Table-top fully suspended laser interferometery

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Revision 01

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Gravitational Waves Astronomy

“Reaching the sensitivity required to measure space time fluctuations originated by binary collisions millions of light years away, makes the detection of gravitational waves, foremost, a technical challenge”

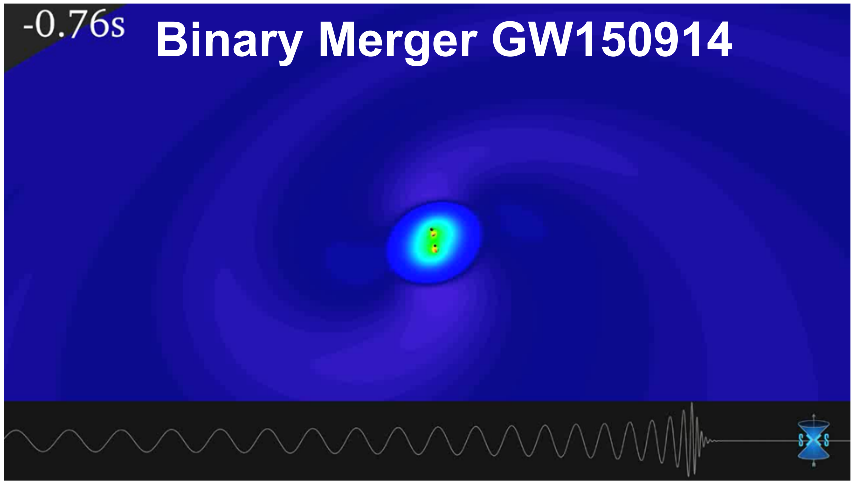
Gravitational waves

Are generated by accelerating masses (changing quadrupole and multipole moments like binary black holes)

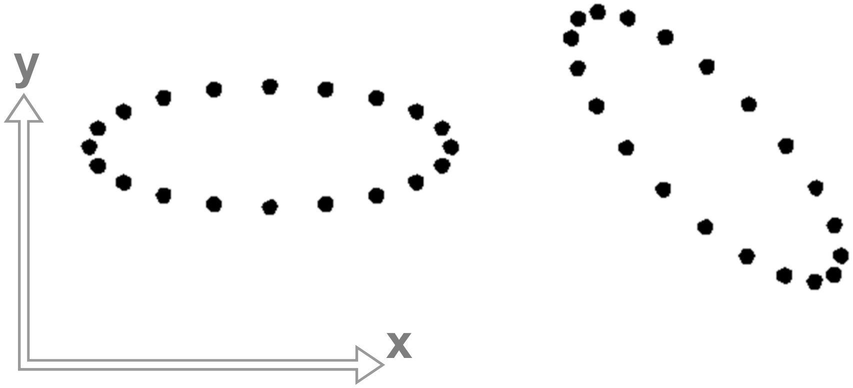
Propagate with the speed of light

Stretches and squeezes space time in transverse directions, in two polarizations

Requiring detectors with extreme strain sensitivity



+ polarization ***x polarization***



Gravitational Waves Detection

“The basic technology behind the LIGO and Virgo detectors is a Michelson laser interferometer, where the effective arm lengths are increased by Fabry-Perot resonance cavities. A wide variety of noise sources must be overcome, eq. quantum noise (shot noise and radiation pressure), seismic noise and thermal noise”

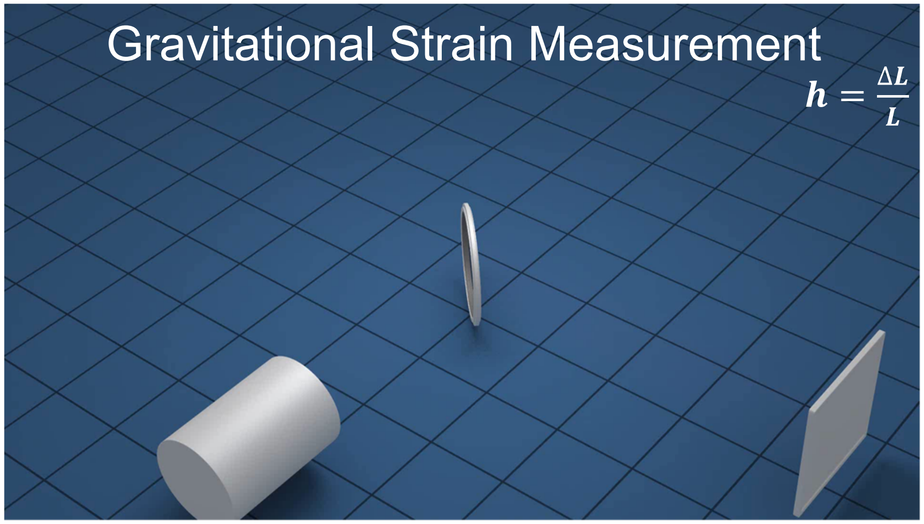
GW Detection

A natural fit for measuring GW is a Michelson laser interferometer

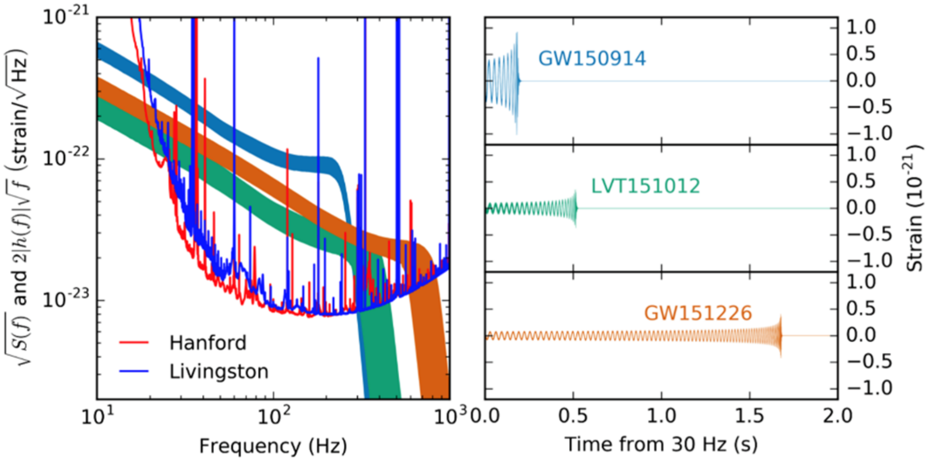
Since the ground is moving by many microns we need free-falling test-masses (mirrors of the interferometers)

Although the earth surface is not an inertial reference frame nevertheless we can lower the seismic coupling with active and passive isolation stages

Active control is necessary to get and keep the interferometer at its working point



Sensitivity plot



Single cavity - Longitudinal Control

“Let’s focus on a single arm cavity. A resonance cavity can not be simply locked by the carrier field. Phase modulation of the carrier is applied to create error signals needed to keep the system at resonance”

Pound-Drever-Hall (PDH) technique

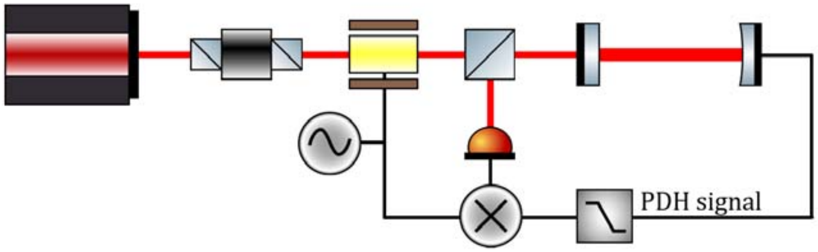
Electro Optical Modulator (EOM)
create sidebands around the carrier

The carrier field resonates inside the cavity while the sidebands are anti-resonant, therefor they are reflected

The PDH error signal is given by the be beat note between the carrier and the sidebands (used as phase reference, carrying the cavity length information)

Phase modulation

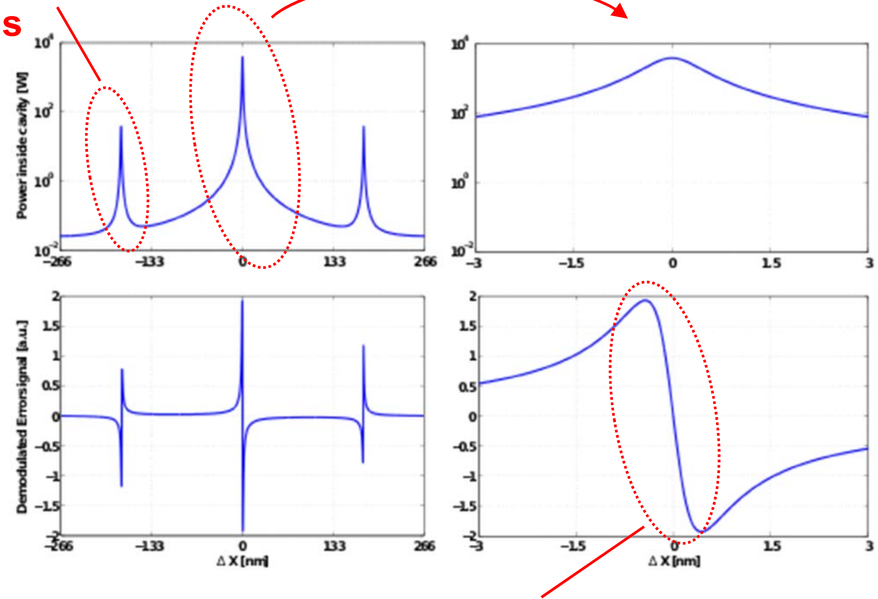
$$E_{EOM} = E_0 \cdot e^{(i\omega_0 t + m\cos(\Omega t))}$$



Carrier

Zoom in

Sidebands



Linear region

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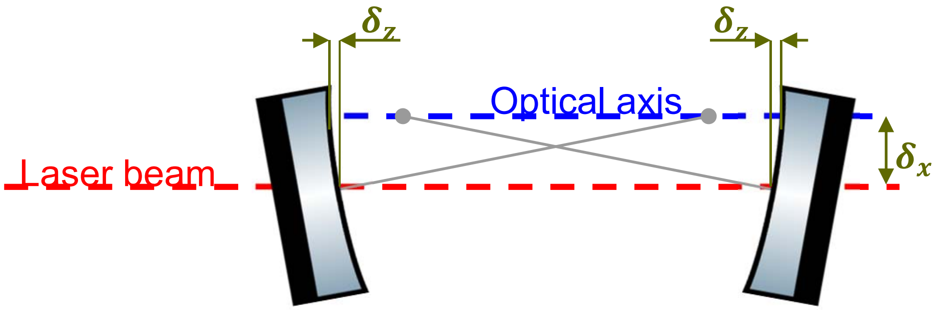
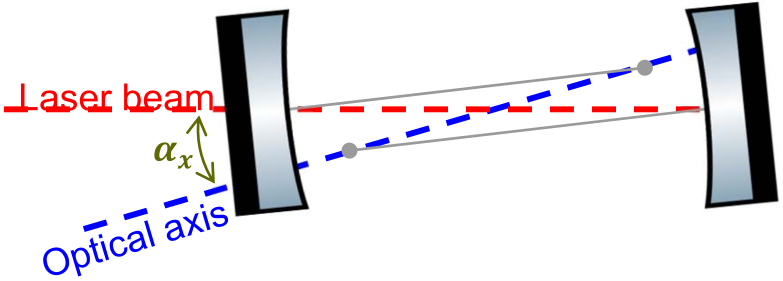
Single Arm Cavity – Angular Alignment

"The input Gaussian beam and the optical axis of a cavity need to be aligned to prevent the occurrence of higher order modes (HOMs)"

Shift of the optical axis



Tilt of the optical axis



Approximation

$for\ \delta_x \ll \omega_o$

$$E(x+\delta_x) \approx A\left[H_0(x) + \frac{\delta_x}{\omega_o} H_1(x)\right]$$

Beam divergence

$for\ \alpha_x \ll \theta_d$

$$E(x+\delta_x) \approx A\left[H_0(x) + \frac{\alpha_x}{\theta_d} H_1(x)\right]$$

Four angular degrees of freedom / cavity

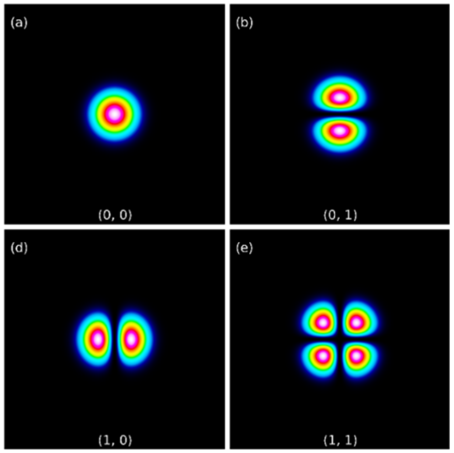
Misalignments introduce HOM

HOMs decrease the power of the fundamental mode

Misalignments change the cavity lengths

Hermite-Gaussian modes

(with degrees, n and m)



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Single Arm Cavity – Angular error signals

Dithering line (mechanical modulation)

Angular oscillation $\boldsymbol{\omega_{mij}}$ *of the two rotational DOF of the mirror*

Misaligned optics create a cavity length change $\boldsymbol{\delta_z}$

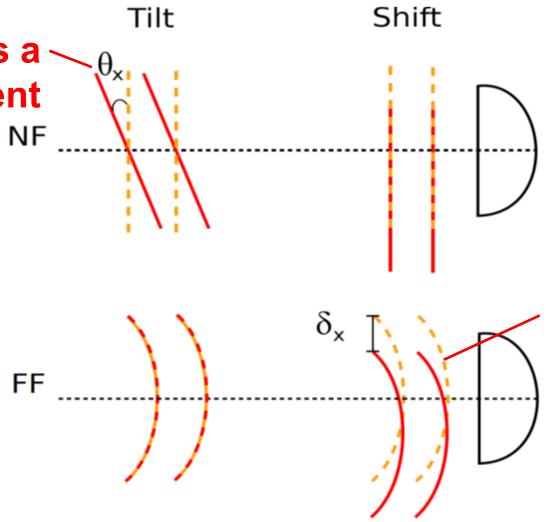
Error signal created by demodulating the longitudinal signal by $\boldsymbol{\omega_{mij}}$

Ward technique (Phase modulation)

Usage of the longitudinal modulation frequency by EOM

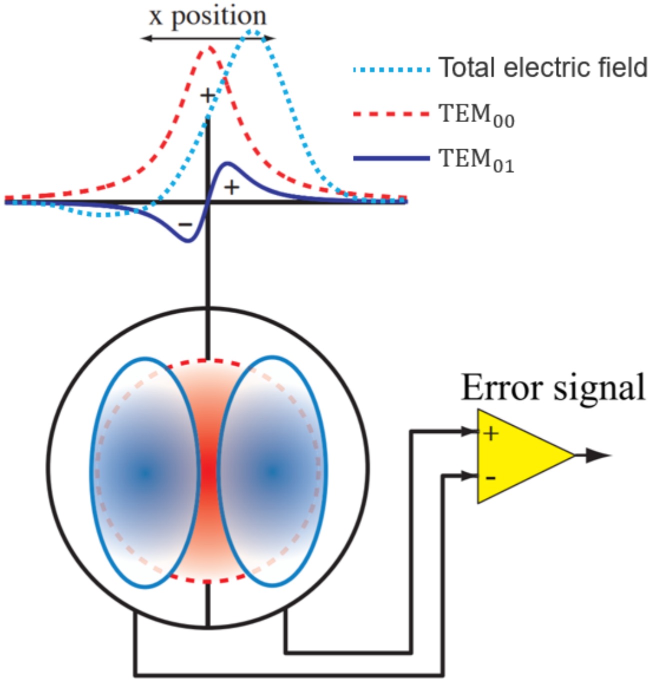
Tip and tilt are both mixed in one error signal

Two QPDs in reflection of the cavity measures the*
spatial beam phase distribution
*(*near and far field)*



Tilt is measured as a phase gradient

Shift generates a phase gradient



VIRGO fact sheet

Test-masses ***longitudinal*** *degrees of freedom 4 (5)*

Test-masses ***angular*** *degrees of freedom 16 (18)*

Seismic Attenuation Systems
for all optical components

Mirror Alignment 10^{-9} *[rad/min]*

Mirror Positioning 10^{-12} *[m/min]*

But there is more

Real time

~10.000 control loops
ranging from a few Hz up to 200 kHz

Complex

Error signals are strongly nonlinear functions of the mirror positions and can only by linearized in a very small fraction of phase space

Lots of complex tricks and manual actions are involved to enable classical controls

Making the commissioning a continuous challenge relying on well trained, highly experienced people

…M€ systems

GW Observatory → one can not afford downtime

Trade-off between interventions and the risk of downtime

Simulations and test facilities are key to drive break-through innovations

Longitudinal DOF

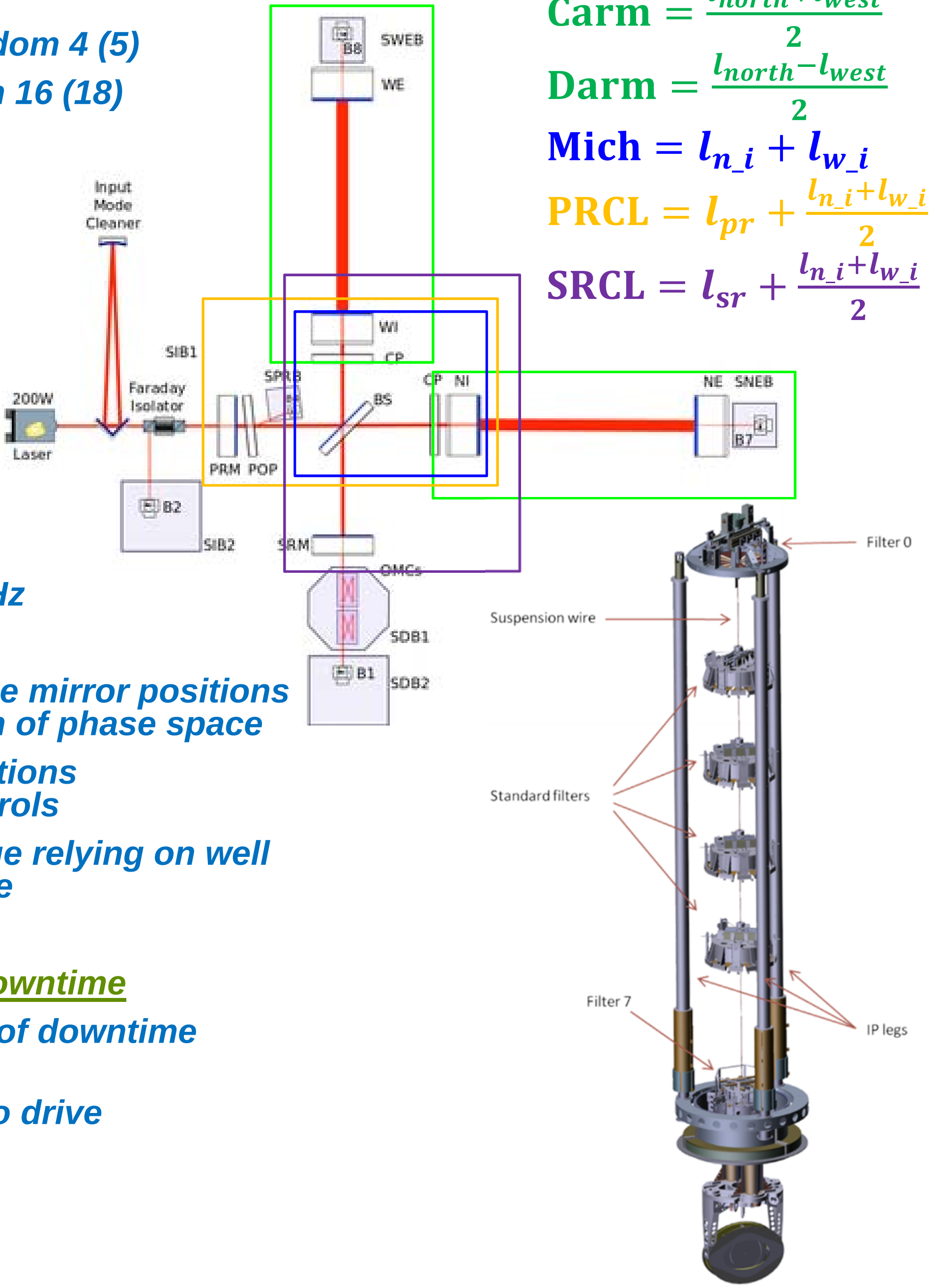
$$\mathrm{Carm} = \frac{l_{north}+l_{west}}{2}$$

$$\mathrm{Darm} = \frac{l_{north}-l_{west}}{2}$$

$$\mathrm{Mich} = l_{n\_i} + l_{w\_i}$$

$$\mathrm{PRCL} = l_{pr} + \frac{l_{n\_i}+l_{w\_i}}{2}$$

$$\mathrm{SRCL} = l_{sr} + \frac{l_{n\_i}+l_{w\_i}}{2}$$



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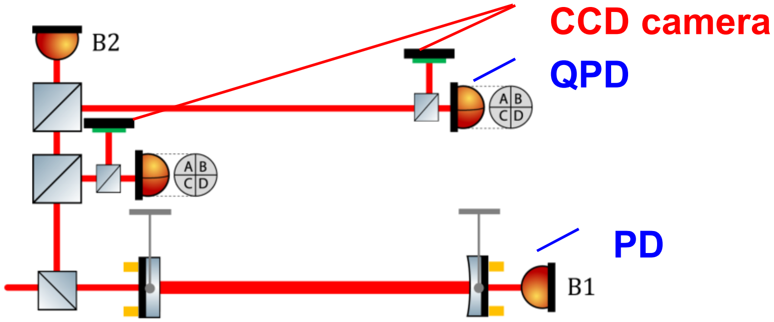
The table-top fully suspended laser interferometer

"At Nikhef we are realizing a table top fully suspended laser interferometer. Enabling the development and deployment of alternative auto-alignment systems and locking procedures in a secure environment to improve the ITF robustness and reduce control noise"



Setup

Single Fabry-Perrot resonance cavity

full-state controller using the a-priori(physics) knowledge and real-time observations to reconstruct the states of the system

Method

Beam Images (Simulation or data)

Alignment Algorithm

Update Mirror Position

Status

- Generating simulated data
- Optimizing camera position

Status

- First version of the CRNN ready
- Developing Reinforcement algorithm

Finally

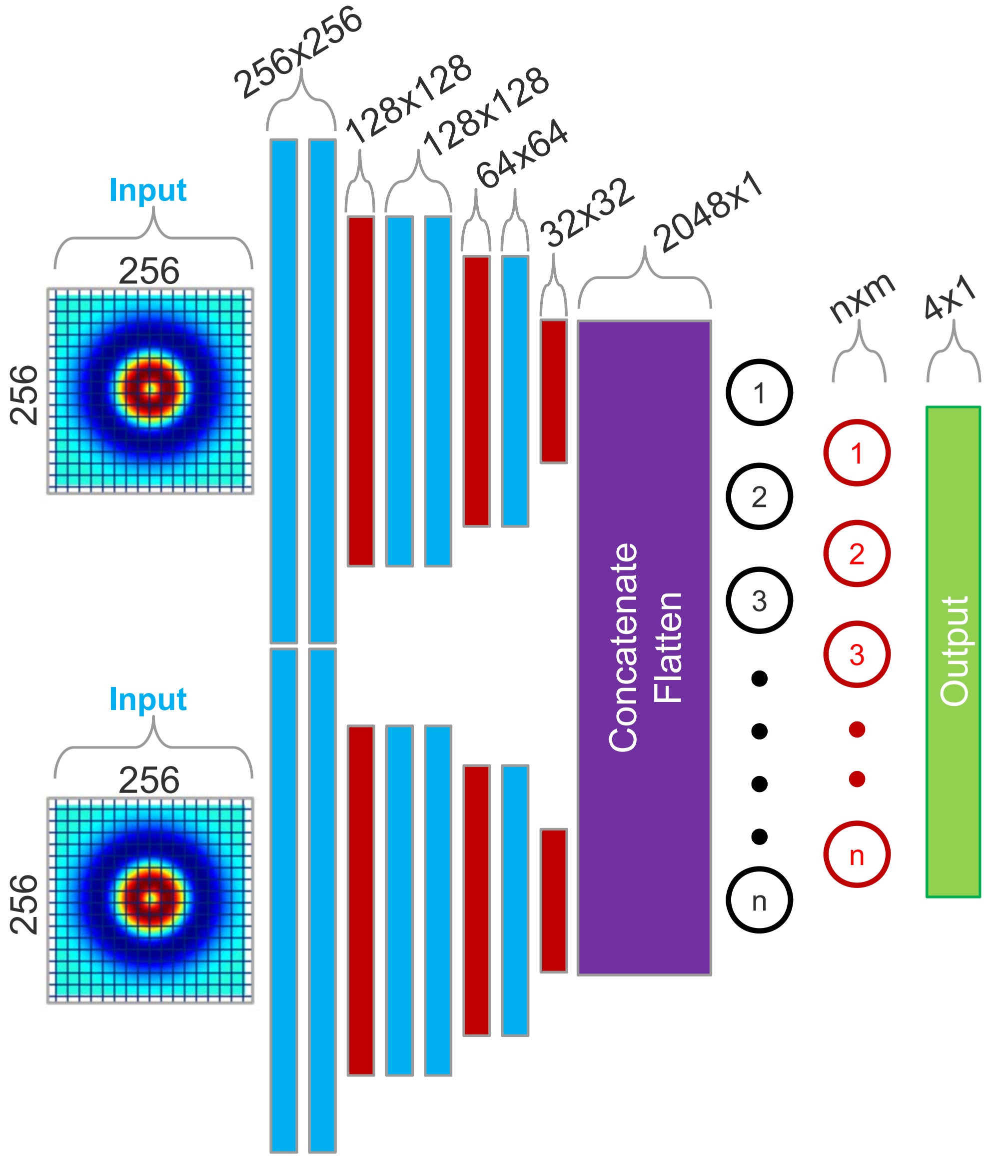
Deploy algorithms in the real setup

Ultimately

Enroll to other DOF

Convolutional Recurrent Neural Network

CCD Image → CRNN → Mirror position



Convolutional Layer

Containing a RELU activation layer

Pooling Layer

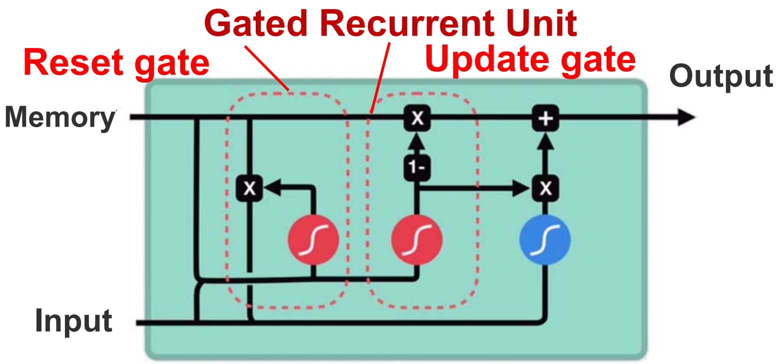
Containing a drop-out to reduce overfitting

Output

Containing a Sigmoid activation function

The auto-alignment systems needs to deal with <u>discontinued and time varying signals</u>

- ***The convolutional recurrent neural network will include Long Short-Term Memory (LSTM) like in speech recognition algorithms***
- ***The CRNN enable auto alignment of the Fabry-Perrot resonance cavity***
- ***(Atmospheric) disturbances can be compensated to maintain the lock***



Simulated training data

“Pythons Pykat package with Finesse is used to generate a dataset of the reflected cavity error signals, the time varying data is used to divide angular misalignment in 5 regimes, resulting in 625 combinations to train the network. Include the longitudinal lock acquisition this will be about 4375 combinations”

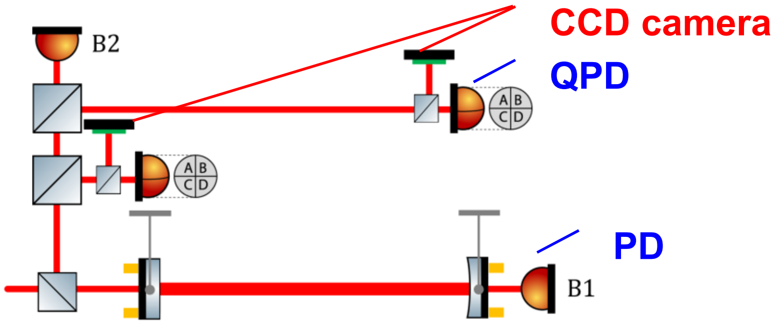
Generated data from GW optics simulations software (finesse)

- ***Four TEM modes included (TEM00/01/10/11)***
- ***Separate the angular misalignments into 5 main regimes along each axis (up to 10^{-4}rad)***
- ***For each misalignment regime we generate 100 additional phase map images***
- ***In our case we have 625 combinations to train the angular DOF***
- ***Labelled data is split 75=25, 75%-training, 25%-testing.***
- ***Next step; The simulated signals need to be augmented with Gaussian random noise, with an amplitude comparable to the sensing level that is estimated from the real signals. This is very important to avoid overfitting of the datasets.***

Labeled experimental data

- ***Run the experiment by classical controls***
- ***Generate labeled experimental data by phase map measurements (CCD cameras)***

Fabry-Perot Cavity modelled in python



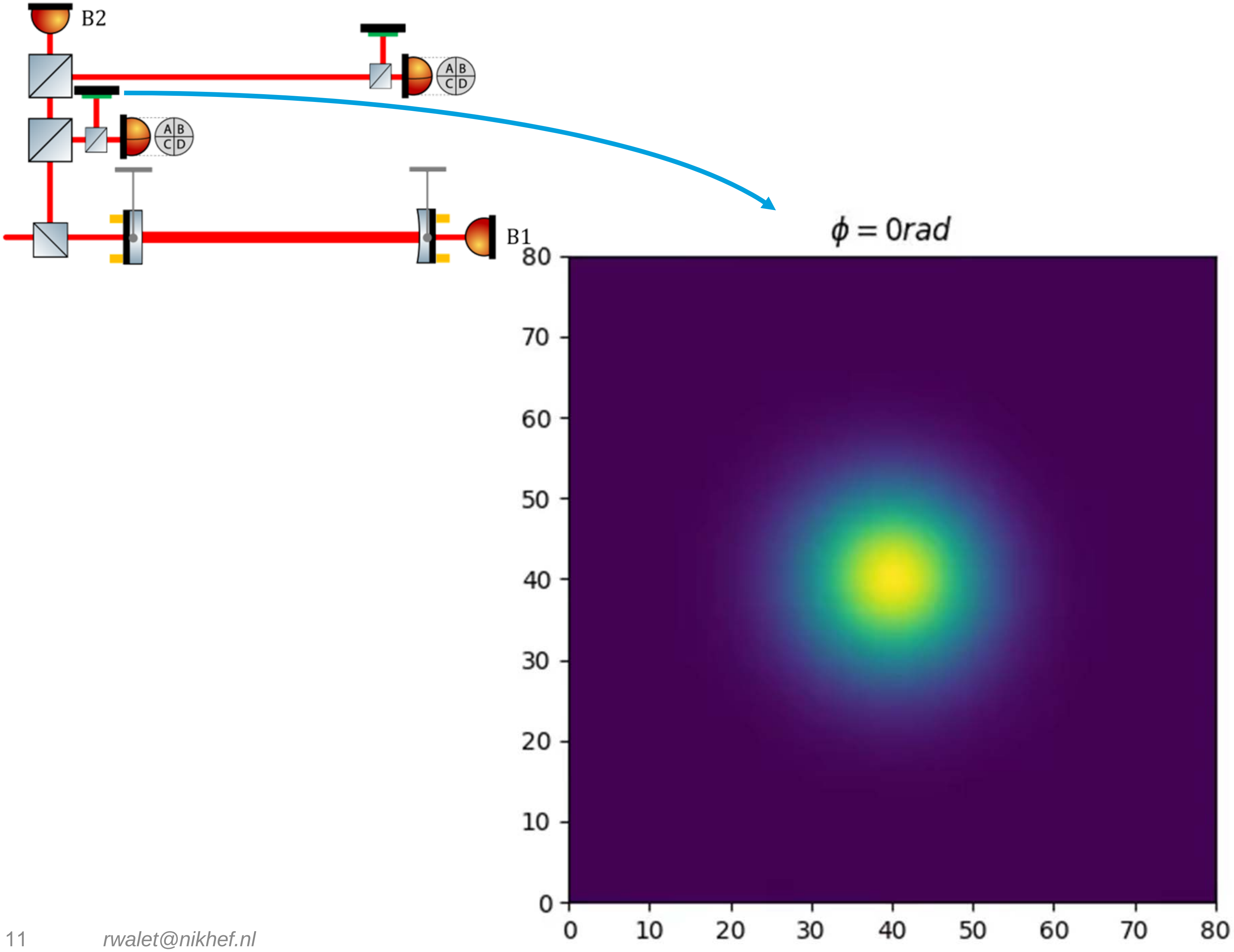
Cavity Parameters

- ***Plano-Concave FP cavity***
- ***Length 0.45 m***
- ***Radius of curvature 0.5 m***
- ***Finesse 95***
- ***Line Width 5.6nm***
- ***FSR 333MHz ~534 nm***

Error signals

- ***QPDs + PDs for classical lock***
- ***CCD cameras for ML***

Example Training Data



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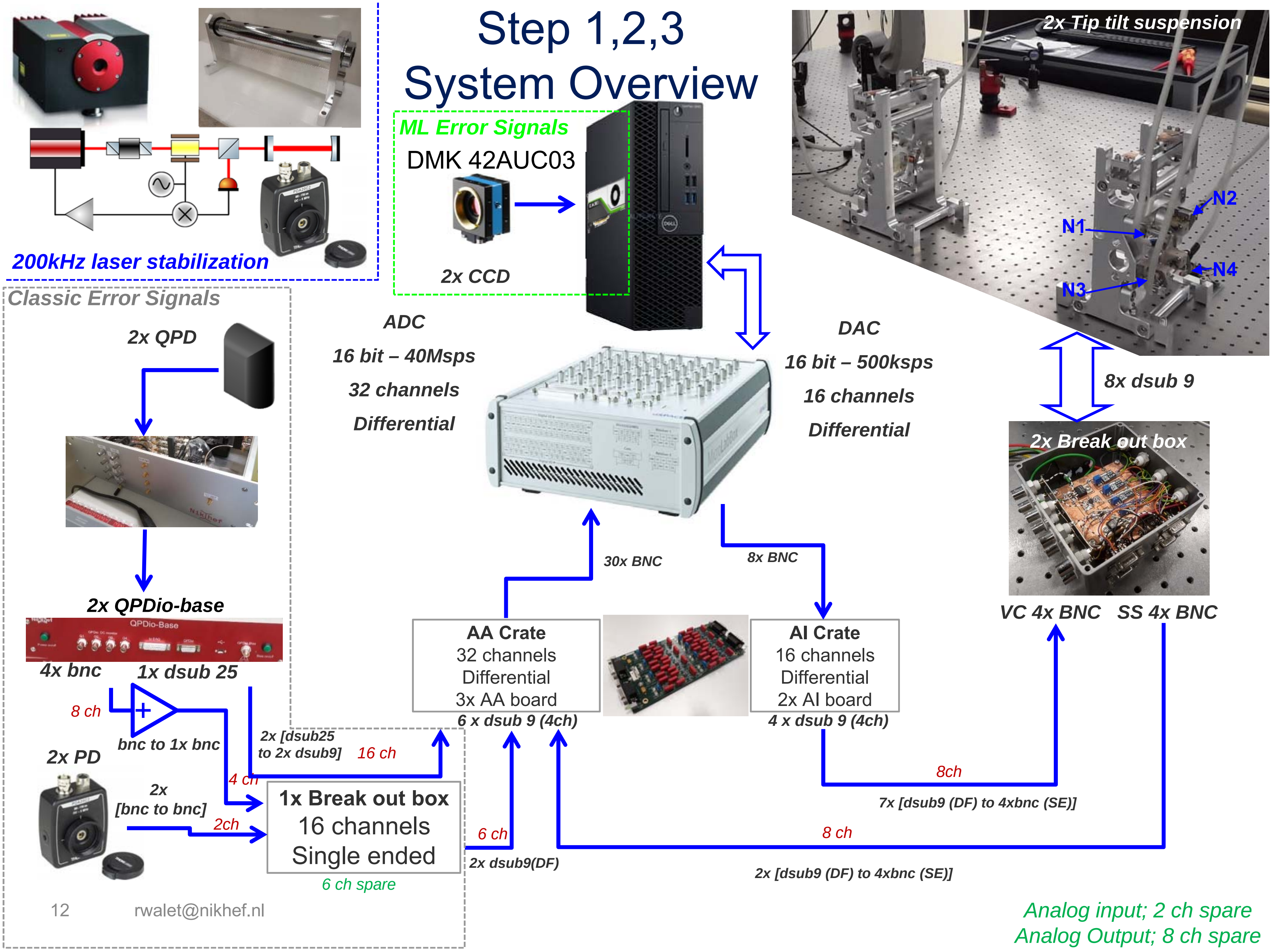
Step 1,2,3
System Overview



200kHz laser stabilization

ML Error Signals

DMK 42AUC03

2x CCD

2x Tip tilt suspension

N1
N2
N3
N4

Classic Error Signals

2x QPD

2x QPDio-base

4x bnc

1x dsub 25

8 ch

bnc to 1x bnc

2x [dsub25 to 2x dsub9]

16 ch

4 ch

2x PD

2x [bnc to bnc]

2ch

1x Break out box
16 channels
Single ended

6 ch spare

ADC
16 bit – 40Msps
32 channels
Differential

DAC
16 bit – 500ksps
16 channels
Differential

8x dsub 9

2x Break out box

VC 4x BNC

SS 4x BNC

30x BNC

8x BNC

AA Crate
32 channels
Differential
3x AA board

6 x dsub 9 (4ch)

AI Crate
16 channels
Differential
2x AI board

4 x dsub 9 (4ch)

6 ch

2x dsub9(DF)

8ch

7x [dsub9 (DF) to 4xbnc (SE)]

8 ch

2x [dsub9 (DF) to 4xbnc (SE)]

Analog input; 2 ch spare
Analog Output; 8 ch spare

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Conclusions and Outlook

The realization of a fully suspended laser interferometer enables the development of alternative control strategies for gravitational waves observatories

Use reinforcement learning to perform adjusting actions in continuous feedback to maximize reward

Increase the robustness

Reduce the downtime

&

Help commissioners to automatize nonlinear tasks

First version of neural network trained with simulated data

Next step: use in experimental setup

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