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Development and Validation of SLyM: A Waterproof and Low-Cost Sky Luminosity Meter

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ABSTRACT

While Sky Quality Meters (SQMs) are vital tools for astrophysical research and monitoring light pollution, their adoption in Malaysian educational and research settings is hindered by high import costs and a lack of environmental durability. This paper introduces SLyM, a locally developed Sky Luminosity Meter engineered to provide a cost-effective and robust alternative to expensive commercial photometers. By utilizing an in-house fabrication approach with an Arduino-based architecture, the production cost of the device was reduced to roughly 10% of standard retail prices. Technological innovations in SLyM include a dual-layer sealing strategy - combining internal epoxy potting with a sealed 3D-printed PLA housing - to achieve full waterproof and weatherproof capabilities for reliable field deployment. To improve measurement precision, the design incorporates a built-in bubble level and a universal tripod mount, ensuring stable and accurate zenith-pointing alignment. Side-by-side performance validation against the industry-standard Unihedron SQM-LU confirms that SLyM produces consistent data trends, maintaining readings between 16.88 and 17.15 mag/arcsec². Although a systematic calibration offset of approximately 0.55 to 0.60 mag/arcsec² was observed due to differing spectral responses, SLyM demonstrated superior sensitivity to transient atmospheric events. It successfully captured real-time fluctuations, such as passing clouds and localized light intrusions, that were attenuated by the commercial unit's narrower field of view. These results indicate that SLyM is a highly accessible and durable solution for astrophysics education and citizen science initiatives.

Keywords: Night-Sky Brightness, Light Pollution, Sky Quality Meter, Low Cost, Waterproof

1. INTRODUCTION

The quality of the night sky has long served as a fundamental observational parameter in astronomy, enabling researchers and educators to assess site suitability, monitor light pollution trends and conduct meaningful astrophysical studies. Night-sky brightness (NSB), typically expressed in magnitudes per square arcsecond (mag/arcsec²) which is closely correlated with the Bortle Scale (Bortle, 2001), a nine-point classification system ranging from Class 1 (pristine, unpolluted skies) to Class 9 (severely light-polluted inner-

city skies) is the primary metric used to quantify this quality and its accurate measurement is essential for both professional observatories and educational institutions running astronomy programmes or even astrophotography hobbyists. The Sky Quality Meter (SQM) is the most widely adopted instrument for NSB measurement; however, due to its high and prohibitive cost, lack of weatherproofing & weatherproofing and absence of mounting support have significantly limited its accessibility in Malaysian educational settings. Therefore, SLyM was developed to address these gaps and offer a locally fabricated, low-cost and fully weatherproof alternative for students, educators and astronomy enthusiasts alike.

1.1 SCOPE OF THE PROJECT

SLyM is a locally engineered, low-cost photometric instrument developed to measure night-sky brightness (NSB), a critical parameter in astrophysical site assessments and light pollution monitoring. This project encompasses the full development cycle of SLyM, from electronic circuit design and component selection, to 3D-printed housing fabrication, waterproofing via epoxy encapsulation and comparative performance validation against the commercially available Unihedron SQM-LU (Unihedron, n.d.). SLyM integrates a TSL235R light-to-frequency converter, Arduino Nano V3 (Type-C), DS3231 RTC module, NEO-7M GPS module, MicroSD card module and a 16×2 I2C LCD display into a compact, self-contained unit designed for field deployment. The project is grounded within the context of astrophysics education and citizen science, targeting students, educators and astronomy enthusiasts in Malaysia and beyond.

1.2 PROBLEM STATEMENT

Despite the growing demand for sky quality monitoring in both educational and research settings, accessibility to reliable photometric instruments remains a significant challenge in Malaysia, stemming from **three core problems**.

First, high cost and import barriers. The Unihedron SQM-LU, a widely used commercial sky quality meter, is priced at approximately RM 2,000 in Malaysia after accounting for currency conversion, international shipping fees, import duties and applicable taxes. This makes it financially prohibitive for most educational institutions and individual researchers/hobbyists, effectively limiting its adoption in Malaysian astrophysics programmes.

Second, the absence of waterproofing and weatherproofing. The Unihedron SQM-LU is assembled using screws and exhibits small structural gaps between its casing panels. These gaps are sufficient entry points for rainwater, condensation and airborne particulates, all of which are highly probable during outdoor and remote astronomical observations. The ingress of moisture or debris poses a direct risk of electrical damage and instrument failure, yet no protective sealing or waterproofing measure is incorporated in the commercial unit by design.

Third, a lack of structural versatility and pointing alignment support. Accurate sky brightness measurements require the photometer to be oriented precisely perpendicular to

the sky, which means pointing directly at the zenith. The commercial SQM-LU, despite its high price point, does not include any mounting hardware, a built-in levelling mechanism, or a standard tripod thread compatible with universal mounts. Users are consequently required to improvise using separate phone clamp mounts or third-party tripods which are additional costs that further reduce the instrument's practical accessibility, particularly in remote, uneven terrain where ground stability cannot be guaranteed.

1.3 OBJECTIVES

This project aimed to achieve the following objectives:

- To design and develop a low-cost sky luminosity meter using locally sourced electronic components and in-house fabrication to reduce the total production cost while maintaining equivalent core functionality.
- To engineer a fully waterproof and weatherproof instrument enclosure to ensure field reliability under adverse environmental conditions.
- To incorporate an integrated structural stability mechanism to enable accurate zenith-pointing alignment without the need for external or improvised mounting solutions.
- To conduct a comparative field analysis against industry-standard instrumentation (Unihedron SQM-LU) to validate the accuracy, sensitivity, and reliability of SLyM's photometric data.

2. METHODOLOGY

The development of SLyM was carried out across five structured phases, progressing systematically from initial research through to final performance validation.

Phase 1: Research & Component Identification

A thorough review of existing literature was conducted, with particular reference to the works of Asmoro et al. (2022) and Daniel (2020), to establish the theoretical and practical foundations of sky photometry. The commercial Unihedron SQM-LU was subsequently reverse-engineered through analysis of its technical manuals and available web resources, enabling a detailed understanding of its core functional components and operating principles. Based on this, a selection of affordable, locally available electronic components were identified to replicate and extend the capabilities of the SQM-LU. The finalised bill of components comprised an Arduino Nano V3 (Type-C) as the central microcontroller, a TSL235R light-to-frequency converter (TAOS, 2007) as the primary photometric sensor, a DS3231 real-time clock (RTC) module for precise timestamping, a NEO-7M GPS module for geographic positioning and UTC time synchronisation, a MicroSD card module for onboard data logging and a 16×2 I2C LCD display for real-time readout in the field.

Phase 2: Electronic Prototyping & Coding

Prior to permanent assembly, all components were integrated on a breadboard to verify circuit connectivity, signal integrity and inter-module communication. Concurrently, the code was developed using Arduino IDE software and iteratively refined to process the TSL235R frequency output into calibrated NSB readings expressed in magnitudes per square arcsecond ($\text{mag}/\text{arcsec}^2$). The code was further developed to integrate GPS-based MYT timestamping, RTC data logging, automatic SD card storage of all recorded measurements and real-time display of readings on the LCD screen. Multiple iterations of the firmware were tested and debugged throughout this phase to ensure stable and reliable operation across all modules simultaneously.

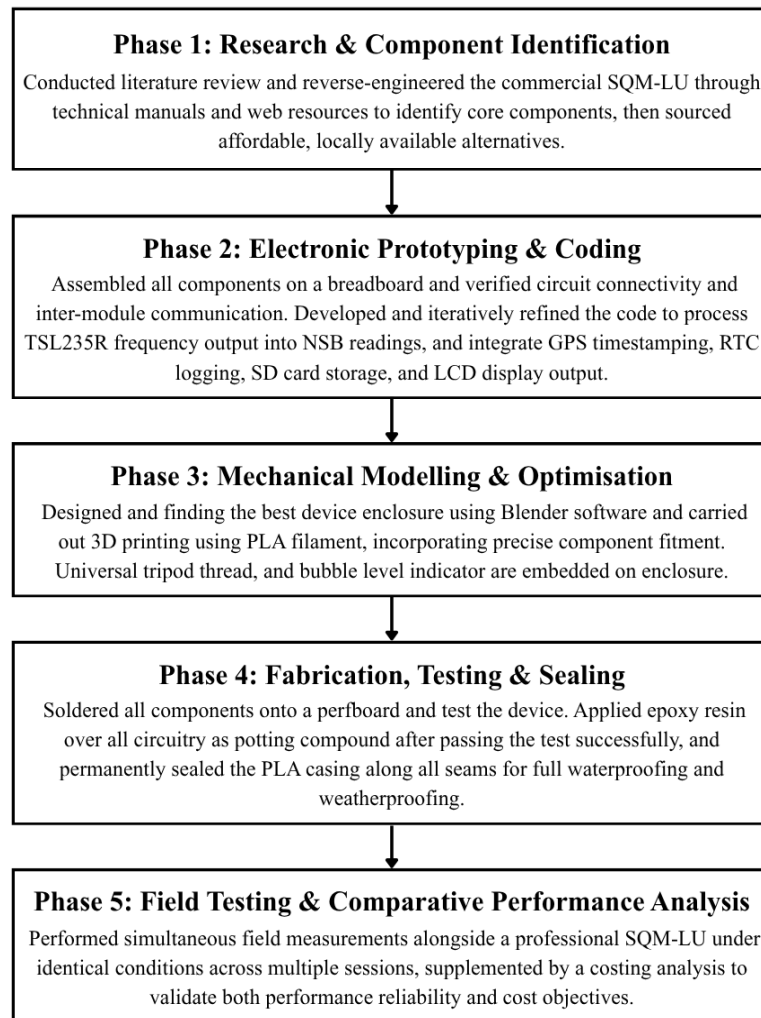


Figure 1. 5-phased Methodology for Development of SLyM

Phase 3: Mechanical Modelling & Optimisation

The instrument enclosure was designed using Blender 3D modelling software, with internal dimensions precisely matched to the physical footprint of each component to minimise internal tolerances and ensure a secure, stable fit. The housing was fabricated via 3D printing using PLA filament, with multiple print iterations carried out to optimize structural integrity, port alignment and overall dimensional accuracy. The enclosure design incorporated a standard universal tripod thread at its base, enabling compatibility with the purpose-designed adjustable tripod included with the unit. A bubble level indicator was also embedded into the top surface of the casing, allowing users to achieve accurate zenith-pointing alignment, which is a critical requirement for consistent NSB measurements, particularly when deploying on uneven or remote terrain.

Phase 4: Fabrication, Testing & Sealing

Once the enclosure design was finalised and the firmware confirmed to be stable, all electronic components were soldered onto a permanent perfboard to ensure robust and durable electrical connections. The fully assembled unit was then functionally tested to confirm that all components operated correctly in their permanent configuration before any sealing was applied. Upon successfully passing this pre-sealing test, epoxy resin was applied as a potting compound over all exposed circuitry and solder joints, encapsulating the electronics to protect against moisture ingress, condensation and mechanical shock. The circuit assembly was subsequently fitted into the 3D-printed PLA enclosure and the casing was permanently sealed using epoxy adhesive along all seams and joints. This dual-layer protection strategy (internal epoxy encapsulation combined with an externally sealed enclosure) renders SLyM fully waterproof and weatherproof, suitable for prolonged outdoor deployment under adverse environmental conditions.

Phase 5: Field Testing & Comparative Performance Analysis

The completed SLyM unit was evaluated through direct side-by-side field measurements with a professional Unihedron SQM-LU under identical observing conditions. Simultaneous NSB readings were recorded from both instruments across multiple observation sessions to assess the consistency, accuracy and reliability of SLyM's measurements relative to the commercial benchmark. A comprehensive costing analysis was also performed, comparing the total fabrication cost of SLyM against the retail price of the SQM-LU, to quantitatively validate SLyM's low-cost objective and establish its viability as an accessible alternative for educational and citizen science applications.

3. RESULTS AND DISCUSSION

Over the 30-minute observation window, both the SQM-LU and SLYM instruments recorded sky brightness continuously under stable atmospheric conditions. While both sensors captured the general behaviour of the night sky, a closer examination of the data reveals important distinctions that highlight the SLYM's sensitivity and responsiveness as a sky quality monitoring tool.

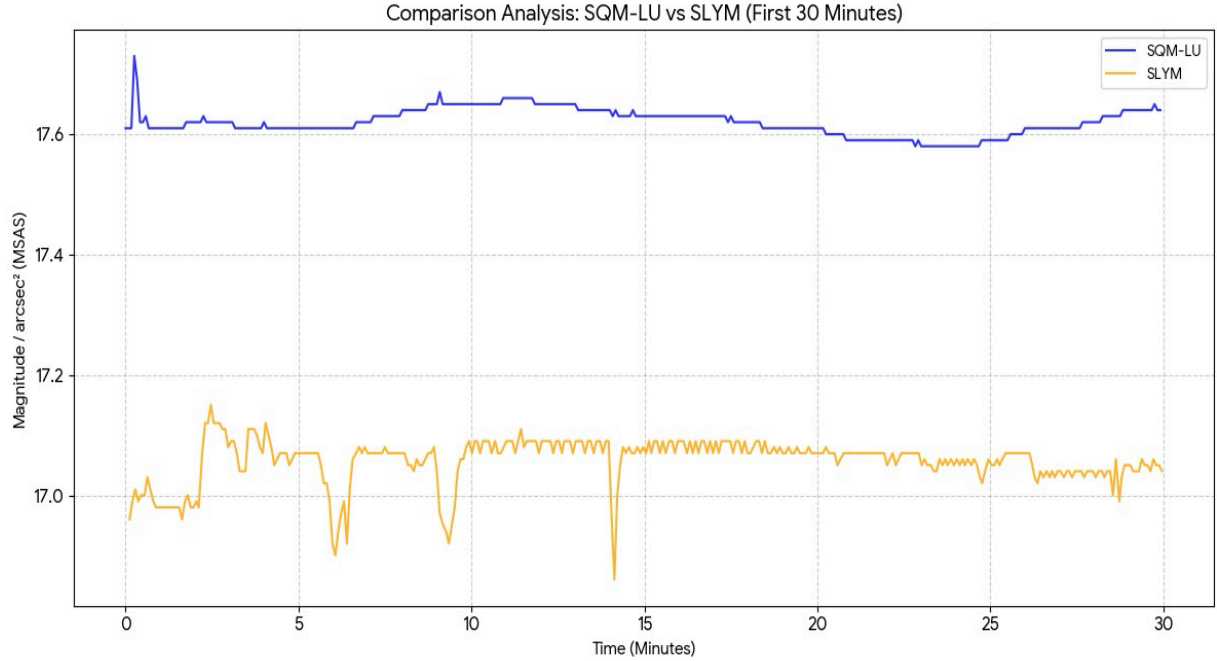


Figure 2. SQM-LU and SLYM Comparative Field Testing

The SLYM recorded values ranging between approximately 16.88 to 17.15 mag/arcsec², consistently sitting around 17.05 to 17.10 mag/arcsec² for the majority of the session. Crucially, the SLYM demonstrated a heightened ability to detect real-time atmospheric changes, capturing three distinct downward excursions at approximately $t = 6$, $t = 10$, and $t = 14$ minutes, the sharpest of which reached approximately 16.88 mag/arcsec². These dips are indicative of the SLYM's wider and more inclusive field of view, which allows it to detect transient sky events such as passing clouds, aircraft interference, or localised light intrusions that narrower instruments would simply miss (Kyba et al, 2011). Rather than a weakness, this sensitivity reflects the SLYM's strength as a more comprehensive sky monitoring device. The higher short-term variability observed in the SLYM trace is therefore a direct consequence of it capturing more of the actual sky environment, rather than a filtered or averaged representation of it.

The SQM-LU, by contrast, returned a noticeably smoother trace hovering between approximately 17.58 to 17.66 mag/arcsec², with a brief spike at session start reaching ~17.73 mag/arcsec², likely attributable to instrument startup settling rather than any genuine sky condition. While the SQM-LU trace appears visually stable, this smoothness may be a product of its narrower field of view and longer internal integration time, which inherently suppress short-term variations and risk masking real atmospheric events occurring in the broader sky environment.

The persistent offset of approximately 0.55 to 0.60 mag/arcsec² between the two instruments across the entire session is best understood as a systematic calibration difference rooted in their differing spectral responses and sensor architectures. The SLYM, with its broader spectral sensitivity, captures a more complete picture of the sky's optical

environment including contributions from diffuse light pollution that the SQM-LU's filtered photodiode is specifically designed to attenuate. This means the SLYM's lower MSAS readings are not a sign of inferior performance but rather a reflection of a more holistic sky measurement approach.

Both instruments agree that sky conditions during this session remained within a relatively narrow magnitude range, confirming general stability consistent with a suburban to semi-rural environment, broadly placing the site within a Bortle Class 6 to 7 classification. Despite the systematic offset of approximately 0.55 to 0.60 mag/arcsec² between the two sensors, the SLYM demonstrated consistent and repeatable sky brightness measurements throughout the session, with its dynamic responsiveness capturing real atmospheric variations that align with expected sky behaviour. Based on these findings, the SLYM is deemed a viable and capable instrument for sky quality monitoring, offering reliable readings that are comparable in trend and directionality to the established SQM-LU, and is therefore suitable for deployment in astronomy and light pollution research, and sky brightness studies with a slight tweak of the code for better stabilization.

4. CONCLUSION AND COMMERCIALIZATION POTENTIAL

SLyM presents a strong case for commercialisation as a locally manufactured Malaysian product, offering a cost-effective and field-ready alternative to imported sky quality meters. At approximately 10% of the retail price of the commercial SQM-LU, SLYM significantly lowers the financial barrier for institutions seeking to equip students and researchers with functional photometric instruments. Its in-house fabrication model eliminates dependency on overseas suppliers, removes import duties and currency conversion costs and enables flexible scaling of production to meet domestic demand.

The primary target markets for SLYM include educational institutions offering astrophysics, earth science and environmental science programmes, particularly pre-university and university level institutions such as the Astronomy Program offered by Pusat PERMATA@Pintar and many more, as well as astronomy clubs, planetariums and citizen science networks across Malaysia. Beyond education, SLYM holds potential for adoption by environmental monitoring agencies and research bodies involved in astronomy or light pollution assessment and dark sky conservation efforts. Its weatherproof construction, integrated GPS logging and self-contained portability further strengthen its appeal for deployment in remote observing sites and long-term sky monitoring campaigns. With refinement and branding, SLYM could also be positioned as a commercial product for the regional amateur astronomy market, contributing to the growth of Malaysia's science and technology instrumentation sector.

In conclusion, this project successfully developed SLYM: The world's first fully waterproof, low cost, and weatherproof Sky Luminosity Meter, as a locally fabricated alternative to the commercial Unihedron SQM-LU. By reverse engineering the SQM-LU and substituting its components with affordable, locally sourced alternatives built around an Arduino Nano platform, SLYM achieves a production cost of approximately 10% of its commercial counterpart, without compromising its core photometric functionality. The integration of a sealed, epoxy-encapsulated PLA enclosure addresses the weatherproofing

limitations of existing commercial units, while the embedded bubble level indicator and universal tripod thread resolve the structural alignment and mounting shortcomings that have long hindered practical field deployment. Comparative field testing against the SQM-LU demonstrated that SLyM is capable of producing consistent and reliable night-sky brightness measurements, confirming its suitability for educational use and basic astronomical observations.

In addressing the challenges of cost, durability, and versatility simultaneously, SLyM represents a meaningful contribution to accessible astronomical instrumentation in Malaysia, with clear potential for broader adoption across educational institutions, citizen science communities and the regional astronomy market.

5. ACKNOWLEDGEMENT

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