On-sky tests of CuReD and HWR (fast wavefront reconstructors) with CANARY

Urban Bitenc
Durham University

Workshop on Real-Time Control for Adaptice Optics, 4th edition
2016 Dec 20

Durham University

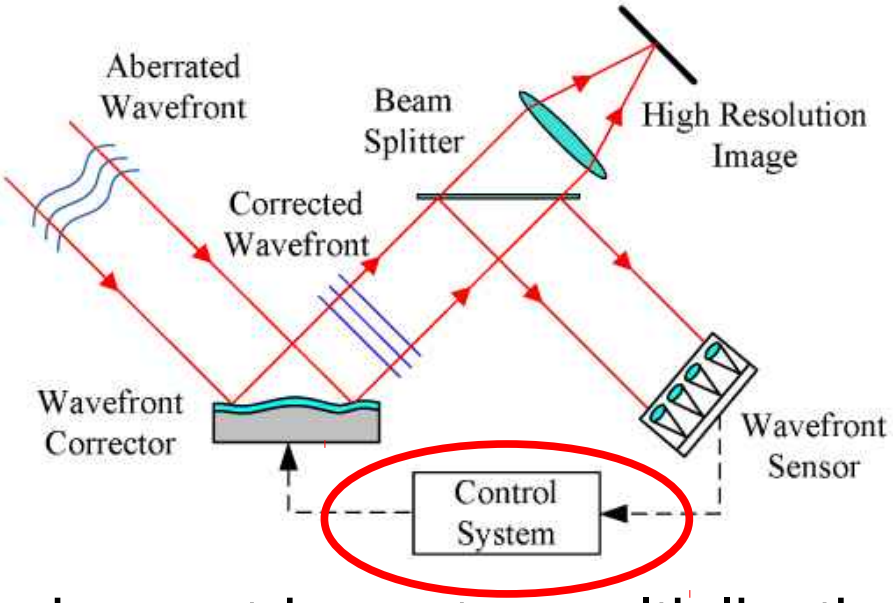
CANARY

Contents

- We're all wasting our time! Just use a *fast* wavefront reconstructor!
- What are CuReD and HWR?
- The missing bit: wavefront-to-actuator mapping
- Test CuReD and HWR:
  - simulation
  - CANARY telescope simulator
  - on-sky with CANARY
- Conclusion

Why fast wavefront reconstructors?

- Astronomy adaptive optics: correction rates of 100 Hz - 2 kHz

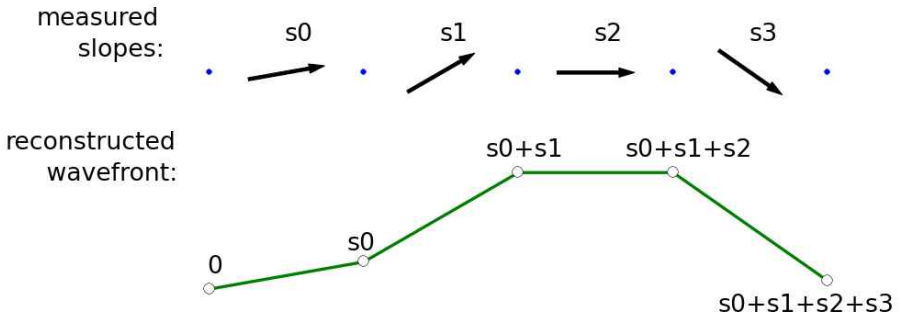


- Control algorithm usually includes **m**atrix-**v**ector **m**ultiplication, MVM:
  - CANARY: 7722 operations in 6.5 ms - easy
  - EPICS (E-ELT): 3.6×10^9 operations in 0.5 ms - no go (even in 2030)
- Way out: a faster algorithm

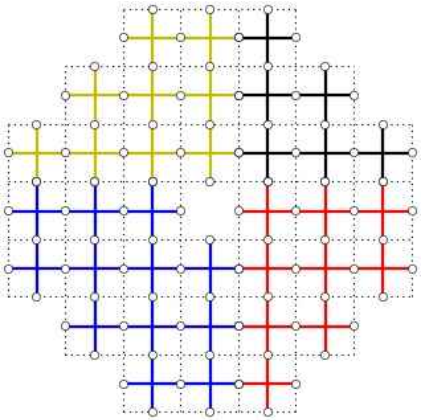
What are CuReD and HWR?

- Algorithms to reconstruct the wavefront from slopes
- **Cu**mulative **Re**construction with **D**omain decomposition: M. Rosensteiner, MathConsult, Austria
- **H**ierarchical **W**avefront **R**econstructor: N.A. Bharmal (+UB)
- Output: wavefront values at subaperture corners
- *Much* faster than MVM (1000x), but *new*: need to be tested

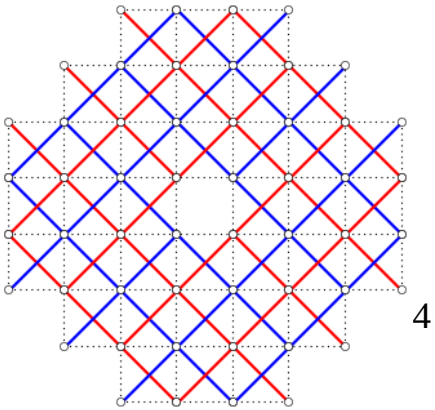
The basic idea:
sum up slopes to get the wavefront



CuReD:
sum up x-y slopes



HWR:
sum up diagonal slopes



CuReD is fast.
Very fast!
But here I won't discuss this.

The point of this talk:
CuReD works.
On-sky!

Wavefront-to-actuator mapping

THE MISSING BIT - NEEDED TO BE DEVELOPED FOR CANARY

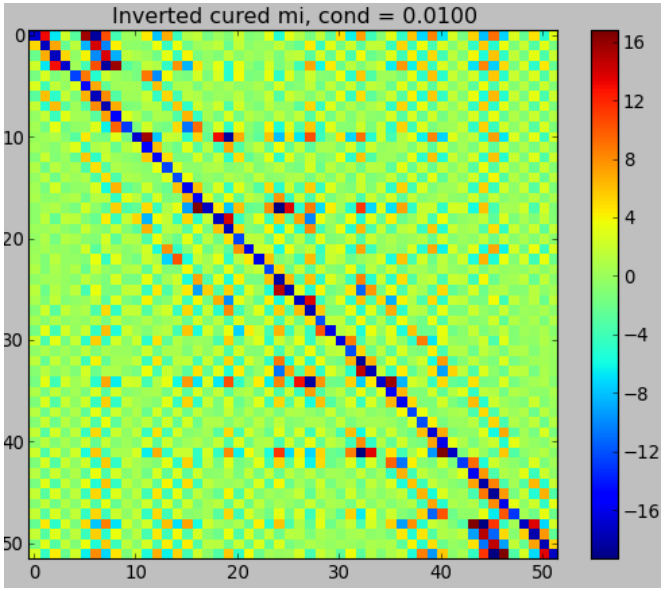
	input	output
MVM	slopes	DM commands
CuReD, HWR	slopes	wavefront values

But you need DM commands!

- Investigated three options:
  - **Full mapping:** easy to implement, slow, theoretically best quality
  - **Identity mapping:** easy to implement, fast; good enough?
  - **Interpolation mapping:** pain to implement, fast, good

Full mapping

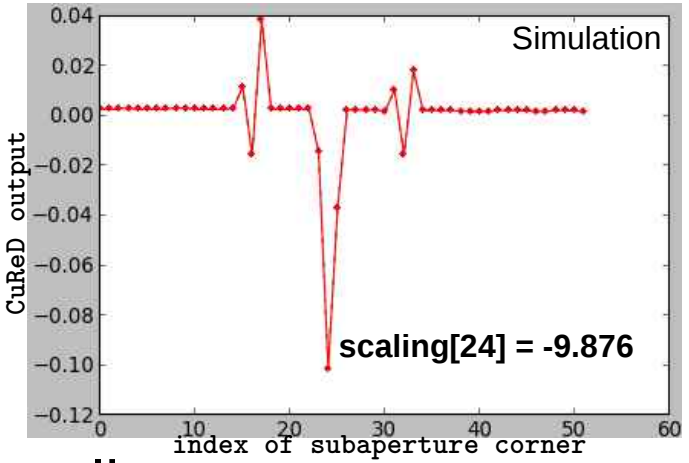
- Mapping matrix = inverted cured (or hwr-ed) poke matrix
- actuator commands = mapping matrix .dot. CuReD/HWR output
- Advantages:
  - Takes care of everything: scaling, misalignment, partially illuminated subaps, inter-actuator coupling, CuReD/HWR response function etc.
  - Straightforward to implement
- Disadvantages:
  - SLOW (MVM-like) - show stopper
  - need to optimize the conditioning.



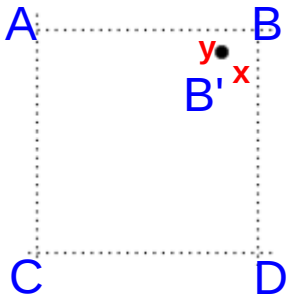
Identity mapping

- Just scale the CuReD/HWR output and put it directly on the DM
- scaling = 1./(max of CuReD/HWR response to a poke)
- actuator commands = scaling * CuReD/HWR output
- Advantages:
  - Simplest and fastest
  - Straightforward to implement
- Disadvantages:
  - Not accounting for anything except scaling

    (is this really good enough??)



Interpolation mapping

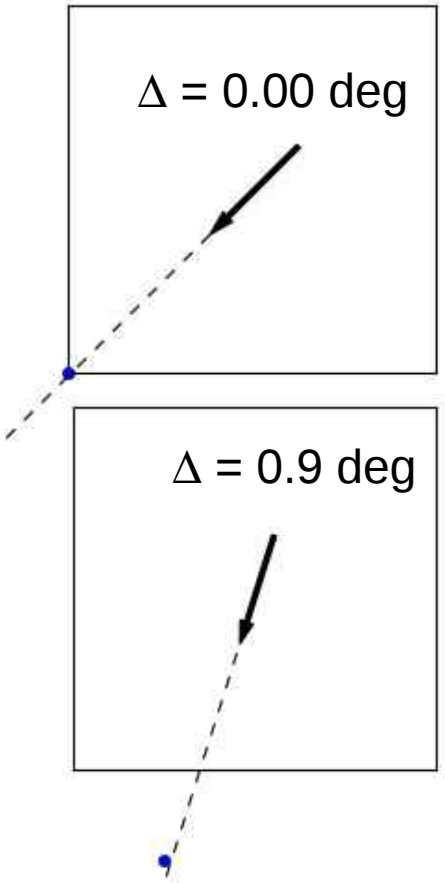


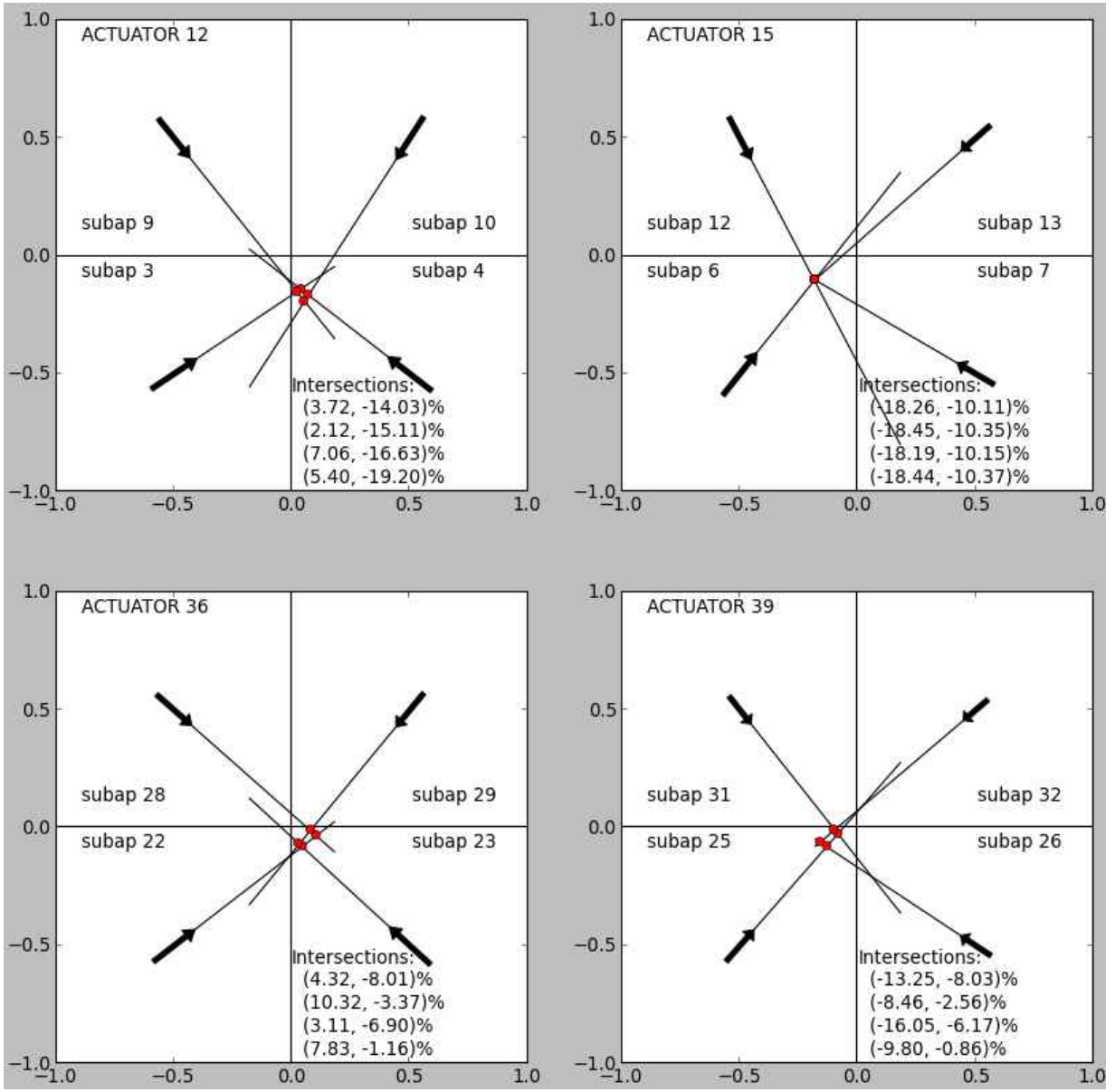
B' = (1-x)(1-y)*B +
x*A +
y*D +
x*y*C

- Bi-linear interpolation:
- Accounts for
  - misalignment between DM and SH lenslet array
  - scaling to actuators
- Advantages:
  - Still fast
  - Accounting for misalignment --> accurate enough??
- Disadvantages:
  - Need to measure the misalignment
  - A bit more work to implement...

How to measure the actuator positions

- Poke an actuator: the gradients point towards the actuator

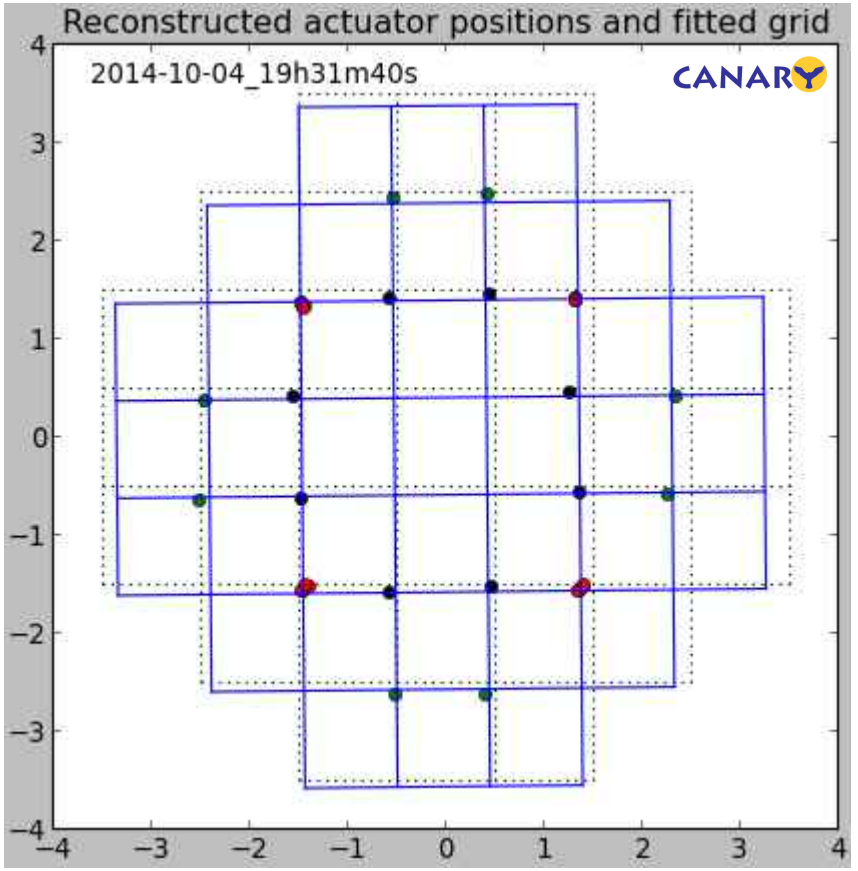




Fit a grid to the measured positions

Fitted parameters:
shift x = -6.65 %
shift y = -8.91 %
rotation = 0.57 deg
zoom x = -5.66 %
zoom y = -0.86 %

Fit quality:
average residual = 5.2 %
max residual = 10.5 %
min residual = 0.8 %



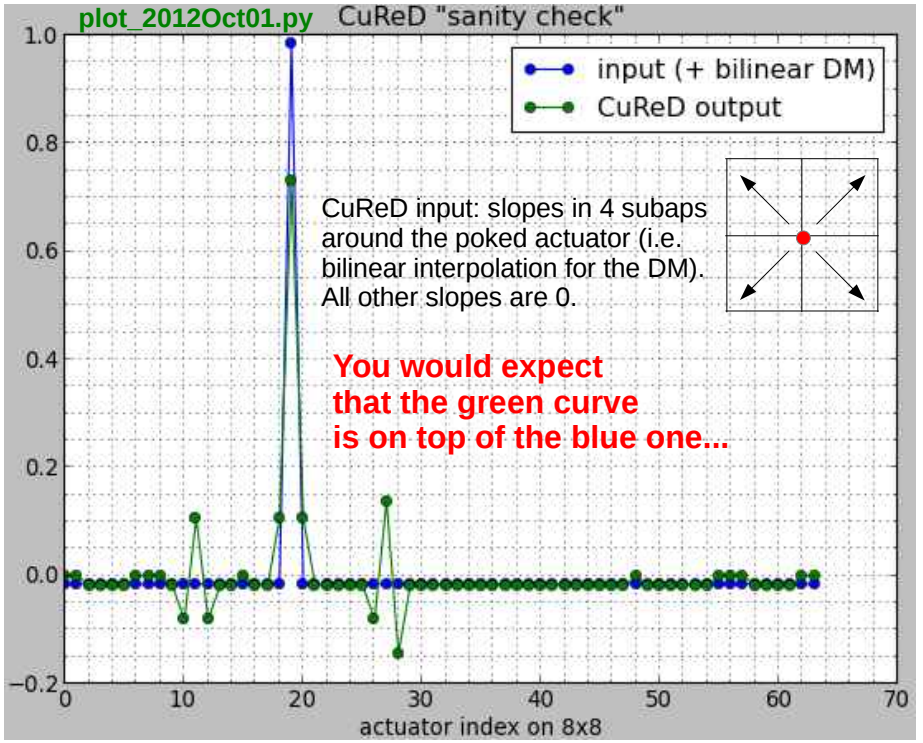
Fitted grid displacement	July 2014 (for HWR)	Oct 2014 (for CuReD)
largest	22 %	28 %
average	9 %	15 %

Test CuReD and HWR

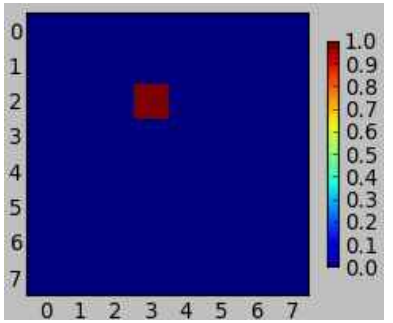
- **SIMULATION:** real-time simulation: DARC-DASP hybrid (thanks, Alastair)
- **CANARY**: MOAO path finder, used in SCAO mode
  - telescope simulator
  - on-sky

- Test the mapping methods
- Do CuReD and HWR work?
- Which gives a better Strehl?
- Do they work *on-sky*?

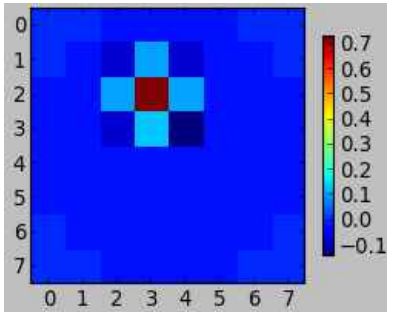
CuReD smoothing effect



Poked actuator:



CuReD reconstruction:

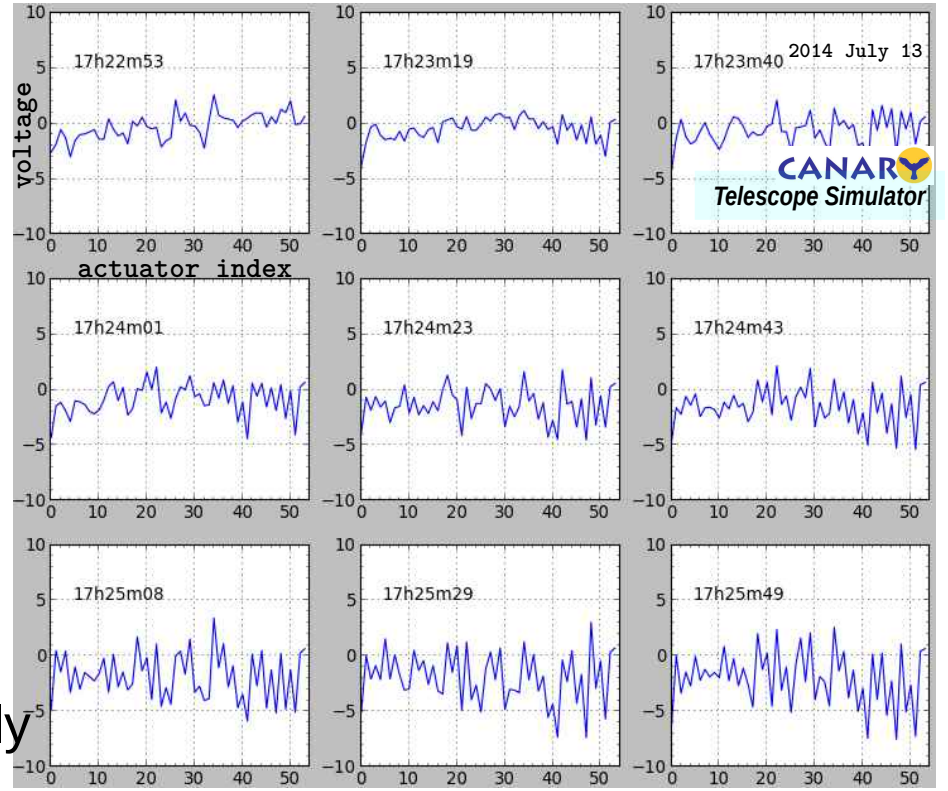


Exactly the same data, once in 1-D, once in 2-D

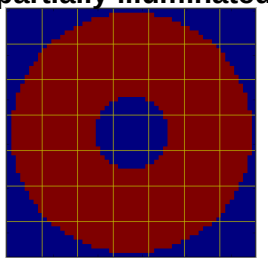
- A very distinctive property of CuReD: smoothing
- HWR does not have this problem - provides a more accurate wavefront!

CuReD instability

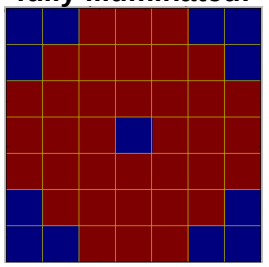
- **CuReD**: sometimes the loop becomes unstable in a few minutes
- Reproduced with DARC-DASP
  - Full mapping: stable
  - Identity/Interpolation mapping:
    - stable if all subapertures are fully illuminated AND bilinear interpolation for the DM
    - partially illum. subaps: unstable
    - for gaussian and bi-cubic DM unstable also with full illumination
    - lower gain --> takes longer to become unstable
- Originally not found by the authors of CuReD but confirmed with my settings



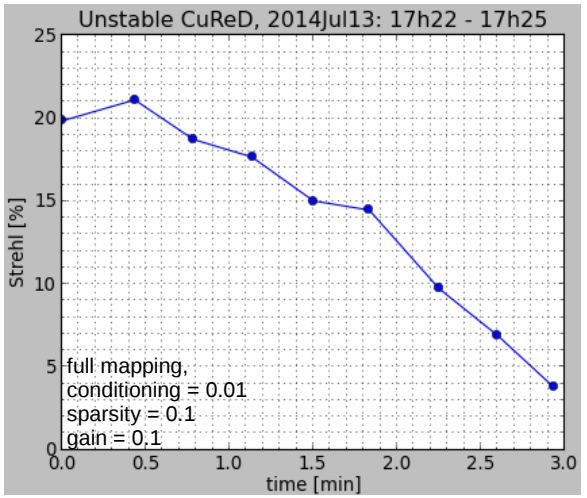
partially illuminated:



fully illuminated:



$v_{i+1} = v_i + gain*\Delta v$

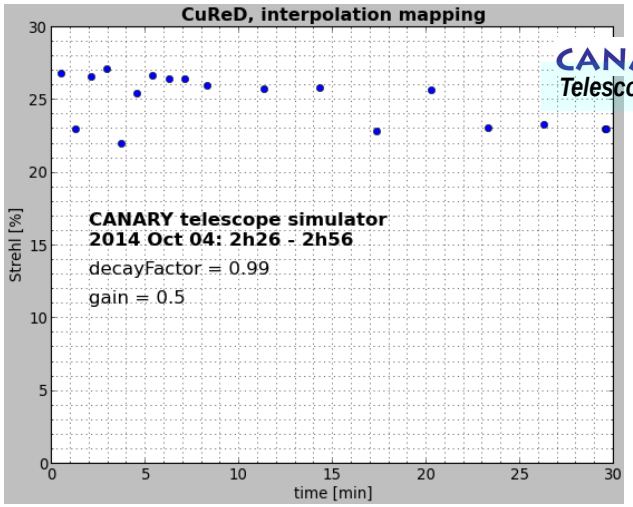


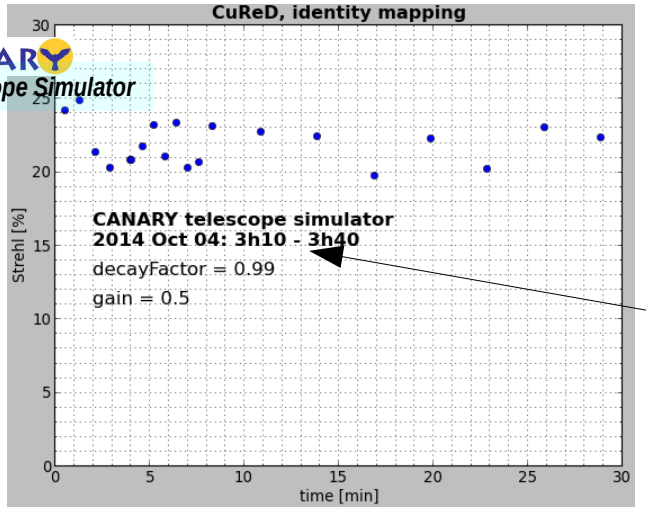
CuReD instability

- With DARC-DASP found a solution: **leaky integrator**

$$v_{i+1} = \text{decayFactor} * v_i + \text{gain} * \Delta v$$

  - `decayFactor = 1.0` --> unstable
  - `decayFactor = 0.99` --> stable for over an hour
- Tested on CANARY: stable for over half an hour





CANARY Telescope Simulator

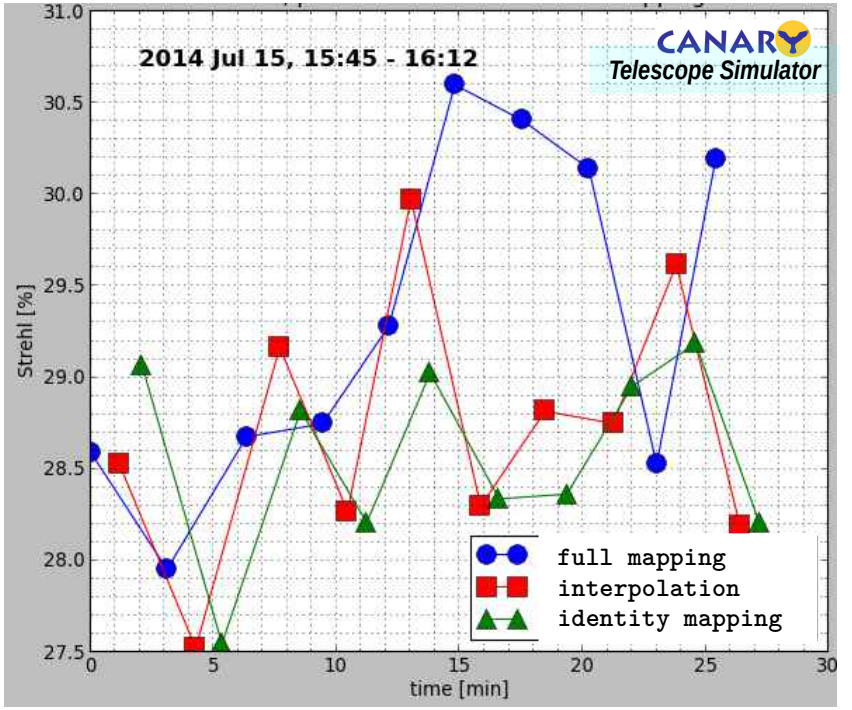
Thanks to Ali Bharmal for taking these measurements at this inhumane hour (AM!!)

- HWR does NOT have this problem - works with any mapping

Testing mapping methods: HWR

Simulation:

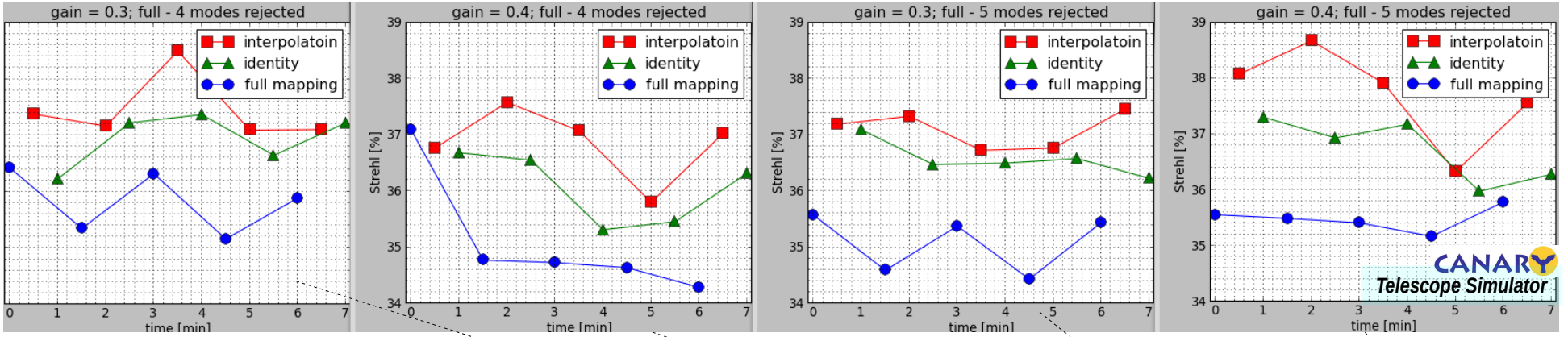
Strehl [%]	linear	gaussian	pspline
identity	25.5	24.7	28.6
full map.	25.6	24.7	28.6



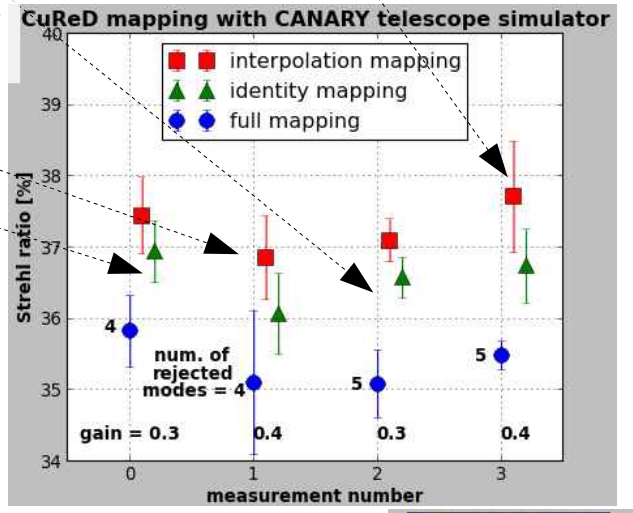

```
CANARY telescope simulator:
full mapping      : 29.3 ± 0.3 %
interpolation     : 28.7 ± 0.2 %
identity mapping  : 28.6 ± 0.2 %
```

- Simulation agrees with CANARY
- All three similar Strehl (*maybe* full mapping slightly better)
  - --> robustness of HWR! (actuator displacement from the subap grid: 22% max, 9% average)

Testing mapping methods: CuReD



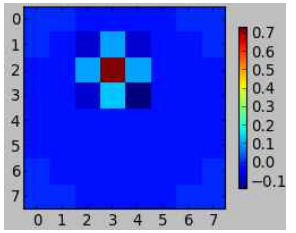
Data taken by
Ali Bharmal



Simulation:

Strehl [%]	linear	gauss	pspline
identity	28.1	27.5	32.7
full map.	27.4	26.9	31.1

- Simulation and CANARY agree
- SURPRISE: Identity and Interpolation clearly better than full mapping!
  - reason: full mapping “un-does” the CuReD smoothing



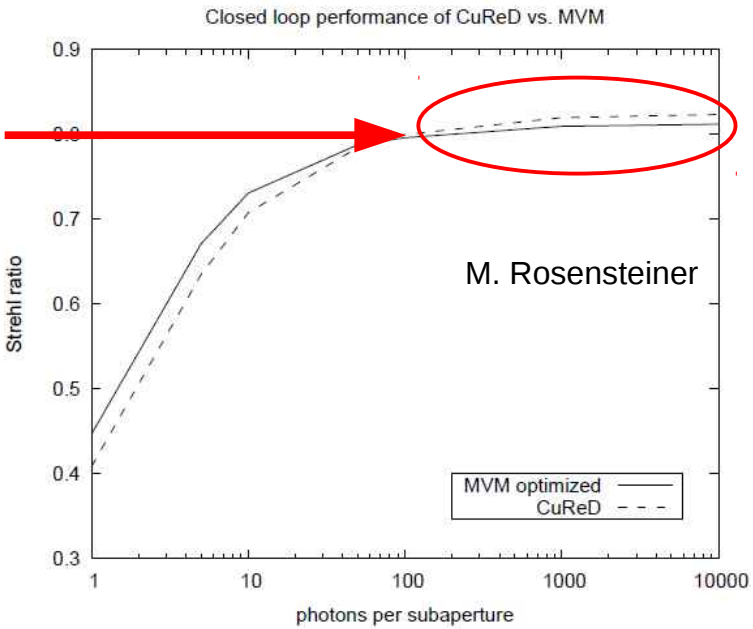
Performance comparison: simulation

Strehl [%]	CuReD	LSE	HWR
r0 = 20 cm	31.3	29.7	28.0
spatial filter	33.7	31.7	30.0
r0 = 60 cm	82.7	81.9	81.2

- Identity mapping used for CuReD and HWR,
- pspline DM (same conclusion for linear and gaussian)

- SURPRISE: CuReD **>** LSE **>** HWR
- Seen also by the author of CuReD:
  - it seems he was a bit confused about that result:

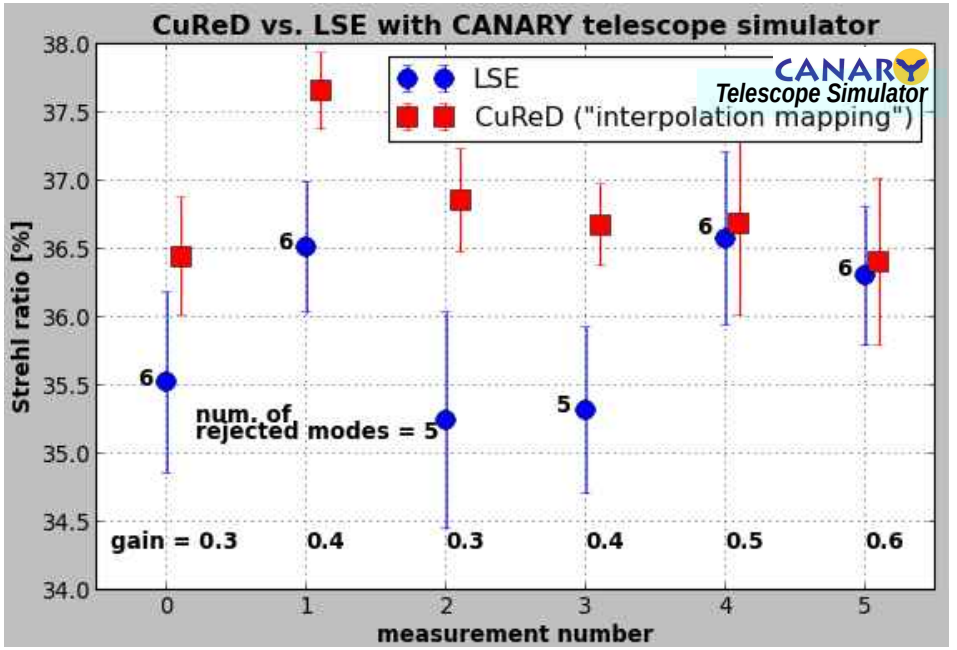
    "We are aware that MAP reconstructor, if optimally tuned, cannot be outperformed."



LSE vs. CuReD (interpolation mapping)

Simulation:

Strehl [%]	linear	gauss	pspline
CuReD	28.1	27.5	32.7
LSE	26.5	26.1	30.4



- **CANARY and simulation agree:**

  CuReD >= LSE

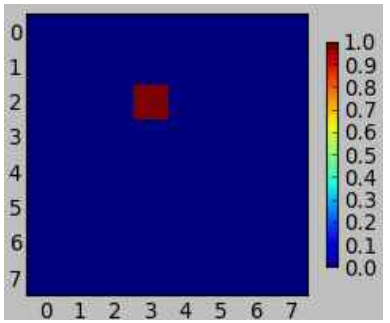
Why is CuReD better than LSE?

- Simulation and CANARY:

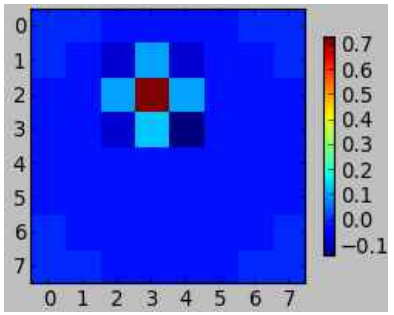
  CuReD (interpolation map.) gives higher Strehl than LSE

- UNEXPECTED!! How can this be?

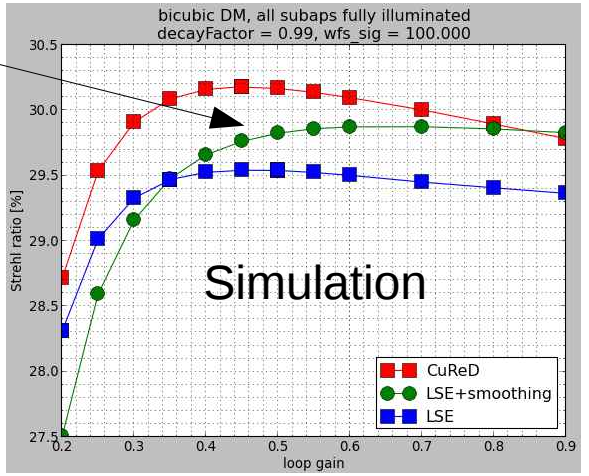
Poked actuator:



CuReD reconstruction:



- Smoothing improves Strehl:
  - Un-smoothened CuReD (full mapping) --> lower Strehl
  - Smoothened LSE --> higher Strehl:

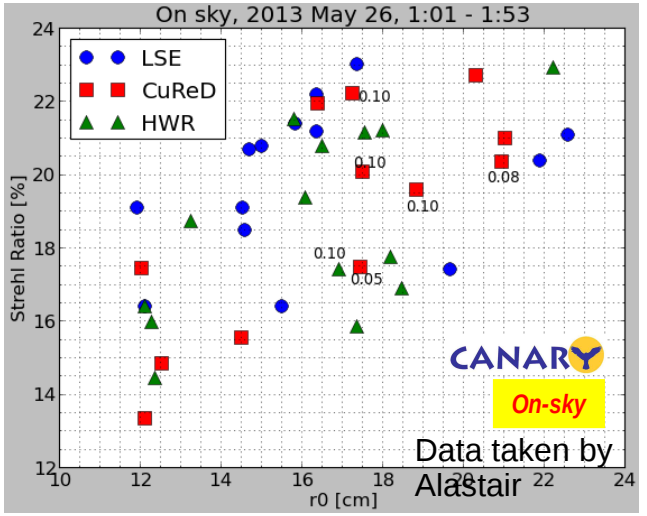


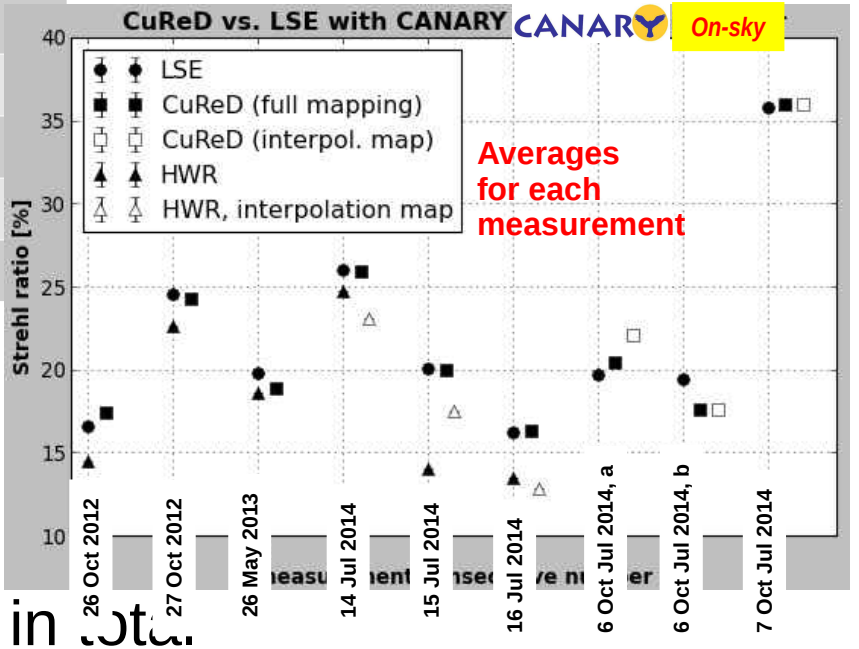
On-sky

Strehl [%] **errors: 0.5%-1.5%**	LSE	CuReD full map	CuReD interp. m.	HWR full map.	HWR interp. m.
26 Oct 2012,a	16.6	17.4	-	14.5*	-
27 Oct 2012,b	24.5	24.3	-	22.6*	-
26 May 2013	19.8	18.9**		18.6	-
14 July 2014	26.0	25.9		24.7	23.1
15 July 2014	20.1	20.0	-	14.0	17.5
16 July 2014	16.2	16.3	-	13.5	12.8
6 Oct 2014, a	19.7	20.4	22.1	-	-
6 Oct 2014, b	19.4	17.6	17.6	-	-
7 Oct 2014	35.8	36.0	36.0	-	-

Averages for each measurement

* ... bug in offloading tip-tilt, possibly affects performance
** ... includes sparse matrix, result possibly affected by instability





- 7 nights, over 5 hours of on-sky time in total.
- CuReD and HWR work stably (30-60 sec. measurements)
- Strehl: CuReD and LSE similar, HWR slightly worse.

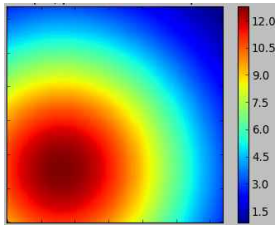
Conclusions

- **Interpolation mapping developed**
  - achieves best result for CuReD
- **CuReD and HWR tested:**
  - simulation and CANARY results agree very well
  - CuReD stable (only) with leaky integrator
  - on-sky: CuReD and HWR both work
  - Unexpectedly, CuReD better than LSE
    - Reason: smoothing
  - HWR slightly worse than LSE
  - Very robust, insensitive to misalignment
- MNRAS 448 (2), 1199-1205 (2015)

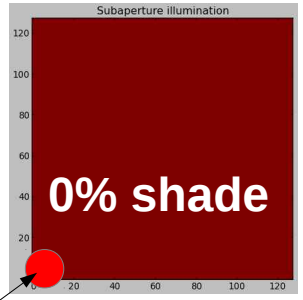
Should we not seriously think about using CuReD as an alternative to LSE?

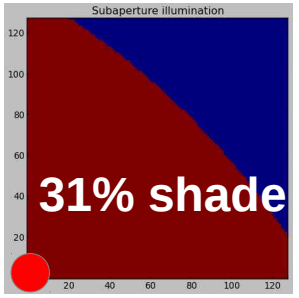
How about non-fully iluminated subaps?

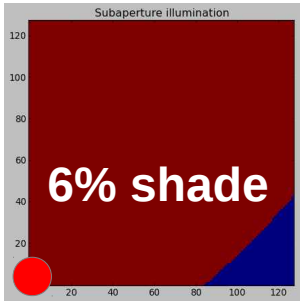
Gaussian
DM response,
width = 0.64:

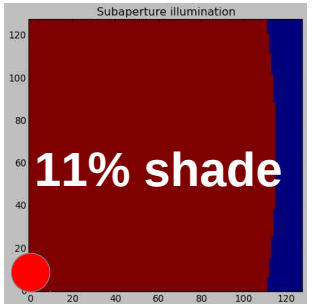


Subaperture illumination

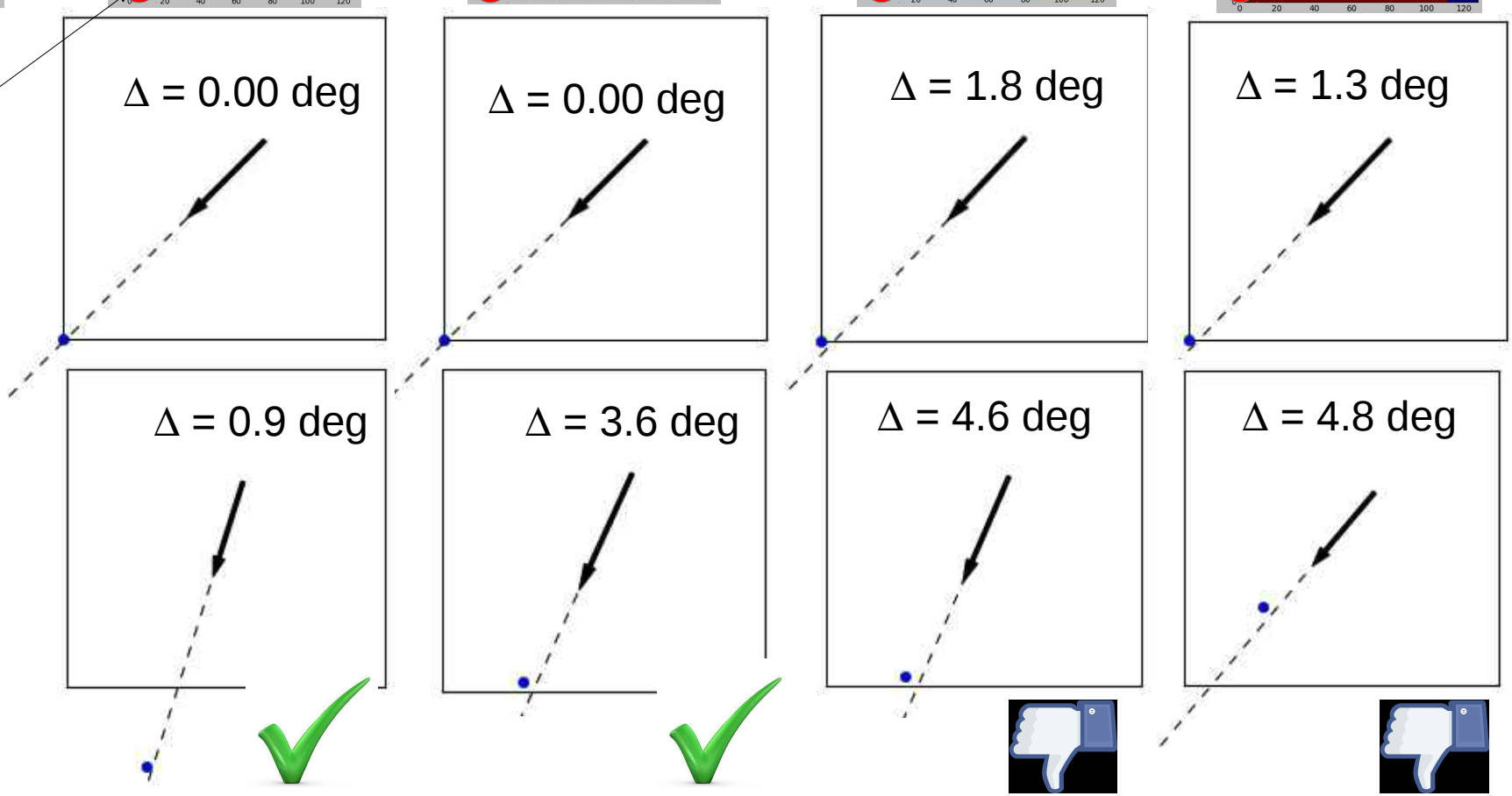






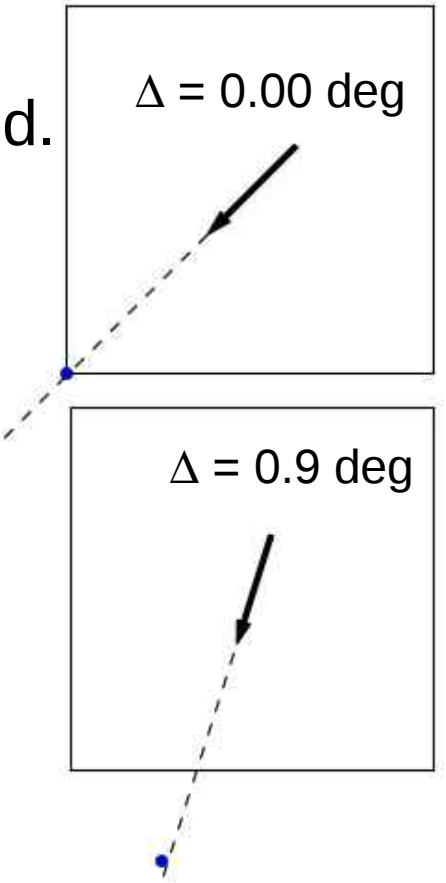


poked
actuator

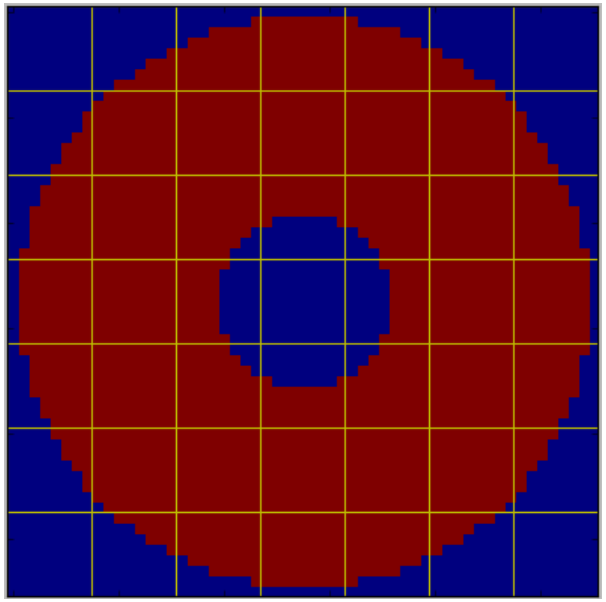


How to measure the actuator positions

- Poke an actuator:
  - --> the gradients point towards the actuator
  - ... as long as the subaperture is fully illuminated.

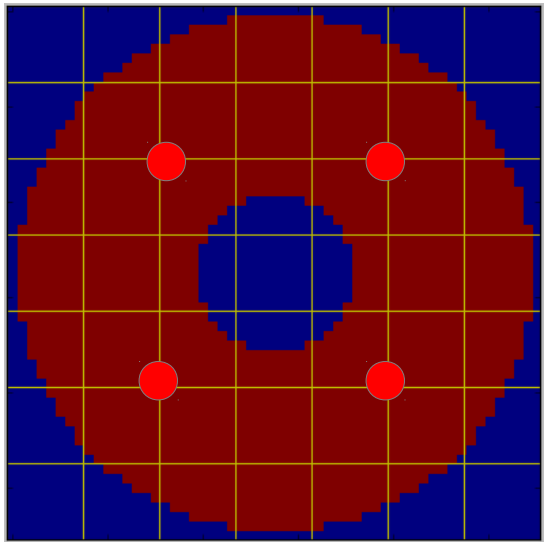


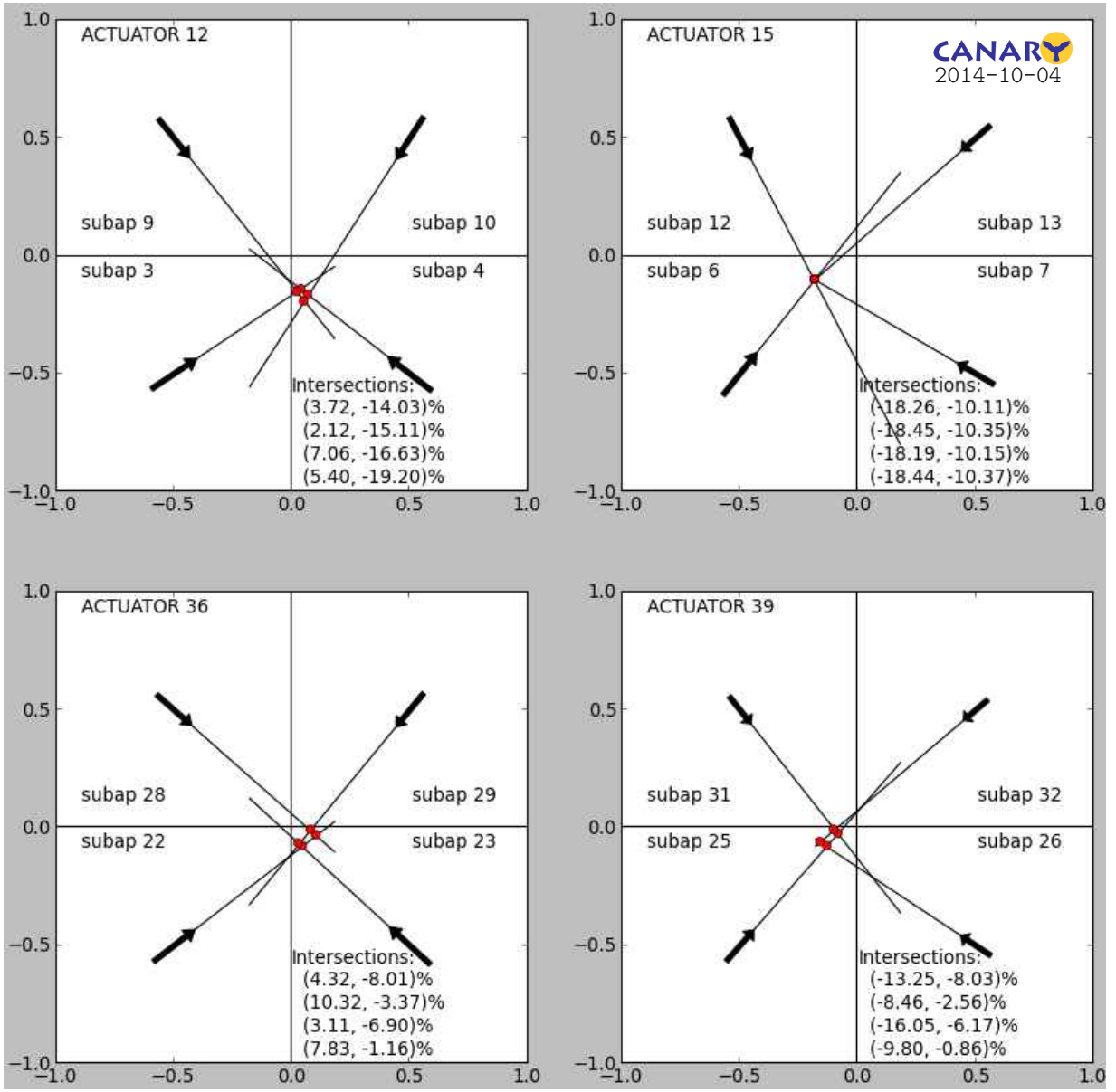
Subaperture illumination on CANARY:
9 out of 36 subaps are fully illuminated



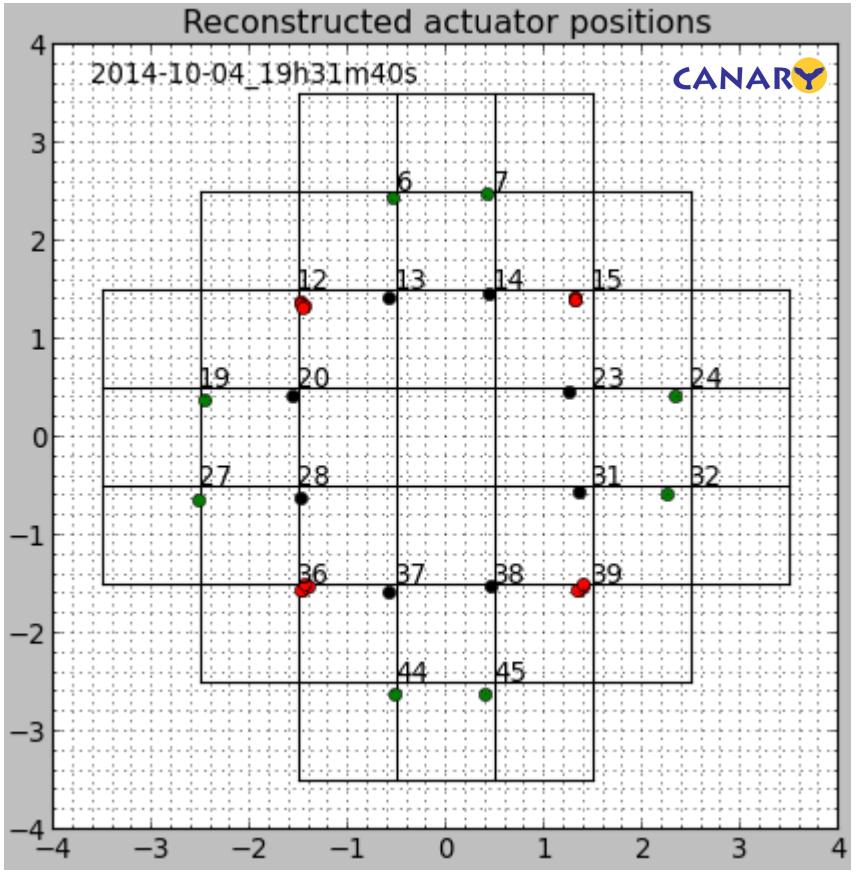
Actuator positions: intersections of gradients

- Four actuators with all four subaps
- Precision: 5% of subap side





20 actuators with measured positions



Offload tip-tilt

- CANARY: DM + TipTilt mirror
  - --> put Tip&Tilt on the TT, the rest on the DM
- Full mapping: just happens automatically
- Identity and Interpolation mapping:
  - fit a plane to the wavefront and subtract it
  - Not sure this is the optimal thing to do but was easiest to implement.

$$k_x = \frac{\Sigma w_i x_i}{\Sigma x_i^2}, k_y = \frac{\Sigma w_i y_i}{\Sigma y_i^2}$$

Summary -
DM commands from CuReD/HWR output

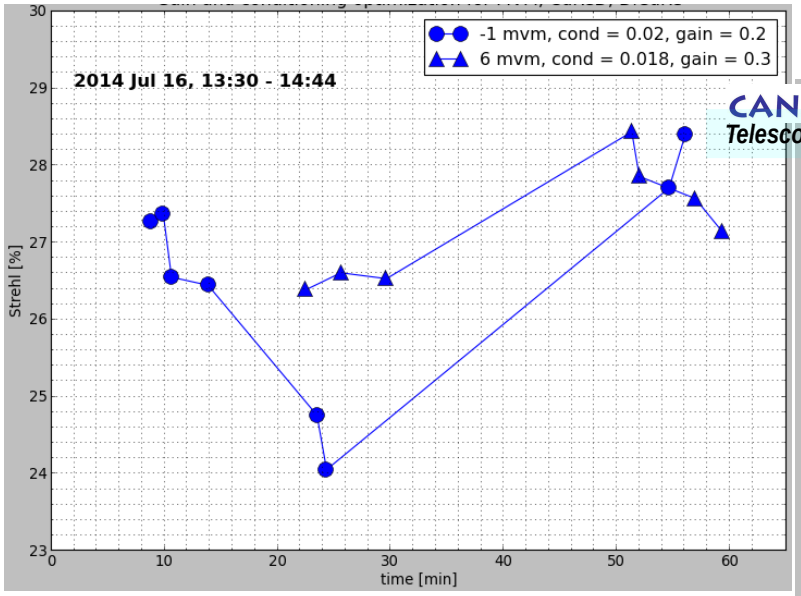
- **Full mapping:**
  - multiply with the mapping matrix
- **Identity mapping:**
  - offload tip-tilt
  - apply scaling
- **Interpolation mapping:**
  - interpolate
  - offload tip-tilt
  - apply scaling

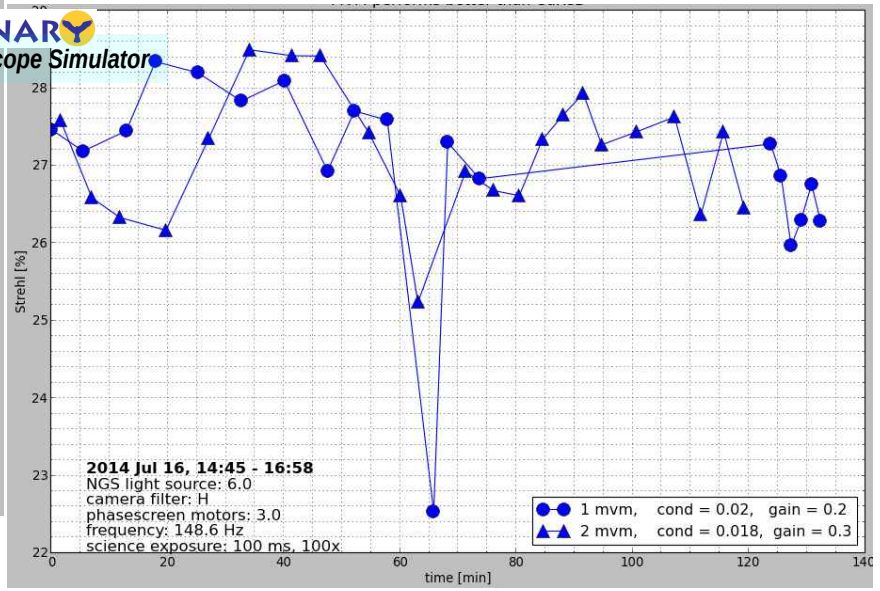
Testing mapping - conclusions

- Identity mapping is good enough
- Interpolation mapping slightly improves Strehl for CuReD
- **Full mapping is not needed**
- HWR: robust - not sensitive to mapping method
- CuReD:
  - **Full mapping** performs **worse** than identity or interpolation because is un-does the smoothing

Note on performance comparison

- Compare reconstructors at their optimal performance:
  - optimize the loop gain [0.2, 0.3, 0.4, 0.5, 0.6, 0.7]
  - optimize the conditioning - reject [1, 2, ... , 6, 7] modes
- A complex endeavour:
  - easy in simulation
  - hard with CANARY as it changes all the time:





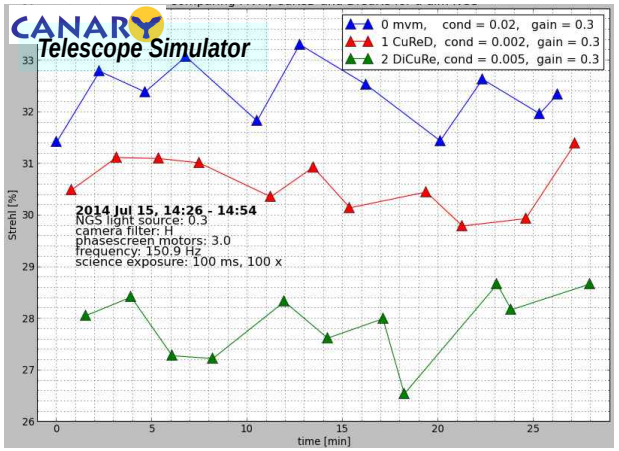
PERFORMANCE COMPARISONS

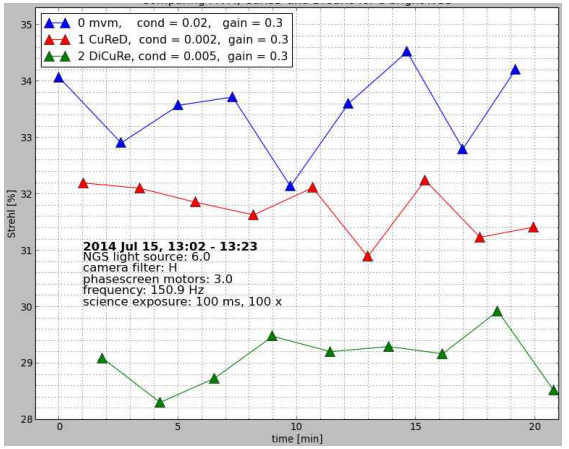
- Figure of merit: Least Square Estimator (LSE)
- **Least Square Estimator - LSE:**
  - pseudo-invert system interaction matrix (aka poke matrix)
    - use Singular Value Decomposition
    - reject a few modes (how many??)
    - --> command matrix
  - MVM of the slopes vector with the command matrix

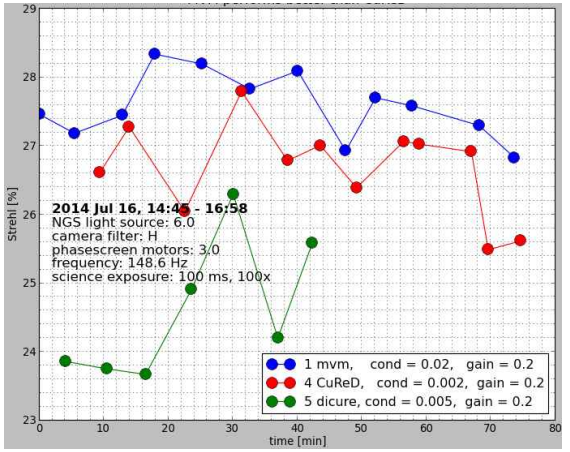
LSE vs. CuReD vs. HWR (full mapping)

Simulation:

Strehl [%]	linear	gauss	pspline
CuReD	27.4	26.9	31.1
LSE	26.5	26.1	30.4
HWR	25.6	24.7	28.6







- HWR lower than CuReD and LSE
- Disagreement between CANARY and simulation:
  - simulation: CuReD > LSE
  - CANARY: LSE > CuReD