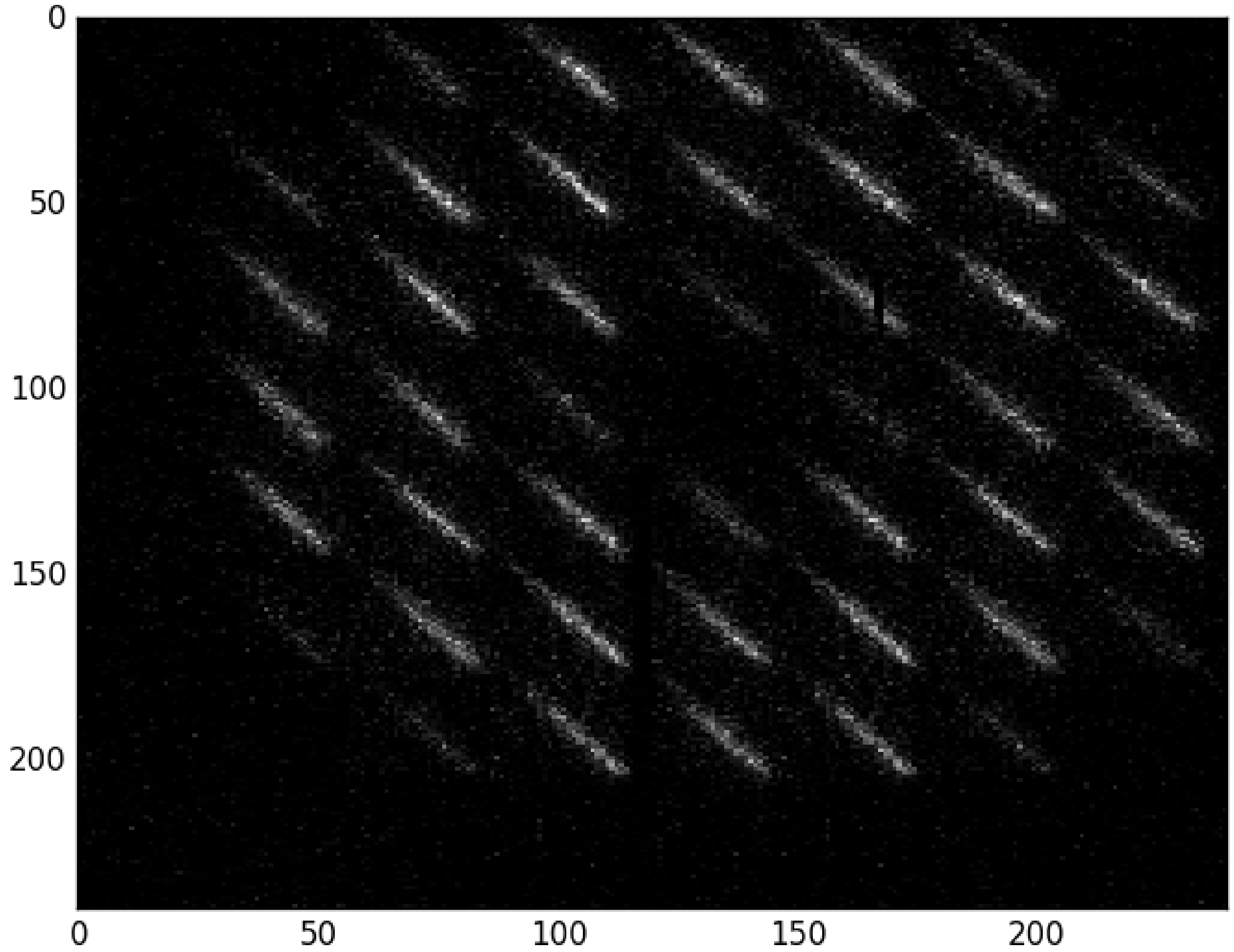
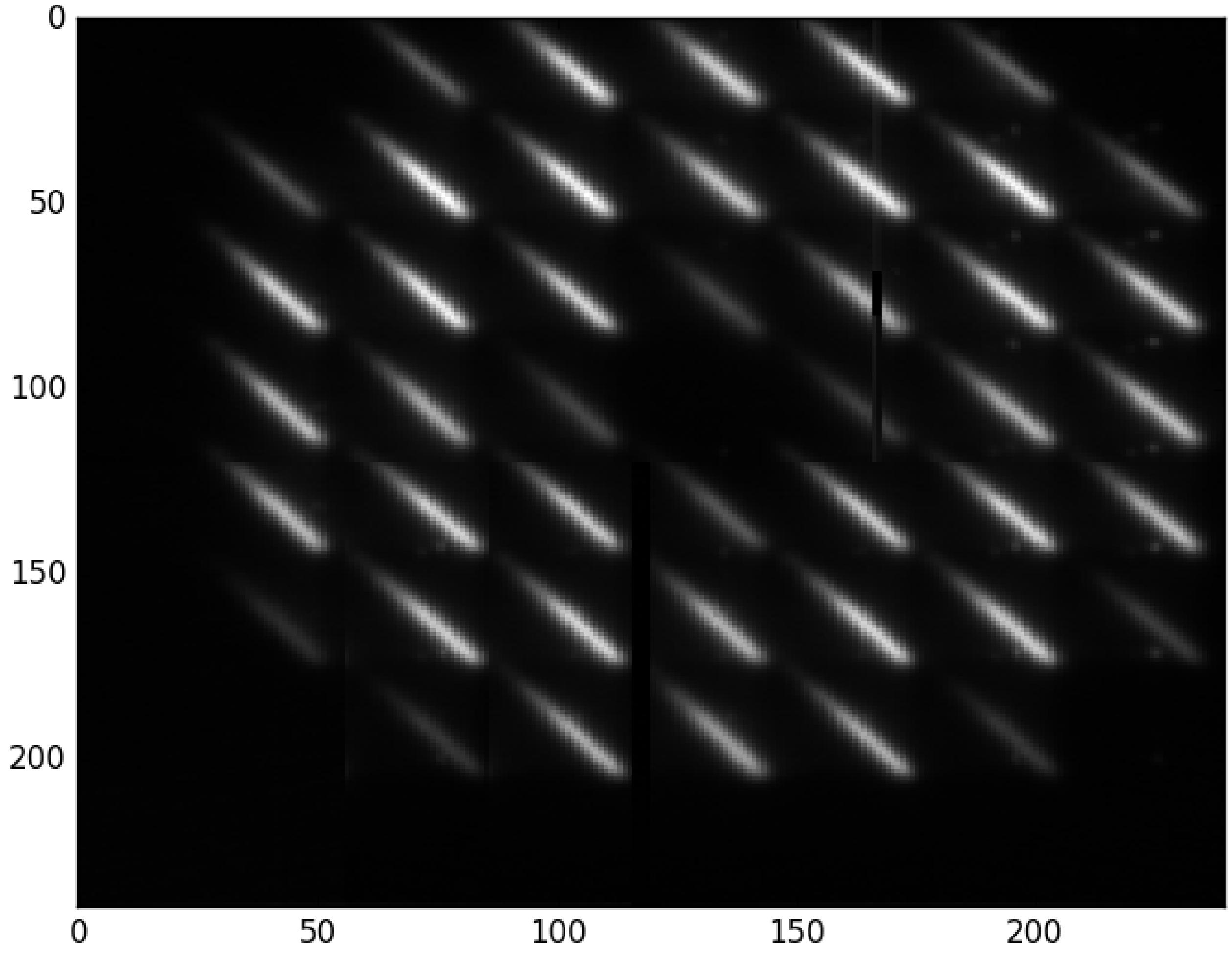
On-sky testing of algorithms for extended LGS spots

Alastair Basden (DU), Andrew P Reeves (DU), Lisa Bardou (LESIA), Domenico Bonaccini Calia (ESO), Tristan Buey (LESIA), Mauro Centrone (INAF-OAR), Fanny Chemla (LESIA), Philippe Feautrier (IPAG), Jean-Luc Gach (LAM), Eric Gendron (LESIA), Damien Gratadour (LESIA), Gianluca Lombardi (GTC), Enrico Marchetti (ESO), Tim Morris (DU), Richard Myers (DU), James Osborn (DU), Thomas Pfrommer (ESO), Marcos Reyes Garcia Talavera (IAC), Gerard Rousset (LESIA), Eric Stadler (IPAG), Robert G Talbot (DU), Matthew J Townson (DU), Fabrice Vidal (LESIA)

CANARY LGS WFS



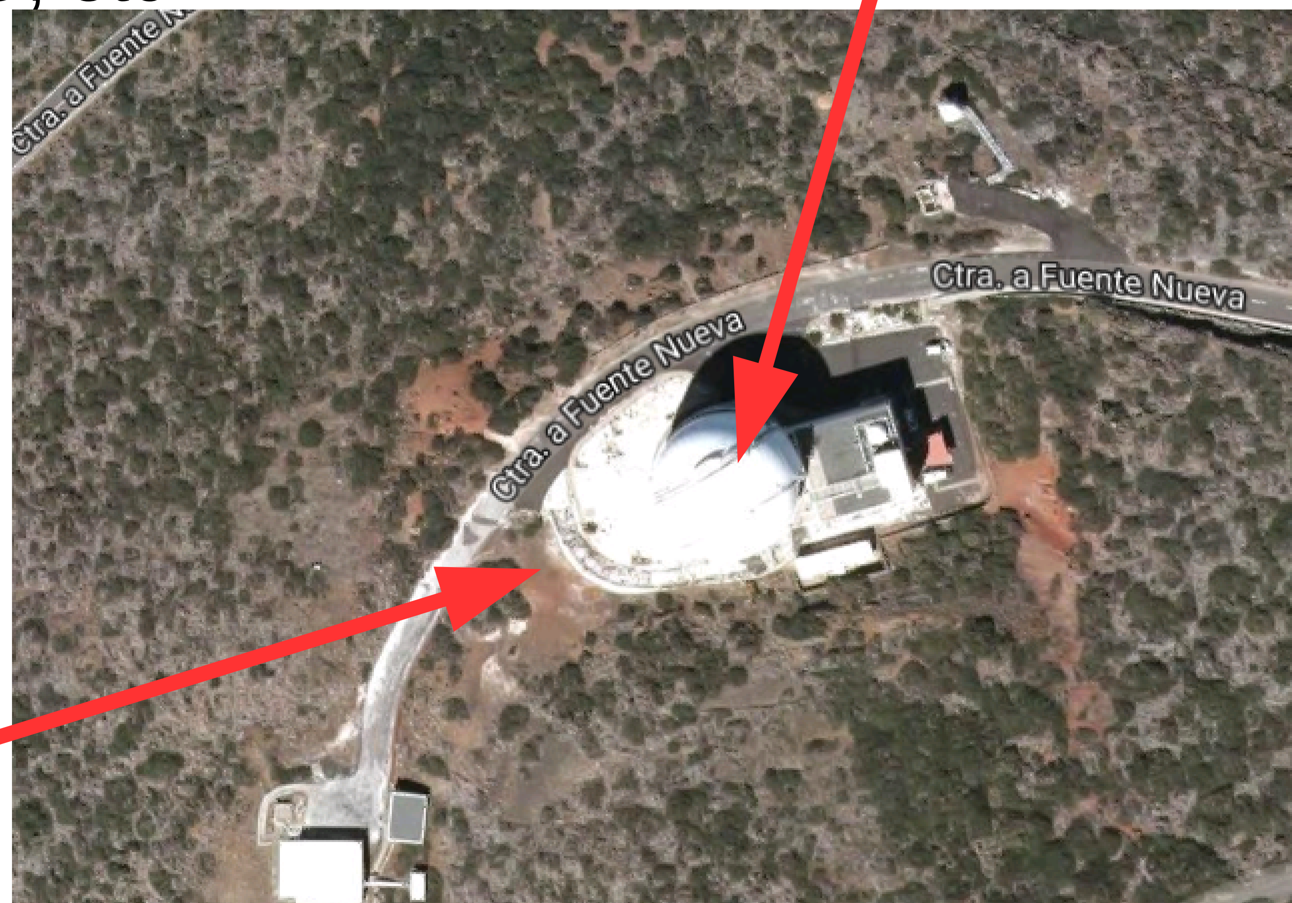
CANARY LGS WFS



CANARY

- AO technology demonstrator
  - MOAO, LTAO, etc
  - Many algos
  - etc

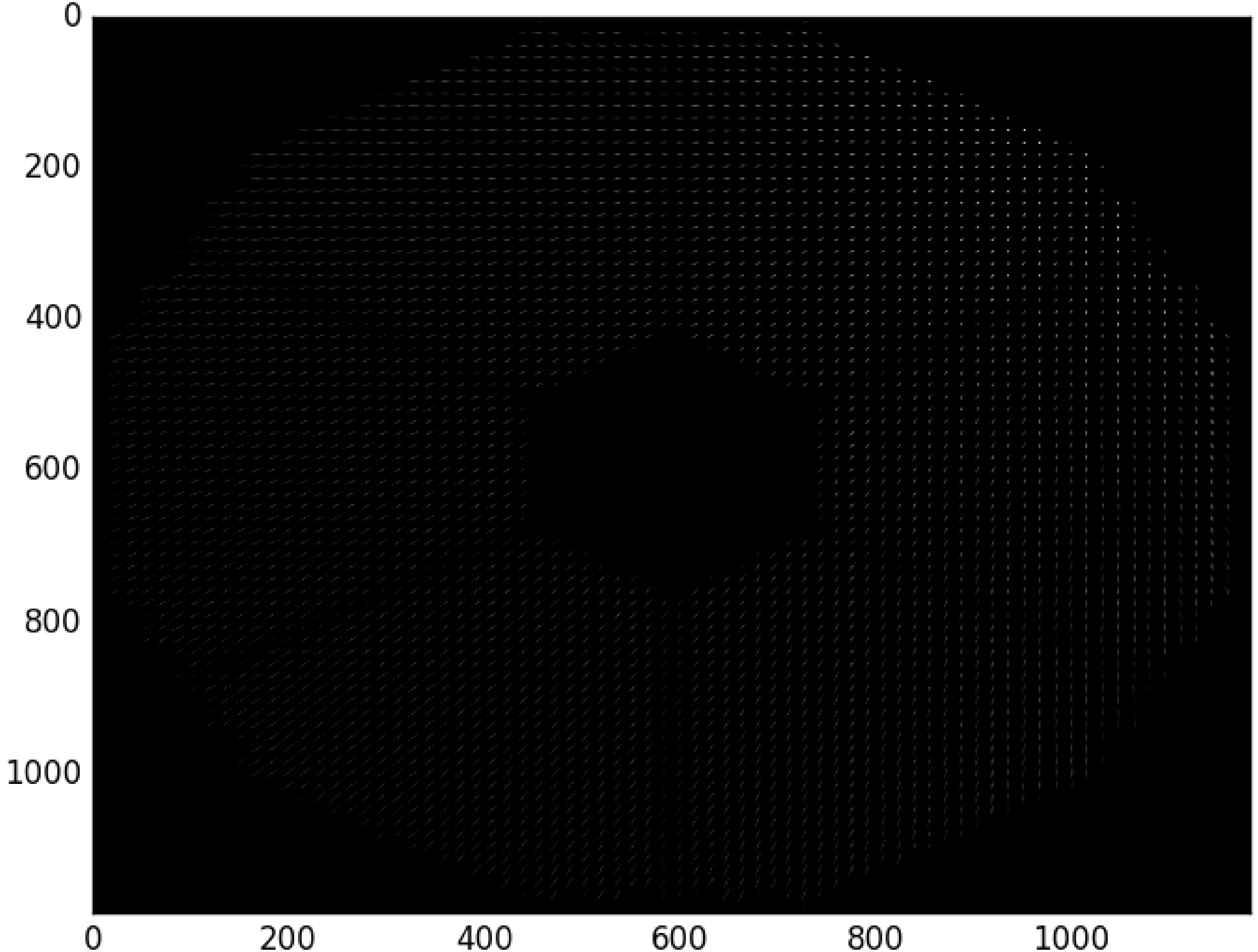
WHT
(CANARY
inside!)



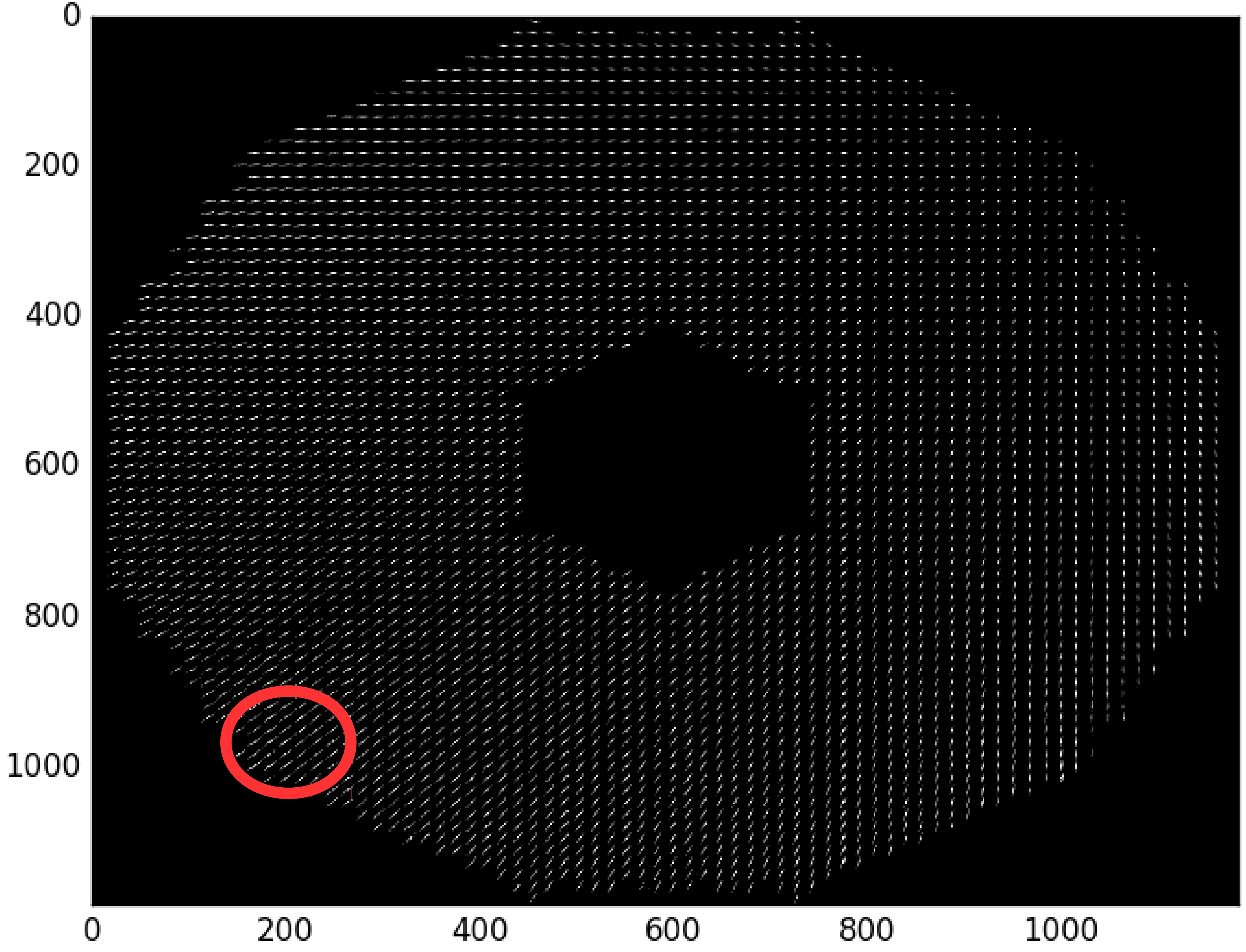
ESO WLGSU

Credit: Google

On the ELT...

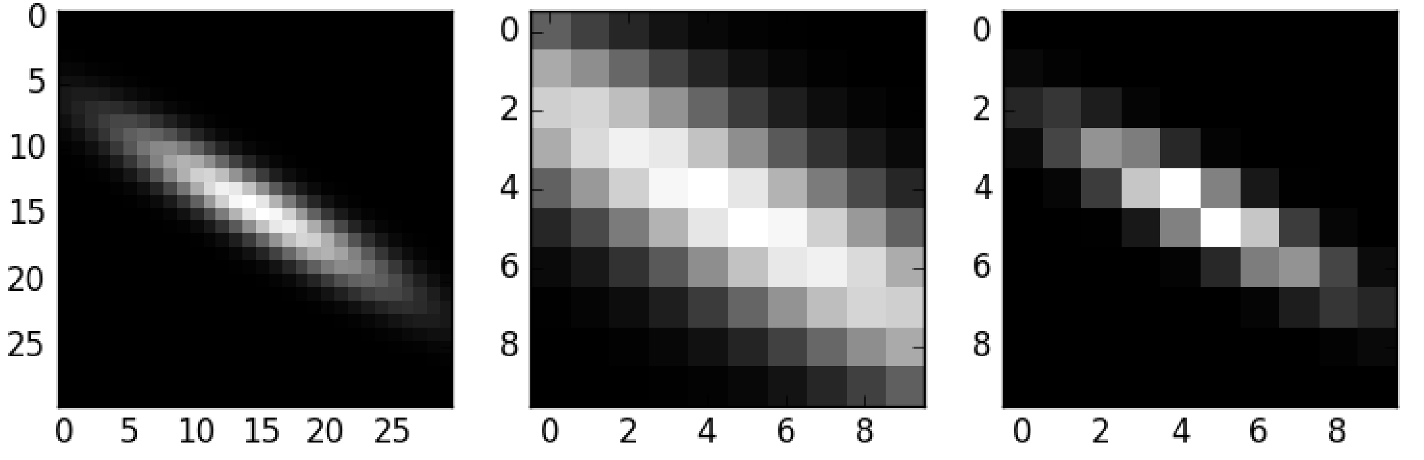


Normalised...



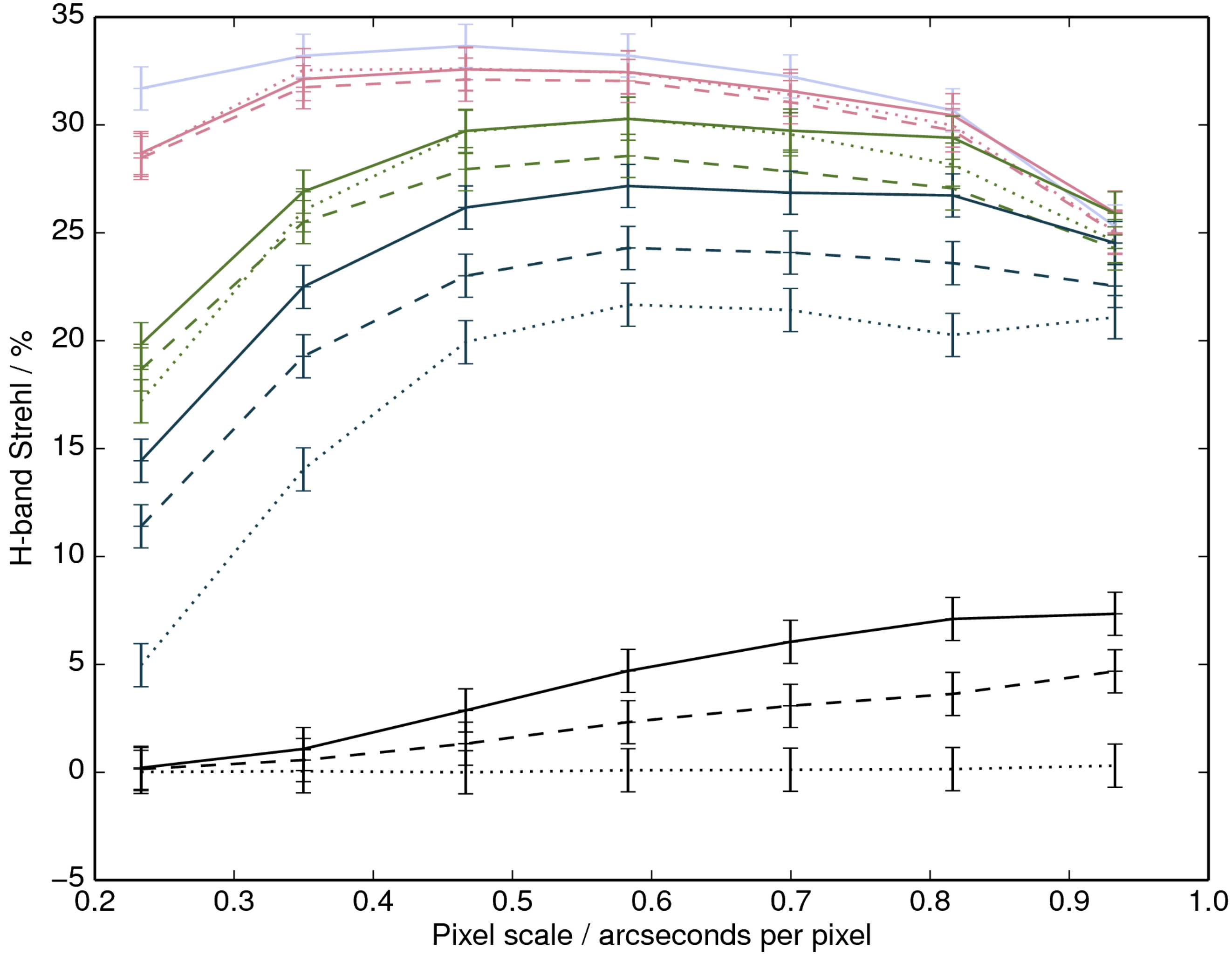
Pixels, pixel scale or field of view

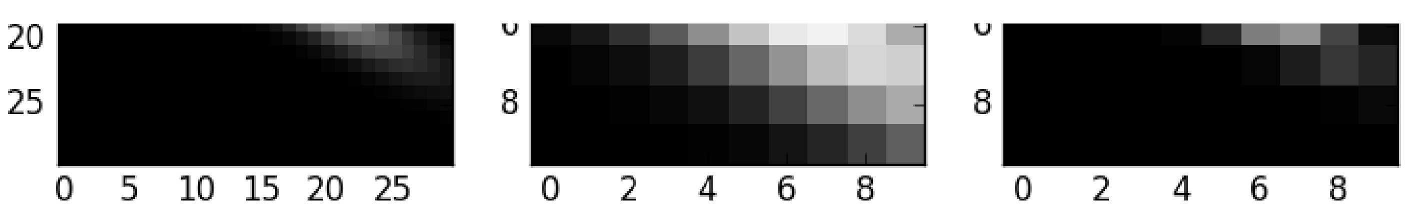
- CANARY: 30x30 pixels
- Available detectors for ELT:
  - NGSD/LVSM: 10x10 pixels per subap, ~1kHz
  - LGSD (?)
  - Fairchild LTN4625A: 30x30 pixels, 240Hz (small pixels)
- Increase truncation
- Increase field of view (pixel scale)
  - Reduced sensitivity



Pixels, pixel scale or field of view

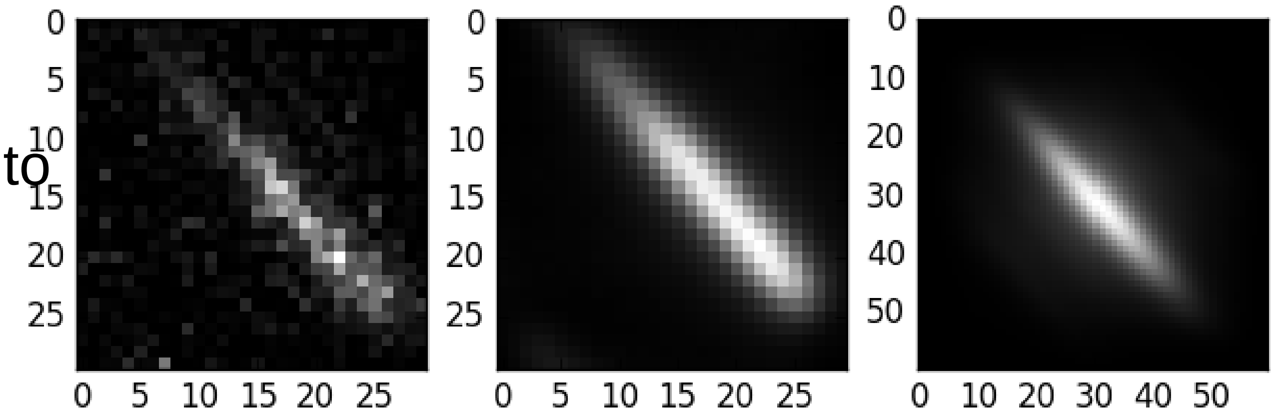
- CAN
- Avai
  - NC
  - LC
  - Fa
- Incre
- Incre
  - Re

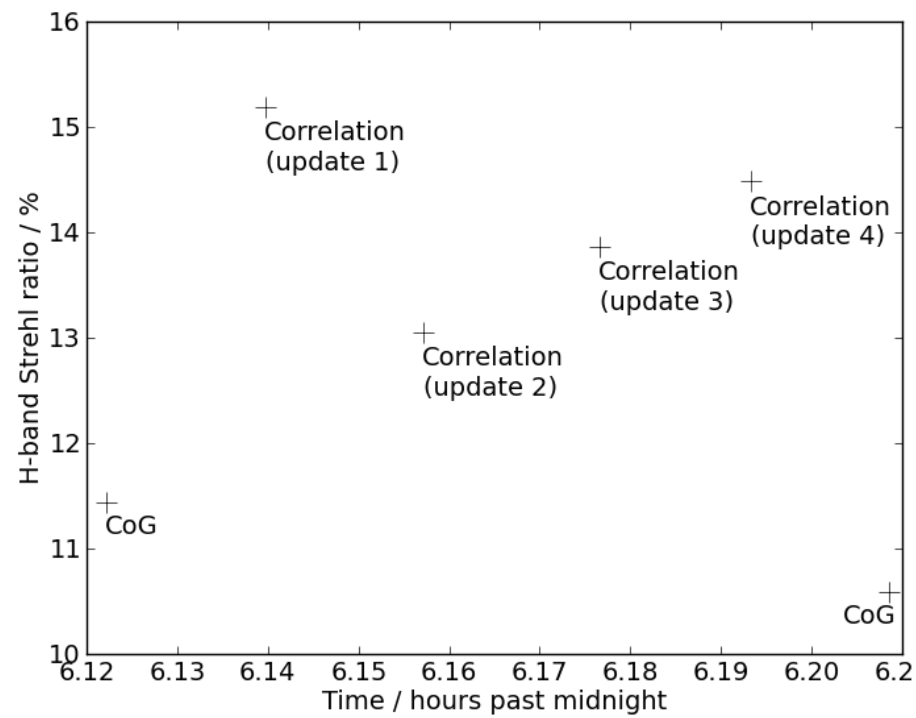




On-sky tests: Correlation

- FFT-based correlation
  - Zero padding essential to avoid bias
- Method:
  - Sub-aperture reference images obtained
    - ~100 frames, shift and add
  - Loaded into DARC, along with ref-slope modifications
  - Process repeated
    - While the AO loop is engaged





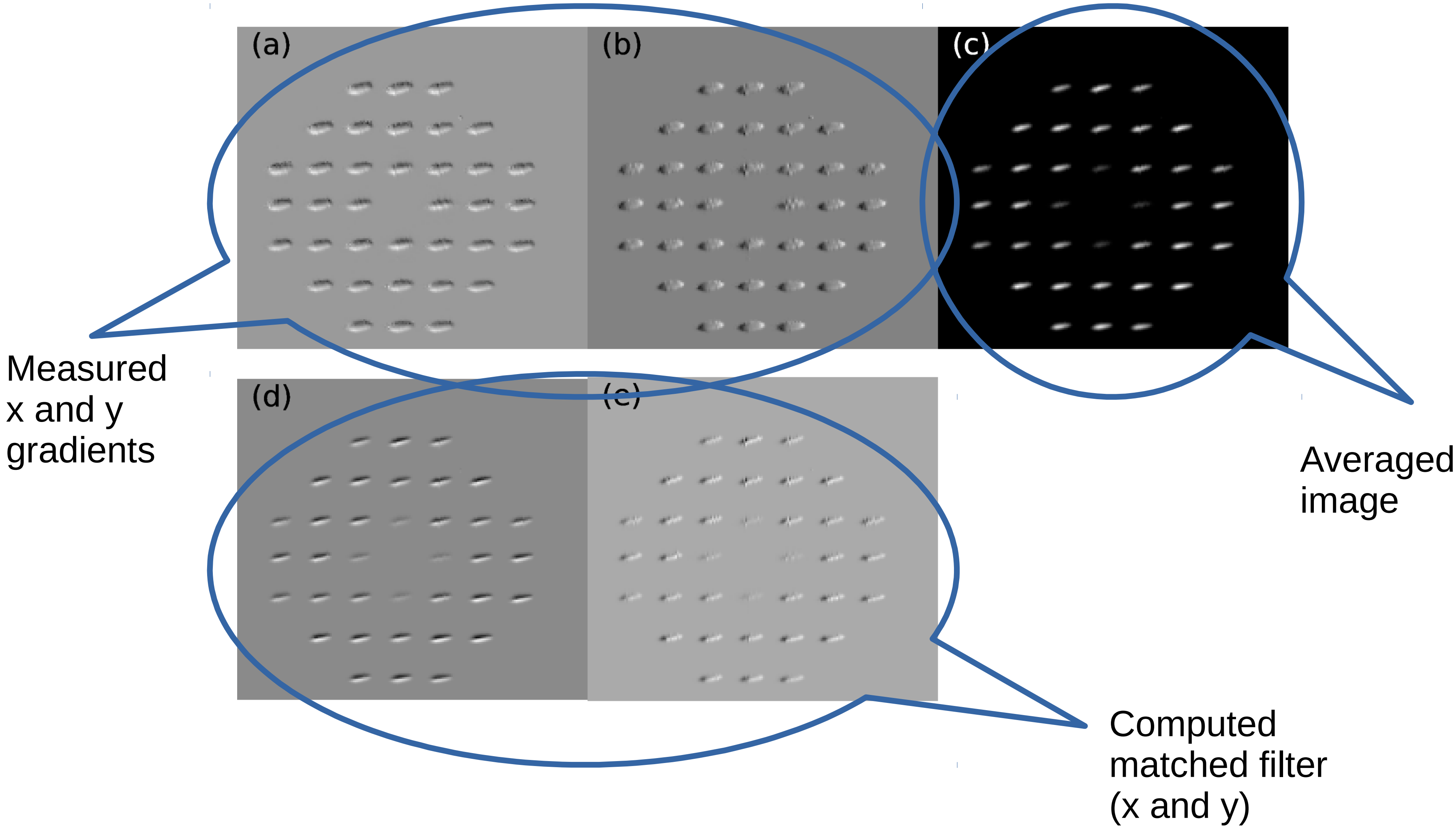
Automatic reference update

- Functionality to continually update reference images
  - And corresponding reference slopes
  - Every iteration
  - Rolling shift-add average of sub-aperture images
- Ideal for use when profile is changing
  - Keeps SNR optimised
- Note – computational load is high
  - So, we can also update on a rolling basis if necessary
- Lots of telemetry is useful for diagnosis!
  - Ref images, ref slopes, correlation pattern

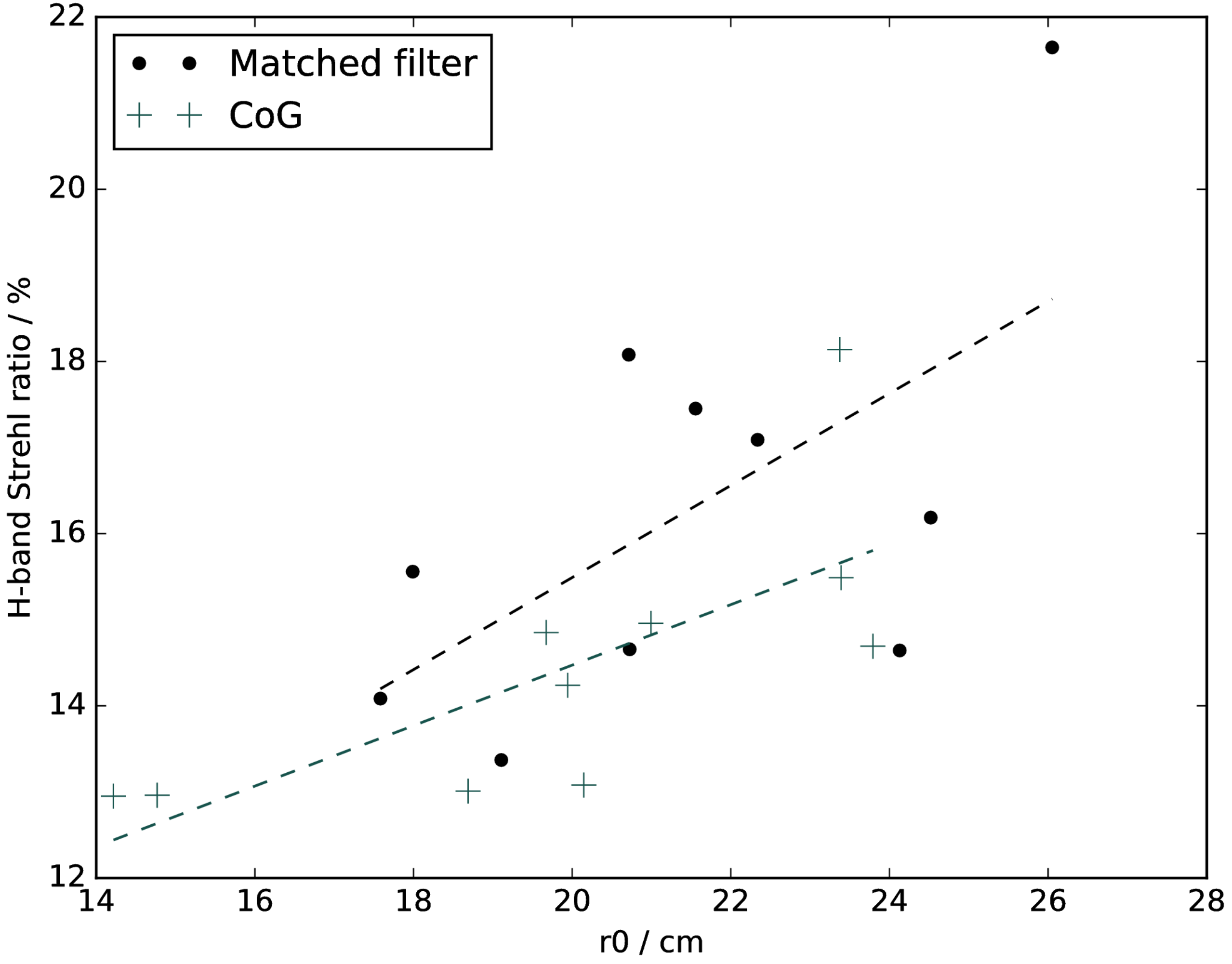
On-sky tests: Matched filtering

- Noise optimal technique for slope estimation (wavefront gradient or spot position)
  - Proposed for use with TMT
    - Lots of maths
  - Virtually no more computation than CoG (for the RTCS)
- Requires a measurement of sub-aperture image gradients
  - Dithering on-sky
  - Depends on atmospheric conditions
- Matched filtering is non-linear
  - We use a range extension algorithm to extend linear range to ~1 pixel
  - And active spot tracking to further mitigate this problem
- Separate matched filter for each sub-aperture
  - Sub-apertures can be different sizes
- Reference slopes require updating on-sky
  - (cannot be computed well from the matched filter since non-linear)

Example data



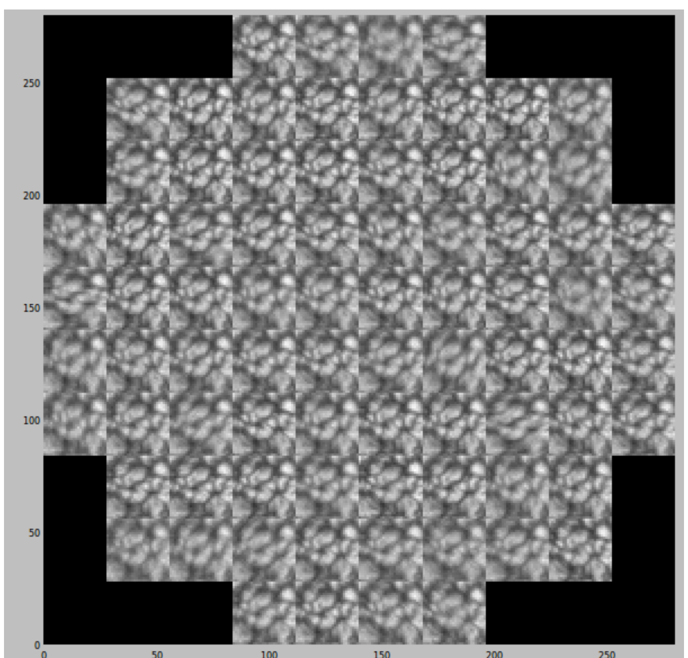
It works!

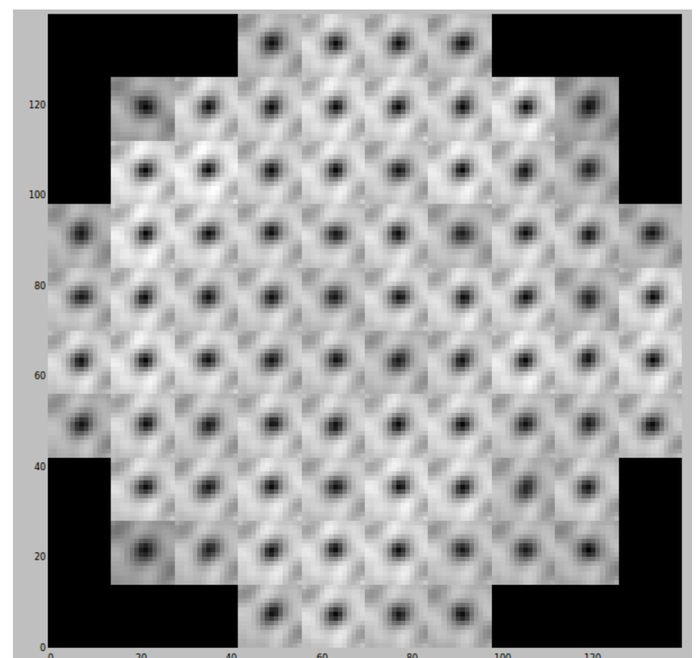


Matched filter
CoG
22
20
18
16
14
12
H-band Strehl ratio / %
14
16
18
20
22
24
26
28
r0 / cm

Difference-squared correlation

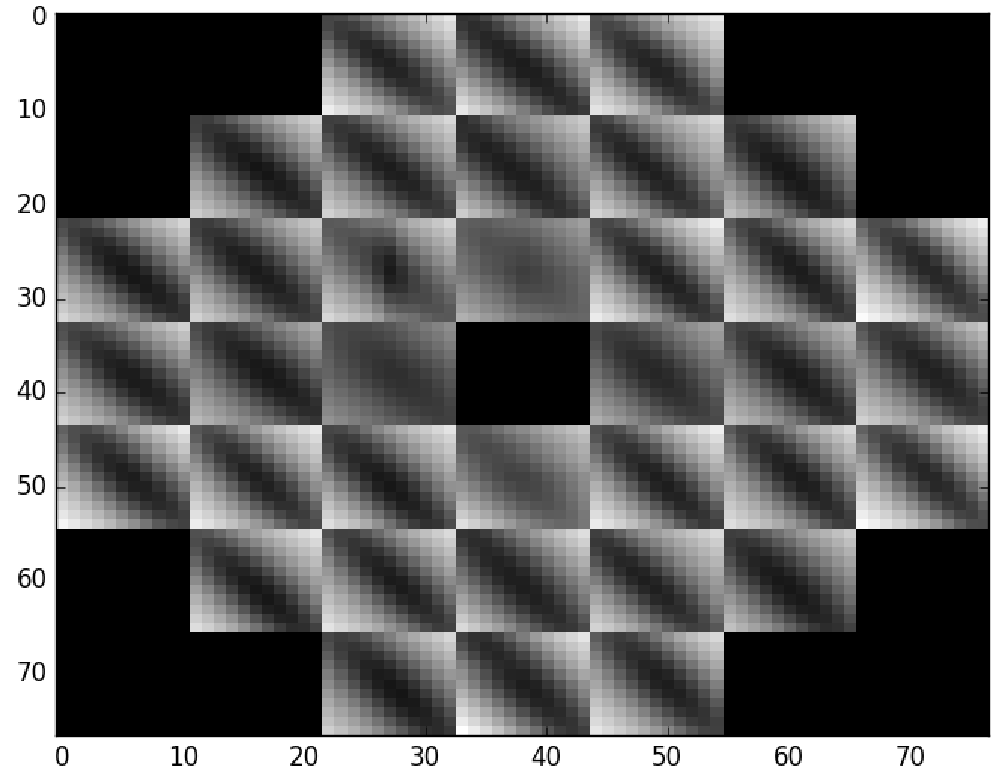
- See solar poster (Tuesday!)
- Compute sum[$(\text{Img-Ref})^2$] as a function of x and y offset between Img and Ref
  - Highly effective for Solar AO





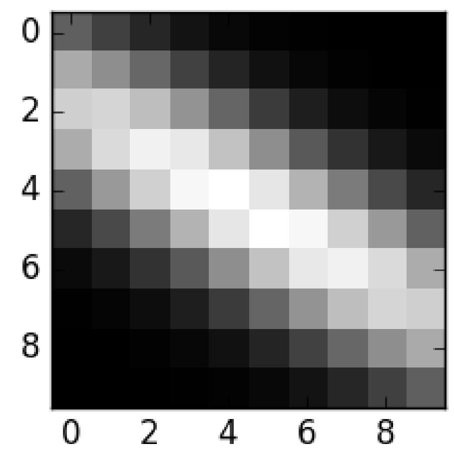
Difference-squared correlation

- But for LGS, its not so good yet
  - Research ongoing
  - Potential to offer an ideal way to handle spot truncation



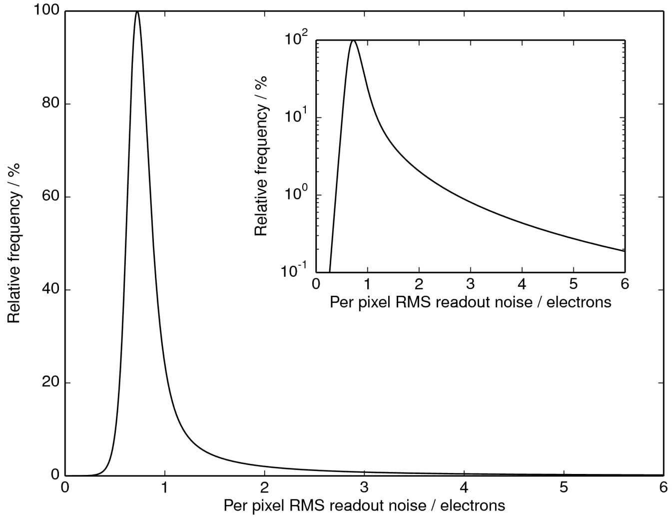
Truncation mitigation

- Difference-squared correlation could be promising
  - But a work in progress
- FFT-correlation works well up to some degree of truncation
  - But better if not truncated!
  - Windowing functions add bias
  - A truncated reference can be used
    - i.e. a 2-step process:
      - Estimate crude spot position
      - Truncate reference to this position
      - Estimate position using this reference
    - But requires finer parameter tuning, not so robust
  - Over-sized reference also has potential
    - Investigations ongoing
    - Matt Townson's talk yesterday
- Neural networks
  - Train the network to deal with truncation



Detector modelling

- CMOS detectors have a different RMS readout noise for each pixel
  - Suppliers often quote the Median RMS noise
  - Distribution has a large tail
    - Some pixels have far higher noise
  - (Matched filtering can take this into account)
- Noise model used can have a significant effect on estimated AO performance



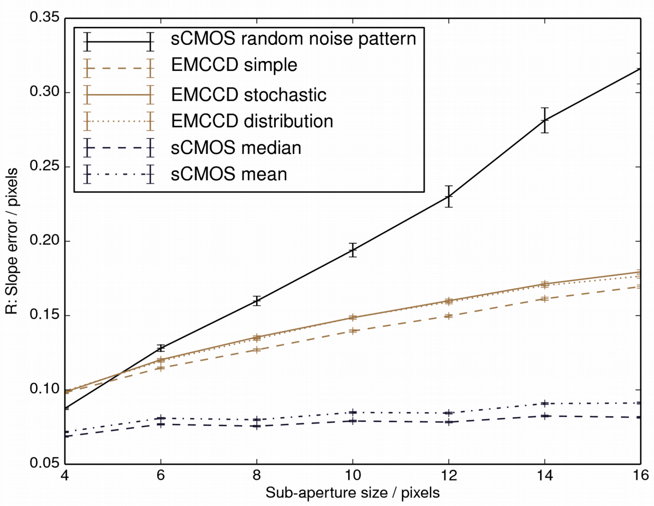
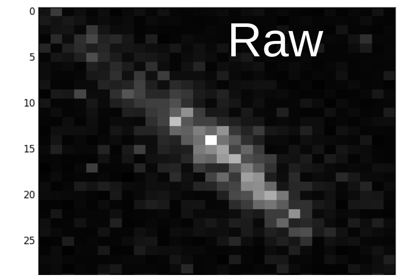
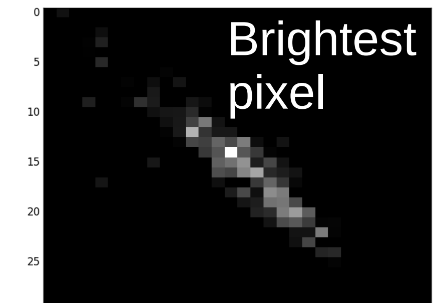
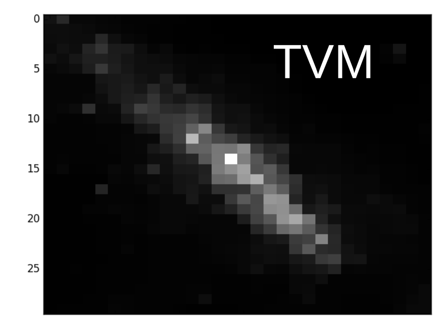


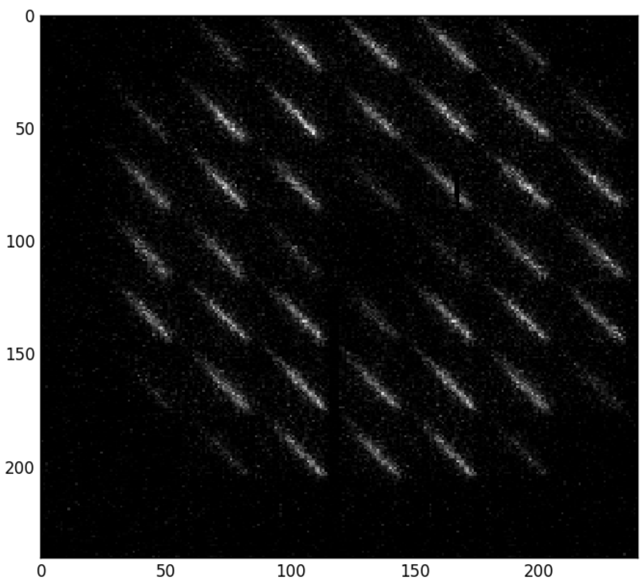
Image calibration approaches



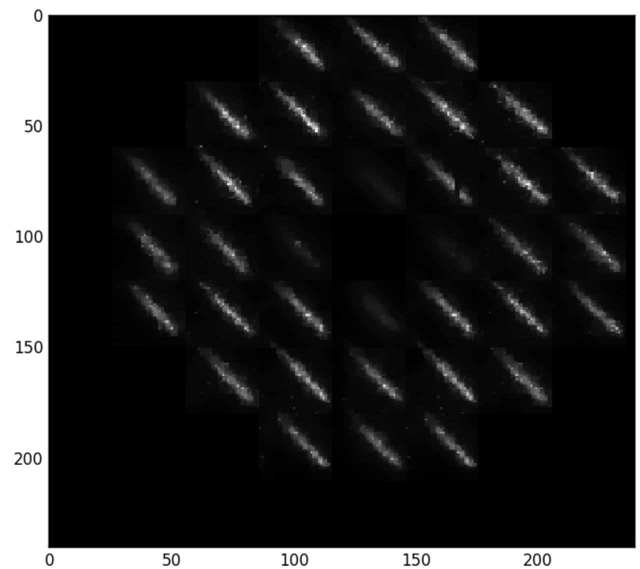
- Spot tracking
  - Ideal with significant launch jitter
- Brightest pixel selection (automatic variable thresholding)
  - Automatically select only pixels with signal (assuming area is known)
- Arbitrary shaped sub-apertures
  - Reduce the number of pixels containing just noise
- Total variation minimisation



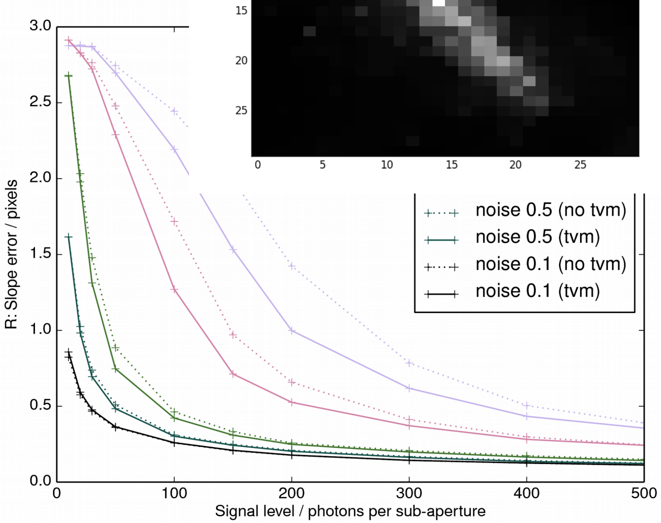




Raw image

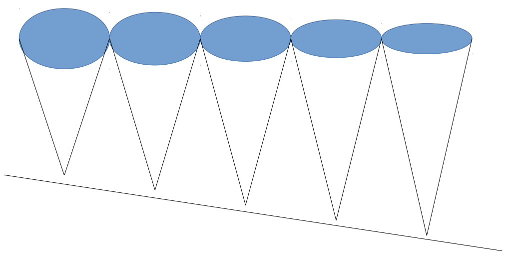


After TVM

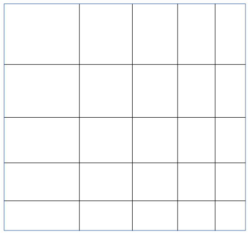


Other concepts

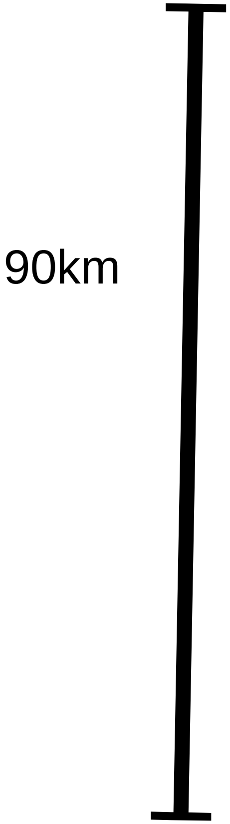
- Astigmatic lenslets
  - Compress the spot (and sensitivity) along elongation
- Variable pixel scale LGS WFS
  - Change lenslet focal length across the wavefront
  - Detector tilted
  - Allows spots near launch axis to be well sampled
  - Spots further from launch axis avoid truncation, but have reduced sensitivity
  - Simulations ongoing



- Variable sampling
  - Larger sub-apertures as elongation increases
  - Greater light collecting area
    - More signal for the elongated spots



Other concepts (continued)



Credit: ESO

Other concepts (continued)

- The Domenico star

90km

Credit: ESO

Conclusions

- Lots of techniques to aid processing of highly extended LGS spots
  - Improvements in performance can be achieved
    - Correlation
    - Matched filtering
    - Spot tracking
    - Noise reduction
    - Variable thresholding
- My prediction:
  - We will all end up using CoG!
    - At least initially!
    - Robustness will outweigh performance gain

"Workshop Week 2018" Durham

- 19^{th} - 23^{rd} March 2018
- Back-to back 1-2 day workshops
  - Turbulence Profiling
  - Wavefront Reconstruction
  - Real-time Control
  - AO Simulation
  - PSF Reconstruction
- www.dur.ac.uk/cfai/adaptiveoptics/workshopweek2018

Search for "Durham workshop week"

We also have jobs available (for free!)

Durham University

CfAI

AO4ELT5

On-sky testing of algorithms for extended LGS spots

Alastair Basden (DU), Andrew P Reeves (DU), Lisa Bardou (LESIA), Domenico Bonaccini Calia (ESO), Tristan Buey (LESIA), Mauro Centrone (INAF-OAR), Fanny Chemla (LESIA), Philippe Feautrier (IPAG), Jean-Luc Gach (LAM), Eric Gendron (LESIA), Damien Gratadour (LESIA), Gianluca Lombardi (GTC), Enrico Marchetti (ESO), Tim Morris (DU), Richard Myers (DU), James Osborn (DU), Thomas Pfrommer (ESO), Marcos Reyes Garcia Talavera (IAC), Gerard Rousset (LESIA), Eric Stadler (IPAG), Robert G Talbot (DU), Matthew J Townson (DU), Fabrice Vidal (LESIA)

Room is 30m long

CANARY LGS WFS

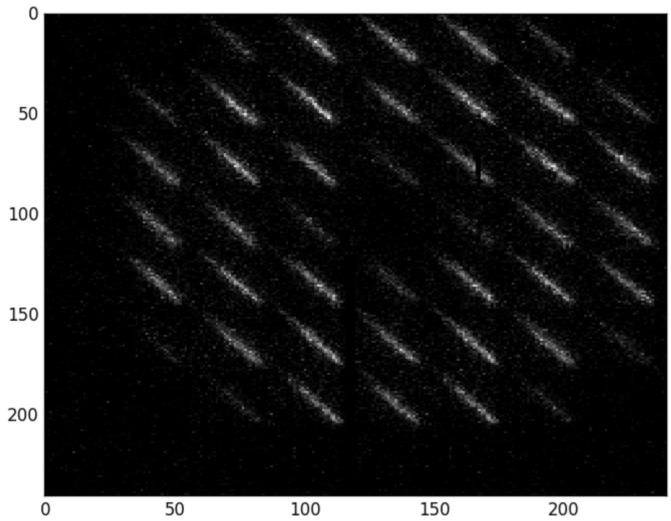
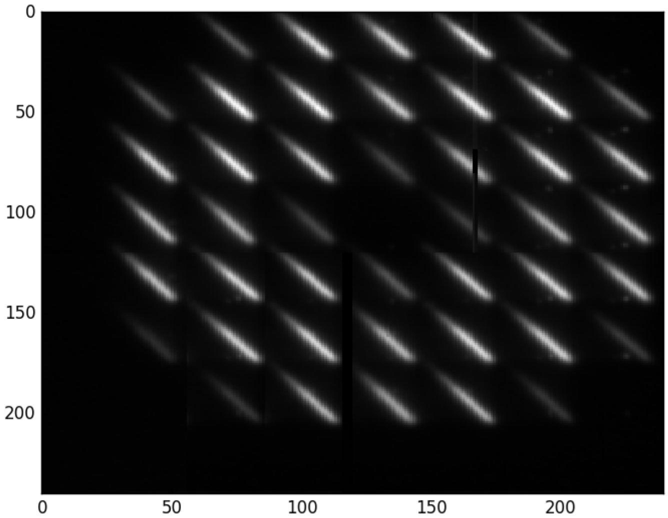


Image from start of June.
LGS launched 40m off-axis, but projected off-axis distance seen here is less.
5000 frames

30x30 pixels per subap

Many papers with details about canary

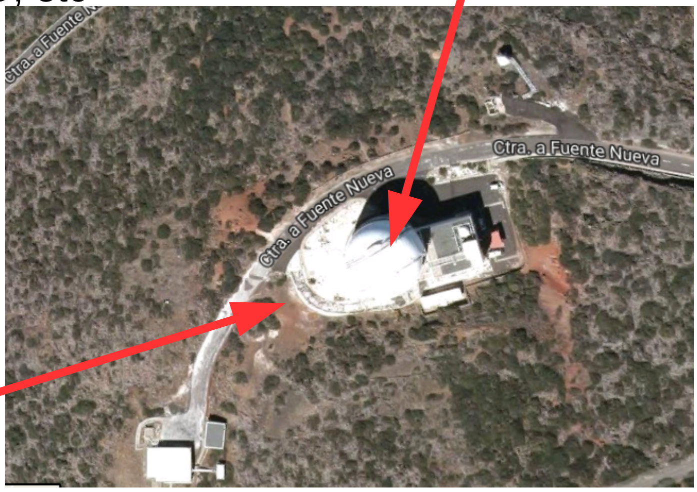
CANARY LGS WFS



CANARY

- AO technology demonstrator
  - MOAO, LTAO, etc
  - Many algos
  - etc

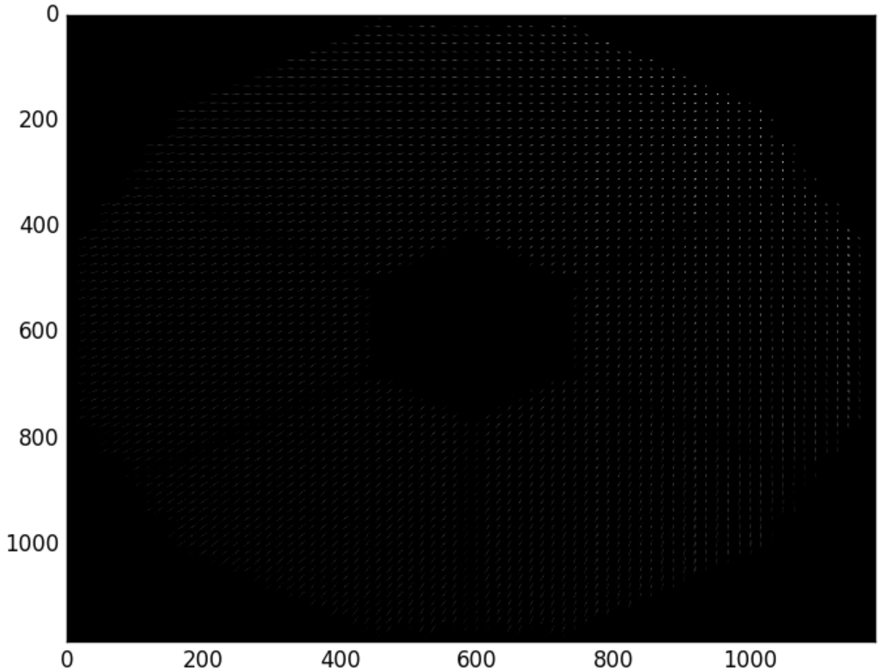
WHT
(CANARY
inside!)



ESO WLGSU

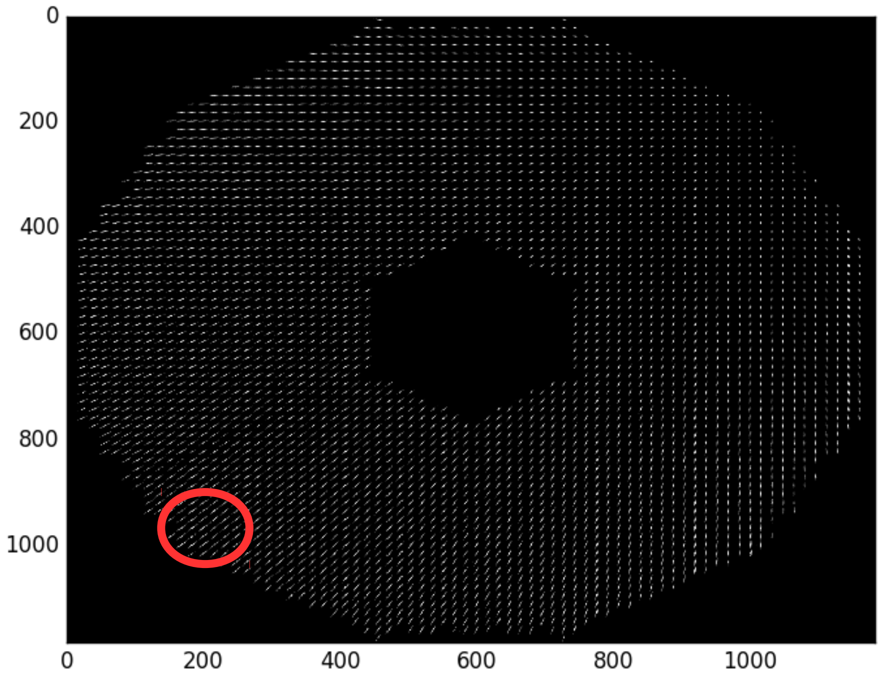
Credit: Google

On the ELT...



Dasp monte-carlo simulation
Many papers about these results

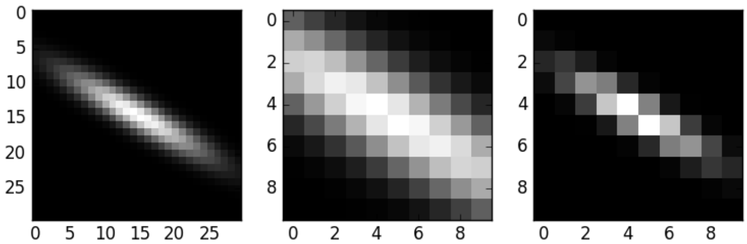
Normalised...



Normalised to brightest pixel=1
Note, with 9 bits, only about 6 for elongated spots

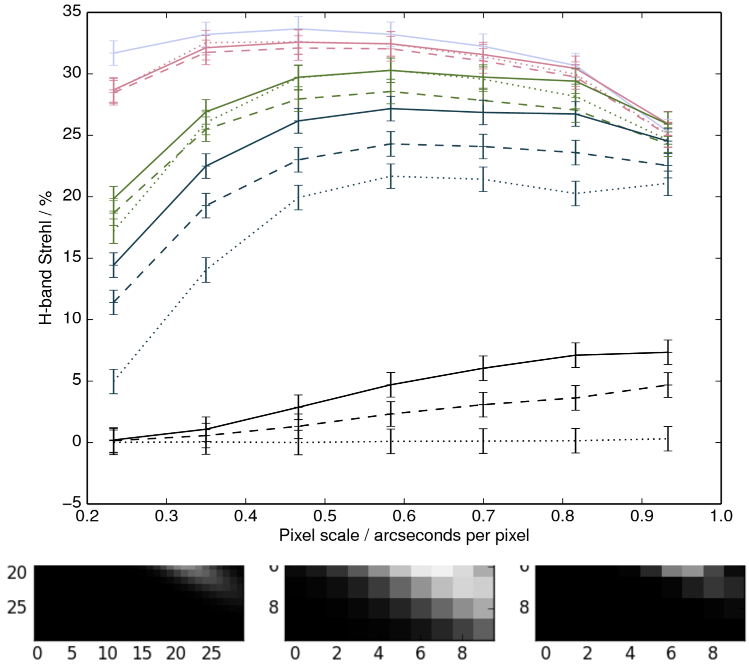
Pixels, pixel scale or field of view

- CANARY: 30x30 pixels
- Available detectors for ELT:
  - NGSD/LVSM: 10x10 pixels per subap, ~1kHz
  - LGSD (?)
  - Fairchild LTN4625A: 30x30 pixels, 240Hz (small pixels)
- Increase truncation
- Increase field of view (pixel scale)
  - Reduced sensitivity



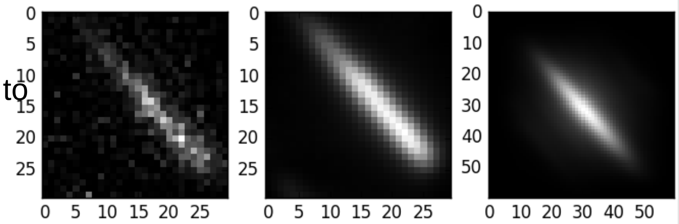
Pixels, pixel scale or field of view

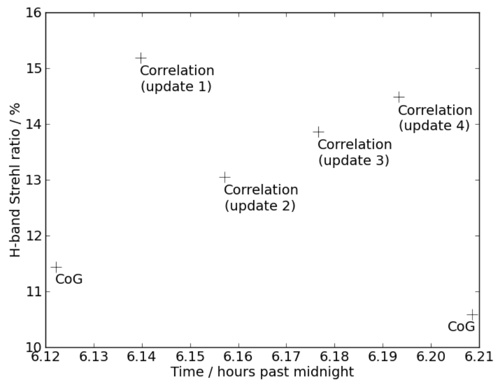
- CAN
- Avai
  - NO
  - LO
  - Fa
- Incre
- Incre
  - Re



On-sky tests: Correlation

- FFT-based correlation
  - Zero padding essential to avoid bias
- Method:
  - Sub-aperture reference images obtained
    - ~100 frames, shift and add
  - Loaded into DARC, along with ref-slope modifications
  - Process repeated
    - While the AO loop is engaged





Paper in mnras

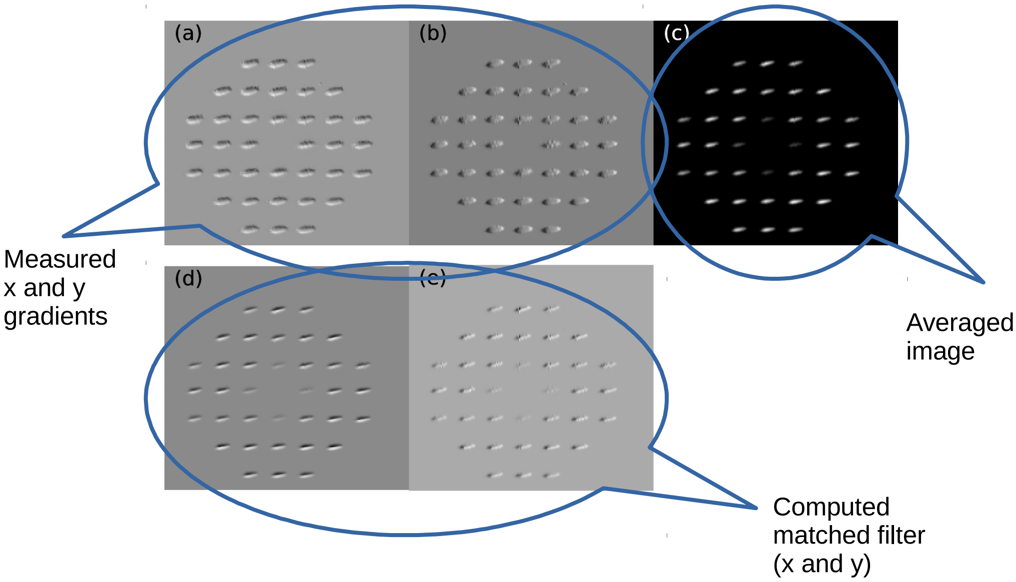
Automatic reference update

- Functionality to continually update reference images
  - And corresponding reference slopes
  - Every iteration
  - Rolling shift-add average of sub-aperture images
- Ideal for use when profile is changing
  - Keeps SNR optimised
- Note – computational load is high
  - So, we can also update on a rolling basis if necessary
- Lots of telemetry is useful for diagnosis!
  - Ref images, ref slopes, correlation pattern

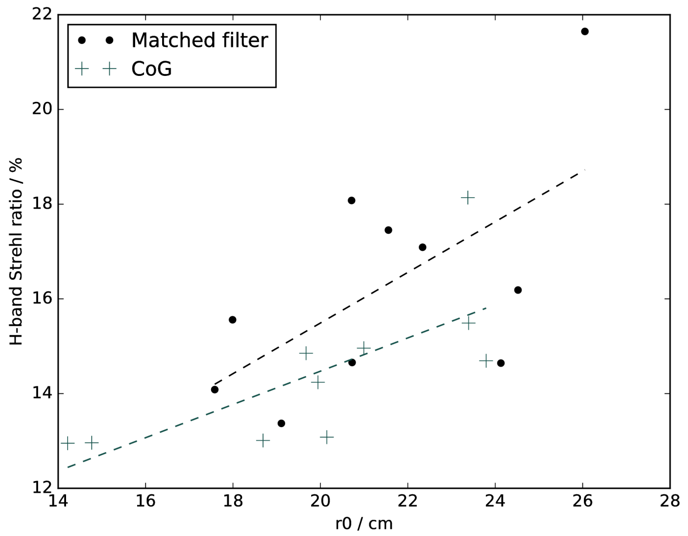
On-sky tests: Matched filtering

- Noise optimal technique for slope estimation (wavefront gradient or spot position)
  - Proposed for use with TMT
    - Lots of maths
  - Virtually no more computation than CoG (for the RTCS)
- Requires a measurement of sub-aperture image gradients
  - Dithering on-sky
  - Depends on atmospheric conditions
- Matched filtering is non-linear
  - We use a range extension algorithm to extend linear range to ~1 pixel
  - And active spot tracking to further mitigate this problem
- Separate matched filter for each sub-aperture
  - Sub-apertures can be different sizes
- Reference slopes require updating on-sky
  - (cannot be computed well from the matched filter since non-linear)

Example data



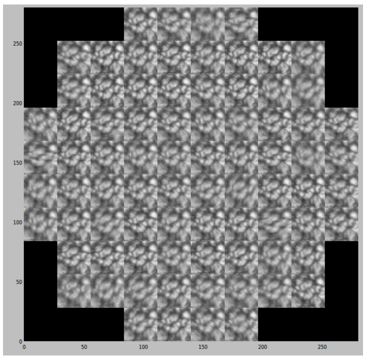
It works!

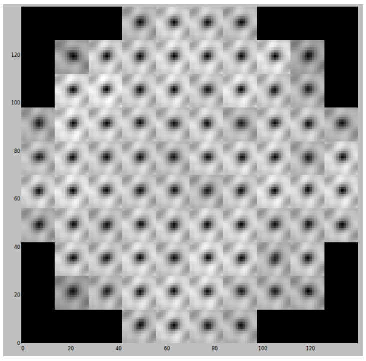


Matched filter
CoG
H-band Strehl ratio / %
r0 / cm
22
20
18
16
14
12
14
16
18
20
22
24
26
28

Difference-squared correlation

- See solar poster (Tuesday!)
- Compute sum[(Img-Ref)^2] as a function of x and y offset between Img and Ref
  - Highly effective for Solar AO

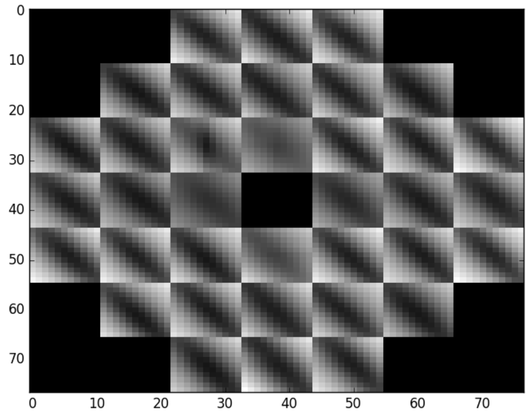




Why interested in solar in Durham?!?

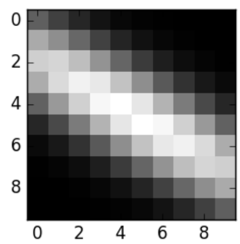
Difference-squared correlation

- But for LGS, its not so good yet
  - Research ongoing
  - Potential to offer an ideal way to handle spot truncation



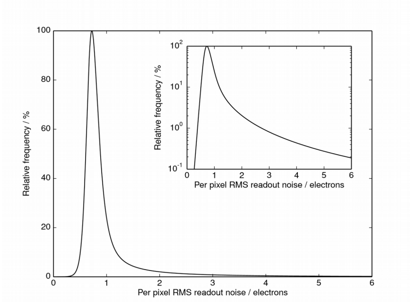
Truncation mitigation

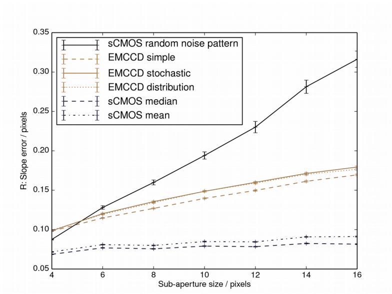
- Difference-squared correlation could be promising
  - But a work in progress
- FFT-correlation works well up to some degree of truncation
  - But better if not truncated!
  - Windowing functions add bias
  - A truncated reference can be used
    - i.e. a 2-step process:
      - Estimate crude spot position
      - Truncate reference to this position
      - Estimate position using this reference
    - But requires finer parameter tuning, not so robust
  - Over-sized reference also has potential
    - Investigations ongoing
    - Matt Townson's talk yesterday
- Neural networks
  - Train the network to deal with truncation



Detector modelling

- CMOS detectors have a different RMS readout noise for each pixel
  - Suppliers often quote the Median RMS noise
  - Distribution has a large tail
    - Some pixels have far higher noise
  - (Matched filtering can take this into account)
- Noise model used can have a significant effect on estimated AO performance

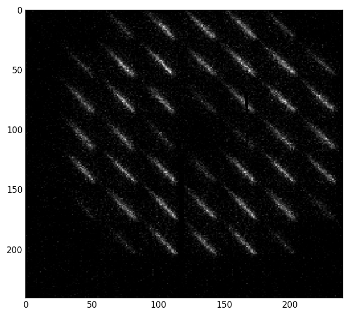




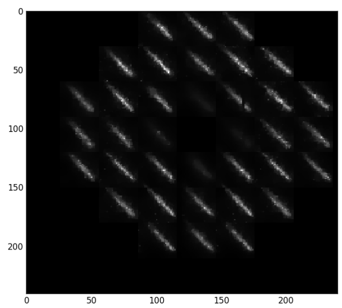
Paper in jatis

Image calibration approaches

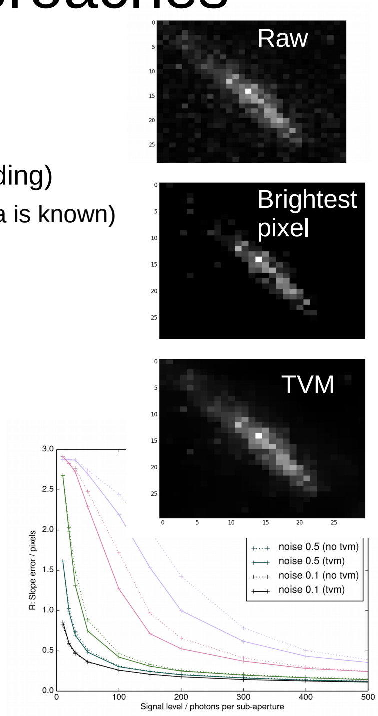
- Spot tracking
  - Ideal with significant launch jitter
- Brightest pixel selection (automatic variable thresholding)
  - Automatically select only pixels with signal (assuming area is known)
- Arbitrary shaped sub-apertures
  - Reduce the number of pixels containing just noise
- Total variation minimisation



Raw image



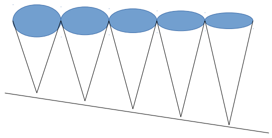
After TVM



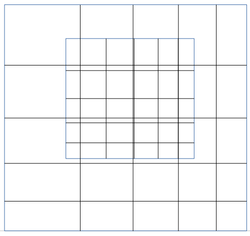
Couple of papers
Mention darc

Other concepts

- Astigmatic lenslets
  - Compress the spot (and sensitivity) along elongation
- Variable pixel scale LGS WFS
  - Change lenslet focal length across the wavefront
  - Detector tilted
  - Allows spots near launch axis to be well sampled
  - Spots further from launch axis avoid truncation, but have reduced sensitivity
  - Simulations ongoing



- Variable sampling
  - Larger sub-apertures as elongation increases
  - Greater light collecting area
    - More signal for the elongated spots



Other concepts (continued)

90km

Credit: ESO

Other concepts (continued)

- The Domenico star

90km

Credit: ESO

Conclusions

- Lots of techniques to aid processing of highly extended LGS spots
  - Improvements in performance can be achieved
    - Correlation
    - Matched filtering
    - Spot tracking
    - Noise reduction
    - Variable thresholding
- My prediction:
  - We will all end up using CoG!
    - At least initially!
    - Robustness will outweigh performance gain

"Workshop Week 2018" Durham

- 19th - 23rd March 2018
- Back-to back 1-2 day workshops
  - Turbulence Profiling
  - Wavefront Reconstruction
  - Real-time Control
  - AO Simulation
  - PSF Reconstruction
- www.dur.ac.uk/cfai/adaptiveoptics/workshopweek2018

Search for "Durham workshop week"

We also have jobs available (for free!)

Durham University

CfAI

AO4ELT5