Exploring the phase camera at Advanced Virgo and in the lab

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What is the phase camera

• The phase camera can generate amplitude and phase 2D images of the laser wavefront.

• Uses a heterodyne technique to image the wavefront at any frequency of interest

Phase camera developed at Nikhef

How does it work?

- Beam wavefront is scanned over a photodiode by a piezo scanner.
- Beam is combined with a reference in order to produce a measurable beat signal.
- Signal is digitised and then demodulated for each beat frequency of interest.
- Amplitude and phase maps are built from the demodulated I and Q signals.

$$A = \sqrt{I^2 + Q^2} \quad \phi = \arctan\left(\frac{Q}{I}\right)$$
Sidebands in gravitational wave interferometers

- Sidebands are used to generate error signals to keep the cavities in resonance.
- The phase camera can monitor a high number of beat frequencies.

Currently 11 frequencies demodulated; 1Hz frame-rate.

Thermal compensation system assisted by the phase camera

- Absorbed laser power changes the optical path length in the mirrors, causing a thermal lens effect.
- This affects resonance conditions for laser carrier as well as sidebands.

The thermal compensation system corrects for this using mirror ring heaters and compensation plates.
How it has been used: thermal effects

Thermal effects in sidebands with increasing power

How it has been used: mode content analysis

Carrier mode content at dark port

- Requires manually picking modes to be included in the fit.
- Tested only in limited data-set.


Phase information can improve the analysis of thermal effects and high-order mode (HOM) content. Difficult to do because of phase noise.
Monitoring the phase cameras at Advanced Virgo

Weekly meetings with the phase camera group.

- Phase camera “babysitting”. Identify figures of merit, like sideband imbalance:

\[
\frac{P_{USB} - P_{LSB}}{P_{USB} + P_{LSB}}
\]

- Phase camera tests: reference beam power, single bounce experiment.

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Simulations in OSCAR

OSCAR is a FFT code in Matlab.

- Simulate the locking procedure.
- Simulate asymmetries in the CITF that may cause sideband imbalance.

Future plans for Advanced Virgo work

• Identify figures of merit from the phase camera that correlate to ITF conditions, like misalignments, asymmetries and mixture of these.

• Relate PC observables to other observables on site (Dark port power, power in the arms, etc).

Understanding the phase images and use the extra information to improve the thermal effects interrogation and HOM identification.

Effect of ring heater on the west arm input mirror is visible in the phase map

Phase camera in the lab to characterize mode matching

We have mode mismatch when...

- the input beam waist position $b$ and/or size $w$ are not matched to those of the cavity eigenmode;

$$E_{\text{pos}} \propto \left[ \Psi_0 + i \frac{b}{2kw_0^2} (\Psi_0 + \Psi_2) \right]$$
$$E_{\text{size}} \propto \left[ \Psi_0 + \frac{\Delta w}{2w_0} \Psi_2 \right],$$

Why do we care?

- More power means more absorption in the mirror: RoC changes degrading mode matching.
- No current GW detector has automatic MM control.
Building a setup at UCLouvain to test the PC for Mode Matching characterization at 1550nm. Future detectors, ET and possibly others will use 1550nm.
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- The reflected beam is analysed with 2 sensors:
  1. Mode converter sensor that will act as benchmark;

![Diagram of phase camera setup]

The reflected beam is analysed with 2 sensors:
1. Mode converter sensor that will act as benchmark;
2. The phase camera by Nikhef.

Combining experience at VIRGO and LIGO, we want to prove that phase cameras can minimise mode mismatch.
Synergy between the work with AdVirgo and Nikhef and our work in the lab.

• Phase information is important to improve mode content analysis and thermal effects, as well as for mode mismatch mitigation.

Providing 2D wavefront maps for carrier, upper and lower sidebands in all beat frequencies, the phase camera is far from being used to its full potential!

We believe it can be an important tool to better understand the non-ideal behaviour of GW interferometers, especially as we move to higher power.
Reference beam before or after the scanner


1-beam scanning

- Addit. phase shift caused by scanning just test beam (tilt) – visibility loss.
- Higher SNR

2-beam scanning

- No addit. phase shift caused by scanning just test beam.
- Lower SNR, might need calibration of the reference beam profile

For low scanning angles, 1-beam scanning gives better sensitivity.

For lower modulation depth of sidebands, also 1-beam scanning is better.
Frame rate:

- Typically 1 scan per second (amplitude and phase images for all frequencies are generated.
- Maximum is 10Hz, due to 500Hz scanning bandwidth maximum of scanner.


Thermal effects on sidebands and carrier

Sideband imbalance on site