The Development and Characterization of the Laser Ranging System on the RANGE CubeSat Mission

AE 8900 MS Special Problems Report
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In Spring 2016, Georgia Tech Space Systems Design Laboratory (SSDL) will begin operations on the Ranging And Nanosatellite Guidance Experiment (RANGE) Mission. A crucial element of this mission is the Inter satellite ranging system. This system will determine the relative distance between the two RANGE sister CubeSats providing validation that such a system can function in orbit on a CubeSat. This document describes the factors considered in choosing the Voxtel Laser Range Finder (LRF) Module as the flight unit for both satellites, the integration and testing of this system, and the preliminary analysis of laboratory testing data to predict on-orbit performance.

Nomenclature

A_{cc}	=	Area of Corner Cube (M^2)
ADCS	=	Attitude Determination and Control System
A_{lens}	=	Area of Receiver Optic (M^2)
APD	=	Avalanche Photodiode
A_{sat}	=	Cross Sectional Area of satellite as seem by transmit laser (M^2)
C	=	Speed of Light (M/S)
C_{ref}	=	Coefficient of Reflection
EOSL	=	Electro Optical Systems Lab
FAC	=	False Alarm Count
FAR	=	False Alarm Rate (Hz)
F_{return}	=	Laser Power Return Flux (W/M^2)
$F_{returncc}$	=	Laser Power Return Flux from Corner Cube (W/M^2)
F_{targ}	=	Laser Power Flux at the Target (W/M^2)
GTRI	=	Georgia Tech Research Institute
ICD	=	Interface Control Document
LRF	=	Laser Range Finder
NEI	=	Noise Equivalent Irradiance
OBC	=	Onboard Computer
P_{targ}	=	Total Power Incident on Target (W)
P_{tx}	=	Transmitter Peak Laser Power (W)
R	=	Range to Target (M)
RANGE	=	Ranging And Nanosatellite Guidance Experiment
SSDL	=	Space Systems Design Laboratory
ToF	=	Time of Flight
Tx	=	Transmit
Θ	=	Half Angle of Transmit Optic

I.   Background and Motivation

The RANGE mission is a Georgia Tech Space Systems Design Laboratory CubeSat mission. 2 RANGE satellites will enter into low earth orbit after being deployed by a Terra Bella launch vehicle. Once in orbit the satellites will being performing their mission. They will generate three categories of data, ground based laser ranges, space based GPS data and inter-satellite ranging data. By using differential drag to control distance between the satellites the range mission aims to achieve 3 objectives [4]:

   – Improve absolute and relative positioning capabilities of nanosats
   – Explore propulsion-less formation control techniques
   – Transmit low-rate optical (laser) communications

A concept of operations for the mission is shown below in Figure 1. This figure shows the 3 data types generated from the mission as well as the UHF/VHF data downlink. This paper focuses on the development of a dual way inter-satellite ranging system for this mission. This dual way system is the first step in enabling an inter-satellite ranging and laser communications system.
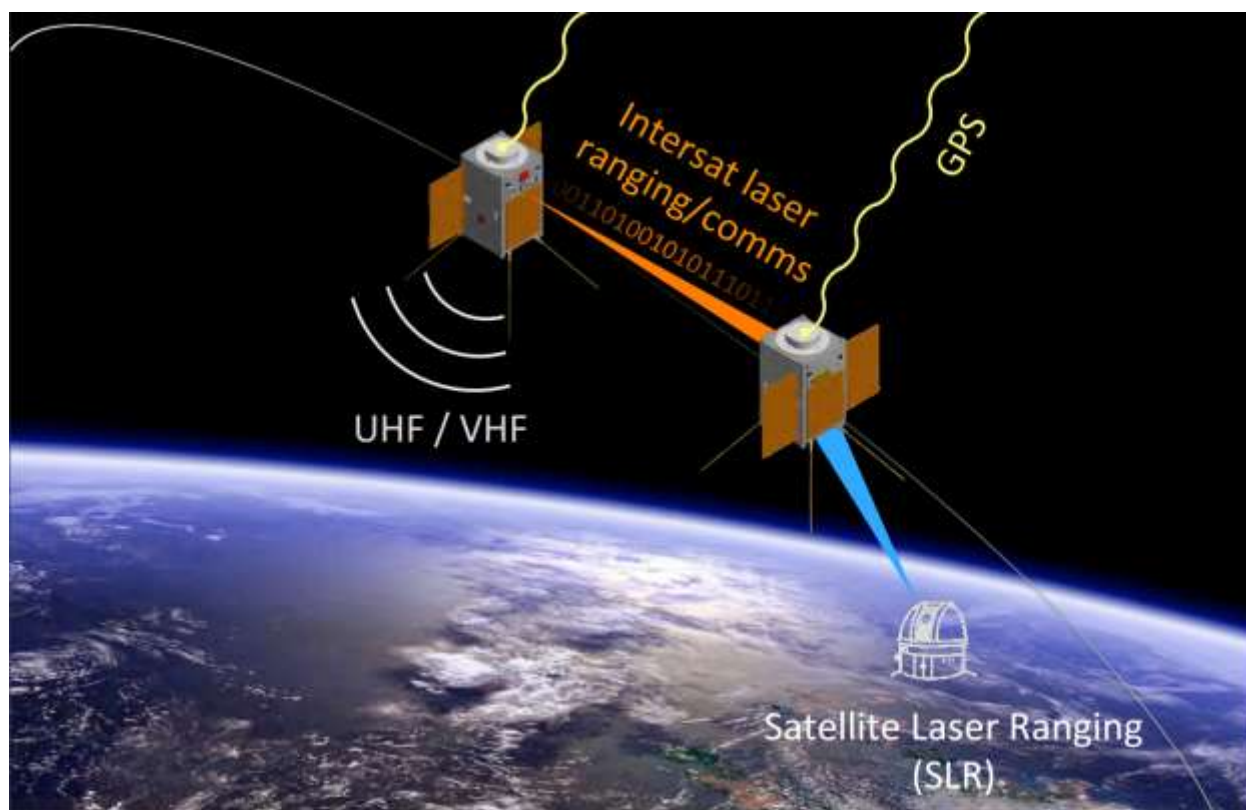
Figure 1 RANGE Concept of Operations

II. Requirements and System Selection

A. Requirement Development

A crucial part of the RANGE mission, inter-satellite ranging allows GPS data to be validated and even augmented with high precision via independent instrumentation. The RANGE Mission will serve as a proof of concept for a laser ranging system on a CubeSat [4]. Thus, validating a laser ranging system in orbit is the major requirement driving the development and integration of this system. In traditional requirements form:

The Laser Ranging system shall obtain relative distance measurements between the two satellites in orbit to the performance of the selected laser range finder.

This broad baseline requirement drove the initial development and design of the ranging subsystem. As requirements development is an iterative process, specifics such as maximum range and system accuracy are determined once a final system is selected and characterized.

B. Lower Level Considerations

This high level requirement defines lower level considerations. These considerations are both physical and practical and drove the selection process for the RANGE laser range finding unit.

1. Modularity, Cost and Schedule

Modularity, cost and schedule are key considerations a university CubeSat project like RANGE must account for. The RANGE mission cannot afford to have a completely custom built laser ranging system. The Mission requires two Laser Ranging systems and schedule and cost margins do not allow for in house, ground up development.

2. Laser Safety

A practical consideration of development in a university setting is Laser safety. The Georgia Tech Aerospace department does not have the facilities required to test high powered lasers. As a result, any ranging system used must be an eye safe system that can be tested and integrated without additional safety precautions.

3. Pointing Accuracy of RANGE

Because of ADCS limits, RANGE will not have the pointing accuracy associated with land based or large space based laser ranging systems. The expected pointing accuracy of the ADCS system is between 3 and 5 degrees. The system must accommodate for this by increasing the beam divergence of the transmit laser. This is rarely done in laser ranging systems as typically a narrow transmit been is desired to lower power requirements and increase range.

4. Optics

Any Laser Ranging system integrated on RANGE should be easily compatible with commercially available optics. This allows freedom in the design to increase receiver gains as well as increase beam spread to increase the chance that the satellites pass through one another's field of view.

5. Volume Constraints

By nature, CubeSat missions are heavily volume constrained. This is exacerbated on RANGE as the each CubeSat is only 1.5 U and the ranging system must share this space with all other mission critical systems. Typical low power laser transmitters and receivers are compact and already fit within the form factor of a CubeSat. Thus, the range finder itself is not a large factor in volume consideration. However, the optics that will be added to any off the shelf system can be large relative to a CubeSat. As a result, volume constraints become the driving factor in optics selection.

6. Receiver Sensitivity and Laser Power

Because of the power limited nature of RANGE, extremely sensitive receiver electronics are required. In practice, this is often achieved by using a highly sensitive type of detector known as an Avalanche Photodiode (APD), in combination with a wavelength with low background noise and optical and electronic filters. Considering the operational Environment of RANGE in Low Earth Orbit, a wavelength well beyond peak solar emission is ideal. Figure 2 shows the emitted Solar Power at each wavelength. Clearly a visible laser (400-700 nm) will have a lower single to noise ratio than an infrared wavelength (1000+nm). Thus, to obtain optimal sensitivity, a laser/receiver pair in the infrared band is favored.
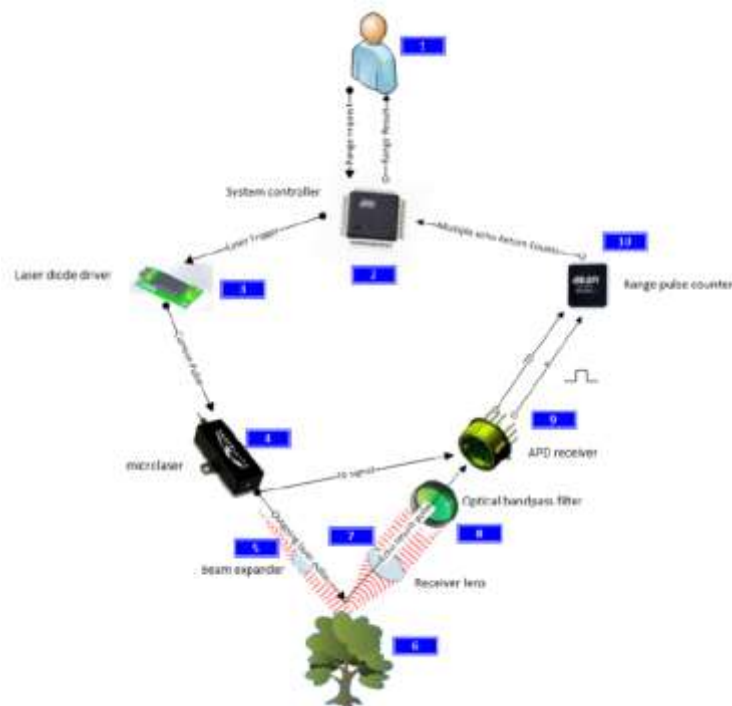

Figure 2 Solar Emission Spectrum
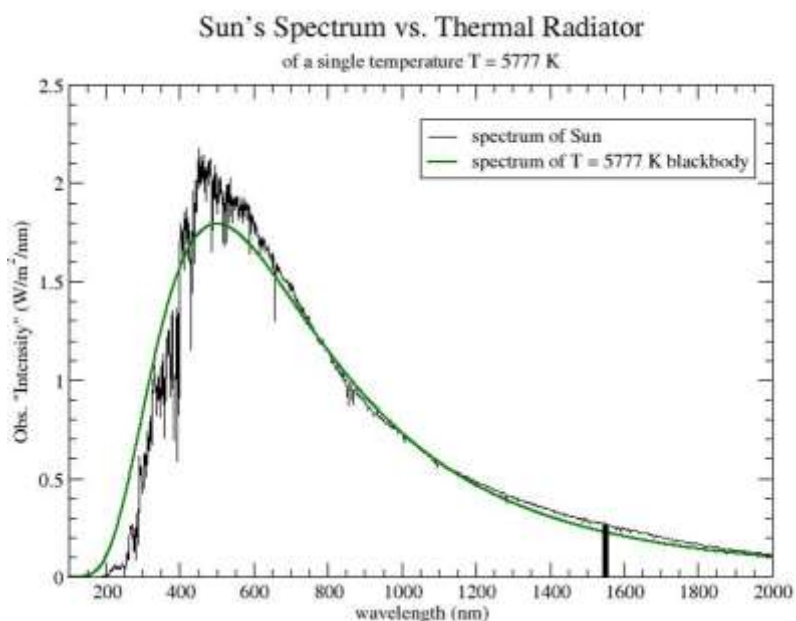
C. Selection of Baseline System

The considerations above define a complex trade from which a baseline system is selected. Due to the extremely complex circuitry and development associated with this these components, the main consideration was selecting a system that could be integrated and tested with little modification (especially to the circuitry itself). With the help of Georgia Tech Research Institute's (GTRI) Electro Optical Systems Lab (EOSL) the decision was made to use a Voxtel Laser Rangefinder (LRF) Module with Thor Labs optics as the baseline system.

7. Voxtel Laser Rangefinder

The Voxtel Laser Rangefinder "combines a small form factor APD diode-pumped solid state laser, an InGaAs avalanche photodiode (APD) receiver, custom amplification and pulse processing circuits, and a programmable

interface"[1]. Figure 3, taken from the Voxtel user manual[1], describes the process of obtaining a dual way range measurement from the Voxtel LRF. Table 1 follows the order of the flow chart (counterclockwise) and describes events occurring at each step.

**Figure 3 Voxtel Laser Rangefinder Module Flow Chart**

Table 1 Steps in Figure 3

| Step	Description
1	User sends a Range Rate request through a computer or microcontroller.
2	System Controller receives the Range Request command
3	Signal is sent to the laser diode driver to activate the laser
4	The current is sent to the laser
5	The laser pulse is emitted. Some light reflects of the transmit optics and reaches the APD receiver, this is called the T0 signal. This causes the APD to emit an analog signal which is routed to the Range Pulse counter (10). Once the Range pulse counter receives this T0 single it starts a timer which is accurate to picoseconds.
6	The transmitted laser pulse bounces of the target object.
7	The returning light goes through a receiver lens which focuses the beam on the center of the detector.
8	The light passes through an optical bandpass filter to remove noise outside of the 1535 nm range.
9	The APD receives the return pulse and outputs an analog signal.
10	The Range pulse counter receives the analog output signal from the APD and stops the timer that was started in step 5. The time between the T0 pulse and this return pulse is the time of flight of the laser pulse. Half the time of flight (the one way travel time) multiplied by the speed of light is the distance to the target.
End	The distance to the target is digitally sent to the computer or microcontroller.

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[1] Voxtel manuals can be found at the Voxtel website, http://voxtel-inc.com/products/laser-rangefinder-modules-and-devices/

8. Thor Labs Optics

The Optics to pair with the Voxtel LRF were selected by GTRI EOSL Engineer Nathan Meraz. The selected optics are shown in the figures below.
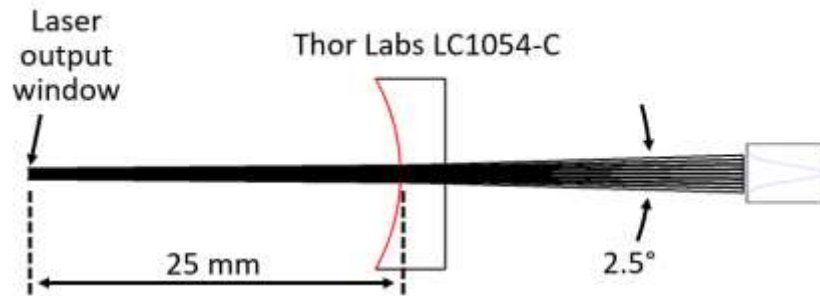
Figure 4 Transmitter Optics
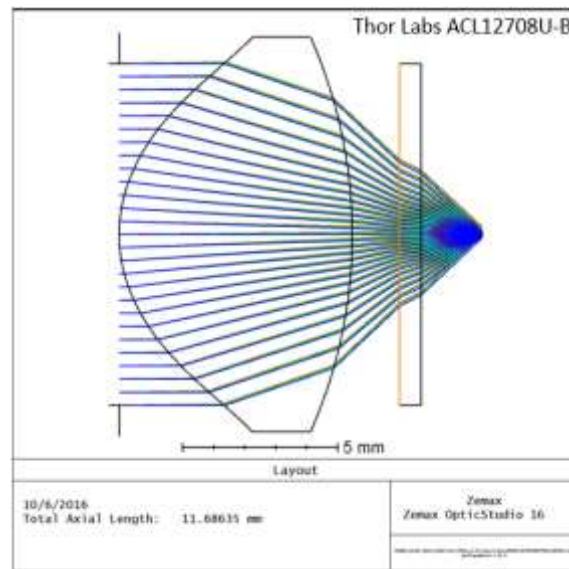

Figure 5 Receiver Optics

D. Final Baseline System

The key parameters of the final system as flown on RANGE are shown in Table 2 below. Note that the only parameter to change from the baseline Voxtel System are the transmitter and receiver field of view.

Table 2 Voxel LRF Transmitter and Receiver Key Specifications

Optical Specifications	Min	Typ	Max	Conditions
Transmitter Wavelength		1535nm		
Transmitter Pulse Energy	100µJ	150µJ		at 25°C
Transmitter Pulse Width		4ns		
Transmitter Peak Power		30kW		
Transmitter Repetition Frequency		Single shot	10Hz	
Transmitter Beam Diameter		0.2mm		
Transmitter Beam Divergence		**2.5 deg**		
Transmitter Beam Quality (M²)		1.2		
Receiver Diameter		200um		
Receiver NEI		500pW		
Receiver Field of View		**1.5 deg**		
Timing resolution		60ps		
Range Precision		200mm		
Maximum Range		50km		
Minimum Range		10 m		

9. Nominal System Performance

Using basic radiometry we deduce the baseline performance of the system. Figure 6 shows the geometry from which notional system performance was derived. Geometric parameters of interest are θ, the half angle of the transmit beam divergence, and R, the distance between the transmit laser and the target.
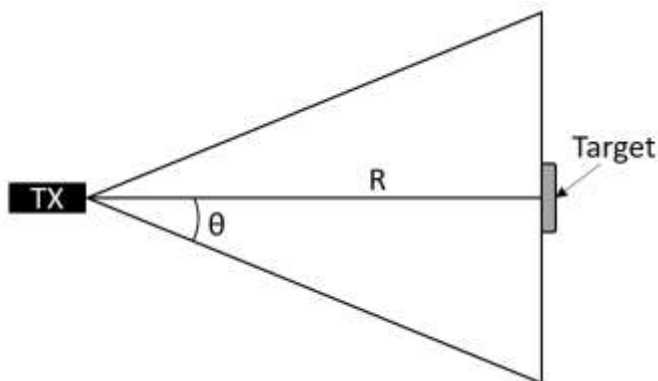
Figure 6 Notional Radiometry Geometry

The radiometry calculations will determine the maximum effective range of the LRF Module. To first order, the driving factor behind this is the APD sensitivity. Thus the required equation will relate range between the transmitter and the target to power received back at the transmitter. Following the chain of Equations below for the nominal

case of the laser reflecting of the CubeSat in orbit, we arrive at Equation 5 which, showing that power decays of as a function of R to the negative forth power[2].

$$F_{targ} = \frac{P_{tx}}{\pi(Rtan\theta)^2} \qquad (1)$$

$$P_{targ} = A_{sat} * F_{targ} \qquad (2)$$

$$F_{return} = C_{ref} * \frac{P_{targ}}{4\pi R^2} \qquad (3)$$

$$P_{return} = A_{lens} * F_{return} \qquad (4)$$

$$P_{return} = \frac{A_{lens}A_{sat}C_{ref}P_{tx}}{4\pi^2 tan^2\theta R^4} \qquad (5)$$

Incorporating a corner cube retroreflector, which directly reflects light to its source, the radiometry equations change slightly. The power returned when the target is a corner cube is shown in equation 10.

$$F_{targ} = \frac{P_{tx}}{\pi(Rtan\theta)^2} \qquad (6)$$

$$P_{cc} = A_{cc} * F_{targ} \qquad (7)$$

$$F_{returncc} = \frac{P_{cc}}{\pi(Rtan\theta)^2} \qquad (8)$$

$$P_{return} = A_{lens} * F_{returncc} \qquad (9)$$

$$P_{return} = \frac{A_{lens}A_{cc}C_{ref}P_{tx}}{\pi^2 tan^4\theta R^4} \qquad (10)$$

Taking the ratios of Equation 10 to Equation 5, we obtain an expression for the effect of the Corner Cube on the returned power. This effective Gain from the corner cube, G_{cc}, is seen in Equation 11. The only variable in this equation for the RANGE system is A_{sat}. Thus G_{cc} is inversely proportional to the cross sectional area of the target. The boundary values for G_{cc} are shown below in Table 3.

$$G_{cc} = \frac{4A_{cc}}{tan^2\theta A_{sat}C_{ref}} \qquad (11)$$

Figure 7 shows Equations 5 and 10 plotted on a logarithmic axis using parameters for laser power obtained by Voxel in conformance testing. Table 3 defined the constants used in the plot. In Figure 7, the top horizontal line indicates the damage threshold of the receiver, any return above this power may permanently damage the APD. The bottom horizontal line is the sensitivity of the receiver equivalent to Noise Equivalent Irradiance in W/M^2 * receiver area. The black dashed line indicates the power returned if the light reflects off the minimum possible area of the target, the red dashed line indicates the power returned from a reflection off the maximum possible area. The black dotted dashed line indicates the return from a Corner Cube.

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[2] Equations are derived from first principals and from email correspondence with GTRI EOSL
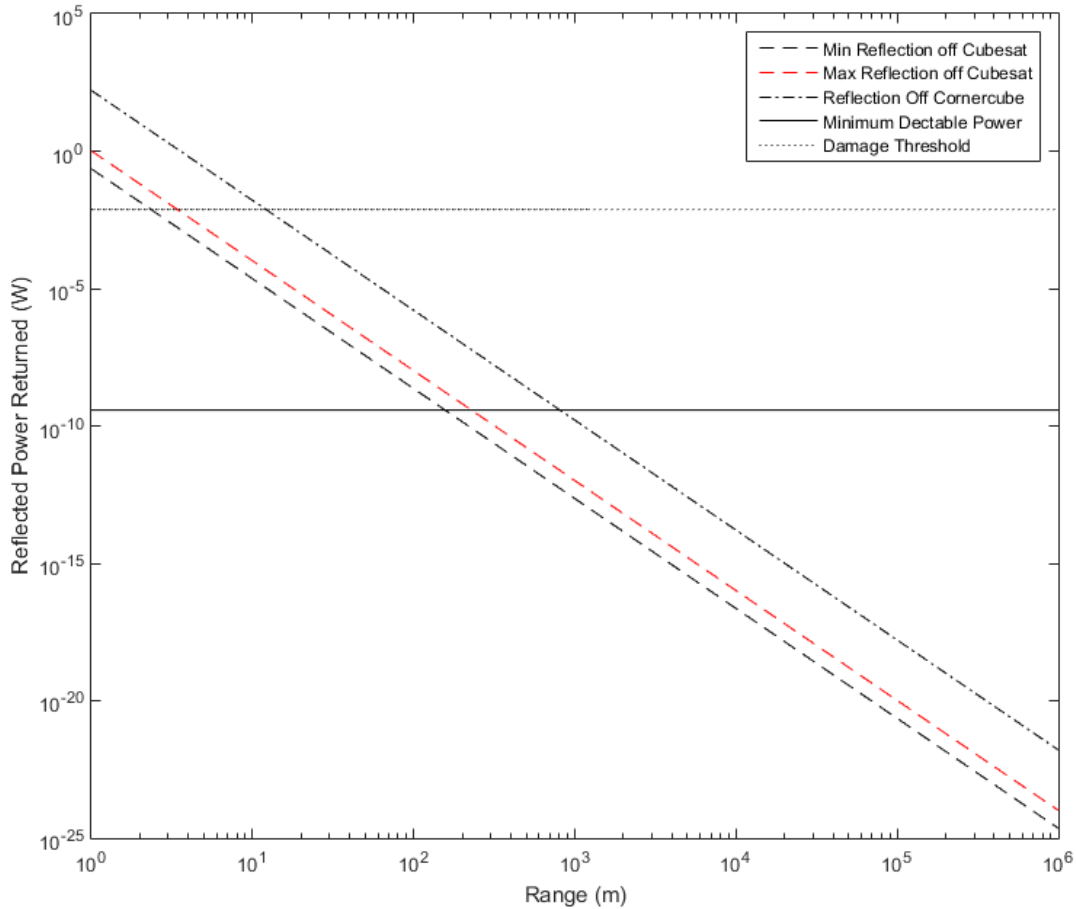
Figure 7 Performance of LRF 1 to First Order Using Voxtel Conformance Parameters

Table 3 Values of Parameters used in Figure 7

Parameter	Value		Comments
	Data Sheet Values (Not Plotted) [5]	**LRF 1 Actual Values (Plotted)**	
A_{cc}	.000127 m^2	.000127 m^2	Area of ½ inch diameter corner cube
A_{lens}	.000127 m^2	.000127 m^2	Area of ½ inch diameter optic
C_{ref}	0.15	0.15	Reflectance of the target
Maximum A_{sat}	0.045 m^2	0.045 m^2	Area of smallest side of a RAGE CubeSat, 15 by 30 cm
Minimum A_{sat}	0.01 m^2	0.01 m^2	Area of smallest side of a RAGE CubeSat, 10 by 10 cm
P_{tx}	30,000 W [1]	**22,400 W**	Peak transmit power of the laser
Minimum Detectable Power (NEI)	500 pW [1]	**627 pW**	Not Tested by Voxtel for Individual APD, conservatively assumed to be the ~25% more than the data sheet value (Same Percentage Difference from Data Sheet as Laser Transmitter)
Damage Threshold	0.0075 W	**0.0075 W**	Not Tested by Voxtel for Individual APD

Θ	21.8 mrad	21.8 mrad	Half angle of transmit beam (2.5 degree full angle)
$G_{cc\ Max}$	711	711	Equation 11 with Asat Min
$G_{cc\ Min}$	158	158	Equation 11 with Asat Max

Taking the intersection points of the three sloped lines with the sensitivity and damaged thresholds, it is clear six points define the LRF performance envelope to first order. The LRF should be operated within these ranges to obtain returns and avoid damage to the APD. These values are listed below in Table 4 for both the conformance tested values of LRF1 and the notional data sheet values.

Table 4 Key Points on Figure 7

	Max Range (m) Datasheet	Damage Threshold (m) Datasheet	Max Range (m) LRF 1	Damage Threshold (m) LRF 1
Minimum Cross Sectional Area Reflection	156	2.5	138	2.2
Maximum Cross Sectional Area Reflection	229	3.6	200	3.4
Corner Cube Reflection	820	13	753	12.4

III.   Integration

The LRF must be integrated into a 1.5U CubeSat to perform its mission. This section describes the system, mechanical, electrical, and software integration of the LRF Module.

E. System Level Integration

The Ranging System is mostly self-contained with only one external cable connection. It will perform all ranging related internal tasks upon receiving a command from the OBC. Once these tasks are performed, the ranging system will output the requested data back to the OBC. Figure 8 is an ICD of the ranging system. All blocks with the dashed box are internal to the Voxtel LRF Module. The J12 Port on the LRF system board controls all power and communication between the OBC and the ranging system. The pin outs of the 10 pin J12 port are defined in Table 5.
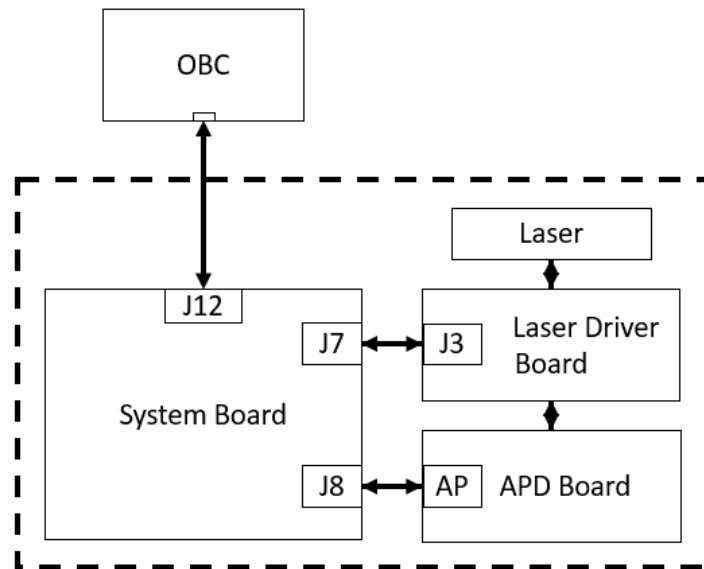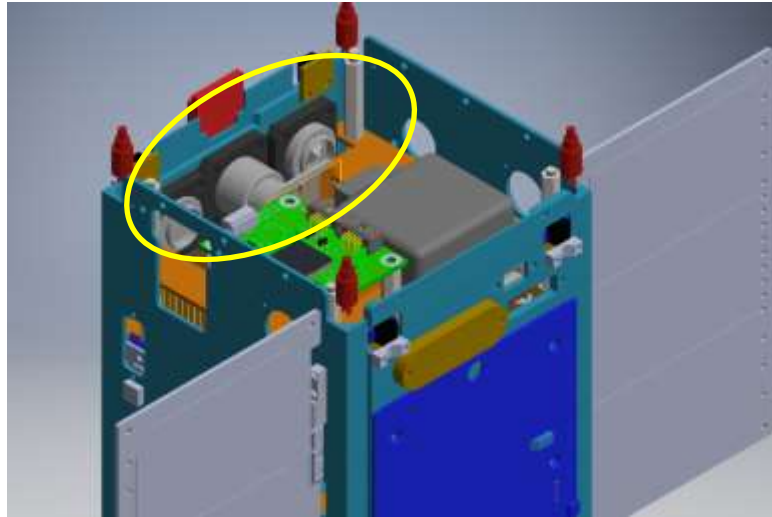

Figure 8 Ranging System Flight System ICD

Table 5 J12 Pinouts

| PIN	Signal	Description
1	+3.3VDC	3.3VDC
2	+5VDC	5VDC
3	Tx	UART Transmitter
4	T0in	Digital To input
5	Rx	UART Receiver
6	+1.8V	1.8VDC
7	-	Internal
8	Ext RR cmd	Digital RR cmd
9	DC Gnd	DC Gnd
10	LaserGate	Laser Trigger

F. Mechanical Integration

Optics are mounted in a standard Thor Labs ½ inch optics mount with a lens tube. The APD Lens is mounted directly to the lens tube at so that the receiver optic is optimally focused. A CAD version of the final system, in its flight configuration is shown circled in yellow, in Figure 9 below. A more detailed image of the system is shown later in the Testing section.

Figure 9 Laser Ranging Subsystem Flight Configuration

The Laser is rigidly coupled to its optic via a custom made bracket. Rigidly mounting optics is best practice in Lidar opto-mechanics as it prevents small deformations in the structure from causing optical misalignment. This is especially important for a space-based application where vibrations and thermal cycling may cause structural deformation and thus misalignments. The machined coupler for the laser transmitter is shown below in Figure 10. The APD is also rigidly coupled to its optics, although this coupling is simpler as the APD rests directly in the lens tube.
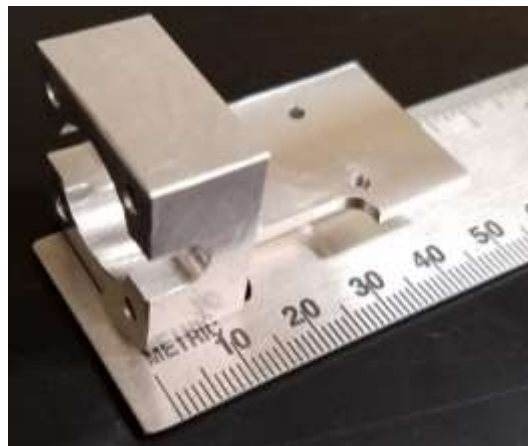
Figure 10 Optics Couplers

Receiving a proper T0 pulse is a crucial and unique aspect of Voxtel's LRF. In LIDAR operation, The T0 pulse is a laser pulse that is sent out to initiate the timer on a laser ranging event. The highly accurate timer is initiated when the detector detects a T0 pulse and stopped when it the detector detects the returned pulse. In Voxtel's design, the APD must detect both the T0 pulse and the return pulse. This means that a small amount of transmitted light must reach the

APD as it exits the CubeSat. To account for this, "T0 Holes" were drilled in the Transmitted and receive lens tubes between the optics and the transmitter and receiver. These holes allow the small amount of transmitted light scattering of the transmit optic to reach the receiver. The placement of these holes in the integrated system is shown below in Figure 11.

Figure 11 T_0 Hole Placement

G. Electrical Integration

The J12 port on the LRF System Board requires 3 different Voltage types; 5V, 3.3V and 1.8V. The Onboard Computer (OBC) can only provide 5 volts from the assigned port, thus a small power regulation board will be used to obtain the 1.8 and 3.3 Volt signals required. This small board is stacked with the rest of the boards. A block diagram of this board is shown below in Figure 12.

Figure 12 LRF Power Regulation Board

H. Software Integration

The Voxtel LRF communicates via a universal asynchronous receiver/transmitter (UART) port using RS-232 serial communication profiles. The RS-232 settings are stated below in Table 6.

Table 6 LRF RS-232 Settings

57000 BAUD
8 Data Bits
1 Stop
No Parity
No Flow Control

The flight software will have several operational modes depending on the mission mode. Nominal operational modes are described in Table 7.

Table 7 Flight Software Modes

Mode	Activation Condition	Description
Sleep	Default, active unless another mode is explicitly executed	The LRF system is in an extremely low power mode waiting for command to wake up.
Low Rate Ranging	RANGE sister CubeSat is within a solid angle and range where it can possibly be detected by the LRF.	The LRF system sends out a pulse at a rate dependent on the dynamics, and the positions of the RANGE satellites in orbit. This rate will be determined in-situ.
High Rate Ranging	A returned pulse from Low Rate Ranging Mode	LRF sends Range Rate commands at the maximum frequency of 10 Hz logging the data to a text file for later downlink.
Detection Only	The Satellite is told to expect a 1 way ranging pulse from its sister Satellite	This functionality is not covered in this paper and will be further developed.
Laser Communication	The Satellite is told to expect low bit rate laser communication from its sister satellite	This functionality will be a further development of the detection mode

IV. Testing

LRF Tests are designed to repeatedly verify and characterize the survivability and functionality of the system at every point of the integration process.

I. Mechanical Ground Support Equipment

To appropriately characterize alignment, a test mount must rigidly fix all optics, and the transmitter and receiver, in a configuration as close to flight as possible. The test mount should be extremely rigid once components are fixed in place to allow for repeatable testing. An image of the test rig is shown in Figure 13. Key components of the mount are described in Table 8.
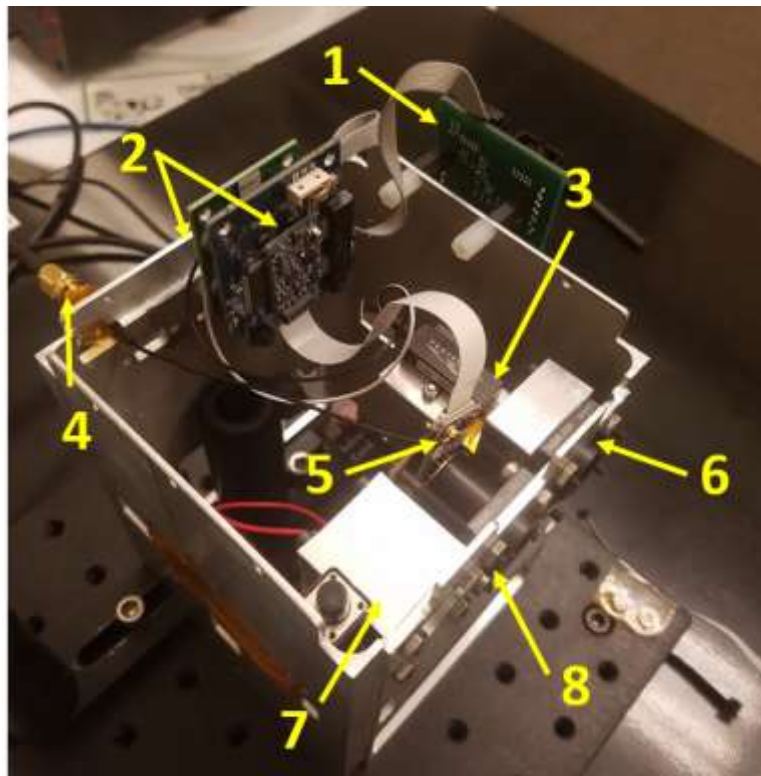

Figure 13 Test Mount

Table 8 Components on LRF Test Mount

Number	Description
1	Test micro controller. Test only component.
2	Laser driver and LRF system boards
3	Laser and laser mount
4	Analog output from the APD, this connects through a 50 ohm oscilloscope port. Test only component.
5	APD Board, the circuitry which directly supports the APD and the APD itself
6	Transmitter Optics
7	Targeting laser and on off button
8	Receiver Optics

In addition to the mounting rig, additional mechanical hardware is required to perform repeatable testing of the LRF. These are described below Table 9.

Table 9 Additional Mechanical Support Equipment

Equipment	Purpose
IR detector card	Allows the laser beam to be visualized to verify functionality
Target	A uniform target so that tests can be performed against the same target for repeatability

J. Electrical Ground Support Equipment

A Voxtel provided microcontroller and a Tektronix TDS 3014B Oscilloscope are the 2 major components of Electrical Ground Support equipment used in LRF ground testing. The Voxtel provided microcontroller allows for quick testing from a PC without having to separately provide conditioned power to the unit. It also provides a serial terminal to communicate with the LRF itself. The Oscilloscope allows return voltages from the APD to be characterized in a repeatable manner. The oscilloscope used for in house testing is a Tektronix TDS 3014B Oscilloscope with a 50 ohm impedance connection.

A final piece of electronic support equipment is a visible sighting laser. This allows a test engineer to verify where the invisible IR beam is pointing. The sighting laser is mounted flush to the structure so that it is precisely co-aligned with the IR beam, the center of the visible laser and the IR laser differs by only a small and constant horizontal offset.
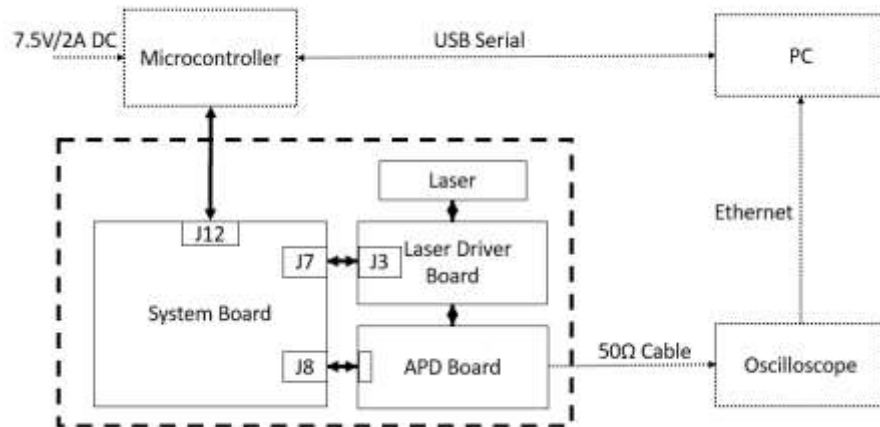
K. Ground Support Software

A compiled python script, written by GT Aerospace Student Chris Butterfield, provides the software necessary to control and automate LRF test. This software, called LRFCharTest.exe, is resident on a test PC and communicates with both the LRF and the oscilloscope. Use of this software is key to the test process and described in detail in the next section.

## L. Functionality Test Procedure: Inputs and Running the Test

The functionality test is run through a macro enabled excel document which calls a compiled python script to communicate serially with the Voxtel LRF. There are 3 types of inputs to the functional test. The physical and hardware set up, the Voxtel LRF Configuration, and inputs to the compiled python script LRFCharTest.exe. Each of these inputs sections is shown and described in the following sections.

To run tests from the excel sheet the LRF, PC and oscilloscope must be wired as depicted in the testing ICD in Figure 14. The dotted lines and boxes are unique to testing and thus not depicted in the flight ICD.

Figure 14 LRF Functionality Test ICD

Once the system is wired in this manner, and all connections have been verified, the test support software can be run from the excel sheet. Figure 15 depicts the logic flow of the test control software.
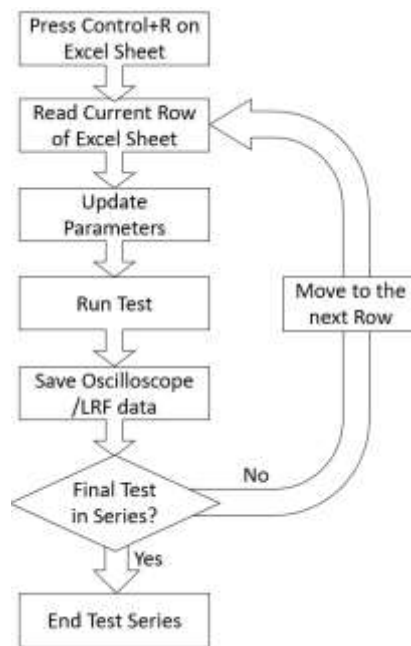

Figure 15 Test Control Software Logic Flow

10. Physical and Hardware Setup

An exact and well defined physical setup is required to have a repeatable characterization experiment. The excel document assures the parameters required for a repeatable test are recorded. Figure 16 shows the excel document inputs for the Physical and hardware setup while Figure 17 illustrates the geometry of the setup.

Set Up						
Physical/Harware Set Up						
Run	Target Material	Axial Range (m)	Horizontal Offset (m)	Vertical Offset (m)	Reciever Tilt	Transmitter Tilt
1	Cardboard	20	0	0	0	0
2	Cardboard	20	0	0	0	0

Figure 16 Hardware and Software Setup Section of Excel Test Document
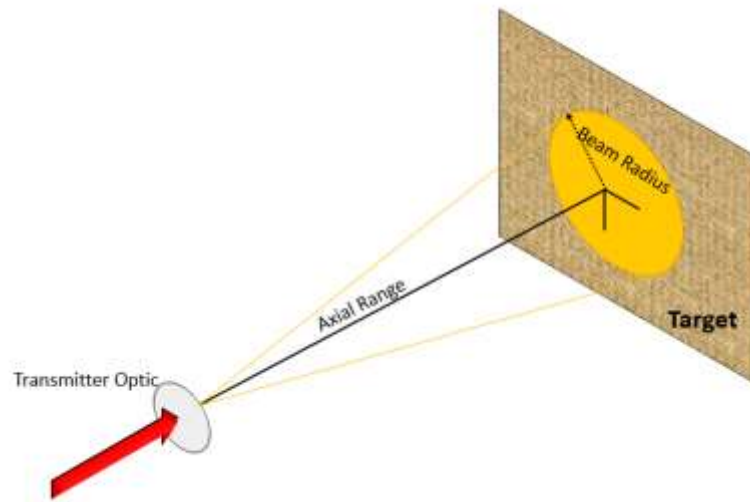
Figure 17 Functionality Test Geometry

Baseline tests are performed with the beam radius not exceeding the target size, and with the beam centered on the target. There is no horizontal or vertical offset of the beam. The beam is only impacting the intended target, not the ground or objects to the side of the target. The beam is always aimed normal to the target surface. When placing the target note that Axial range is defined as distance from the transmitter optic to the target. Later iterations of this test allow the freedom to tilt the optic mounts if adjustments need to be made to alignment.

11. Voxtel LRF Configuration

The Voxtel LRF operating settings are updated through the excel sheet. The LRFCharTest.exe program reads these values from the excel sheet then serially communicates with the LRF using the RS-232 protocol defined in the ICD. This methodology allows for the LRF to be quickly updated and for multiple tests to be run from the exact same physical setup.

Once the macro in this excel sheet is activated the LRFCharTest.exe programs reads the first row of parameters, updates the LRF parameters, then runs the test. It repeats this process for every row of parameters in the excel sheet.

These parameters are described in detail in Voxtel's Software ICD [2] for the LRF module. Figure 18 shows the Voxtel LRF Configuration settings section of the test excel sheet.

Inputs							
Voxtel LRF Configuration							
External Trigger	TVT	FAR	Gain Mode	Vth Hi (V)	Vth Lo (V)	Vth ErLo (V)	Ext T0
0	1	1	0	0.7	0.5	0	0
0	1	1	0	0.7	0.6	0	0

Figure 18 Voxtel LRF Configuration Section of Excel Test Document

Of particular importance in this section are the Gain Modes. Tests will attempt to characterize the performance of these gain modes in given test set up. The Gain modes the LRF is capable are shown below in Table 10.

Table 10 LRF Gain Modes

Gain Mode in Software	Gain
0	1
1	Optimum Sensitivity for 15Hz FAR
2	0
3	Optimum Sensitivity for 60Hz FAR

Gain Modes 1 and 2 are based on the False Alarm Rate (FAR) for the LRF. This quantity is dependent on the desired False Alarm Count (FAC), the speed of light and the range to the target. The equation describe this relationship is found in the Voxtel User guide [1] and show below:

$$FAC = \frac{C * FAR}{2 * Range}$$

12. LRFCharTest Settings

The Python script LRFCharTest.exe is an executable that only takes in 3 out parameters, Laser Pulse Frequency, Number of Tests to Run, and the name of the output .csv files. These inputs are specified in the LRFChar test section of the Excel Test Document as seen below in Figure 19.

LRFCharTest				
Freq	# of Tests	Range Filename (.csv)	Oscilloscope Filename (.csv)	
8	32	Styrofoam_gain_0_1_range	Styrofoam_gain_0_1_osc	
8	32	Styrofoam_gain_0_2_range	Styrofoam_gain_0_2_osc	
8	32	Styrofoam_gain_0_3_range	Styrofoam_gain_0_3_osc	
8	32	Styrofoam_gain_0_4_range	Styrofoam_gain_0_4_osc	
8	32	Styrofoam_gain_0_5_range	Styrofoam_gain_0_5_osc	

Figure 19 LRFCharTest Section of Excel Test Document

13. Running the Test

After all inputs have been specified in the excel sheet the tests are run by simply pressing "Control+R" while in the excel document. It is best practice to verify a response from both the oscilloscope and the LRF Module during the first test run. This is done by simply looking at the oscilloscope for a waveform and by looking at the PC for range print outs. For each test in the test series 2 .csv files will appear in the working folder.

M. Functionality Test Procedure: Outputs

2 separate .csv files are output for each test. One file contains data from the LRF module, the other contains the oscilloscope data from the same test. The total number of .csv files outputted is equal to 2 times the number of individual tests in the test series. The sections below describe the format of the output files.

14. LRF Output .CSV File

The LRF Output.csv file is named in column R of the Excel test document. This CSV contains data obtained directly from the Voxtel LRF system. No oscilloscope data is in this file. The first row is a print out of the current firmware version number on the Voxtel unit, the return of the :VE command. This row confirms that the test computer was properly communicating with the Voxtel LRF unit. The Second row contains the response to the :DC command, this shows the current configuration of the LRF unit and contains the same information found in the Voxtel LRF Configuration section of the excel test document.

The fifth row of this CSV contains information on the number of trials run. 5A is the frequency in hertz of the tests run and 5B in the total number of tests run. The 8th through $8+n-1^{th}$ rows contain the :RR response for the n tests run. Each :RR request returns values of range in decimeters from up to 5 returns. If the test is set up as instructed in previous sections only the first response will be filled as the light is all incident upon a single target. Figure 20 below shows the layout of the LRF .csv output.

	A	B	C	D	E	F	G	H	I
1	b'~VE 1.1.2 OK\r\n'								
2	b'~DC TVT: on Gain: 0 VThHi: 1400 VThLo: 1000 Cal: 0 LC: 75 VThLoExRng: 0 ExtT0: off OK\r\n'								
3									
4	Freq	n							
5	8	80							
6									
7	Test #	Response							
8	1	130	0	0	0	0			
9	2	130	0	0	0	0			
10	...	131	0	0	0	0			
11	n	130	0	0	0	0			

Figure 20 LRF Test Data .CSV

15. Oscilloscope Output .CSV File

The oscilloscope file is named in column S of the Excel test document. This CSV contains data obtained directly from the Tektronix Oscilloscope. No LRF data is in this file. The first column is time in seconds from the start of the recording and the second column is the voltage in Volts recorded at that time.

	A	B
1	0.00E+00	-3.13E-04
2	2.00E-10	4.16E-02
3	4.00E-10	3.81E-02
4	6.00E-10	-6.00E-02
5	8.00E-10	2.05E-02
6	1.00E-09	6.02E-02
7	1.20E-09	3.94E-02

Figure 21 Oscilloscope Output .CSV File

N. Baseline Functionality Test Results

Once the functionality test is run for a variety of LRF settings. The outputted CSV files are read through a Matlab code to parse the data and obtain useful relevant information. The 2 most important questions to answer for baseline functionality characterization are listed below:

For the current physical set up and ambient conditions:

1. How does the T0 Pulse change with Voltage Thresholds and Gain Modes?
2. How is the range number returned by the Voxtel LRF effected Voltage Thresholds and Gain Modes?

To test these questions a test must be run in a variety of test cases reasonable voltage thresholds for each of the four available gain modes. Thus an excel test document (of the format described in section L above) was created with the parameters described below in Table 11. Noting that the VthLo cannot be higher than VthHi there are 36 test cases for each gain mode for a total of 144 test cases.

Table 11 Baseline Functionality Test: Test Cases

Parameter	Value
Max VthHi	1.2 V
Min VthHi	0.5 V
Max VthLo	1.1 V
Min VthLo	0.4 V
Vth Resolution	0.1 V
Test Cases Per Gain Mode	36
Gain Modes	All (4)
Total Number of Test Cases	144

After running the test series described above a total of 288 CVS files were produced, 144 containing LRF data as described in Section 14 and 144 containing oscilloscope data as described in section 15. To parse and analyze this data a Matlab script was written. This script reads the initial test excel sheet from which the sheets were run to obtain the parameters for each test. It then reads the oscilloscope output LRF CSV file for each test. It creates a graph of oscilloscope data with points of interest highlighted. Final it outputs a power point with 144 graphs (1 per slide) and an excel document summarizing key data points from each test case. An example of a graph type for a "Test Case 10" is shown below and used as a general template to exemplify parameters of interest which are described in Table 12.
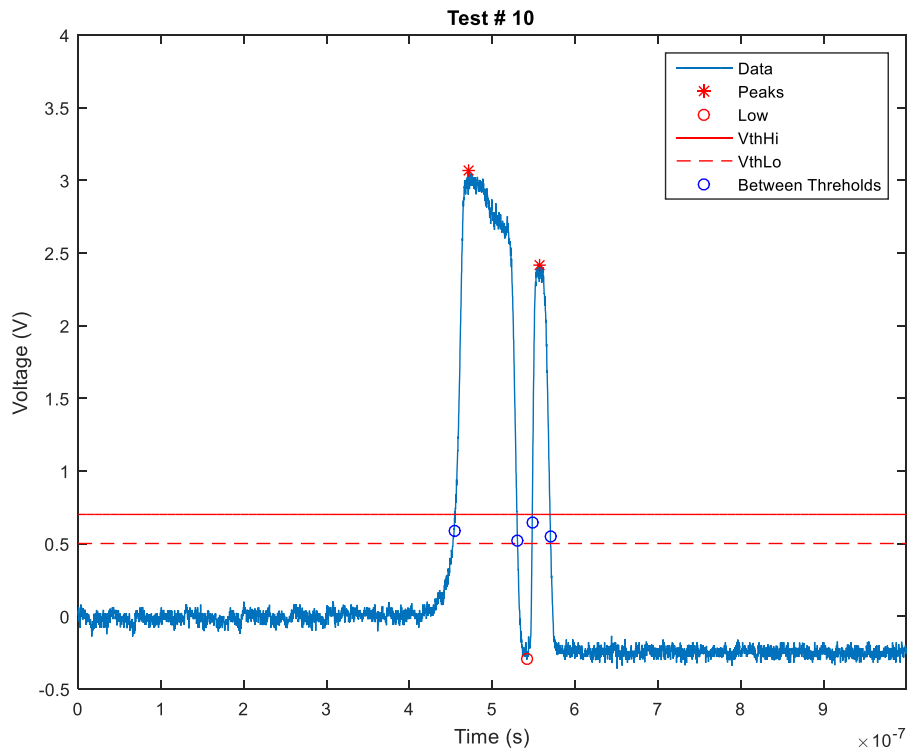
Figure 22 Sample Test Case Waveform

Table 12 Test Case Waveform Parameters

Parameter	Description
Data	Raw recorded oscilloscope waveform during the test run
Peaks	The Left most peak it the T0 peak, the right most peak is the returned peak.
Low	The Low voltage between the T0 and return peaks
VthHi	The High Voltage Threshold setting on the current test
VthLo	The Low Voltage Threshold setting on the current test
Between Thresholds	A point where the wave form is between the thresholds for both the T0 and the return wave form.

When looking at this waveform it is unclear exactly which time measurements correlates to the actual range. Clearly there are 2 distinct signals, however each signal has a non-negligible width. As a result the question must be answered where is between which 2 points in the range measured? This is answered by plotting the range resultant from every possible combination of start and stop times. To calculate the range resulting from a time of flight measurement the following simple formula is used:

$$Range = Tof * \frac{C}{2} \tag{12}$$

Where Tof is the time it takes light to travel to the target and back to the receiver and C is the speed of light. Thus the time of flight is the only parameter that is varied. Referencing Figure 22 it is apparent that there are five permutations of start and stop times. These permutations, along with the symbols used to describe them in the following graph (Figure 23) are listed below in Table 13. It is important to note that the location of the rising edge is dependent on the Voltage Thresholds. Rising edge is defined as the time when the signal cross the Vth Lo and falling edge is defined

as the time when it crossed Vth Hi. Thus it is that noted the time of flight measured will be slightly dependent on the specified threshold voltages.

Table 13 Possible Permutations of Time of Flight

Start Time	Stop Time	Symbol
T0 Rising Edge	Return Rising Edge	Dot
T0 Falling Edge	Return Rising Edge	Circle
T0 Falling Edge	Return Falling Edge	Plus Sign
T0 rising Edge	Return Falling Edge	Triangle
T0 Middle (T0 RE +(T0FE –T0RE)/2)	Return Middle (TR RE +(TR FE –TR RE)/2)	Square
Unknown (:RR Print Out)	Unknown	Asterisks

Table 14 Legend for Analysis Graphs

Gain Mode	Color
0	Red
1	Green
2	Black
3	Blue
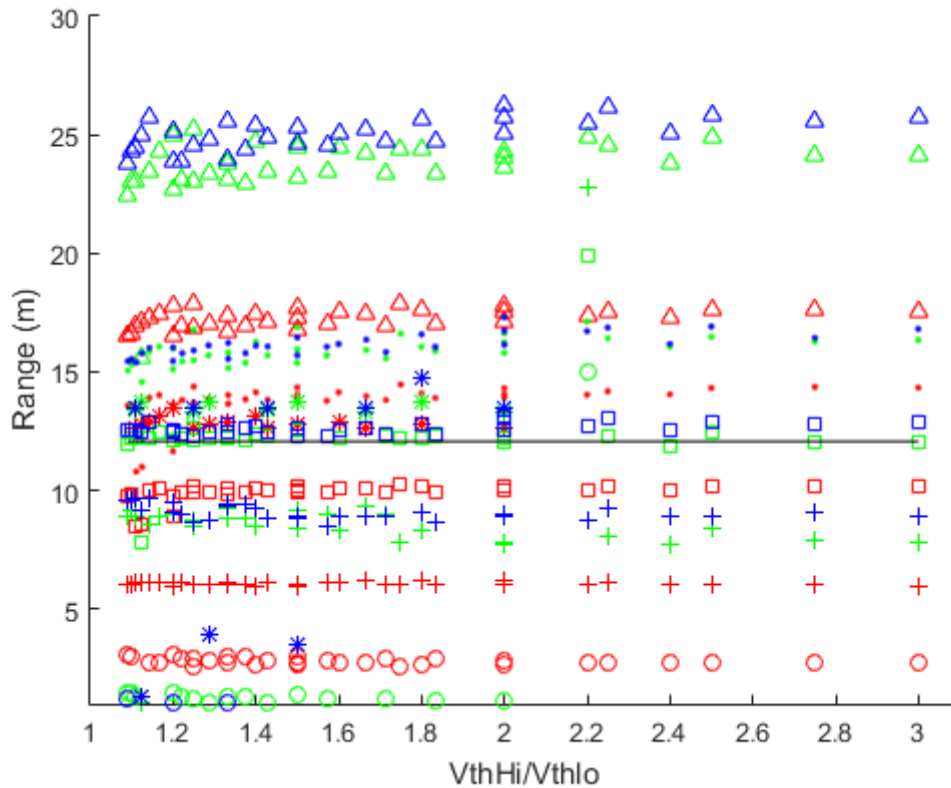
Figure 23 Range output using Time of Flights Described in Table 13
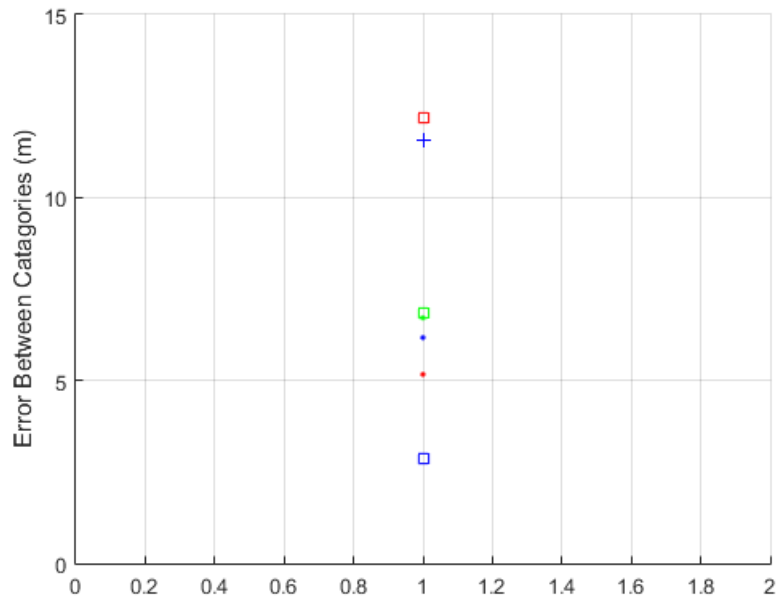
Figure 24 Error Between Group and :RR Print out at the Same Gain Mode

In Figure 23 values are plotted for the calculated time of flight for the 3 gain settings where :RR returned values (the 0,1,3 settings as described in the software ICD[2]) . The red is gain mode 0 the green gain mode 1 and the blue gain mode 3. The possible time of flight combinations listed in Table 13 are plotted at each gain setting for a total of 15 data sets. In addition the true range data (obtained via a measuring tape) is plotted as a solid black line for reference.

Figure 24 shows the error between each measurement method and the: RR return. Although the green square is the lowest single point, in general the green red and blue dots are the lowest set of data. These dots correlate to taking the Time of Flight measurement as time between the rising edge of the T0 pulse and the rising edge of the return pulse. This fits with knowledge about the operation of digital chronometers which the Voxtel LRF uses. These devices measure the time between leading edges of two signals. It is concluded that the :RR function returns the value of the range the time of flight between the rising edge of the T0 pulse and the rising edge of the return pulse.

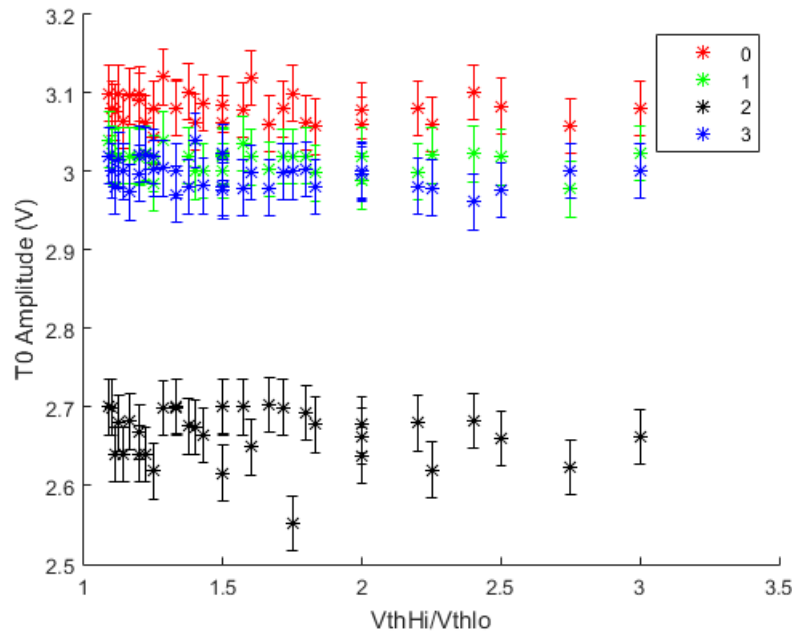*16. Effect of Gain Modes and Voltage Thresholds on T0 Pulse*

Understanding how Time of Flight is measured allows meaningful analysis of variations due to gain and voltage threshold on the shape and size of the T0 pulse. The T0 Pulse width is characterized by width and its peak amplitude. The same color convention defined in Table 14 is used in the graphs that follow.

Figure 25 below shows the T0 pulse width at all four gain modes. T0 Pulse width is the time between the rising edge and the falling edge of the T0 pulse. Again the rising edge is defined as the first time when the T0 pulse is between the voltage thresholds and the falling edge is defined as the time when the pulse cross the threshold voltage going down. Figure 25 shows that the T0 pulse width is a changes slightly with Gain mode but remains mostly constant across threshold voltage ratio. The most dramatically different T0 pulse is gain mode 2, where the APD Gain is set to 0, i.e. no bias voltage is going to the APD. This drastically shortens the pulse width from any other gain mode. We also see that the higher gains modes 1 and 3, lead to wider T0 pulses than the smaller gain mode 0. This important observation is further characterized in Section 17 below.
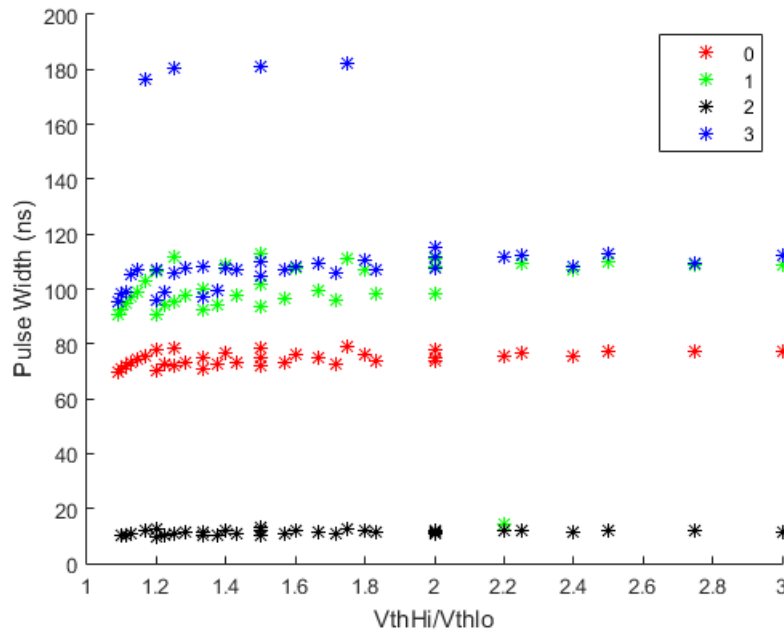
Figure 25 T0 Pulse Width vs Threshold Voltage Ratio

The other characteristic dimension of the T0 Pulse is its height, measured in volts. Error bars must be included in this measurement equivalent to the standard deviation of the steady state noise of the oscilloscope. The plot of T0 Peak height is show below in Figure 26. Again the gain mode 2, with zero APD bias is far below the other 3 gain modes. However clearly T0 pulse height is weaker function of the gain mode than T0 pulse width. The peak voltages between the minimums 0 gain case and differ by about 15% whereas the T0 pulse widths differ by around 400%.

Figure 26 T0 Peak Height vs Threshold Voltage Ratio

17. Effect of Gain Modes and Voltage Thresholds on :RR Return

It is crucial to understand and characterize the performance of Voxtel's software on the ground so that dynamic changes can be made in an on orbit situation. Since oscilloscope measurements cannot be made in orbit, information available in orbit, i.e. information from the Voxtel software and firmware, must be linked as explicitly as possible to waveform data on the ground. The first step towards characterizing the LRF performance is to note for what gain modes and voltage ratios the LRF returns a plausible range. A plausible range is defined as a range close to the truth data or only off by a constant offset.

Thus the first step towards characterizing the :RR return involves looking only at the LRF data and temporarily ignoring the oscilloscope data. Figure 27 uses the same color convention on as the previous figures to show where the :RR returned a numerical value. As stated previously each gain mode had 36 tests with different threshold voltages. During these tests, Gain mode 0 had 15 numerical: RR returns, gain mode 1 had 15 gain mode 2 had 21 and gain mode 3 had 15. It is important to note that a RR returned number is no necessarily accurate,. As seen in Figure 24 many returns at gain modes 2 and 3 were 0.
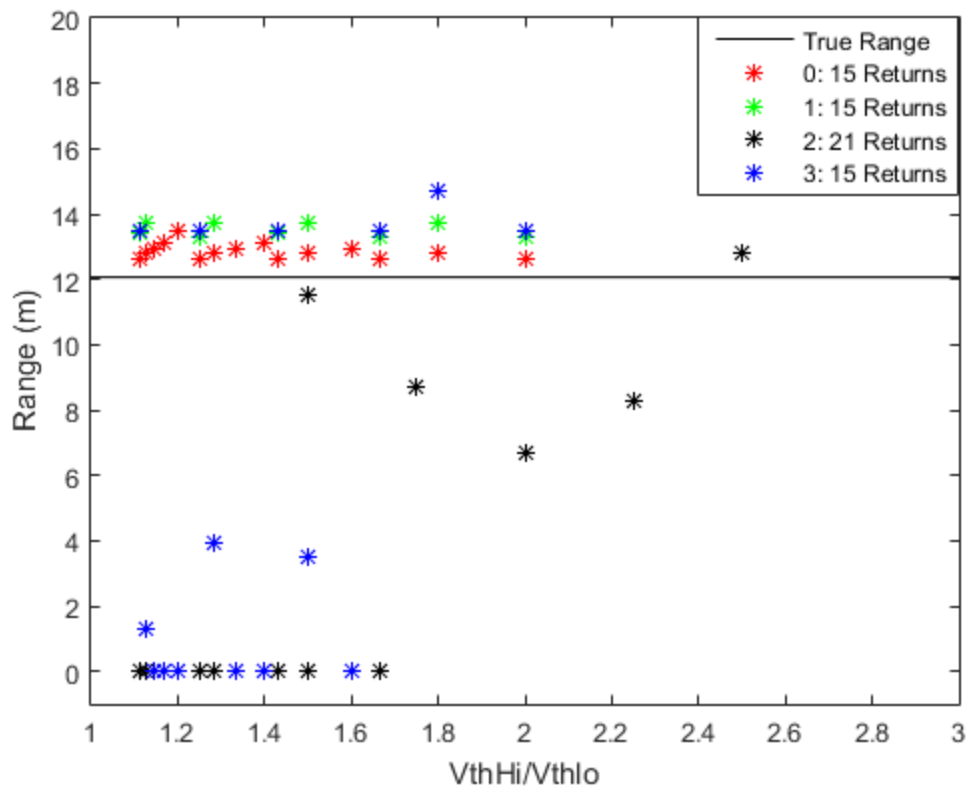

Figure 27 :RR Return Data Where Returned vs Threshold Voltage Ratio

In order to understand when the :RR returns should be considered valid ranges. A definition of valid range is created. For the purposes of this analysis a :RR return was considered valid if it was within 50% of the true range (for this test series between six and 18 meters). Table 15 below shows the number of valid range rate returns for each gain mode. Cleary for this test series Gain Mode 0 was the most reliable with 100% of its returns providing valid ranges. The other gains modes are far more sporadic.

Table 15 Number of Valid :RR Returns

Gain Mode	Number :RR Requests Sent	Number of :RR Requests with Any Return	Number of :RR Requests with a reasonable Return
0	36	15	15
1	36	15	9
2	36	21	5
3	36	15	6

To explain why Gain mode zero is the most ideal for this test series, the T0 pulse data must be analyzed. From visual inspection of graphs of higher gain mode (1,3) responses it is clear that the T0 pulse begins to merge with the return pulse. The APD voltage did not get back to a low enough to know to expect a return pulse. This phenomena is demonstrated below in Figure 28. Table 16 provides a legend with which to interpret the graph. As Figure 28 is one of the most important results of the test, it is discussed in detail below.
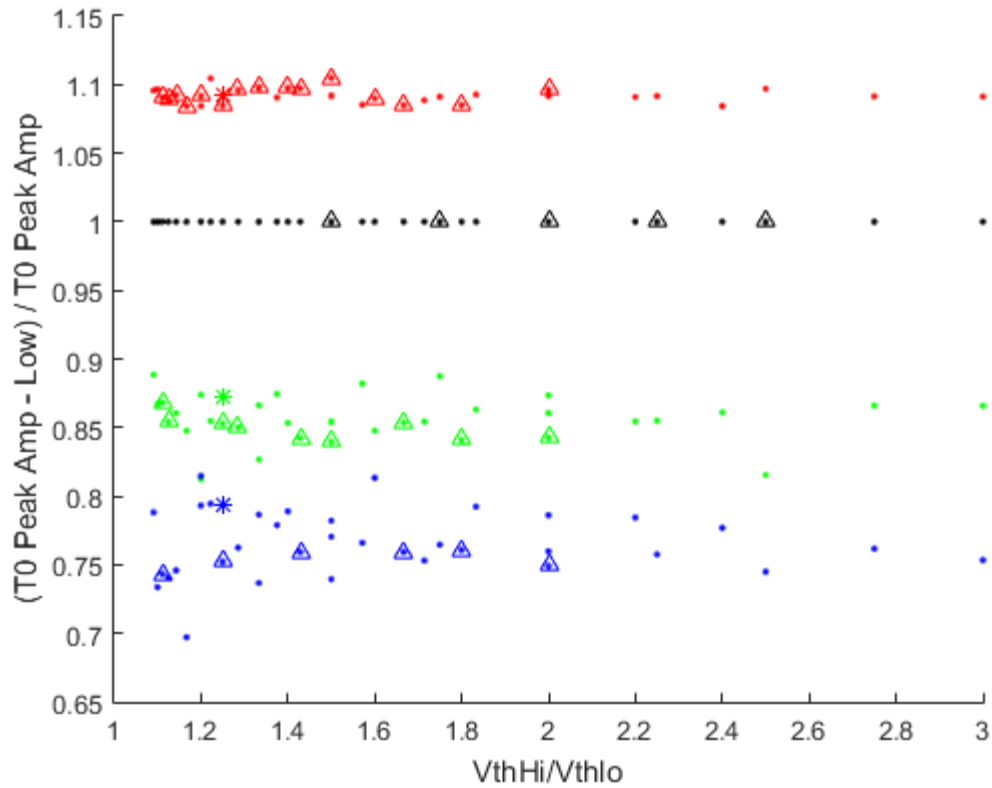
Figure 28 T0 amplitude change vs Threshold Voltage Ratio

Table 16 Legend for Figure 28

Symbol	Meaning
Dot	:RR request sent out
Asterisks	:RR Request returned any value
Triangle	:RR Returned a value within 50% of the true rang, in this these series between 6 and 18 meters.

Figure 28 can be broken into three important elements. Gain modes with a valid :RR return, Voltage Thresholds with a valid :RR return and lastly amplitude changes with a valid :RR return. Gain mode zero, is unequivocally the most reliable at this range and in this test set up. Looking at Figure 28 it is clear that gain mode zero also has the largest drop between the high T0 voltage and the low voltage. It appears that this large drop assures that end of the T0 pulse will drop through the voltage threshold and thus register as the end of the T0 pulse. This allows the timer to know to expect a new pulse and, once the return pulse is received, the timer can be stopped.

This theory is further supported by inspecting which voltage threshold ratios returned valid ranges. The wider the voltage threshold ratio, the more likely a :RR was valid. In fact at the widest threshold voltage ratio, all gain modes returned valid ranges[3].

Thus from this test an optimal operational mode can be recommended for these test conditions. For a short range test on the order 10 meters, where the entire beam is diffusely reflected off a single surface the LRF operational mode that will result in the most reliable data is as follows:
Gain Mode: 0
Voltage Threshold Ratio:2 (VthHi=1 VthLo=0.5)

O. Environmental Testing

18. Vacuum Testing

In order to function in orbit, the laser ranging system must be able to survive and function in a vacuum. As the Voxtel LRF is not specifically designed for a space environment, the hardware its self must be space hardened before vacuum testing. This is done in two steps, staking and conformal coating. Staking involves using an epoxy to "stake" down large chips to the boards. This process help the system survive vibrational tests and prevents some out gassing of components. Conformal coating involves coating the boards in a rubber like material, this coating seals the boards insulating then to prevent short and out gassing. Both sets of LRF boards were staked and conformal coated in preparation for vacuum testing.

An initial vacuum test is meant to show survivability of components expected to be vulnerable to a vacuum. This test is designed to verify that the system still function after exposure to a vacuum. A separate test will be required to determine performance under vacuum. Of principle concern for the survivability test was the Laser driver board which had a large bag capacitor to aid in powering the laser. A close up of this capacitor is show below in Figure 29.


Figure 29 Laser Driver Board Capacitor

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[3] Note that the LRF returned errors, and no valid :RR returns for threshold voltage ratios greater than two. This happened for any gain mode where the APD bias voltage was on (modes 0, 1, 3). The cause of this will need to be investigated in future testing.

The capacitor board was placed alone, unpowered and unconnected, in a vacuum to assure it would not explode and damage other components. It was brought down to 0.06 Torr let to sit or a few minutes and brought back up to atmospheric pressure. A post-test visual inspection indicated no obvious damage to the capacitor or board. It was deemed safe to test for a longer duration with the other system components, however as a precaution it would still be placed in a separate metal box within the chamber. Figure 30 shows the LRF components in the vacuum chamber just before the door was closed.
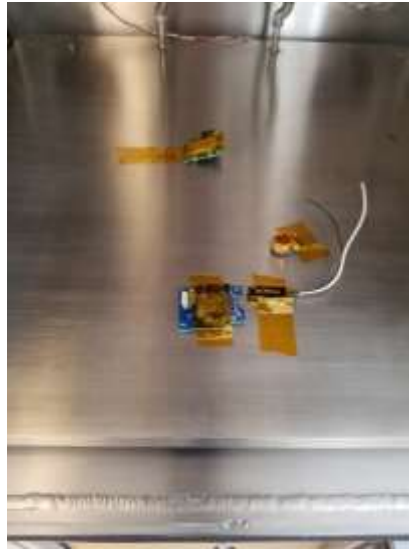
Figure 30 LRF Components in the GT SSDL Vacuum Chamber

The components were left in the vacuum chamber at a temperature of 46.9° Celsius at a pressure of 0.0655 Torr for approximately 16 hours. A post-test visual inspection indicated slight deformation of the bag capacitor.

The system was then reconnected to the test mount and a quick :RR was sent. The system performed poorly and inconsistently, it could not maintain both an APD gain and fire the laser at a steady rate. The laser would only fire at all if the APD gain was set to 0 (mode 2) and even then it sputtered and pulsed at a far lower rate than commanded.

This test, along with the deformation of the capacitor post-test pointed to the likelihood of a damaged capacitor. Another vacuum test was preformed where the capacitor board would be visible during the entire test. The capacitor was filmed as the pressure in the chamber was slowly decreased. It was observed to inflate dramatically. It is unlikely that the capacitor would function in such a state. It is concluded that the capacitors will need to be replaced on the final flight units.

V.   Conclusion

To conclude, the following recommendations are made for operating the Voxtel LRF. Table 17 summarizes the recommended software settings for the Voxtel LRF based on the shot 12 meter range test.

Table 17 Recommended Operational Modes

Parameter	Value
External Trigger	0

TVT	1
FAR	1
RxGain	0
Vth hi	2000 (1 V)
Vth Low	1000 (0.5V)
Vth ErLo	0
Ext T0	0

These are optimal for results at a short distance, as may be expected at the beginning of the RANGE mission. In order to find optimal setting for larger distances (100m+) more tests will have to be performed to replicate these circumstances[4]. Another urgent issue is to replace the current capacitors on the laser driver boards, these must be replaced with a capacitor of the same size that can function in the vacuum of space.

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[4] Planning has begun to fly a UAV directly above the LRF, to simulate the scenario encountered on orbit where a satellite will be the sole source of reflected returns.

VI.   References

[1] ROX™ OEM Laser Rangefinder Module User Guide, Version 2.0, Voxtel Inc.

[2] ROX™µLASER RANGEFINDER MODULE SOFTWARE INTERFACE CONTROL DOCUMENT, Version 1.4, Voxtel Inc.

[3] Technical Information Bulletin: TIB-EVKI-15-01 OEM LRF Module T0 Signal Reference, Voxtel Inc.

[4] Gunter, B.C., *Davis, B.T., Lightsey, E.G., Braun, R.D., 2012. "The Ranging And Nanosatellite Guidance Experiment (RANGE)," Proceedings of the AIAA/USU Conference on Small Satellites, Session V: Guidance and Control, SSC16-WK-17. http://digitalcommons.usu.edu/smallsat/2016/S5GuidCont/3/.

[5] OEM Commercial Laser Rangefinder Module ROXc™ Series Datasheet, Voxtel Inc.

VII.   Acknowledgements