Test Vehicle Detector Characterization System for the Boeing YAL-1 Airborne Laser

by

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Abstract

The test vehicle detector characterization system provides a convenient and efficient tool for rapidly evaluating the optical sensitivity of the GAP6012, GAP100, GAP300, and GAP1000 indium gallium arsenide detectors used on the vendor produced detector strips, which are used in the MARTI program at MIT Lincoln Laboratory. This characterization system exploits the approximately linear relationship between the radiant intensity of the gallium arsenide light emitting diodes (LEDs) and the forward current through the LEDs to correlate the expected irradiance with the observed detector counts. Illumination tests of different intensities are performed to characterize each detector’s performance over its entire operating spectrum. Each test is performed multiple times to determine the statistical variance of each detector. A detector which exhibits a high statistical variance will not pass the qualifying stage. The results of these tests and others are saved and indexed by strip serial number; allowing for future reference if the need should arise. The system was developed in a modular fashion so as to be compatible with both the high power (HP) and low power (LP) detector strips with only minor hardware and firmware updates.

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# Contents

1 Introduction .................................................. 13
   1.1 A Brief Introduction to the YAL-1 Airborne Laser (ABL) .... 13
   1.2 MIT Lincoln Laboratory’s Missile Alternative Ranging Test Instrument (MARTI) ........................................... 15
   1.3 MARTI Modules ............................................. 17
   1.4 Testing the MARTI Strips .................................... 19

2 Improving the Evaluation Procedure .......................... 21
   2.1 A Brief Description of the Current Sensor Strip Evaluation Procedure 21
   2.2 Goals for the Improved Evaluation System ................. 22
   2.3 Principles of Operation .................................... 23

3 A Closer Look at the Detectors ................................ 31
   3.1 Detector Specifics and Illuminator Selection ............. 31

4 System Design .................................................. 35
   4.1 Mechanical Design ........................................ 35
   4.2 Electrical Design .......................................... 39
      4.2.1 Illumination Circuits ................................ 40
      4.2.2 Power Diode Test Circuits .......................... 44
   4.3 Firmware Design ........................................ 49
   4.4 Software Design ........................................ 52
5 Design Lessons Learned
   5.1 Illuminator Design .................................... 57

6 Linear Least Squares Algorithm ............................ 61
   6.1 Application Theory .................................... 61
   6.2 Numerical Example .................................... 63

7 Concluding Remarks .................................... 67

A Schematics .................................... 69
List of Figures

1-1 Integration of the COIL in a 747-400F aircraft [15]. .................. 14
1-2 MARTI stack-up. ................................................................. 16
1-3 Cut away showing main components of the MARTI module (left). Cut 
    away showing the orientation of the sensor strips (right). ........... 17
1-4 MARTI module signal chain. .................................................. 19

2-1 Pictorial and mathematical representation of the illumination and con-
    version sequence. .............................................................. 24
2-2 Complete mathematical representation of the first order illumination
    system characterization and ideal detector output profile. .......... 26
2-3 Ideal detector output profile with pass/fail qualifiers. ............... 27
2-4 Schematic representation of power diode network for one supply rail. 28

3-1 Graph of responsivity as a function of wavelength and temperature for 
    the GAP100 InGaAs Photodiode [5]. ..................................... 32
3-2 Spectral density and directivity characteristics for the LNA2904L GaAs
    LED [14]. ................................................................. 33

4-1 Dimensions of the Zero Centurion Elite 105x carry case. ............ 36
4-2 Representation of the mechanical structure of the MARTI strip char-
    acterization system. ...................................................... 39
4-3 The simplified schematic on the left illustrates the principle ideas of
    the circuit and the schematic on the right expresses the implementation
    details. ................................................................. 41
4-4 Current measurement circuit for current being sourced by the positive 8 volt supply. ................................................. 45
4-5 Current measurement circuit for current being sourced by the negative 8 volt supply. ................................................. 46
4-6 On the left is a diagram of the positive switch implementation, on the right is the positive switch schematic. .................. 47
4-7 The diagram on the left represents the functionality of the negative supply rail switch. The schematic on the right shows the implementation of the switch I used in my design. .................. 48
4-8 Simplified state diagram of the main finite state machine. ........ 51
4-9 Screen capture of the sensor strip GUI. .......................... 54
4-10 Dialogue box for the failed parts list. ......................... 54
5-1 Original illuminator drive circuit. ............................... 58
5-2 Voltage waveforms at the current sense resistor (TP1) in Figure 5-1. 59
5-3 Waveforms illustrating the voltage across the current sense resistor (TP1) in Figure 5-1 after the feedback loop was closed. ....... 60
6-1 Graphical representation of the LMS approximation[13]. ....... 62
6-2 Graphical representation of the LLS numerical example. ....... 64
6-3 Plots of the detector output. The figure on the right clearly shows the diode turn on nonlinearities. .............................. 66
A-1 Schematic for the digital to analog converter for the Illuminator circuit. 69
A-2 Schematic for the analog to digital converter for current measurement in the illuminator circuit. ............................ 70
A-3 Schematic for the digital to analog converter for the power diode test circuit. ..................................................... 70
List of Tables

2.1 Logic table for power diode test. ............................... 29

6.1 Output detector counts and forward LED current. .......... 65
Chapter 1

Introduction

This chapter will provide a brief description of the history and goals of the Airborne Laser (ABL) project in order to explain the role of the test equipment that is being developed for the ABL at MIT Lincoln Laboratory.

1.1 A Brief Introduction to the YAL-1 Airborne Laser (ABL)

The ABL project that exists today began in 1996 under the direction of the United States Air Force. In 2001 management of the project was handed over to the Ballistic Missile Defense Organization, an organization which is now known as the Missile Defense Agency (MDA) [11]. The goal of the YAL-1 ABL is the destruction of theater ballistic missiles (TBMs) while in their boost phase.

The ABL incorporates a chemical oxygen iodine laser (COIL) to provide directed energy to its target. The COIL is a mega-watt class laser and can provide the same amount of energy in five seconds that a typical American household uses in one day. The COIL is integrated into a Boeing 747-400F aircraft (see 1-1) which provides the mobility required to get the COIL to the theatre of operations and within range of its target.

The ABL is meant to destroy TBMs in their boost phase. The theory behind
the ABL is that if the outer skin of the TBM is damaged by the intense energy emitted by the COIL, then the natural flight stresses which are present will rip the missile apart and render it useless. The ABL’s effectiveness is predicated largely on its ability to focus the energy of the COIL on the weakest point of the TBM, which in most cases is the fuel source [4]. There are five primary stages in an ABL engagement. First there is the detection stage. Infrared detectors are used to detect missile launches (which are often easily detectable due to the extreme amount of heat and large plume that are generated). In the second stage the ABL uses the reflection from a tracking illuminator laser (TILL) to determine the trajectory of the target and provide feedback for tracking the object. This is the acquisition and tracking stage. The third stage is the atmospheric compensation stage. The reflection of a beacon illuminator laser (BILL) is used to measure atmospheric distortion that will degrade the beam integrity (certain compensating strategies using adaptive optics may be employed to improve beam integrity at the target, but these will not be discussed in this paper). The fourth stage is the engagement stage, during which the COIL is fired on the target. The fifth stage is the kill stage. Assuming enough damage has been done to the structure of the rocket, it will break apart.

At this point there exists plenty of speculation regarding other possible uses of the ABL, including shooting down everything from inter-continental ballistic missiles (ICBMs), to low orbiting satellites, to engaging land targets. These additional applications introduce a whole litany of complications, tracking/targeting difficulties as
well as excessive atmospheric degradation of the laser, just to name a few. Ultimately the effectiveness of the ABL, whether we are talking about its intended purpose or an additional application, comes down to its ability to apply enough power and fluence to its target to destroy the object. Careful characterization of both the lasers used to track the target and the laser used to engage the target must be performed in order to understand the capabilities of the ABL. This is the goal of MIT Lincoln Laboratory’s Missile Alternative Ranging Test Instrument (MARTI), which is discussed below.

1.2 MIT Lincoln Laboratory’s Missile Alternative Ranging Test Instrument (MARTI)

The MARTI program’s main objective is a mid-flight characterization of the ABL’s tracking illuminator laser (TILL), beacon illuminator laser (BILL), and surrogate high energy laser (SHEL) or high energy laser (HEL), if so equipped. Data acquired for the TILL will be used to evaluate the ABL’s ability to locate and track the target of interest during mid-flight, data from the BILL will indicate how accurately the ABL identifies atmospheric turbulence, and the SHEL or HEL data will be used to characterize the beam pattern and irradiance of the incident laser. As its charter suggests, this is a mid-flight test, which means that the MARTI system must be a fully integrated, non-recovered fly away package.

The MARTI device was designed to present the same profile as a TBM. Presenting the “correct” target fuselage allows the system to better simulate and evaluate the ABL’s performance against the targeting and energy delivery challenges that will be faced during a live deployment. The MARTI is the next step in a long series of tests that have been conducted to assess the feasibility of this endeavor. Notable prior tests include the 2000 test on the Caravan target board [2], the 2004 test on the Proteus target board [5], and the 2007 test on the Big Crow target board [6]. As these names suggest, all of the previous tests have been against missile shaped target boards which have either been towed, or attached to aircraft. The Caravan
target board was a missile shaped target that was towed behind a Cessna. These tests demonstrated that a stationary (land based) version of the ABL’s system could perform both atmospheric compensation and tracking of a moving missile shaped target [2]. The Proteus target board was a missile shaped target that was mounted to the underside of a Proteus aircraft. The TILL, BILL, and SHEL lasers were once again tested from a land based platform. This time the land based system was placed on the 8,000 foot high North Oscura Peak in New Mexico [1]. The Big Crow test was the first mobile test of the ABL electronics. During this test the Boeing 747 equipped with the ABL took off from Edward’s Air Force Base and began tracking a target board mounted to an NC-135E aircraft after a simulated launch. The ABL used its TILL laser to track the target board and used a BILL simulator mounted on the target board to simulate the reflection that it will see from its own BILL laser. The ABL used this data to successfully track and fire its SHEL laser at the Big Crow target board [6]. The MARTI will be the first target to simulate every aspect of the ABL’s performance. The ABL will have to detect the launch of the MARTI and use its TILL, BILL, and SHEL lasers to engage and “destroy” the MARTI.

The need for an accurate test of the ABL’s effectiveness against a real TBM has significantly impacted the design of the MARTI. The MARTI device is the aggregate of three main modules and one telemetry module. Each of the three main modules contains three overlapping sensor arrays, one for each of the TILL, BILL, and SHEL lasers. The modules are cylindrical in shape and couple together to form the payload of the missile. All four modules will be joined together and mounted onto a Terrier MK70 and BBVC MK1 rocket motor to form the final MARTI device (see 1-2).

Figure 1-2: MARTI stack-up.
1.3 MARTI Modules

The main modules described above house the sensor arrays that are responsible for collecting the TILL, BILL, and SHEL data. Understanding the composition of these modules will illustrate the need for the preliminary test equipment that is the subject of this thesis. The image to the left in Figure 1-3 shows the main components of the MARTI module, the extension flex cable, the data formatting unit (DFU), the battery packs, and the electronics shelf which holds everything in place during flight. The image to the right in Figure 1-3 shows the orientation of the sensor strips and indicates how many strips are present in each module, a detail we will return to shortly, but first let us understand how the module functions.

![Figure 1-3: Cut away showing main components of the MARTI module (left). Cut away showing the orientation of the sensor strips (right).](image)

Figure 1-4 below presents an excellent pictorial representation of the MARTI signal chain and is invaluable to maintaining an overall understanding of the MARTI system’s functionality; however, it can seem a little daunting to the uninitiated. The signal chain begins with the initial acquisition of data. This data is acquired through Indium Gallium Arsenide (InGaAs) detectors. The specific model numbers of these detectors are different for high power (HP) and low power (LP) MARTI modules, as different active areas are required depending on the expected irradiance level; a more in-depth discussion of these detectors will occur in later chapters. These detectors
are mounted to sensor strips which are rigidly mounted to the inside of the physical MARTI module. The detectors are positioned in front of carefully machined holes and separated from the exterior of the rocket body by a window, a neutral density filter, and a spectral filter. The neutral density filter's value is chosen to correspond with the intensity of light that is expected to be incident on the sensor. These filters prevent the sensors from becoming saturated. The analog photocurrent output of the sensors is immediately converted to a digital signal by a 20-bit DDC101 analog to digital converter. This provides high sensitivity and decreases cross talk between adjacent detectors.

The sensor strips are grouped into quadrants, with a forward and aft bus for each module. In the LP modules, each quadrant contains 14 strips (eight SHEL, four BILL, and two TILL). There are four quadrants in each forward and aft bus, resulting in a total of 112 sensor strips per module. Each LP MARTI payload contains three modules; this indicates that a total of 336 sensor strips are required for each payload. The HP modules are similar to the LP modules, but they do not contain BILL or TILL strips. HP tests will not be conducted until the BILL and TILL lasers have been tested on the LP modules. Each HP module contains only 64 sensors strips for a total of 192 sensor strips per HP MARTI payload.

The strips quadrants are connected to the appropriate field programmable gate array (FPGA) by the extension flex cables. The FPGAs are the first component in the DFU to be active in the signal chain. The FPGAs are responsible for reading out each strips detector data, which has already been converted to a digital value by the DDC101 located on the strip. Since the MARTI modules will not be recovered, all of the collected data must be sent out before the missile crashlands. As previously indicated, there are as many as 336 sensor strips per payload, and each sensor strip may contain up to eight detectors (SHEL strips have eight, BILL strips have four, and TILL strips have two). Each LP MARTI module contains 2016 sensors that need to be read out. Needless to say, that results in a lot of data. With the relatively short transmission window that corresponds to the flight time of the module, it is necessary to compress the detector data before transmission. This is accomplished by
the digital signal processors. The DFU collects all of the data from each sensor strip and sends it to a digital signal processor (DSP) for compression. After compression the data is encrypted in the telemetry module and transmitted to the ground stations below. Multiple ground stations will be used to ensure that the data will not be lost due to a single fault failure. As indicated in Figure 1-4 there is also a connector on the module that facilitates testing on the ground.

![MARTI module signal chain](image)

**Figure 1-4: MARTI module signal chain.**

### 1.4 Testing the MARTI Strips

As was mentioned above, the signal chain begins with the individual detectors on the sensor strip. Under the current configuration a simple functional evaluation of the sensor strip becomes a complicated endeavor involving a considerable amount of equipment. From Figure 1-4 we see that a typical test requires the sensor strip, a DFU, and a workstation to readout the data (the telemetry module can be bypassed for in lab testing). This means that all functional evaluations of the strips must be
performed at MIT Lincoln Laboratory, as the equipment required to test the strips is both too large and too complicated to be used by the vendor who is manufacturing the strips. This fact, coupled with the high failure rate of the initial vendor produced strips, is the motivation behind this thesis.
Chapter 2

Improving the Evaluation Procedure

This chapter will discuss the current sensor strip evaluation procedure and highlight some of its detractors. This introduction will be used as motivation for the design requirements of the characterization system. The chapter will conclude with a high-level overview of the functionality of the improved evaluation module.

2.1 A Brief Description of the Current Sensor Strip Evaluation Procedure

The current strip evaluation procedure begins with a technician connecting an entire quadrant’s worth of strips to the flex cables, a difficult task in and of itself due to the high insertion force of the flight-qualified strip connectors. Next the flex cable is hooked up to a DFU and a workstation is loaded to watch the data as it is read out. Once the system is configured correctly and data is streaming out, a sheet of optically opaque cloth is placed over the strips. The data readout is then checked to determine the dark current level. The cloth is then removed, and a flashlight is used to test each detector for light sensitivity. Any notes that are required regarding the performance of a strip must be hand recorded for future reference. This system is effective for
performing a light sensitivity test, but it does not produce statistically useful data. There are too many extraneous factors such as excitation due to ambient light and an unknown responsivity characteristic to the many wavelengths of light emitted by the incandescent flashlight. This method is also highly time consuming and does not lend itself well to future scrutiny. Many strips pass the initial light sensitivity test, but are found to have excessive dark current, an incorrect responsivity profile, or unacceptable standard deviations during the full calibration procedure. Catching faulty strips during the calibration phase becomes a very costly problem as the module has to be taken apart to replace the strip, which is time consuming, and then the module has to be run through calibration again, a procedure that takes a minimum of two hours.

2.2 Goals for the Improved Evaluation System

The description of the current evaluation procedure above highlights the problem that this thesis was charged with addressing. The MARTI program at MIT Lincoln Laboratory needs a portable, easy to use, fast, accurate, and reliable piece of test equipment that is capable of storing the recorded data for the initial evaluation of sensor strips before they are built up into a module.

The test system needs to be portable and easy to use so that sensor strip functionality can be verified at the vendor before the strips are sent to Lincoln; this saves time on both ends, as strips can be immediately fixed instead of being sent to Lincoln and then back to the vendor. The system needs to be fast, relative to the current testing system described above, because it is assumed that the vendor will be both unwilling to perform the test if it is lengthy, and that the individual overseeing the test will become impatient and misuse the equipment if it takes too long. Accuracy is important, since the testing equipment is aimed at detecting deficiencies that would cause the detector to be rejected during the full calibration, and the requirements on the detectors are extremely strict during the calibration procedure. Reliability is an issue that every system faces; it is particularly important in this situation because
the equipment is to be used by individuals who have no training in its use, and it will need to withstand a few thousand strips being run through it. The final requirement, that it store the collected data, is particularly important because the tests will not be performed at Lincoln.

As the MARTI program progresses, it is possible that the acceptable performance metrics of the detectors may change. Having a repository of detector data makes it possible for the strips to be evaluated against the new performance criteria without physically testing the strips again; a script can be written to take in the stored output data and compare the measured results to the new performance criteria. Another advantage of having the stored output data is that if future problems arise with a particular strip or detector, the original output data can be consulted to determine which parts on the strip were found to be faulty, or barely passed qualification.

2.3 Principles of Operation

Chapter 4 will specifically address how the challenges above motivated the design for the MARTI strip tester. For now, we will describe the theory behind and development of the illumination test and power diode tests that were used in the implementation of this system. Understanding the general purpose and flow of the tests will make the initial design steps that are discussed in Chapter 3 more insightful.

Having no previous experience with the characterization of InGaAs detectors, it was decided to approach the design of the characterization process from first principles. All optical detectors must be excited by some incident light. This explicitly defines the need for an illuminator. The illuminator emits an irradiance which is measured in units of power per area. The detector has a fixed active area (the region that is photo sensitive). This region is a result of the fabrication process and is a fixed constant of the system; not surprisingly, it is expressed in units of area. The detector also has an effective responsivity. The responsivity will be discussed in further detail in Chapter 3, but for now, consider it to be a constant. The units of responsivity in this specific detector are units of current per incident power (amps per watt). Often
responsivity will be expressed as an output voltage per incident power; this is not the case with regards to the GAP family of detectors. In the case where a quantification of incident light is expressed as a digital number, an analog to digital conversion must be performed. This necessitates the utilization of an analog to digital converter. Dimensional analysis of the aforementioned parameters reveals that, for this system, the analog to digital converter must have a conversion factor that is expressed in units of digital counts per input current. Grouping the above parameters, we have a high level understanding of the illumination to conversion process. Both a simple pictorial and mathematical model are presented in Figure 2-1 below for the reader's consideration.

![Diagram](image)

**Figure 2-1:** Pictorial and mathematical representation of the illumination and conversion sequence.

Figure 2-1 illustrates a simple mathematical model that establishes the basis for a linear characterization routine. The product that is labeled as the "constant" can be thought of as the system constant. Conversely, it can be thought of as the variable of the system, but since the parameters it involves are related to devices contained on the strip, which neither the user nor the characterization system have control over, it will be referred to as the system constant. The "Input Variable", or irradiance, is a
function of the illumination source. This mathematical model immediately indicates that there is no absolute reference in the system, and as such it should be apparent to the reader that characterization of the irradiance is required if meaningful data is to be obtained for the characterization device. The specific details of characterizing the irradiance will be elaborated upon further in Chapter 4. The "Output Variable" is the simplest element of the mathematical expression as it is a digital quantity that will be read from the data registers on the strip into the data registers in the characterization device. There are two additional parameters that must be added to our mathematical mode; dark current, and the digital offset that is present in the analog to digital converter.

All practical detectors have some positive, non-zero value of dark current. Entire theses have been written on the causes, effects, and physics behind dark current, but for our purposes it is sufficient to note that there will always be a thermal contribution to dark current. The lowest possible detector output, assuming the detector is functioning correctly, is 4096 counts; this assumes no dark current. These 4096 counts are from the digital offset that is intentionally added to the analog to digital converter. In order to operate the analog converter in unipolar mode and ensure that the chip is safe against any extraneous AC coupled transients that may be present (this is only a problem for low DC currents where a small AC waveform could send the input negative), a small positive number of counts, in this case 4096, must be added to the analog to digital converter's nominal input to ensure that the input is never pulled negative. The other option is to run the analog to digital converter in a bipolar operational mode, but this sacrifices significantly more dynamic range. The dark current and digital offset add to our mathematical model in Figure 2-1 as a constant offset. The result of including this parameter is represented in Figure 2-2, along with an ideal representation of our detector output profile.

The equation in Figure 2-2 has been suggestively labeled, \( y = mx + b \), to reveal the linear nature of the ideal detector output profile. The plot of the ideal detector output profile reveals that the y-axis intercept "b" corresponds to the dark current level plus the digital offset of the analog to digital converter, and the slope "m" corresponds to
Figure 2-2: Complete mathematical representation of the first order illumination system characterization and ideal detector output profile.

the system constant. This is, of course, assuming that the conversion factor of the input variable is well defined, or in our case measured. The analog to digital converter will have a saturation level that corresponds to the maximum number of bits that are used to express the digital output. In this specific system a DDC101 analog to digital converter was used (a 20 bit analog to digital converter). This implies that our saturation level should be at $2^{20}$ or 1048576 counts. The linear nature of this model suggests natural pass/fail qualifiers for the detectors.

In the ideal case the pass/fail criterion for the dark current would be represented as an upper threshold on the y-axis intercept. This corresponds to the sum of the maximum acceptable dark current and the 4096 digital offset. Evaluation of the system constant is done through selecting a range of acceptable slopes; in practice this is not an absolute range, but rather a percent deviation from the slope of the linear approximation computed from the calibration strip. Saturation of the detector is the easiest performance metric to evaluate, as the analog to digital converter on the strip issues a high order saturation bit as the converter saturates. Figure 2-3 below is a pictorial representation of our pass/fail qualifiers.

Now that the reader has an understanding of the illumination test, let us discuss the theory behind the power diode test. As previously mentioned, the MARTI system
Figure 2-3: Ideal detector output profile with pass/fail qualifiers.

is a flyaway package. As such, it has been designed with backup power sources to prevent single fault failure due to mid-flight failure of a battery pack. Each strip requires three different voltage levels: a positive and negative analog eight volt supply, and a six volt positive digital supply. Each of these supplies has three power diodes to connect them to three separate power sources: a ground power source for preflight testing, a main battery bank, and an auxiliary battery bank in case the main battery bank fails mid-flight. During the initial testing of the first run, vendor produced MARTI strips it was discovered that a significant number of strips had at least one power diode that was miss-inserted, shorted, or missing. The initial functionality tests of the strips did not include diode tests. This means that some of these failures were discovered after the modules were built up, while their backup power supplies were being tested. This resulted in a new requirement that the strip power diodes be tested before buildup. Testing each strip by hand to guarantee that the diodes are correctly inserted would be an extremely time consuming process, as 27 measurements are required to uniquely determine the orientation of each diode. Figure 2-4 below shows what the power diodes for one supply rail look like.

The network in Figure 2-4 represents the strip side of the power network and
as such it can not be modified. In order to determine that each diode is properly inserted, we must ensure that each diode turns on and supplies current to the strip when it is forward biased, and that the diode is not shorted. To determine that each diode is correctly placed, we must measure both the voltage at the anode of each diode and the current flowing into the strip when the strip is powered from each individual power source. This means that the characterization system must be able to measure the current flowing out of each power regulator, the voltage at each anode, and be able to switch each power rail independently. The measurements for current and voltage do not need to be very accurate, as all we are concerned with is determining if these parameters are zero or some non-zero value. Once we have obtained these measurements, we can treat them as digital values in software and derive a logic table for each possible diode orientation.

Table 2.1 below indicates the “digital” values associated with each possible diode orientation. The “Test” column refers to which switch is active and when each measurement is made. There are three tests, one corresponding to each switch being closed. During each test, the voltage at the anode of each diode is measured, and the current flowing from the power regulator is measured. The “Current” column displays a logic 1 if current was found to be flowing out of the power regulator, and
Table 2.1: Logic table for power diode test.

<table>
<thead>
<tr>
<th>Test</th>
<th>Current</th>
<th>Voltage</th>
<th>Switch</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>Inserted Correctly</td>
</tr>
<tr>
<td>T2</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>T3</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>Shorted</td>
</tr>
<tr>
<td>T1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>Backwards</td>
</tr>
<tr>
<td>T2</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>T3</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>Missing</td>
</tr>
</tbody>
</table>

a logic 0 if no current was flowing. It is important to remember that the current measurement is from the power regulator and does not specifically indicate through which of the three power rails it is flowing. A logic 1 in the “Voltage” column indicates that a non-zero voltage was measured at the anode of that diode during that test. The “Status” column indicates the diode orientation based on the results in the truth table. This truth table shows the logic values that are evaluated to determine the orientation of each diode for each of the three power rails. The details of the implementation of this functionality are covered in Chapter 4 under the electronics design section.

The remaining chapters will highlight the design and construction of the strip characterization system. Particular attention will be paid to how the two tests described above determined elements of the design.
Chapter 3

A Closer Look at the Detectors

This chapter will focus on the Indium Gallium Arsenide (InGaAs) detectors that are used on the MARTI strips. Special attention will be given to how the responsivity characteristics of the InGaAs detectors determined the system's design and influenced the choice of illumination source for the characterization system.

3.1 Detector Specifics and Illuminator Selection

The following development will focus on the GAP100 InGaAs detector produced by the GPD Optoelectronics Corporation [8]. Different detectors were used on the LP and HP boards, but they are all GPD products, and the following is a general analysis that can be applied to any detector. A preliminary concern was the selection of an illumination source. One of the shortcomings of the simple mathematical model that was presented in Chapter 2 to describe the detector evaluation procedure was its assumption that the responsivity of the detector is a constant. In practice, the responsivity can be a function of both wavelength and temperature, depending on the operating point. The characterization system must be independent of temperature if repeatable, reliable results are to be acquired in different physical locations. Consulting the data sheet for the GAP100 we see that responsivity is temperature independent when excited by incident radiation that has a wavelength between 950 nm and 1600 nm. This determined the selection of an illumination source whose primary
Figure 3-1: Graph of responsivity as a function of wavelength and temperature for the GAP100 InGaAs Photodiode [5].

wavelength falls between 950 nm and 1600 nm. A 1315 nm source would have been ideal, as that is the wavelength of the COIL on the ABL. Unfortunately, it is difficult to find LEDs that produce wavelengths above 1000 nm at sufficient power levels. The decision was made to focus on using LEDs if possible because of the low cost. An alternative illumination source would have been to use low-power lasers, a step that would have significantly increased the cost and reduced the thermal stability of the illumination source. The implementation of a laser illumination source increases the initial cost of the illuminators and also increases the complexity and cost of the drive electronics associated with operating the illuminators. Based on these considerations a 950 nm Galium Arsenide (GaAs) LED [14] was chosen. As illustrated in Figure 3-2 below, the peak of the spectral illumination profile occurs at 950 nm. The directivity characteristics of the LNA2904L will be important in our discussion of the mechanical system design in Chapter 4, but are included now for completeness.
Figure 3-2: Spectral density and directivity characteristics for the LNA2904L GaAs LED [14].
Chapter 4

System Design

Chapter 4 is divided into 4 sections, each of which is concerned with the design considerations related to one particular aspect of the system. The main focus of this chapter will be on the electronic and mechanical design considerations, with relatively little emphasis put on the software and firmware design.

4.1 Mechanical Design

As mentioned in the introduction to this project, one of the main goals is to make this characterization system portable. This introduces three mechanical constraints: the system must be light enough to be carried by someone with the characteristic physique of a practicing engineer, it must be small enough that it is not unwieldy to transport, and the mechanical design must be robust enough to ensure that the system geometries will not be altered as a result of its relocation.

The basis of the mechanical platform for this system is a Zero Centurion Elite carrying case. The dimensions are as illustrated in Figure 4-1. Zero cases are lightweight, yet extremely durable due to their seamless aluminum construction with added styling beads that increase the flat side rigidity of the case. There are several other convenient features that this case provides. It is fully gasketed with a tongue and groove construction that ensures the system is optically isolated from the surrounding room. It is also equipped with an inner mounting rail that encircles the entire case; with
the optional mounting hardware, this allows for the secure mounting of a rigid plate between the upper and lower compartments of this case. This feature was utilized for mounting the platform plate that is described below. The case also features heavy-duty latches that secure the case during the illumination tests, and are designed not to fail during transportation of the case.

The platform plate is a $\frac{1}{16}$ inch aluminum plate that separates the electronics compartment from the user accessed illumination compartment. The electronics compartment contains the electronics expansion board that was designed for this system, as well as a Spartan-3 FPGA evaluation board, positive and negative 12 volt supplies, and the positive 5 volt supply. All of the external connections to the case are made through the sides of the case below the platform plate mounting line. This allows for all of the power and data wires to be run below the platform plate, where they are isolated from the user. This makes these connections safer, more reliable, and aesthetically pleasing. The illumination compartment contains the illuminator alignment rail, and the cam clamp.

The illuminator alignment rail consists of five main pieces: the LED mounting rail, the housing for the LED mounting rail, the piano hinge, the four rubber mounting feet, and the cam clamp. The LED mounting rail was machined on a CNC lathe out of a single piece of aluminum stock. The mounting holes for each of the LED illuminators were drilled by a computer controlled drill press to the same spacing constraints as were specified to the strip manufacturer. This removes one geometric degree of freedom from the long list of geometric variables; the spacing between the illuminators...
mounted to the rail and the detectors built into the strip are the same. The housing for the LED mounting rail was also machined from a single piece of aluminum, and represents the most rigid structure in the system. The housing for the LED mounting rail is “U” shaped with equal length legs; assuming the platform plate is flat, the housing for the LED mounting rail will hold the mounting rail perpendicular to the plane of the detectors. This ensures that the incident radiation will be normal to the detector. The housing for the LED mounting rail and the LED mounting rail were designed as two separate pieces, so that the vertical distance between the detectors and the illuminators could be adjusted through the addition of spacers between the LED mounting rail and the housing. The two main benefits to this feature are that it allows for geometric tuning of the irradiance, and if in the future a need arose to test a strip with the spectral filter and neutral density filter stack-up applied to it, the mechanical system is expandable to allow this test. The housing for the LED mounting rail is attached to the platform plate via a piano hinge. The advantage of a piano hinge is that it provides multiple points of contact and does not allow for alignment walk due to only two points of contact. The mounting holes on the piano hinge were beveled to ensure that the mounting screws hold it in firm alignment, the mounting screws were then coated with Loctite to minimize the chances that they will back out. The four rubber feet make contact with the strip when the housing for the LED mounting rail is in the down position. This performs several functions. First, this contact applies a constant force to the custom fabricated, low insertion force connector that was constructed for this application. This ensures that the strip maintains constant and continual contact with the system connector. Next, this force holds the strip and the illuminator rail in the same reference frame. Prior to the addition of these rubber feet, if the table housing the characterization system were bumped, a slight variation in the reported output counts would be detected. Lastly, these rubber feet provide a force to the strip that ensures the strip will be flat during the test. Some of the strips that have come back from fabrication have been rather seriously warped. When the strip is mounted in the MARTI module, any strip curvature will be taken care of by the mounting screws. Prior to the addition
of these rubber feet, the test characterization system would not have been looking at a properly aligned strip. The cam clamp provides a locking point for the front side of the housing for the LED alignment rail. The advantages of the cam clamp are that it is quick and easy to use. Unlike a screw fastener, it is easily adjustable to provide more or less downward force, and it swings completely out of the way to offer unimpeded access to the housing for the LED alignment rail.

Alignment considerations for the illumination rail have been covered, but I have delayed my discussion of the alignment of the strip itself. Alignment of the strip is equally important. The first generation of this tester assumed that alignment of the strip would be provided by the strip connector. This was before a low insertion strip connector was designed. The original strip connector required 44 pound-feet of force to make the connection and was clearly unacceptable for a high volume, fast piece of test equipment. The new low insertion force connector provides no alignment help. In an effort to produce repeatable strip alignments, a new intermediate plate between the platform plate and the strip was machined that has the same specifications as the mounting plates for the MARTI module, complete with tapped alignment holes. Tapered alignment pins were then inserted into these alignment holes so that as the rubber feet apply pressure to the strip, the alignment pins will guide the strip into the same position as the previous strip. This means that alignment of the strip is determined by the position of this mounting plate and the strip connector.

The alignment between the strip and the illuminator rail was performed by visual inspection the first time and then the strip mounting plate and connector were firmly secured to the platform plate.

The need for the alignment pins was deduced from the following test. First a series of tests were performed to establish a relative accuracy baseline. A strip was inserted in the system and then a series of six tests were run. The slopes of the linear approximations described in Chapter 2 were computed and then compared to the slopes from each of the other six tests. The worst variation in slope was found to be 0.1%, with the typical variation being closer to 0.02%. The strip was then removed and the system was packed up and carried around the lab. The strip was
reinserted and the strip test was performed again. The worst variation was found to 2.2% and the typical variation was 1.2%. Introducing the alignment pins is a control measure to determine if the increase in variation is a function of changes in the system geometry or the strip insertion alignment. The utilization of alignment pins reduces the variation to 0.1%, indicating that the variation is a function of strip alignment, and not due to mechanical variations in the system. A visual representation of the mechanical aspects of this system is presented in Figure 4-2. This is a good way for the reader to picture how the system comes together as a whole and to reflect on the main components of the system that were just described.

![Figure 4-2: Representation of the mechanical structure of the MARTI strip characterization system.](image)

4.2 Electrical Design

Early on, the decision was made to design the electronics board to interface with an existing Spartan-3 evaluation board. Digilent sells these evaluation boards complete with programmer and power supply for 99 dollars. There was no cost advantage to placing the FPGA on my board (especially since we already had the FPGA evaluation board left over from a cancelled program). The evaluation board has significantly more functionality than is needed, but also has some useful features that might not
have been included if the FPGA had been put on a custom board, such as indicator LEDs that can be programmed to indicate the current state of the FPGA. The other advantage to using the existing evaluation board is that it allowed me to begin writing and testing my FPGA code while my board was being fabricated. The only drawbacks to using the existing evaluation board are the increase in the size of the overall board combination, and the aesthetic factor associated with having additional wires in the system.

4.2.1 Illumination Circuits

The design began by considering the parts that would be required to implement all of the functionality described in the tests in Chapter 2. Design of the support electronics for the illumination test was the first priority. The illumination test requires that a controlled illumination source be turned on to a known illumination level, and that the strip be read out during each illumination period. This means that the illumination level must be controlled by the FPGA to ensure that the strip readout and illumination levels coincide. This requires a digital to analog converter. A digital to analog converter by itself is not sufficient to drive the LEDs so we also need an illumination drive circuit. The other constraint on the illuminator performance is that we know the illumination level. For a high accuracy system it is not sufficient to assume that the illumination circuit will emit the same intensity without variation even though it is driven with the same input command. The implication of this requirement is that we correlate the actual performance of the illuminator circuit with the commanded performance. The nearly linear relationship between LED forward current and LED irradiance can be exploited to perform this correlation. This indicates a need to measure the current that is flowing through the LEDs at each illumination level.

The choice of which digital to analog converter to use was determined by the fact that some of the low power MARTI strips contain only four detectors (the BILL strips) and some of them contain only two detectors and two triggers (the TILL strips). The fact that for some tests only a subset of the illuminators are required and that this
subset is always a multiple of two led to the decision to group the illuminators into pairs that are always illuminated together. This means that only four illuminator drive circuits are needed, and that these four drive circuits need to have the ability to be driven independently. This led to the use of a digital to analog converter that has a four channel output, the AD5665RBRUZ-2[9]. The AD5665 is a convenient digital to analog converter because it provides a four channel output, and has the ability to either update all channels simultaneously or to update any combination of channels individually. This means that when TILL or BILL strips are being evaluated, only the illuminators that are necessary to characterize the detectors on the strip will be turned on. This reduces the possibility of light pollution from adjacent illuminators. The AD5665 is a 16 bit digital to analog converter which means that it has 65,535 possible drive levels between 0 and 5 volts (the lower limit is actually 3mV). This provides excellent drive resolution. Once the drive source for the illuminator circuit was determined, the focus was shifted to the actual drive circuit.

An advantage of using an LED as an illumination source is that the drive circuitry becomes very easy to design. What we effectively want is a constant current source whose forward current is adjustable. This circuit is reproduced in both block form and schematic form in Figure 4-3 below.

![Figure 4-3: The simplified schematic on the left illustrates the principle ideas of the circuit and the schematic on the right expresses the implementation details.](image)

The digital to analog converter that drives this circuit is the AD5665 that was
discussed above. The op amp is an AD820[10] which is a single supply, rail-to-rail op-amp. The role of the op amp is to close a feedback loop around the transistor. This feedback loop allows the digital to analog converter to directly set the voltage across the emitter degenerating resistor. This voltage defines the forward current through the transistor based on the standard current to voltage relationship, $V=IR$. Without this feedback loop, the voltage across the emitter resistor is set to be a diode drop below the digital to analog converter output voltage; the implications of this behavior will be discussed in Chapter 5. The down side to this implementation is that if the digital to analog converter is not capable of driving its output to 0V (which in this case it is not) then the voltage at the emitter resistor will be set to whatever the lowest output voltage of the digital to analog converter is, which in this case is 3mV. This non-zero voltage across the emitter resistor leads to some forward current through the transistor. This small amount of forward leakage current will cause the LED to emit, making it impossible to obtain an accurate dark current measurement. A solution to this problem is to increase the nominal operating point of the voltage at the emitter resistor to be greater than the lowest output voltage of the digital to analog converter. In this implementation this was done by adding a 100k ohm pull-up resistor to 5V. This sets the nominal operating point at the emitter to be 10mV, which is greater than the 3mV that the digital to analog converter can drive to, and thus allows the illumination circuit to turn off.

The schematic on the right of Figure 4-3 has some added resistance between the op-amp output and the base of the transistor, as well as some added capacitance between the base and collector of the transistor. These additions are there to damp out any oscillations that may otherwise occur.

The last topic of the illuminator circuit that we will discuss is the choice and role of the analog to digital converter. The purpose of the analog to digital converter that measures the voltage at the emitter of the transistor is to determine the current that is flowing through the LED at each illumination level. The measured voltage is converted in software into the current that is flowing through the illumination LEDs. This information, coupled with the conversion profile between current and irradiance,
is used to determine the irradiance of the LED, which is ultimately used to determine the linear approximation for the system. The slope of this approximation is used as a means to evaluate the system constant that was defined in Chapter 2. Provided that the conversion profile between the current through the LED and irradiance is linear, the linear approximation can be calculated using current instead of irradiance as the \( x \) variable. This will result in a linear approximation between output detector counts and current through the LED that will be different from the linear approximation between output detector counts and irradiance by a constant multiplication factor. As long as the windowed range for the system constant is established using a calibration strip, and the same linear approximation that will be used to evaluate subsequent strips, the system will maintain its relative accuracy. However, concerns over the consideration of adequate bit depth for the linear approximation have motivated me to use a power meter and characterize the nonlinear regions of the diode's irradiance versus current curve. The nonlinearities are highly repeatable, which means that a nonlinear fitting function can be applied to correlate the current through the LED with the irradiance of the LED at low forward currents. This fitting function allows for a software correction of the diode nonlinearities and expands the region of output detector counts that may be used for the linear approximation. The underlying concern is that if the linear approximation is being computed using only a windowed range of data between 300,000 counts and 800,000 counts, then data from only 1.5 bits is being used. Considering the analog to digital converter on the strip is a 20 bit converter, we see that we are making a judgment on a very small amount of data.

The analog to digital converter that was chosen for the emitter voltage measurement is an AD7655ASTZ\[8\] quad input, 16 bit analog to digital converter. The 16 bit output is high enough in resolution to make accurate measurements of the forward current. Its single supply operation, simultaneous conversion (of two of the four channels at a time), and four channel input makes this chip an excellent choice for my system. The implementation specifics of the digital to analog converter and analog to digital converter that are associated with the illumination tests are presented in Appendix A.
4.2.2 Power Diode Test Circuits

The power diode tests require that the anode voltage of each of the nine power diodes be measured, as well as the input current to the strip from each voltage regulator. The FPGA must also be able to individually select which power diode is connected to the supply; this requires nine switches. In order to measure current flow from the supplies, we need to make a differential measurement; this means that we need six analog to digital converter inputs to handle the current measurements. In total we have 15 voltages to measure to determine the diode orientation, and nine switches to implement. Since one of the supplies is a negative supply, we will have to design two different switch implementations, one for the positive supplies and one for the negative supply.

It was decided that the ideal component would be an analog to digital converter with nine or more inputs, so that one chip could be used for the voltage measurements on the diodes. The device of choice was the AD7708BRUZ[7]. The appeal of this chip is that it has ten analog inputs that can be configured as either single-ended inputs or fully-differential inputs. This makes it an ideal chip to choose, because one chip can be used for the voltage measurements with it operating in single-ended mode, and another can be used for the current measurements with it operating in fully-differential mode. This chip utilizes a serial to peripheral interface (SPI) communications protocol. The analog to digital and digital to analog converters that were chosen for the illumination circuits use an Inter-Integrated Circuit (I²C) protocol. I thought that this would be a good way to motivate myself to become fluent in VHDL as I would be forced to implement two different communications protocols. The implementation details of the AD7708BRUZ chips that I used in this design are expressed in Appendix A.

Measuring the current from the positive supplies is a straightforward endeavor. As indicated in Figure 4-4, I added a series resistance between the positive 12V supply and the input to the LM317EMP[18] linear regulator. I then used a resistive divider network to divide the voltage down to a voltage that is compatible with the input of
my analog to digital converter. These divided down voltages are provided as inputs to an AD7708 that is configured in fully differential mode. The AD7708 outputs a digital number that represents the voltage drop across the series resistance. This information, along with the known value of the series resistance, is used to determine the current that is flowing through the supply. There will always be some non-zero current flowing through this path due to the power dissipated in the LM317, but the difference in current levels between the current dissipated in the regulator and the current supplied to the strip is readily distinguished, as it differs by two orders of magnitude. When the strip is connected to the supply, the current flowing through the series resistance is measured to determine if the connected path is supplying power to the strip. This is a critical measurement in determining diode orientation, and also serves as an evaluation step to determine if there are any shorts from the power rail to ground on the strip itself. The LM317 includes output short protection circuitry that will prevent the strip from damaging the characterization system, should a short circuit exist on the strip. I chose the LM317EMP regulator because it is the same regulator that is being used in the actual MARTI modules.

The principle behind measuring the current from the negative supply is the same,
but is complicated by the fact that the supply is at a lower potential than the input to my analog to digital converters will allow. Since I chose to design my system to run from a positive supply, I decided not to look for an analog to digital converter that could take negative inputs, but rather to level-shift my resistive divider network to compensate for the negative potential of this supply; Figure 4-5 illustrates this implementation. The AD820 op-amp buffers the 2.5V reference voltage and applies

![Figure 4-5: Current measurement circuit for current being sourced by the negative 8 volt supply.](image)

this voltage across the resistive divider network between the negative 12 volt supply and the reference voltage. In this situation, as more current is drawn from the supply, the voltage at the input to the LM337[17] becomes less negative. Figure 4-5 indicates the correct orientation of the positive and negative inputs to the differential analog to digital converter. This biasing scheme allows for the measurement of the current flowing through the negative supply using the same differential analog to digital converter that was used to measure the current flowing from the positive 8 volt and positive 6 volt supplies.

The last design consideration related to the power diode tests that needs to be discussed is the design of the switches. The switches for the positive analog and digital supplies are identical, since they have the same polarity. The schematic representation
of my positive switch implementation is included in Figure 4-6 below.

![positive switch implementation diagram](image-url)

Figure 4-6: On the left is a diagram of the positive switch implementation, on the right is the positive switch schematic.

FPGAs are logic arrays and, as such, their outputs are not designed to drive a low impedance load. They are only capable of supplying a milli amp or two at most. As such, it is important to design any circuit that interfaces directly with the FPGA such that it does not draw more current than the FPGA can supply; otherwise the FPGA may be permanently damaged. The advantage of using a metal oxide semiconductor field effect transistor (mosfet) as opposed to a bipolar junction transistor (bjt) in this application is that the mosfet behaves like a voltage controlled current source, whereas the bjt functions as a current controlled current source. The mosfet therefore presents a lighter load to the FPGA output. Examining the schematic in Figure 4-6, we see that when the FPGA output goes high, a positive voltage is applied to the gate of the n-channel mosfet; this allows current to flow from the drain to the source and grounds the drain of the mosfet. When the voltage goes low at the drain of the n-channel mosfet, the p-channel mosfet will turn on and begin to conduct current from its source to its drain. This provides a current path to the strip from the positive eight volt analog supply rail. The resistor divider network on the drain of the p-channel...
mosfet divides down the input voltage to a level that is compatible with the input to my analog to digital converters. The 1k ohm resistor to 12 volts on the drain of the n-channel mosfet is a pull-up resistor that forces the p-channel device to turn off once the FPGA output has gone low. While we can use the same switches for both the positive analog and digital supplies, we must come up with another topology for the switches on the negative analog supply.

The problem with using the same topology for the negative switches that we used on the positive switches is that if we hook the source of the p-channel device to the negative eight volt regulator, we won’t be able to turn the device on because we won’t be able to pull the gate of the p-channel device more negative than the source. There are many ways to implement a simple negative supply switch; the method I chose is illustrated in Figure 4-7.

Figure 4-7: The diagram on the left represents the functionality of the negative supply rail switch. The schematic on the right shows the implementation of the switch I used in my design.

The diagram on the left in Figure 4-7 was included to show the simplicity of this switch, since schematic representations such as the one on the right can often mask the simplicity of elegant circuits. Grounding the gate of the p-channel mosfet causes the p-channel device to turn on whenever the output of the FPGA goes above high. Once the lower transistor is conducting, the voltage on the gate of the n-channel device will go high because it is tied to the drain of the p-channel transistor. With
the n-channel device biased on, the negative eight volt supply is connected to the strip and current is allowed to flow from the strip to the negative supply. The 10k ohm resistor between the source of the n-channel and drain of the p-channel transistors acts as a pull-down resistor to ensure that the n-channel device turns off once the FPGA output voltage has gone low. In the schematic on the right in Figure 4-7 there is an inverting buffer attached to a resistive divider network. This allows the output voltage to be divided down and then inverted to become a positive voltage that is less than five volts, which is compatible with the analog to digital converter that I selected.

Reflecting back on the necessary elements for the power diode test, we see that we now have implementations for all nine switches, methods for measuring the supply current from both the positive and negative power supplies, and a means to measure the voltages at the anodes of each power diode, regardless of their polarity. This is all of the functionality that is required to implement the power diode test that was described in Chapter 2. The implementation details of the analog to digital converters are included in Appendix A.

4.3 Firmware Design

Firmware serves the middle ground between elegant analog circuits and utilitarian digital software. It is programmed like software but implemented in hardware, which gives it the advantage that it can be rapidly updated and modified to meet evolving needs while still maintaining the functionality of hardware, namely the ability to perform truly parallel computing.

This project utilizes a Spartan-3 FPGA to facilitate the collection of data from the analog to digital converters, to drive the digital to analog converters, and to interface with the sensor strip. I chose to implement the FPGA design in VHDL (a hardware description language that was originally developed for the Department of Defense) instead of in Verilog, because I was advised that VHDL is more widely used in industry. The system uses the FPGA as an intermediary between the computer
the user is interacting with and the hardware that collects the data. This provides a clean break between data collection and data processing, and ensures that all of the necessary raw data is available on the computer should future processing be necessary.

The overall firmware structure of the test characterization system is a modular one that consists of one main module to implement the global clocks, resets, and logic interconnects, and it contains individual sub-modules to interface with each chip. During development, this structure was utilized to allow for incremental system expansion. Once the output data structure from a chip was known, a placeholder module was created and inserted to provide test data for transmission and processing. This facilitated the implementation of a complete skeleton structure of the system early on in the development stage. Placeholder modules were systematically updated with functional blocks, allowing for incremental testing of the system as its complexity grew.

The long term advantage of a modular approach is that it is easily expanded and updated if the data collection requirements or hardware interfaces change. The original goal of this system was to take a dark current measurement, a midlevel measurement, and a saturation measurement. As the project progressed and the detector evaluation routine became more complex, the need for higher data resolution arose. Due to the modular design of the system, accommodating this change was relatively straightforward. A few additional storage registers were added and a few iteration counters were incremented, but the fundamental structure of the system was unchanged.

The underlying structure of the majority of the sub-modules is a finite state machine (FSM). The overall progression of the testing sequence is controlled by a main FSM that coordinates each test based on the logic signals that are received from the other sub-modules. Transitions in a FSM are synchronized to the rising edge of the system clock (50 MHz in this case), and occur when the conditional governing that state evaluates true. When no conditional is specified for a state, the transition occurs on the rising clock edge. Figure 4-8 contains a simplified model for the FSM that governs the progression of the power diode and illumination tests. Many states have
been omitted from this model, such as the delay states that occur between the strip analog power turn on state and the strip digital power turn on state, a delay which is necessary to prevent reverse biasing of the diodes on the strip. However, despite these omissions, Figure 4-8 still illustrates the concepts behind the implementation of a finite state machine and indicates the relative ease with which the number of samples or test points captured can be modified. State transitions in Figure 18 are indicated by arrows. States that are controlled by conditionals have a '1' or '0' next to their arrow to indicate that the transition occurs when the conditional evaluates true or false. Transitions that are only a function of the rising edge of the clock are left un-marked. It can be seen in Figure 4-8 that adjusting the counter values for the “Check number test points” and “Check number samples” states will result in an increase or decrease in the number of samples or data points that are evaluated. If the number of evaluated test points is increased, then the number of illumination levels that the system drives to must be adjusted. The details of this adjustment are not presented here.

This characterization system was designed to be sent to the company that is producing the sensor strips. As such, there are certain additional design requirements that must be satisfied. Namely, the system must be able to recover (on its own) from
user requests that deviate from the standard operating procedure. Instead of trying to anticipate and design for every possible user initiated failure mode, a global watchdog timer was established. The watchdog timer begins counting when the system is told to begin, and continues counting until the system returns to the idle state. In the event that the system does not return to the idle state within 30 seconds (the upper limit on how long the test may take), the watchdog will reset the FSM to idle and restore all values to their power-on state. The test may then be repeated.

Communication between the FPGA and the software is handled by a universal asynchronous receiver/transmitter (UART) module. This allows for communication over a standard RS-232 serial connection. The UART module on the FPGA constantly monitors the incoming data line and raises a flag when it has received a byte. This byte is then interpreted by a read module, and based on its value, it either sends some logic signals (such as the start signal) or is discarded.

4.4 Software Design

The software written for this project allows us to perform the linearization techniques that were described in Chapter 2, and conveniently catalogues the data for future tests. The purpose of this section is to inform the reader how the software receives, organizes, and processes the data, and how the user may interface with this software.

Data from the FPGA is read into the software over a standard RS-232 comport. Data capture in my software is performed in a different manner than on the FPGA. The FPGA is capable of continuously listening to the send and receive lines, because the UART module does not have to compete for processor cycles like software receive modules do. Instead of having a program that constantly monitors the receive line, the program has to be configured to receive the data at the appropriate time. There are more efficient ways of reading the data into the software, but in most cases they involve complex threading functions which are unnecessary for the relatively small amount of data that we are sending. The program opens the comport and sends a start signal to the FPGA. It then listens to the line waiting for the output data.
Data from the FPGA is sent in the same order that it is obtained. This makes decoding the data on the software side less complicated as it follows the same order as the logical progression of the tests. To simplify the organization of the data, I defined type definition structures that read in the data organized as a series of arrays, where the lowest order structure contains all of the data collected for one sample at one test point for each detector. The next highest structure contains an array of all of the samples for each test point for each detector. The highest order structure contains an array of all of the data for all of the test points for each detector. This hierarchical structure makes it easy to process the data, as all of the evaluation instructions can be written as for loops, and automatically applied to every sample of every test point for each detector. After the data has been processed, both the raw data and the processed data are printed out to a file that is indexed by the strip serial number (which is provided by the user at the beginning of the test). Also included in this output file is the output data in comma separated value (CSV) form. This allows the data to be ported into MATLAB or Excel without any formatting changes.

The graphical user interface (GUI) was designed to be as simple as possible. The target user of this program is unlikely to be interested in the test data, only in whether the strip has passed its evaluation. Based on this fact, the decision was made not to display the measured data on the GUI. A screen capture of the GUI is shown in Figure 4-9. The user is prompted to type in the serial number of the strip before inserting the strip into the tester. The program checks to see that this serial number is a three digit number, as it should be for the HP MARTI program. If the user hasn’t typed in a three digit number, he or she is prompted to do so before running the test. The directory in which to store the data can be selected by the user, or the preprogrammed default directory can be used. The progress bars to the right of the input boxes indicate which test is being performed and how much of the test has been performed. The three white boxes in Figure 4-9 that say “Idle” will turn either green or red to indicate either a pass or fail for each of the tests. If a test is failed, the reference number that corresponds to the faulty part will be displayed in a pop-up box as illustrated in Figure 4-10. The reference number that is displayed corresponds
Figure 4-9: Screen capture of the sensor strip GUI.

Figure 4-10: Dialogue box for the failed parts list.
to the designator that is printed on the actual strip and allows for identification and visual inspection of the device without consulting a full schematic. The output file contains additional details regarding the failure mode for each device listed in the “Failed Parts” dialogue box.
Chapter 5

Design Lessons Learned

Chapter 5 focuses on some of the challenges that were encountered during this project and how they were overcome. While the goal of this project was to create a sensor strip characterization unit, the purpose of it was also to help me grow as an engineer. The topics I address below represent some of the lessons I found most interesting.

5.1 Illuminator Design

In Chapter 4, the illuminator circuit that this system uses was explained. However, no insight was provided regarding the development of this design. Let us take a brief look at some of the characteristics that motivated the implemented topology.

The original goal of this system was to test light sensitivity, a goal that is easily achieved with a single measurement in the midrange of the output detector profile. As such, commanding an exact illumination level was not a concern. As requirements for the system evolved, it became clear that a precise illumination level needed to be set. Instead of immediately redesigning the illuminator circuitry to include a feedback path, it was decided to try and use the simple current source circuit that was originally implemented, as presented in Figure 5-1.

The reader should immediately note the differences between this circuit and the one presented in Chapter 4 (Figure 4-3). There is no op-amp in the drive path from the digital to analog converter to the transistor. Without this feedback loop the current
exhibits noticeable temperature dependence due to the transistor. The explanation of this phenomenon is quite straight forward. The longer the current flows through the transistor, the warmer the transistor becomes. As the transistor heats up, the voltage drop between the base and the emitter decreases, which causes more current to flow. The additional current further increases the temperature. It is easy to see that without an emitter resistor, the transistor enters a thermal run away state. Once the power dissipated by the device has stabilized, the current will level off (at a value higher than commanded). The output data clearly showed a monotonic ramping function in the detector counts that were being collected at each sample point. This monotonic function highlighted the existence of a problem; however, diagnosing this type of problem in an untested system was tricky.

The initial suspect was the output of the digital to analog converter. It was first assumed that the drive circuitry for the transistor was introducing oscillations onto the base of the transistor. In an effort to test this theory, an oscilloscope was used to measure the output voltage on the current sense resistor. The results of this measurement are displayed in Figure 5-2.

The waveforms in Figure 5-2 represent the voltage levels as three consecutive tests are performed. Each test has a dark current measurement which corresponds to the
lowest voltage on the plot, a midlevel range reading, and a saturation reading. The image on the left shows a slight ramping function, an artifact that is clear when we zoom in on the waveform, as illustrated by the image on the right. In an effort to classify these effects, the system was modified to take in an adjustable time delay between when the illumination level was commanded and when the detector value was read out. As the delay was increased, the slope of the monotonic function decreased and eventually settled out. Careful consideration of the length of the delay that was applied, on the order of seconds, revealed that this time constant was much slower than the slowest electronic time scale in the system. The slowest time scale in the system is the strip readout function, and it is on the order of a few milli-seconds. This suggested that the problem might be caused by thermal effects. The thermal time constant of the system is set by the thermal capacitance and the thermal resistance of the components, and is on the order of seconds. Modifying the system to remove this thermal dependence was relatively simple, as indicated by the final illuminator circuit (Figure 4-3). Figure 5-3 below shows the same waveforms as Figure 5-2 after the feedback loop was added. The midlevel voltages in Figure 5-3 are higher than in Figure 5-2 because the op-amp is driving the base of the transistor to a diode drop above the commanded voltage, which directly sets the voltage across the current sense resistor to the voltage commanded by the digital to analog converter.
Determining that the nonzero off state output voltage of the digital to analog converter was raising the dark current floor was relatively straightforward. Since data had already been collected for the dark current level of the system, it was easy to see that the new dark current levels were approximately 100 counts higher across all of the detectors. The take away lesson from this exercise is that in some cases, characterizing the time constants of a system can be extremely valuable to diagnosing and solving errant circuit behavior.
Chapter 6

Linear Least Squares Algorithm

Chapter 6 focuses on the linear approximation that is necessary for the illumination test that was described in Chapter 2. There are many possible linear fitting models that are suitable for this application, but only the Linear Least Squares (LLS) algorithm will be considered here.

6.1 Application Theory

The goal of the LLS algorithm is to fit a linear function as closely as possible to a set of observed data points. This fitting strategy considers that the target form is a linear regression of the form $y = \beta_0 + \beta_1 x$, and then adjusts $\beta_0$ and $\beta_1$ to minimize the squared residuals (the difference between the fitted data and the measured data). In order to pick the best model, we chose the line that has the minimum mean squared error, i.e. the line whose slope and intercept minimize equation 6.1 below.

$$S(\beta_0, \beta_1) = \sum_{i=1}^{n}(y_i - \beta_0 - \beta_1 x_i)^2 \quad (6.1)$$

Figure 6-1 graphically illustrates the LLS regression. As illustrated, the least squares line minimizes the sum of the squared vertical deviations from the observed points. To calculate $\beta_0$ and $\beta_1$ we take the partial derivatives of equation 6.1 with
Figure 6-1: Graphical representation of the LMS approximation[13].

respect to $\beta_0$ and $\beta_1$ and set them equal to zero [16].

\[
\frac{\partial S}{\partial \beta_0} = -2 \sum_{i=1}^{n} (y_i - \beta_0 - \beta_1 x_i) \tag{6.2}
\]

\[
\frac{\partial S}{\partial \beta_1} = -2 \sum_{i=1}^{n} x_i (y_i - \beta_0 - \beta_1 x_i) \tag{6.3}
\]

Setting 6.2 and 6.3 to zero yields equations 6.4 and 6.5. Solving these equations yields a closed form solution for $\beta_0$ and $\beta_1$ as represented in 6.6 and 6.7.

\[
\sum_{i=1}^{n} y_i = n\beta_0 - \beta_1 \sum_{i=1}^{n} x_i \tag{6.4}
\]

\[
\sum_{i=1}^{n} x_i y_i = \beta_0 \sum_{i=1}^{n} x_i + \beta_1 \sum_{i=1}^{n} x_i^2 \tag{6.5}
\]

\[
\beta_0 = \frac{\sum_{i=1}^{n} x_i^2 \sum_{i=1}^{n} y_i - \sum_{i=1}^{n} x_i \sum_{i=1}^{n} x_i y_i}{n \sum_{i=1}^{n} x_i^2 - (\sum_{i=1}^{n} x_i)^2} \tag{6.6}
\]

\[
\beta_1 = \frac{n \sum_{i=1}^{n} x_i y_i - \sum_{i=1}^{n} x_i \sum_{i=1}^{n} y_i}{n \sum_{i=1}^{n} x_i^2 - (\sum_{i=1}^{n} X_i)^2} \tag{6.7}
\]

After applying an appropriate amount of algebra, the following simplifications for
equations 6.6 and 6.7 can be made. In equations 6.8 and 6.9 below, \( \bar{x} \) and \( \bar{y} \) represent the means of the measured \( x \) and \( y \) parameters.

\[
\beta_0 = \bar{y} - \beta_1 \bar{x} \quad (6.8)
\]

\[
\beta_1 = \frac{\sum_{i=1}^{n} (x_i - \bar{x})(y_i - \bar{y})}{\sum_{i=1}^{n} (x_i - \bar{x})^2} \quad (6.9)
\]

Solving equations 6.8 and 6.9 yield the slope \( \beta_1 \) and intercept \( \beta_0 \) for the LLS approximation to the measured data. It is reasonable to question how well this approximation fits the data, particularly because no reference was made to the significance of the presence of "noise" in the data. The statistical significance of "noise" in the data is dismissed in this consideration, as the data will all come from the same characterization system. This means that whatever "noise" the system may introduce into the data will be random (assuming the noise is white) across all collected samples and therefore will not distort the relative accuracy of the system.

6.2 Numerical Example

Section 6.1 introduced the general theory behind the LLS approximation. Now let us apply this theory to our data and compute an example LLS regression. Table 6.1 shows the output detector counts and LED currents for detector number five on the calibration strip. This is the example data that we are going to apply the LLS algorithm to.

From equations 6.8 and 6.9 we see that we will need to compute the mean for each column. This is done by summing the elements of each column and then dividing by 17, the number of elements in each column. The average detector output is 431,040 counts and the average LED current is 6.7531 mA. We begin by computing \( \beta_1 \), as it is expressed as a function of only the observed data and is independent of \( \beta_0 \). The output detector counts will be considered the \( y \) variable and the LED current will be...
the $x$ variable. Plugging into equation 6.9 we get equation 6.10.

$$
\beta_1 = \frac{\sum_{i=1}^{n} (x_i - 6.7531)(y_i - 431040)}{\sum_{i=1}^{n} (x_i - 6.7531)^2}
$$

(6.10)

Evaluating equation 6.10 yields $\beta_1 = 8.6726 \times 10^4$. We can use this result along with equation 6.8 to compute $\beta_0$. Plugging into equation 6.8 we get that $\beta_0 = -1.546386726 \times 10^5$. Figure 6-2 shows the measured data with the superimposed LLS regression. Based on the grouping of the measured data in Figure 6-2 we can

![Figure 6-2: Graphical representation of the LLS numerical example.](image)

anticipate one of the flaws with the LLS approximation. If we have an extreme $x$ value, in this case the LED current at $10.5$ mA, it will exert leverage on the linear approximation and may disproportionately affect the slope of the approximation. This is an argument for careful selection of the sampling points to ensure that adequate data resolution is achieved in the region of interest to prevent the excessive influence of outliers. The data used in this exercise was from an early evaluation run of the system, the sample points have since been moved to include a broader range of data.

The reader may be alarmed by the y-axis intercept that the LLS regression predicts. From the description of the illumination test in Chapter 2 we expect the
Table 6.1: Output detector counts and forward LED current.

<table>
<thead>
<tr>
<th>Output Detector Counts</th>
<th>LED Current (mA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>305189</td>
<td>5.258</td>
</tr>
<tr>
<td>307380</td>
<td>5.288</td>
</tr>
<tr>
<td>311690</td>
<td>5.343</td>
</tr>
<tr>
<td>320460</td>
<td>5.450</td>
</tr>
<tr>
<td>338062</td>
<td>5.667</td>
</tr>
<tr>
<td>373905</td>
<td>6.098</td>
</tr>
<tr>
<td>447100</td>
<td>6.959</td>
</tr>
<tr>
<td>447180</td>
<td>6.963</td>
</tr>
<tr>
<td>447302</td>
<td>6.965</td>
</tr>
<tr>
<td>447624</td>
<td>6.967</td>
</tr>
<tr>
<td>448129</td>
<td>6.975</td>
</tr>
<tr>
<td>449320</td>
<td>6.988</td>
</tr>
<tr>
<td>456237</td>
<td>7.070</td>
</tr>
<tr>
<td>465603</td>
<td>7.177</td>
</tr>
<tr>
<td>484262</td>
<td>7.393</td>
</tr>
<tr>
<td>522137</td>
<td>7.825</td>
</tr>
<tr>
<td>756043</td>
<td>10.416</td>
</tr>
</tbody>
</table>

The intercept to be around 4096 counts, but the model predicts the y-axis intersection at \( \beta_0 = -1.546386726 \times 10^5 \). This discrepancy is caused by nonlinearities in the LED irradiance curve due to turn-on effects of the LED. Figure 6-3 shows the output detector profiles for all eight detectors on one strip. The zoomed in version in the right of Figure 6-3 clearly shows the diode turn on nonlinearities. With careful characterization of the irradiance curve, a linearization correction can be applied to this nonlinear data and the bit depth of the measurement can be improved. Computing the LLS regression for the windowed region of counts above the diode nonlinearities results in an artificial prediction of the y-axis intercept. Since the dark level measurement is a direct measurement and not derived from this linearization technique, the predicted y-axis intercept point is of little consequence.
Figure 6-3: Plots of the detector output. The figure on the right clearly shows the diode turn on nonlinearities.
Chapter 7

Concluding Remarks

The end product of this project is a highly capable characterization tool that will be used to speed up the evaluation of vendor produced sensor strips. This characterization system addresses the many flaws of the formerly used process. It is portable and quick (15 seconds). It doesn't require any mechanical assembly; the strips are simply placed in position. It clearly designates which parts have been found to be at fault, and what their failure mode is (i.e. backwards or shorted diode). It catalogues all of the recorded data for easy evaluation in the future.

This project presented many challenges, the most difficult of which was taking a systems-level approach to designing and implementing a product that needs to be more than just the typical engineering grade system that is built for in lab evaluation. As is often the case, the most challenging aspects of the project were also the most rewarding. Defining and executing a project with many aspects that are outside of my area of expertise has been an invaluable tool in learning how to define and approach problems in an engineering environment.
Appendix A

Schematics

Figure A-1: Schematic for the digital to analog converter for the Illuminator circuit.
Figure A-2: Schematic for the analog to digital converter for current measurement in the illuminator circuit.

Figure A-3: Schematic for the digital to analog converter for the power diode test circuit.
Bibliography


