Scattered light study in Advanced Virgo Plus

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GWADW
Scattered light workshop
17/05/2021
Fundamental noises
Beyond fundamental noises
Scattered light studies

• ‘Scattered light studies’: new activity started in September 2020 with the aim of working across AdV+ subsystems to identify gaps in the design or preparation

• Initially identifying issues with the current design or implementation

• To structure this, started with looking at one specific aspect, i.e. ghost beams

• Identifying gaps in knowledge or tools: do we have the right tools to understand and mitigate scattered light issues at the design and noise-hunting level? Are we collecting the expert knowledge for the whole team and for the next generation?

• Work organized in Reviews by subsystem

• Final goal: to take actions to limit scattered light problem in AdV+
Stray light - detection system
Stray light - detection bench

\[ \tilde{h}(f) = T(f) \sqrt{\frac{f_r P_{\text{out}}}{P_{\text{in}}}} \mathcal{F} [\cos(\phi_r(t))] \]

Transfer function: linear response of the ITF to noise

Fourier transform

Variation of phase of the recoupled field
Stray light - detection bench

\[ \tilde{h}(f) = T(f) \sqrt{\frac{f_r P_{\text{out}}}{P_{\text{in}}}} \mathcal{F} [\cos(\phi_r(t))] \]

\( f_r = 0.002 \text{ ppm} \)

detection bench
Stray light

\[ \tilde{h}(f) = T(f) \sqrt{\frac{f_r P_{out}}{P_{in}}} \mathcal{F} [\cos (\phi_r(t))] \]

\[ f_r = f_{sc} + f_{sp} + f_{Rayleigh} \]

- Fraction of scattered light re-coupled to the main mode of the ITF (mirrors...)
- Fraction of back reflected re-coupled light (lenses, photodiodes...)
- Fraction of scattered light by atoms or molecules, i.e. crystals (TGG)

⚠️ SECONDARY BEAMS!!

They are produced and propagates on the benches hitting mounts, optics, vacuum chambers and so on: \textit{extra scattered light}!
We want to \textit{identify} and \textit{stop} them before they re-couple.
Ghost beams study

**Ghost beams** are unwanted secondary beams generated by not perfect HR and AR coating of optical components, like mirrors.

**Goal of the work:**
- Trace the ghost beam as a Gaussian beam through all the optics of AdV+ benches and get its information: position, size and power
  - done with **Optocad**: Fortran 95 module for tracing Gaussian TEM$_{00}$ beams through an optical set-up
- Understand if and how we have to stop them to prevent extra scattered light
Ghost beams on Optocad

Optics definition on Optocad:

Input lines on the file.octd:

c (General surface/component), d (dual surface component), h (hole in a component):

<table>
<thead>
<tr>
<th>letter</th>
<th>action</th>
</tr>
</thead>
<tbody>
<tr>
<td>c</td>
<td>start cavity</td>
</tr>
<tr>
<td>d</td>
<td>dump beam</td>
</tr>
<tr>
<td>h</td>
<td>hide surface</td>
</tr>
<tr>
<td>i</td>
<td>interfere</td>
</tr>
<tr>
<td>n</td>
<td>neglect surface</td>
</tr>
<tr>
<td>r</td>
<td>reflect beam</td>
</tr>
<tr>
<td>s</td>
<td>split beam</td>
</tr>
<tr>
<td>t</td>
<td>transmit beam</td>
</tr>
</tbody>
</table>

+ (secondary surface): action + extra information

x, y positions of the center of the optics wrt a reference point

Angle of the optics
Ghost beams on Optocad

Mirror definition on Optocad:

d (dual surface component), reflect beam, x (meter), y (meter), angle (degree), reflectivity, transmittivity, RoC (meter)
+ (secondary surface) transmit beam, thickness (meter), wedge (degree)

Example: mirror SQB2_M23

d r, 0.250, -0.660, -45, 1.0, 0.0, rc=1e99
+ t, dm=0.0105, da=179.5
Ghost beams on Optocad

**Ghost beam on Optocad:**

**Example:** mirror SQB2_M23

\[ d \quad \text{srt}, \quad 0.250, \quad -0.660, \quad -45, \quad 1.0, \quad 0.0, \quad rc=1e99 \]

Split of the beam: it is first transmitted and then reflected at the first surface

\[ + \quad r, \quad dm=0.0105, \quad da=179.5 \]

Beam reflected from the second surface and then transmitted again by the first surface.

**Ghost beam power:**

\[ P_{GB} = \eta_{HR}^2 \eta_{AR} P_{in} \]

HR coating residual transmission  \quad AR coating residual reflection

\[ \eta_{HR} \sim \text{few ppm}, \quad \eta_{AR} < 500 \text{ ppm} \]
Ghost beams on Optocad

Wedge optimization:

d   srt, 0.250, -0.660, -45, 1.0, 0.0, rc=1e99
+   r,  dm=0.0105,  da=179.5

+   r,  dm=0.0105,  da=180.5

Better!
Ghost beams on Optocad

Ghost beam dumping:

d  srt, 0.250, -0.660, -45, 1.0, 0.0, rc=1e99
+  r, dm=0.0105, da=179.5

Diaphragm to stop ghost beams
Ghost beam diaphragms

Diaphragm aperture and size chosen in order to:

1) don’t clip the main beam
   - limit power losses due to clipping and lateral misalignment of the beam
   - limit mismatch losses due to hole diffraction

2) properly dump the ghost beam
   - design of the diaphragms

Different size and apertures, depending on beam parameters
Mitigation strategies

Some of the *mitigation strategies* adopted for Advanced Virgo Plus:

- Wedge optimization
- Diaphragms installation
- Baffle installation
- Absorbing disks behind mirrors
- Diaphragms on quadrants
- Small beam dumps
- Dumpers on photodiodes
- Lens tilting
- Absorbing screws
Mitigation on squeezing system

Credit to IFAE: baffles

VIR-0833B-20
Mitigation on detection system

SDB1
VIR-0187A-21

: beam dumps to be installed (31st May)
Conclusion and future works

- Scattered light is limiting the sensitivity of the detector
- We recently started a new activity in order to review the scattered light provisions in the Advanced Virgo plus design
- Initial tasks focused on ghost beams: they produce extra scattered light that propagates and hits objects that cause a phase modulation
- Ghost beams traced for squeezing/detection systems
- Dumping strategies already implemented or ongoing

Next steps:

- Conclude the ghost beam study also on the injection system
- Review simulation tools and mitigating solutions across all subsystems
- Scattered light 'noise hunting': ongoing discussion on more precise estimation of $f_r$
Thanks for the attention
Extra slides
Stray light

\[ \tilde{h}(f) = T(f) \sqrt{\frac{f_r P_{\text{out}}}{P_{\text{in}}}} \mathcal{F} [\cos (\phi_r(t))] \]

\[ f_r = f_{sc} + f_{sp} + f_{\text{Rayleigh}} \]

Fraction of scattered light re-coupled to the main mode of the ITF (mirrors...)

Fraction of back reflected re-coupled light (lenses, photodiodes...)

Fraction of scattered light by small particles, i.e. crystals (TGG)

\[ f_{sc} \approx \frac{\text{BRDF} \lambda^2}{\pi \omega_0^2} = \frac{\lambda^2}{\pi^2 \omega_0^2} \]

\[ f_{sp} = \frac{\alpha R^2 z_0^2 \exp \left[ -\frac{2\pi D^2 z_0 \beta^2}{2\lambda} \left( \frac{1}{D^2 + z_0^2} + \frac{1}{(D-R)^2 + z_0^2} \right) \right]}{(D^2 + z_0^2)[(D-R)^2 + z_0^2]} \]

\[ \alpha_{\text{sca}} = \frac{8 \pi^3}{3 \lambda^4} \left( n^4 p \right)^2 k T \beta_T \]
Stray light

How much scattered light coupled into cavity mode?

- Scatter 1: Ok : Use FFT & mirror maps
- Scatter 2: Tricky : Use BRDF to estimate
- Scatter 3: Ok?: Use FFT & mirror map (but what field?)
- Coupling: ? : How exactly does it couple?

From R.Day, G1300532
Stray light from ghost beam

Overlap integral

Back reflected
Ghost beam dumping
Stray light from detection benches