EGO

Using the phase camera in advanced interferometers

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Overview

- Motivations for using phase camera.
- What is a phase camera ?
- Past experiences and new strategy for Advanced Virgo.
- Tackling measurement of “large” aberrations.
- Poor man’s phase camera.
- Using phase camera in aLigo.

Motivation

• Sidebands resonant in marginally stable power recycling cavity are extremely sensitive to aberrations.

• In Advanced Virgo all aberrations are important:
→ Thermal aberrations due to coating/substrate absorption.
→ “Cold” aberrations due to imperfect optics.
→ Mismatching between recycling cavity and arm cavity.

• Aberrations **must** be corrected for successful operation of AdV

• Two elements for success :
→ Actuation: CO_2 ring, heating ring, scanning CO_2.
→ Sensing: Hartmann sensor, Phase camera

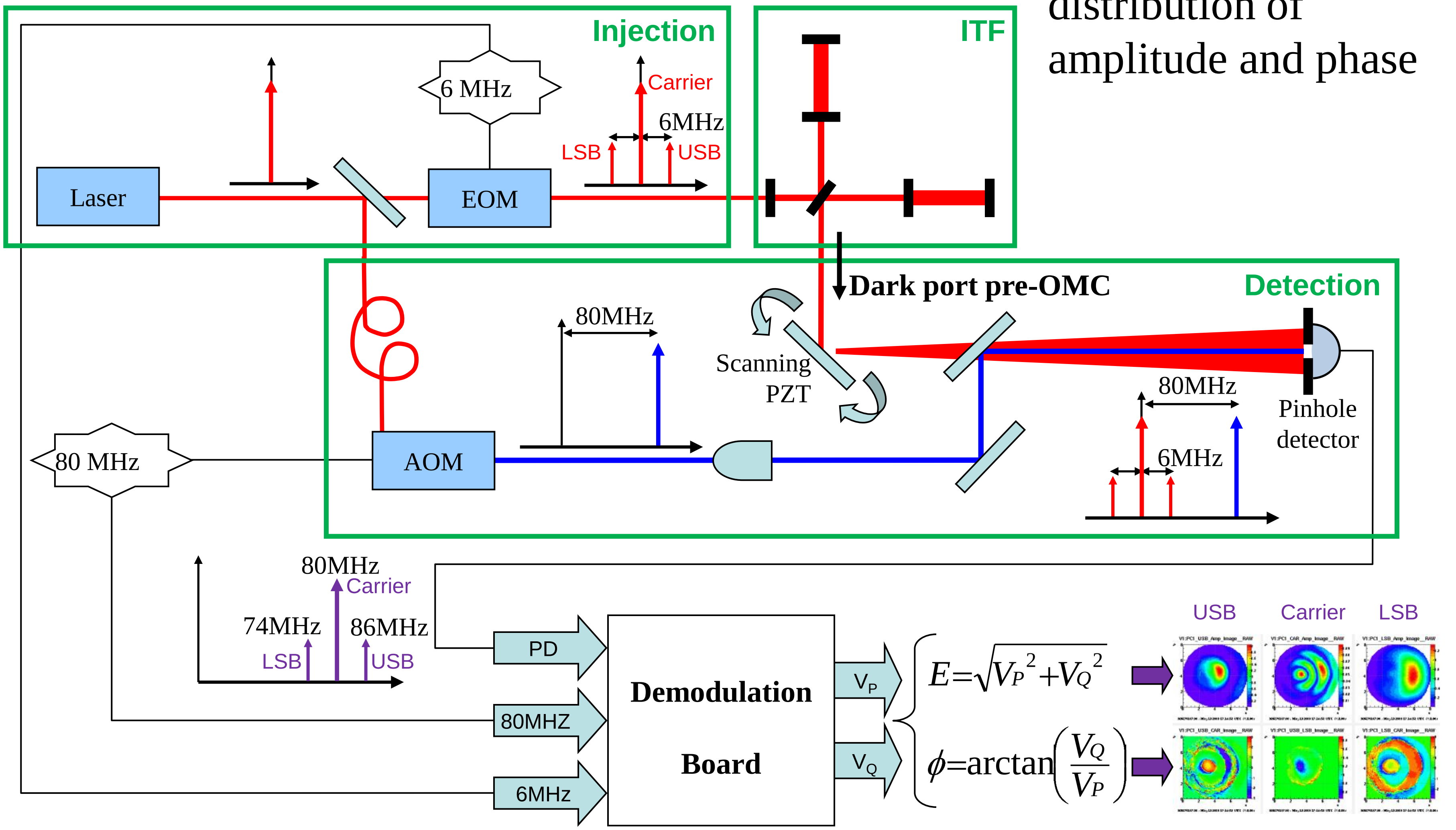
• Hartmann sensor only sensitive to relative phase changes
→ useful only for thermal aberration sensing

• In the past, Phase camera signals never totally understood.

Use simulation to understand how phase camera should be used in AdV

What is a Phase Camera ?

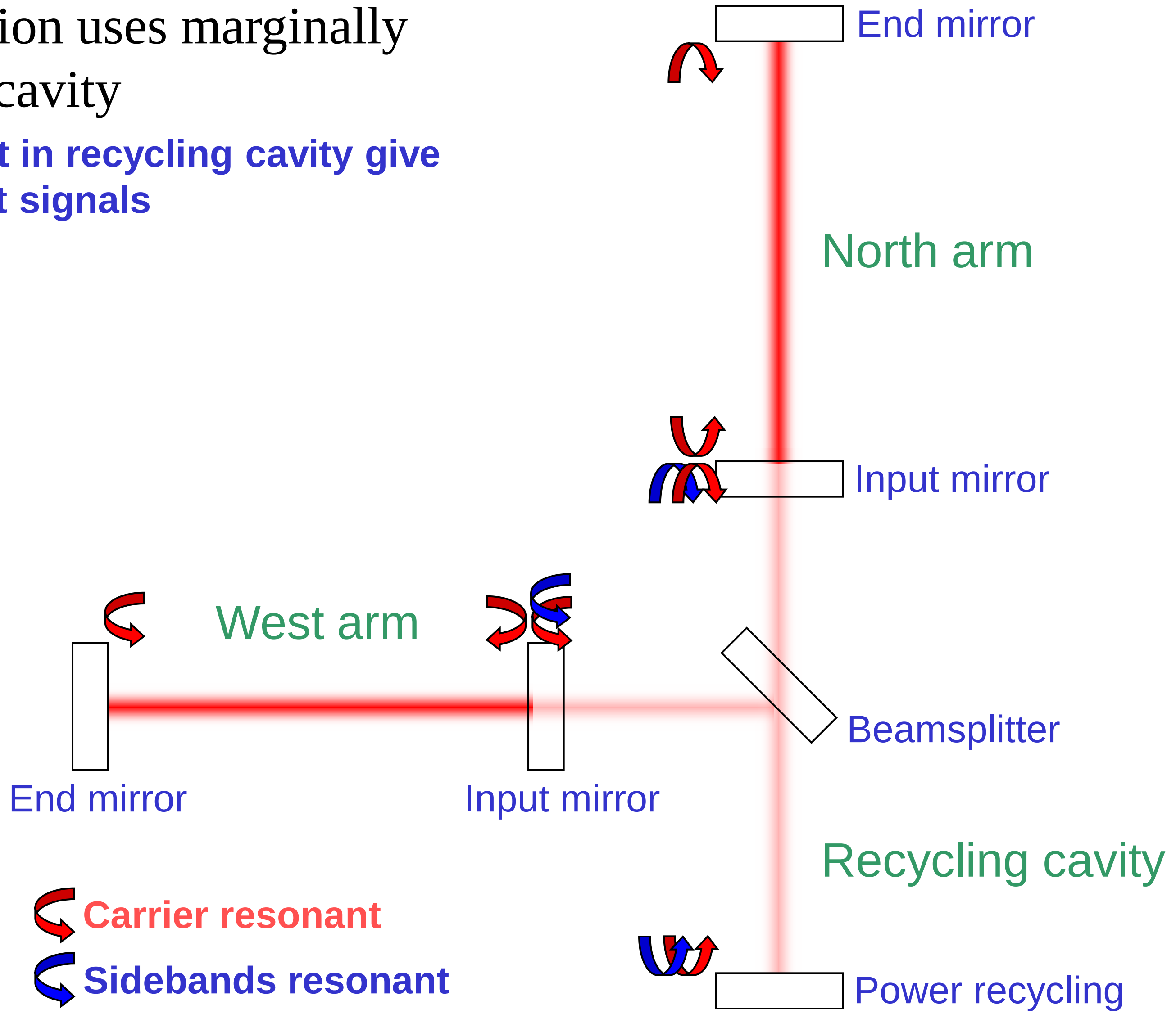
For each frequency component of laser field : Measure spatial distribution of amplitude and phase



The problem

Virgo configuration uses marginally stable recycling cavity

- **Sidebands resonant in recycling cavity give locking & alignment signals**



The problem

Virgo configuration uses marginally stable recycling cavity

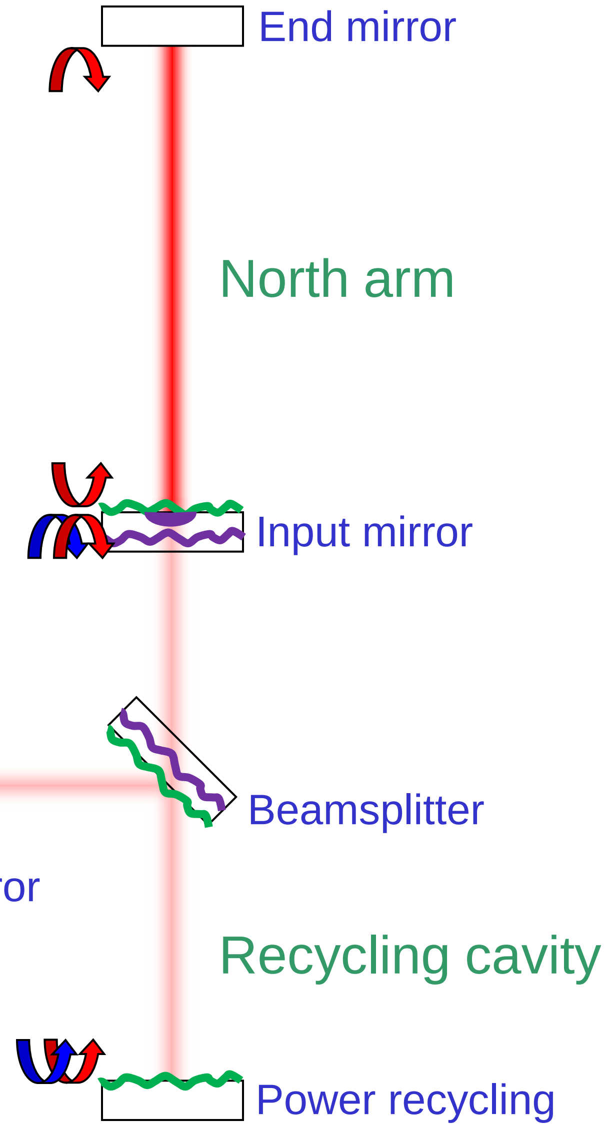
Sidebands resonant in recycling cavity give locking & alignment signals

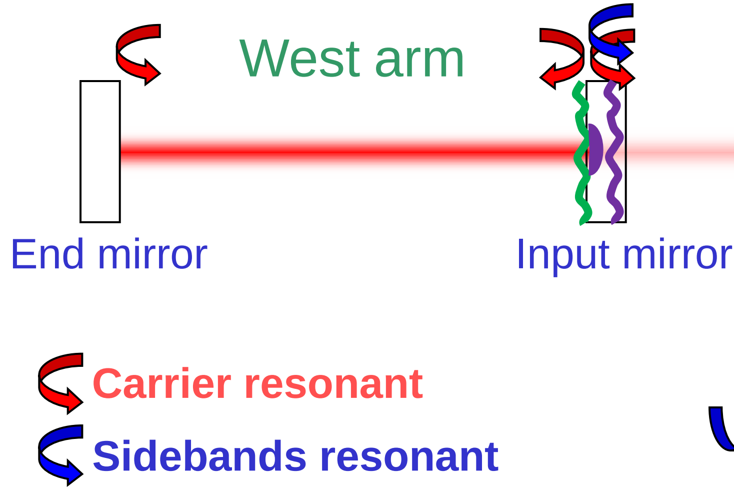
But sidebands extremely sensitive to aberrations :

- → Thermal lensing
- → Substrate inhomogeneities
- → Surface figure errors

→ Sideband power reduces

→ Locking & alignment signals become unstable

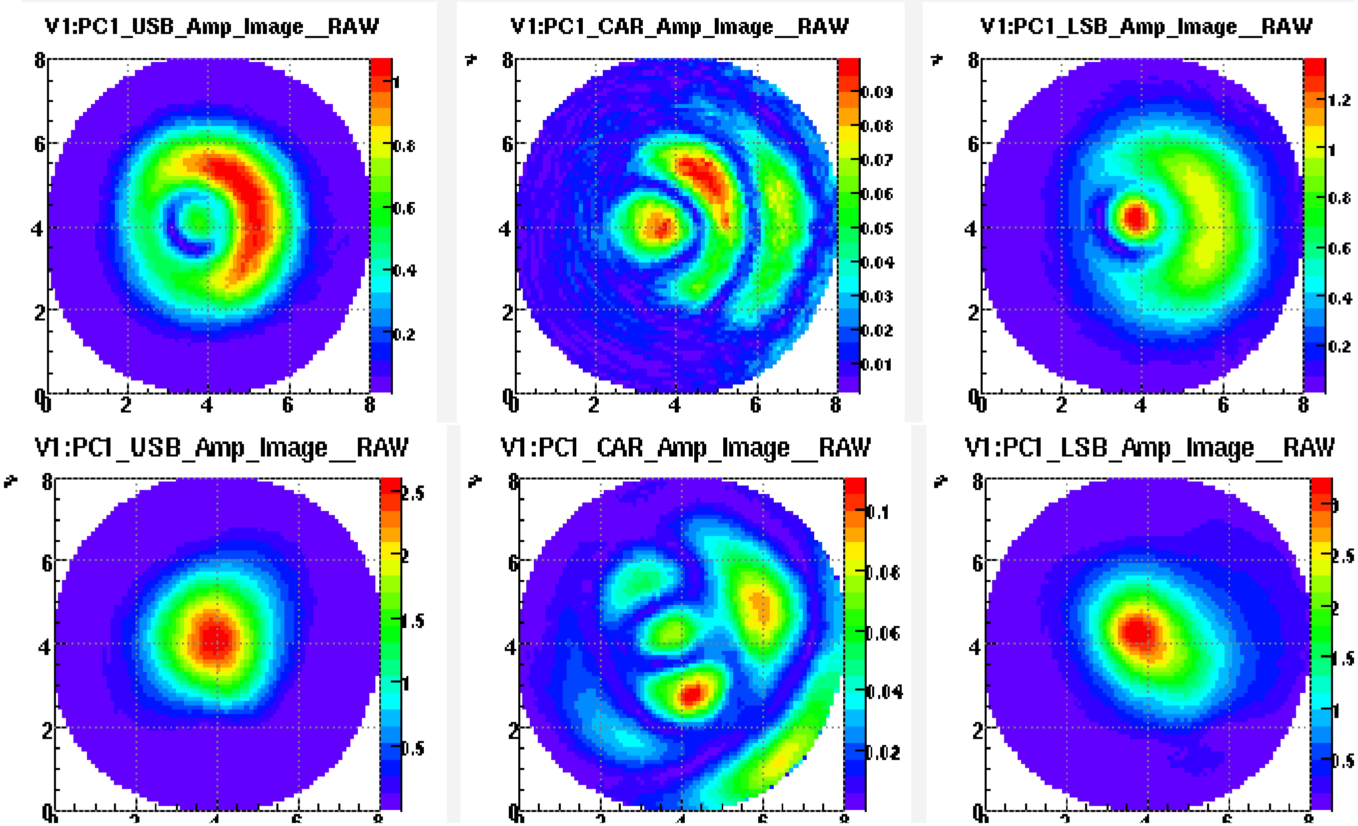




In Virgo+ : To measure thermal lensing, Phase camera used on dark port

Phase information difficult to interpret → Amplitude of sidebands used empirically

Upper sideband | Carrier | Lower sideband



Input power = 13W

No TCS

Input power = 17W

West TCS = 6.5W

North TCS = 4W

We will need to do much better for Advanced Virgo

Results from presentation “Multi-field wavefront sensor for measuring thermal effects in a gravitational wave detector” Amaldi8, New York

Advanced Virgo will be much more challenging, as round-trip Gouy phase in recycling cavity is even smaller than Virgo+ → 0.6 down to 0.1 degrees
→ will be much more sensitive to aberrations

Use FFT simulations to understand effect of aberrations in recycling cavity
Note : In this study we consider only the power recycled interferometer.

Aberrations can be classed into two categories :
• **Common** : PR aberration & average aberration of two short arms.
→ Reduction in recycling gain.
• **Differential**: Difference in aberrations of two short arms.
→ Leakage onto dark port.

Primary concern for Advanced Virgo is **common** aberrations.
In this presentation we will concentrate on measuring common aberrations

Warning: This is work in progress, so many open questions remaining

Proposed Phase camera setup

Put Phase camera on **recycling cavity beam**.

We would like to use the **phase information** of the sidebands.

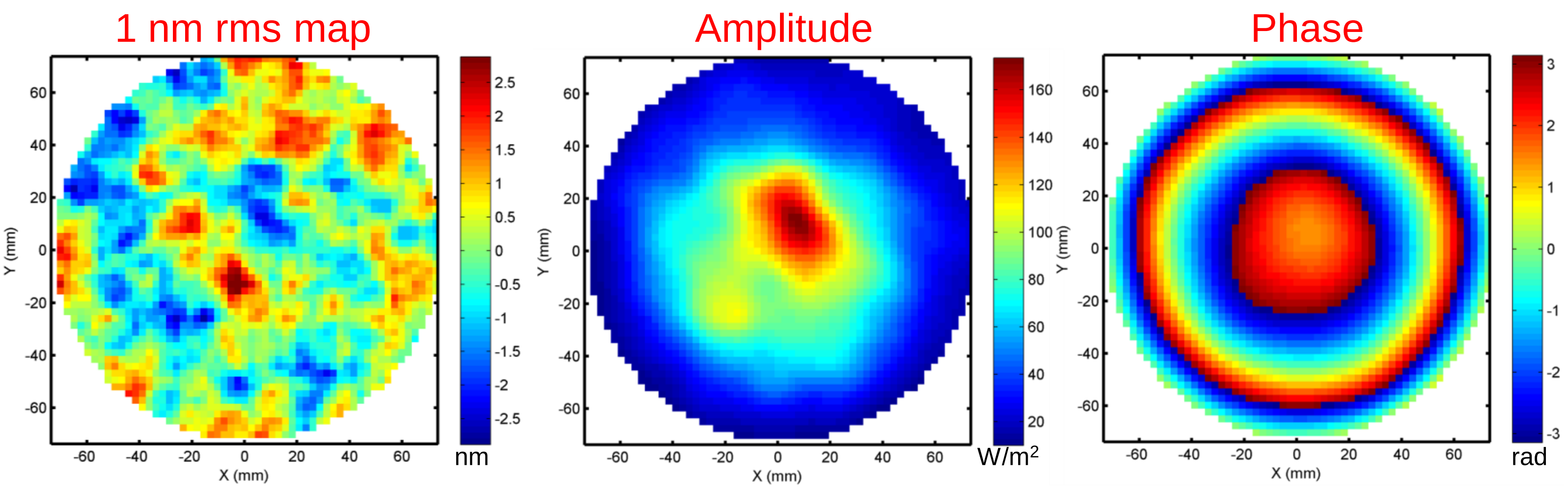
→ We think that it will be easier to make quantitative measurement of aberrations

FFT simulation of power recycled interferometer with **common** aberration :

→ Advanced-like maps on FP arm end mirrors (to give realistic arm response)

→ Identical transmission map on each input mirror with variable rms
(Note: one map flipped left-right due to beamsplitter reflection)

Choice of mod frequency 6270777Hz → upper & lower sidebands almost identical



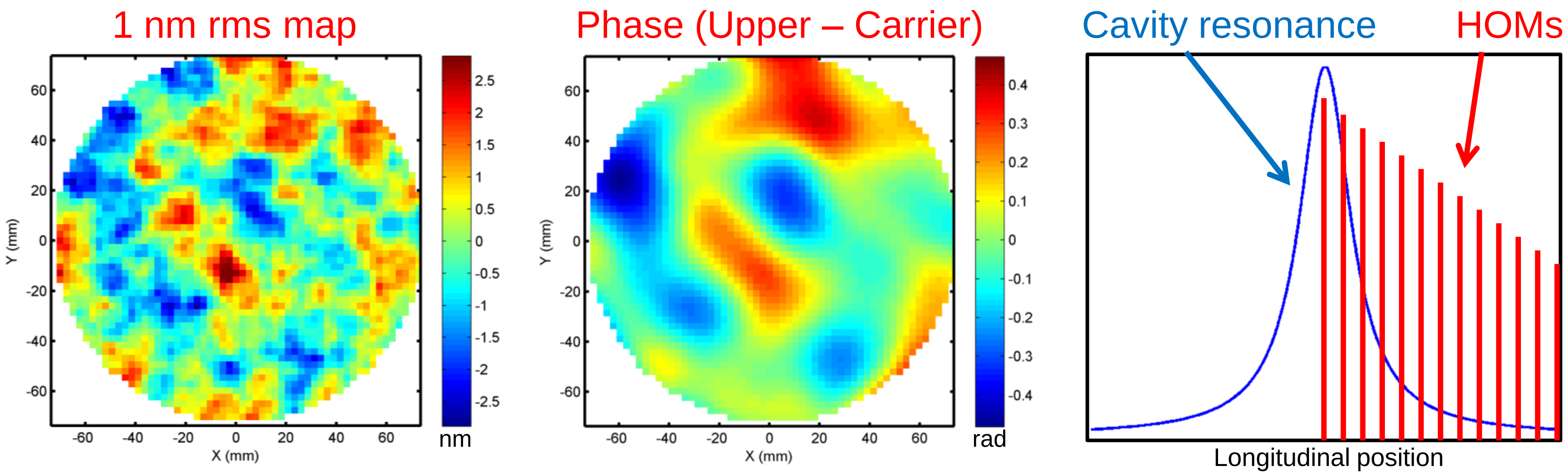
Past experience using sideband phase image has been negative

→ very sensitive to vibration & suspended bench motion.

Proposed Phase camera setup

We actually want the difference in phase between carrier and sideband
→ in perfect interferometer it should be zero.

Experimentally this is feasible
→ In scanning phase camera, for each "pixel" all fields measured simultaneously



Now we can see what looks like a low-pass filtered mirror map

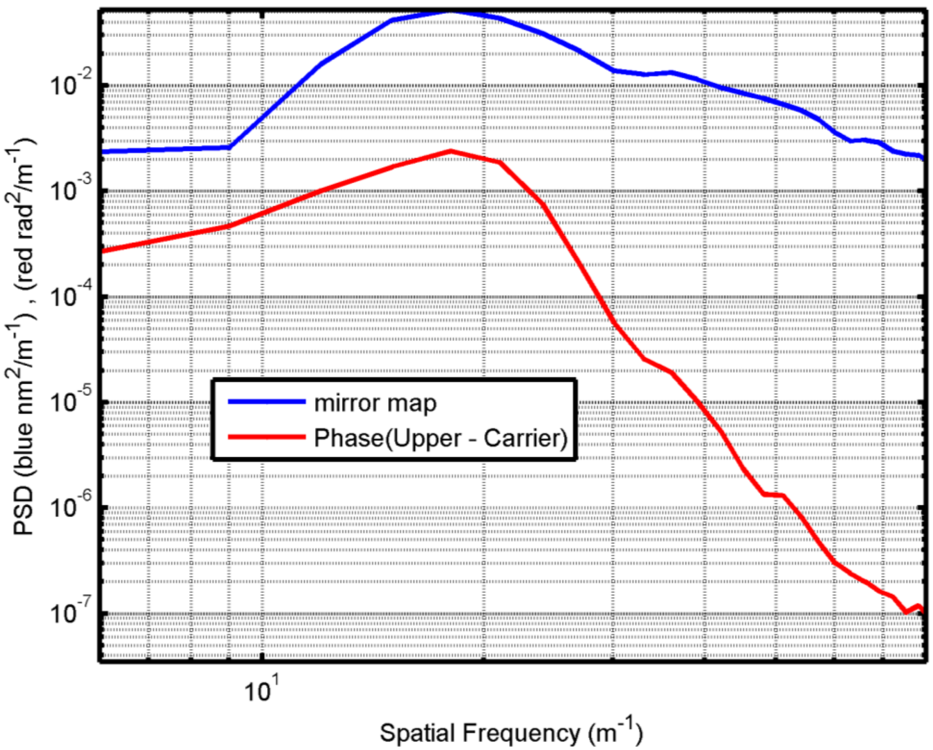
Gouy phase is non-zero → Cavity is not completely degenerate.

Increasing higher order modes "creep" away from resonance

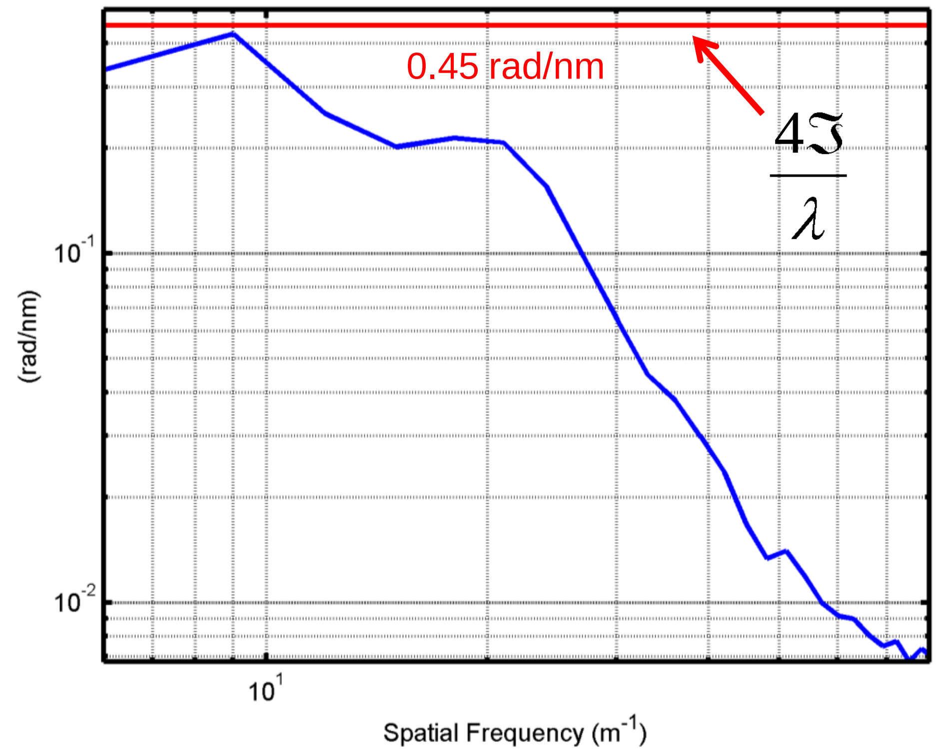
Proposed Phase camera setup

We would like to have a quantitative measurement of the aberration.

We calculate the power spectral density of the real map and the phase image



Find scaling factor vs. spatial frequency and compare with analytic estimation

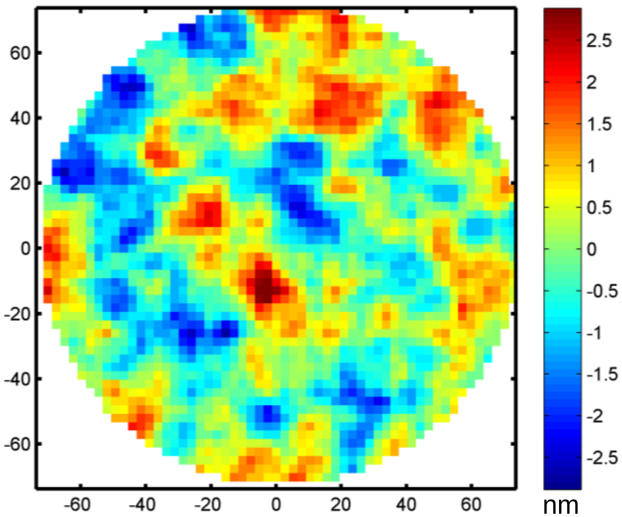


At low spatial frequency the scaling factor is close to what we might expect

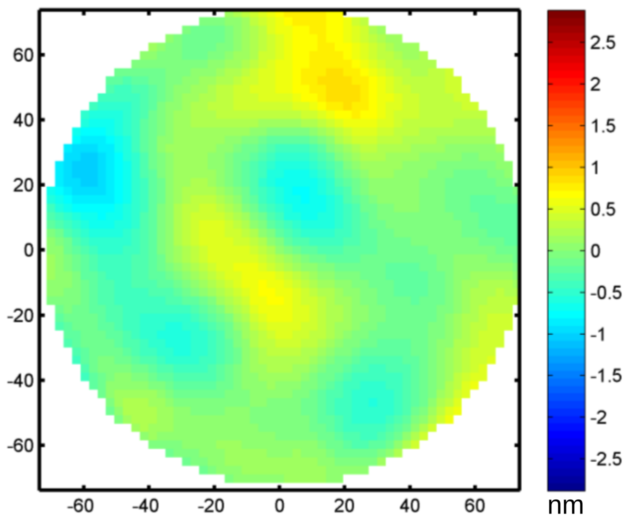
Proposed Phase camera setup

We're now ready to reconstruct the aberration map from phase image

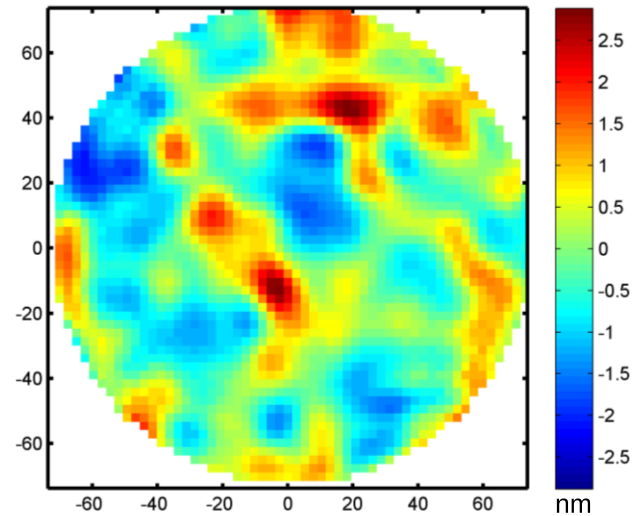
1 nm rms map



Reconstruct using $\frac{4\Im}{\lambda}$



Reconstruct using frequency dependent scaling factor



Frequency independent reconstruction looks washed out due to attenuation of high frequencies

Frequency dependent reconstruction gives good approximation of aberration map

Closing the loop

Now we can simulate closing the loop.

We pretend we don't know what the common aberration looks like.

We will try to correct the aberrations just using the phase camera signal.

This is the procedure we follow:

Set map rms to 4 nm → factor 2 larger than requirement for good operation.

1) Run simulation

2) Use phase image to reconstruct map

→ We use frequency independent method for simplicity

3) Add correction map to power recycling mirror

→ Note: Due to small Gouy phase, correction can be applied anywhere in PR cavity

→ Using the same logic, the aberration can be anywhere in PR cavity

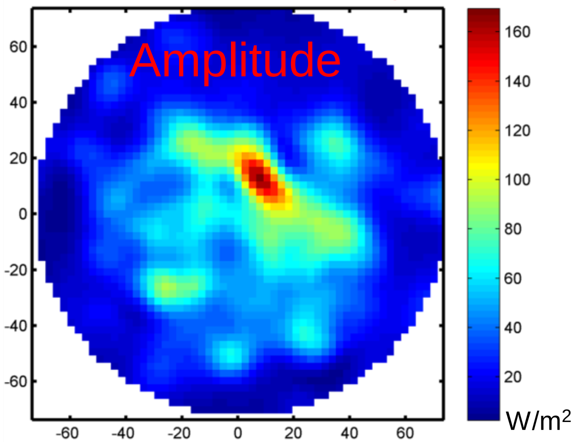
4) Back to step 1

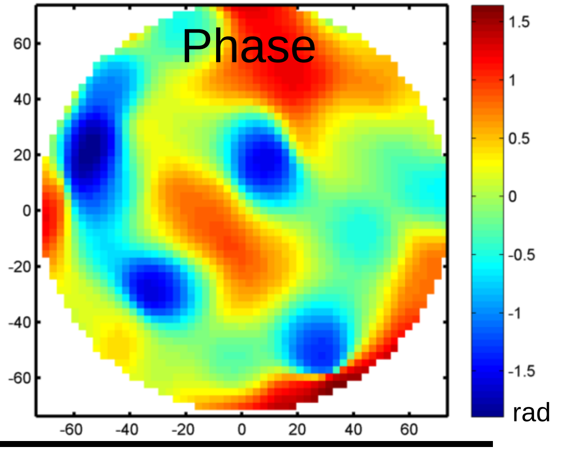
Continue iterating until recycling gain in TEM00 converges

Closing the loop

Recycling gain of TEM00 is just 23% of ideal recycling gain

Phase camera images

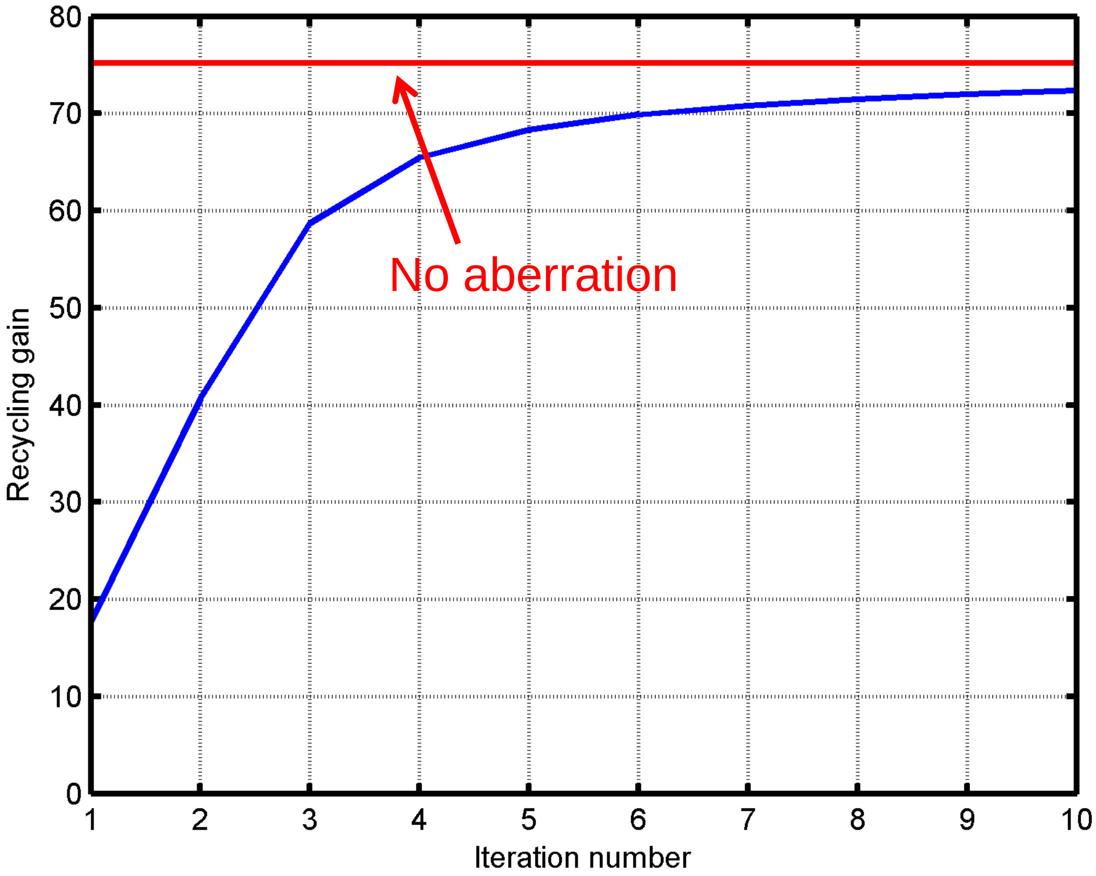




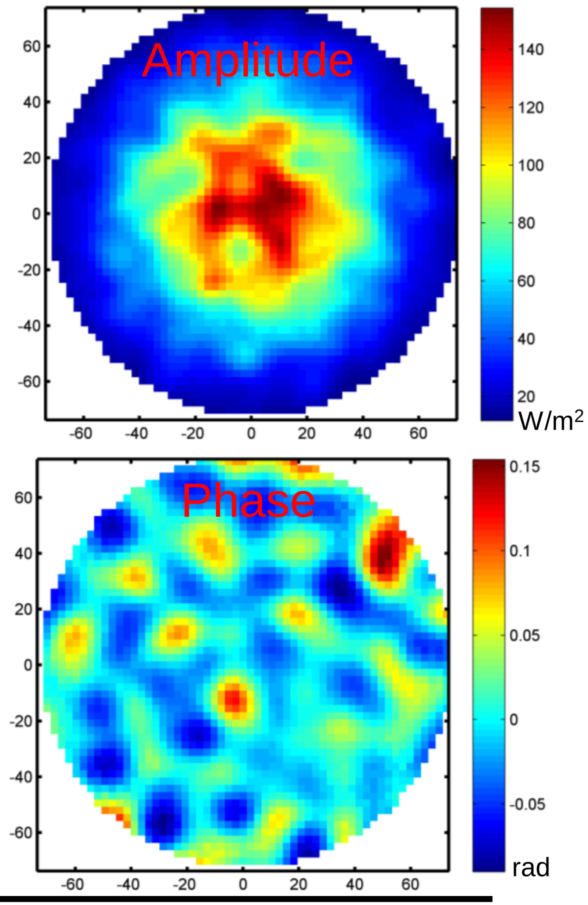
Closing the loop

Recycling gain of TEM00 increases from 23% to 96% in 10 iterations

Residual aberrations due to incomplete convergence .

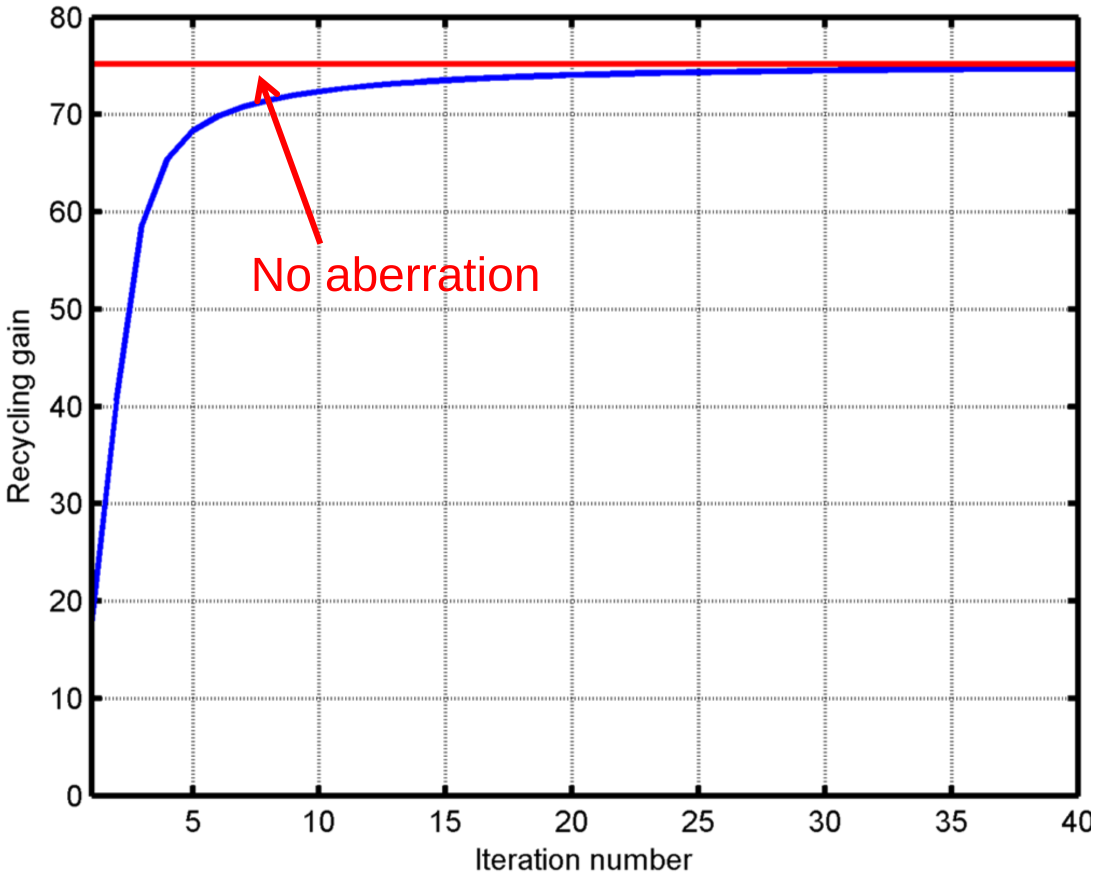


Phase camera after 10 iterations

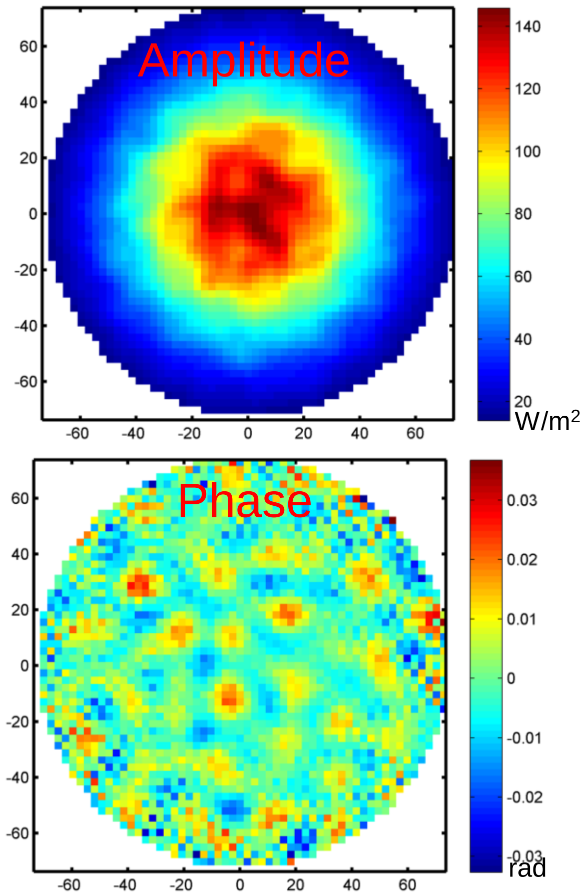


Closing the loop

Recycling gain of TEM00 increases from 23% to 99.4% in 40 iterations



Phase camera after 40 iterations



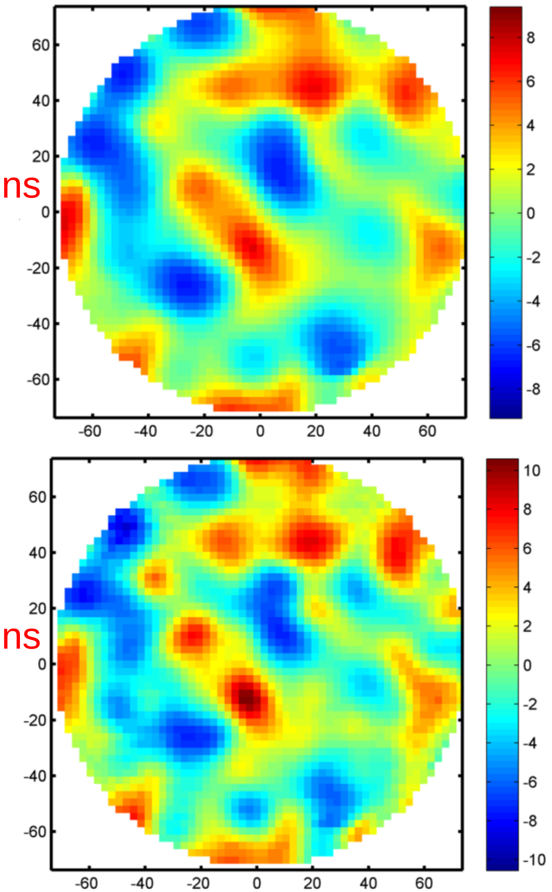
Good recycling gain achievable with predominantly low spatial frequencies.

→Well suited for planned heat pattern projection systems with bandwidth ~ $40 m^{-1}$

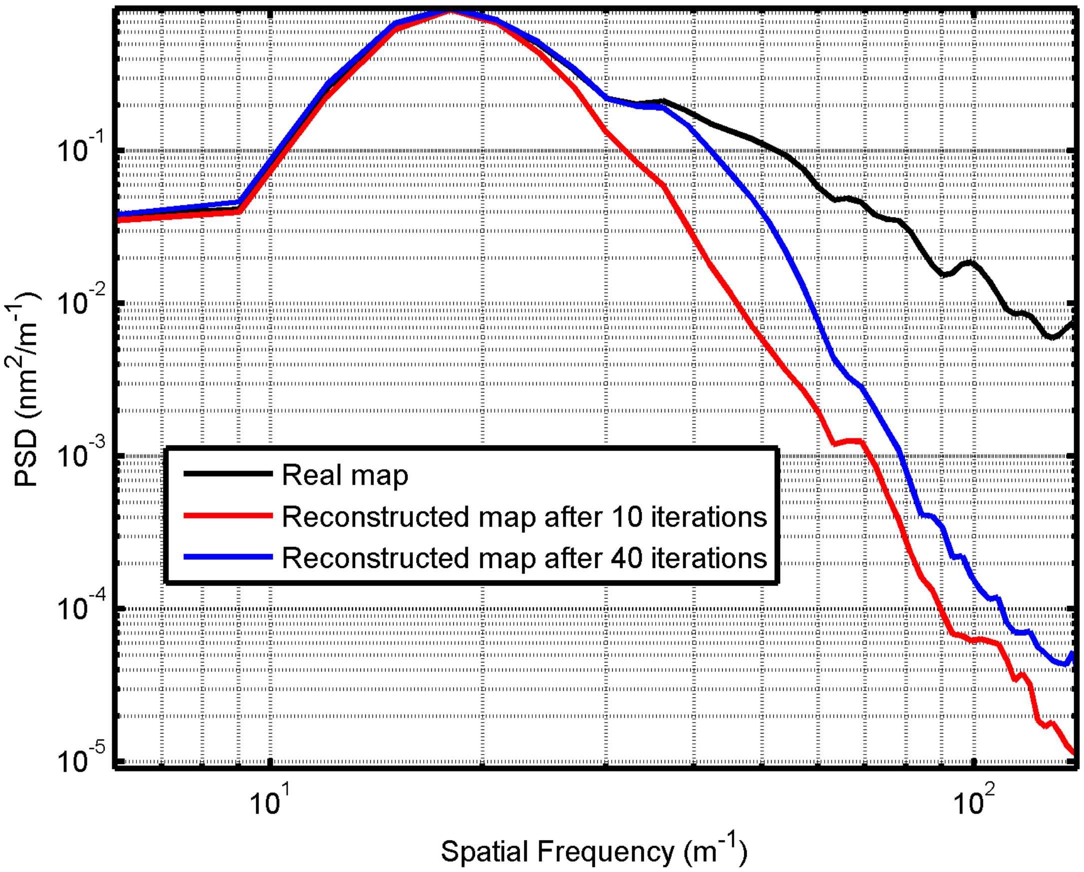
Correction maps

10 iterations

40 iterations



Power spectral density of correction map



Coarse measurement

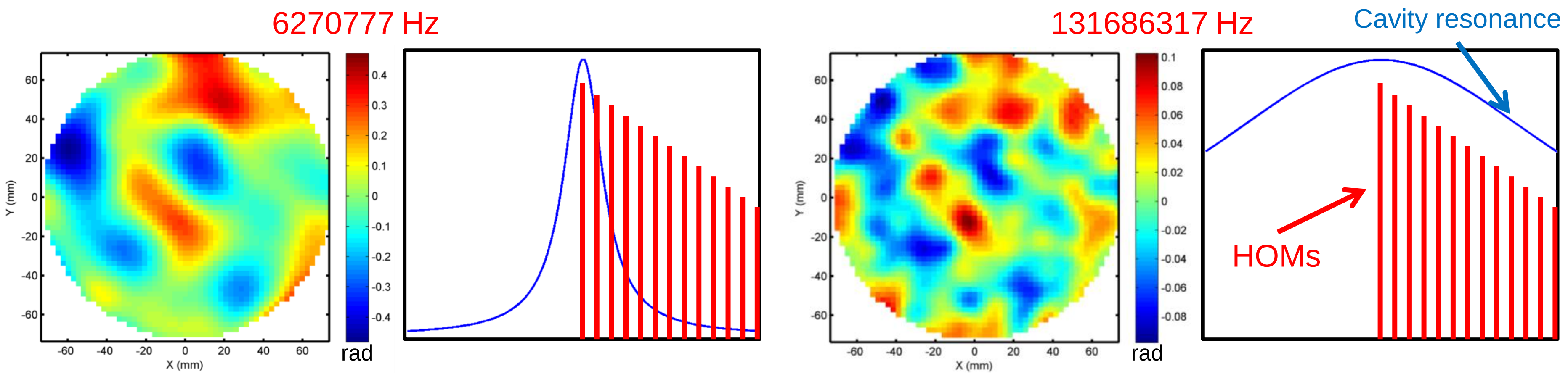
Locking will become challenging with aberrations > 5 nm rms
→ almost inevitable that accumulated common aberrations > 5nm

Therefore need a way to keep highly aberrated RC locked for measurement.

Solution is to use a second modulation frequency of 131686317Hz

Due to Schnupp asymmetry this frequency leaks much more onto dark port
→ finesse is factor 10 lower
→ **factor 10** less sensitive to common aberrations

With coarse measurement can compensate common aberrations up to ~ 40 nm rms



Resulting phase camera image contains higher spatial frequencies
→ Resonance is factor 10 wider so more HOM's resonant.

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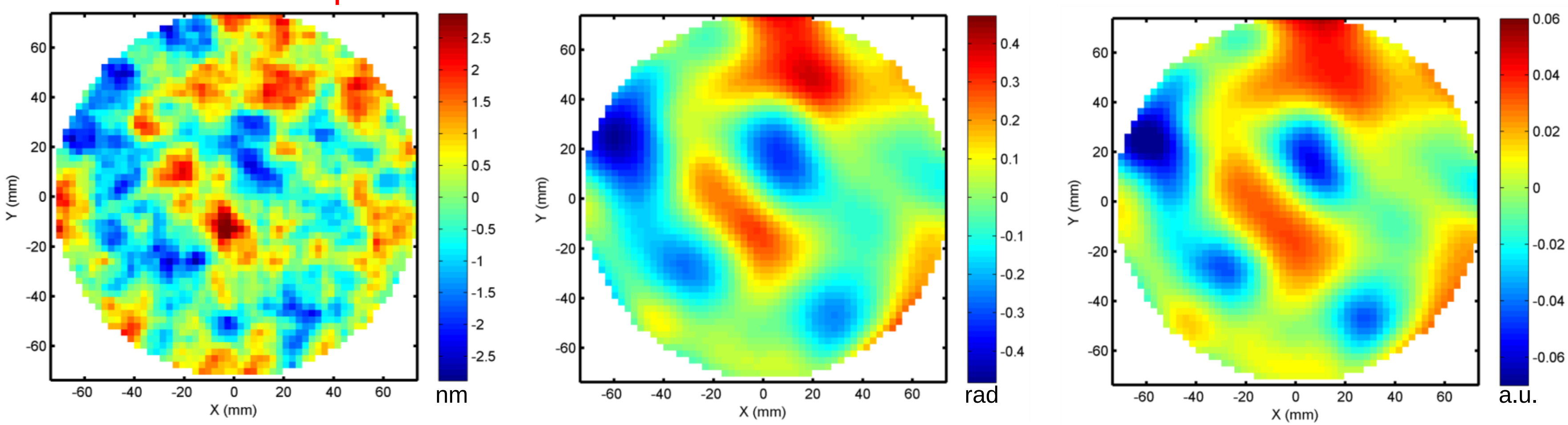
Poor man’s Phase camera

For locking we use a Pound-Drever error signal → one point measurement

Try to apply this to our problem:

- Make a 2D Pound-Drever error signal by scanning beam over a pinhole detector
- Normalize by DC component of demodulated signal

1 nm rms map | Phase camera | Pound-Drever



Gives a very good error signal for correcting common aberrations

Scaling factor dependant on more parameters

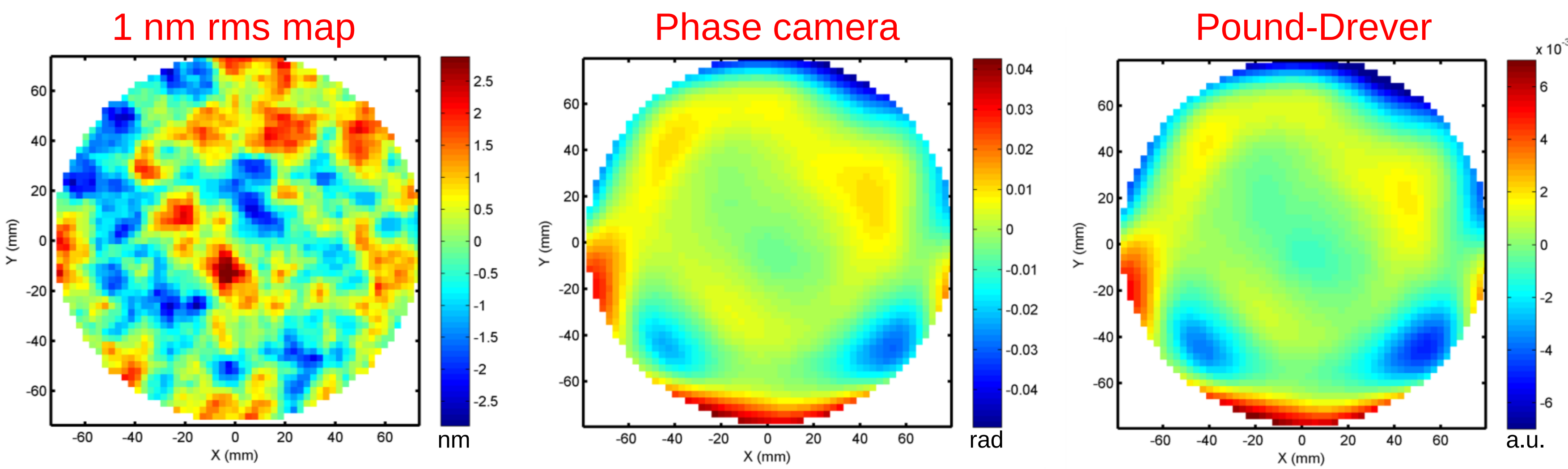
→ However “gain” required probably same as “gain” for locking error signal.

A good complimentary method → No reference beam needed , no dedicated electronics

aLigo has a non-degenerate (stable) recycling cavity
→ much much less sensitive to aberrations.

However they will be confronted with problem of thermal lensing at high power
→ Hartmann sensor in baseline design to measure these aberrations.

Can the phase camera act as a complimentary sensor ?



Results are less clear due to large round-trip Gouy phase in recycling cavity

However the information is there.
→ More work needed to extract the required information from these images.

Conclusion

- Phase camera has been around for a long time but has never been fully exploited
- Presented a strategy for measuring common aberrations in marginally stable recycling cavity using phase information of phase camera.
- First simulations indicate that aberration measurement can be used directly in-loop to get back lost recyling gain.
  → Spatial frequency of correction is compatible with thermal correction systems
- In order to increase dynamic range by factor 10, a second modulation frequency is used which is factor 10 less sensitive to aberrations.
  → Aberrations can be measured and corrected up to ~ 40 nm rms
- 2D Pound-Drever type error signal is a good complimentary solution.
- More work is needed to apply the phase camera measurement to aLigo

Simulation has helped us understand how to use the phase camera in Advanced Virgo

The phase camera will be an essential tool for our “unstable” future.