# Electronic Lock-In Amplifier for Low Cost Radiation Thermometry

By Sam Maxwell

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# Temperature Measurement

- Accurate and reliable temperature measurement is a common problem across a range of Industrial Sectors [1].
- Examples are the Pharmaceutical, Chemical and Steel Industries.
- The most commonly used type of thermometer is the contact thermometer [2].

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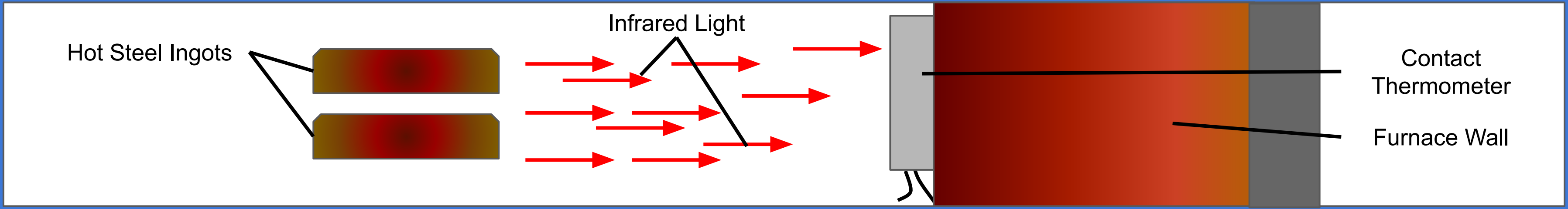
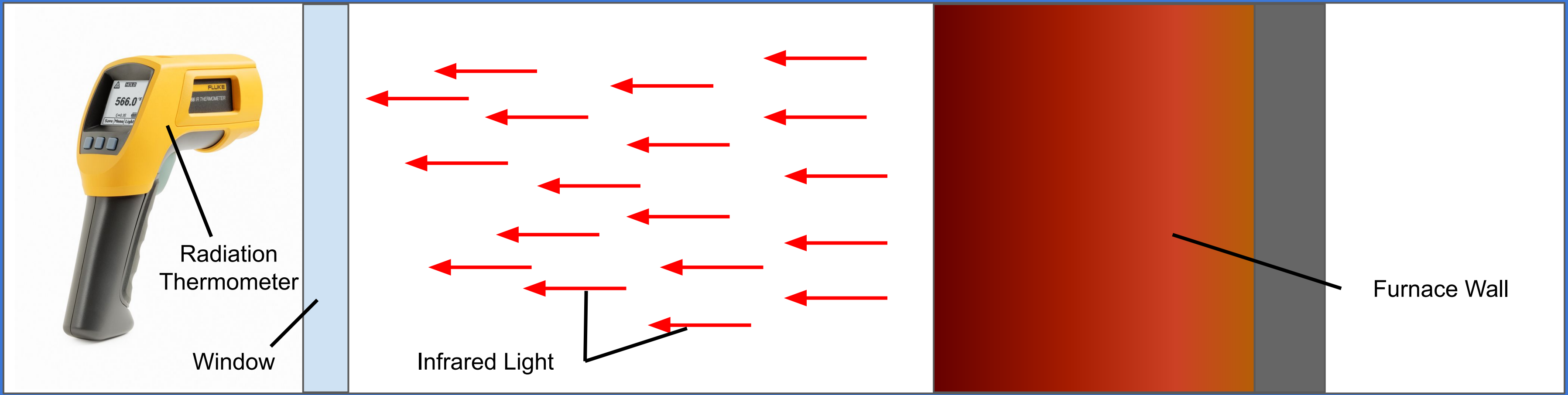
# Contact Thermometers

- Unfortunately, contact thermometers do not operate effectively in high temperature environments:
  - Sources of radiation in the environment heat up the contact thermometer. This makes the reading an average of the contacted surface and environment temperature [2].
  - Maintenance and repair is also more difficult as the Thermometer has to be installed inside the measured environment.



# Radiation Thermometers

- Radiation Thermometers measure the Black Body Radiation (mostly Infrared) emitted by objects at a temperature above 0K [2].
- This allows a small section of surface temperature to be measured from a distance, with lenses focusing the light onto the detector.



# Radiation Thermometers

- Unfortunately, several factors externally influence a Radiation Thermometers output signal [2]:
  - Reflections (Reflective Materials)
  - Emissivity
  - Atmospheric Scattering
  - Atmospheric Absorption

**This leads to a small output signal from the detector!**

# Detecting these Signals

- Sensitive and Low-Noise circuitry is required to accurately measure these signals and produce a reliable temperature reading.

**Lock-In Amplifiers are a method of measuring these signals, they can measure down to *pA* [3].**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- Mechanical components: require maintenance, calibration, fluctuate.
- Cost upwards of £1000 for unit alone [4]. Mechanical chopper forms additional cost.

# Project Aims and Specifications

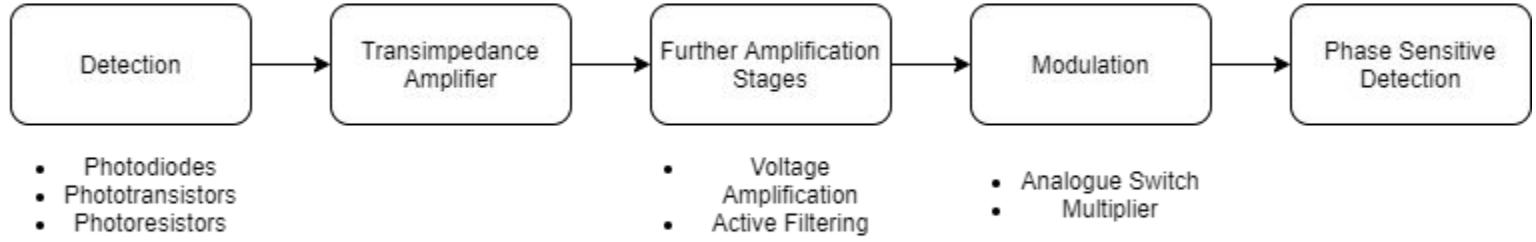
**Develop a Low-Cost, Fully Electronic Lock-In Amplifier.**

**Key Points:**

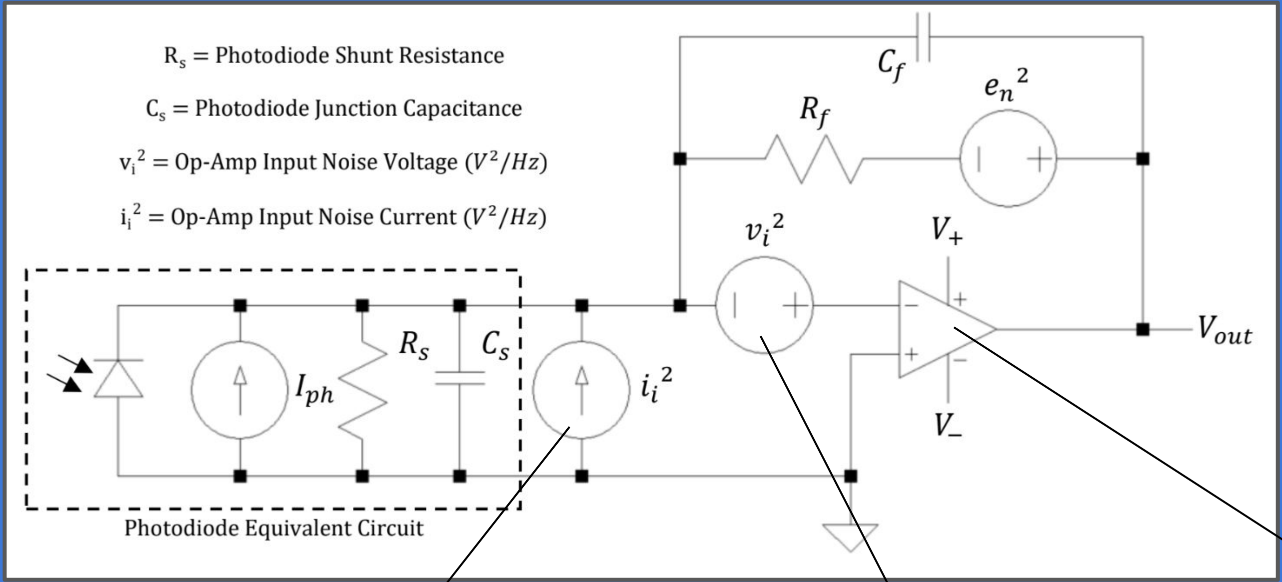
- Fully Electronic ⇒ No mechanical components.
- Low Cost ⇒ Approximately £100 target.
- Small Form Factor, capable of being adapted to Hand Held Units.
- Detectable temperature range of 400 to 1000 degrees celsius. I.e measurement down to *pA*.
- Improve performance over previous design by Tarick Osman [5].

# What is a Lock-In Amplifier?

# Key components of a Lock-In Amplifier System [6]



# Transimpedance Amplifiers [3]




Gain and Corner Frequency

$$\frac{V_{out}}{I_{in}} = -\frac{R_f}{j\omega C_f R_f + 1} \quad \Omega$$

$$\lim_{\omega \to 0} \frac{V_{out}}{I_{in}} = -R_f \quad \Omega$$

$$f_c = \frac{1}{2\pi C_f R_f} \quad Hz$$

Johnson Current Noise Spectral Density

$$i_n = \sqrt{\frac{4kT}{R}} \quad \frac{A}{\sqrt{Hz}}$$

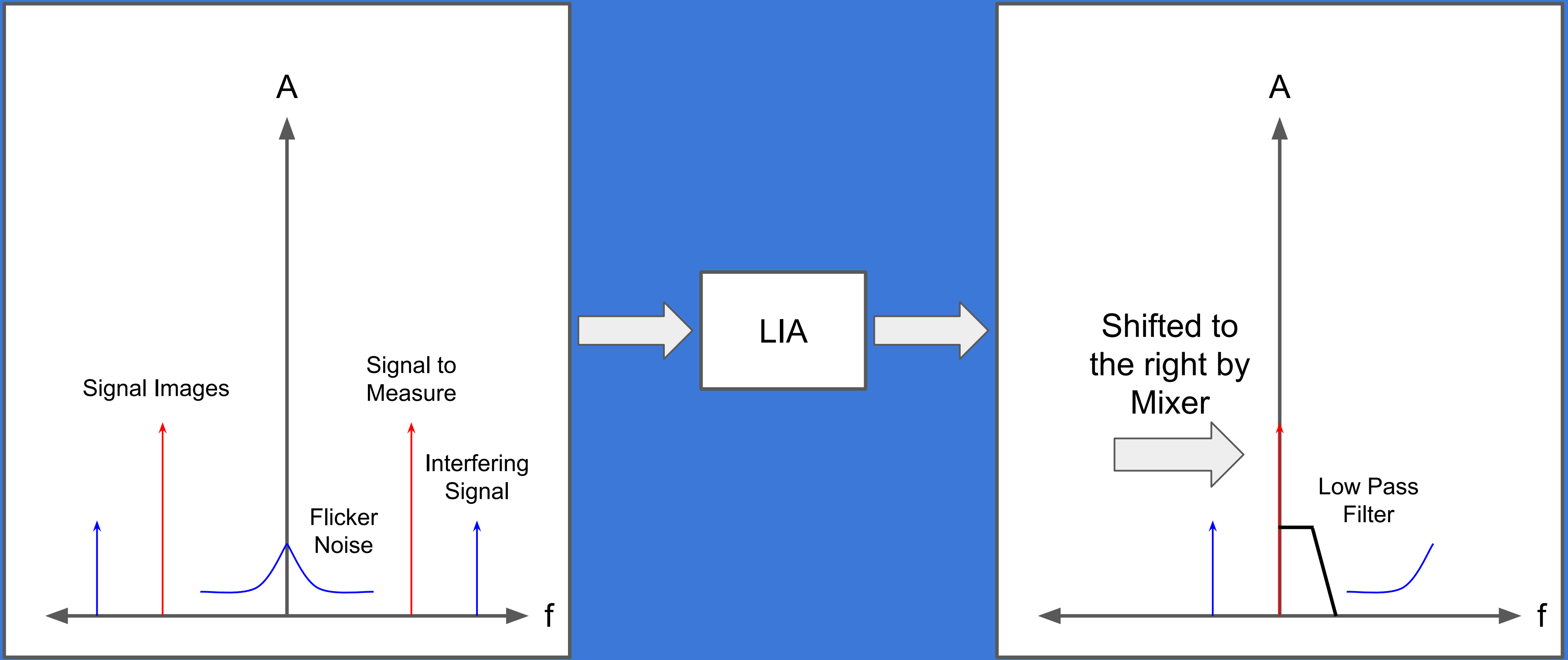
Johnson Voltage Noise Spectral Density

$$e_n = \sqrt{4kTR} \quad \frac{V}{\sqrt{Hz}}$$

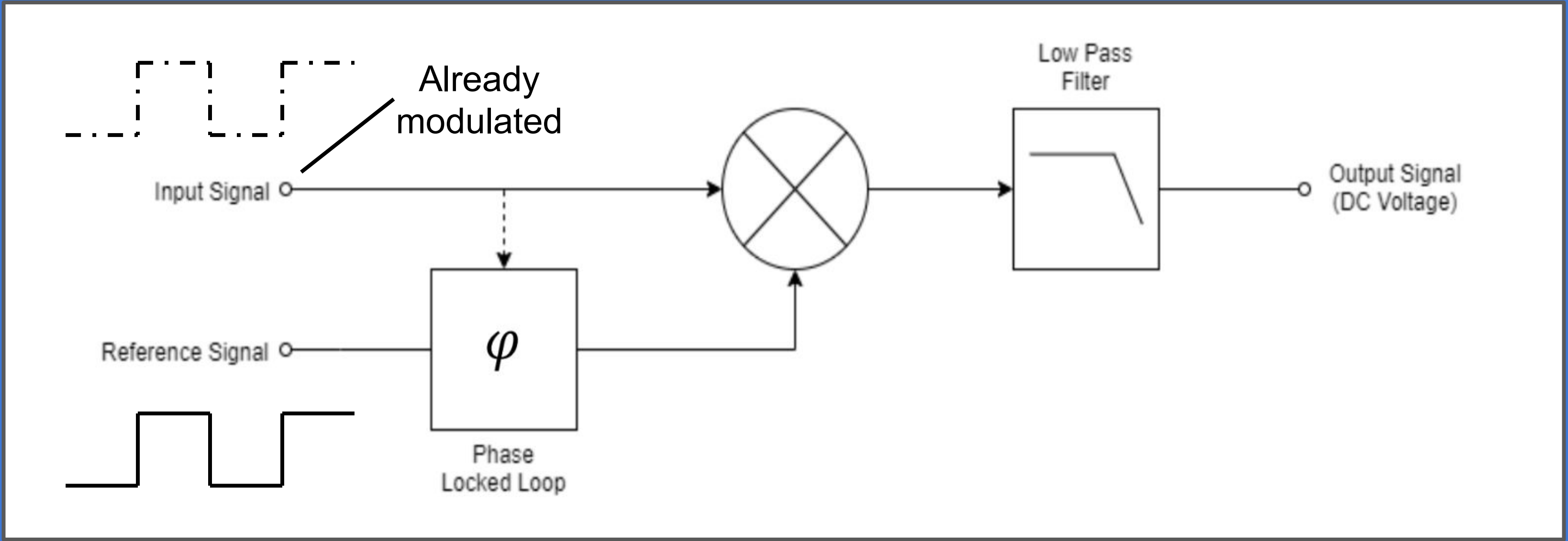
Shot Noise Spectral Density

$$i_n = \sqrt{2qI_{dc}} \quad \frac{A}{\sqrt{Hz}}$$

# Lock-In Amplifiers [6]



# Lock-In Amplifiers [6]




$$Output\ DC\ Signal \approx \frac{664 V_S V_R}{75\pi^2}$$

# Producing a Design

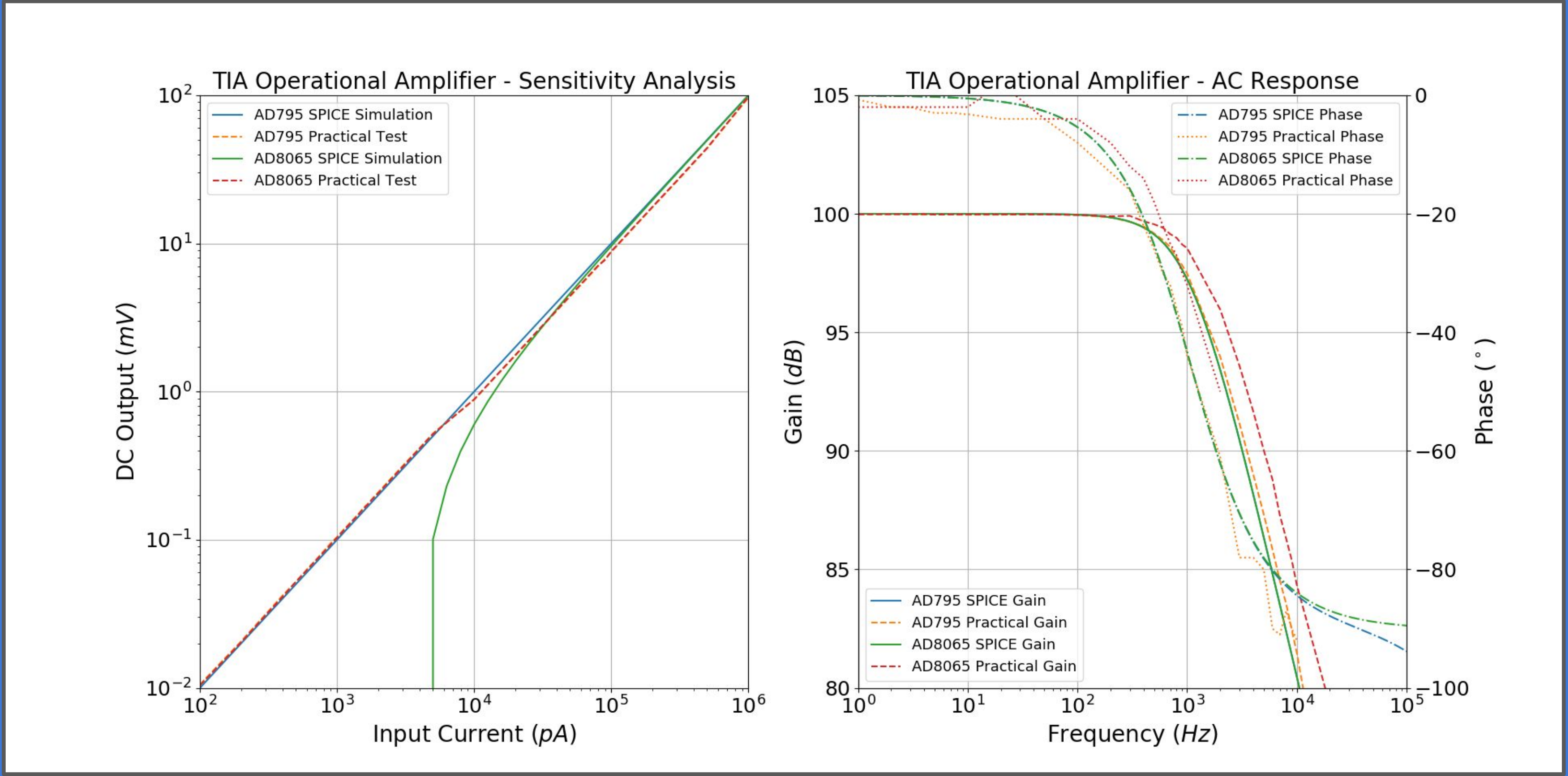
# TIA Operational Amplifier Selection

**Key Requirements:**

- Low Input Noise Current and Voltage
- Low Flicker Noise
- Low Input Bias Current
- Standard IC Package
- Gain of 100,000 (To facilitate pA to nA signal detection)

**Based upon these requirements a list of candidate Operational Amplifiers was produced.**

# TIA Operational Amplifier Selection [7]



# TIA Operational Amplifier Selection

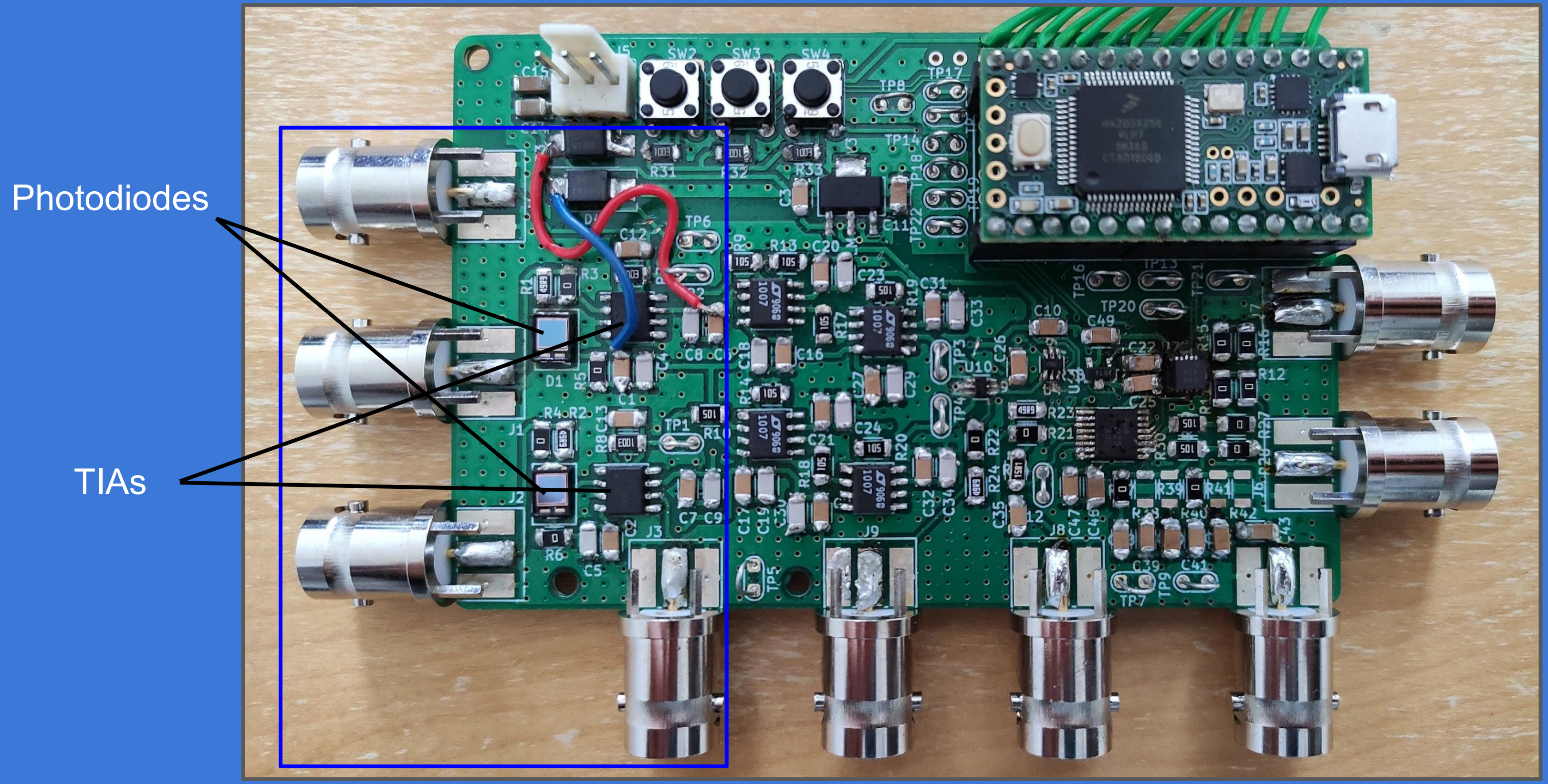
**Based upon these results:**

- AD795 and AD8065 selected for further testing. AD8065 primary candidate due to its lower cost of £3.20 [8] [9].
- Selected because of their optimal frequency, linearity and noise response across operating frequency spectrum.
- Standard SOIC 8 Pin package provides component flexibility for the future.

# LIA IC Selection

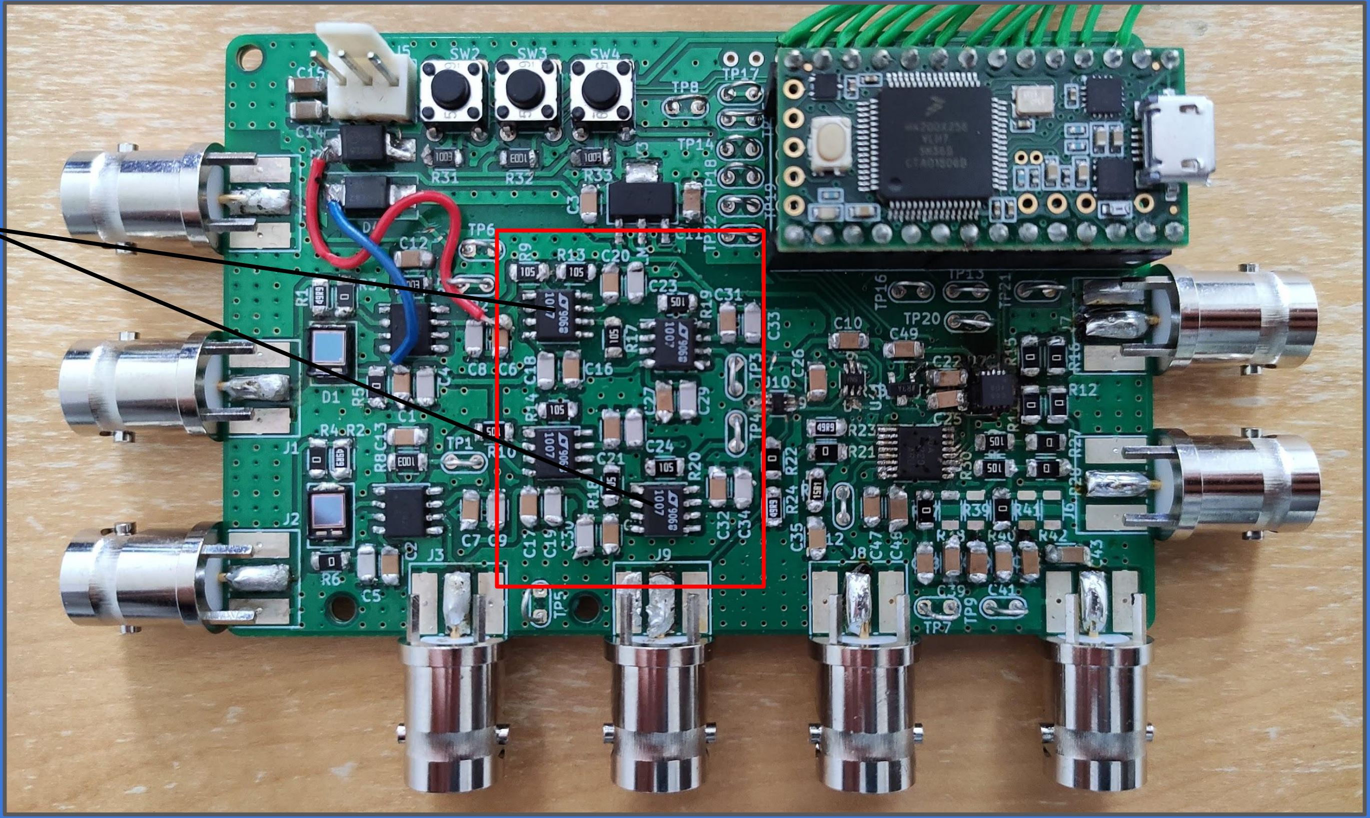
- Tarick Osman’s design uses the AD630 [5] ⇒ **DISCONTINUED!**
- Replacement IC provided, the ADA2200 [10]. This performs a digital implementation of a Lock-In Amplifier.
- Provides simplicity in design with near “Black Box” performance.
- Additional benefits include programmable IIR Filter and in-phase and quadrature detection.
- A 16 Bit ADC (AD7171) was also paired with the ADA2200 to provide more granular digital measurements.

# Version 0.3 - An Overview



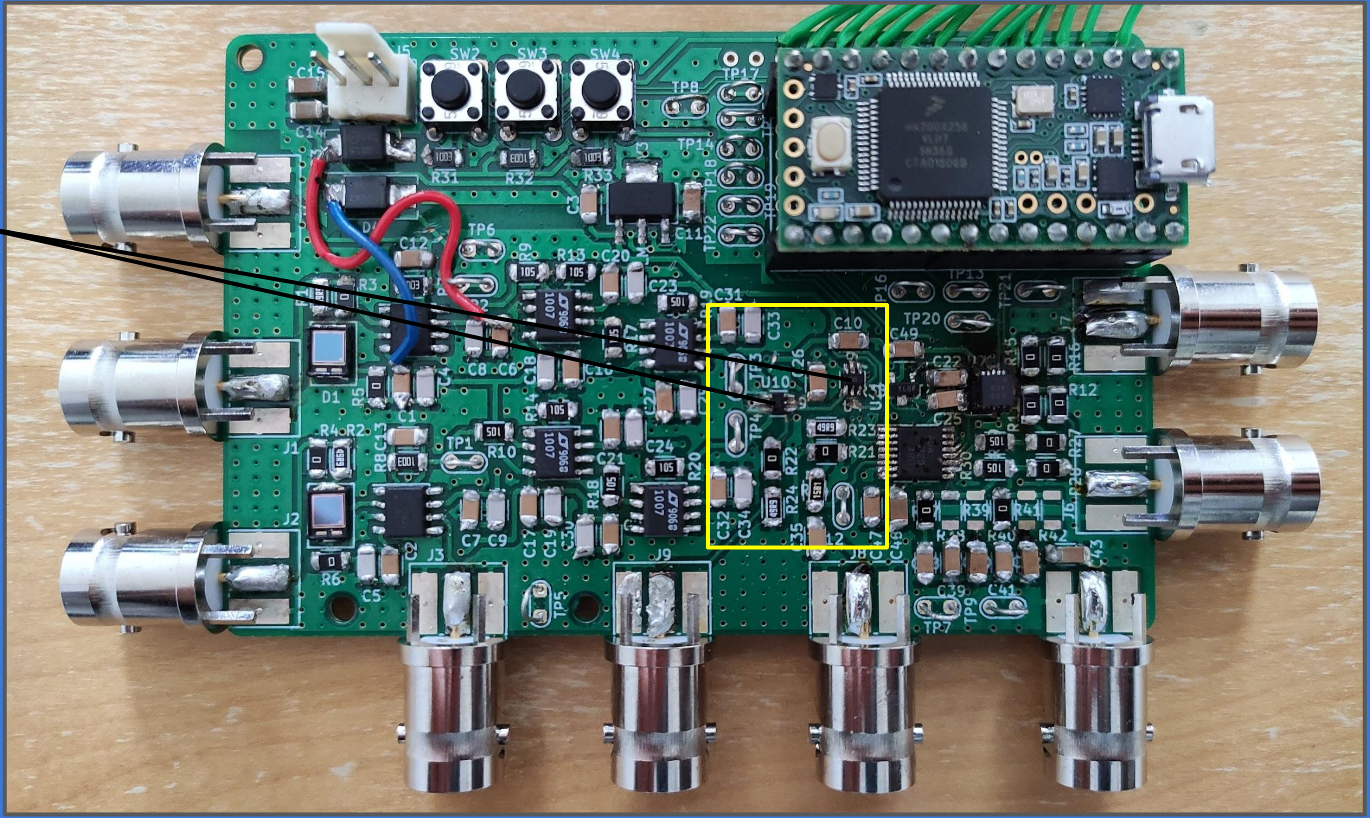
# Version 0.3 - An Overview

Inverting Voltage Amplifiers

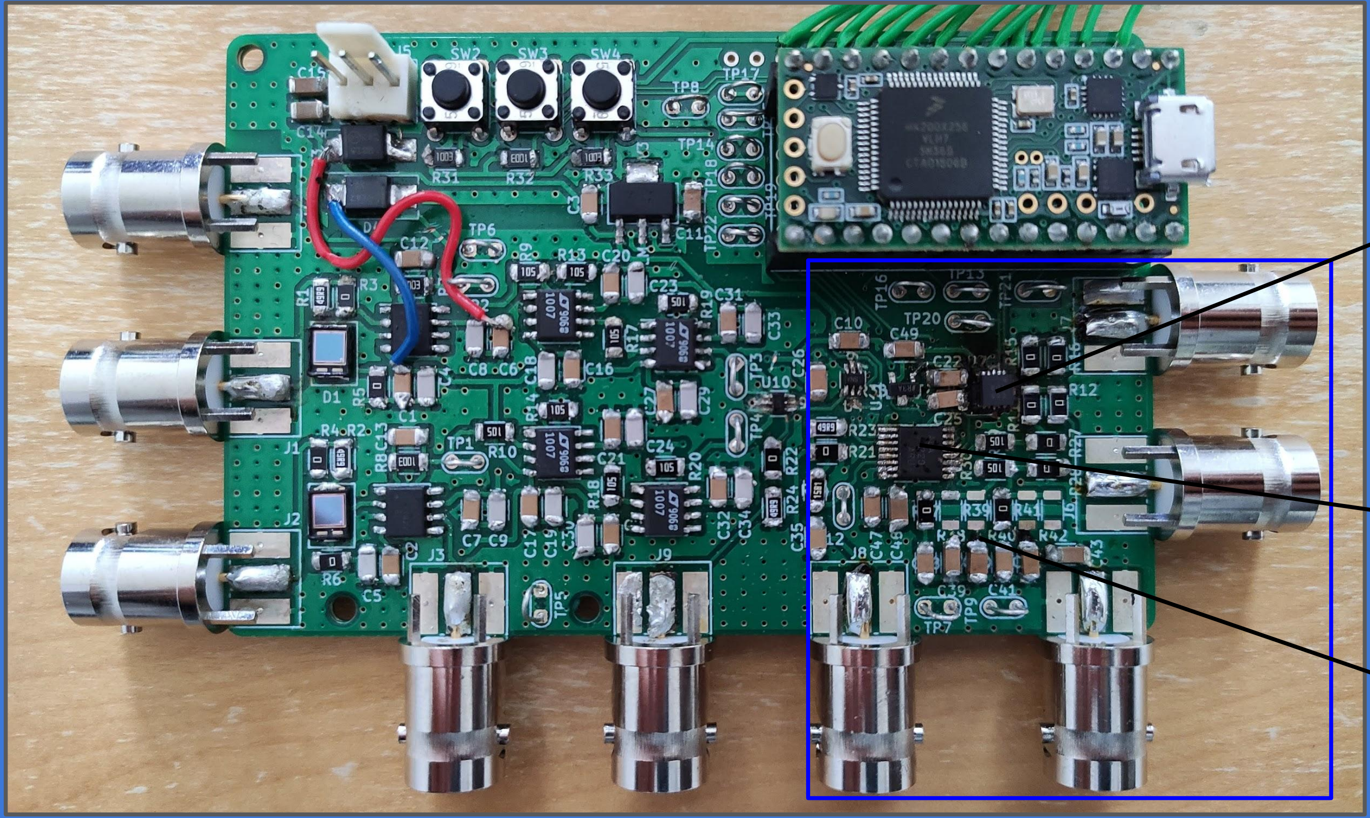


# Version 0.3 - An Overview

Analogue Switches for Modulation and Multiplexing



# Version 0.3 - An Overview

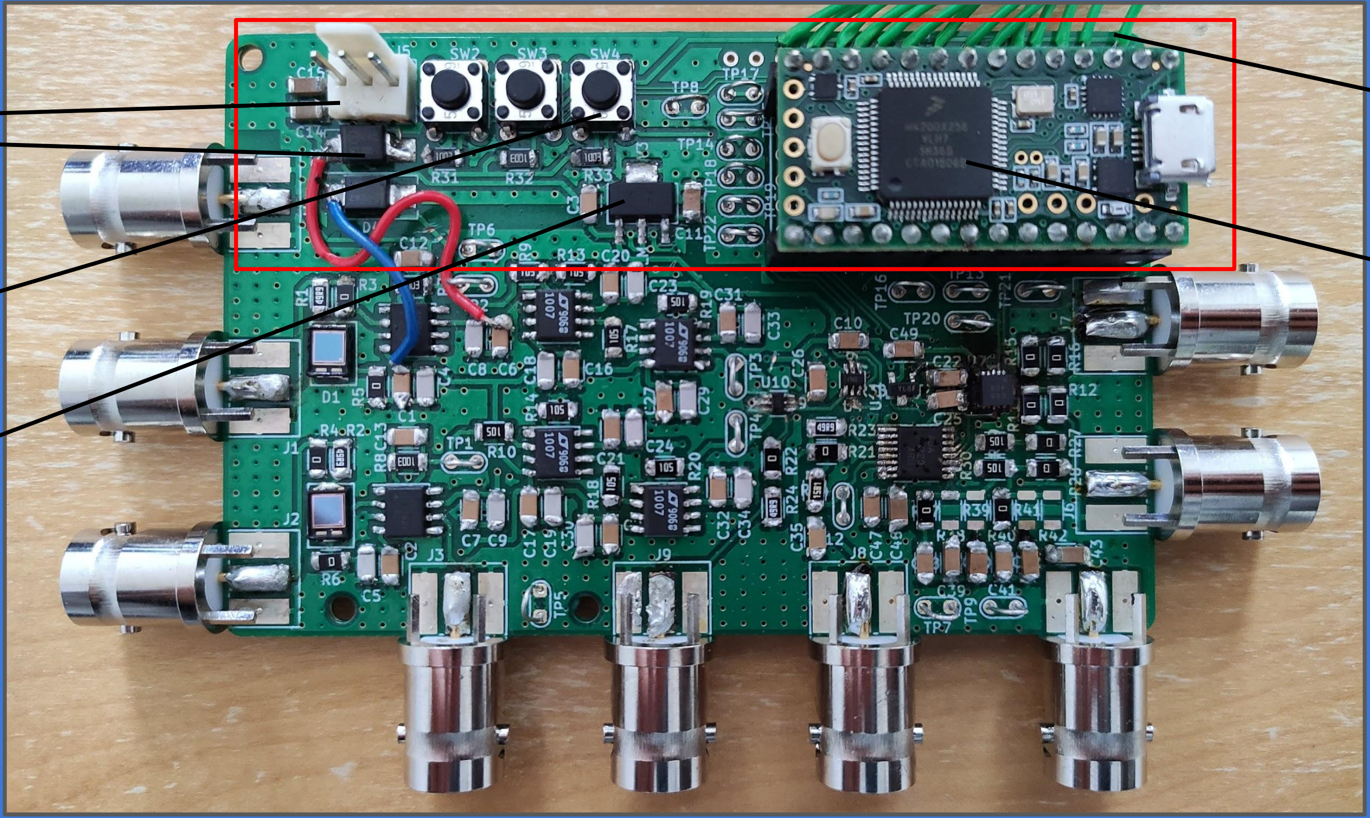


ADC

Lock-In Amplifier IC

Low Pass Filter

# Version 0.3 - An Overview



Power Connection and Voltage Protection

Control Buttons

3.3V Regulator

LCD Connection

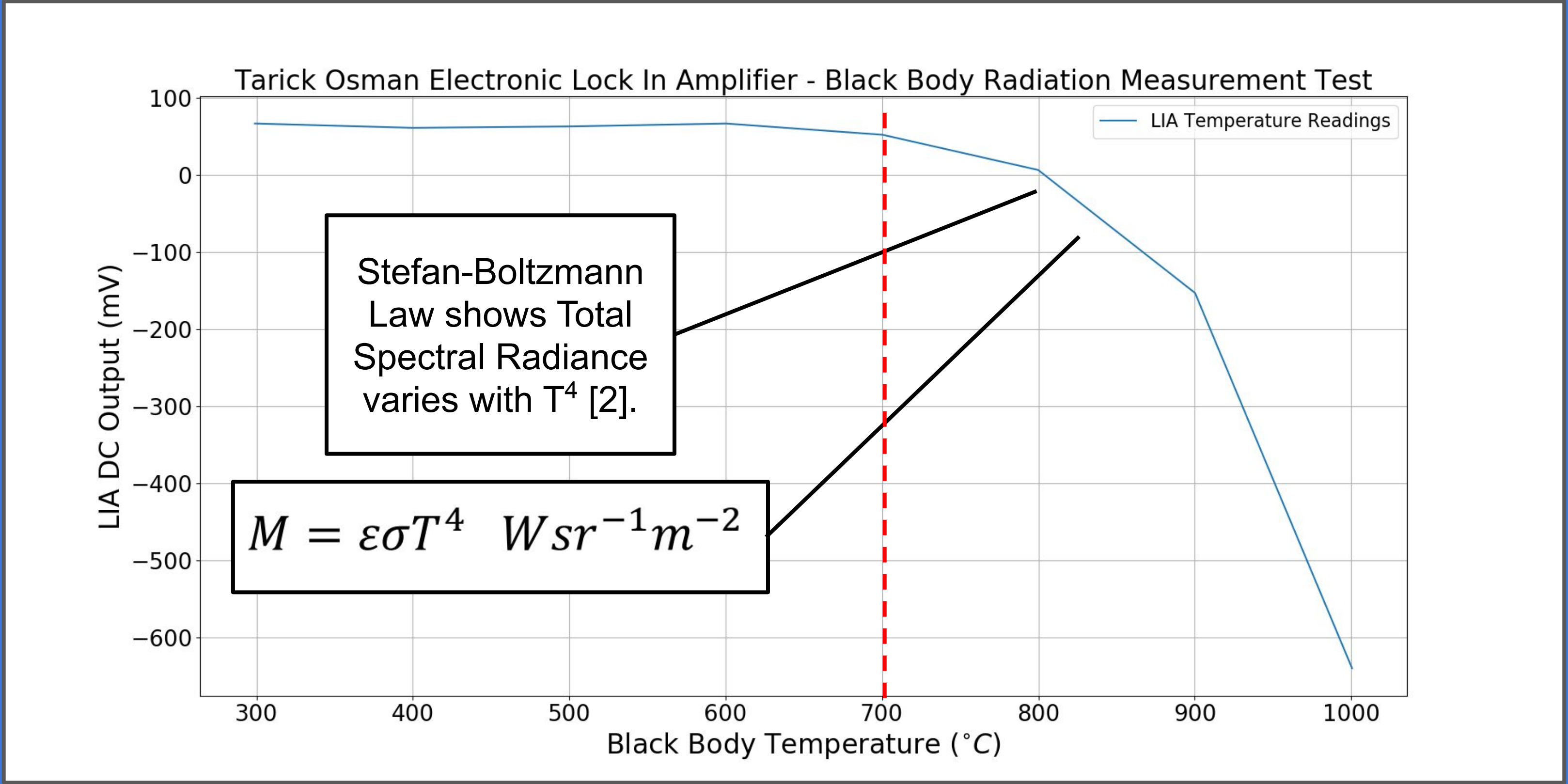
Teensy 3.2 MCU

# Design Benefits

- Modern Lock-In Amplifier IC allows for In-Phase and Quadrature measurements [10]. The phase difference of the Input and Reference signals is not important.
- Capable of 1 Billion Gain before the LIA.
- BNCs allow for flexible usage of the design.
- Teensy 3.2 supports Arduino programming. Allows for onboard DSP, a User Interface and Serial Communications over USB.
- Small Form Factor, roughly the size of a Raspberry Pi.
- Low Cost design at £95 (More information in BOM).

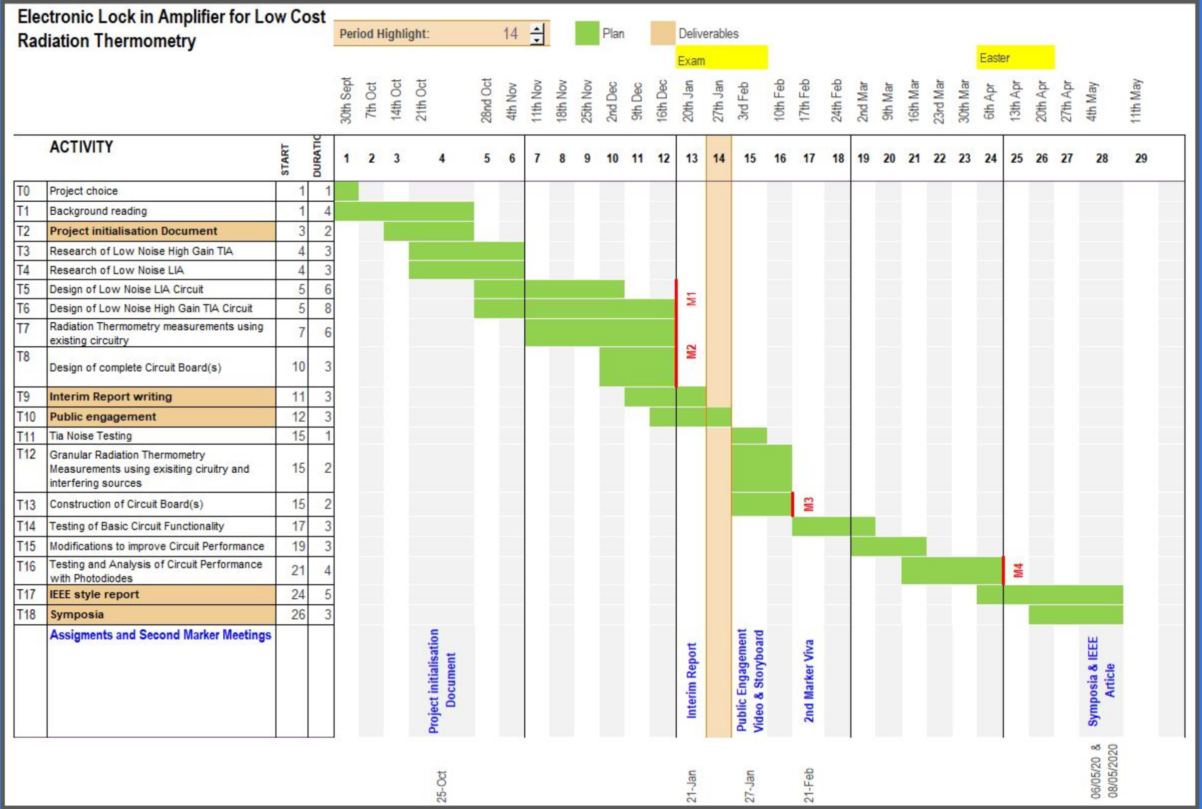
# Benchmark Testing

# Black Body Radiation Testing



# Milestones and Future Work

# Milestones and Gantt Chart




**M1 ⇒ Completed Low Noise High Gain TIA/LIA Circuit Design.**

**M2 ⇒ Completely Radiation Thermometry Measurements and TIA/LIA PCB Design.**

**M3 ⇒ TIA/LIA PCB Constructed.**

M4 ⇒ TIA/LIA PCB performance with Photodiodes tested.

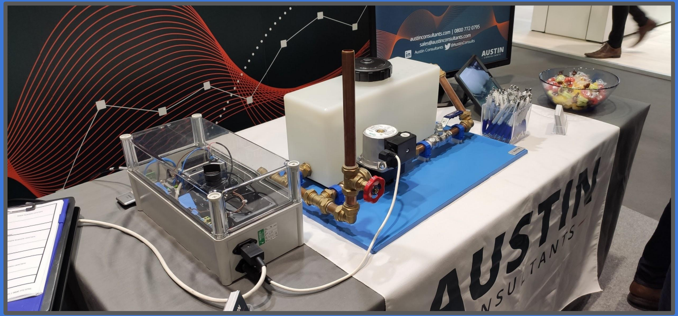
# Future Work

1. Additional characterisation of TIA Noise Performance.
2. Additional Black Body Radiation Testing to produce a more granular curve for TO LIA and ascertain the effect of interfering external sources of Infrared.
3. Continued testing of Lock-In Amplifier PCB to find problems with the first practical version. Revised version to be tested following manufacture.
4. Development of a custom serial interface and GUI to allow for PC control of the LIA.
5. Perform further Black Body Radiation Testing with the new design to quantify the improvement in performance Tarick Osman's design.

# Wider Developments in Electronics

# The Internet of Things

- Connection of a range of devices to the internet and cloud for granular data logging and communications.
- Very large applications in Industrial Sectors, particularly in Manufacturing where sensors track production activities and failures.
- Companies such as Siemens and Festo developing integrated IOT and Cloud Computing platforms that integrate closely with their manufacturing equipment, such as MindSphere.
- IOT works hand in hand with new technologies such as Machine Learning to allow for more accurate and reliable predictive maintenance and production planning.




# ML, DSP and FPGAs

- Many processor developers and manufacturers (ARM, Intel, AMD) are providing dedicated hardware for Machine Learning and DSP applications as part of their designs.
- This attempts to improve computing performance on small devices, allowing embedded systems to perform more complex signal processing and analysis.
- FPGA manufacturers are now packaging processors into designs. FPGAs include optimised DSP and ML "slices" to provide improved performance in custom hardware designs.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# To Conclude

- Radiation Thermometry can solve many of the problems produced by Contact Thermometers in High Temperature environments.
- Lock-In Amplifiers are a good method of detecting signals from Photodiodes down to *pA* range.
- A fully electronic Lock-In Amplifier circuit has been developed and manufactured at the proof of concept stage. Further revision is required.
- Testing of the new design with the Radiation Thermometry setup will be completed to ascertain the improvement in performance over the previous design produced by Tarick Osman.

# References


[1] D. P. DeWitt, Applications of Radiation Thermometry. ASTM, 1985.

[2] P. Saunders, Radiation Thermometry - Fundamentals and Applications in the Petrochemical Industry. Bellingham, Washington 98227-0010 USA: SPIE, 2007.

[3] P. Horowitz, The Art of Electronics, Third edition. New York, NY: Cambridge University Press, 2015.

[4] 'Stanford Research Systems SR810 and SR830 Lock in Amplifiers', Stanford Research Systems, Jan-2020. [Online]. Available: https://www.thinksrs.com/products/sr810830.html.

[5] T. Osman, 'Electronic Lock-In Amplifier for Measuring Low Optical Power', Univ. Sheff., 2019.

[6] 'About Lock in Amplifiers'. Stanford Research Systems, Jan-2020.

[7] Analog Devices, 'LT SPICE', LT SPICE Design Center, Jan-2020. [Online]. Available: https://www.analog.com/en/design-center/design-tools-and-calculators/ltspice-simulator.html.

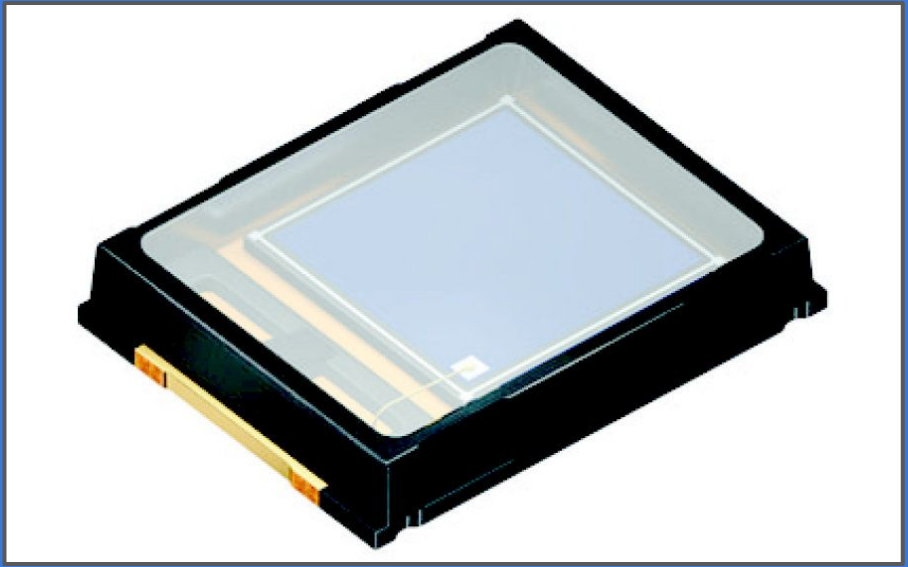
[8] Analog Devices, 'AD795 Operational Amplifier Datasheet'. Analog Devices, 2019.

[9] Analog Devices, 'AD8065 Operational Amplifier Datasheet'. Analog Devices, 2019.

[10]Analog Devices, 'ADA2200 Synchronous Demodulator Datasheet'. Analog Devices.

# Additional Slides

# Photodiode Selection



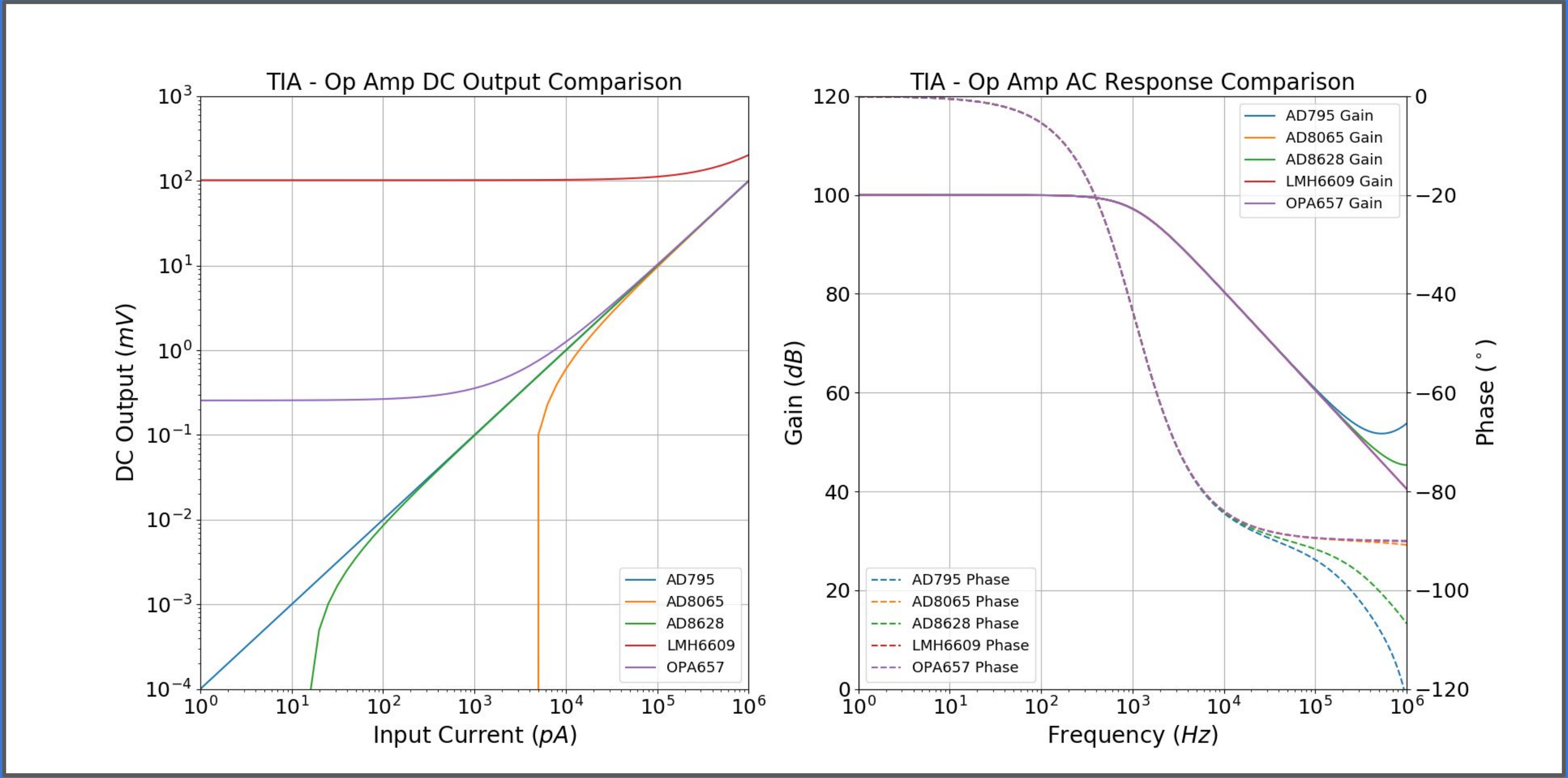
www.osram.com

- 1nA Dark Current
- 7.02mm$^2$ Radiant Sensitive Area
- 300 - 1100nm Operating Wavelength Range
- 0.7 A/W Peak Spectral Sensitivity
- 60pF Junction Capacitance

- Lower junction capacitance ensures TIA Gain is not adversely affected.
- Wide wavelength response ensures that the a wider section of the Black Body radiation spectrum is absorbed.
- Larger sensitive area provides a larger signal for measurement.

**Provides a good tradeoff between Junction Capacitance and Radiant Sensitive Area.**

# TIA Operational Amplifier Selection



# TIA Operational Amplifier Selection