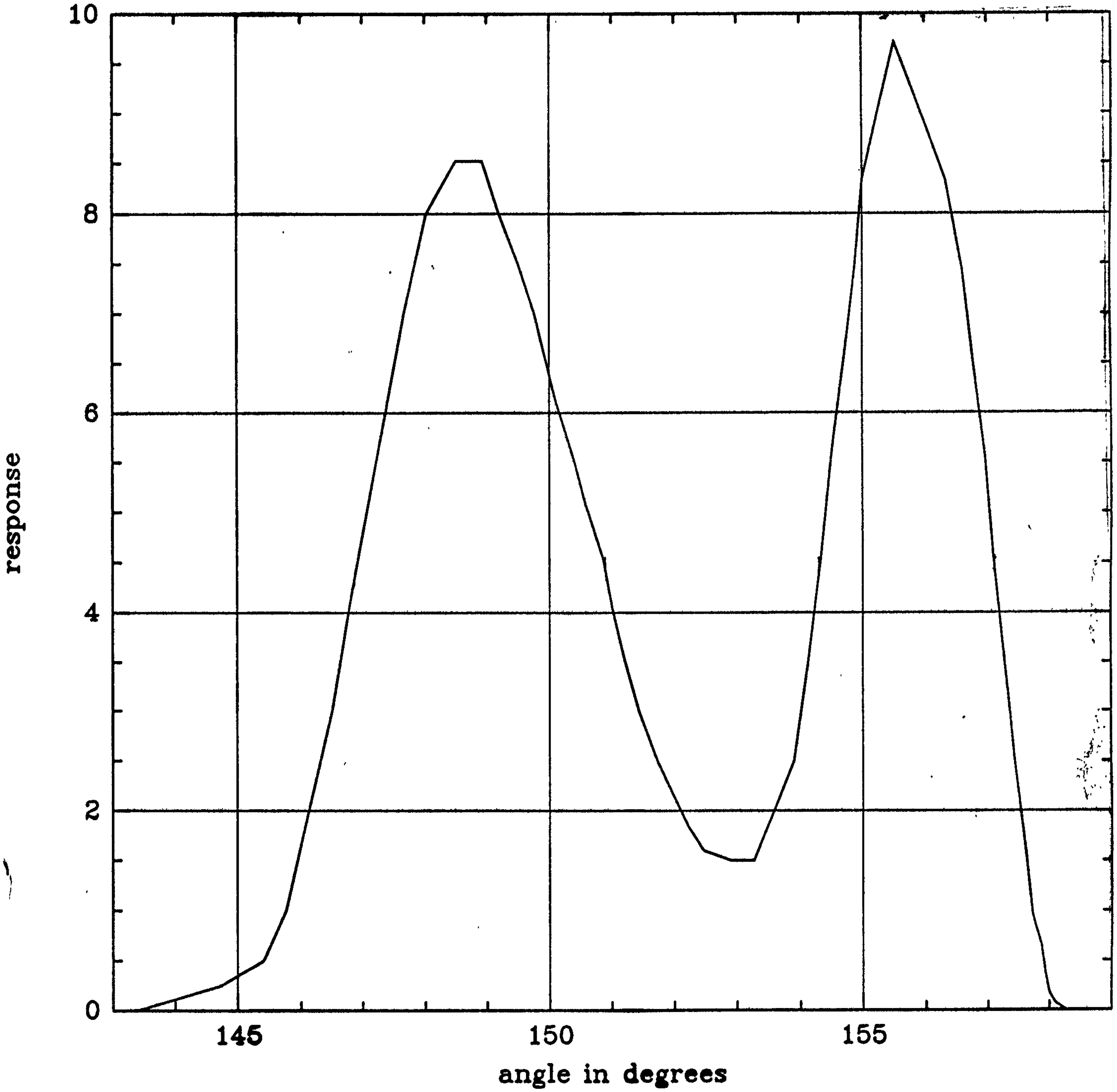
Angular acceptance of detecting system = 11 degrees
Defining aperture at detector = 0.746 cm
Photomultiplier detector RCA (Burle) 4903
  aperture = 3.35 cm
  spectral response = S20

Electronics:

Mechanical chopper frequency = 343 Hz
Transimpedence amplifier: 1M, 10M, 100M (ohm); thermal noise limit on all
Detected noise equivalent power (100M) = 4.6 x 10^-14 watts/sqrt(Hz)
Detection bandwidth = 5.3 x 10^-1 Hz

Calibration:

Martin Black: dP/d(omega)/Pinc normal incidence = 2 x 10^-3 sr^-1



Photomultiplier angular response : Mon Jan 2 22:36:50 1995

pmtangresp.ps