Institute of Applied Physics

Research Group Activity for

Contribution to LIGO Development

Alexander SERGEEV

46 Uljanov st., 603600 Nizhny Novgorod, Russia

LIGO-G980113-04-M

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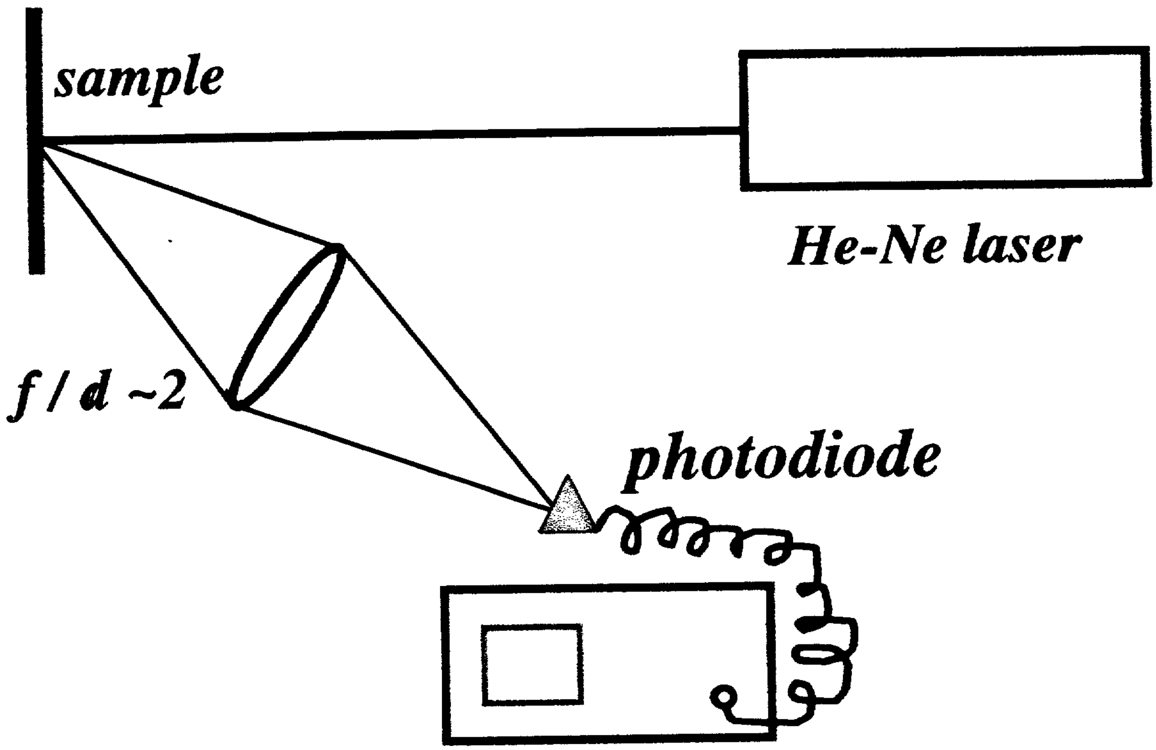
Method of Total Integrated Scattering (TIS)



$$TIS = P_d / (P_s + P_d),$$

where P_d - diffuse reflectance,

P_s - specular reflectance

for $\sigma << \lambda$

$$TIS = 1 - exp[- (4 \cdot \pi \cdot \sigma \cdot cos\,\theta_0 / \lambda)^2]$$

where θ_0 - incident angle

so $\sigma = (\lambda / 4 \cdot \pi \cdot cos\,\theta_0) \cdot \sqrt{TIS}$

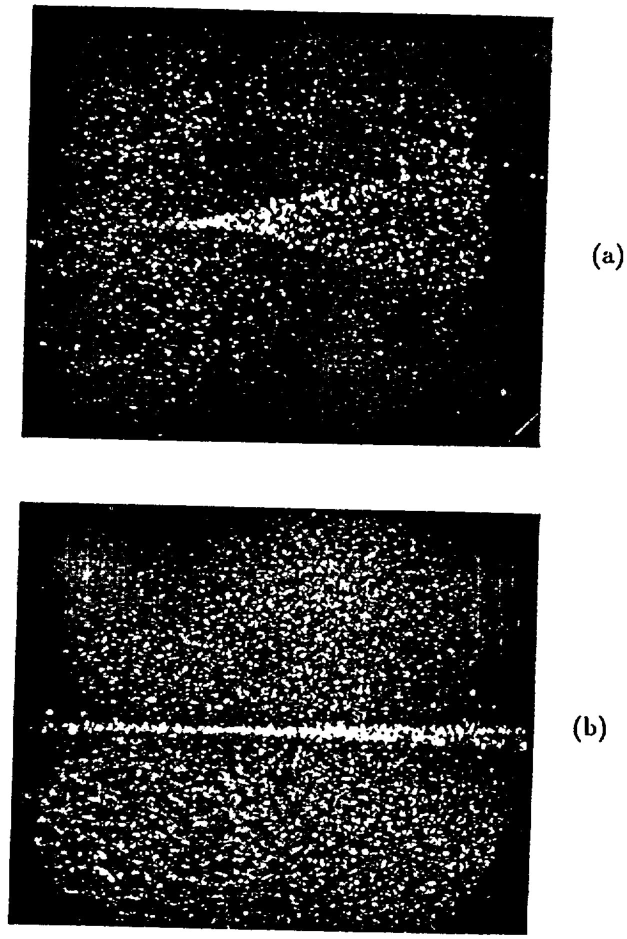
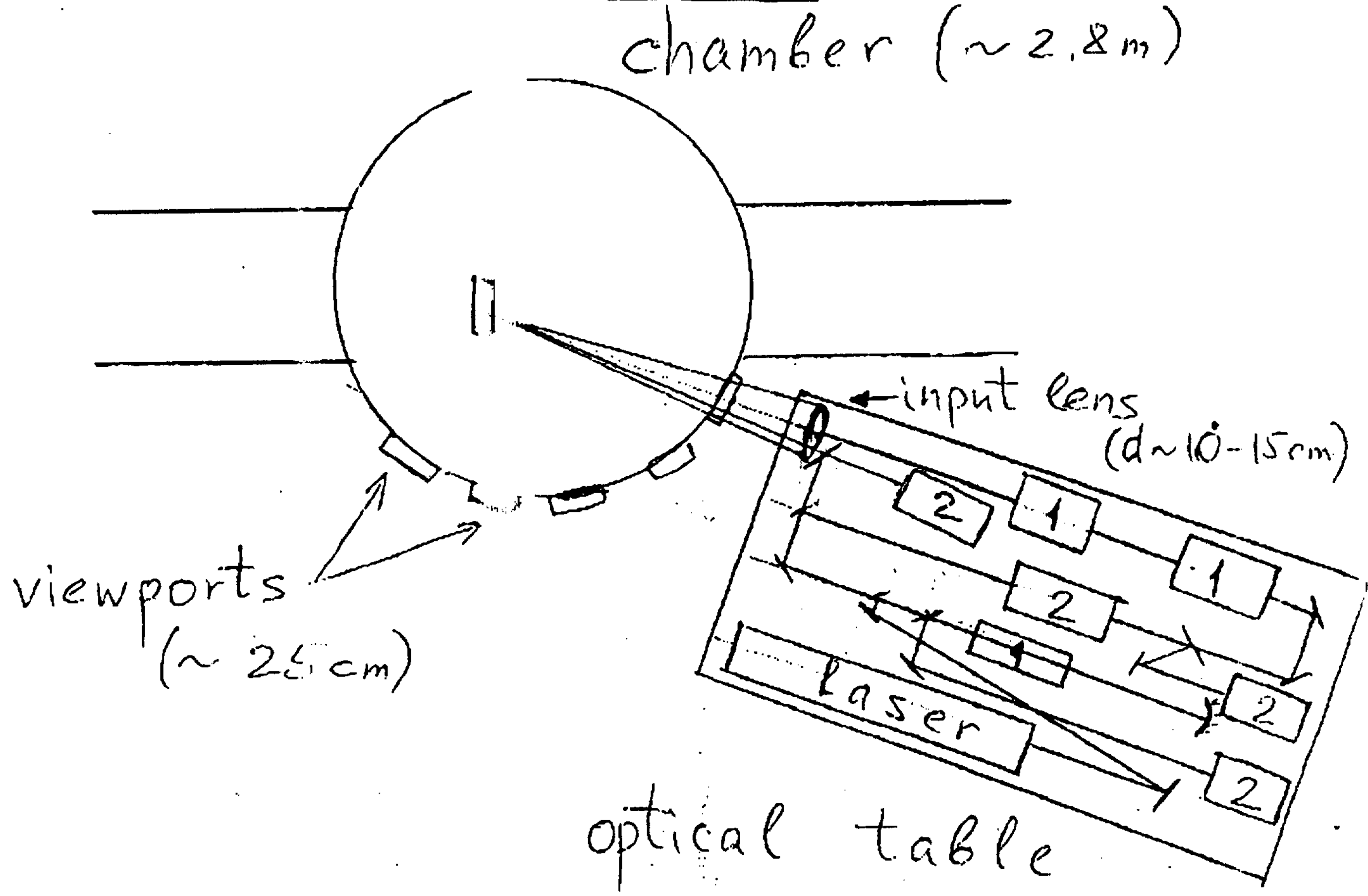


Fig. 10. Image of the transverse structure of scattered radiation for (a) $\varphi = 5°$ and (b) $\varphi = 30°$

Appr. scheme of small-scale contamination measurement



optical table

(appr. 1×2 m (3'×6'))

1 - laser amplifiers

2 - SBS cells

EXPERIMENTAL FACILITIES

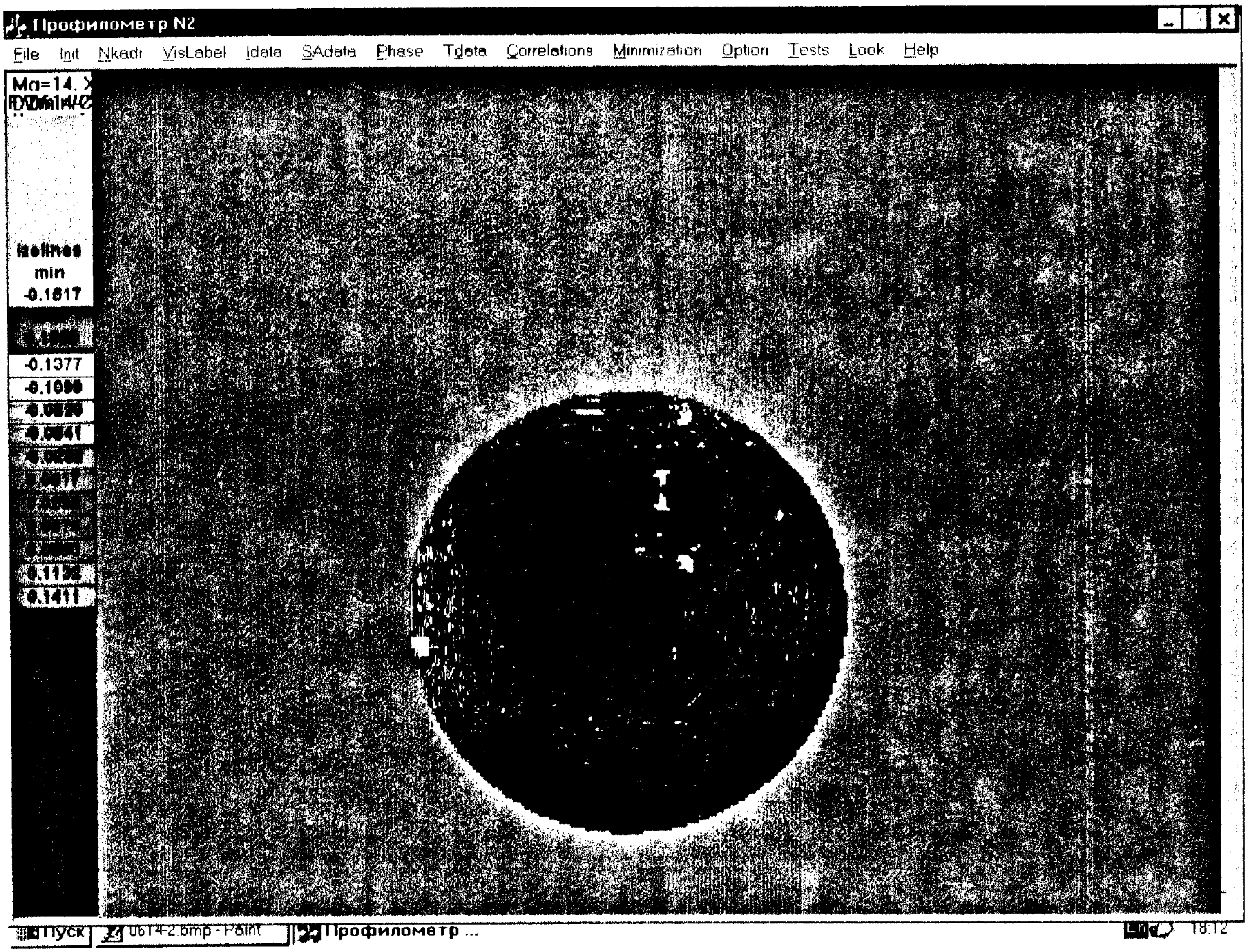
1. Experimental facilities based on nonlinear optical effests for remote (in situ) probing of LIGO optics components, including

- **1.1. Laser projection image receiver based on the four-wave phase-conjugation effect for remote probing of small-scale absorbtive inhomogenieties on LIGO mirror surfaces**

- **1.2. Laser facility using the radiation self-focusing effect to measure wave-front distortions with the absolute precision λ/1000- λ/2000**

- **2. Phase-modulated white-light interferometer to characterize the surface quality of the LIGO core optics and input optics components (clear apperture up to 25 cm, absolute accuracy better than λ/1000, measured radius of curvature 3000 m and more)**

3. Experimental facility to study self-induced thermal distortion effect of laser radiation in Faraday isolators on the isolation ratio in the LIGO input optics scheme



LIGO input Optics Spherical Mirror
d = 2.8cm , R = 25.16 m $P/V \simeq \frac{\lambda}{50}$ (residual) + Measureme
of R curv.

● Advanced Phase-Modulated White-Light Interferometer

• **Traditional interferometry** using phase modulation of the incident light, which allows one to eliminate effects of temporal fluctuations, transverse inhomogeneity, etc.

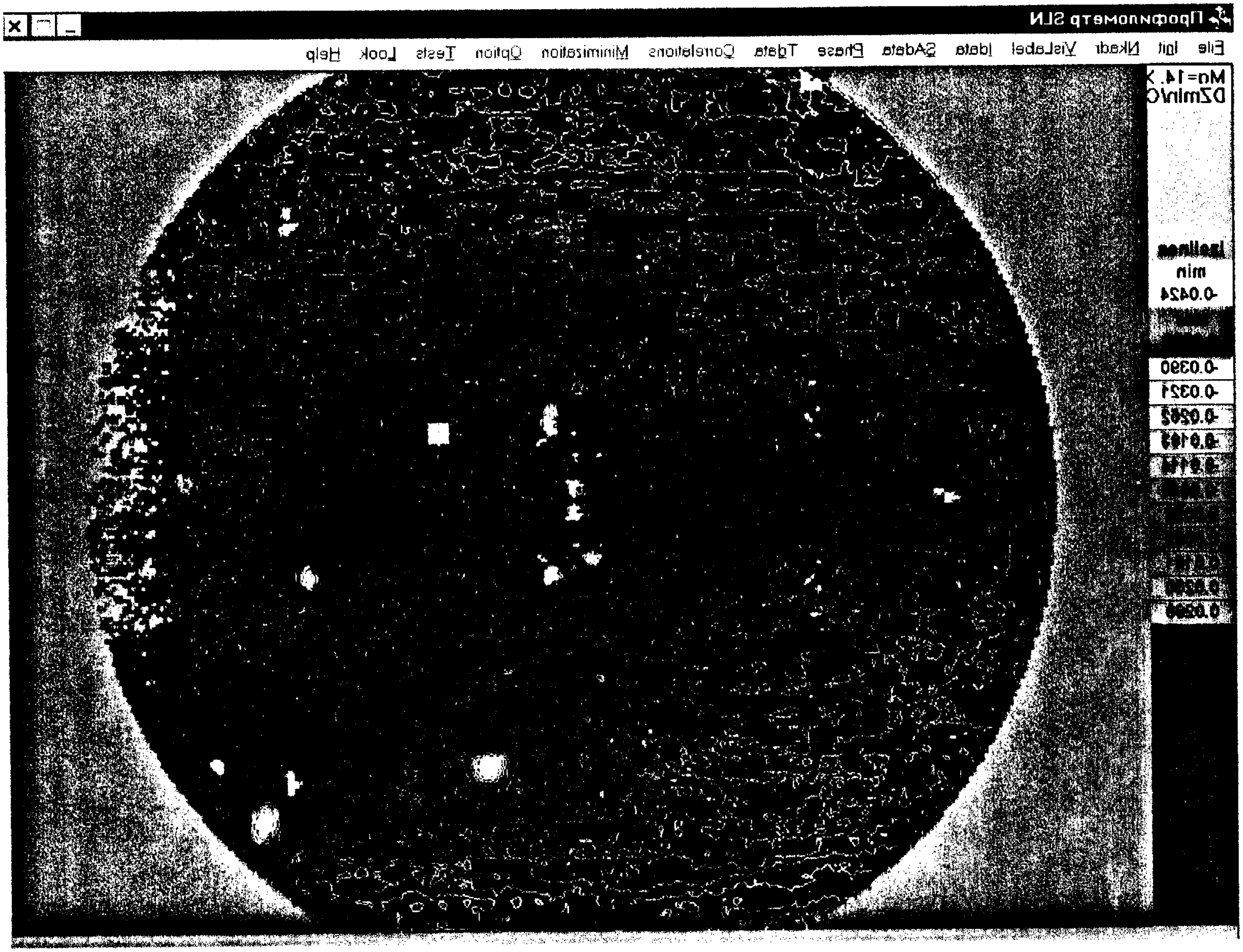
• **Nontraditional approach,** where we use a white-light source and modulate its spectrum in time

Advances:

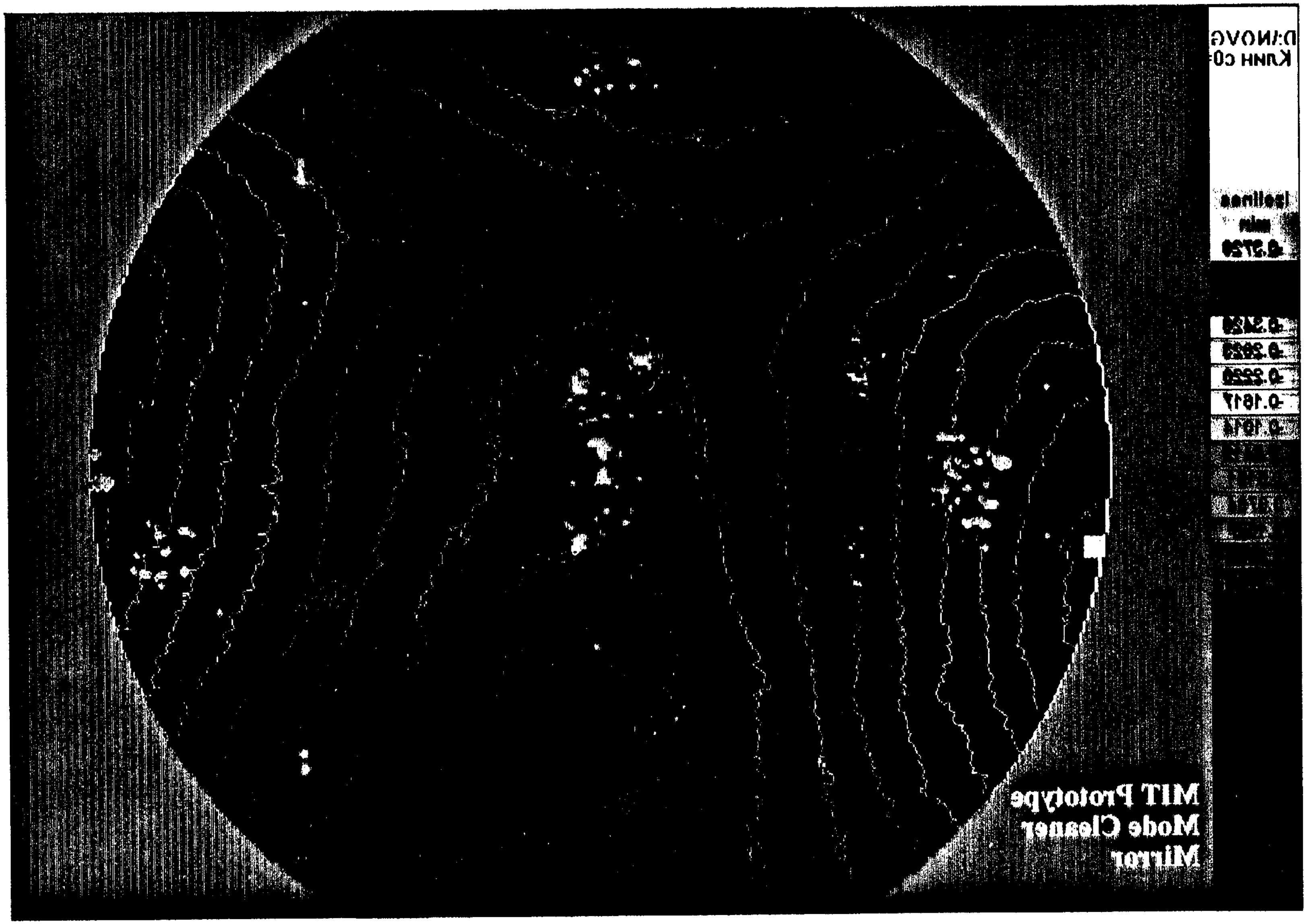
1. Tuning the probing wave-length for better performance (transparent coatings, measurements of non-flat surfaces)
2. Absence of speckle structures that deteriorate the interference pattern (typical for coherent laser sources)

Results:

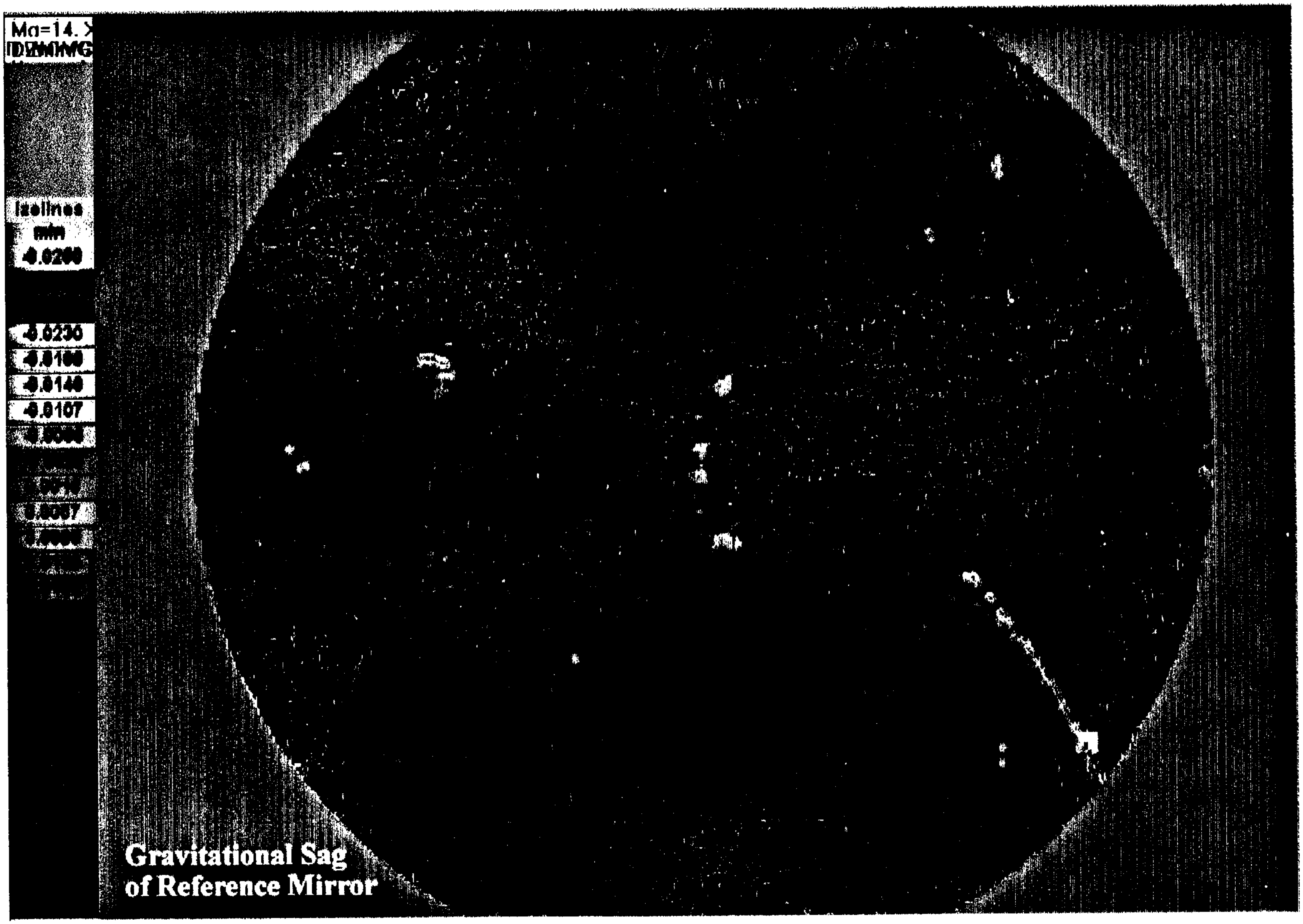
1. Absolute measurement accuracy $\lambda/1000$ in the visible has been demonstrated over 9 cm diameter aperture of flat mirrors
2. Sperical mirrors have been characterized by measuring the current radius of curvature and the residual surface deviation
3. Several LIGO mirrors have been tested, including large diameter core optics mirror and input optics spherical mirrors



60 Core Optics Pathfinder Mirror Edge Defect P/V = $\frac{\lambda}{130}$

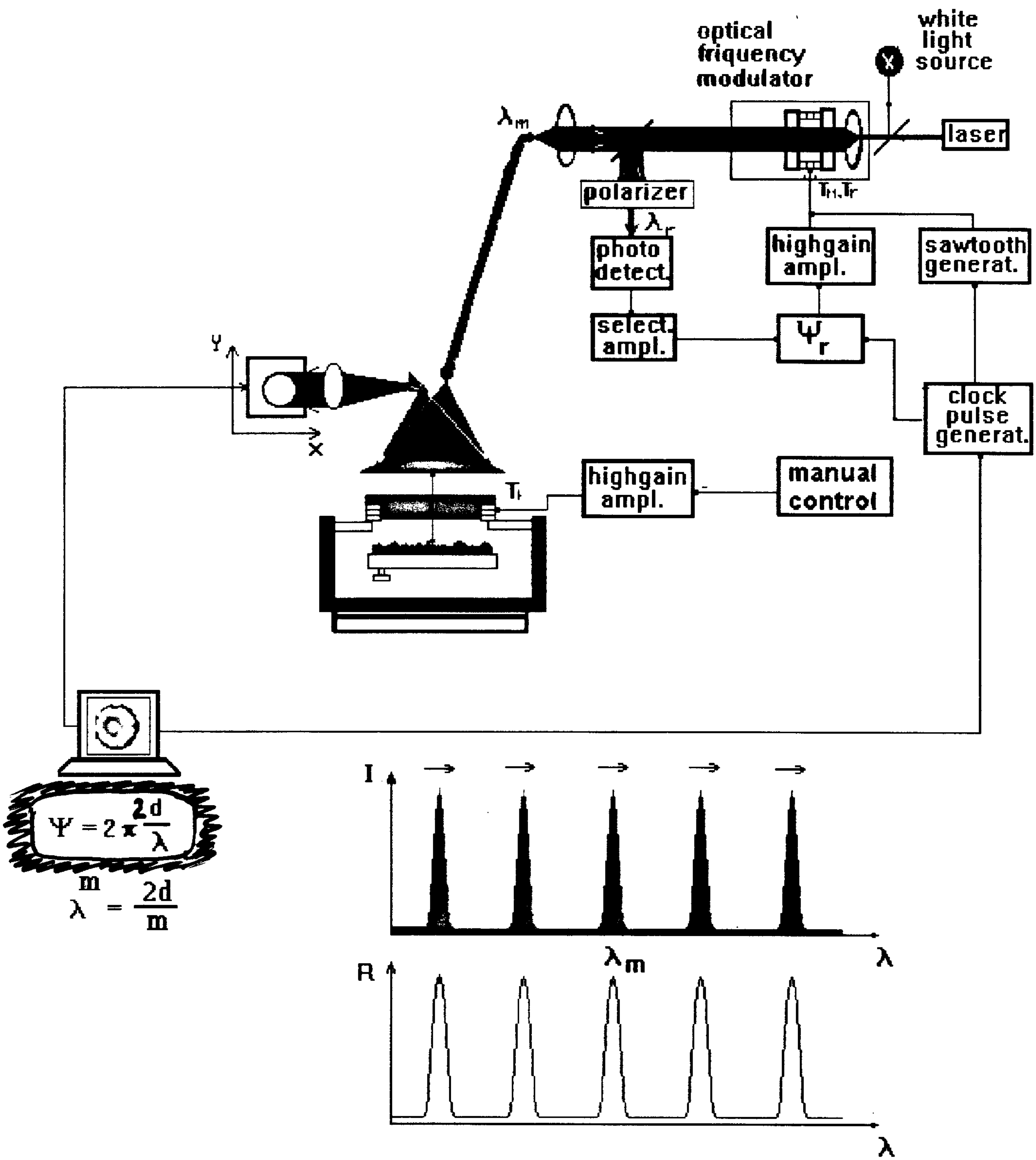


d = 8cm



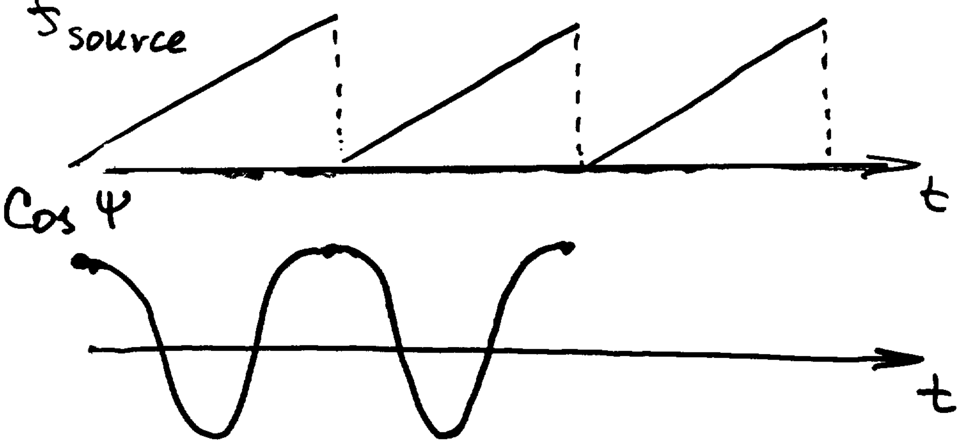
240 x 320 pixels
d = 8 cm

$P/V \simeq \frac{\lambda}{500}$

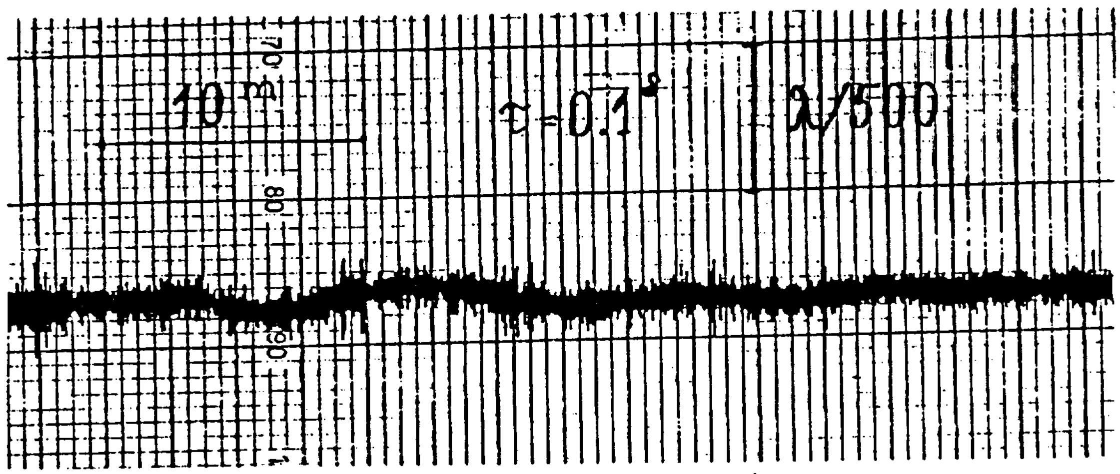

optical
friquency
modulator
white
light
source
laser
λ_m
polarizer
λ_r
T_H, T_r
photo
detect.
highgain
ampl.
sawtooth
generat.
select.
ampl.
Ψ_r
clock
pulse
generat.
Y
X
T_f
highgain
ampl.
manual
control
$\Psi = 2\pi \frac{2d}{\lambda}$
$\lambda^m = \frac{2d}{m}$
I
λ_m
λ
R
λ

$$\cos\Psi = \cos\left(2d\frac{2\pi}{\lambda}\right) = \cos\left[\frac{(f_0+\alpha t)}{c}2d\right] =$$

$$= \cos\left(F_M t + \Psi_0\right) = \cos\left(\frac{2\pi\cdot 2d}{c}\alpha t + \frac{2\pi}{\lambda_0}2d\right)$$



Phase of LF signal contains information on d

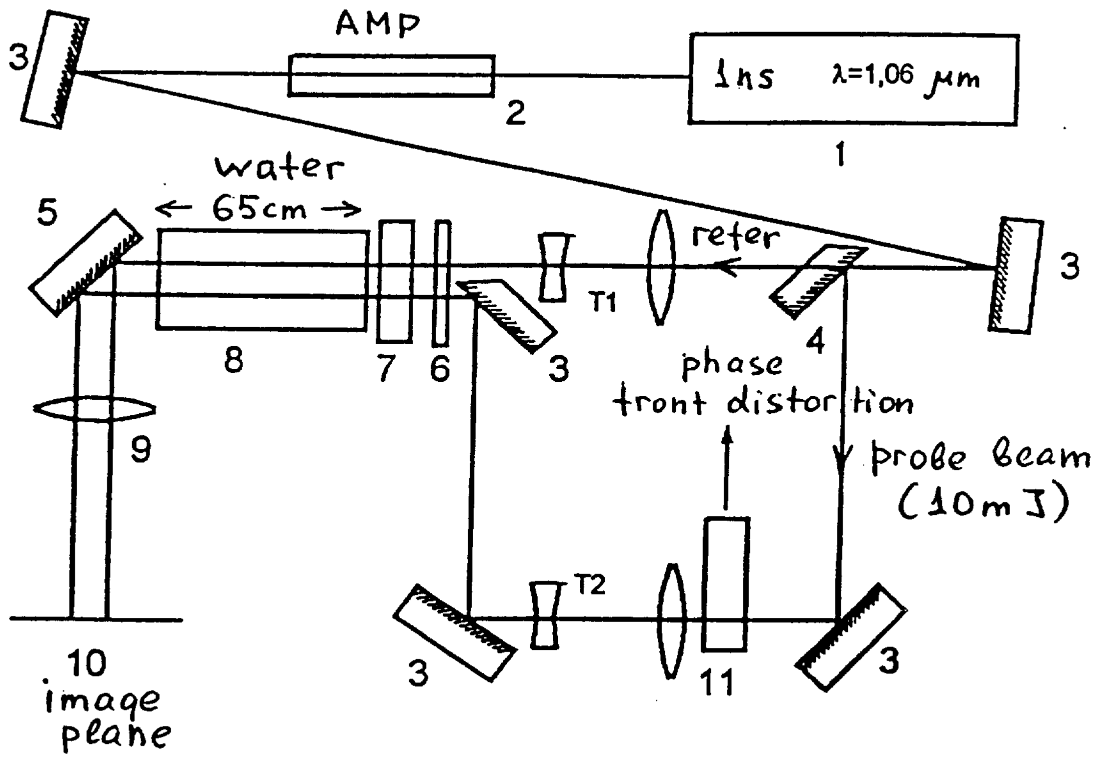


Fragment of a measurement recording obtained at a single point of a surface.

Isolated optical table

$\frac{\lambda}{1000}$ is the limit

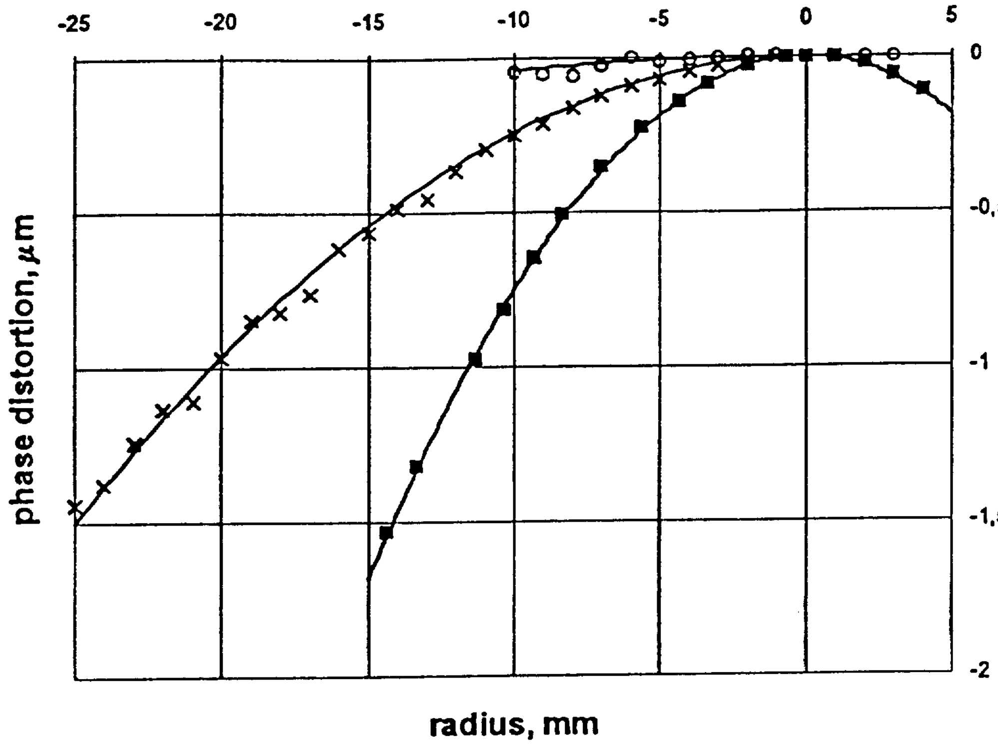
due to residual mechanical noise



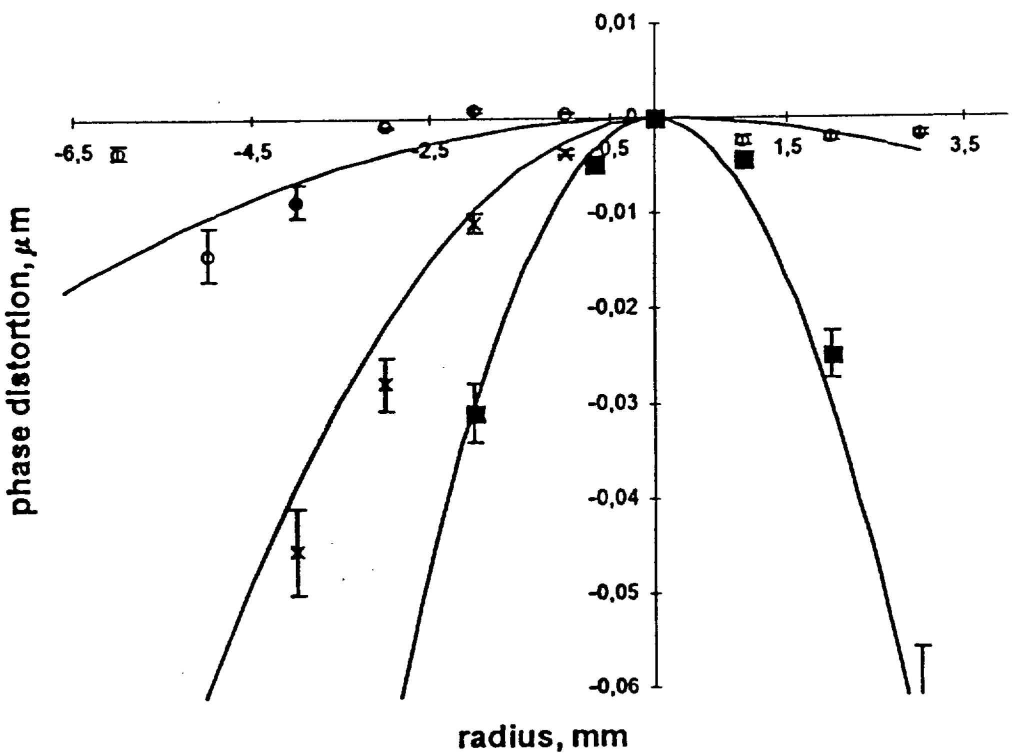
• **Facility uses:**
second harmonic radiation of Nd:glass laser with the pulse energy 20 mJ, pulse duration 1 ns;
water as a nonlinear medium 65 cm long, focal spot size 20 micron

$h \approx \lambda/500$ has been demonstrated in the experiment

• **Next step:**
Decrease of the focal spot size down to ≈ **5 micron** by using a shorter pulse duration and other nonliner liquids should result in **$h \approx \lambda/2000$**



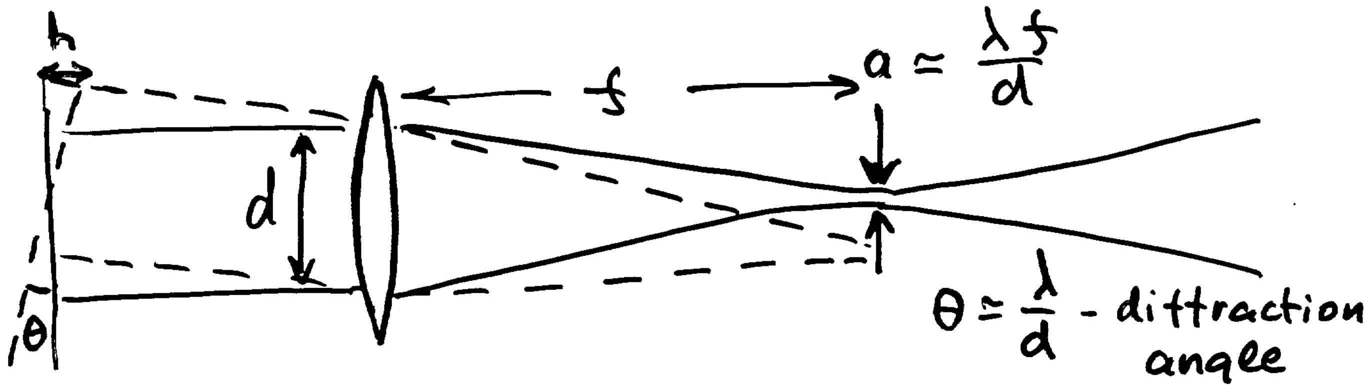
Radial dependence of the deviation of a phase front from a planar front for long-focus lenses with F1=-67 m - □, F1=-248 m - x, and F1=-1218 m - o.



Enlarged fragment of the dependence

Laser Facility Using Radiation Self-Focusing Effect to Measure Wave-Front Distortions

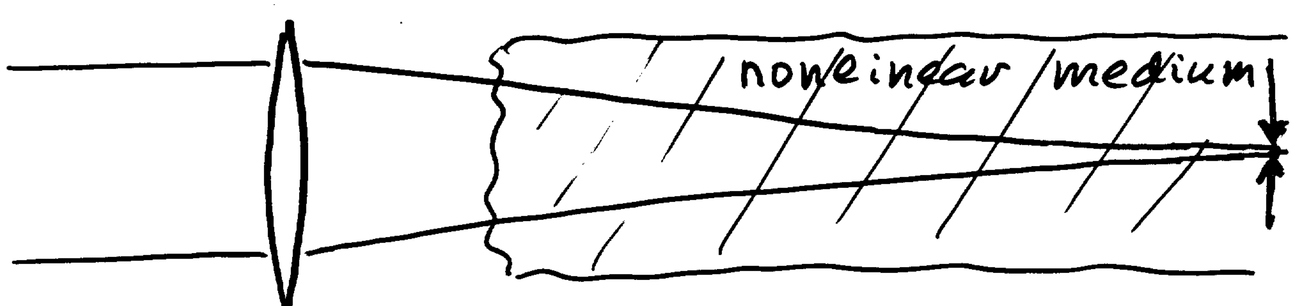
In linear electrodynamics the major limitation to measure phase front deviation angles comes from a finite size of the focal spot



$h = \lambda/20 - \lambda/50$ is achieved by an accurate measurement of the transverse beam distribution.

How to get $h < \lambda/1000$?

Use self-focusing to decrease the size of the focal spot



At $P > P_{critical}$ $a \rightarrow 0$ and is determined by nonlinear medium properties

Sensitivity of Laser Projection Receiver at surface parameter measurements

From LPR geometry the input signal energy W_p from one object pixel was calculated:

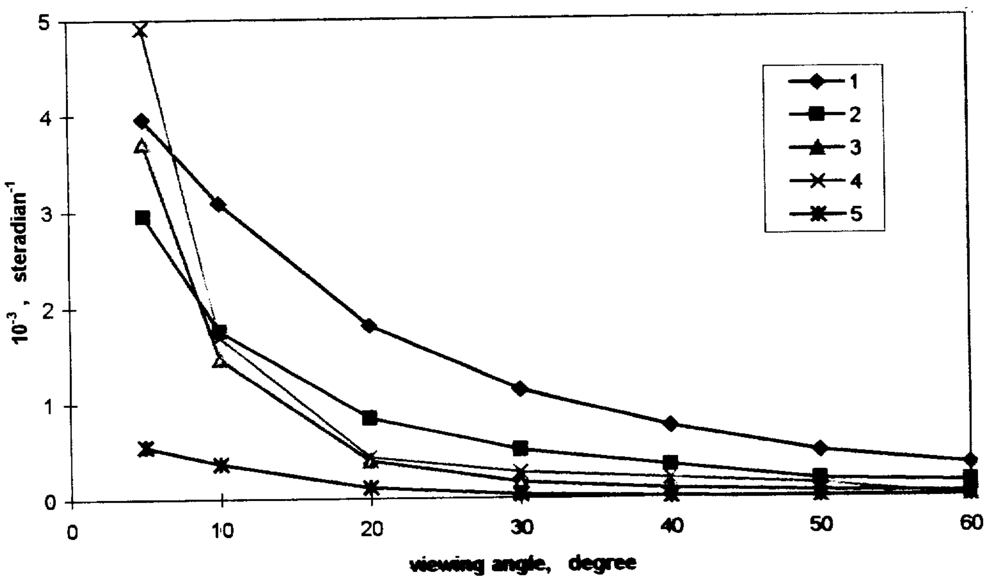
values \ samples	(1)	(2)	(3)	(4)	(5)
w, J/cm^2	$2.75 \cdot 10^{-5}$	$2.7 \cdot 10^{-5}$	$3.2 \cdot 10^{-5}$	$7.8 \cdot 10^{-4}$	$2.6 \cdot 10^{-4}$
W_p, J$\cdot 10^{-18}$	1.5	1.1	1.3	1.1	1.0

For diffuse reflection measurements the LPR sensitivity was near 10^{-18} J, i.e. approximately 5 signal photons at 1.06 μm

Conclusions

- **Remote sensing of LIGO optical elements is quite possible without any disturbance of LIGO operations, for instance the detection of surface thermal distortions induced by LIGO laser is possible too. For roughness near 0.1 nm it is enough small signal energy densities ~ 10^{-3} J/cm^2.**
- **If the object distance near 10 m and input lens aperture 10cm, the LPR object resolution is about 0.1 mm, i.e. the remote detection of small-scale contamination of optical elements is possible by LPR**

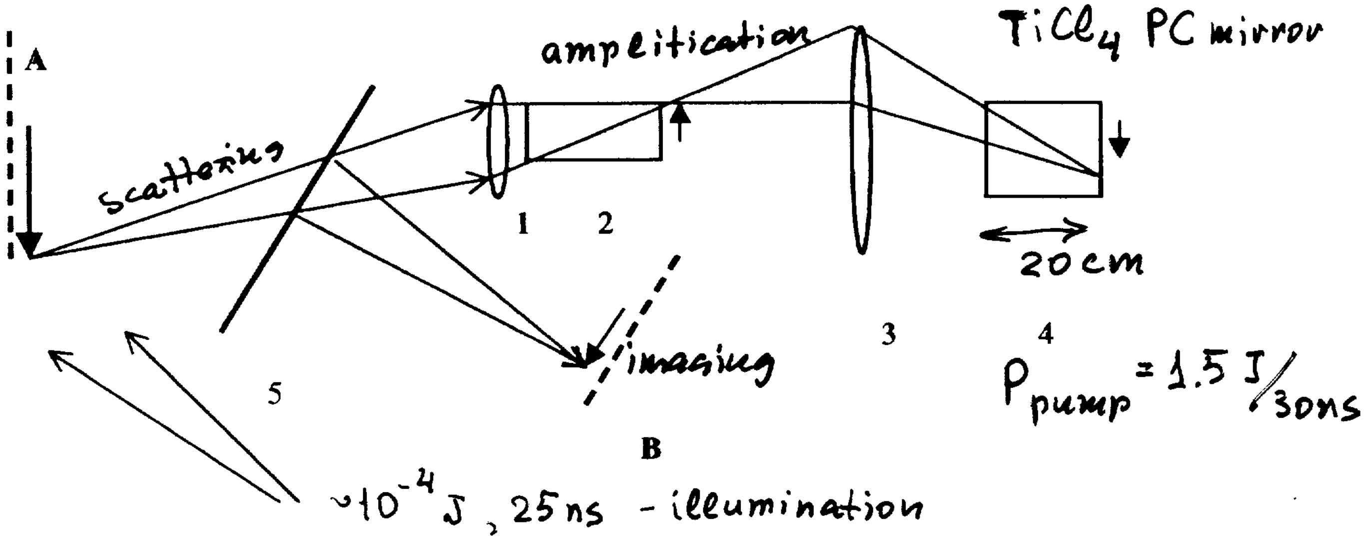
- usual optical glass plate (wafer for mirror) - (1);
- dielectric mirror, (R ~ 99.5% for 0.53 μm) on the plate like to (1) - (2);
- dielectric mirror (R ~ 99.9% for 0.515 μm) from LIGO prototype - (3);
- quarts glass plate - the wafer for X-ray mirror (σ ~ 0.4-0.7 nm) - (4);
- the same plate (4) after special washing for X-ray mirror deposition -(5).



Angle distribution of specific diffuse reflectance (divided by specular one).

# sample / parameters	(1)	(2)	(3)	(4)	(5)
σ , nm	2.8	2.0	1.4	1.6	0.6
τ , μm	0.4	0.4	~0.5	0.3 - 0.8	0.7

Experimental scheme of LPR

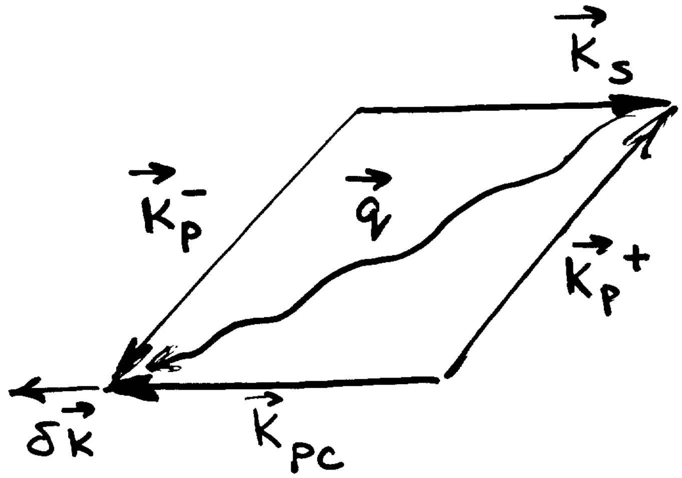


1 - input lens; 2 - quantum amplifier; 3 - PC-mirror lens; 4 - PC-mirror; 5 - beam-splitting mirror; *A* - object plane illuminated by laser beam; *B* - image plane.

Parameters of Laser Projection Receiver

- sensitivity (a minimal recorded signal) is limited by level of quantum noise on the laser wavelength 1.06 μm and it is equal to $4.8 \cdot 10^{-19}$ J per pixel;
- utmost narrow frequency band – 2 dimensionless frequency-temporal modes;
- rather large field of vision - 350 X 350 pixels;
- high amplification at weak signal - approximately 10^{12}.

Four-Wave Mixing for Phase Conjugation



$\vec{K}_s$ - signal wave
$\vec{K}_{pc}$ - phase conjugated wave
$\vec{K}_p^-$ and $\vec{K}_p^+$ - pump waves

$$Q \sim E_s^* \cdot E_p^- \quad \text{(Brillouin scattering)}$$

$$E_{pc} \sim Q\, E_p^+ \sim E_s^{*} E_p^+ E_p^- \quad \text{(Anti-Stokes)}$$

↑ Phase Conjugated

Phase Conjugation with Ampeification 10^6 can be achieved

IAP

> is a part of the Russian Academy of Sciences
>
> is situated in the Nizhny Novgorod City
>
> has more than 1000 people in the staff
>
> has been engaged in the collaboration on laser optics with the University of Florida since 1991

- Collaboration with LIGO started in 1997 through

  the University of Florida LIGO Group

- Main Direction:

Development of high-precision optical techniques for testing quality of LIGO optical components

~ 12 people (8 researchers + 4 technicians, 6 people full time)

- 4 experimental facilities are engaged in this research,

  2 of them having been tested in Florida

Note 1, Linda Turner, 08/20/98 10:58:45 AM
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