Characterizing Coherent Scatter from Interferometer Mirror Roughness

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Amaldi8 6/23/09

LIGO-G0900467-v2

Full analysis of the diffracted field, with roots in "speckle" theory unifies data interpretation

- Net surface distortions, being strictly perturbative ($h_{\mu,\nu} \ll \lambda$), contribute only in first diffraction order scatter per [discreet] Fourier component (DFC).
- Each such DFC order comprises a Gaussian "beamlet" propagating in the central diffractive direction with amplitude $E_0\, 4\pi\, h_{\mu,\nu}/\lambda$
- Assume *surface* distortion is specimen of a homogeneous (as well as isotropic) ensemble
- The phases of the DFCs are *random* (homogeneity condition), allowing for true random speckle fields even while the distortion has [isotropic] spatial correlation

Non-Imaged data via photo-diode and radiometry sampling

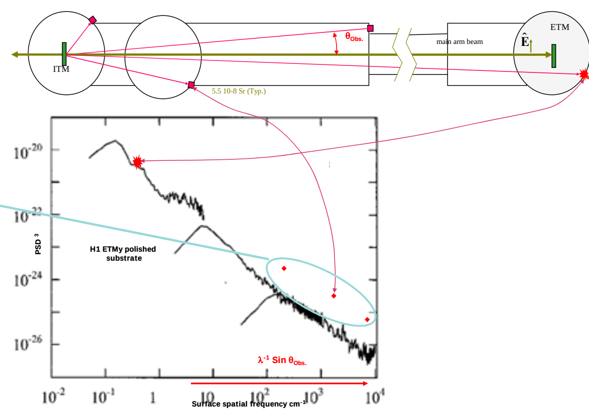
Does minute $d\Omega$ sampling adequately give correct azimuthal mean $I(k)$?

Speckle theory predicts correlation length (speckle "size") < 0.4mm<<ϕ_{PD} for all LIGO data. Therefore PD intensity sampling statistics are excellent.

Polarization bias is < few % at Θ_{Obs} of interest

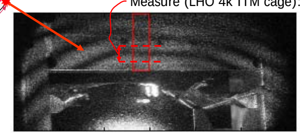
Cage intensity correlation width >5cm, but homogeneity assumption breaks down.

The very large number of point defects contribute incoherently with also negligible statistical fluctuation.

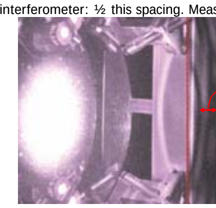


Simple diffraction theory predicts ring-fringes in scatter field with spacing $2\lambda R/\phi_{mirror} \approx$ 3.6cm for R=4000m

Measure (LHO 4k ITM cage): 4.1 cm

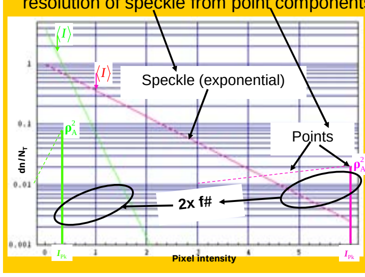


2km interferometer: ½ this spacing. Measure ~1.95cm



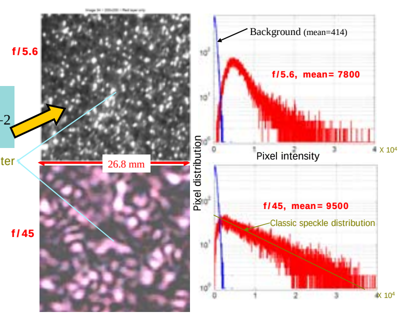
Imaged data via diffraction limited digital camera capture

High imaging resolution (low f#) allows resolution of speckle from point components

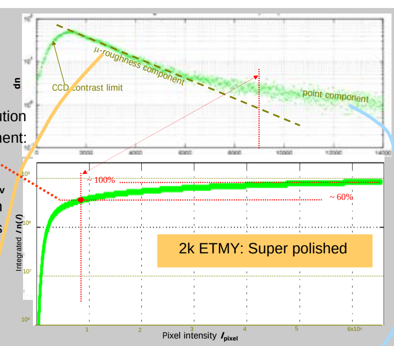


Contrast $\propto$ f#$^{-2}$

Beam center



Quantitative resolution of speckle component: fractionally at this Θ_{Obsv} & for superpolish grade roughness

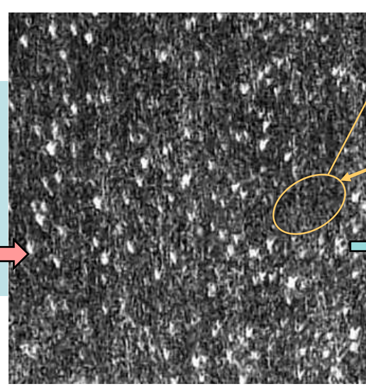


Background Speckle due to unresolved μ-roughness

Validity of pure speckle interpretation for non-point background holds when in "resolved" imaging regime:

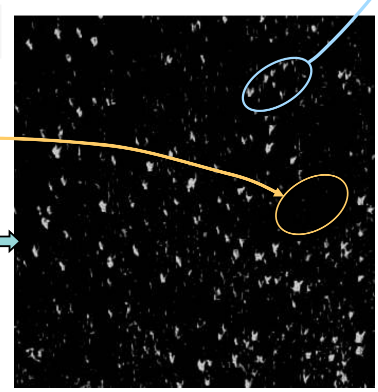
$$2\rho_{Airy} \ll \phi_{\text{beamspot image}} = 2w \bullet fl/R$$

Non-super polished mirrors have ~2-3 larger μ-roughness with noticeably higher speckle background



Identical image: enhanced contrast

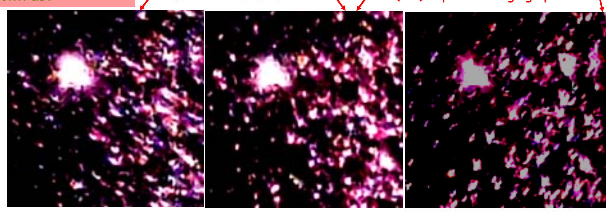
4k ITMx @1.2m, f/5.6, 210mm fl.



2k ETMy(Super-polish) Image detail @ high contrast

Adjacent imaging apertures

Far (16°) separate imaging apertures



Signatures of true speckle background:

- Θ_{Obsv} rotation of $\geq \frac{fl}{R\ f\#} \Rightarrow$ image pattern randomly morphs
- Imaged points defocus, while speckle invariant to focal plane
- Speckle will always "twinkle" with inter-cavity motion. Large (>λ) points will not.

FUTURE DIRECTIONS:

Beyond the capability to distinguish defect from μ-roughness loss, it is predicted that speckle scatter analysis can distinguish squeezed state of the incident field (*PRL* **102**, *193601*)