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Optical Read-out Techniques for the Control of Test-masses in Gravitational Wave Observatories

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Introduction

- **This presentation is based on my recently submitted thesis:-**
  - **S. Aston. "Optical Read-out Techniques for the Control of Test-masses in Gravitational Wave Observatories". January 2011**
  - **Available (once the official embargo has lifted on 19th July 2011) via the following address http://etheses.bham.ac.uk/1665/**
- **Focusing on two core chapters:-**
  - **Advanced LIGO UK work carried out during 2003-2011, in developing the**

BOSEM = Birmingham Optical Sensor and Electro-Magnet actuator

  - **STFC funded research carried out from 2001-present, in developing the**

EUCLID = Easy to Use Compact Laser Interferometric Device

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Overview

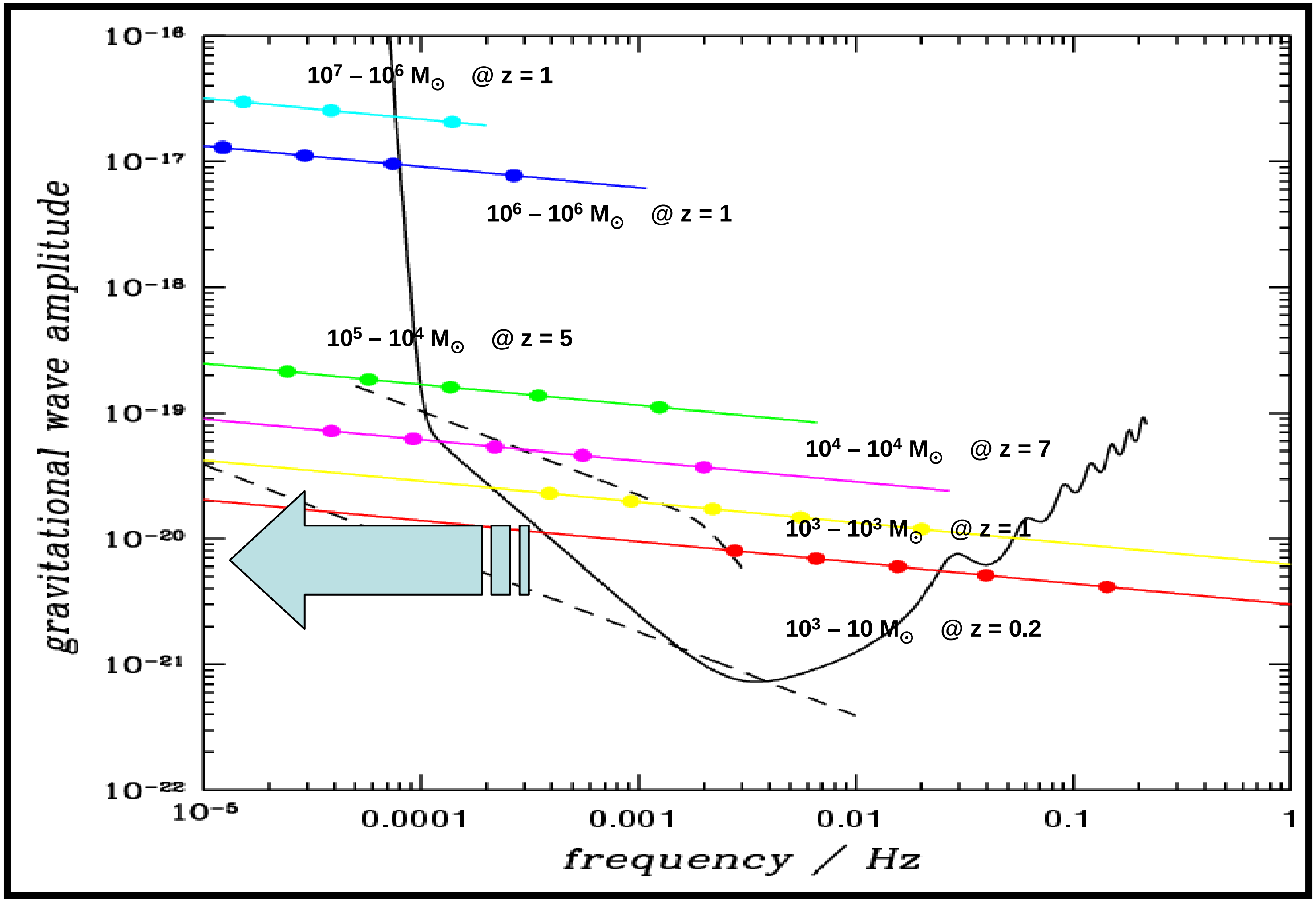
Part 1

- **Introduction**
- **Primary Motivation**
  - LISA Drag-free Control
  - Advanced LIGO Suspensions
- **Geometric Sensor Development (BOSEM)**
  - Requirements
  - Imaging Sensor Design & Characterisation
  - Shadow Sensor Design & Characterisation
  - BOSEM Mechanical Design & Fabrication
  - BOSEM Characterisation
  - Excess Noise Investigation
    - Hunting for the Source
    - Identification of Alternative IRLED
    - Screening & Retrofitting Proposals
  - Final BOSEM Characterisation Results

Part 2

- **Interferometric Sensor Development (EUCLID)**
  - Prototype Design
  - Fringe Interpolation
  - Final Design
  - Optical Modelling
  - Laser Selection Criteria
  - Fabrication
  - Misalignment Measurements
  - Noise Characterisation
- **Conclusions**
  - Sensor Performance Comparison
  - Lessons Learned & Future Development
- **Acknowledgements**

Motivation - LISA Drag-free Control



- Goal is to improve LISA's low frequency sensitivity to enable the study of massive binary black hole coalescences [1]

[1] S. A. Hughes and D. E. Holz. Cosmology with coalescing massive black holes. Classical and Quantum Gravity, 20, S65-S72. 2003.

Motivation - Advanced LIGO Suspensions [1]

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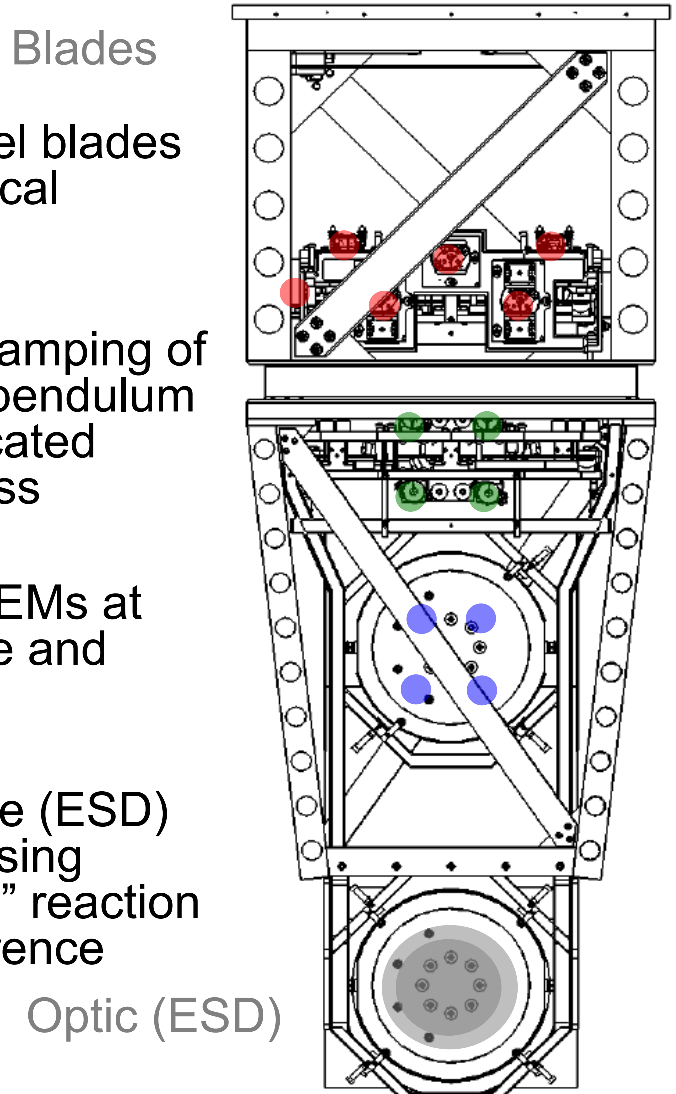
- Two stages of steel blades for enhanced vertical isolation
- Local control for damping of all low frequency pendulum modes by 6 co-located OSEMs at top mass
- Global control OSEMs at upper intermediate and penultimate mass
- Electro-Static Drive (ESD) actuator at optic using adjacent "identical" reaction pendulum as reference



Quad Suspension OSEM Counts

Top Mass = 12

6 BOSEMs Main Chain

6 BOSEMs Reaction Chain

Upper Intermediate Mass = 4

4 BOSEMs Reaction Chain

Penultimate Mass = 4

4 AOSEMs Reaction Chain

Total = 20 OSEMS + 20% spares policy = 24

12 Quads in total ⇒ 288 units

[1] N. A. Robertson et al. Quadruple suspension design for Advanced LIGO. Classical and Quantum Gravity, 19, 4043–4058. 2002.

Initial Sensor Requirements

- Initial Sensor Requirements [1]:-
  - Assuming a minimal amount of passive eddy-current damping

Specification	Frequency Band	
Worst Case Noise	1 Hz to 10 Hz $\approx 2\times10^{-11}$ m $Hz^{-1/2}$	10 Hz to 20 Hz $\approx 2\times10^{-11}$ m $Hz^{-1/2}$
Specification	**Displacement (peak-peak)**	
Operating Range	Minimum 3.00 mm	Target 3.00 mm

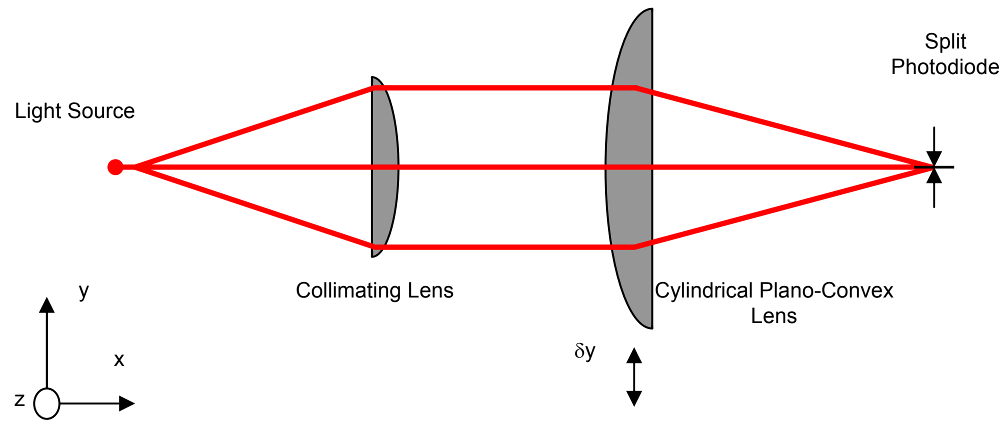
- Proceeded to identify and evaluate suitable sensor schemes, starting off with a clean-slate to meet these reasonably challenging requirements

- Considered PSDs and optical lever schemes, but believed the geometric sensor scheme to be most suitable

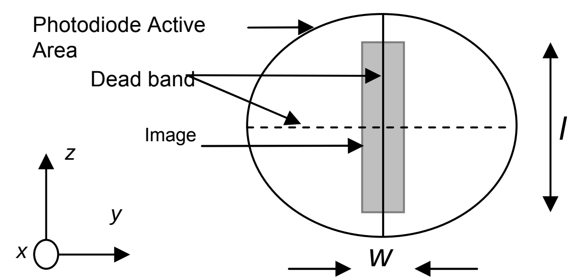
[1] K. Strain. Advanced LIGO suspensions general interpretation of requirements for sensors - for use as an initial planning aid by the UK project team v1.01. ALUKGLA0005aJUN03. 2003.

Imaging Sensor Design

- Simple design, where a collimated beam is imaged / focused along one axis onto a split photodiode
- The object to be tracked is attached to the cylindrical lens
- All the light emitted is captured by the detector
- Insensitive to displacement in the *x* and *z* axes, or rotation about *z* axis
- Shot-noise limited sensitivity obtained analytically for this configuration of ~1×10^{-11} m $Hz^{-1/2}$ which was encouraging!



Imaging Sensor Optical Configuration



Photodiode Active Element Nomenclature

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Imaging Sensor Prototype

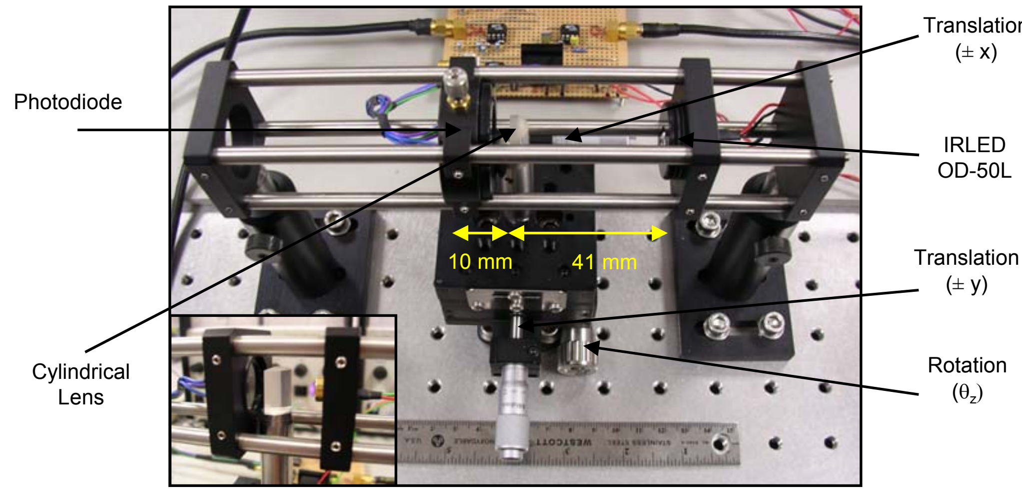
- Shot-noise limited sensitivity leads to an admissible technical noise of ~3.3 pA Hz$^{-1/2}$

- Attainable by careful component selection, op-amps, feedback resistor, and ensuring Johnson noise does not dominate

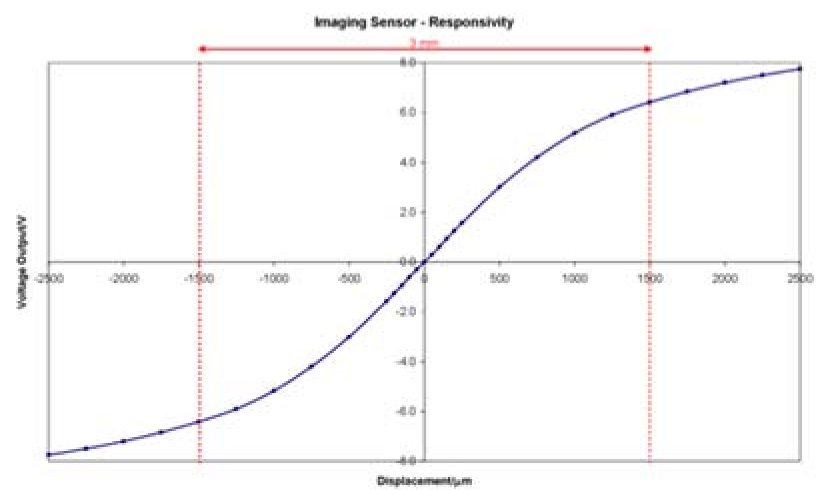
- Opto Diode Corp (OD-50L) IRLED was selected with typical output power of 50 mW at 500 mA (880 nm peak emission)

- UDT (SPOT-9D) photodiode is employed as the split detector with maximum rated incident power density of 100 W m^{-2}

- Measured responsivity of ~4.5 kV m^{-1} over a 3 mm (peak-peak) linear operating range



Imaging Sensor Bench-top Prototype



Imaging Sensor Responsivity

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Imaging Sensor Noise Characterisation

- Sensitivity measured for both modulated (lock-in) and un-modulated schemes

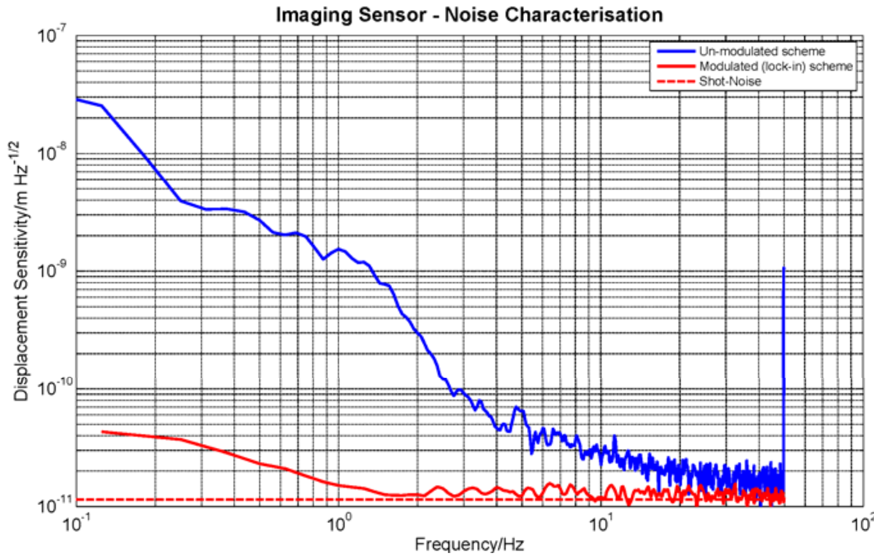
- Comparable high frequency performance above 25 Hz, significant divergence at frequencies below 25 Hz

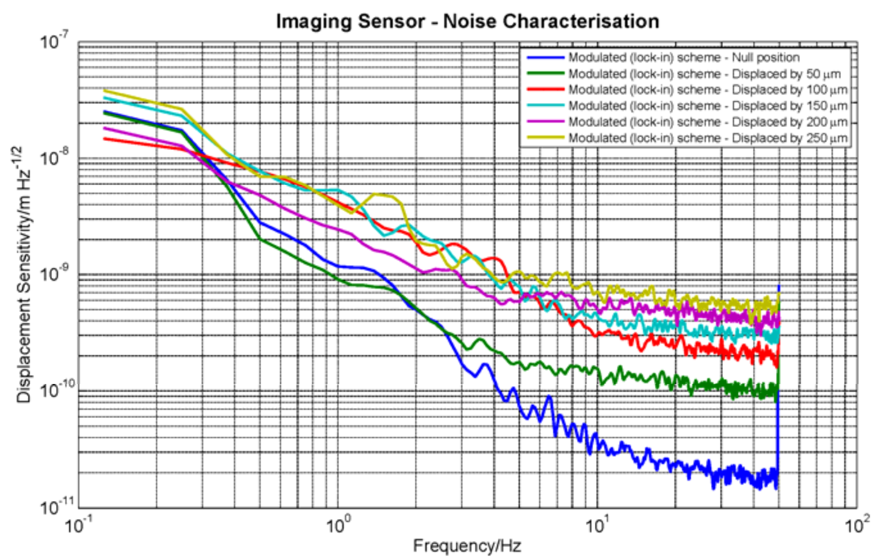
- Modulated scheme reaches the shot-noise limited performance at around 2 Hz, but this scheme was not permitted for aLIGO

- A problem was uncovered for all off-null measurements, the noise floor deteriorates significantly as you move away from the null position

- Consistent with measurements taken by collaborator (N. Lockerbie), common IRLED suspected to be the cause

- Pursued no further, requirements refined





Final Sensor Requirements

- Initial Sensor Requirements [1]:-
  - Assuming a minimal amount of passive eddy-current damping

Specification	Frequency Band	
Worst Case Noise	1 Hz to 10 Hz $\approx 2\times10^{-11}$ m $\mathrm{Hz}^{-1/2}$	10 Hz to 20 Hz $\approx 2\times10^{-11}$ m $\mathrm{Hz}^{-1/2}$
Specification	**Displacement (peak-peak)**	
Operating Range	Minimum 3.00 mm	Target 3.00 mm

- Final Sensor Requirements [2] agreed 12 months later:-
  - Assuming a moderate amount of passive eddy-current damping

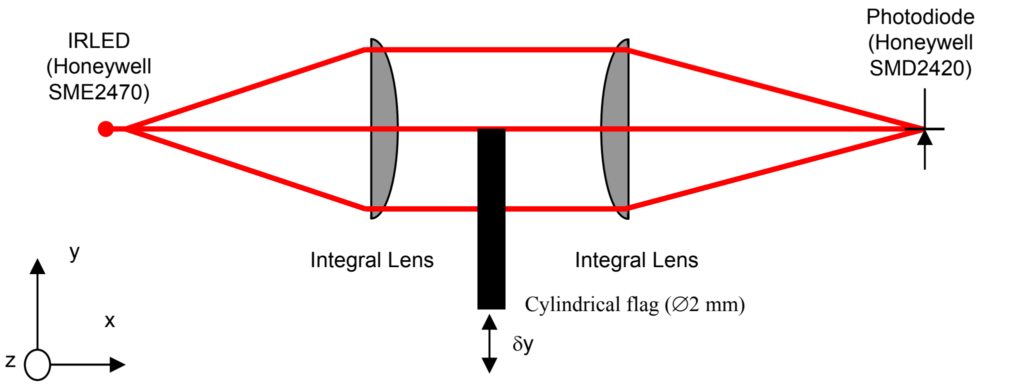
Specification	Frequency Band	
Worst Case Noise	1 Hz to 10 Hz 3×10^{-10} m/√Hz	10 Hz to 20 Hz 1×10^{-10} m/√Hz
Specification	**Displacement (peak-peak)**	
Operating Range	Minimum 0.35 mm	Target 0.70 mm

[1] K. Strain. Advanced LIGO suspensions general interpretation of requirements for sensors - for use as an initial planning aid by the UK project team v1.01. ALUKGLA0005aJUN03. 2003.

[2] K. Strain. Input to the OSEM selection review decision. LIGO-T040110-01-K. 2004.

Shadow Sensor Design

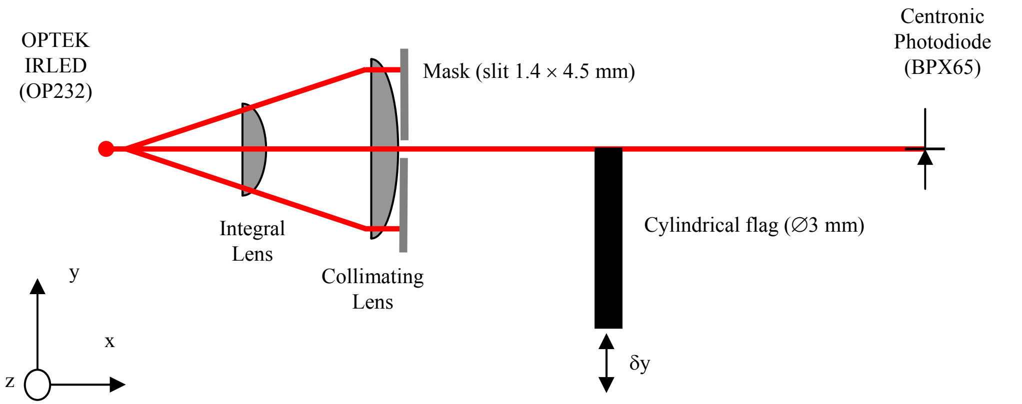
- Initial LIGO shadow sensor employs surface mount components with integral lenses with a single element photodiode
- Linear operating range of 0.7 mm (peak-peak)
- A shot-noise limited sensitivity for this configuration of ~7×10^{-11} mHz$^{-1/2}$
- Final design proposed courtesy of collaborator (N. Lockerbie [1]) sensor components identified via sensor study



Initial LIGO Sensor Configuration

OP232 IRLED

BPX65 Photodiode



Final BOSEM Sensor Configuration

[1] N. Lockerbie. Measurement of shadow-sensor displacement sensitivities. LIGO-T040136-00-K. 2004.

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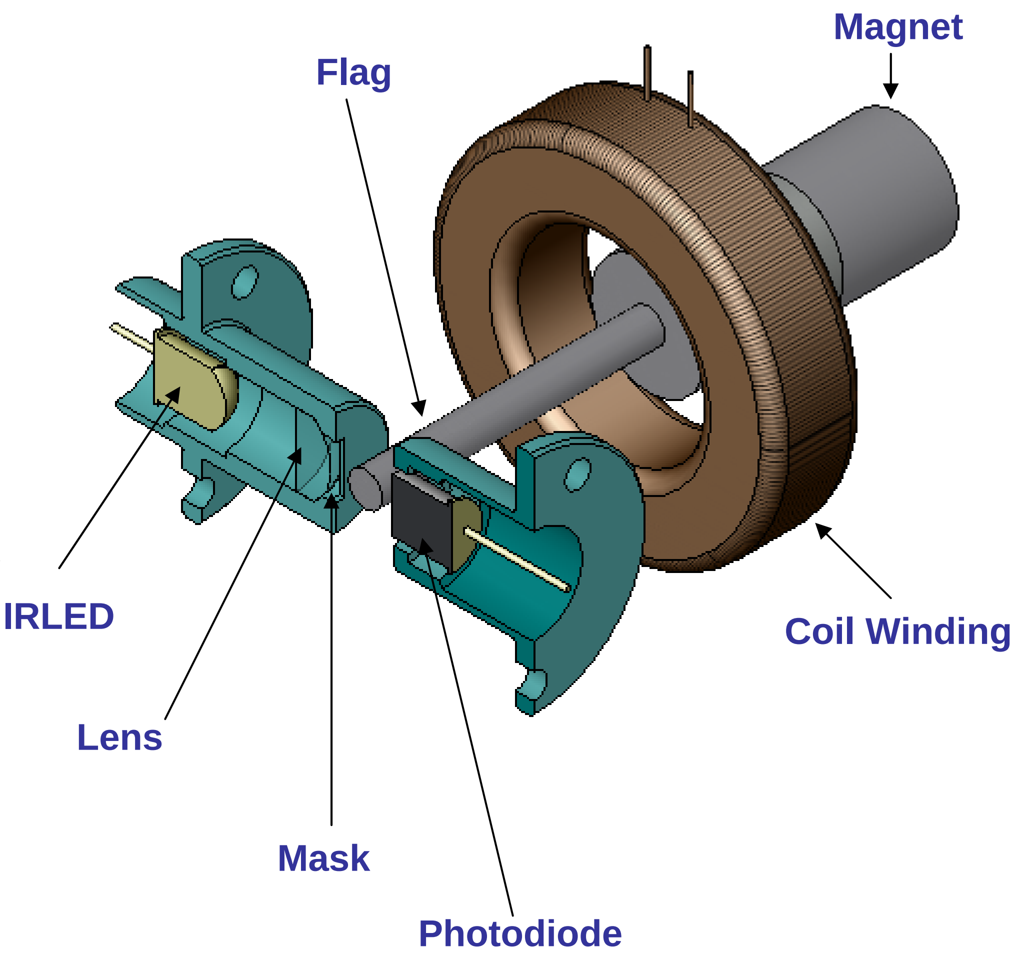
Shadow Sensor & Actuator Implementation

- Key sensor and actuator components *(highlighted)*
- Significant changes from Initial LIGO OSEMs
  - Stronger actuator force 50mN -> 500mN
    - Higher coil current
    - More coil windings
    - Larger magnets
  - Standard leaded device packages (i.e. not surface mount)
  - No epoxies or Ceramabond used in assembly process
  - Commercial-of-the-shelf connectors (sub-D to μ-D)
  - Custom flexi-circuit for interconnections

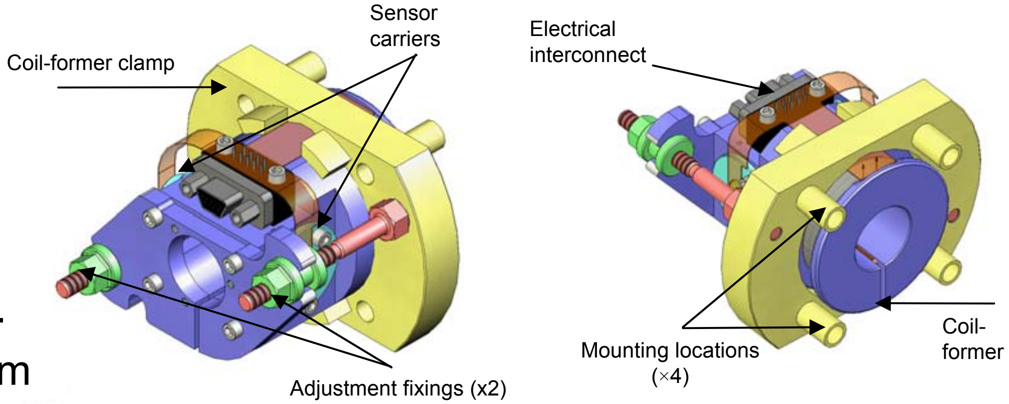


BOSEM Sensor and Actuator Assembly

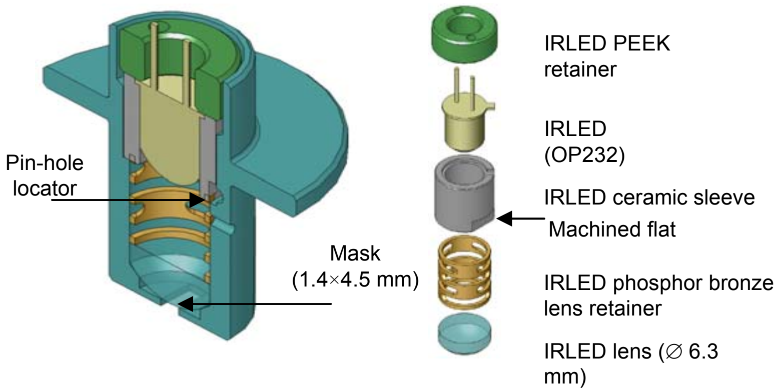
BOSEM Mechanical Design

- Initial LIGO OSEM design issues to overcome:-
  - Tricky assembly
  - High failure rate
  - Non-intuitive alignment and adjustment

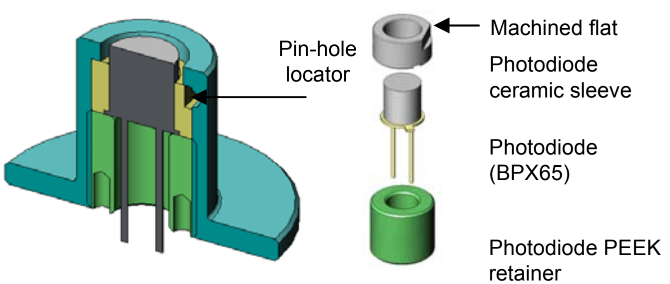
- BOSEM Design Specification [1]:-
  - Overall dimensions 62x45x66 mm
  - Mass 170 g
  - Adjustment range ~11 mm



BOSEM Assembly (Left) Rear isometric view. (Right) Front isometric view



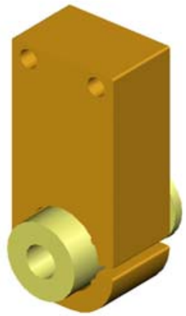
Sensor IRLED Carrier Sub-Assembly Section View



Sensor Photodiode Carrier Sub-Assembly Section View

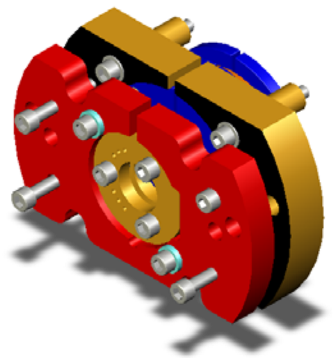
[1] S. Aston. BOSEM Design Document and Test Report. LIGO-T050111-04-K. 2009.

Evolution of OSEMs



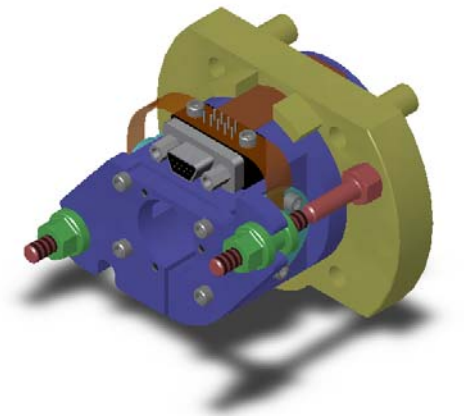
Initial LIGO

(OSEM)



Advanced LIGO

Controls Prototype (Hybrid OSEM)



Advanced LIGO

Noise Prototype &
Production article (BOSEM)

1st Generation Observatories

2nd Generation Observatories

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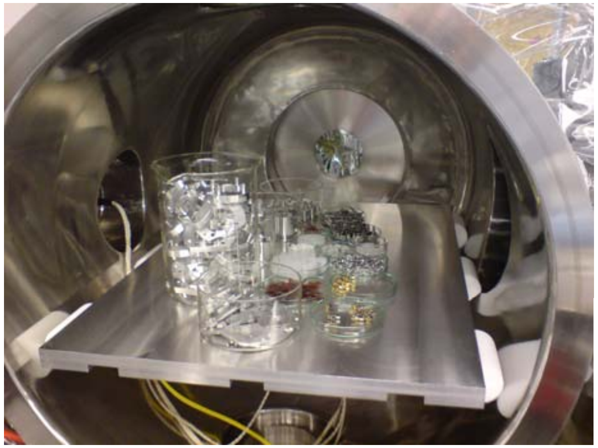
BOSEM Fabrication Summary

- 88 NPOSEMs completed in total
  - 32 units (D060218-A) shipped in December 2007
  - 56 units (D060218-B) shipped in January 2009
- 700 production BOSEMs (D060218-C) completed in total by September 2009
  - 16 units sent to ANU (including 8 for tip-tilt suspensions and 8 PEEK prototypes)

- All units tested using in-house Automated Test Equipment (ATE) [1]
- Full capacity at Birmingham clean-room facilities ~100 units/month
- Shipped in batches UHV-clean to Caltech on an agreed schedule



Pre-assembly bake out & RGA scan

Dedicated clean-room assembly facility

Assembled BOSEMS at testing station

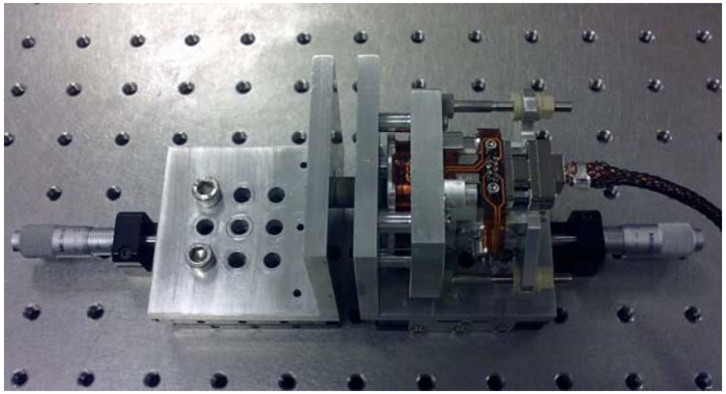
[1] S. Aston. BOSEM Test Specification. LIGO-T070107-06-K. 2011.

BOSEM End-to-End Testing

- Prior to shipping the assembled and tested units a request was received to provide noise measurements for <u>every</u> channel / unit
  - Noise performance is <u>not</u> measured by our ATE
  - Intensive process, not a straightforward activity to undertake in a clean-room
  - Agreed to test a small random sample of 10 units

- For full noise characterisation the aim is to conduct a realistic end-to-end test
  - Use a Satellite Box (developed by D. Hoyland, R. Culter and J. Heefner) which incorporates:-
    - Stable 35mA supply (1 of 4 channels used)
    - Low-noise photodiode amplifier front-end (1 of 4 channels used)
  - BOSEM + Flag mounted on linear translation stage and damped optical bench

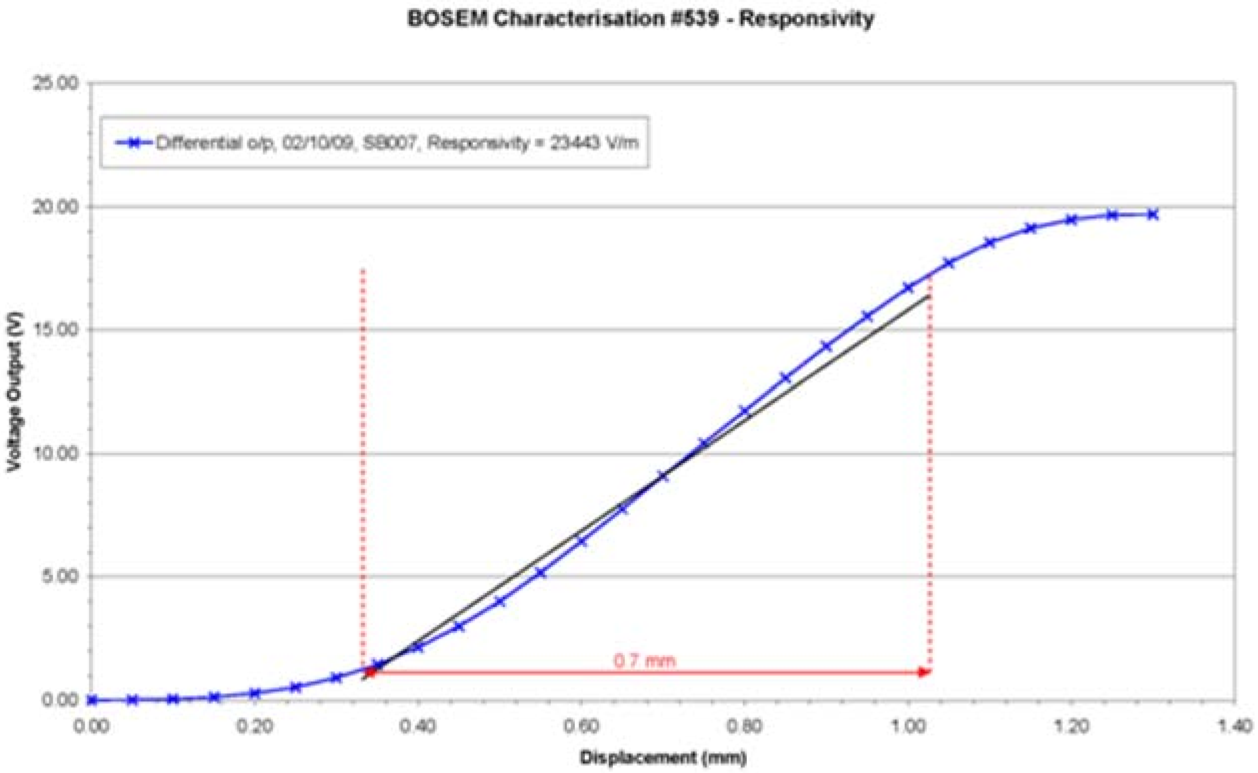
UoB Satellite Box (#007)



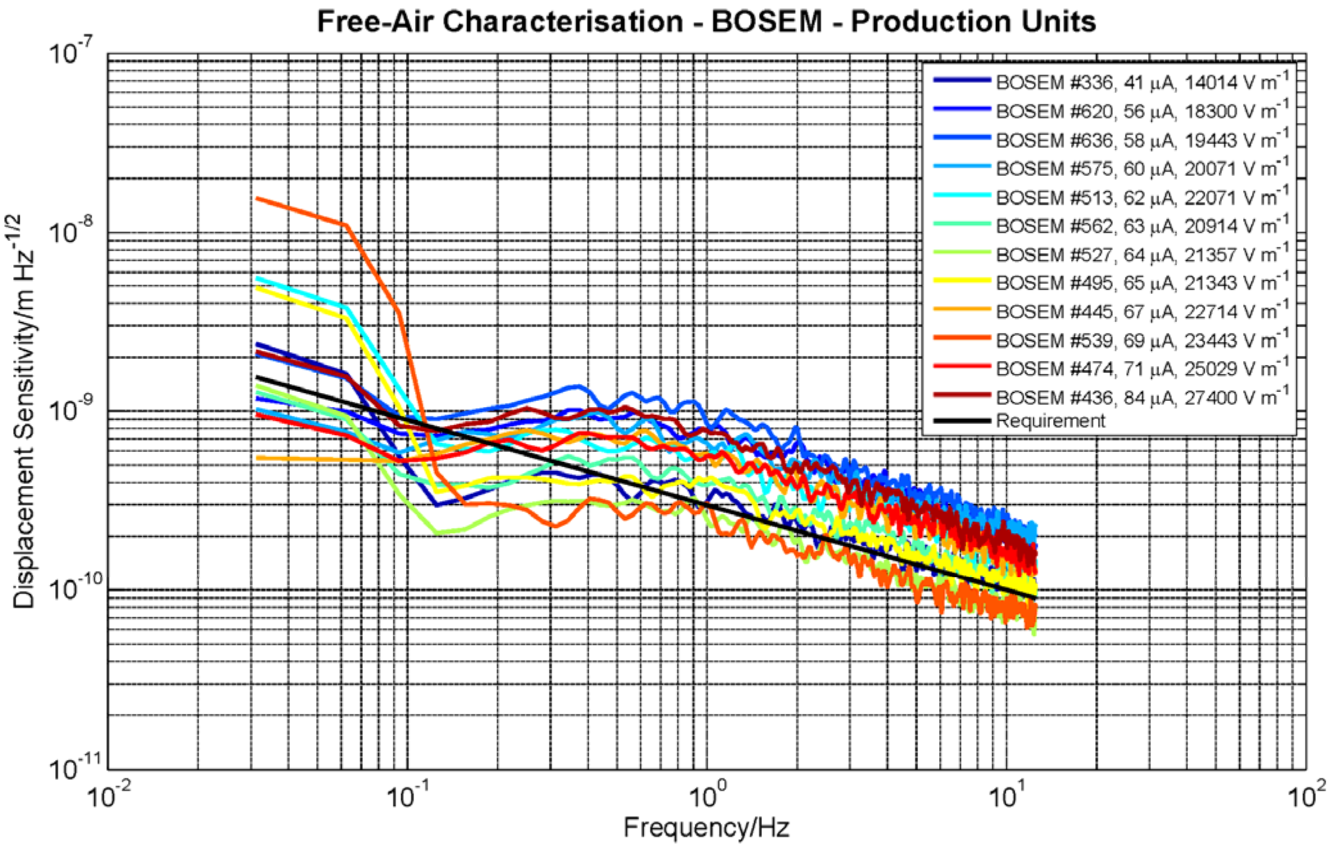
BOSEM + Flag on Optical Bench

BOSEM Responsivity

- First determine BOSEM operating range:-
  - Measure open-light voltage (ideally 20 V) i.e. with flag fully withdrawn
  - Measure closed-light voltage (ideally 0 V) i.e. with flag fully inserted
  - Determine responsivity (typically around 25 kV m^{-1})
  - Determine mid-point of operating range (ideally 10 V) and take noise measurement



BOSEM Noise Characterisation



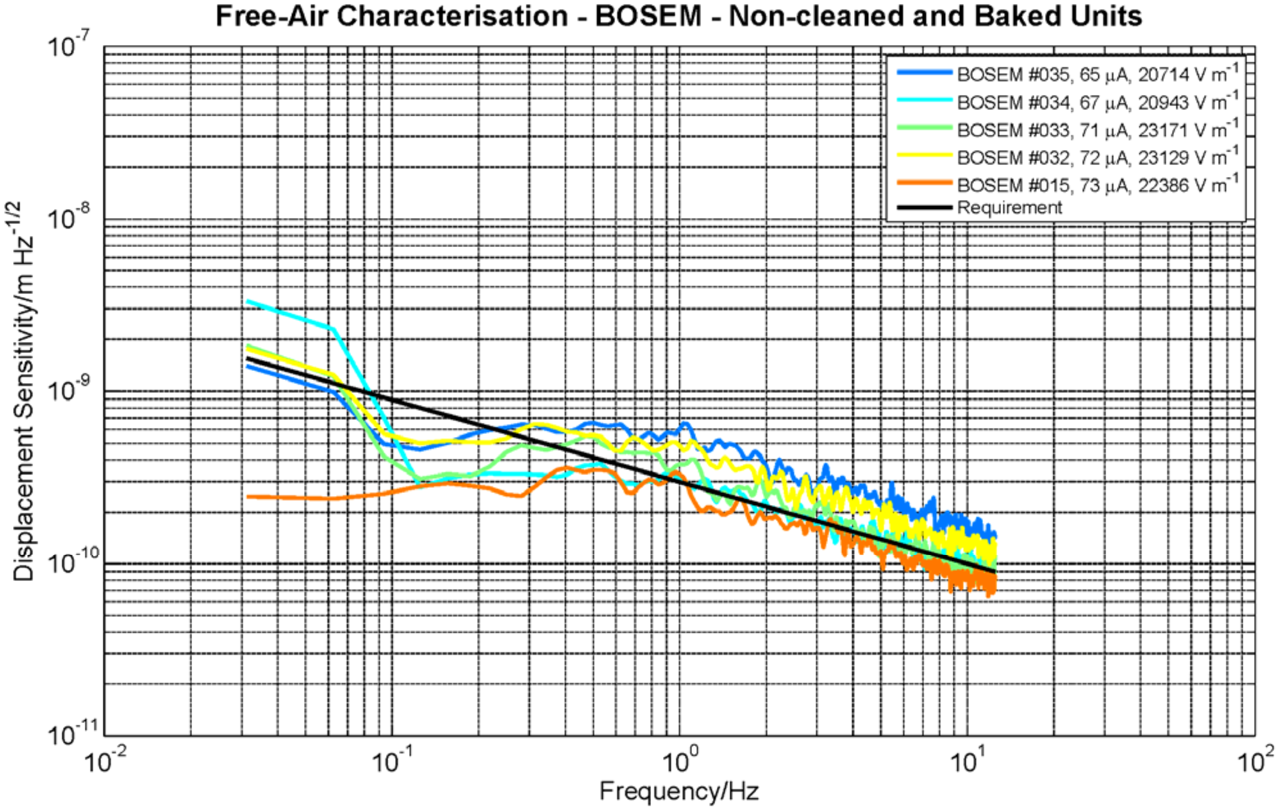
- The results observed [1] were somewhat disappointing!
  - Only ≈10% of units appeared to meet the noise requirement
  - Not observed previously

[1] S. Aston. Advanced LIGO BOSEM Noise Measurements. LIGO-T0900496-v4, 2011.

BOSEM Noise Investigation (1)

- A thorough investigation followed into the source of the excess noise
  - First established if it could be due to the cleaning or baking processes
  - Reconstituted 5 ‘dirty’ NPOSEMs for noise testing and found the same excess noise

  $\Rightarrow$ Nothing to do with cleaning or baking



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BOSEM Noise Investigation (2)

- After confirming repeatability of all of these measurements, it was possible to eliminate many other potential causes, such as:-
  - Photodiode (variation in responsivity etc)
  - Collimating lens (geometry, placement, back reflections and coatings)
  - Flexi-circuit (bending changing the track resistance, distribution of solder flux etc)
  - Mechanical carrier assemblies (tolerances, debris, MACOR part failures)

- All the measurements pointed towards the IRLED
  - Alignment (axial orientation) issue?
  - A consequence of the burn-in procedure? (thermally induced degradation)
  - Package tolerance, geometry and placement of the integral lens?

  $\Rightarrow$ None of the above

- Concluded that the excess noise is <u>intrinsic</u> to the IRLED

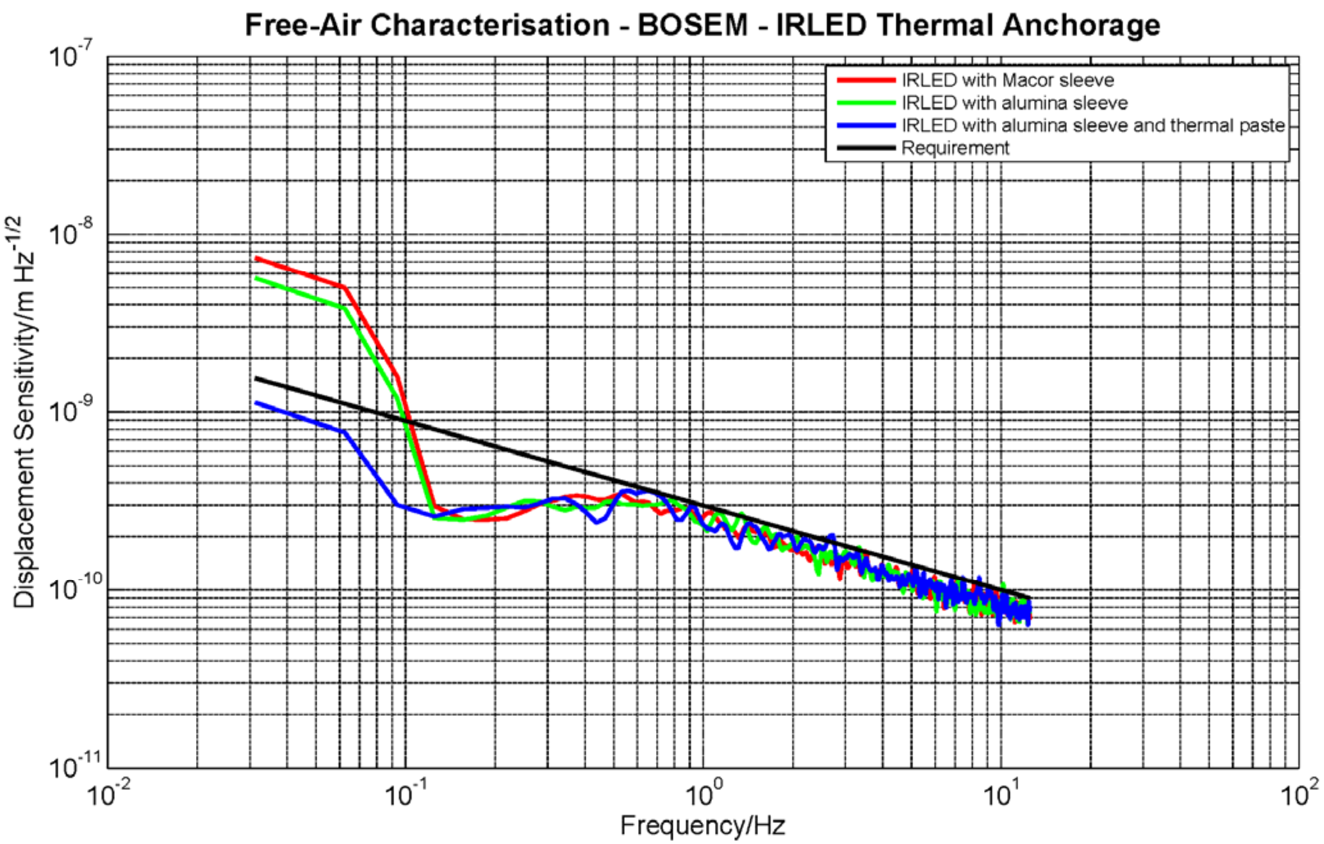
- Statements made above cover the highlights of the investigation, but a more detailed blow-by-blow account is also available [1]

[1] S. Aston. Advanced LIGO BOSEM Noise Measurements. LIGO-T0900496-v4, 2011.

BOSEM Noise Investigation (3)

- Thermal anchorage of IRLED, i.e. conductive link to environment
  - Potential device-to-device inconsistency

  ⇒ Could also be discounted



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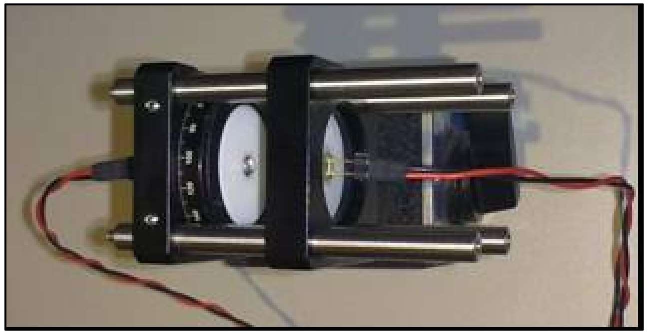
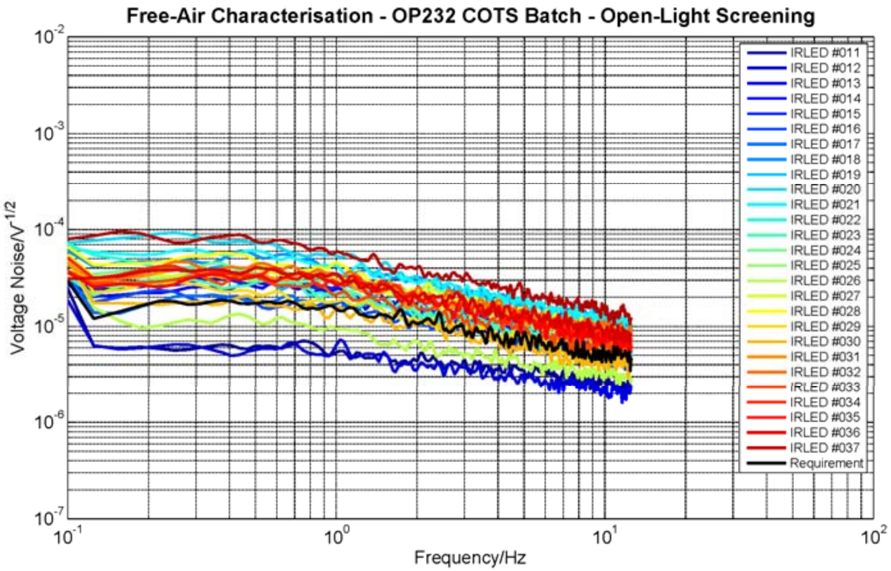
BOSEM IRLED Screening

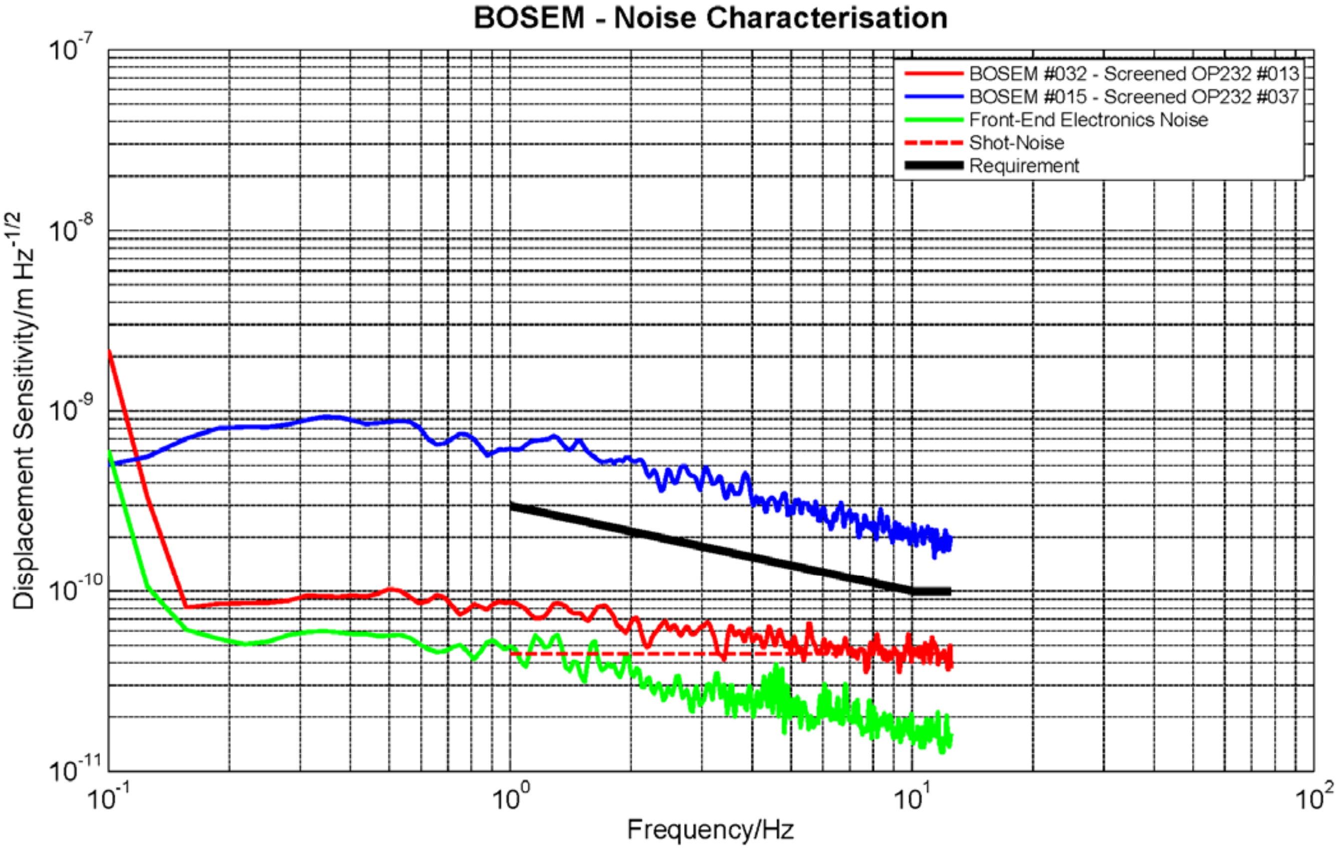
- Screening of IRLEDs is carried out in a simple fixture
  - Parameters measured include
    - Forward Voltage
    - Distance to Focal Plane
    - Open-light photo-current noise
  - Noise spectra taken on DSA
    - 10 spectra averaged over 0 to 50Hz
    - Takes ≈ 3 minutes per device
- Observed significant device-to-device variation of intrinsic noise in off-the-shelf devices
- Typical ≈10% 'pass' rate for OPTEK OP232
  - Not all units shown
  - Black line illustrates the approximate requirement



IRLED Screening Fixture



BOSEM Screening Verification



- Selected best and worse case examples of screened OP232's to retro-fit
  - Exhibited lowest photo-current noise IRLED (#013)
  - Exhibited highest photo-current noise IRLED (#037)
  - ⇒ Can be up to a magnitude difference between extremes
  - ⇒ Has the potential to be present in existing sensors

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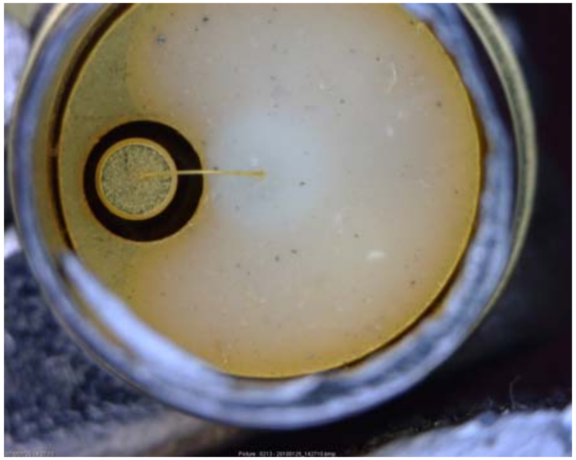
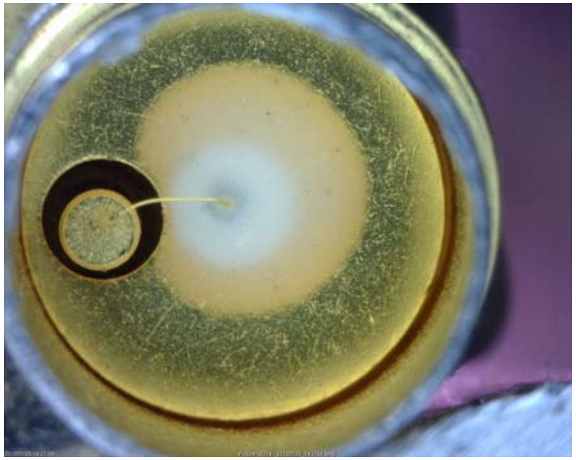
BOSEM IRLED Dissection

- Digital microscope images of section through IRLED active area



OP232 #020 (High Photo-current Noise)



OP232 #013 (Very Low Photo-current Noise)

Scrap OP232 (Unknown Photo-current Noise)

TSTS7100 #004 (Low Photo-current Noise)

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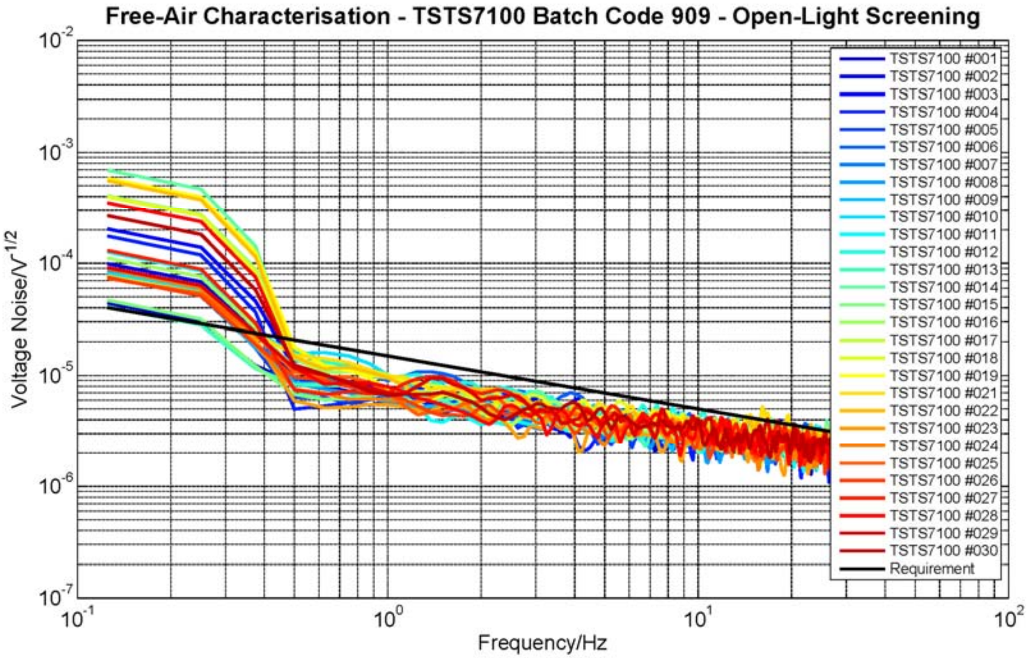
BOSEM Alternative IRLED

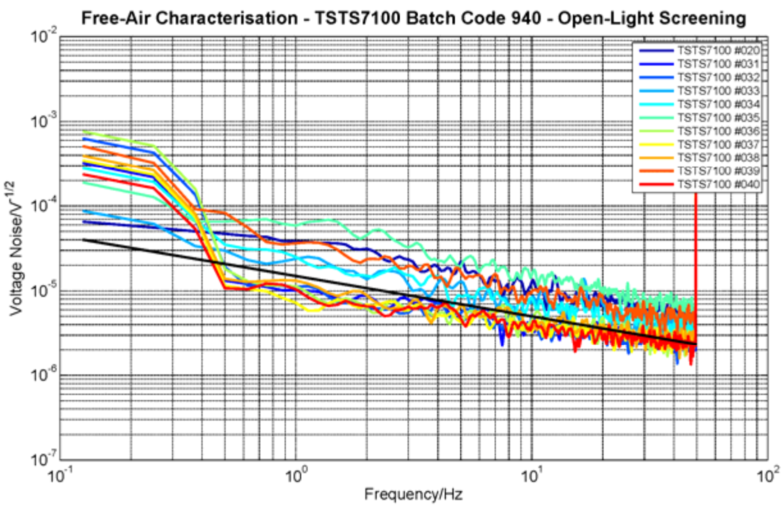
- During testing I identified a promising alternative candidate (Vishay TSTS7100)
  - Represents a more recent ‘state-of-the-art’ device
  - Opto-mechanical properties of TSTS7100 and OP232 are virtually identical
  - Pin-outs reversed and TSTS7100 larger forward current capability (up-to 250mA)

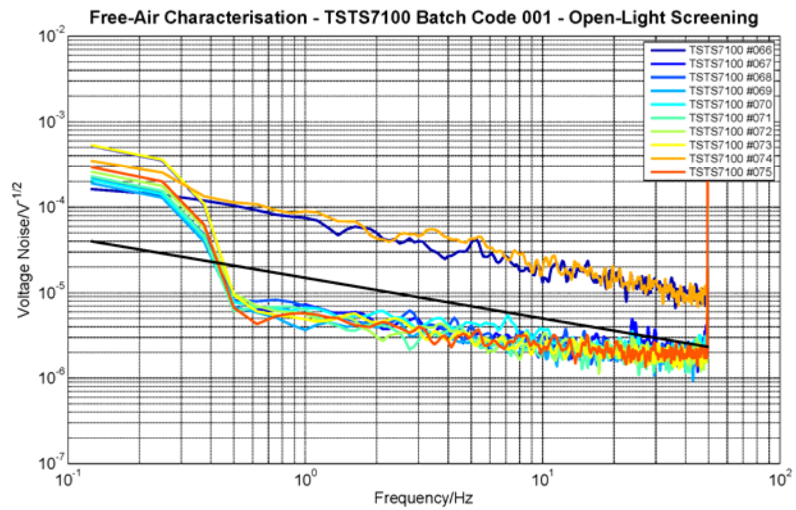


- 1st batch open-light photo-current noise test results (54 units)
  - Not all units shown
  - Black line illustrates approximate requirement, i.e. 100% Pass!

BOSEM IRLED Batch-to-Batch Variation

- However, for subsequent batches we purchased the pass rate has fallen:-
  - 2nd batch (940) ~50% pass rate (11 tested)
  - 3rd batch (001) ~80% pass rate (10 tested)
  - ⇒ Indication of significant batch-to-batch variation



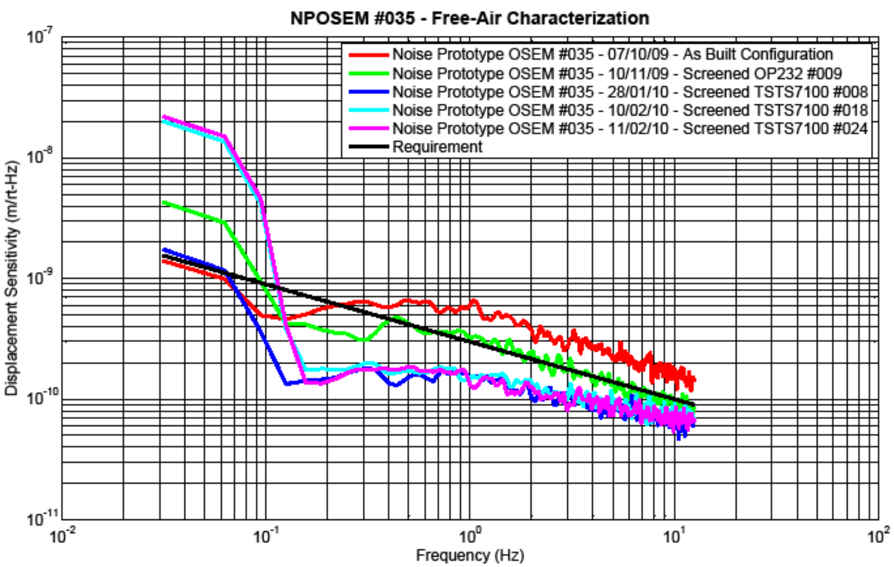


- Manufacture acknowledged the issue
  - But notes this is not something that they can measure
  - Not within their control i.e. used same process/parameters for each of above batches
- Screening offers the only solution
  - Willing to hold a batch of 2,000 devices and send us a sample of 20 for characterisation
  - We can then decide to accept or reject the batch depending upon results

BOSEM IRLED Mitigation Options

- (1) Stick with existing OPTEK OP232 device
  - Screen a sufficiently large quantity of devices to retro-fit into BOSEMs
  - Observed a ~10% pass across batches, but there is no guarantee that this will hold for future batches procured
  - Implies we would need at least 7,000 devices
  - Would take at least ~10 weeks of screening effort! (challenging screening ‘continuum’)

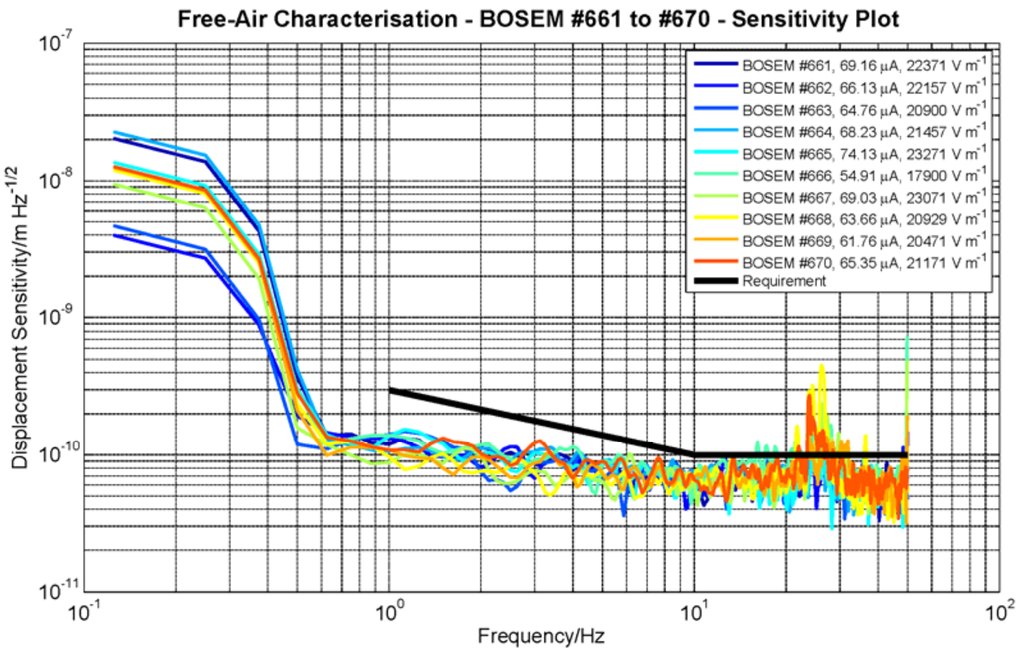
- (2) Switch to the alternative Vishay TSTS7100 device
  - Again screen all devices
    - Worst case this could be1,400
    - Best case this could be 700
  - Other obstacles had to be overcome
    - Burn-in testing complete
    - Seeking UHV approval
    - Obtain MTBF data from manufacturer
    - Identify fix for reverse polarity issue (electronic or mechanical)



- Option 2 proposed and approved

Production BOSEM IRLED Retro-fitting

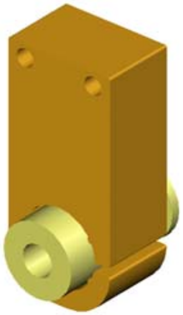
- Generated IRLED screening procedure [1] following which, compliant parts are burned-in, cleaned baked and retro-fitted into BOSEMs
- A random sample of ~12% from each batch of completed BOSEMs have been noise characterised with no failures observed [2]
- Retro-fitting of production BOSEMs completed and shipped to Caltech by March 2011
- Official end of UoB ALUK STFC Grant
- Still supporting ATE set-up at the aLIGO sites



[1] S. Aston. Advanced LIGO BOSEM Noise Measurements. LIGO-T0900496-v4, 2011.

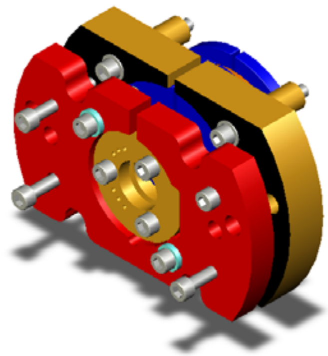
[2] S. Aston. BOSEM Production Summary. LIGO-T1100108-v2. 2011.

Evolution of OSEMs



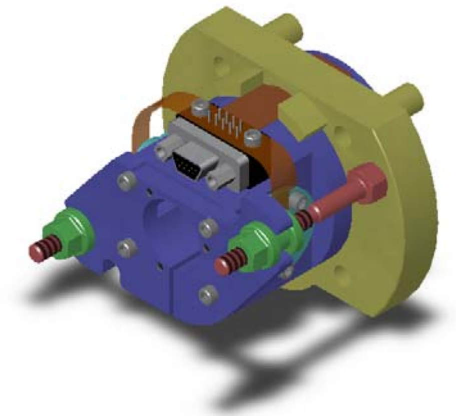
Initial LIGO

(OSEM)



Advanced LIGO

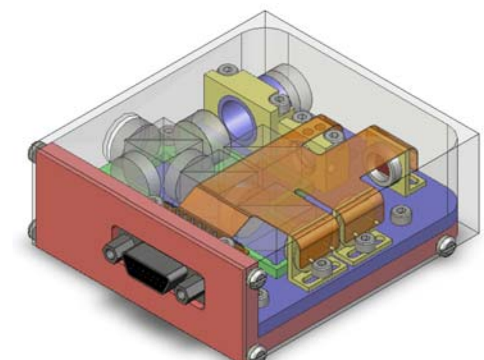
Controls Prototype (Hybrid OSEM)



Advanced LIGO

Noise Prototype & Final Production (BOSEM)

- Next generation observatories will place higher demands on sensor performance
  - BOSEMs offer the best sensitivity you can readily achieve with shadow sensor technology
  - Therefore need to adopt a different approach!

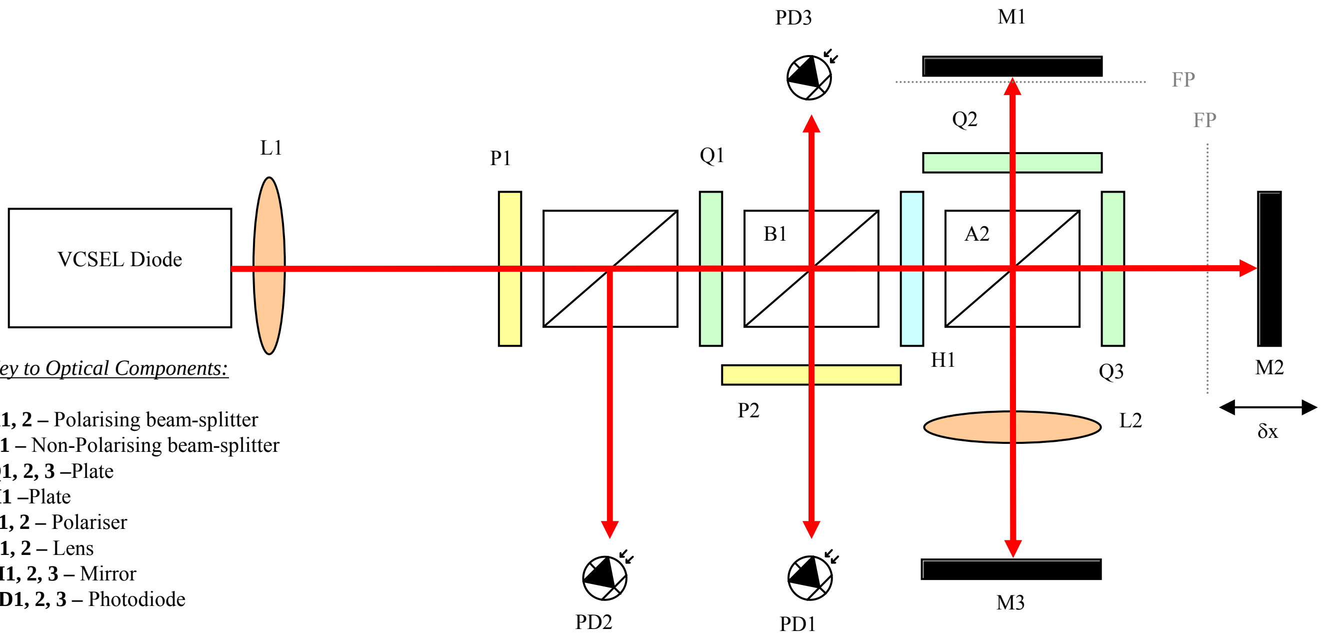


LIGO2, 2.5 or 3?

Interferometric Sensor (EUCLID)

EUCLID Prototype Design Motivation

- To ensure good low frequency stability need to avoid active parts that can age, thermally expand, generate heat, exhibit hysteresis, e.g. piezos, AOMs, EOMs etc.
- Required to be, easy to use, compact, portable and robust against misalignment, led to the development of a homodyne interferometric sensor (EUCLID)



Key to Optical Components:

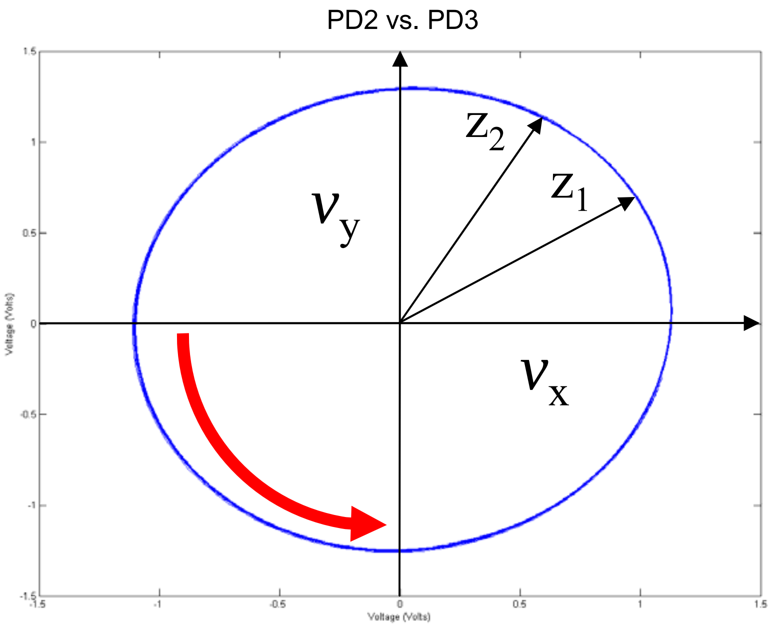
A1, 2 – Polarising beam-splitter
B1 – Non-Polarising beam-splitter
Q1, 2, 3 –Plate
H1 –Plate
P1, 2 – Polariser
L1, 2 – Lens
M1, 2, 3 – Mirror
PD1, 2, 3 – Photodiode

Optical Layout [1]

[1] C. C. Speake and S. M. Aston *"An interferometric sensor for satellite drag-free control".* IOP, Class. Quantum Grav. 22 (2005)

EUCLID Fringe Interpolation

- Two fringe intensities I_2, I_3 are 90^o out of phase (PD2 and PD3)
- Target mirror motion (Mirror 2) generates a circular Lissajous figure with I_2, I_3 plotted as v_x, v_y



- Phase calculation:-

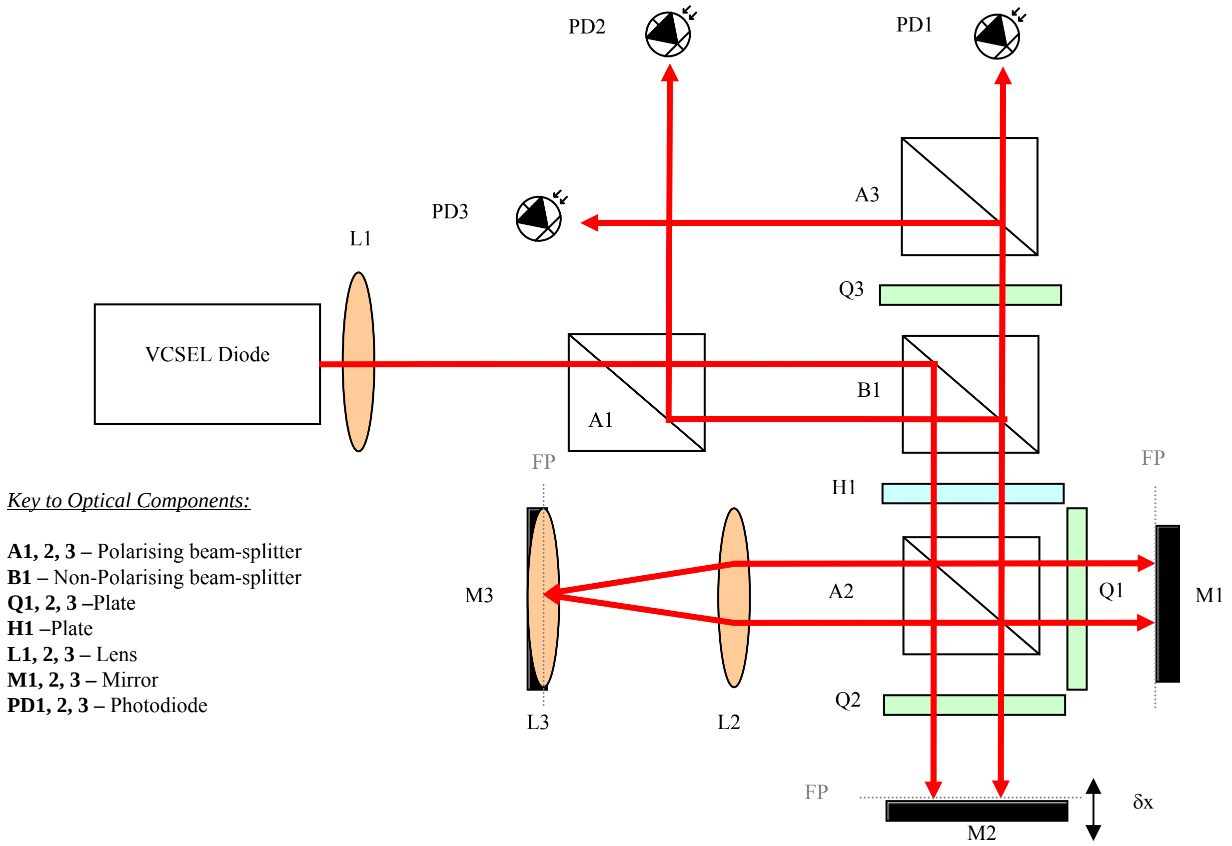
$$\Delta\phi = \arctan\left(\frac{\left(v_{y_2} - v_{y_0}\right)}{\left(v_{x_2} - v_{x_0}\right)}\right) - \arctan\left(\frac{\left(v_{y_1} - v_{y_0}\right)}{\left(v_{x_1} - v_{x_0}\right)}\right)$$

- Displacement calculation:-

$$\Delta z = \frac{\Delta\phi}{2\pi} \cdot \frac{\lambda}{4}$$

EUCLID Final Design Motivation

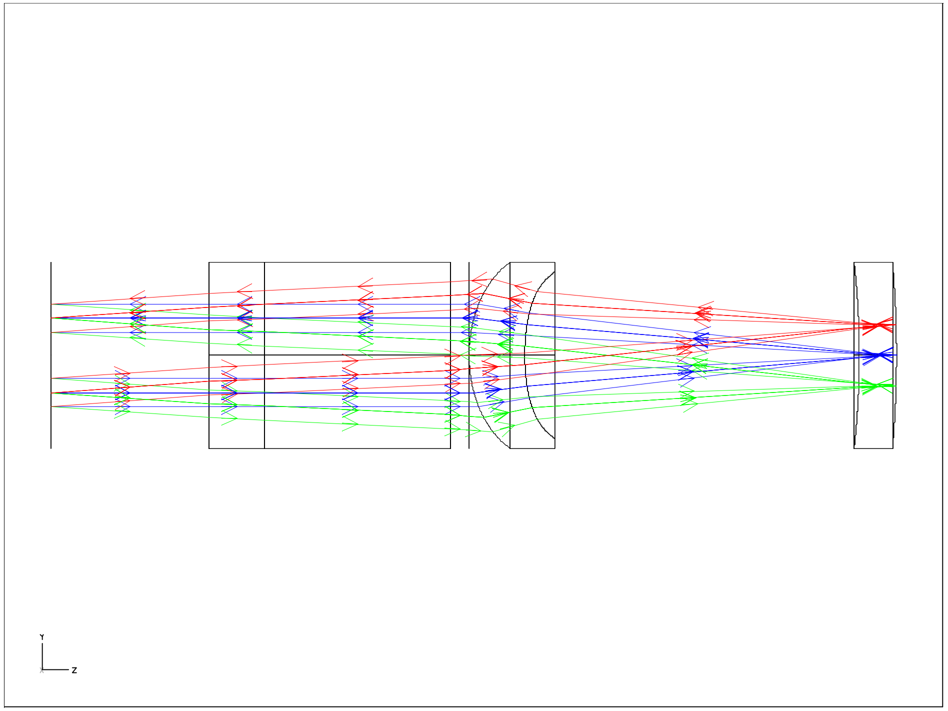
- To eliminate optical feedback into the VCSEL, the optical axis has been offset
- A third photodiode output, corresponding to –cosθ has been implemented
- Cats eye configuration has been further optimised



Optical Layout

EUCLID Optical Development

- Optimisation of the lens shape with Zemax (developed by Fabián Peña Arellano) [1]
- The effect of aberrations on the wavefront is minimised
- The parameters are also adjusted using other configurations in order to achieve the best mirror tilt immunity possible
- Enabling calculation of the fringe visibility

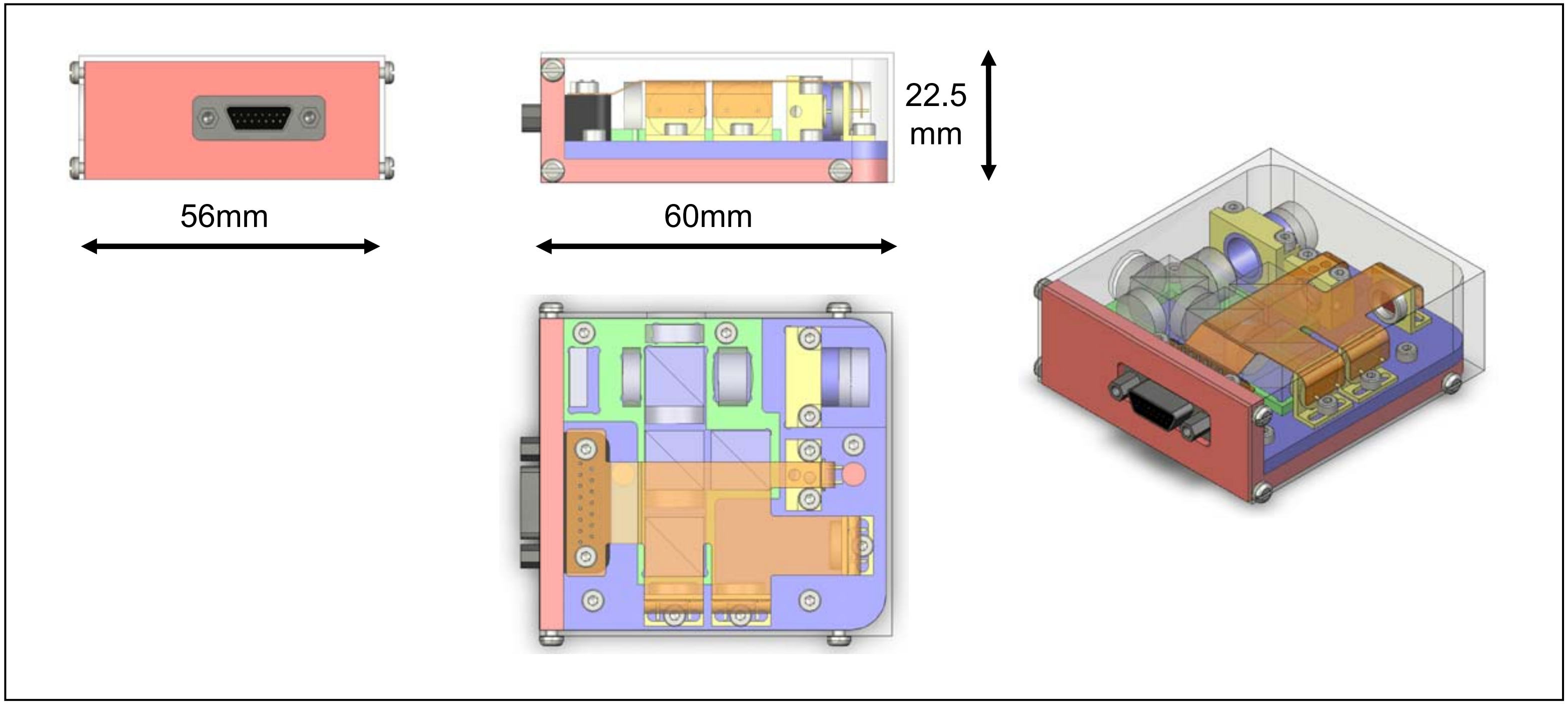


OPTO CAD Model

[1] F. E. Peña-Arellano and C. C. Speake. Mirror tilt immunity interferometry with a cat's eye retroreflector. Applied Optics, Vol. 50, No. 7. 2011.

EUCLID Specification and Design Goals

- Compact dimensions of 60x56x22.5 mm, Mass = 131 g
- Robust against misalignment +/- 1°
- Resolution of up to 1 pm/√Hz over a large working range > 2mm
- Can be constructed to be LIGO UHV compliant (using alternative UV adhesive)
- Incorporates VCSEL with known high MTBF

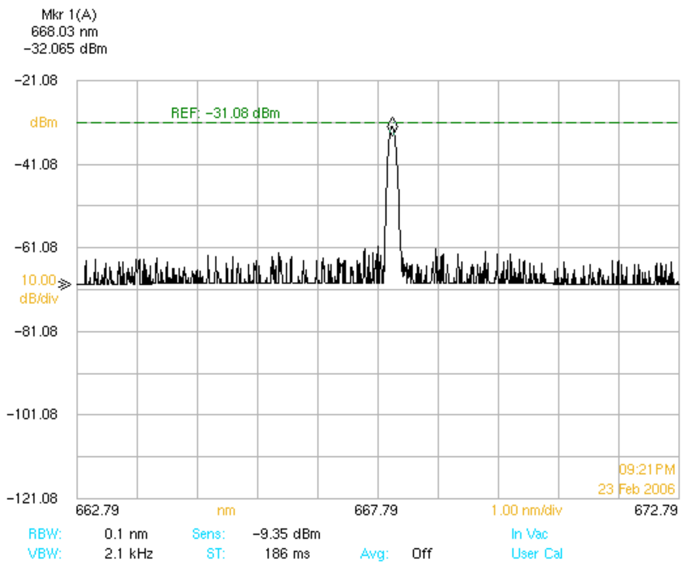


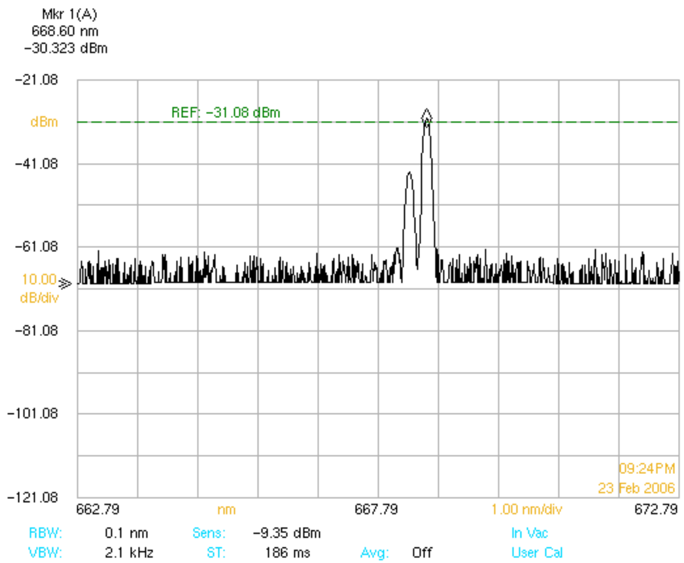
3D CAD Model Engineering Drawing

EUCLID Laser Selection

- Require a polarisation stable, mono-mode device
  - Laser Diodes, 665 to 850nm few mW output
  - VCSEL Diodes, 665 to 850nm few mW output and with integrated TEC option
  - DFB Lasers, 1550nm with ten's of mW output

- Various laser sources have been characterised for EUCLID suitability
  - Using Optical Spectrum Analyser to observe suppression of secondary modes
  - Measuring device-to-device threshold currents
  - Indentifying optimal drive current regime (each device requires to be screened)





Typical VCSEL emission spectra characterisation results

EUCLID Fabrication Summary

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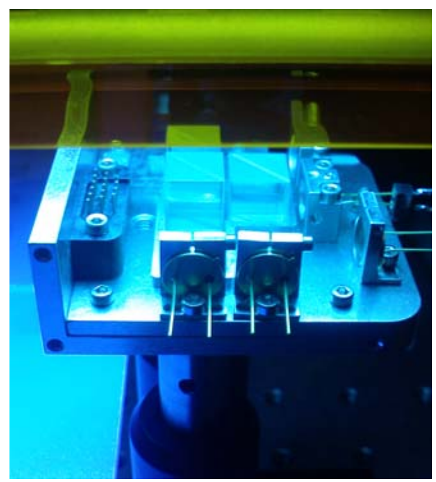
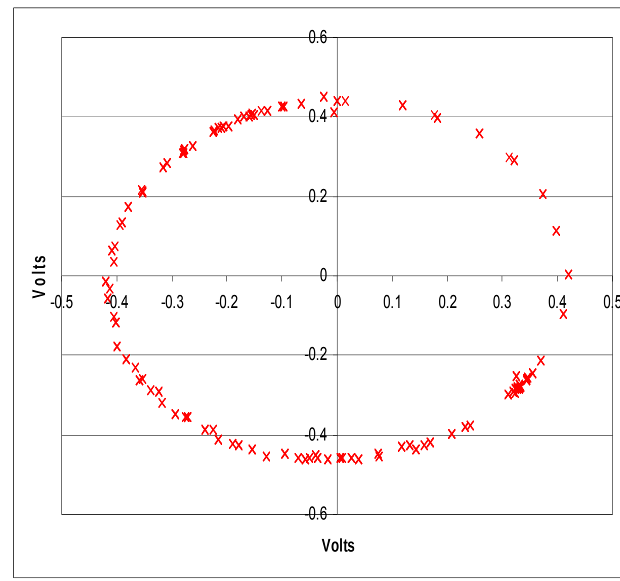
- 4 EUCLIDs have been fabricated so far:-
  - 2 for evaluation at MIT (contact R. Mittleman)
  - 1 for evaluation by ONERA
  - Processing further orders…
- New Electronics Module (developed by D. Hoyland)
  - Phase calculation determined via on-board FPGA (CORDIC engine)
  - 1 MHz, 18-bit analogue-to-digital converter
  - Enables tracking rates of upto ~10 cm s^{-1}

EUCLID Electronics Module



UV curing optical adhesive



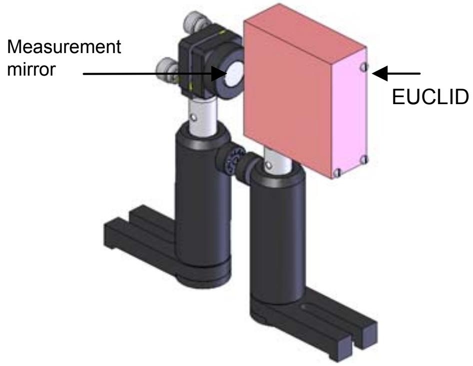
First-light fringe visibility

EUCLID Characterisation (1)

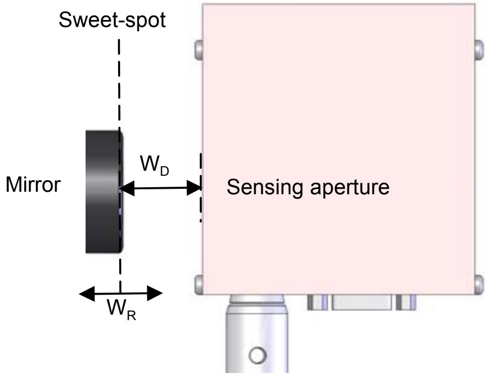
- All 4 units produced were first characterised at Birmingham
  - Can be seen to exceeded original design goals

EUCLID #	Fringe Amplitude/V	Tilt Immunity/θ	Working Range/mm	Working Distance/mm
1	≈ 10	± 1	≈ 6	6
2	≈ 7	± 1	≈ 4	6
3	≈ 9	± 0.5	≈ 10	6
4	≈ 9	± 1	≈ 6	6

- To assist with measurements, the following conventions have been defined [1]



EUCLID in Operation

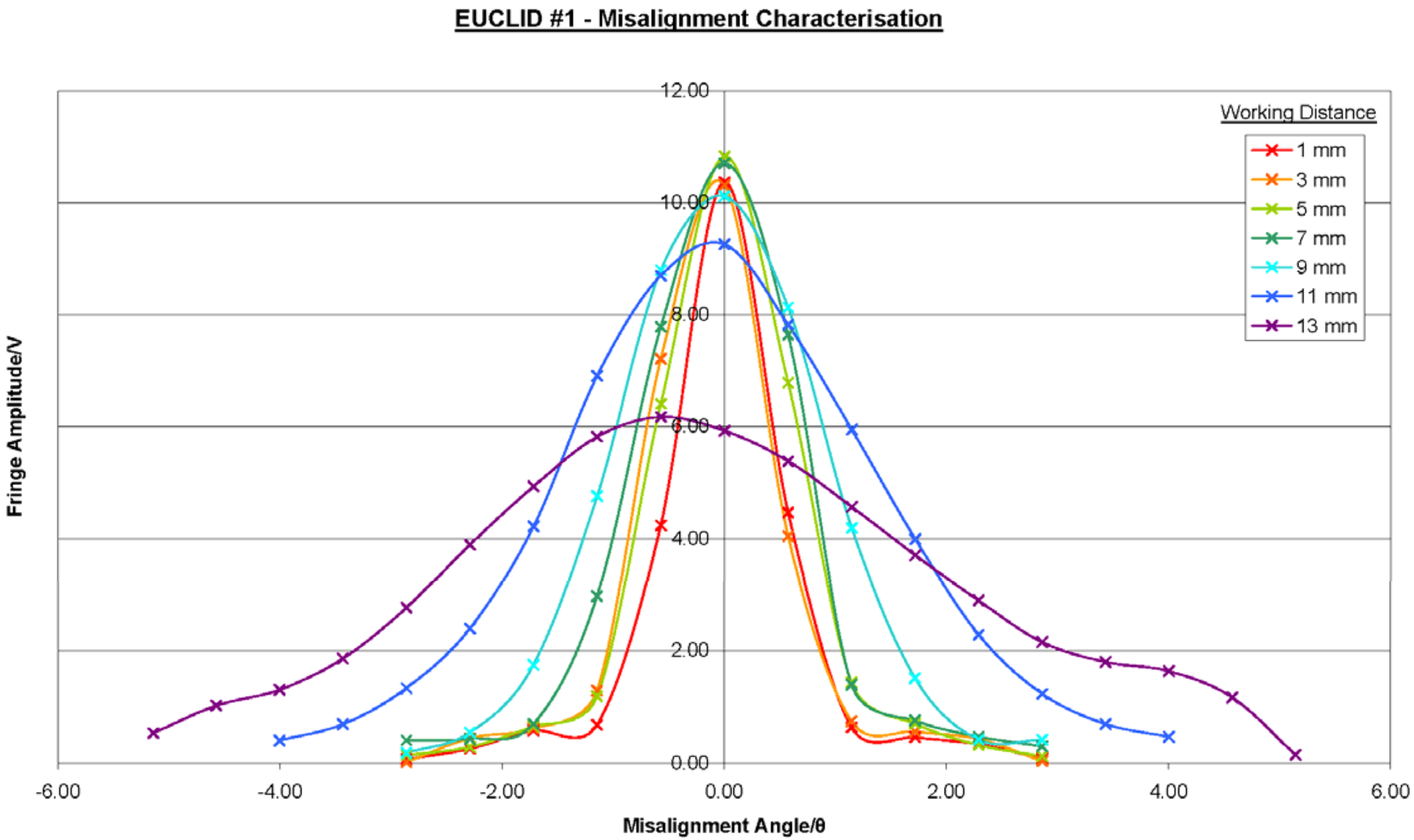


EUCLID Naming Conventions

[1] S. Aston, D. Hoyland and C. Speake. EUCLID User Guide (version 2.2). 2011.

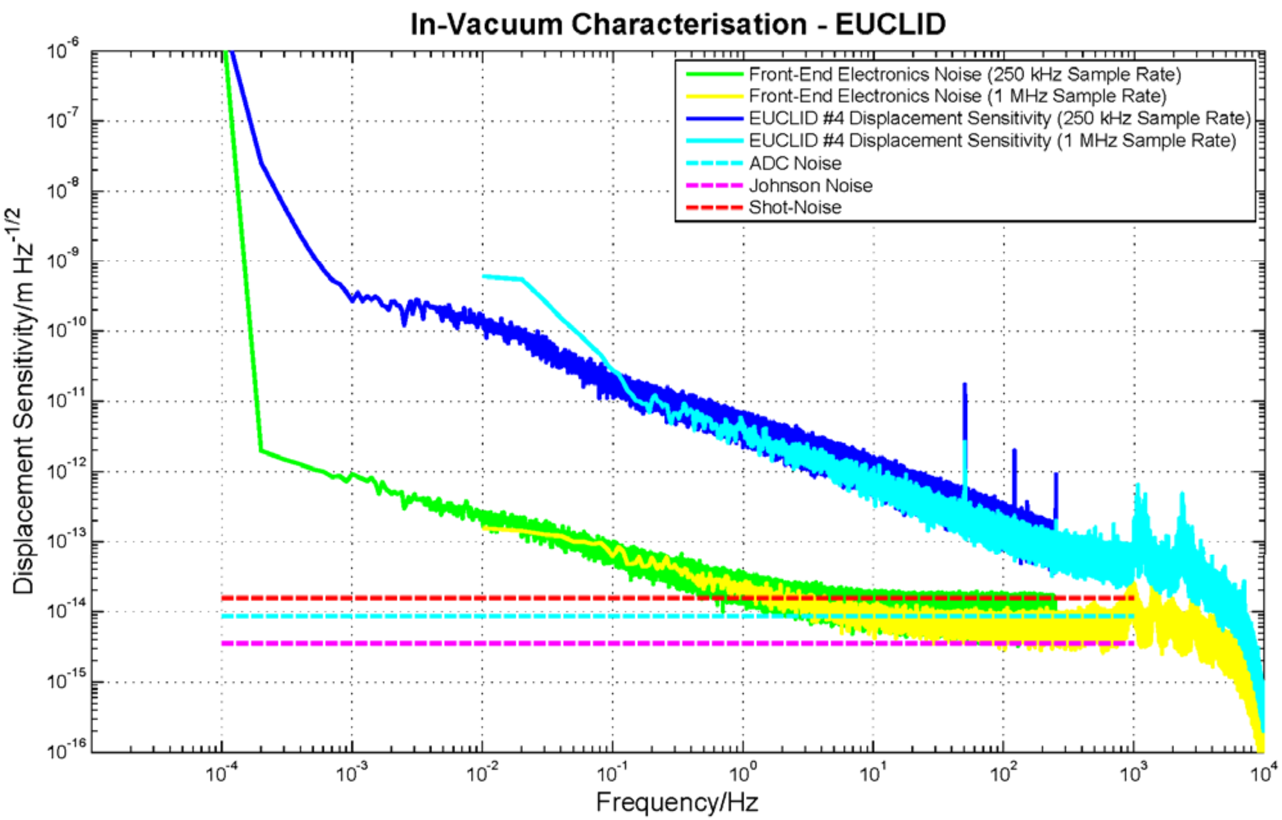
EUCLID Characterisation (2)

- Misalignment measurements
  - Working range ≈ 6 mm
  - Tilt-immunity ≈ ±1 degree



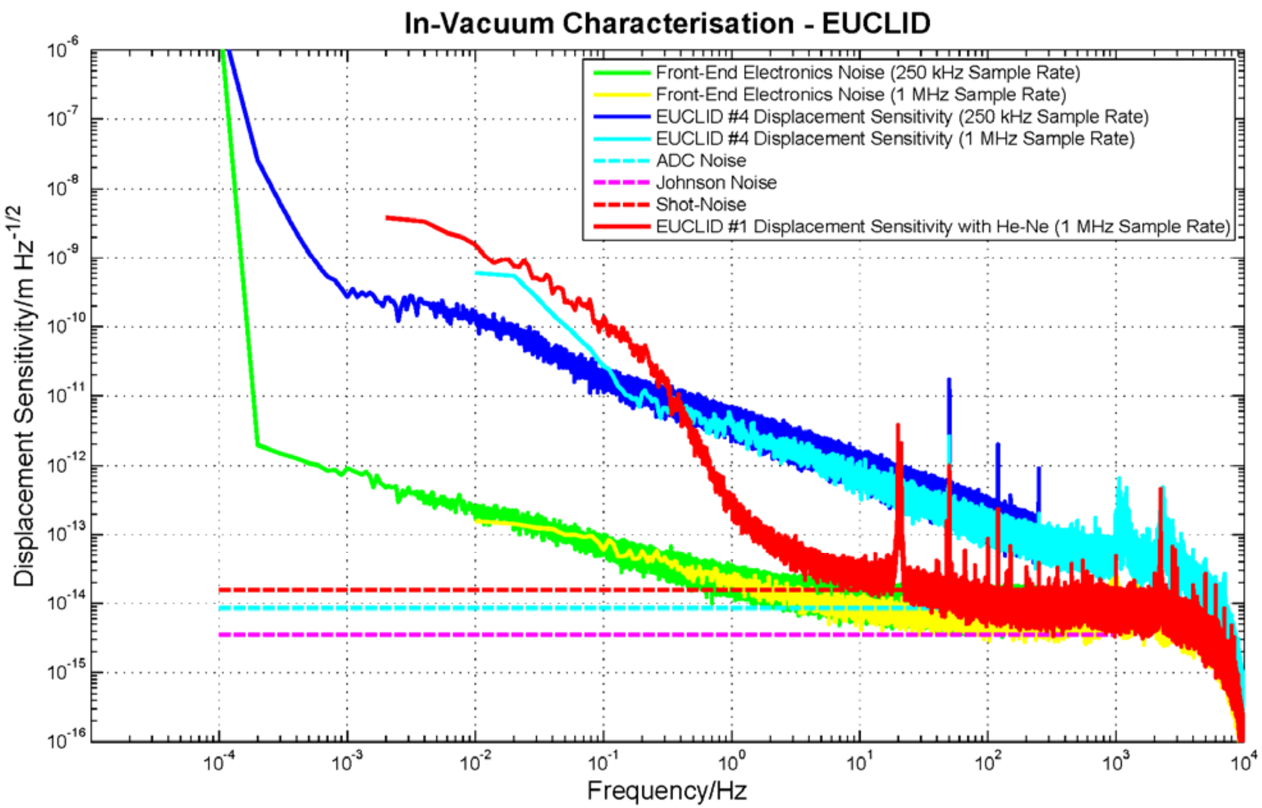
EUCLID Characterisation (3)

- In Vacuum sensitivity measurements
  - Achieve a vacuum level of ≈ 10 milliTor (10^{-2} millibar)
  - Reaches shot-noise limited sensitivity at ≈ 1 kHz
  - Sensitivity at 1 Hz ≈ 50 pm $Hz^{-1/2}$ and at 10 Hz ≈ 4 pm $Hz^{-1/2}$



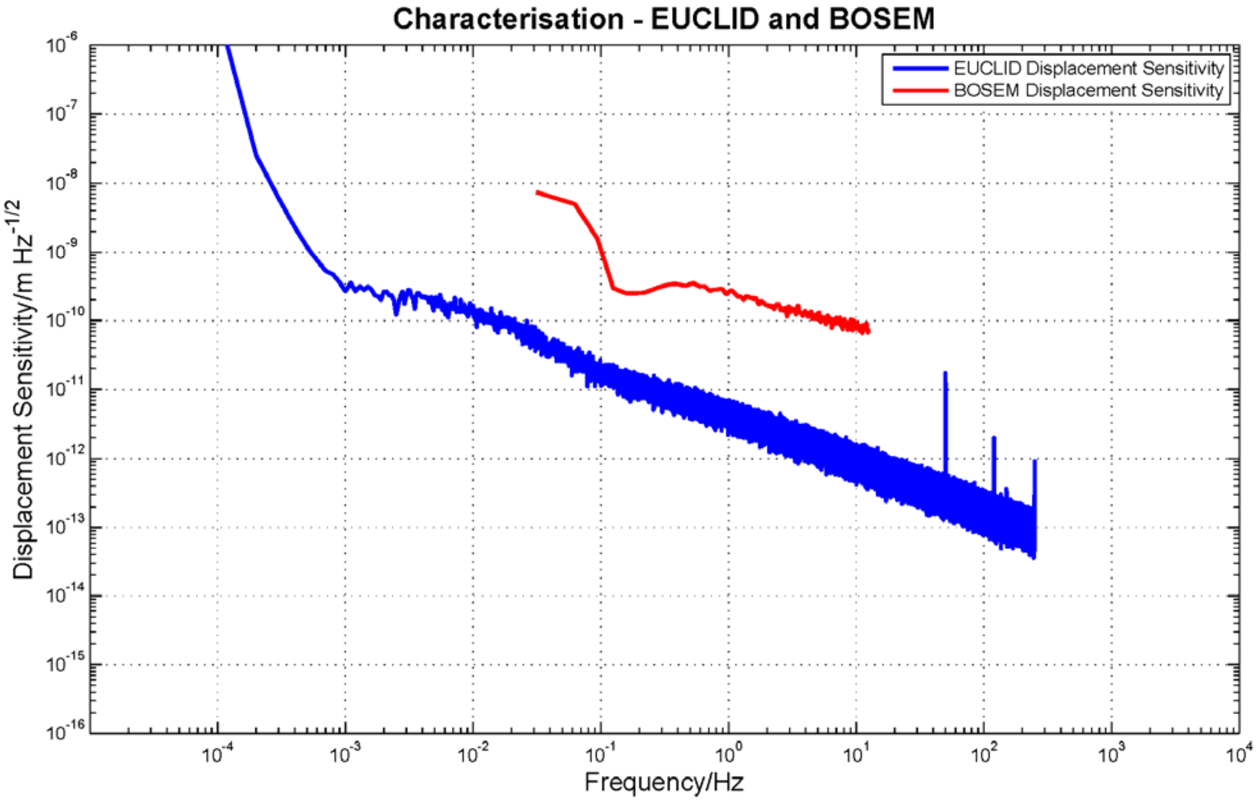
EUCLID Characterisation (4)

- Replace internal VCSEL with an external He-Ne 633 nm laser
  - Reaches shot-noise limited sensitivity at ≈ 50 Hz
  - High frequency sensitivity has improved
  - Worse at very low frequencies than VCSEL



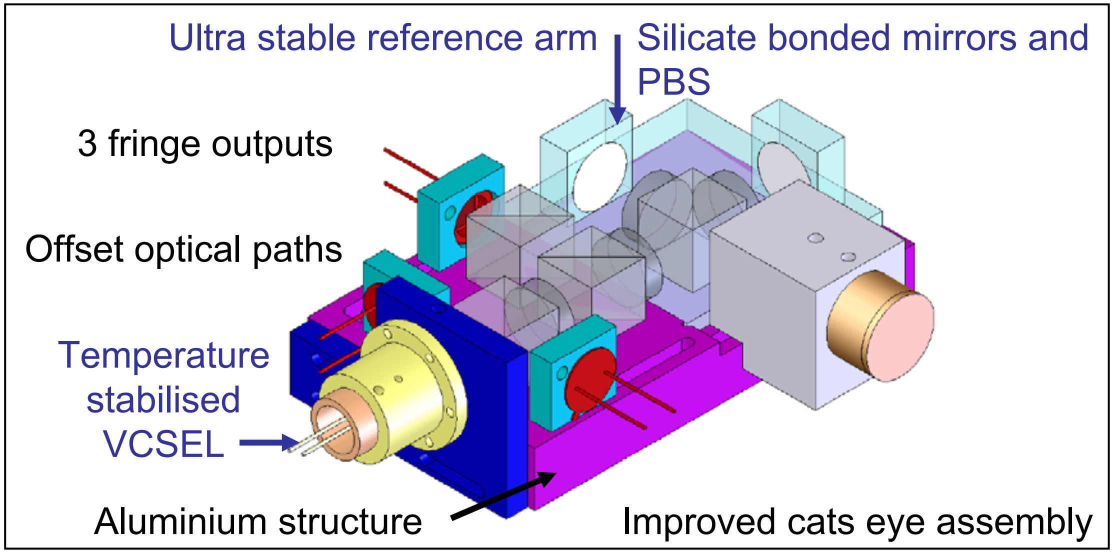
EUCLID and BOSEM Comparison

- EUCLID provides approximately 2 orders of magnitude sensitivity improvement over the BOSEM across the band and extends it towards lower frequencies
- Also offers almost 1 order of magnitude in working range from 0.7 mm to ~6 mm
- Achieved for a modest factor of ~5 increase in cost per unit

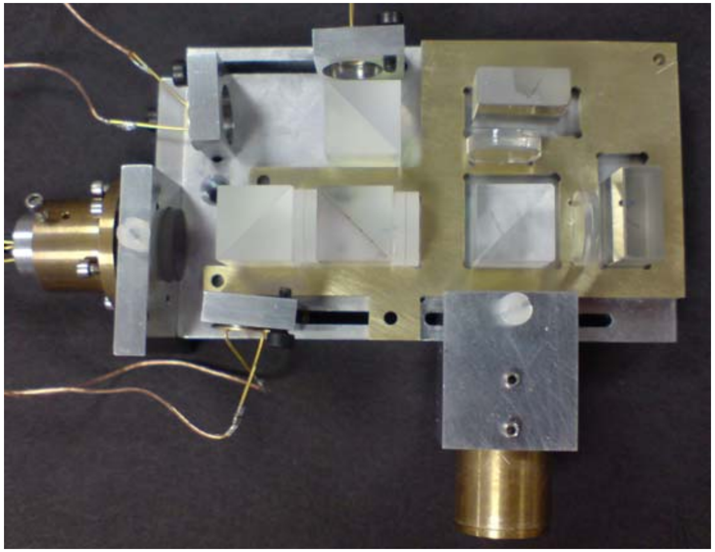


EUCLID Future Development

- Optimise working distance of cats eye configuration
- Migrate away from visible to near infrared VCSEL diodes
- Alternative rotational sensor version developed known as ILIAD
  - Cryogenic version being tested in ISL superconducting torsion balance experiment
- Aim to push down the sensitivity at low frequencies
  - Sensitivity goal of 10^{-11} m Hz$^{-1/2}$ over an extended LISA sensitivity band
  - Sensitivity goal for 3rd generation ground based GW observatories is unknown(?)



3D CAD Model



Bench-top Prototype

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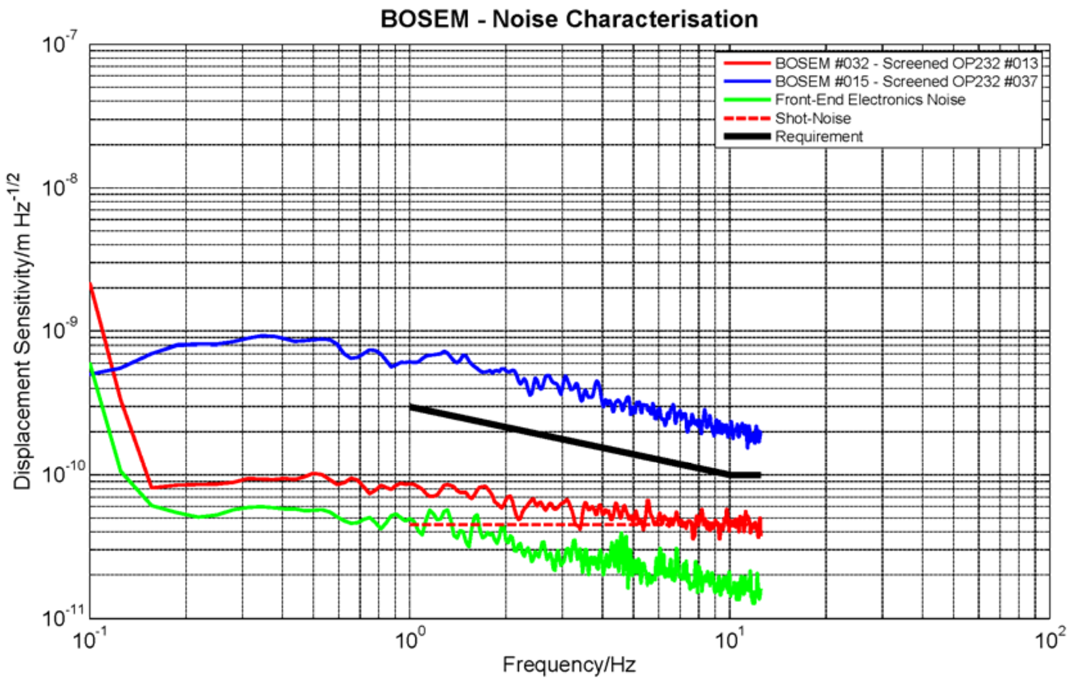
BOSEM Future Development

- Key lessons learned from the BOSEM experience
  - To be confident that all items meet the requirements it is absolutely necessary to rigorously characterise every single channel / unit
  - No surprise, that were pushing the boundaries of what technically feasible and can be duplicated on a large scale

- Possible scope for improvement in any future optical shadow sensors
  - Some super low photo-current noise devices were identified during the IRLED screening process, providing up to a factor ~3 improvement across the band
  - However, the amount of screening effort required would likely make this option unattractive



Acknowledgements

Thank you for your attention

I wish to acknowledge the support of collaborators both at Birmingham and further afield. I have tried to give credit where it is due during this presentation, but I apologies if you have been accidently left out!