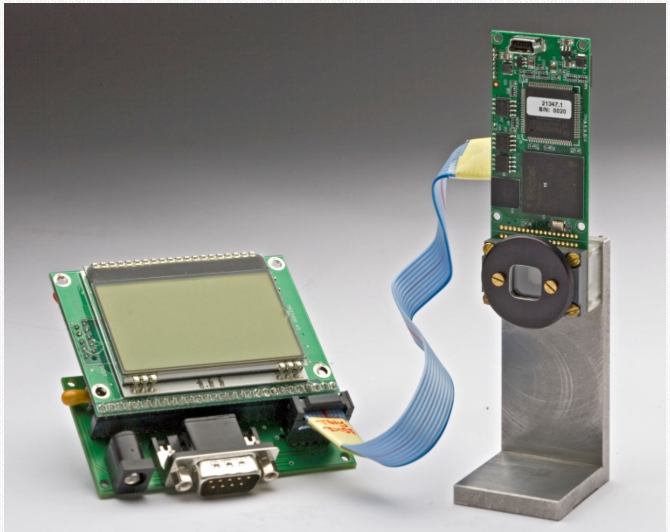
Engineering Diploma of the ENSPS

Master IRIV Nanophotonics

Thibaud MAGOUROUX

University year 2010

« DEVELOPMENT OF A MINIATURISED WAVEFRONT SENSOR BASED ON A NEURAL NETWORK »



Supervisors

Marc Eichhorn

Alexander Pichler

01/03/2010 – 31/08/2010

OUTLINE

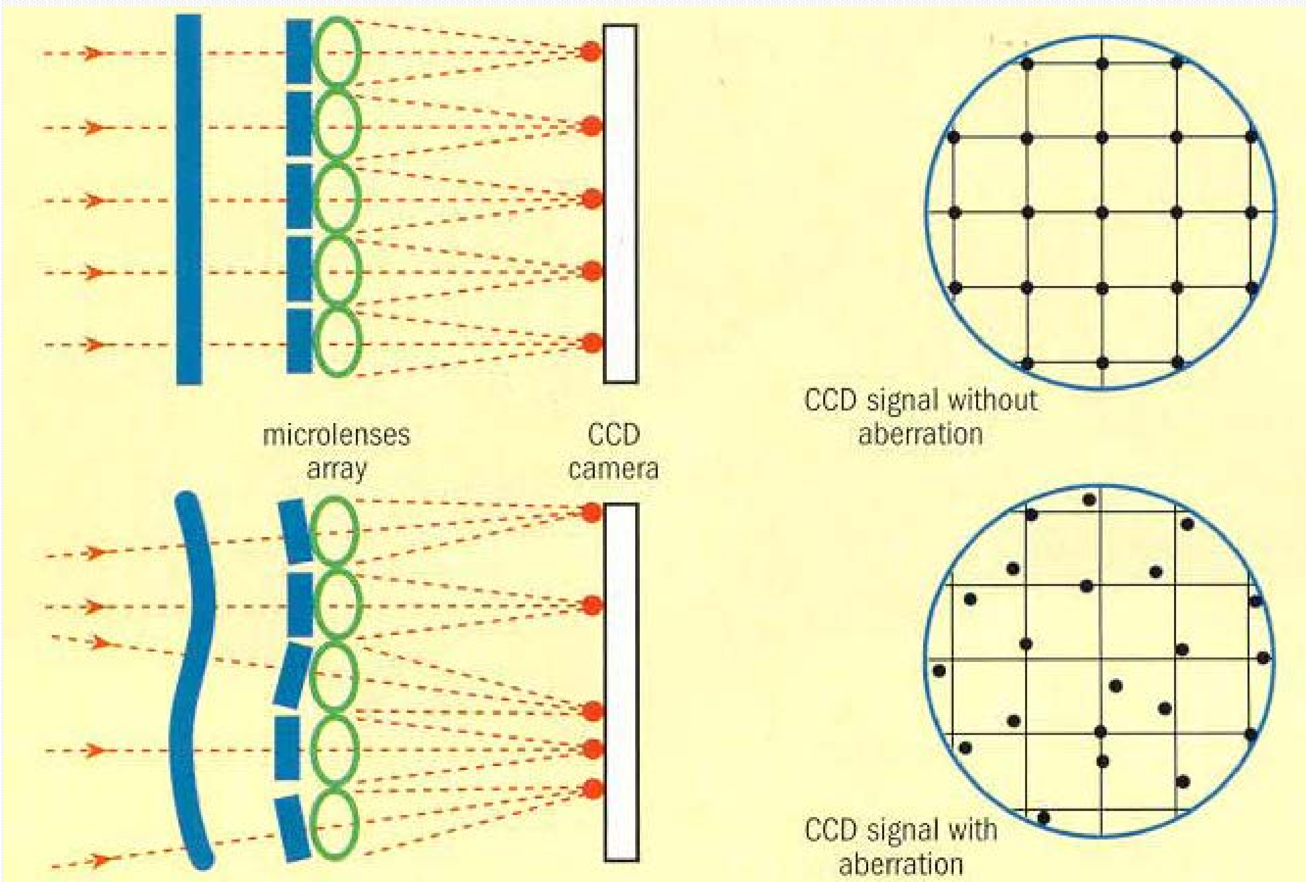
- Possible applications of wavefront sensors
- Wavefront sensors : state of the art, problem and specifications
- Real-time embedded approach
- New miniaturised wavefront sensor : my contribution
- Conclusion and outlook

SPECIFICATIONS & TASKS

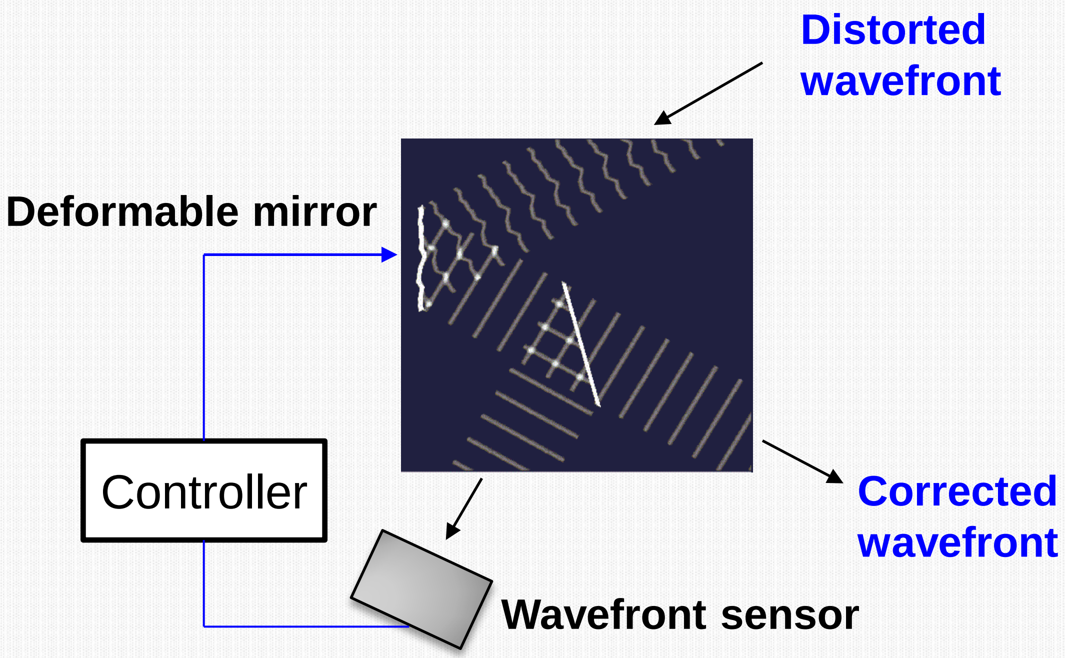
- Miniaturisation and optimisation of an ISL concept of a stand-alone, real time and low cost wavefront sensor
- Validation and tests of the new prototype
- Simulation of the effect of scintillations and physical sensor defects on the quality of the results

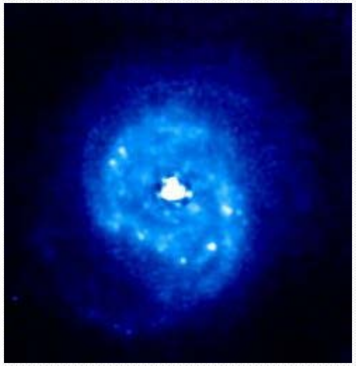
SHACK-HARTMANN WAVEFRONT SENSOR

- Microlens array
- CCD camera



MAIN APPLICATION : ADAPTIVE OPTICS



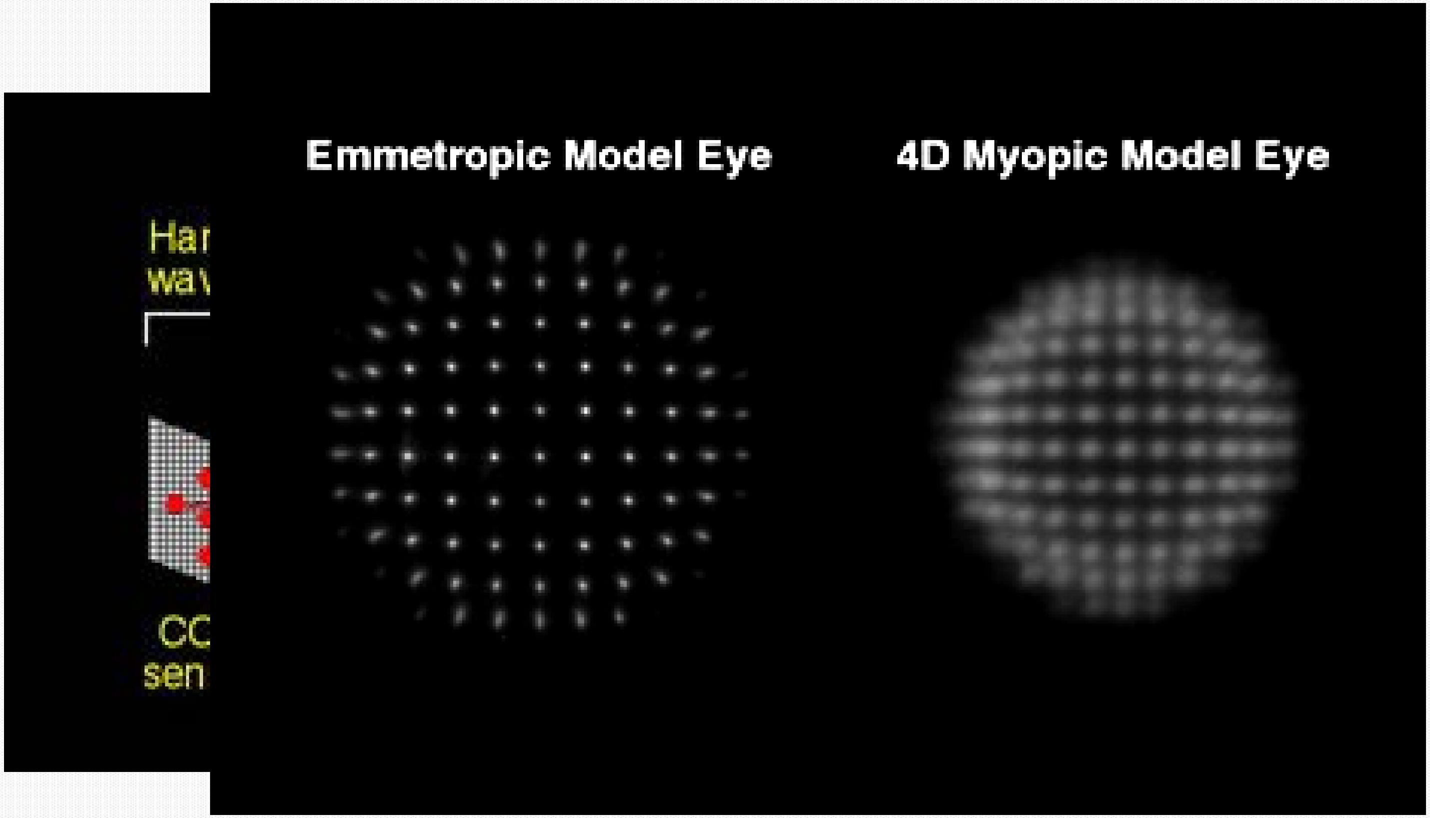


Allows active control of the wavefront:

- Generation of plane wavefronts
    - Propagation and target illumination efficiencies
    - Image enhancement (e.g. astronomy)
- Generation of specific wavefronts for metrology and sensorics

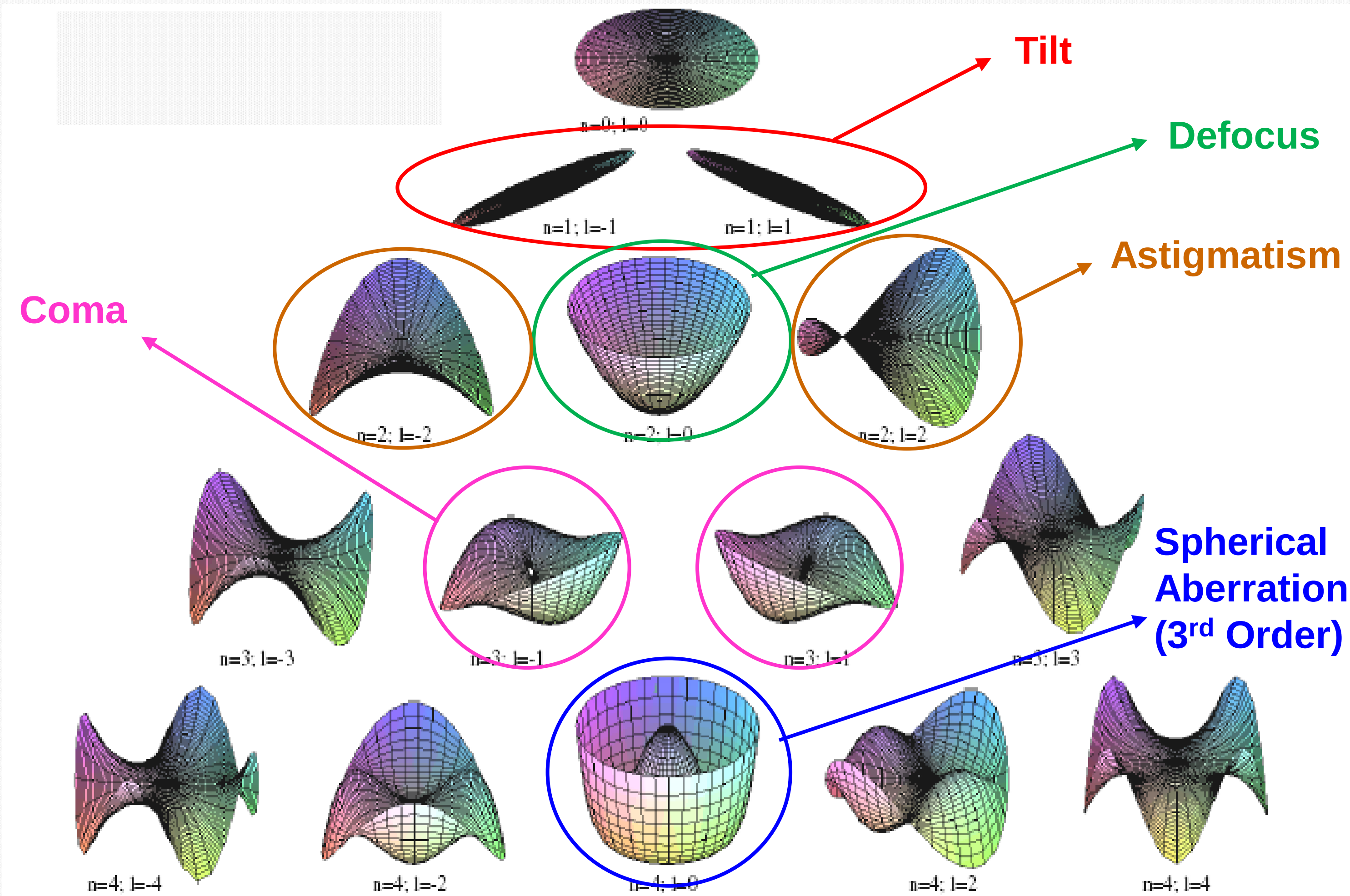
MEDICAL APPLICATION

- Ophthalmology: detecting eye aberrations



WAVEFRONT MEASUREMENT

Characterisation of the wavefront in the Zernike base



WFS : STATE OF THE ART

Classical approach :

Shack-Hartmann Sensor

⇩

spot displacement ~ local phase front slope

⇩

numerical integration

⇩

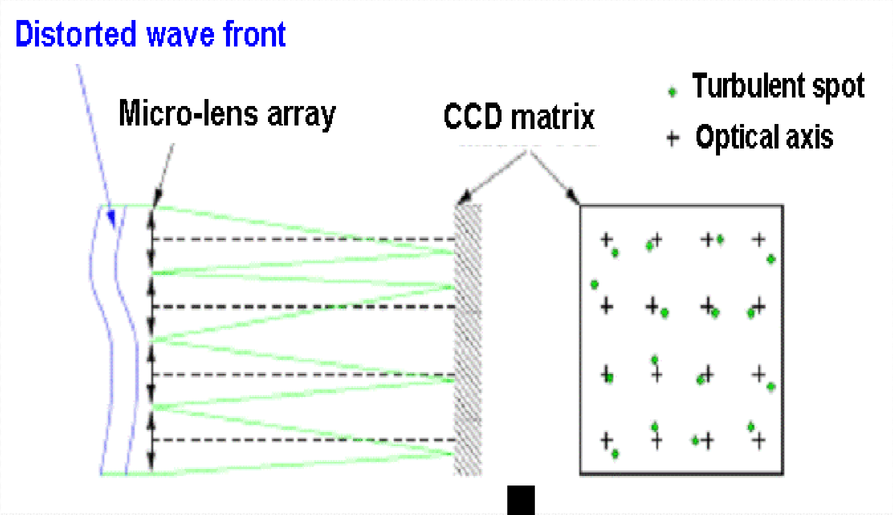
Phase front

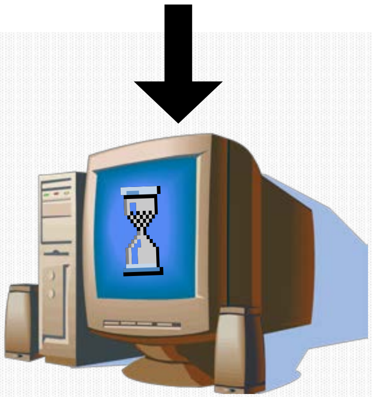
⇩

multiplication with one $\mathbf{Z}_k$ + numerical integration

⇩

contribution coefficient

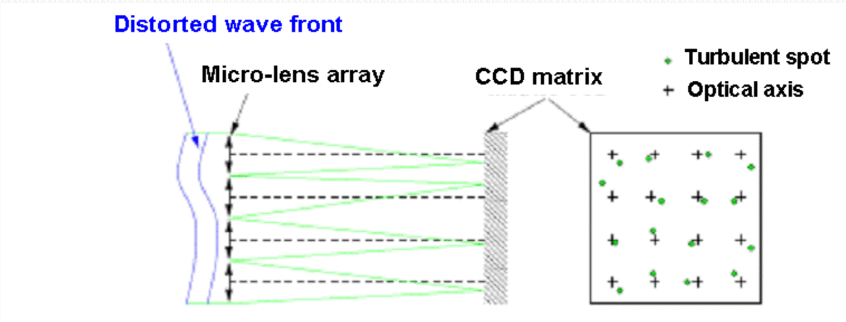




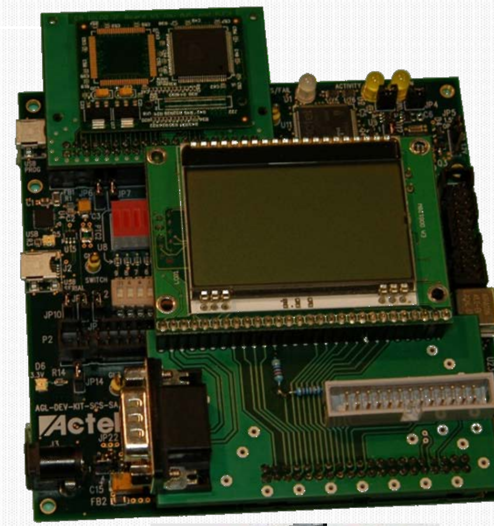
Problem: High quality & real time ➔ high-resolution ➔ powerful computer ➔ significant **volume, price** and **power** consumption

ISL NN WAVEFRONT SENSOR PATENT

Wave front measurement (Shack-Hartmann)



PC-based wave front calculation



Challenge: fast autonomous smart sensor with no PC in the loop

First proof of concept prototype needs to be optimized:

- Communication between each part of the board
- Clock frequency improvement by shortening electrical wire lengths
- From the prototype towards industrial product

MY CONTRIBUTION

- Specification of a new miniaturised wavefront sensor platform (➔V1KU)
- Technical comparison of existing prototype \ V1KU
- New FPGA firmware for embedded applications
- Performance and quality analysis

Bonus

- Complementary studies to fulfill new questions and requirements:
  - Specific DLR performance analysis

IMPROVEMENTS

Miniaturization

First IS design

NEW FPGA FIRMWARE

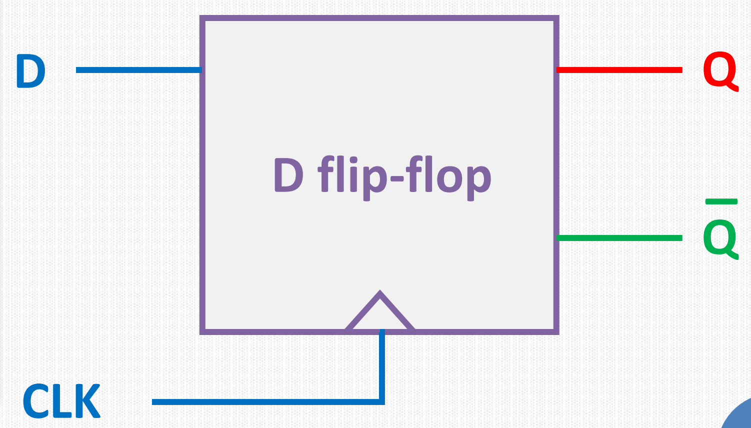
- New components imply new FPGA firmware
  - Flash memory access (restore NN topology)
  - Communication protocol with the computer relying on high speed USB (previously RS232 to USB)

➔Parallel computing on a parallel structure using Verilog programming language

VERILOG HDL

- Used to describe a digital system, a network switch, a microprocessor, a memory or a flip-flop

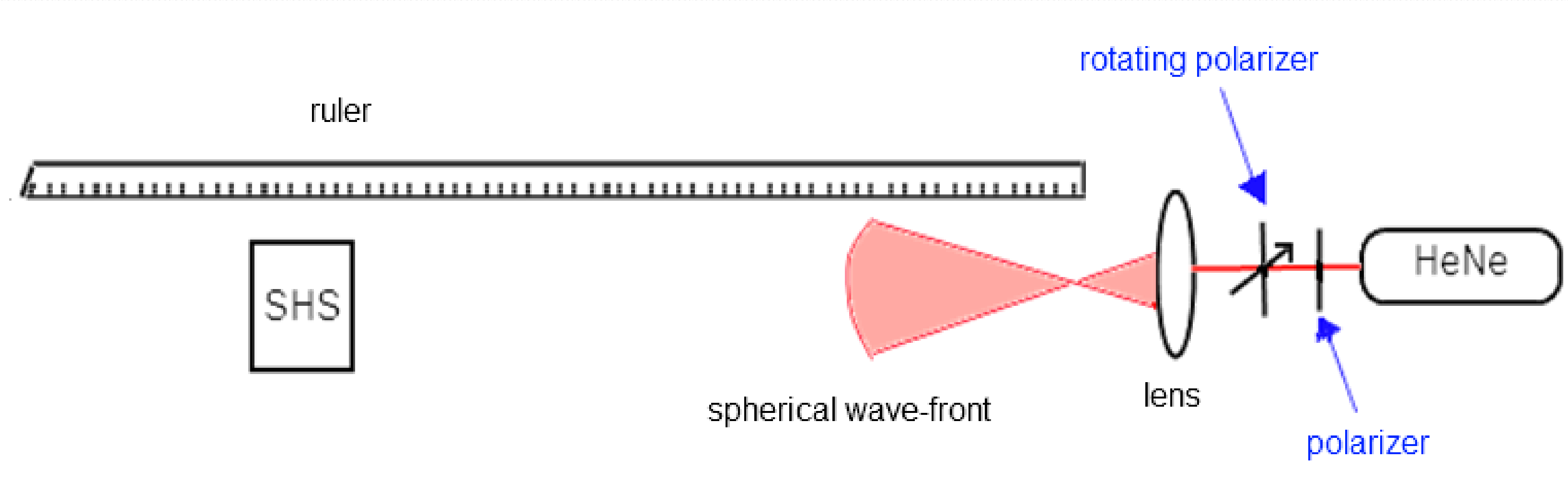
```
module D flip-flop(
    input wire data,
    input wire clk,
    output reg q,
    output reg q_bar
);
    always @(posedge clk) begin
        q <= d;
        q_bar <= !d ;
    end
endmodule
```



VALIDATION AND TESTS

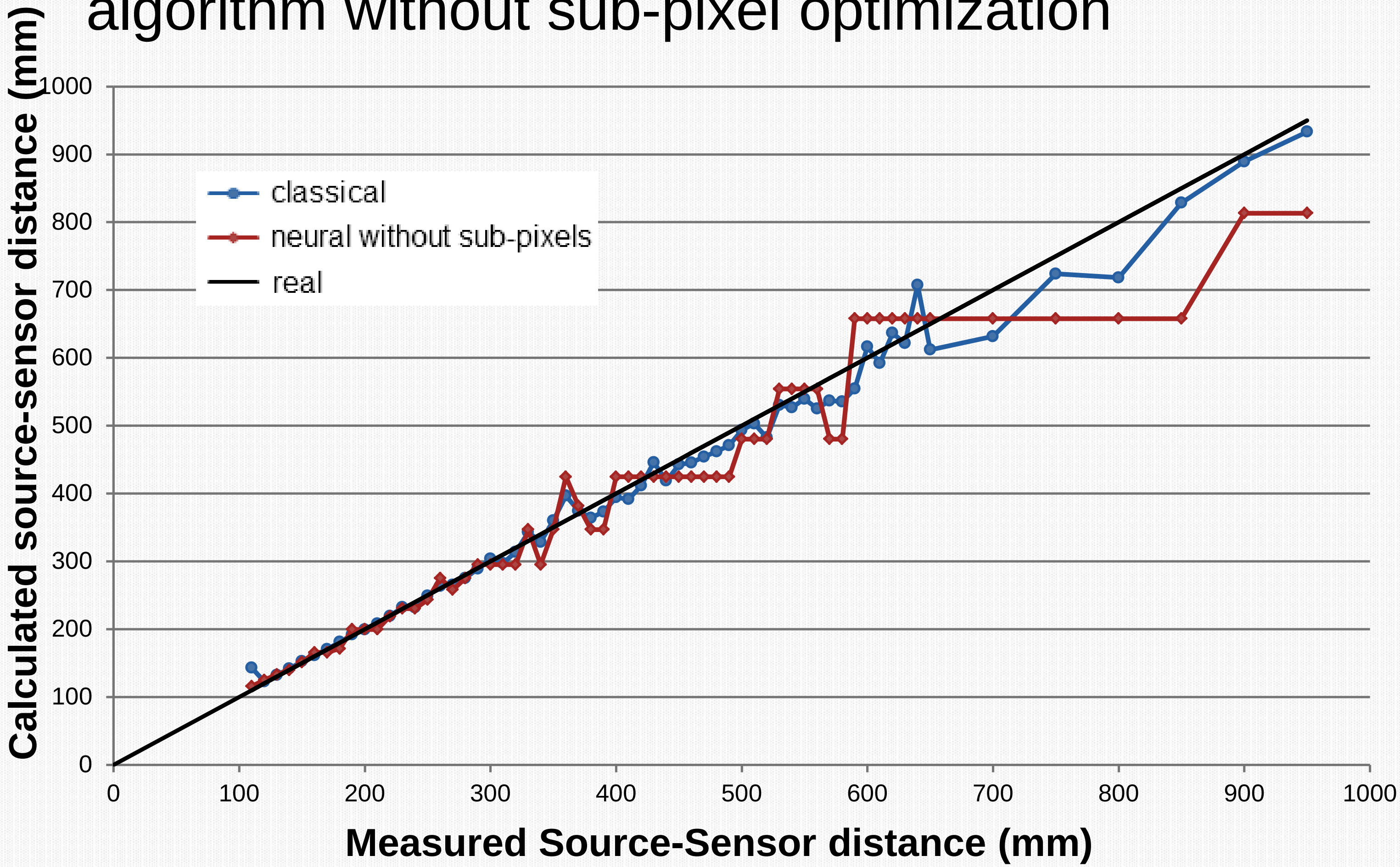
Comparison of focal distances (between a point source and sensor surface) :

- Measured with a ruler
- Calculated from the determined Z^0_2 polynomial from the SHS



VALIDATION AND TESTS

Comparison between classical and neural network algorithm without sub-pixel optimization



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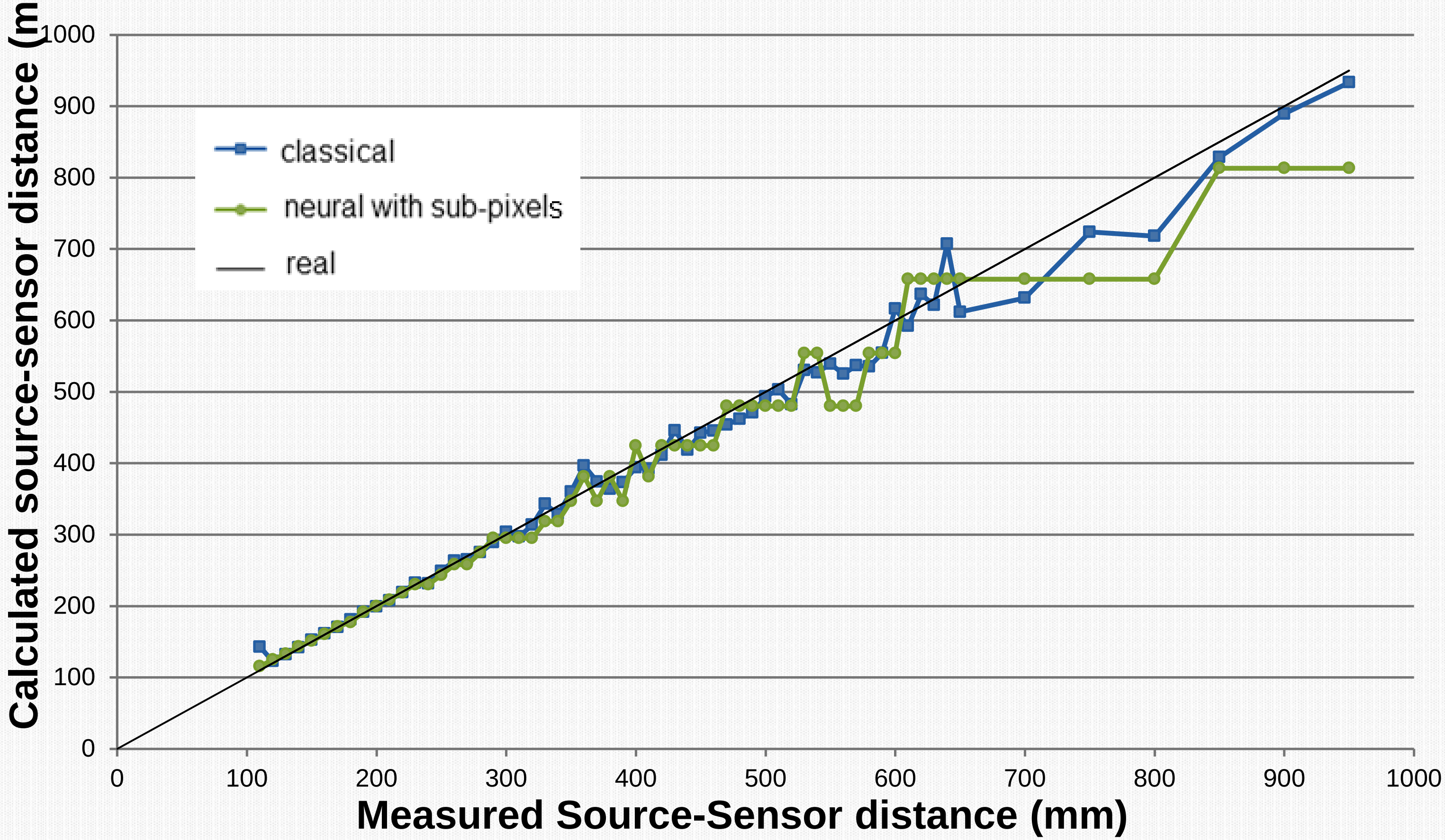
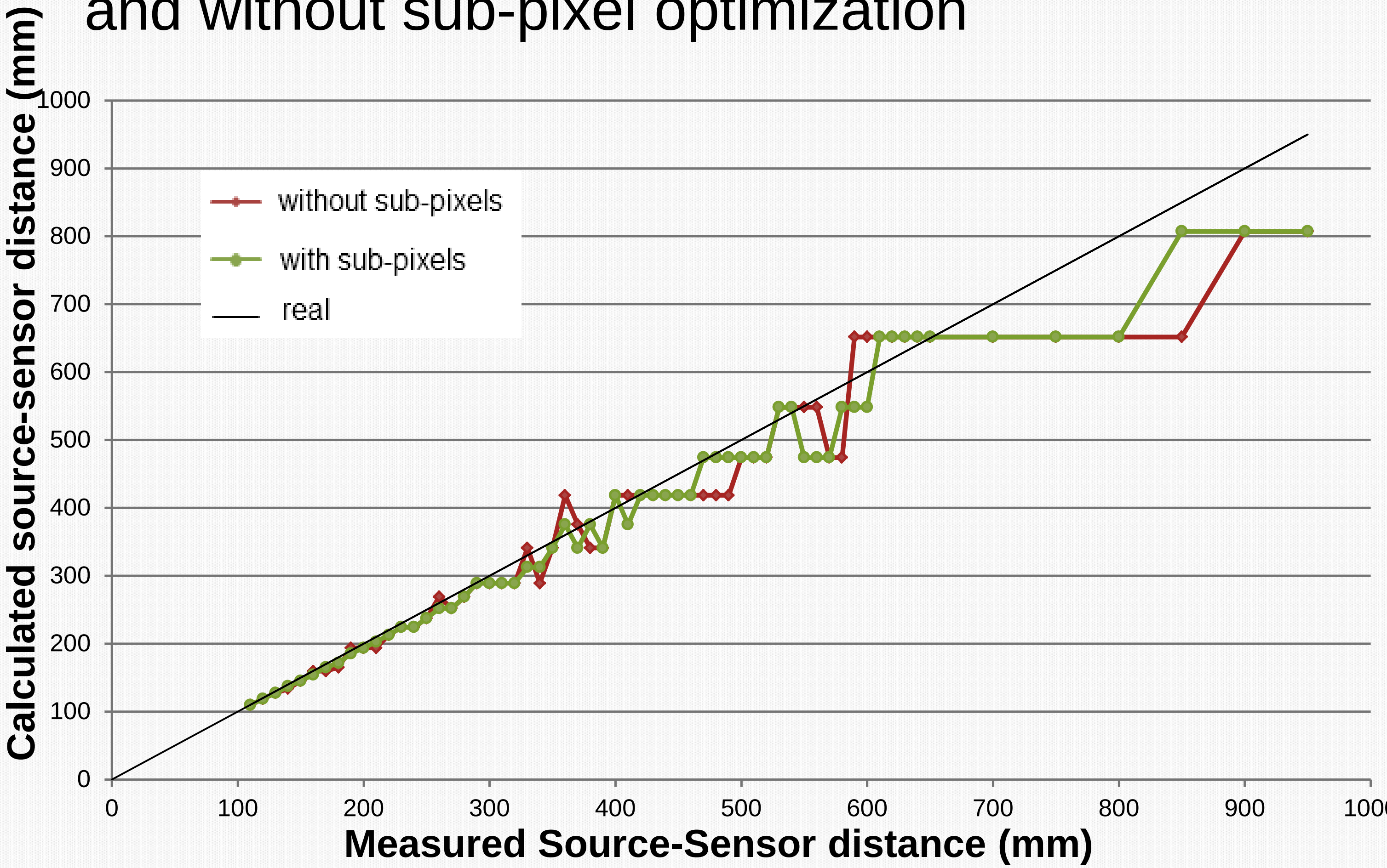


VALIDATION AND TESTS

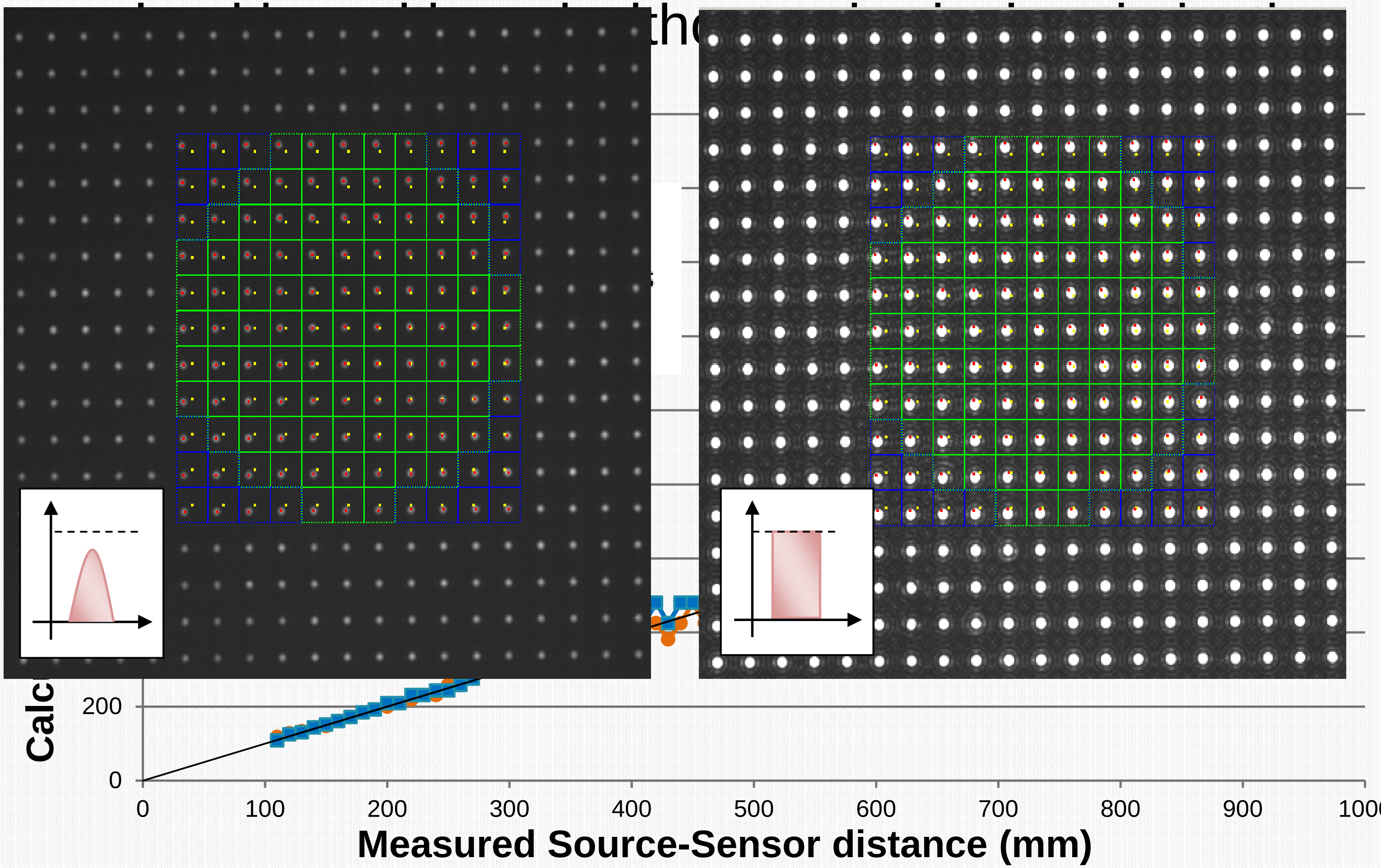
Comparison between neural network algorithm with and without sub-pixel optimization

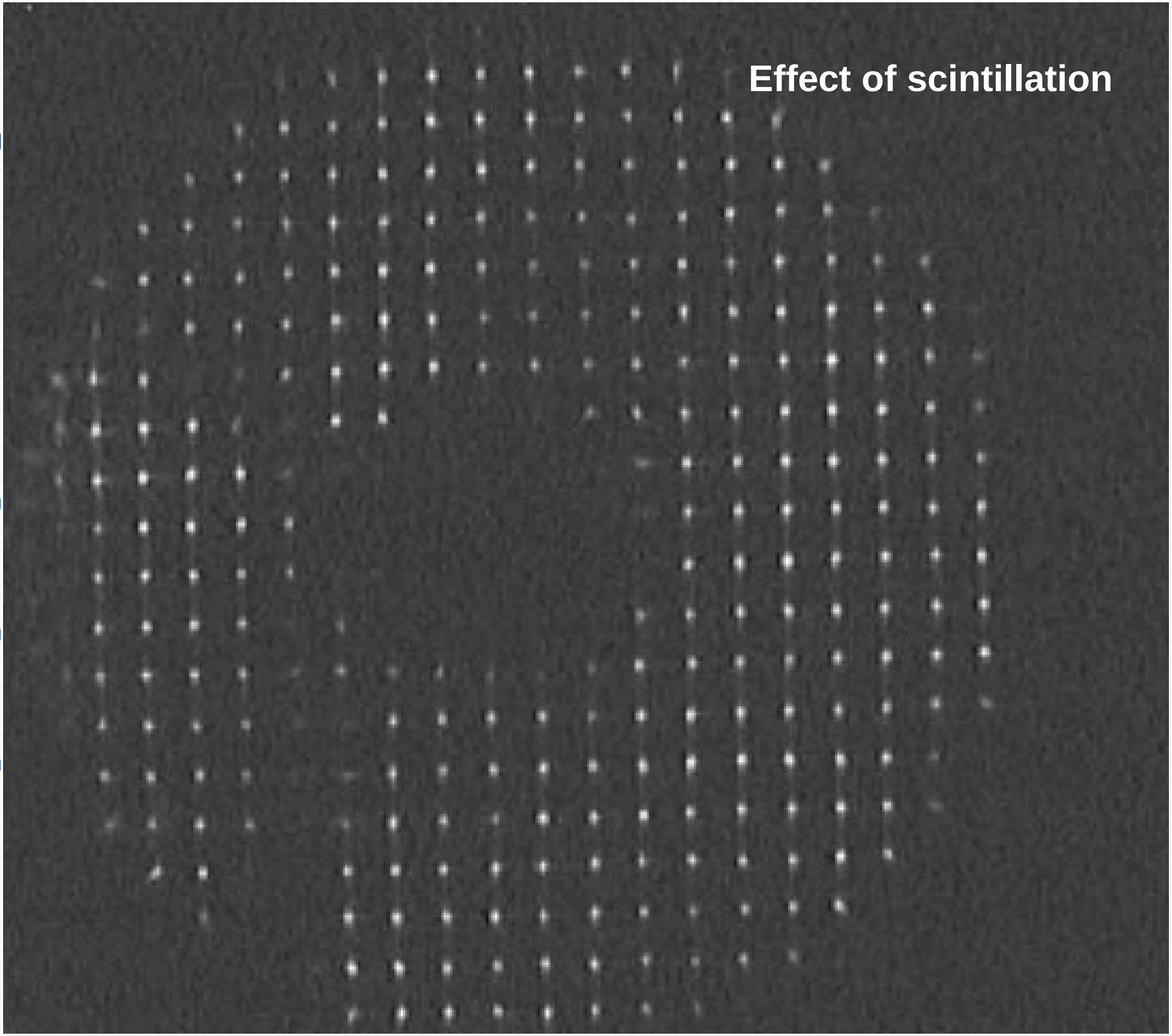


VALIDATION AND TESTS

Influence of saturation

Saturation: comparison between neural network





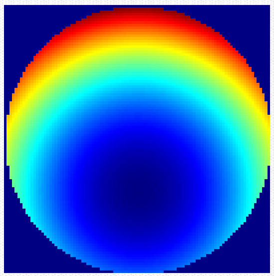
http://www.astrosurf.com/cavadore/optique/shackHartmann/index.html

TEST PROCEDURE

- Image acquisition (C #)
- defect simulation (Matlab)
  - Single cell defect
  - Cluster defect
- Load images with simulated defects (C#)
- Wavefront reconstruction with a neural algorithm simulated on PC (C#)
- Results saved in an Excel file (C#)
  - Zernike polynomials
  - Images of the reconstructed wavefront

EXPERIMENTATION RESULTS

Reconstruction of the wavefront without simulated defects

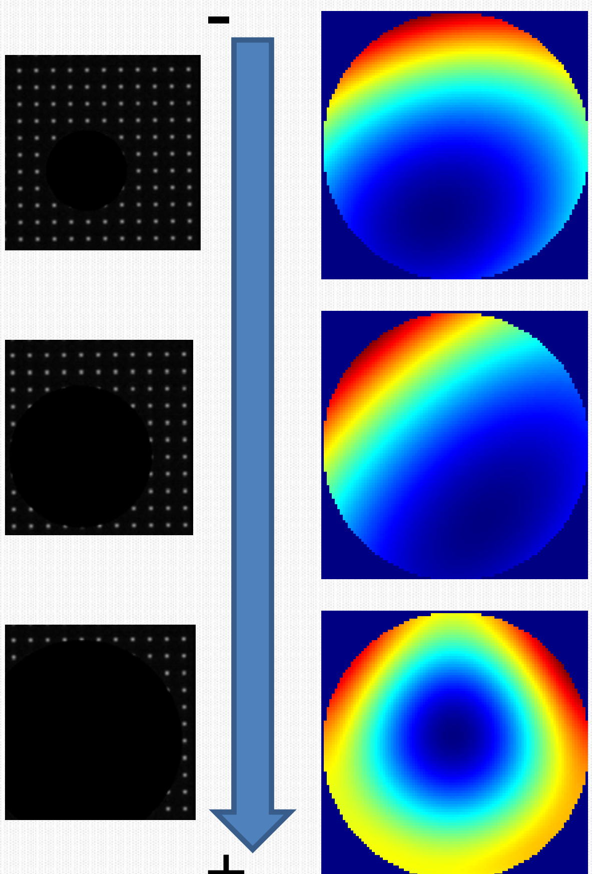


Reference wavefront

(no cell defect)

- Same algorithm
- Only one parameter changed

Reconstruction of the wavefront with simulated defects and varying size



R = 60 pixels

R = 105 pixels

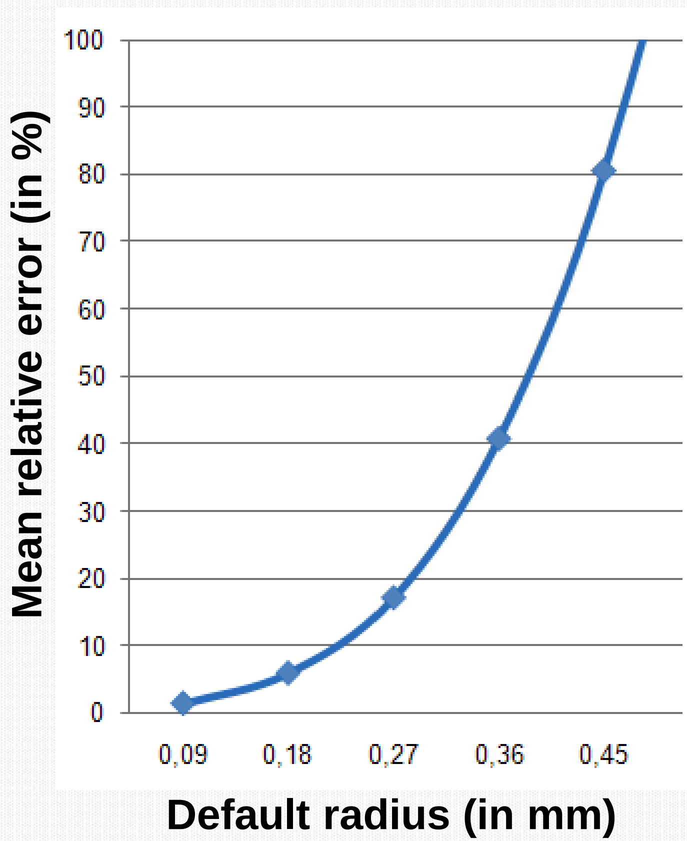
R = 150 pixels

Radius of the defect

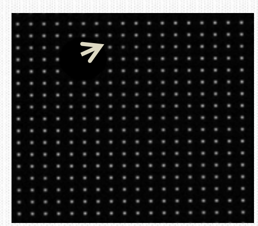
ERROR QUANTIFICATION

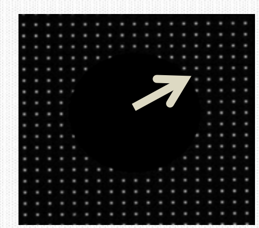
- Influence of the ‘radius’ on the relative error

$$\text{Error } \varepsilon = \frac{\sum (|\text{measured Z. coeff.} - \text{ref. Z. coeff.}|)}{\sum (|\text{ ref. Z. coeff }|)}$$



- Mean relative error < 2% for a single cell defect
- Error increases exponentially with radius





PROJECT CONCLUSION

- The specifications are successfully met
  - Verilog firmware is completed
  - Miniaturized prototype available with LCD display
    - ✓ tested and validated
    - ✓ ready for industrialization
  - Test and validation tools
- Complementary study for DLR achieved
  - One toolbox for defect simulations is available

PROJECT PERSPECTIVES

- Perspectives:
  - Influence of the NN parameters
    - Improvement of NN technology (simulation)
  - Further improvements of FPGA firmware
  - Packaging and advertising flyer
  - IEEE publication

- Multidisciplinary study
  - Specific optics, electronics and programming skills
    - Shack-Hartmann sensors
    - FPGA, memory, USB, NN technologies
    - Real time requirements
  - International team working : ISL, DLR, CEA

Thank you for your attention

Very pleasant team and

exciting subject