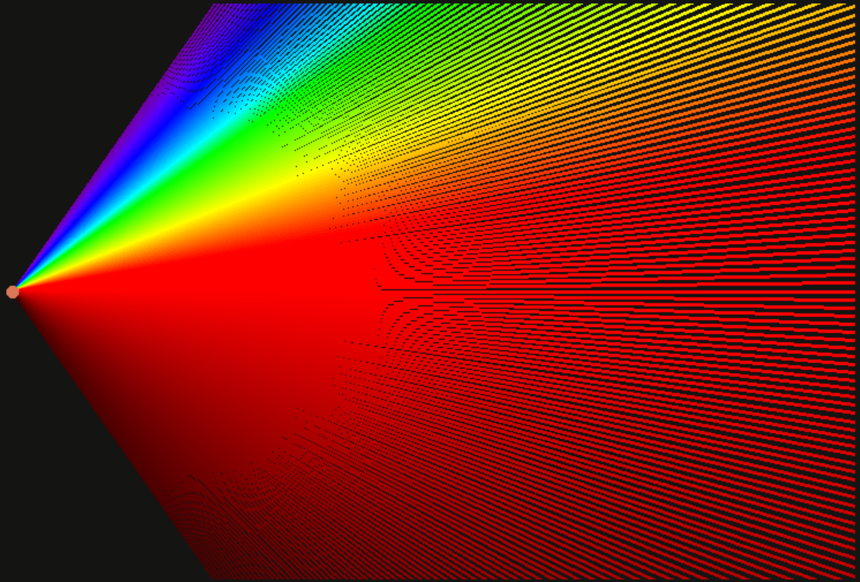
CySpectra Portable VIS-NIR Spectrometer

400–1000 nm Biomedical Imaging Platform



Senior Design — EE 4910 / 4920
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Client: Dr. Avishek Das · Biomedical Imaging Lab · Iowa State University

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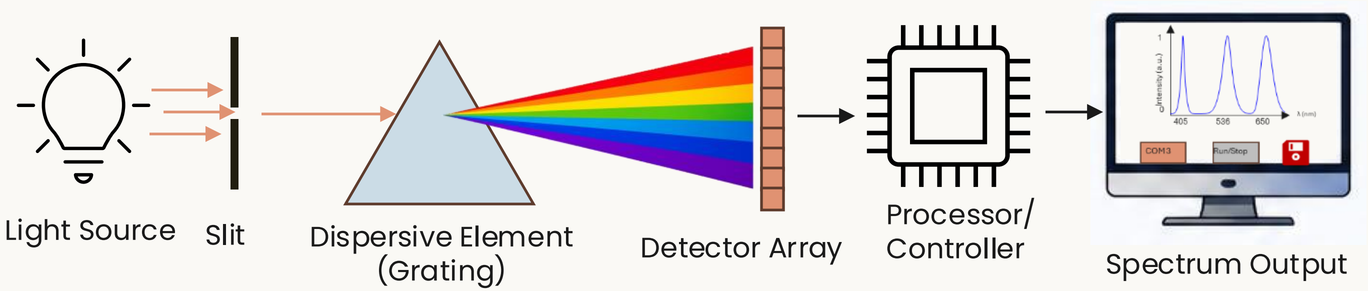
What is a Spectrometer?

A quantitative tool for converting light into spectral information

A spectrometer measures the intensity of light as a function of wavelength.
It separates light into spectral components and produces a spectrum that reveals material composition, optical absorption, and other physical properties.

Why is it important?

- Identifies substances and concentration
- Fast, non-destructive measurement
- Useful in chemistry, biology, optics, and electronics
- Enables data-driven material analysis



The result is a spectrum: Intensity vs Wavelength → a material fingerprint

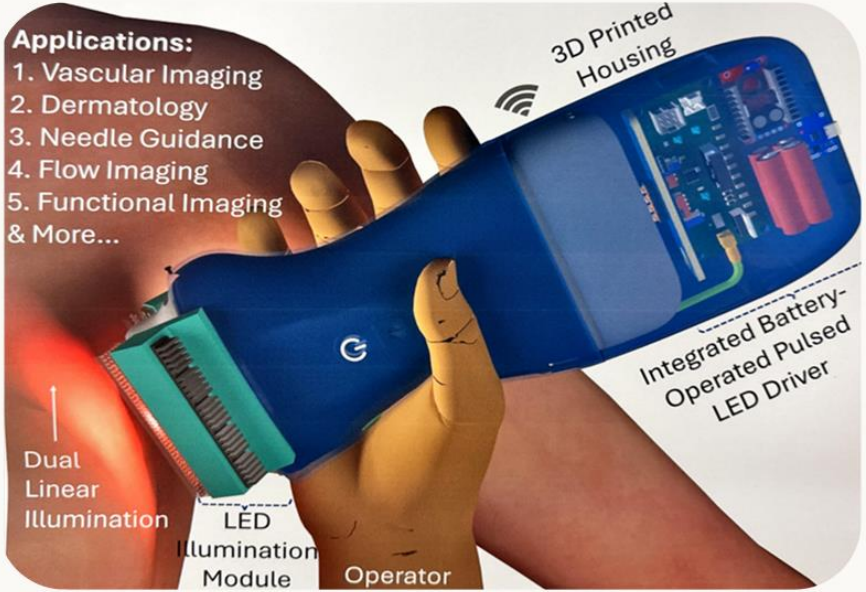
Goal & Motivation

Project Goal

Develop a portable, cost effective, modular VIS-NIR spectrometer which can detect optical wavelengths ranging from 400 nm to 1000 nm. This instrument will be used in BILAB in biomedical imaging research. The applications includes:

- Measure the spectral profile of unknown, and lab made light sources
- Log spectral data over time
- Fluorescence (light reflected from body at higher wavelength) imaging.
- Versatile benchtop or handheld operation

Research performed in the BILab @ ISU

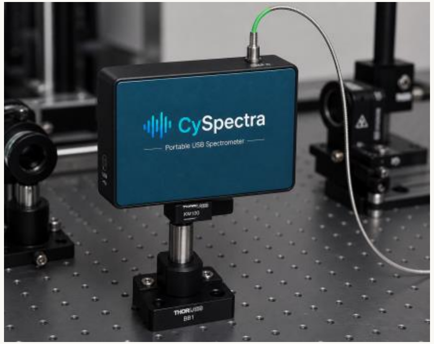


Parameter	Agilent Cary 60	Ocean Optics HR4	CySpectra (Our Proposal)
Size	4770 × 5670 × 1960 mm	~149 × 106 × 48 mm	Comparable to HR4 (Max: 10x10x10cm)
Cost	$10k–$25k+	~$4k–$8k (typical)	<$500
Spectral Range	190–1100 nm	~200–1100 nm	~400–1000 nm
Triggering (External)	❌ No	✅ Yes (multiple trigger modes)	✅ Full control
Frame-rate	~80 fps	74 fps	125 fps
Real-time Sync	❌	⚠️ Limited	✅ Fully customizable
Handheld/Portable	❌	⚠️ Semi-portable	✅ Battery powered
Customization	❌ Closed system	⚠️ Limited	✅ Fully modular
Use Case	Lab-grade absorbance	Field + lab spectroscopy	Instrumentation / imaging / research

CySpectra Features – Project Specifications

Parameter	CySpectra (Proposed System)
Type	Portable Embedded Spectrometer
Spectral Range	VIS–NIR (~400–1000 nm, configurable)
Spectral Resolution	<10 nm
Acquisition Method	Line-scan spectral acquisition
Trigger Capability	External + Internal trigger supported
Data Access	Raw spectral data available
Communication	USB + Wireless (ESP32 / Wi-Fi / BLE)
Fiber Optics Interface	SMA (top-mounted fiber input)
Light Input Geometry	Fiber-coupled / free-space configurable
Integration Time	Programmable (μs–ms range)
Frame Rate	Max 125 fps
Power Supply	USB + External battery pack
Battery Option	Modular attachable battery pack
Power Consumption	Low (<1 W estimated)

Modular & Portable System Architecture



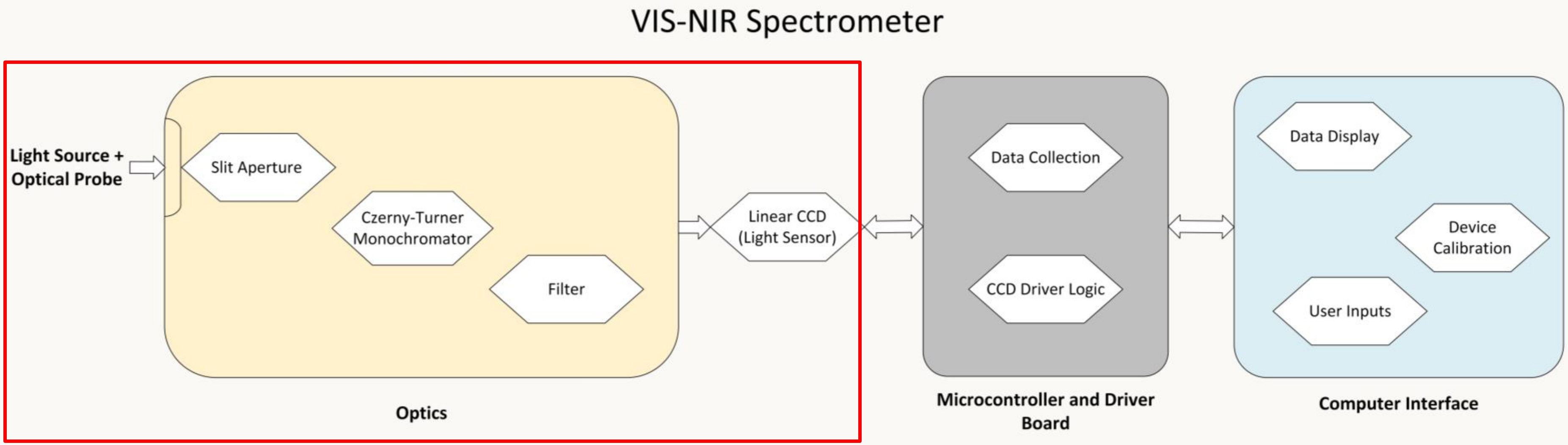
Supports optical-breadboard mounting

Handheld Operations

Wireless, remote operation

Battery driven

System Overview

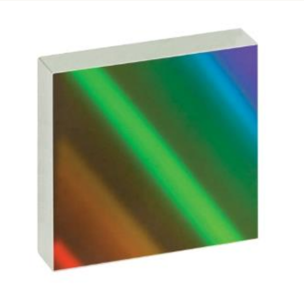


Process flow: incident light is spectrally dispersed by the diffraction grating, focused onto the linear CCD, digitized by the onboard ADC, raw ADC values transmitted to a host PC via USB-CDC, and finally processed and displayed by the desktop interface,.

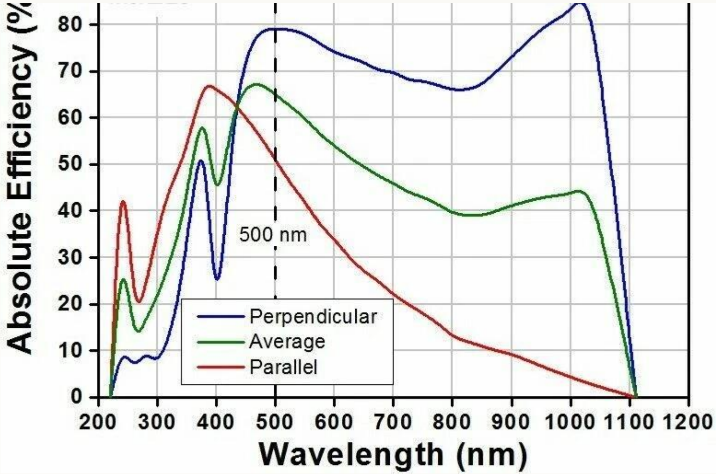
Choice of optical grating

Aspect	Prism	Transmission Grating	Reflective Grating (Chosen)
Spectral Range	Poor (Limited by material)	Wide	**Wide**
Spectral Resolution	Low–moderate, nonlinear dispersion	High	**High**
Linearity (λ vs position)	Nonlinear	Near-linear	**Near-linear**
Optical Design	Bulky, longer path	Straight-through, long path	**Folded, compact design**
Efficiency	Poor	Moderate	**High**
Alignment Complexity	Moderate	Moderate	**High**
Cost	Moderate	Moderate	**Moderate**
Customization	Limited	Moderate	**High**
Suitability for Portable Systems	❌ Not ideal	⚠️ Moderate	✅ **Best choice**

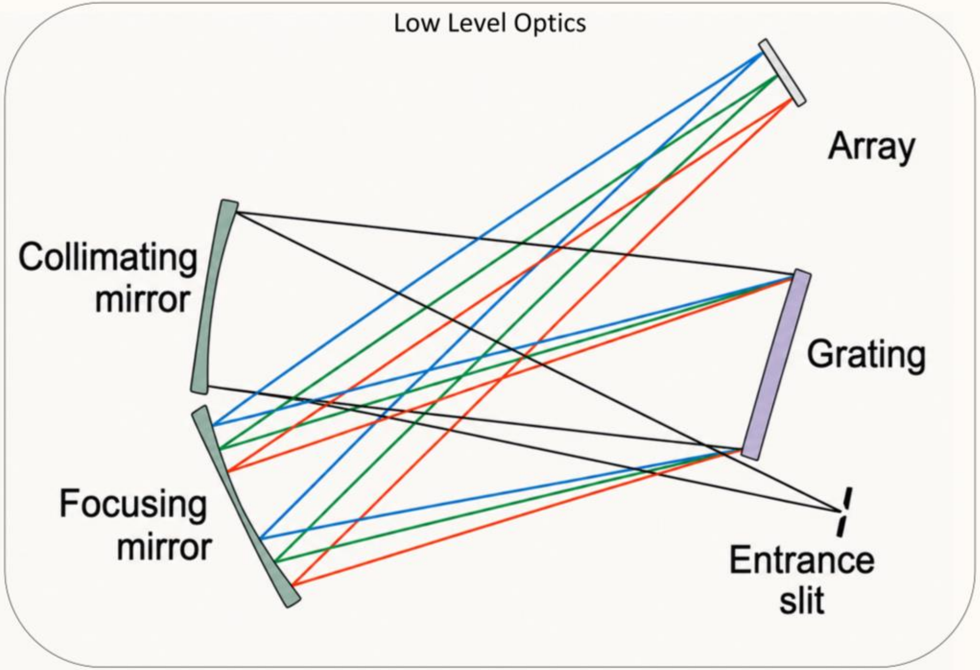
Reflective Grating



GH13-18V, Thorlabs
Visible Reflective Holographic Grating, 1800/mm, 12.7 mm x 12.7 mm x 6 mm



Optics Subsystem



Czerny-Turner Monochromator

- Used to meet the physical design specification of the project.
- Light will make first contact with collimating mirrors which produces parallel light rays.
- The parallel light hits a plane diffraction grating. Because the light is polychromatic, the grating spreads the light into its constituent wavelengths at different angles.
- The diffracted light hits the second concave mirror (the focusing mirror). This mirror takes the dispersed, parallel rays and focuses them toward the CCD.
- This is the design that will be placed in the housing; a transmission grating is being used for testing.

Optics Subsystem Testing

Laser Diodes

Known wavelengths (405, 520, 660 nm) provide precise reference sources for calibration

Collimating Lens

Collimates laser beam into a parallel, uniform beam before reaching the grating

Transmission Grating

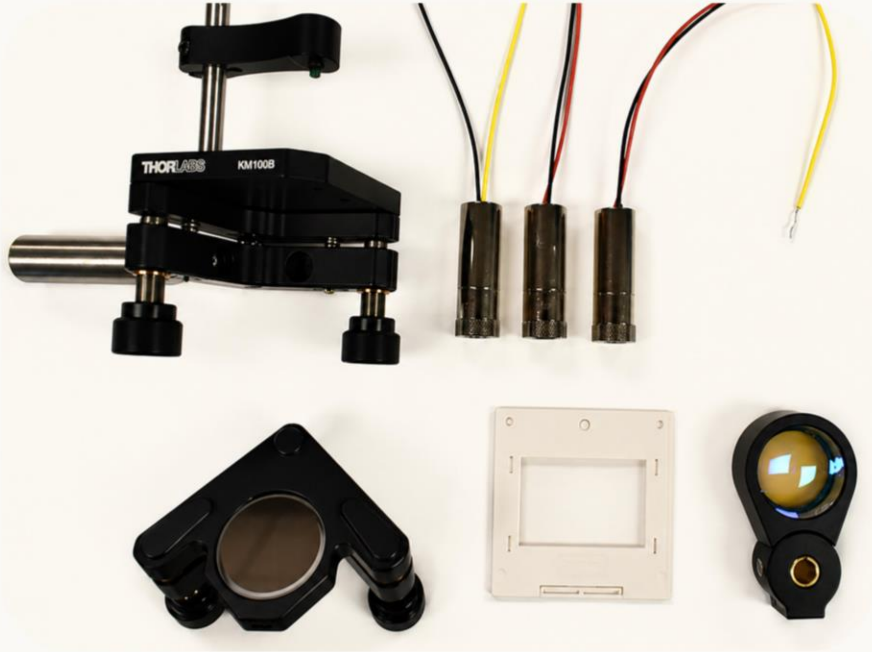
Disperses collimated light onto the CCD for wavelength calibration and testing

CCD Detector

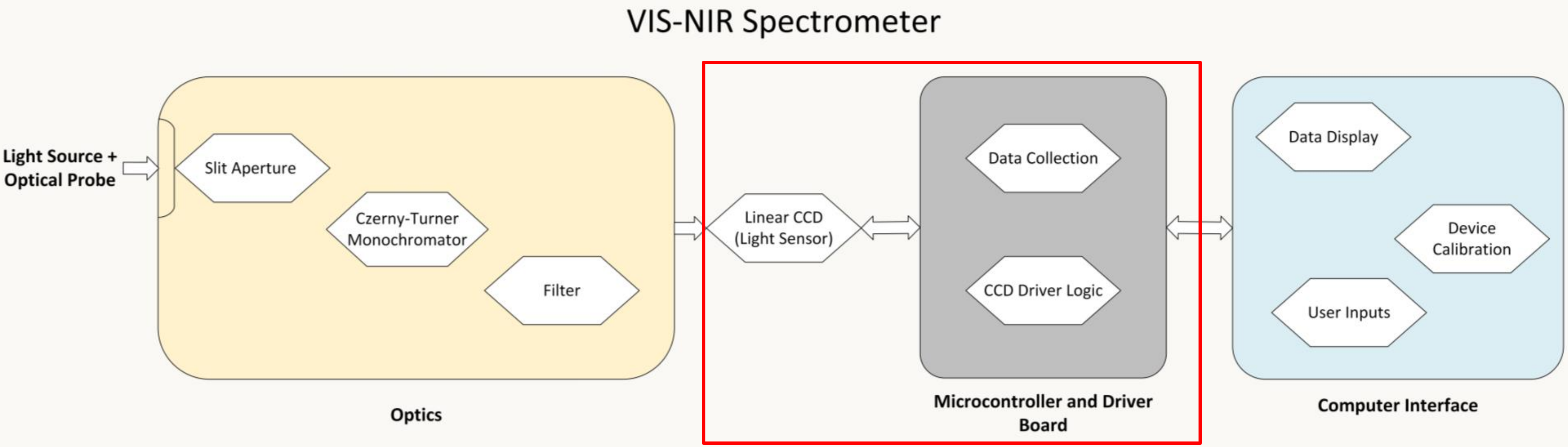
Captures the dispersed spectrum; pixel-to-wavelength mapping validates accuracy

Calibration Process

Compare measured peak positions against known laser wavelengths to build calibration curve

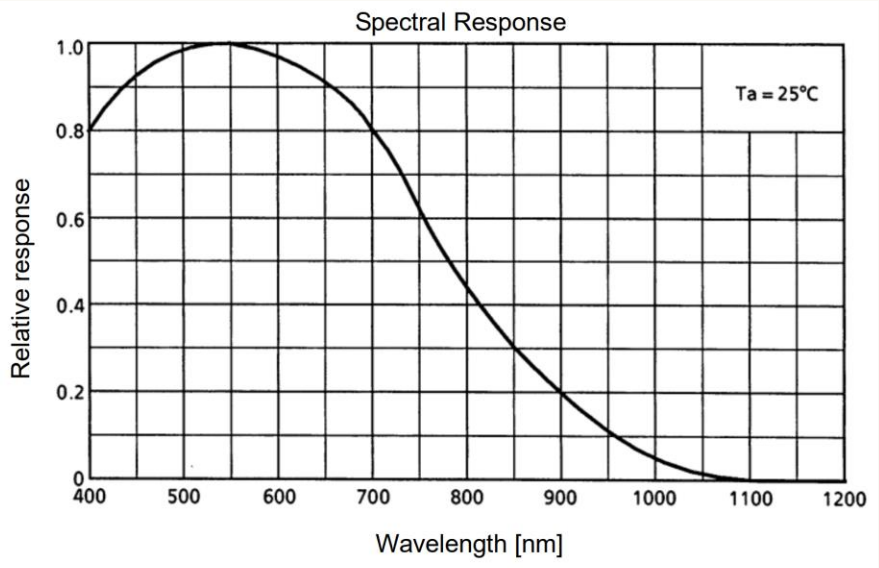


System Overview



Process flow: incident light is spectrally dispersed by the diffraction grating, focused onto the linear CCD, digitized by the onboard ADC, raw ADC values transmitted to a host PC via USB-CDC, and finally processed and displayed by the desktop interface,.

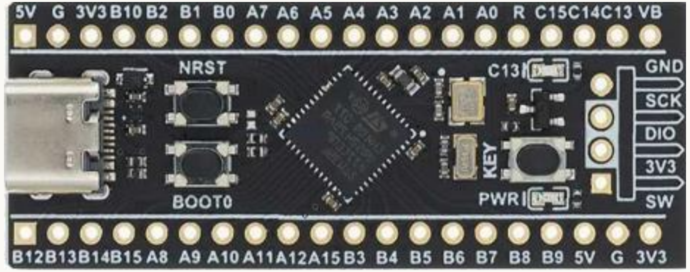
Choice of CCD



Toshiba TCD1304DG Linear CCD

- **350 - 1000 nm Spectral Range** - Covers the visible to near-infrared region for a wide range of applications.
- **External Trigger Capability [125 fps — 8 ms integration]** - Allows precise timing and fast spectrum acquisition synchronized with the microcontroller.
- **Linear Geometry [8 =« 200 um pixel size]** - Optimized for high sensitivity and uniform spectral response.
- **3648 Pixels** - High pixel count provides excellent spectral resolution.
- **Cost Effective (~545)** — Enables a high-performance spectrometer at a low cost,

Choice of Microcontroller



STM32x Series

- **High Clock Rate (100 MHz)** - Enables fast control and high-speed data acquisition.
- **ADC [12 bit, 2.4 MSPS]** - Provides high-resolution analog measurements for monitoring signals.
- **DMA (Direct Memory Access)** - Efficiently transfers data from the CCD to memory with minimal CPU load.
- **Multiple Timer Control [100 MHz]** - Precise timing signals allow trigger and integration control.
- **USB-FS (12 Mbps)** - Fast and stable communication with a PC for data streaming and control.

Detector & Electronics Subsystem

Signal Chain

Timers → CCD → STM32 ADC1 (12-bit, DMA circular mode)

SH Timer

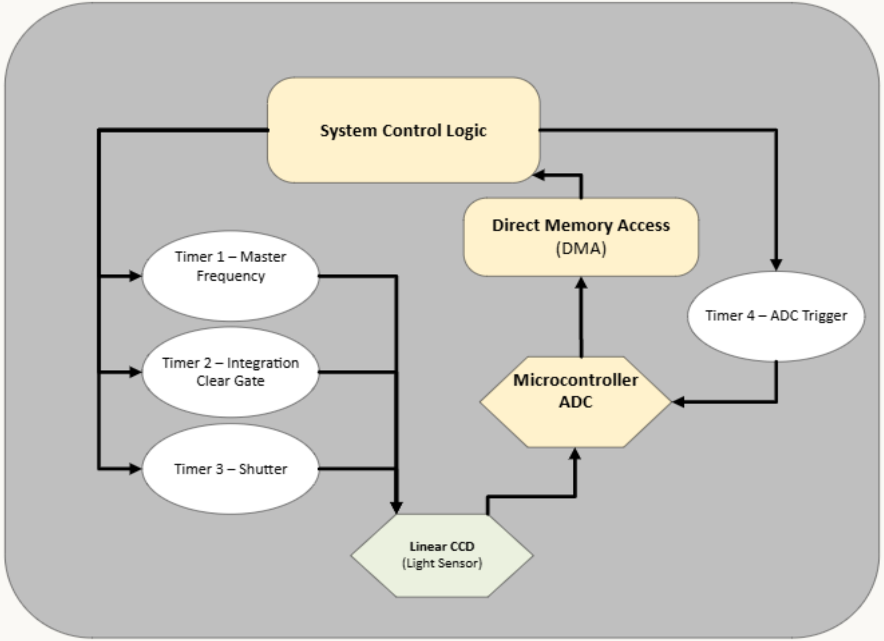
Shutter integration time: adjustable via firmware

ICG Timer

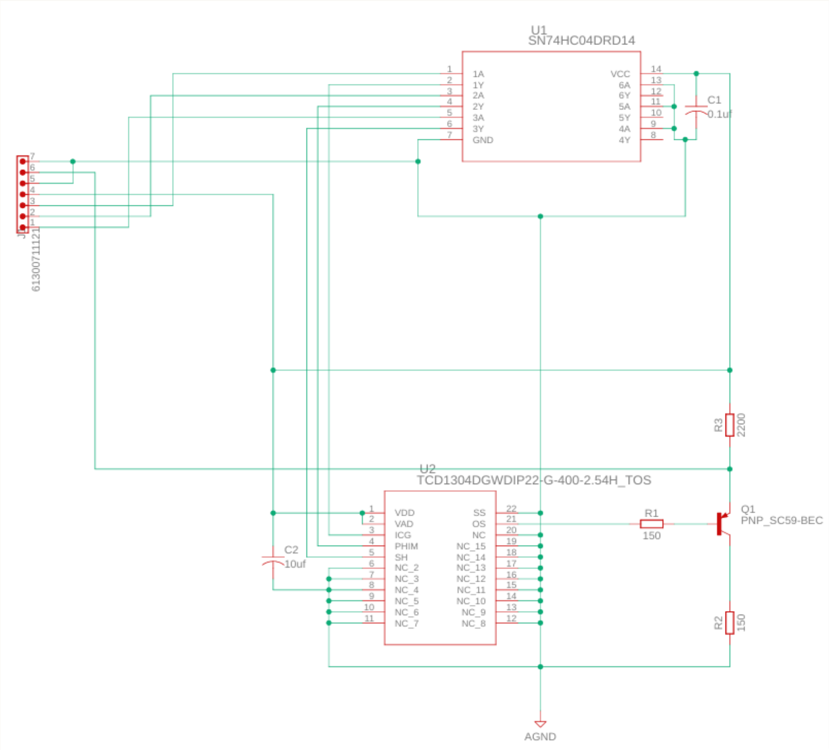
Controls total measurement time (8 ms)

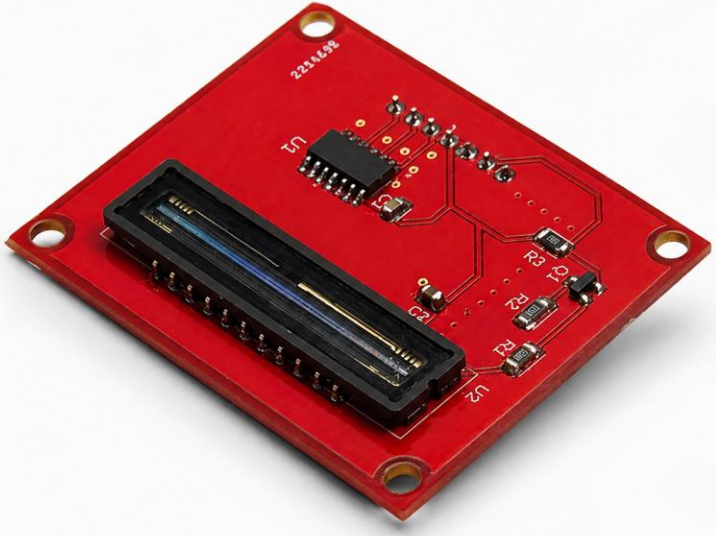
Master Clock

PWM signal (2 MHz)

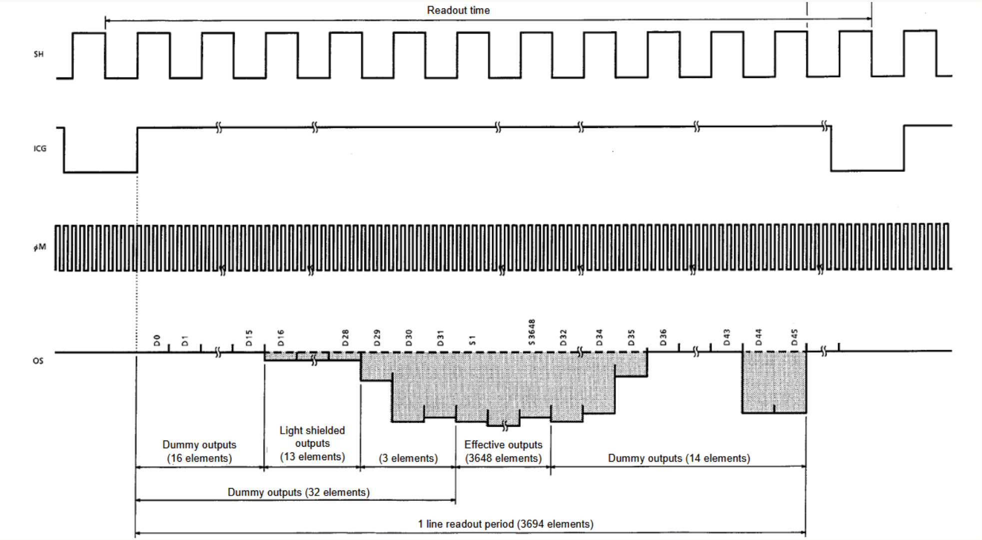


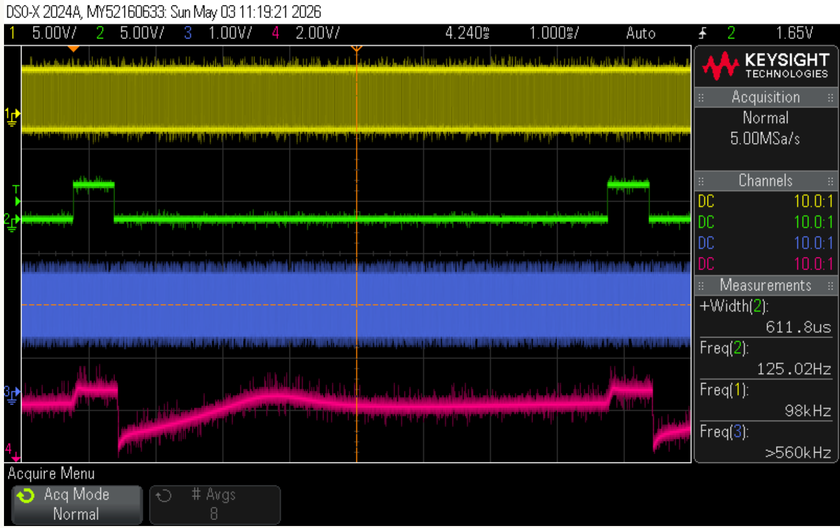
Detector & Electronics Subsystem

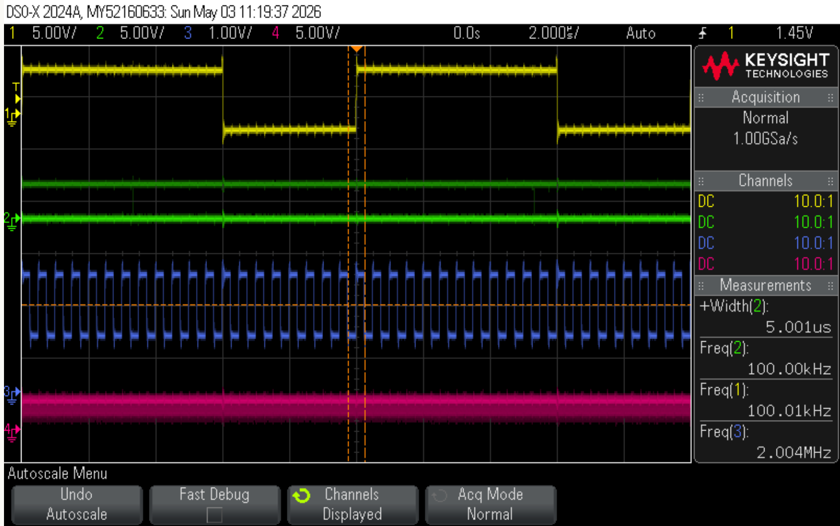




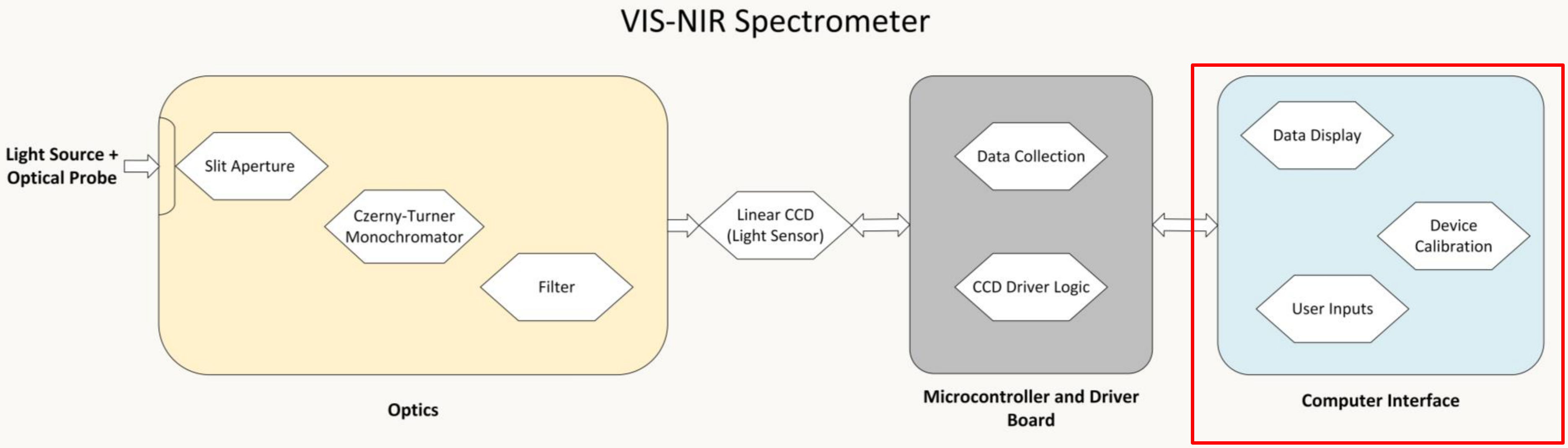
Running the CCD





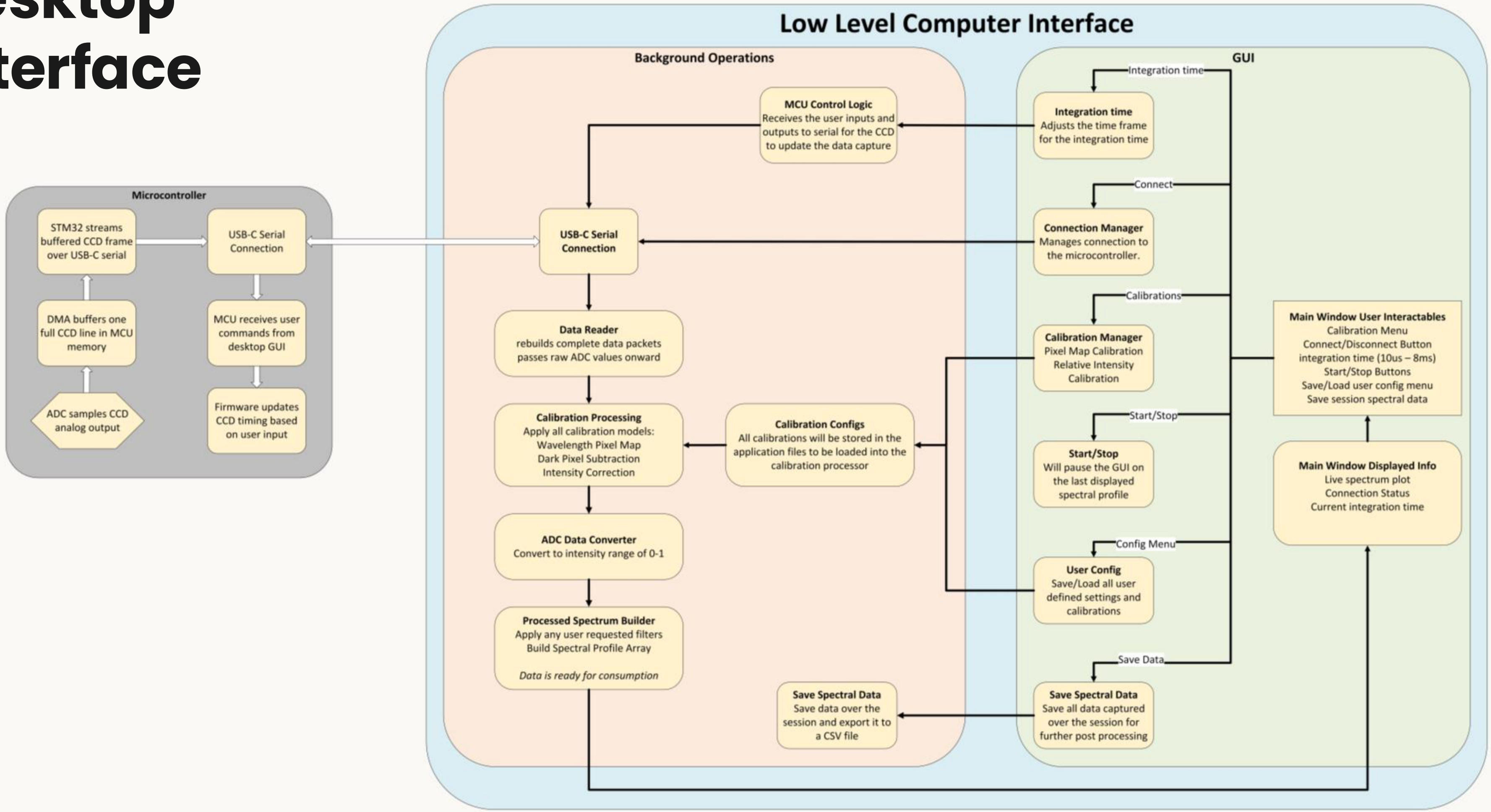


System Overview



Process flow: incident light is spectrally dispersed by the diffraction grating, focused onto the linear CCD, digitized by the onboard ADC, raw ADC values transmitted to a host PC via USB-CDC, and finally processed and displayed by the desktop interface,.

Desktop Interface

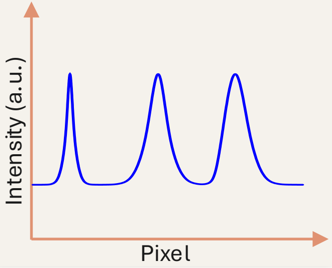


Data Processing Pipeline

1

Microcontroller Readout

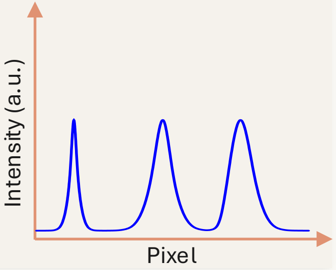
The STM32 creates CCD timing, captures the CCD line, and sends a binary USB frame.



2

Bias and Dark Correction

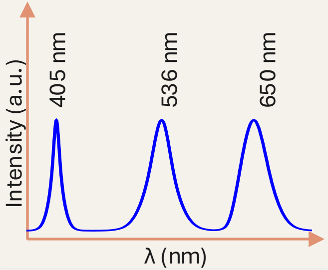
Bias and dark baselines are removed so the remaining signal tracks light intensity.



3

Wavelength Calibration

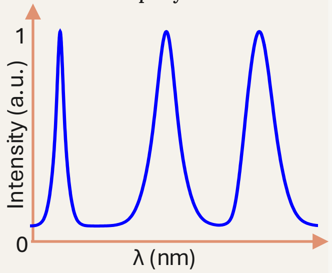
Known spectral lines map pixel index to wavelength with a fitted polynomial.



4

Response Correction and Normalization

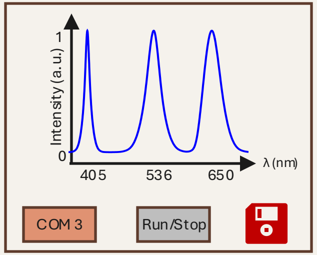
Quantum Efficiency corrections compensate instrument response, then the signal is scaled for display.



5

Display, Spectrogram, and Export

The GUI renders a calibrated spectrum or spectrogram and exports raw plus processed data.



λ = Wavelength; a.u. =Arbitrary Unit

Microcontroller Readout

1

Firmware Timing

Timers drive the CCD captures, trigger ADC sampling, and define the ICG-synchronized frame boundary.

2

Frame Capture

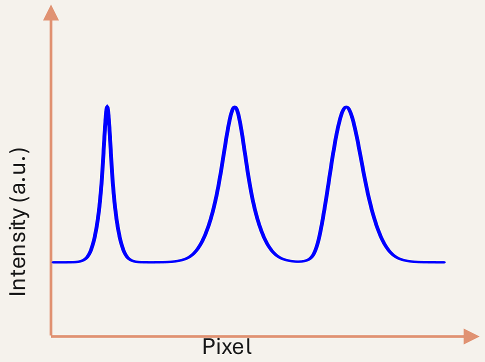
STM32 captures each 3694-sample CCD line, including dummy pixels, effective pixels, and trailing samples.

3

USB Output to Python

Each captured frame is sent to the Python host as packets over USB CDC.

Raw Captured Frame



Bias and Dark Correction

1

Raw Frame Intake

Python converts the USB payload into raw ADC counts and preserves the unprocessed frame.

2

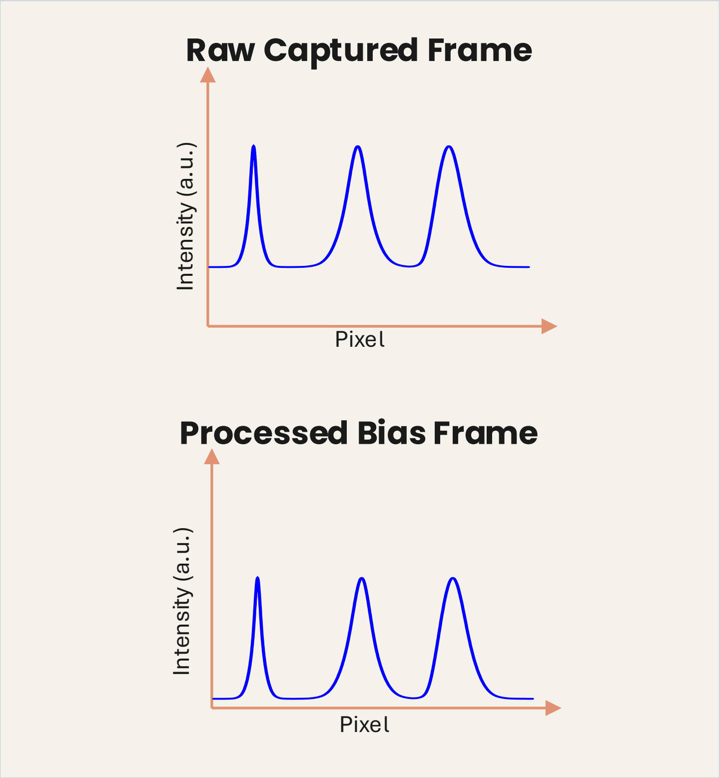
Baseline Removal

Stored bias/shielded-pixel dark reference offsets are removed.

3

Corrected Signal

The output is a baseline-corrected signal ready for wavelength and response calibration.



Wavelength Calibrations

1

Reference Peaks

Known laser or spectral lines are captured at their measured pixel locations.

2

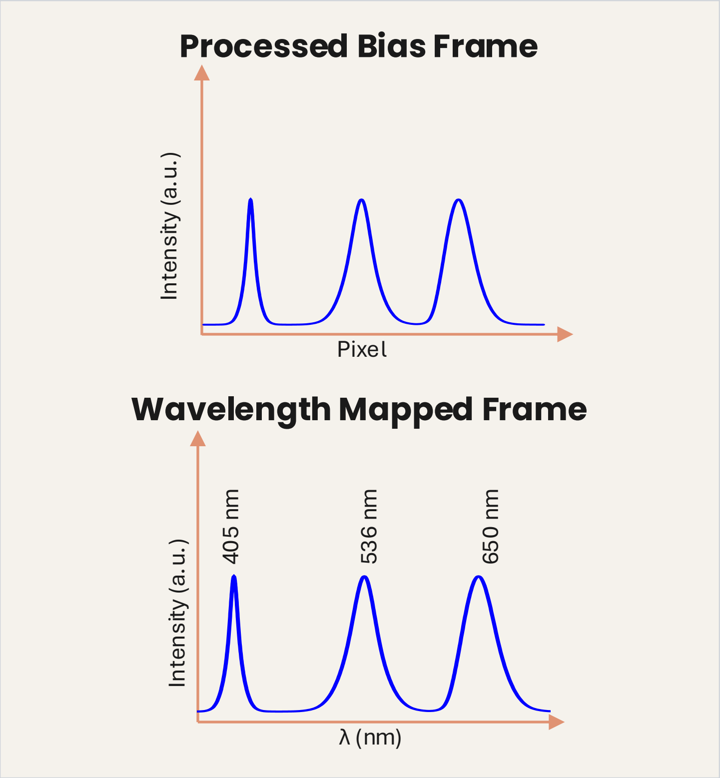
Polynomial Fit

Pixel-wavelength pairs are fit to a third order curve across the CCD.

3

X-Axis update

The spectrum x-axis changes from pixel index to wavelength in nanometers.



Quantum Efficiency and Normalization

1

Correction Factors

Wavelength intensity correction factors are loaded and interpolated to build an efficiency curve.

2

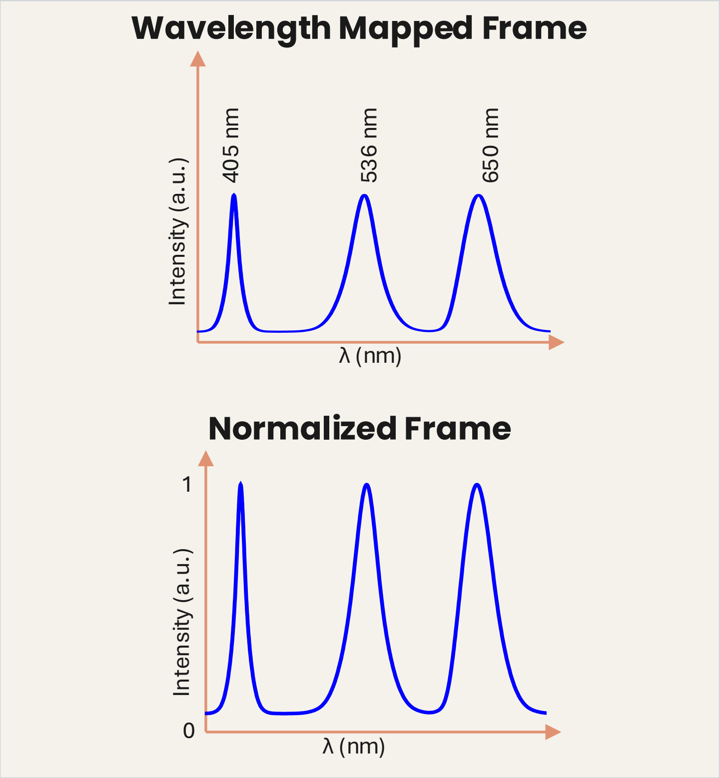
Response Application

Corrections are applied to compensate wavelength-dependent instrument response.

3

Data Scaling

Corrected intensity is normalized to a 0 to 1 display range.



Desktop Interface

1

Live Spectrum

The GUI plots the current processed line spectrum from effective pixels only.

2

Rolling Spectrogram

Recent frames are stacked into a time-varying intensity map.

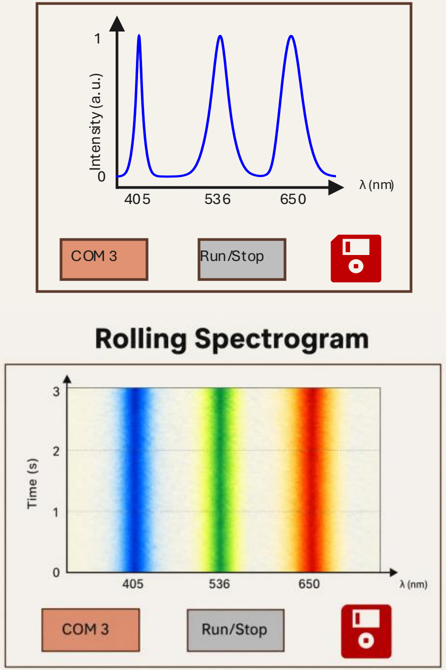
3

CSV Export

Raw and processed columns are saved for later analysis and verification.

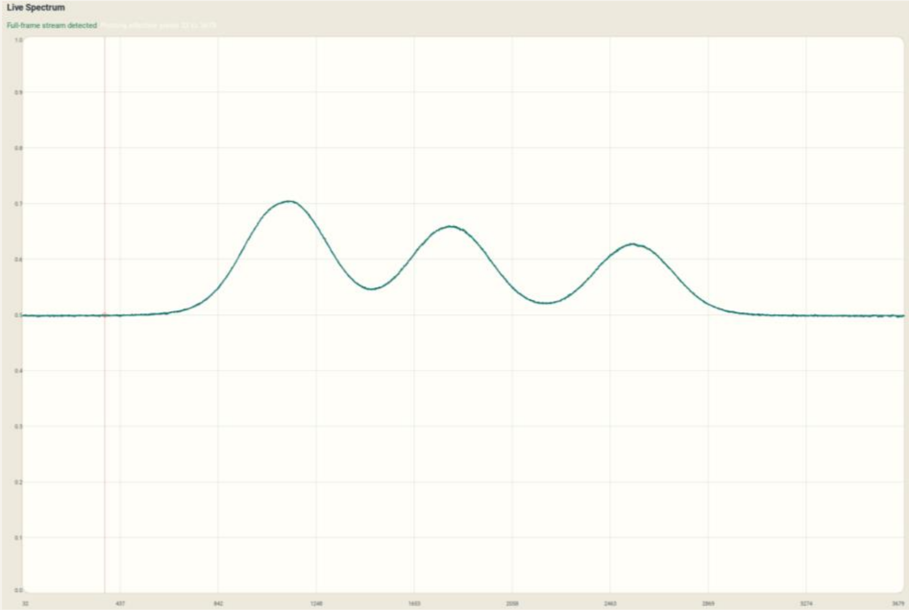
Live Spectrum

Rolling Spectrogram

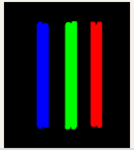


Current Display Output

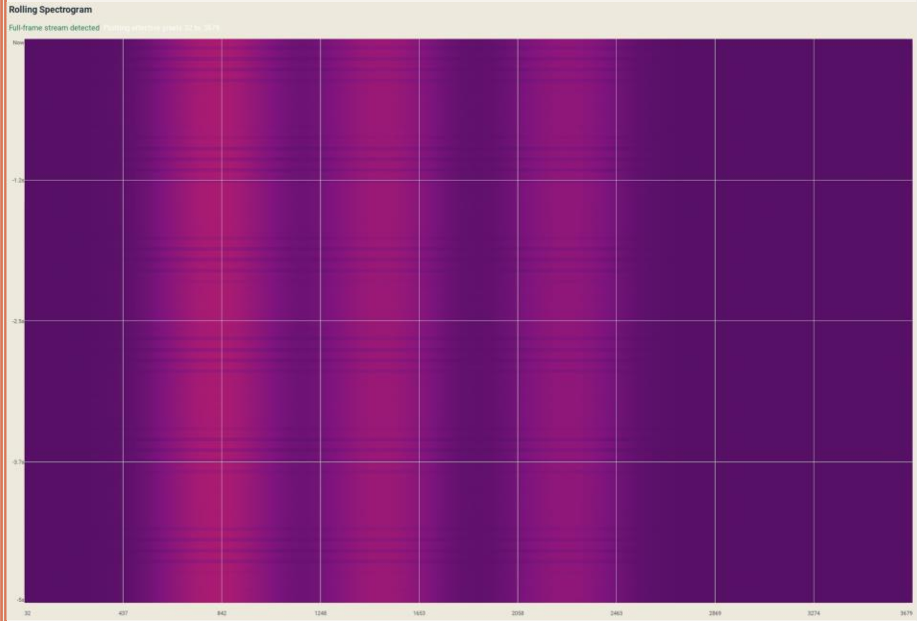
Live Spectrum



Test Image



Rolling Spectrogram



Testing & Validation Plan

Parameter Under Test	Desired Result	Verification Method / Test	Issue Mitigation
Wavelength Range (Δnm)	Consistent and accurate pixel response from 400-1000 nm.	Multi-point verification using known Laser Diode sources.	Adjust optics alignment
Spectral Accuracy + Width (λnm)	High correlation with calibrated lab equipment.	Side-by-side comparison with a calibrated spectrometer available in the BILab.	Optics + Calibrations
SNR & Noise Floor (dB)	Stable ADC floor	Analyze baseline mean, standard deviation, and noise across the CCD .	Data processing
Thermal Stability	Minimal spectral drift across operating temperatures.	Track peak shift, baseline drift, and grating-related wavelength movement over various temperatures.	Active/Passive Cooling

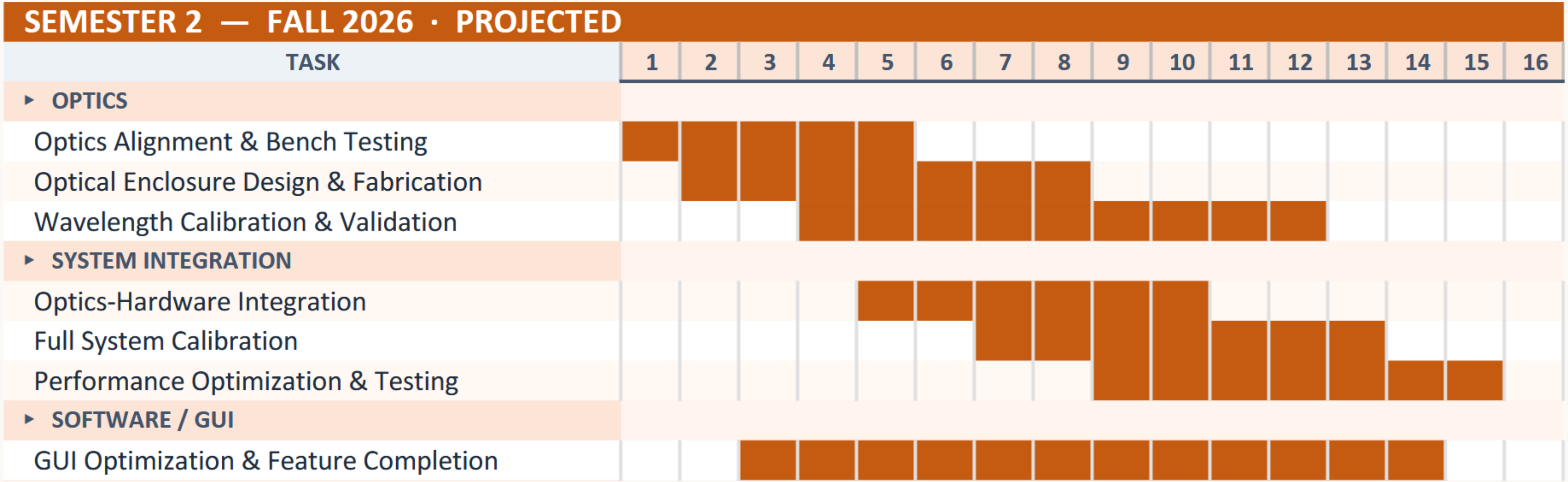
VIS-NIR Spectrometer · Project Timeline

EE 4910 · Group 06 · Developing a Cost-Effective VIS-NIR Spectrometer · Spring 2026 → Fall 2026 (Projected)

SEMESTER 1 — SPRING 2026

TASK	1	2	3	4	5	6	7	8	9	10	11	12	13	14
▸ PLANNING & RESEARCH														
Project Scope & Requirements	■	■												
▸ HARDWARE														
PCB Schematic Design	■	■												
PCB Fabrication & Component Orders		■	■	■	■									
CCD Driver Board Assembly & Testing						■	■							
▸ FIRMWARE														
MCU Dev Environment Setup (CubeIDE)		■	■	■										
Timer & ADC Configuration				■	■	■	■	■	■					
MCU-CCD Integration							■	■	■					
▸ OPTICS														
Optical Component Research		■	■	■	■	■	■	■	■	■	■			
Preliminary Optics Testing											■	■	■	■
▸ SOFTWARE / GUI														
Desktop GUI Development (Kivy)											■	■	■	■

Next Steps



SEMESTER 2 — FALL 2026 · PROJECTED
TASK
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
OPTICS
Optics Alignment & Bench Testing
Optical Enclosure Design & Fabrication
Wavelength Calibration & Validation
SYSTEM INTEGRATION
Optics-Hardware Integration
Full System Calibration
Performance Optimization & Testing
SOFTWARE / GUI
GUI Optimization & Feature Completion

Possible Added Features

Mobile Integration

Expand Kivy codebase to support mobile architecture.

Wireless Communication

Integrate a Wi-Fi Module to enhance ease of use in lab setting.

Hardware Upgrade

Upgraded CCD + Microcontroller to improve QE and increased frame rates

Budget

Item	Cost ($)
Convex Mirrors	120
TCD1304DG CCD	45
STM32F411CEU6	20
PCB Fabrication	10
Enclosure / Mechanical	10
Grating	135
TOTAL	340

Future Expected Costs:

- Fiber Optic Cables
- Optic Filters
- Enclosure Material

Ethical Considerations

Considerations	Our Solutions
Accuracy and reliability	Calibration
User safety	Protective housing
Device longevity	Reliable components and materials
Environmental Impact	Lead-Free Solder, ethical component sourcing
AI Usage	Responsible Use

Let’s Demo!

Conclusion & Next Steps

What We've Achieved

- PCB design and fabrication
- STM32F411 firmware at testable state (ADC + DMA + CCD timing)
- Python based desktop interface
- Calibration Laser Diodes received
- Initial diffraction demo confirmed visible dispersion across multiple orders
- Proof of concept completed

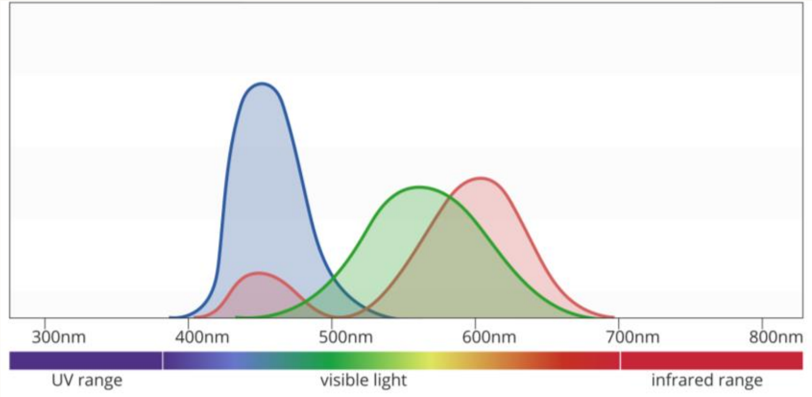
Remaining Work

- Optical assembly and mechanical housing
- System integration and first-light spectrum
- Wavelength calibration against known spectral lines
- Validation testing and biomedical demonstration
- Resolve 2nd-order reflection issue for 800–1000 nm range

Thank you — Questions?

Can you see colors? “~~Sky~~ *EYE* is the limit…..”

Color Sensitivity of the HUMAN EYE



The eye sees color, but not the spectrum → We need a Spectrometer.

Feature	Human Eye	Spectrometer
Wavelength range	400–700 nm	UV–VIS–NIR
Resolution	❌	Nano meter scale
Quantitative	❌	✅
Speed	❌	✅

How we see color:
- Brain interprets the relative signals
- Perception is qualitative

Limitations:
- 400~700 nm only
- Cannot see UV / IR
- No spectral resolution

Cannot measure:
- Wavelength
- Spectral width
- Intensity
- Fast changes

https://www.en.silicann.com/blog/post/difference-vis-nir-spectroscopy/

Challenges & Mitigations

Challenge	Mitigation Strategy
Stray light contamination	Optical slit aperture, 3D printed enclosure
Optical alignment sensitivity	Confinement and alignment testing on tabletop prior to 3D printing the housing
Calibration Procedures	Mapping known wavelengths to the pixel position on the CCD
2nd-order grating reflections contaminating 800–1000 nm	*Dual operation modes (400–750 nm and 600–1000 nm) or long-pass order-sorting filter*