Stray light from dust in Virgo

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Stray light problem

- Stray light injects additional noise into the ITF: currently visible as bumps and peaks at low f
- Need to develop mitigation strategies by finding the main scatterers & quantify the stray light power
- Tapping/shaking tests help find mechanical resonances
- Stray light simulations can provide estimates of the fraction of stray light that couples back into the ITF & its main sources
Stray light sources

Main sources:
- **Surface roughness**
- **Dust contamination**

Optics have extremely low roughness -> dust can be the leading contributor to stray light in Virgo

**Surface roughness**

Scattering due to non-perfectly smooth surfaces

Dust contamination

Dust scattering is described by **Mie Theory**:
- Particles are considered spherical & dielectric
- Their surface distribution function $f(D)$ is modeled
- Particles produce both forward and back scatter components

VIR-0511A-21
Dust particle distribution \( f(D) \) in clean environments is usually modeled via IEST CC21246D:

\[
f(S, CL, D) = -\frac{d}{dD} N_p(S, CL, D)
\]

\[
N_p(S, CL, D) = 10^{|S|\left[\log_{10}(CL) - \log_{10}(D)\right]}
\]

- \( N_p \) is the **number of particles**/0.1m\(^2\) with diameter \( \geq D \)
- \( S \) is the particle distribution **slope** (\( S = -0.926 \) in IEST, experimental data not very much in agreement)
- \( CL \) is the **cleanliness** level of the surface: in IEST it’s equivalent to the maximum particle size/0.1m\(^2\) (x-intercept)

\( S \) is the slope
\log^2 CL is the x-intercept

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**Dust particles distribution**

VIR-0511A-21
**Dust particles scattering**

\[ \Theta_i = \text{AOI} \]
\[ \Theta_s = \text{scatter angle} \]

- CL < 200: pristine surface
- CL = 600: visibly clean surface
- CL > 1000: visibly dirty surface

The **BSDF** (the scattering property) is a strong function of CL.

**Comparison with standard CL levels:**
- BSDF from dust
- BSDF from roughness

In Virgo no measurements of CL: Need to directly measure it.
If modeled with IEST CC21246D the CL is calculated as:

$$\log_{10} CL = [1.08(\log_{10} h + \log_{10} \rho + \log_{10} t + 0.773 \log_{10} X_c - 1.248)]^{1/2}$$
Dust contamination monitoring campaign

MOTIVATION & PURPOSE
- Have reasonable cleanliness (CL) estimates
- Produce realistic estimates of stray light from dust

GOALS
- Monitor level of cleanliness of optics in different environments and over time
- Highlight critical situations and adopt mitigation strategies

METHOD
- Expose clean silicon wafers next to optics in representative locations (first in the squeezing environment SQZ)
- Take pictures of exposed wafers to extract particle size distribution
Dust images

**CAMERA SYSTEM**
- Images of wafers taken via camera system in ISO 3 Clean Room
- Camera with resolution ~5 µm is mounted over an illuminating LED ring
- Wafers’ area of 2.8x1.8 cm is imaged
- Correspondence pixel-µm is determined

**IMAGES ACQUISITION**
- Optimal values for numerical aperture and height of illuminating LED ring were set
- Multiple identical images for noise-averaging purposes are taken
- Images are acquired via **PixeLINK Image Capture** (freeware)

**IMAGES PROCESSING**
- **ImageJ**: images are combined as projection of image stacks
- **LIGO MATLAB** code to count particles and determine diameters (set the luminosity **threshold**, below which pixels are considered background and discarded)

Details are in [LIGO-G2001405](#)
Analyses of O3 wafers

Fits results are displayed in the table

- Wafers placed horizontally except SQZVertical (placed vertically)
- Wafers exposed for a month except WS1 (exposed for a week)

Comment & Conclusions

- Fit results are similar in spite of wafers’ variety of placement locations
- Overall: CL higher than standard values considered in initial analyses
- Saturation effect visible at small diameters in the data distributions (especially for smaller apertures) due to camera resolution
- Fit not in agreement with IEST model: other theoretical particle distribution include Gaussian and uniform
- SQZVertical and WS1 are not cleaner than the others, as one would expect (possible handling process “spoiled” the wafers in a similar way?)

<table>
<thead>
<tr>
<th>Position</th>
<th>Camera aperture</th>
<th>-Slope</th>
<th>CL</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDB2</td>
<td>5.6</td>
<td>0.45 ± 0.02</td>
<td>1429 ± 170</td>
</tr>
<tr>
<td>SDB2</td>
<td>8</td>
<td>0.39 ± 0.03</td>
<td>1702 ± 320</td>
</tr>
<tr>
<td>EDB</td>
<td>5.6</td>
<td>0.53 ± 0.02</td>
<td>881 ± 60</td>
</tr>
<tr>
<td>EDB</td>
<td>8</td>
<td>0.48 ± 0.02</td>
<td>998 ± 110</td>
</tr>
<tr>
<td>SQZVertical</td>
<td>5.6</td>
<td>0.38 ± 0.05</td>
<td>1312 ± 410</td>
</tr>
<tr>
<td>SQZVertical</td>
<td>8</td>
<td>0.42 ± 0.04</td>
<td>918 ± 200</td>
</tr>
<tr>
<td>WS1</td>
<td>5.6</td>
<td>0.34 ± 0.02</td>
<td>1642 ± 300</td>
</tr>
<tr>
<td>WS1</td>
<td>8</td>
<td>0.28 ± 0.03</td>
<td>2678 ± 800</td>
</tr>
</tbody>
</table>

Analyses of O3 wafers

First we analyzed wafers placed in the SQZ environment employed during the third observation run O3
Images acquisition: fine tuning

Calibrated metal-based powder (Molybdenum & Titanium)

Use calibrated powder to determine **best** correct camera system **parameters** by taking pictures with different:

- Exposure time
- Camera aperture
- Focus

Extract particle counts via MATLAB code: For each image, code will output particle size distribution as a function of luminosity threshold

Determine best values of parameters: Analyze distributions and find the ones more **similar** to the known one
Example of analysis: Titanium particle distributions with calibrated mean diameter = 38 µm for 4 different exposure times

Curves in each graph are distribution for different luminosity thresholds

Legend displays the computed mean diameter for each curve

Calibrated Titanium particles mean diameter = 38 µm: exposure time > 30 ms works better

Analyses just started, more work in progress
Simulations of stray light from dust are performed via FRED Optical Software Engineering (https://photonengr.com/):

Particle distributions from wafers’ images will be the input values for the simulations.

Wafer -> particle distribution -> scattering model to apply to nearby optics.
Dust scattering simulations

Extract dust distributions of two mirrors used in O3 in SQZ
Put the distributions in FRED and derive dust BSDF & TIS
Measure TIS directly at 0° AOI with an Integrating Sphere
Results obtained @0° AOI are comparable (table)

<table>
<thead>
<tr>
<th>Mirror</th>
<th>Integrating Sphere TIS [ppm]</th>
<th>Dust Analyses TIS [ppm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>M4</td>
<td>258(4)</td>
<td>169</td>
</tr>
<tr>
<td>M5</td>
<td>241(12)</td>
<td>228</td>
</tr>
</tbody>
</table>

**Dust scattering simulations**
Conclusions

PRELIMINARY STUDIES

• Dust is projected to be a major source of scattering in SQZ
• Dust distribution on optics difficult to model, better measure it

DUST IMAGES WITH CAMERA SYSTEM

• We have identified a procedure for determining surface particulate contamination in a cleanroom environment
• Preliminary studies on O3 wafers: found CL values are much higher than standard values (which are up to CL = 1000)
• Preliminary studies on O3 wafers: experimental data distributions not in agreement with IEST STD CC1246D: this could suggest a need for more data, shortcomings in IEST’s ability to represent our environment, or handling contamination
• Dust images with calibrated distribution of powder can aid setting right parameters for imaging system and will allow to increase the accuracy of measured distributions
Future work

DUST IMAGES WITH CAMERA SYSTEM

• Analyze dust images of samples placed in SQZ environment during O4 Commissioning
• Setup numerical simulations of stray light from dust, once reliable particle distributions are derived
• Investigate other particle distributions available in FRED to fit the data

CALIBRATION WITH SAMPLED DUST

• Analyze images from different areas of wafers
• Study the criticality of focus
• Use other calibrated parameters like 10 & 90 percentiles to help differentiate between curves
• Calculate integrals of curves to determine total #particles
• Develop a strategy to discern between threshold values and determine the right one
• Explore other types of combinations in ImageJ (e.g. use sum rather than minimum intensity projections)
Additional slides
In order to see how much the BSDF is affected by the choice of the CL, we plotted the BSDF as a function of CL for a fixed value of the particle distribution slope $S$.

By taking the ratio between the BSDF for each CL value and the BSDF for CL = 200, a scale factor can be derived:

- CL = 400: scale factor = 23
- CL = 600: scale factor = 174
- CL = 800: scale factor = 787
Wafers in O3 (SQZ environment)

- WS1: on ESQB, one week exposure
- SQZVertical: on ESQB, vertical
- SDB2: on top of threshold of tower structure, behind detection bench minitower
- EDB: on top of external detection bench (EDB)
• Lower thresholds tends to overestimate the number of particles (by counting background pixels as real particles) and their diameter
• Higher thresholds tends to underestimate the number of particles and their diameter
• A compromise is needed to be found
Wafers in O3 (SQZ environment)
# M4 & M5 particle distributions

<table>
<thead>
<tr>
<th>Mirror</th>
<th>Slope</th>
<th>CL</th>
</tr>
</thead>
<tbody>
<tr>
<td>M4</td>
<td>0.378 ± 0.008</td>
<td>2786 ± 143</td>
</tr>
<tr>
<td>M5</td>
<td>0.460 ± 0.008</td>
<td>1703 ± 69</td>
</tr>
</tbody>
</table>

![Graph of particle distribution for M4](image1)

- Slope = 0.38

![Graph of particle distribution for M5](image2)

- Slope = 0.46