EEE381 - Project Initialisation Document

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1 Project Brief

Measurement of temperature is a key problem across many sectors. Accurate and reliable measurements are required in order to regulate systems in factories for a wide range of applications; including the Chemical, Pharmaceutical and Steel industries[1]. At present, two major methods of measuring temperature exist: Contact Thermometers and Non-Contact Thermometers [2, p. 3].

Contact Thermometers are a commonly used technology due to their ease of installation and the accuracy of their measurements. However, they struggle to operate effectively in high temperature environments due to interference from other objects that could be radiating heat around the detector [2, p. 9]. The measurement then becomes an average of the environment temperature with the contacted surface temperature [2, p. 9].

Radiation Thermometers[1], a type of Non-Contact Thermometer, avoid this problem by measuring the infrared radiation emitted from an object. This allows them to be located outside high temperature environments and measure the surface temperature of equipment from a distance [2, p. 3].

At present, industry standard Radiation Thermometers use standard PN or PIN Photodiodes as detectors, providing single point measurements. To achieve accurate measurements, detectors with larger dimensions are used. This increases the spectral power of the radiation hitting the detector. Unfortunately, this creates a large cone of detection[2], forcing the temperature measurement to be an average rather than a precise single point.

This project primarily aims to explore the use of Lock in Amplifiers (LIAs) to improve the circuitry used in conjunction with Photodiodes for detection. LIAs can extract signals from large amounts of noise (upwards of 100dB) [3, p. 575-576]; thus, they act as a good candidate for Radiation Thermometry where input signal amplitudes are very small. The smaller the signal that can be detected, the smaller the dimensions of the Photodiode can be. To facilitate this, a LIA circuit for Photodiodes will be developed, building on previous work by Tarick Osman [4].

Additionally, as a project stretch goal; the use of Avalanche Photodiodes (APDs) with LIAs will be explored to evaluate the benefits and drawbacks of Avalanche Gain and the noise it introduces into the Photodiode output signal.

2 Background Theory

2.1 Radiation Thermometry

Radiation Thermometers allow for the remote measurement of surface temperature. The object to be measured is treated as a Black Body Radiator [2, p. 3, 5]. Black Body Radiator's emit a spectrum of Infrared light where the wavelength of peak power is proportional to their temperature [2, p. 10]. The spectral radiance at a given wavelength for an object at a given temperature is described by Planck's Law (1).

$$L_b(\lambda, T) = \frac{c_1}{\lambda^5}[exp(\frac{c_2}{\lambda T}) - 1]^{-1} \quad (1)$$

[1]also referred to as Infrared Thermometers or Pyrometers.
[2]the area of the surface the detector is receiving radiation from.

Where L_b represents spectral radiance of the Black Body, $c_1 = 1.19104282 \times 10^{-16}\ Wm^{-}2$ (first radiation constant) and $c_2 = 0.014388\ mK$ (second radiation constant) [2, p. 11]. Additionally, the wavelength of maximum spectral radiance can be calculated using Wein's Law [2, p. 12] (2).

$$\lambda_{max} = \frac{2898}{T}\ \mu m \tag{2}$$

Finally, the total spectral radiance of a Black Body can be calculated using the Stefan-Boltzmann law [2, p. 14] (3).

$$M = \epsilon \sigma T^4 \tag{3}$$

Where σ is the Stefan-Boltzmann constant (5.67×10^{-8}) and ϵ is the emissivity of the Black Body. Emissivity refers to how well an object radiates compared to a perfect Black Body[3] and has a value between 0 and 1 [2, p. 8]. When making measurements of real world objects; the emissivity, reflectivity and absorption rate of the atmosphere between the surface and the detector must be accounted for [2, p. 8,16,21]. Failure to do so can result in readings that have an error of 10°C or more.

2.2 Lock in Amplifiers

As discussed in **Section 1**, Lock in Amplifiers can extract signals from upwards of 100dB of noise [3, p. 575-576]. This is achieved through modulation/demodulation techniques similar to those used in communication electronics. The desired section of the input signal is modulated at a known frequency (f_m), the Lock in Amplifier then demodulates the input signal [3, p. 575].

A common method of demodulation is multiplying the input signal by a fixed reference oscillating at the modulation frequency f_m, the multiplied signal can then be low pass filtered to produce a DC output proportional to the desired section of the input signal [3, p. 575]. Either a Sine wave with a small amplitude or a Square wave with a large amplitude compared to the desired section of the input signal can be used for modulation [3, p. 577]. The described structure can be seen in **Figure 1**.

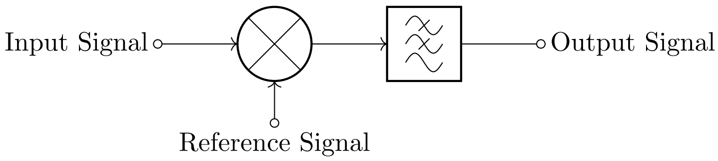

Figure 1: A block diagram of the basic operation of an LIA.

Lock in Amplifiers are commonly used with Transimpedance Amplifiers (TIAs) in Photodiode applications.

2.3 Transimpedance Amplifiers

Transimpedance Amplifiers are used to convert current based input signals to voltage based output signals. At a basic level, they are formed using an operational amplifier in an inverting amplifier configuration using a single feedback resistor [3, p. 537]. An example of a TIA configuration can be found in **Figure 2**.

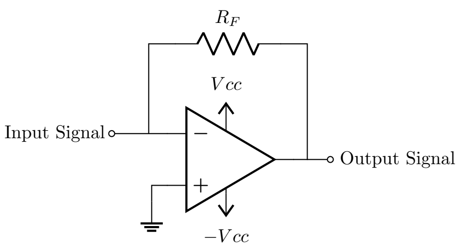

Figure 2: A basic Transimpedance Amplifier Circuit.

[3] perfect Black Bodies have an emissivity of 1

Unfortunately, Transimpedance Amplifiers suffer from problems with oscillation. This is due to the lag induced by the feedback resistor and input capacitance forming a low pass filter in combination with the Operational Amplifiers internal lag. If R_F has too large a value then the phase shift will surpass 180° and the circuit will oscillate [3, p. 537]. To combat this effect, a capacitor is placed in parallel with the feedback resistor. Unfortunately, this also has the effect of reducing the TIA's bandwidth [3, p. 537].

For Photodiode applications it is important to produce a low noise TIA, especially if we are attempting to detect signals within the pA to nA range [3, p. 538]. The noise added to the signal by the TIA is influenced by the noise of the Operational Amplifier (flicker noise) [3, p. 538] and the noise of the Feedback Resistor (johnson or thermal noise) [5] [3, p. 538].

2.4 Avalanche Photodiodes (APDs)

Avalanche Photodiodes provide an additional benefit for applications where the input spectral power is low; they have an internal gain[4], referred to as Avalanche Gain [6, p. 348]. This gain is achieved using strong electric fields that accelerate free carriers within the lattice; some of these carriers gain enough energy to ionise fixed carriers in the lattice, these carriers in turn may ionise other fixed carriers [6, p. 349]. This process is referred to as Avalanche Multiplication [6, p. 349-350] [7, p. 109].

Unfortunately, there is an inherent noise associated with the Avalanche Gain. The number of times carrier ionisation will occur for a single photon is represented by a probability distribution rather than a single value [6, p. 349]. This means that the Avalanche Gain has a range of possible values, this range manifests as noise [6, p. 349].

3 Project Specification

Based upon the information from **Section 1** and **2**, the project has the following primary specifications[5]:

1. Explore the use of Electronic Lock in Amplifiers for Radiation Thermometry by performing test measurements with existing hardware [4].
2. Improve the existing circuit [4] to detect below nA, aiming for pA.
   (a) Construct a new Low Noise Transimpedance Amplifier with a gain to facilitate measurements in the pA range.
   (b) Construct an Electronic Lock in Amplifier with a filter appropriate for Radiation Thermometry.

Additionally, the project has the following stretch goals/specifications, should time allow for them:

1. Investigate the use of Electronic Lock in Amplifiers with Avalanche Photodiodes to evaluate the benefits and drawbacks of Avalanche Gain.
   (a) Modify the constructed Lock in Amplifier circuit for use with Avalanche Photodiodes.
   (b) Compare and contrast the performance of the APD based system with PN/PIN Photodiodes.

4 Project Schedule

This section outlines an initial plan for the schedule of the work outlined in the Project Specification using the Gantt Chart shown in **Figure 3**. The following milestones are given:

1. M1 →Completed Low Noise High Gain TIA/LIA Circuit design.
2. M2 →Completed Radiation Thermometry measurements and TIA/LIA PCB Design.
3. M3 →TIA/LIA PCB Constructed.
4. M4 →TIA/LIA PCB performance with Photodiodes tested.

[4] APD gain is usually between 2 and 10
[5] It is expected that objectives 1 and 2 will run in parallel

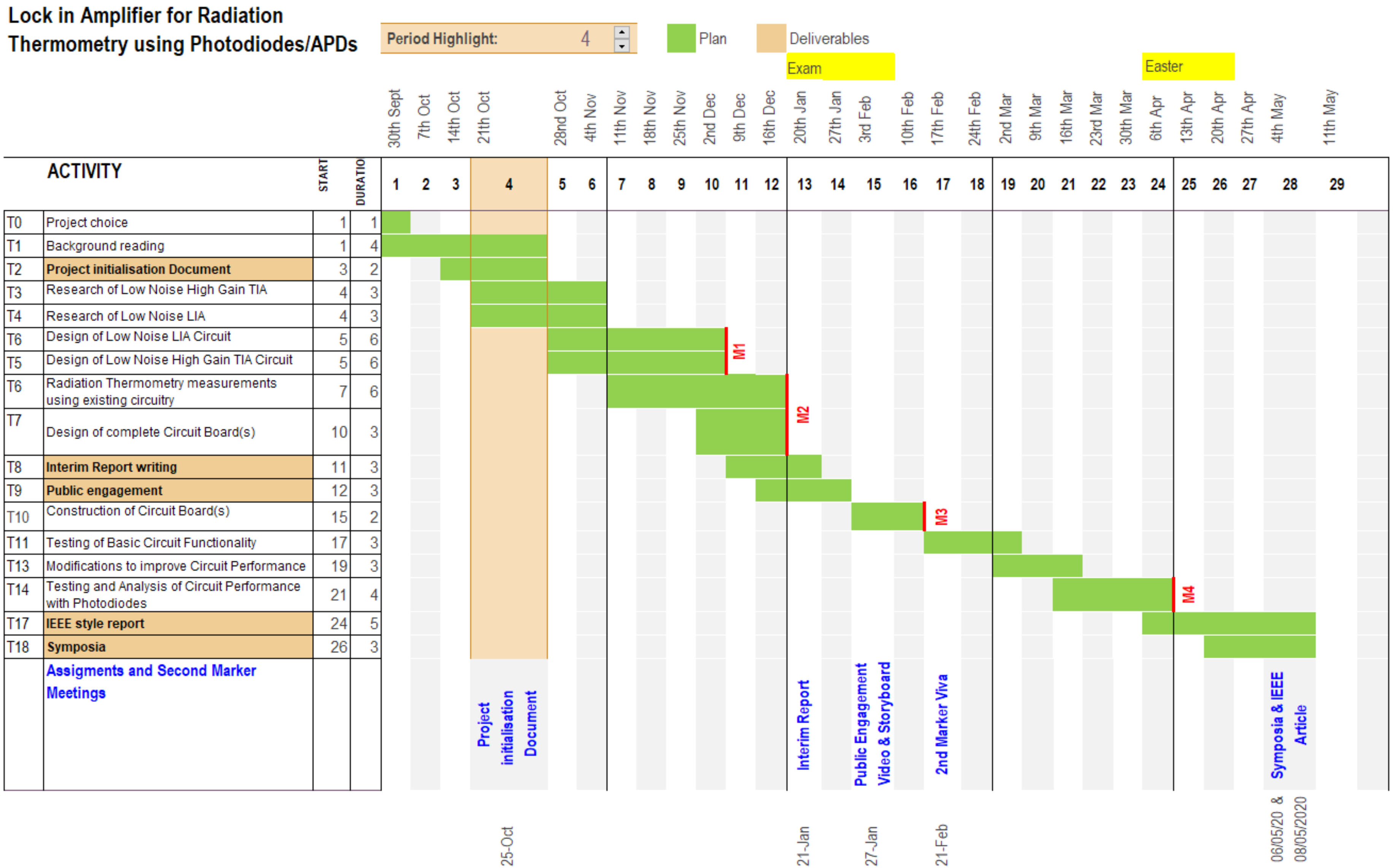

Figure 3: The Project Gantt Chart.

5 Risk Register

This section outlines the risks for this project and the measures that have been put in place to mitigate them. It is important to note that these risks are purely associated with events that may delay or stop progress towards the project goals. This risk assessment is not concerned with Health and Safety (this will be handled in a separate document). The risk register can be seen in **Figure 4**.

Risk Number	Description of Risk	Existing Control Measures	Risk Likelihood (1 - 5)	Risk Severity (1 - 5)	Risk Score (0 - 25)	Additional Control Measures	Amended Risk Likelihood (1 - 5)	Amended Risk Severity (1 - 5)	Amended Risk Score (0 - 25)
1	Loss of Project Data	Project data is stored on a Desktop and Laptop computer. Additionally, it is periodically backed up on Google Drive. Development files (Schematics, PCB Layouts, etc.) will be stored in a Git repository with full history and version control.	1	5	5	**No additional measures required.**	N/A	N/A	N/A
2	Exceeding Project Budget	The EEE department controls all purchasing for 3rd year projects. Components can only be purchased through approved suppliers by EEE staff. Thus, overbudget projects are prohibited. A full costing breakdown will be compiled in a spreadsheet for the project.	1	4	4	**No additional measures required.**	N/A	N/A	N/A
3	Missing Deliverable Deadlines	A Gantt Chart has been created to outline a schedule for project progress against individual specification points. The Gantt Chart will be reviewed on a fortnightly basis (at minimum) with the project supervisor to ensure key project deadlines are met.	1	4	4	**No additional measures required.**	N/A	N/A	N/A
4	Working Time lost due to Injury	Before any practical work is completed a full risk assessment must be completed and signed by the project supervisor. This risk assessment should identify and mitigate any foreseeable project risk.	1	4	4	**No additional measures required.**	N/A	N/A	N/A
5	Incorrect PCB Design	PCB Design package used to simplify the design process and lower the likelihood of mistakes. A full simulation of the circuit in SPICE should be completed before committing to hardware design. A design review will be completed before ordering the finished PCB design. PCB(s) should be ordered before the winter holiday (2019/20) to allow for testing and redesign in the Spring Semester.	2	4	8	The PCB should be designed accounting for modification during the testing phase. This allows for changes without a full PCB redesign. **Risk expires once testing phase has been completed.**	2	2	4
6	Failure of Black Body Test Equipment	Equipment is maintained and managed by staff running the EEE B12 Laboratory.	1	4	4	**No additional measures required. Risk expires when Black Body testing is complete.**	N/A	N/A	N/A
7	No access to George Porter F13 Lab due to delayed movement to Mappin Building	Movement from Mappin Building planned for January, outside of term time. Diamond E&C Laboratory and IForge available as a back up space for working.	3	3	9	Induction to B12 Laboratory completed. B12 can be used as an additional back up Laboratory.	3	1	3
8	Construction of High Gain (approximately 10 Million to 1 Billion) Low Noise TIA too complex/not possible	Research of a wide range of low noise TIA construction methodologies. Early research of available Operational Amplifier GBW values to evaluate the possibility of a 1 Billion gain value.	3	4	12	Perform additional research of alternative methods for producing a Photodiode front end that can measure pA signals.	3	2	6
9	Required components for pA capable TIA/LIA circuit are too expensive for project budget	Research TIA/LIA designs that provide the minimum required functionality based upon the specification. Limit PCB design to two layers. Individual Project budgets have been extended to £200 this year.	3	4	12	Perform additional research of alternative methods for producing a Photodiode front end that can measure pA signals.	3	2	6
10	Component obsolescence during development	Use the newest version of a component that exists, where reasonably practicable. Attempt to use components that have been released fairly recently. Periodically check for component obsolescence. Order replacement components.	2	4	8	**No additional measures required. Risk expires when PCB is fully tested.**	N/A	N/A	N/A

	Risk Likelihood				
Risk Severity	**1**	**2**	**3**	**4**	**5**
1	1	2	3	4	5
2	2	4	6	8	10
3	3	6	9	12	15
4	4	8	12	16	20
5	5	10	15	20	25

Figure 4: The Project Risk Register.

References

[1] D. P DeWitt. *Applications of Radiation Thermometry.* ASTM, 1985. OCLC: 1096909952.

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[4] Tarick Osman. Electronic Lock-In Amplifier for Measuring Low Optical Power. *The University of Sheffield*, 2019.

[5] Gino Giusi, Gianluca Cannatà, Graziella Scandurra, and Carmine Ciofi. Ultra-low-noise large-bandwidth transimpedance amplifier: ULTRA-LOW-NOISE LARGE-BANDWIDTH TRANSIMPEDANCE AMPLIFIER. *International Journal of Circuit Theory and Applications*, 43(10):1455–1473, October 2015.

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