

Airborne Optical Systems Test Bed (AOSTB)



A Challenge Project Final Report presented

by

Daniel Dumanis

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STATEMENT OF IMPACT

Project Impact: This project, the Airborne Optical Systems Test Bed (AOSTB) has brought in over \$3,000,000 in externally funded projects on contract in the first year of being offered as a resident capability. This project defrays \$100,000-\$300,000 in costs per program looking to fly an airborne sensor, and over \$3,500,000 for a program that would have to otherwise build its own laser radar sensor to perform data collection. It has enabled low-cost data fusion collections, which involve simultaneously imaging a scene with multiple sensors, to extract as much useful information out of a scene as possible.

Project Achievements: This challenge project created a low cost resident laser radar platform with roll-on/roll-off sensor capability. The new platform provides The Laboratory with an added capability of leveraging existing sensors, and further exploiting them to their fullest potential. The aircraft has the ability to support multiple sensors, as well as provide interfacing to allow simultaneous sensor operation and data collection. Much of the hardware analysis and integration performed for AOSTB has been standardized and simplified for future sensors to be integrated into this common platform. Two multi-sensor, externally funded campaigns have been successfully completed, and the next milestones involve continuing to market this important capability of The Laboratory, and supporting the various sensor configurations required by sponsors for our next programs. Outside the scope of this project, we will seek additional funding to modernize some of our legacy hardware, and to shrink the size, weight, and power (SWaP) requirements of our resident payload, in order to accommodate a wider variety of secondary sensor suites.

Project Value: The work done on the Airborne Optical Systems Test Bed (AOSTB) challenge project defrays costs for individual programs up to \$300,000 in aircraft use fees and up to \$3,500,000 in sensor development and integration costs (for programs that can benefit from having a laser radar). Due to this lower cost of entry, The Laboratory will be able to accept more small, data-centric programs, that each provide up to \$1,000,000/yr in funding. The platform will be a major resource and facility, to be used by the wider Laboratory community, for many years to come.

Candidate Impact: The GEL Challenge Project has had a significant impact on Dan’s leadership skills and abilities. Due to the previous failures of AOSTB, many key stakeholders harbor negative associations with the concept, and are hesitant to commit themselves. Dan showed initiative and influencing skills by convincing the stakeholders to allow him to develop it. The development of the AOSTB has been an interest to The Laboratory for many years, and Dan was able to bring various groups across The Laboratory together, promote communication across disciplines, and deliver a functional laser radar test bed to be used for immediate and future sensor development.

Daniel Dumanis, Gordon Fellow Candidate

Date

Dr. Rajan Gurjar, Industry Sponsor

Date

1 ABSTRACT

This report details the challenge project tasked with the development of an airborne optical testing platform to provide an infrastructure for exploration of novel sensors capable of foliage penetration, and phenomenology exploration. This platform consists of an aircraft, an optical bench, a Geiger-mode laser radar payload, and space for additional sensor integration. The creation of such a platform defrays up to \$3,500,000 in sensor development and integration costs, per customer, and up to \$300,000 in annual aircraft use fees. Due to this lower cost of entry, The Laboratory is able to take advantage of an otherwise unavailable source of revenue from small data-centric programs, to generate an additional \$3-7M in annual revenue.

2 AUTHOR'S BIO

Over the course of seven years of working at MIT Lincoln Laboratory, Dan has taken advantage of opportunities to move through various roles and responsibilities in an effort to broaden his understanding of The Laboratory and try out new challenges. Some of these roles have included IT administration, laboratory testing, sensor development and field validation, logistics, and mission support. As an undergraduate student in pursuit of a Bachelors of Science degree in Computer Engineering at Northeastern University, Dan worked all three co-ops in the same group at MIT Lincoln Laboratory. Leveraging his past experience performing contracted IT work, through former jobs and his own company, Dan secured a role in the IT department of the Active Optical Systems group. As a co-op, Dan pioneered the implementation of a virtualization infrastructure in the group, worked on the collection and aggregation of streaming sensor data, and participated in multiple local and remote test campaigns. Upon graduating in 2012, Dan was hired as a full-time engineering specialist.

Soon after being hired, Dan replaced a recent departure in a computer systems support role on an operational lidar platform, known as "ALIRT", which was deployed operationally from 2010 through 2014. In his support role, he traveled numerous times overseas to perform sensor maintenance, and in the process learned about all aspects of the sensor platform. On his third trip, Dan took on a leadership role in planning and organizing the entire trip. Aided in part by a few untimely employee departures, Dan was promoted to the role of assistant technical lead on the program, and was the primary point of contact for the deployed sensor operators. In addition to providing support to already deployed sensor operators, Dan took on an additional role in training operators before they deployed out.

In 2013, Dan also became part of the follow-on project to ALIRT, known as MACHETE. On this project, he developed some of the back-end processing chains, the operator GUI

for onboard data processing, configured many of the computer systems, and helped perform months of testing of the sensor both locally at the lab, and once deployed out in the field.

Last year, Dan began working on a team that intended on building a ladar sensor for laboratory use; the pre-cursor to this challenge project. The project ultimately failed to deliver for a number of reasons, however Dan saw an opportunity to take the lead and deliver the originally intended result. After being accepted into the Gordon Program, Dan negotiated for the role of Program Manager and was given a second chance at building a functional ladar for an AOSTB.

In choosing this challenge project, Dan took the surface-level/working knowledge he had accrued of these multiple sensor systems, and learned about the underlying scientific principles that enable this technology to ultimately realize the vision of a resident Airborne Optical Systems Test Platform for The Laboratory.

3 ACKNOWLEDGEMENTS

First, I would like to express my sincere gratitude to my advisor, Prof. Chuck DiMarzio, for his vast knowledge and continuous support through weekly working sessions. His guidance helped me learn and understand important concepts that were essential to successfully completing this project.

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My sincere thanks also go out to Col. Steve McGonagle for his insights and encouragements in leadership, Steve Klosterman for his lessons in how to invent, innovate, and implement engineering projects from concept to market success, and the rest of the Gordon Institute cadre for their overall support.

I would like to also thank the entire AOSTB project team at The Laboratory, without whom this project would not be a success, and my group leadership for being supportive throughout this process.

Finally, I would like to thank my wife, Masha, for supporting me throughout this project and in life in general.

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6 INTRODUCTION

The project being presented is an Airborne Optical Systems Test Bed (AOSTB) that provides The Laboratory with a resident platform, or “facility”, to enable development of novel sensors and phenomenology exploration. This platform consists of an aircraft, an optical bench, and a three-dimensional imaging laser radar (3D ladar), utilizing a single-photon-sensitive avalanche photodiode (APD) array and short-pulse laser. Additionally, the platform contains rack and optical bench space for the integration of an additional sensor for multi-sensor data collections. The creation of such a platform defrays up to \$3,500,000 in sensor development and integration costs, per customer, and up to \$300,000 in aircraft use fees per year. Due to this lower cost of entry, The Laboratory is able to take advantage of an otherwise unavailable source of revenue from small data-centric programs, for an additional \$3-7M in annual revenue.

The past model for testing airborne optical sensors typically required building the sensor into the platform (aircraft). This involved custom and costly system designs, additional personnel time for testing, validation, and integration, and an overall longer lease of the platform. This project created a resident sensor suite with roll-on/roll-off capability, coupled to a resident platform (Twin Otter Aircraft). This facility significantly reduces lead times and integration costs by allowing programs to leverage existing sensor modalities, as well as plug in their own sensors for stand-alone or fusion data collections.

The main challenges have been leveraging existing spare hardware from various ladar sensor systems in order to create a single working one. The technical challenges of this project involved 1.) creating an optical design that will provide the ability to easily align and focus the ladar portion of the system in-flight, 2.) designing the core sensor payload with minimized size, weight, and power (SWaP), in order to physically and electrically accommodate additional sensor payloads, 3.) validating that the sensor payload is flight-worthy (through FEA or other analysis), modifying the scanning system to accommodate various orientations and new scan patterns (understanding and implementing rotation matrices), and 4.) producing high-quality data products using the latest coincidence-processing algorithms available.

6.1 Product Mission Statement

Mission Statement: Airborne Optical Systems Testbed (AOSTB)	
Product Description	<ul style="list-style-type: none"> • A resident, Laboratory, roll-on/roll-off ladar sensor platform with an architecture that supports the addition of third-party sensors
Benefit Proposition	<ul style="list-style-type: none"> • Make 3D-ladar available to the wider Laboratory community instead of just specialty programs. • Provide multiple sensors and modalities as “standard options” for data collections • Low-cost data collection with the option of data fusion products • Leverage existing hardware as much as possible
Key Business Goals	<ul style="list-style-type: none"> • Enable low-cost entry point to 3-D ladar data collection • Improve efficiency and time investment in performing data collections for novel phenomenology exploration • Maintain platform at The Laboratory with program lease option “by the week”
Primary Market	<ul style="list-style-type: none"> • Internally funded and/or budget sensitive programs that are interested in low cost data
Secondary Market	<ul style="list-style-type: none"> • Programs whose sponsors are interested in collecting fused data products and/or data with third-party sensors and sensor modalities
Assumptions and Constraints	<ul style="list-style-type: none"> • Assume all hardware components can be made compatible / modified as needed. • Leverage existing software data processing chain with minor modifications for variations in data formatting. • Collect data from two field collection sites by end of fiscal year
Stakeholders	<ul style="list-style-type: none"> • Technology Office (Acting Sponsor) • Division 10 – ISR Systems & Technology (Group 106, Flight Facility) • Division 9 – Space Systems & Technology (Groups 97, 99) • Division 8 – Advanced Technology (Group 87) • Division 4 – Homeland Protection (Groups 44,46) • Division 3 – Air, Missile, & Maritime Defense Systems (Group 38)

6.2 Project Definitions

ACR	<i>Area Collection Rate</i>
ALIRT	<i>Airborne Lidar Research Testbed: a formerly deployed flash lidar sensor that is no longer operationally used in theater</i>
AOSTB	<i>The name of this project, which stands for Airborne Optical Systems Test Bed</i>
APD	<i>Avalanche Photo Diode: a highly sensitive photodiode that operates in reverse bias and converts light to a measurable current through “avalanche” multiplication</i>
CMOS	<i>Complementary metal-oxide-semiconductor (low noise, low power)</i>
COTS	<i>Commercial, Off The Shelf</i>
CP	<i>Coincidence Processing: a method of finding signal in the presence of noise and clutter by using coincident special data</i>
DCR	<i>Dark count rate: Measurement of background noise on the detector</i>
DFPA	<i>Digital Focal Plane Array: A detector array that is mated to a CMOS readout integrated circuit (ROIC), currently available for LWIR.</i>
FEA	<i>Finite Element Analysis</i>
FFRDC	<i>Federally Funded Research and Development Center: unique nonprofit entities sponsored and funded by the U.S. government to meet some special long-term research or development need which cannot be met as effectively by existing in-house or contractor resources.</i>
FoPen	<i>Foliage Penetration</i>
FOR	<i>Field of Regard: The extents of the total area that can be captured by the scan mirror.</i>
FOV	<i>Field of View: The extents of what the sensor can see at any given moment for a single frame.</i>
FY	<i>Fiscal Year</i>
GM / GMAPD	<i>Geiger-mode: a mode of operating an APD above its breakdown voltage, which allows for single photon sensitivity when noise levels are low.</i>
GNSS	<i>Global Navigation Satellite System. GNSS System refers to the receiver used to compute precise location information (GPS)</i>
ISR	<i>Intelligence, Surveillance, and Reconnaissance</i>
L0 Data	<i>Raw range data from Geiger-mode APD</i>
L1 Data	<i>Aggregated noisy point cloud from L0 data</i>
L2 Data	<i>Coincidence processed point cloud broken up by “tiles” or “buckets”</i>
L3 Data	<i>Aggregated L2 tiles that produce a single large “registered” point cloud</i>
L4 Data	<i>Marked up / analyzed L3 data – the final delivered product that can present information such as flood-zone maps, change-detection, etc</i>
Lidar / Ladar	<i>Laser radar (light/laser detection and ranging)</i>
Link Budget	<i>A way of quantifying all of the gains and losses through a medium (air) from the transmitter (laser) to the receiver (detector)</i>
LWIR	<i>Long Wave Infrared</i>
MACHETE	<i>Multi-look Airborne Collector for Human Encampments and Terrain Extraction: a currently operationally deployed flash lidar sensor</i>
Nd:YAG	<i>Neodymium-doped Yttrium Aluminum Garnet: crystal used as a laser medium for solid-state lasers</i>
Phenomenology	<i>Qualitative research methodology that investigates different ways</i>

	<i>people see or experience something.</i>
Q-Switching	<i>A technique by which a laser can be made to produce a pulsed output beam with low pulse repetition rates and high pulse energies</i>
Reflectivity	<i>The property of reflecting light off of a surface</i>
SMCG	<i>Scan Mirror Control Generator: a single board computer system that is responsible for commanding and controlling the scan mirror</i>
SWaP	<i>Size, Weight, and Power</i>
SWIR	<i>Short Wave Infrared</i>
Test Bed	<i>A platform, facility, or space used in performing research or testing</i>
TO	<i>Technology Office: The acting sponsor for internally funded Laboratory efforts</i>
Twin Otter	<i>A twin-engine, unpressurized, turbo-prop de Havilland DHC-6 aircraft</i>
USG	<i>United States Government</i>
WISP	<i>Wide-area Infrared Surveillance Platform [6], mounted on a three-axis continuously rotating gimbal</i>

6.3 Company/industry background

MIT Lincoln Laboratory is a federally funded research and development center devoted to solving problems critical to national security. The Laboratory was established in 1951, tasked to build the nation's first air defense system, shortly after intelligence sources in the United States reported that scientists in the Soviet Union were pushing hard to develop a nuclear capability. The Department of Defense felt compelled to re-evaluate the nation's defenses against nuclear attack, and assigned the U.S. Air Force the task of improving the nation's air defense system. The Air Force, in turn, reached out to MIT for assistance, which led to the formation of MIT Lincoln Laboratory.

Following the development and deployment of the first operational air defense system, designated the Semi-Automatic Ground Environment, or SAGE, Lincoln Laboratory moved on to address other missions and technologies critical to national security.¹

The areas that constitute the core of the work performed at Lincoln Laboratory are sensors, information extraction (signal processing and embedded computing), communications, and integrated sensing and decision support; all of which is built upon a foundation of broad research in advanced electronics.

Research at The Laboratory includes projects in air and missile defense, space surveillance technology, tactical systems, biological and chemical defense, homeland protection, communications, cyber security, and information sciences. The Laboratory takes projects from the initial concept stage, through simulation and analysis, to design and prototyping, and finally to field demonstration.²

¹ "About." *MIT Lincoln Laboratory*. Web. 8 Dec. 2015.

² "Mission Areas." *MIT Lincoln Laboratory*. Web. 8 Dec. 2015.

6.3.1 Organizational Structure

Lincoln Laboratory is organized into the following eight technical divisions, each with its own specific focus areas: Air, Missile, and Maritime Defense Technology (Division 3); Homeland Protection and Air Traffic Control (Division 4); Cyber Security and Information Sciences (Division 5); Communication Systems (Division 6); Engineering (Division 7); Advanced Technology (Division 8); Space Systems and Technology (Division 9); and ISR and Tactical Systems (Division 10). All divisions report to the office of the director, which reports to the MIT Office of the President. The organizational structure can be seen below in Figure 1.

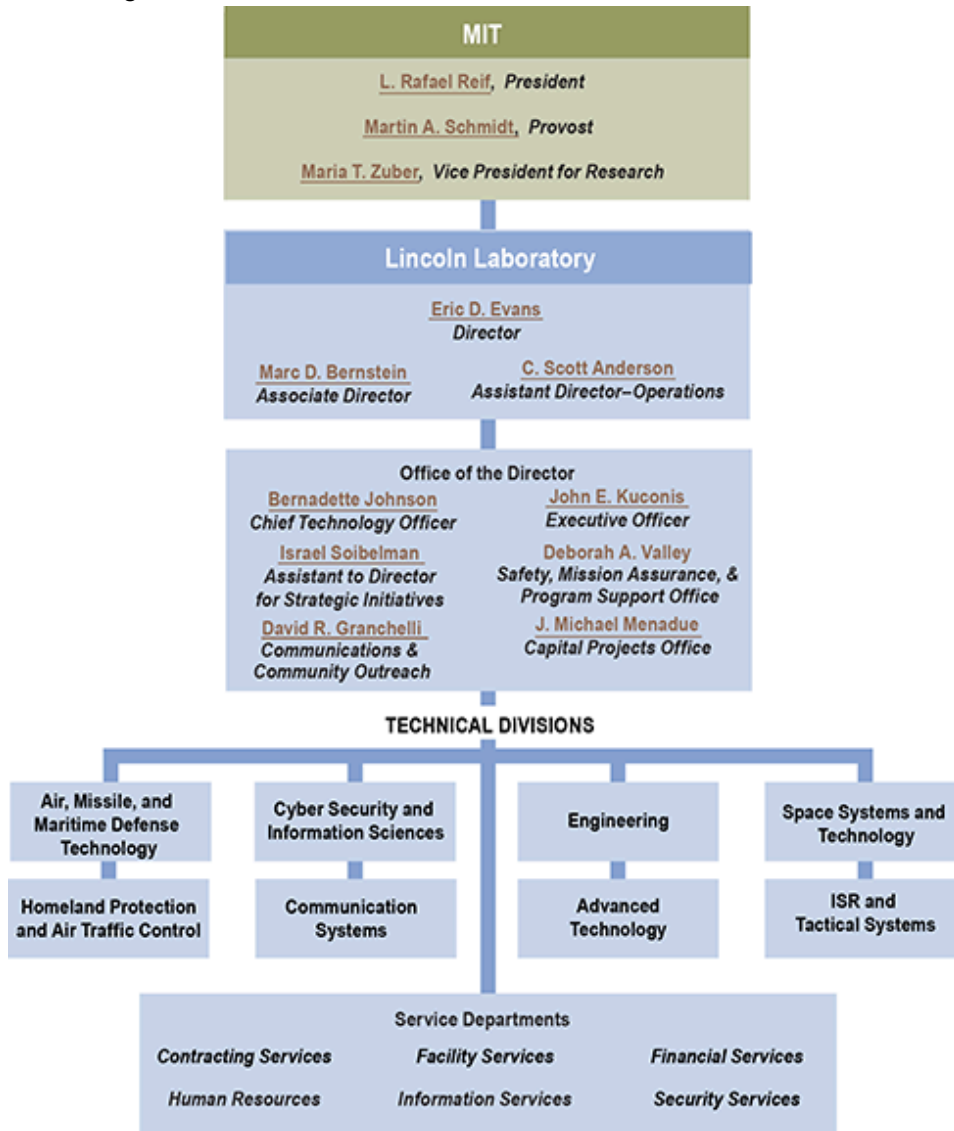


Figure 1 - MIT Lincoln Laboratory Organizational Structure³

³ "Organization." *MIT Lincoln Laboratory: Organization*. Web. 8 Dec. 2015.

7 MARKET AND IMPACT ASSESSMENT

Airborne optical sensors development and novel phenomenology exploration is a major thrust at The Laboratory. While some programs are aimed at designing completely novel sensors, others aim to improve the usability of the data types that already exist by improving algorithms and extracting more information out of them.

The approach, taken thus far, has been for individual programs to pay for platforms and sensor development using sponsor funds. The platforms are then reserved exclusively for that program's use, with limited access to the wider Laboratory community. While this is financially viable for some programs, this model presents a very high cost of entry for performing airborne data collections, and also often requires the programs to develop or build their own sensors.

The Airborne Optical Test Bed platform, or "facility", is equipped with basic infrastructure (power, cooling, optical bench, and racks) to support 'roll-on, roll-off' capability of different sensors at low cost and modest time frames. Additionally, certain key unique Lincoln Laboratory developed sensors, the Geiger-mode 3D imaging ladar, are integrated or made available as roll-on/roll-off capabilities and made available as Laboratory-wide assets to support both internal and external efforts. This test bed facility is the airborne counterpart to the highly successful and highly utilized infrastructure asset known as the Optical Systems Test Facility (OSTF).

7.1 External Market

As a Department of Defense (DoD) FFRDC, Lincoln Laboratory is a unique organization that does not compete with industry. The Laboratory's external customers are project sponsors within the DoD, and occasionally from other branches of the USG. The Laboratory operates on a cost-reimbursement, no-fee agreement.⁴ A breakdown "by customer" of The Laboratory's research expenditures for FY2014 can be seen in Figure 2, with over 90% of The Laboratory's work being performed for the DoD. The total annual budget is approximately \$811.3 Million.⁵

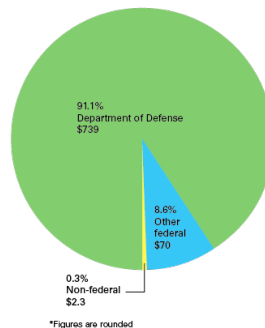


Figure 2 – MITLL Research Expenditures for FY2014 (figures in millions)

⁴ "News." MIT Lincoln Laboratory: : MIT and the Air Force Renew Contract for Operation of MIT Lincoln Laboratory. Web. 12 Dec. 2015.

⁵ "Lincoln Laboratory." MIT Facts 2015:. Web. 8 Dec. 2015.

7.2 Internal Market

Internal research funding at The Laboratory is focused on long-term, high-impact research that is relevant to DoD needs. The internal R&D investment portfolio is strategically developed to both address the critical technology needs of The Laboratory's existing mission areas, and to provide the technical foundation to address emerging national security challenges. A breakdown of The Laboratory's internal investment portfolio for FY14 can be seen in Figure 3. The graphic displays the relative magnitude of 2014 internal funding across mission-critical technology (shaded blue) and basic and applied research (red). The smaller divisions within each block represent individual projects executed in that category.⁶

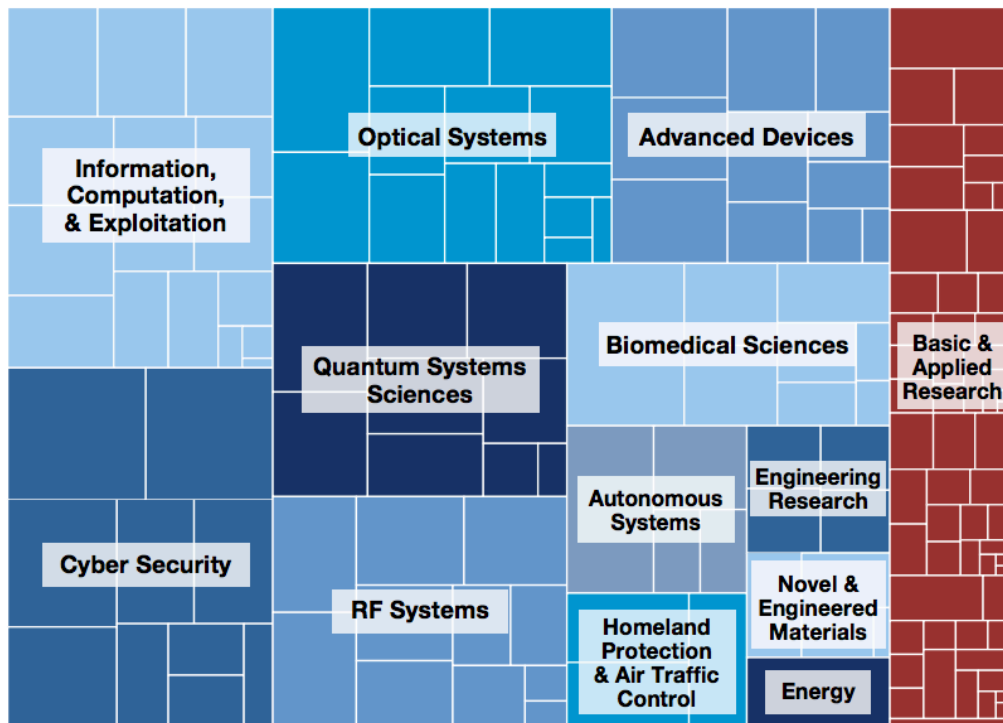


Figure 3 - MITLL Internal R&D Portfolio for FY2014⁶

Internally, the AOSTB project will mainly support programs in the Optical Systems category and the Homeland Protection & Air Traffic Control category. This project will have the ability to defray up to \$300,000 for each program that requires an aircraft lease, and will enable lower cost data-centric programs to collect optimal data per their individual requirements.

7.3 Customer and Customer Needs Assessment

After determining the stakeholders and future customers of this project, a small meeting was organized with all of the involved parties in order to learn about what their needs and requirements were. The exchange of information helped our team understand what

⁶ MIT Lincoln Laboratory. 2014 Annual Report, 2015. Web. 8 December 2015

they were hoping to achieve by using this platform, which in turn guided some of the technical decision that we made. Table 1 shows some of the requirements that came out of the interviews, and describes how these requirements were met.

Table 1 - Customer Requirements

Customer Statement	Requirement	How requirement were met
<i>“We’re not sure what the capabilities are”</i>	<ul style="list-style-type: none"> • <i>Provide information about various sensor capabilities and modalities</i> • <i>Make information easily accessible and available</i> 	<ul style="list-style-type: none"> • <i>Produced documents and presentations that quickly convey sensor capabilities.</i> • <i>Created centralized data share with all relevant information</i>
<i>“We need to fly in various locations and have the ability to test straight lines passes and bounded regions”</i>	<ul style="list-style-type: none"> • <i>Permissions to fly and operate ladar in multiple locations</i> • <i>Implement a scan mode for collecting continuous straight lines</i> • <i>Implement a scan mode for collecting point targets</i> 	<ul style="list-style-type: none"> • <i>Obtained blanket permissions from FAA</i> • <i>Created and implement a “line-of-communication” scan mode.</i> • <i>Implemented and tested target scan mode</i>
<i>“We will want to collect various small-to-medium sized targets over a campground”.</i>	<ul style="list-style-type: none"> • <i>Require ability to scan multiple sized targets</i> • <i>Require FoPen capability</i> 	<ul style="list-style-type: none"> • <i>Implemented preset scan parameters to cover wide range of target sizes (within technical constraints)</i> • <i>Developed scan modes that are optimized for obtaining multiple view-angles of target to enable FoPen.</i>
<i>“We would like to simultaneously fly with multiple sensors”</i>	<ul style="list-style-type: none"> • <i>Require sufficient aircraft power for multiple sensors.</i> • <i>Require space to fit multiple sensors</i> 	<ul style="list-style-type: none"> • <i>Consolidated the ladar sensor to a single rack to minimize SWaP.</i> • <i>Designed larger optical bench that can fit an additional sensor payload within size constraints.</i>

7.4 Economic Impact and Return on Investment

With the additional investment of \$475,000, this project is able to defray over \$3,500,000 for a program that would have to otherwise build its own laser radar sensor to perform data collection, and \$100,000-\$300,000 in costs per program looking to fly a sensor. Previously, a purely data-centric program would likely not get funded at such a high cost of entry, and The Laboratory would miss out on a potentially interesting and rewarding opportunity. By enabling a lower cost of entry for airborne testing, The Laboratory creates a new channel for an additional \$3-7M in annual revenue.

Even with the current model of airborne testing, a program may be required to fund an aircraft's ferry flight to and from the lessor (approximately \$35,000), as well as pay for additional weeks of sensor integration and ground testing (at a cost of \$15,000-\$30,000/week, depending on overhead). By providing The Laboratory with a roll-on/roll-off capability, an interested sponsor is able to request the aircraft for a much shorter period of time, have the flexibility to reconfigure the platform with different and multiple sensors to meet specific program needs, and achieve custom tailored data collections with short lead times and low cost.

The calculations used for creating these estimates are based on actual short-term vs long-term Twin Otter aircraft lease costs, as well as associated overhead of maintaining an aircraft. A table of lease costs and associated overhead can be seen below in Table 2 and Table 3. The tables were created as cost models in Excel, which are now used by programs to easily and quickly estimate how much funding they must plan to allocate for flight programs.

Table 2 - Twin Otter Cost Breakdown for Short-term lease

Required for Lease			
Description	Total Annual Cost	Cost per week	Comments
Lease	\$306,900	\$5,901.92	
Insurance	\$34,000	\$653.85	
Spare Parts	\$80,000	\$1,538.46	
Aircraft pickup & return	\$47,348.82	\$910.55	Includes 1 week travel + 20 hours ferry fuel + Reserve

Flight Facility Costs			
Description	Total Annual Cost	Cost per week	Comments
IOE	\$576,965	\$11,095.48	Includes pilot, mechanic, admin, support staff, & mgmt
Sensor Integration	N/A	\$11,250.00	

Charged per flight			
Description	Charged per week	Cost per flight hour	
Fuel	NA	\$653	
Engine/prop reserve	NA	\$777	
MITLL 2nd Pilot	\$6,250		

Variable Assumptions		Inputs	
Average hours per flight:		1	
Average flights per week:		1	

Cost Calculations			
Lease Cost:		\$9,005	per week
Req'd MITLL/FF Costs:		\$11,095	per week
Fuel + Engine/prop reserve:		\$1,430	per flight hour

Final Costs			
MX Costs		\$20,100	per week, cost to keep/maintain airplane in hangar
MX Cost + One week Integration		\$31,350	per week, cost while integrating sensor
MX Cost + Typical Week Flight(s)		\$27,780.21	program usage cost per week with eight hours flight time

Yearly Total to Own Aircraft: \$1,045,213.82

Table 3 - Twin Otter Cost Breakdown for Long-term Lease

Required for Lease			
Description	Total Annual Cost	Cost per week	Comments
Lease	\$270,000	\$5,625.00	
Insurance	\$34,000	\$653.85	
Spare Parts	\$80,000	\$1,538.46	

Flight Facility Costs			
Description	Total Annual Cost	Cost per week	Comments
IOE	\$576,965	\$11,095.48	Includes pilot, mechanic, admin, support staff, & mgmt
Sensor Integration	N/A	\$11,250.00	

Charged per flight			
Description	Charged per week	Cost per flight hour	
Fuel	NA	\$653	
Engine/prop reserve	NA	\$777	
MITLL 2nd Pilot	\$6,250		

Variable Assumptions	Inputs	
Average hours per flight:	4	
Average flights per week:	2	

Cost Calculations			
Lease Cost:		\$7,817	per week
Req'd MITLL/FF Costs:		\$11,095	per week
Fuel + Engine/prop reserve:		\$1,430	per flight hour

Final Costs**			
MX Costs		\$18,913	per week, cost to keep/maintain airplane in hangar (baseline)
MX Cost + One week Integration		\$30,163	per week, with FF support integrating/de-integrating sensor
MX Cost + Typical Week Flight(s)		\$36,602.32	program usage cost per week based on flight variables above

7.5 Market Challenges and Risks

Potential market challenges and risks that exist with this project are that there may not be enough programs over the years to cover Laboratory investment into the platform. Ideally, the platform should be in use for the majority of the year. In anticipation of this, our team ensured that all relevant and potential users of the platform are aware of its existence and its capabilities. Communication and advocacy have been an essential component of this challenge, in addition to demonstrating that we have a functional sensor platform that is worth using.

A second challenge that exists is the obsolescence of parts, which may render the sensor platform uninteresting to future internal programs and sponsors. In order to anticipate this and maintain it as a useful asset, a yearly or bi-yearly survey will have to be conducted to determine what sensors are of interest, and whether or not it will be possible to recreate them or borrow them for the purposes of a shared Laboratory resource. A re-scope of the project was already once required due to the WISP sensor being unavailable, so better planning and communication will be essential going forward.

Finally, The Laboratory will need to be convinced that this program is deserving of a dedicated funding source to maintain it as a facility. For this year, the program was allocated parts of other program budgets, and therefore used multiple sources to fund the project. The multiple users and stakeholders required managing potentially conflicting program requirements, such as scheduling, optical setup, and resource sharing. If programs are to rely on AOSTB, it has been and will be essential to have clear communication with users from the initial stages of planning to ensure that the asset is not over subscribed, and programs' requirements are not in conflict with one another.

8 TECHNOLOGY DESCRIPTION

Due to the mission-critical nature of many sensors and systems that The Laboratory develops, The Laboratory is often tasked with maintaining a subset of readily available spare parts in the event that a fielded sensor malfunctions.

The AOSTB project made use of some of these spare or extra components in order to deliver a single capable sensor platform. This platform is capable of performing data collections for programs as needed, as well as to be used for further sensor development and data exploitation of existing sensors. The roll-on/roll-off capability that we achieved is essential for allowing this platform to truly be used as a testing facility for existing and novel sensors. The limited real estate available required limiting each sensor to a single rack and some optical bench space. Safety was also taken into consideration in order to protect pilots and other aircrafts from laser radiation exposure. A layout of the aircraft with the installed hardware can be seen in Figure 4.

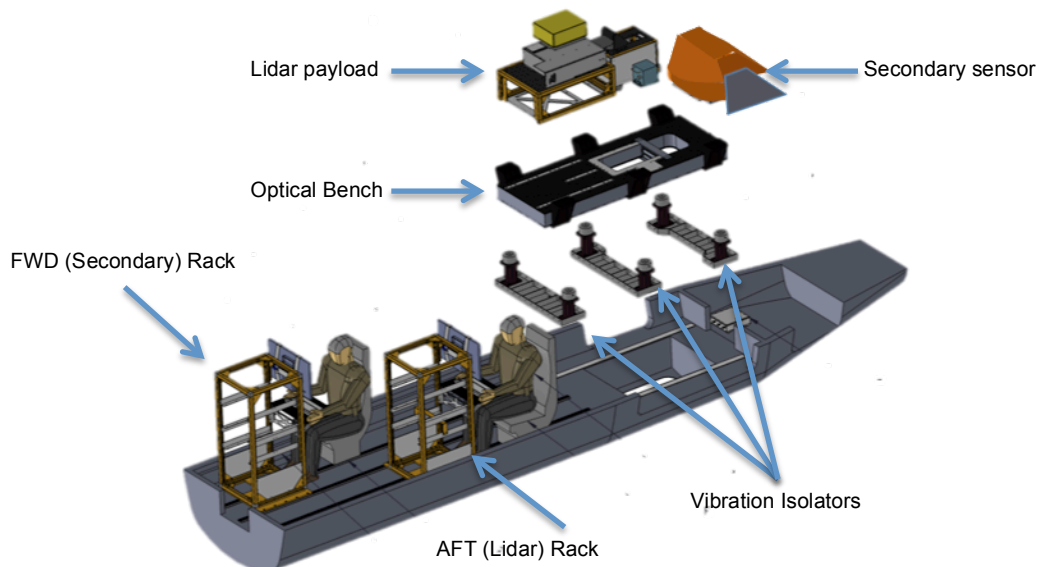


Figure 4 - AOSTB Layout in a Twin Otter Aircraft

8.1 Overview of the Technical Challenge

The main technical challenge has been leveraging existing hardware from various sensors, and combining them into a single, functional, SWaP minimized 3D ladar sensor. Due to the low budget and short timeline, the team had to come up with creative ways of ensuring interoperability, as well as consolidating as much hardware as possible to make the most use of the limited cabin space and available power. Space and power requirements for a secondary sensor were essential to consider from the start of the design process of the overall platform architecture.

The scan system had to be modified to accommodate various sensor modalities, such as down-looking and side-looking scanning. The team had to develop and implement new scan modes into legacy hardware to enable foliage penetration (FoPen) of small target areas as well as completely novel scan modes, such as FoPen map-mode (capable of collecting large stretches of area in either straight lines or along a line of communication, such as a river, as opposed to just a target area of up to 1km²). Physical constraints of the scan mirror, such as field of regard and maximum accelerations, had to be taken into consideration when designing new scan modes.

Additional technical constraints, such as a 1.2W, 15Khz laser (which limits the amount of light with which the sensor can illuminate the ground), a 23x36" "wildcat" hole in the bottom of the fuselage, which limits our FOR (Field of Regard), and others, presented certain design challenges.

Finally, due to the heterogeneity of the hardware components, we were presented with a variety of additional challenges in synchronizing time between the subsystems, changing the optical design, and processing the data.

8.2 Product Specifications

Capabilities were discussed with potential future users in order to identify minimum requirements for area collection rates (ACRs), desired flight patterns / target view angles, and specific targets they would be imaging. Based on these requirements, nominal ground speeds and altitudes were chosen. Certain assumptions were made about average reflectivity of surfaces being imaged (based on prior experimental values), and values for ACR are provided for 25cm, 30cm, and 50cm post-spacing resolution, to provide the users with options for mission planning. Figure 5 captures the resulting calculations for each planned scan mode, using the following formula for calculating ACR:

$$ACR = \left\{ \frac{N_{pixels} * (avg \ num \ detections / pixel / pulse) * (pulses / sec)}{(avg \ num \ detections \ reqd / resolution \ element)} \right\} \left\{ \frac{area}{resolution \ element} \right\}$$

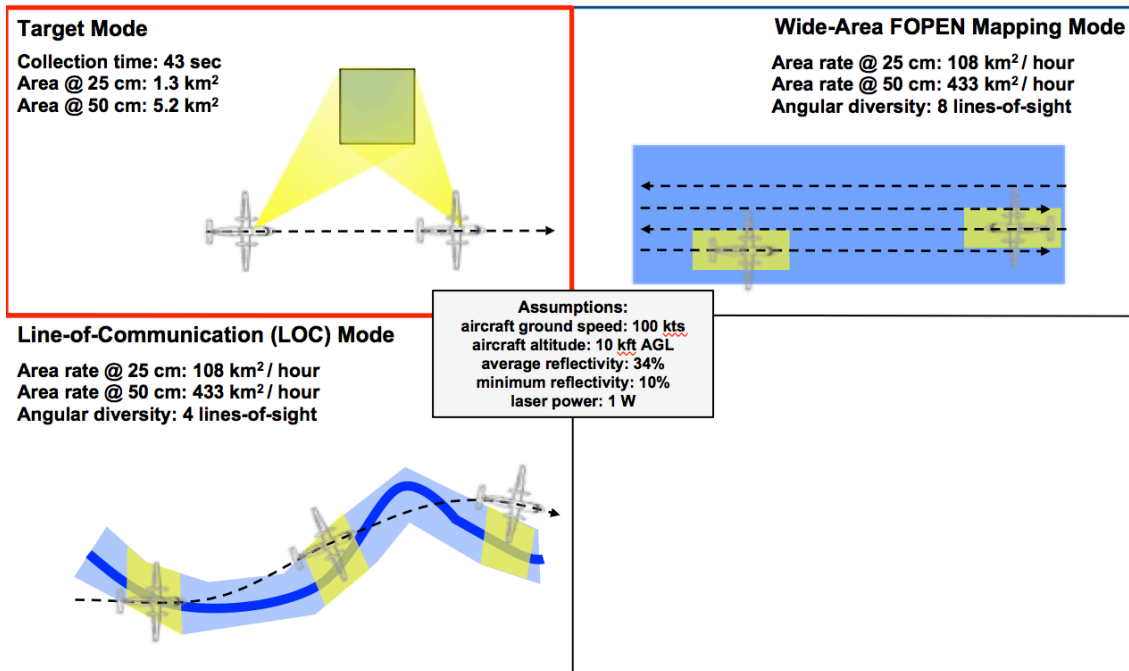


Figure 5 - AOSTB Scan Modes and ACR Calculations

8.2.1 Laser Subsystem

The laser used on AOSTB (Figure 6) is a 1 Watt, 1064nm, passively Q-switched, Nd:YAG laser, built at MITLL, originally for use on the ALIRT platform. The laser is constructed by bonding thin pieces of Nd³⁺:YAG gain medium to thin pieces of Cr⁴⁺:YAG (saturable absorber). The crystals are directly coated with dielectric material, with the input side to the gain medium coated to be highly transmissive for the pump wavelength of 808nm, and to be highly reflective at the laser oscillation wavelength of 1064nm.⁷ With the pump diode radiating at 25W, and an oscillator PRF of 15Khz, the resulting beam is linearly polarized and approximately 1W, with a pulse width of 500ns, and operating in the TEM₀₀ (fundamental transverse) mode.

Two 808nm pump diodes (for the oscillator and amplifier) reside in the Transmit Electronics Driver (TED) box along with control electronics. The TED is responsible for controlling the thermoelectric coolers (TECs) on the oscillator and amplifier, as well as the currents applied to them. The TED optically triggers the pump diodes at a pulse repetition frequency (PRF) that is defined by an external pulse generator. First, an amplifier pump pulse enters the lower amplifier assembly of the laser, and begins to build up energy. After a short delay, a second pump pulse enters the top portion of the laser assembly. The oscillator pump pulse excites the Nd:YAG microchip laser oscillator, which absorbs the 808nm light and emits a 1064nm pulse. This pulse travels through a

⁷ Mid- and High-Power Passively Q-Switched Microchip Lasers, Zayhowski, 1999

set of optics into an inline amplifier, which is seeded by the same 808nm pump pulse that is transmitter through. The majority of the output of the amplifier travels through a roof prism to the lower secondary amplifier assembly, while a small amount of it is picked off and measured for determining whether or not an oscillator pulse fired on time, or whether it timed out. Because the energy in the amplifier is building, in the event that a timeout is detected, the TED inhibits the next pump pulse, which protects the amplifier from overheating, and allows the excited electrons to decay. If the amplifier were allowed to continue to build energy, we would risk cracking the crystal and damaging the amplifier.

Though ALIRT had two physical lasers, each operating at 7.5KHz to achieve a combined PRF of 15KHz, the team was able to reliably run a single laser at 15KHz. This was accomplished by adjusting current and thermal parameters of the oscillator and amplifier on the TED, and resulted in reduced SWaP requirements while achieving the same power output.

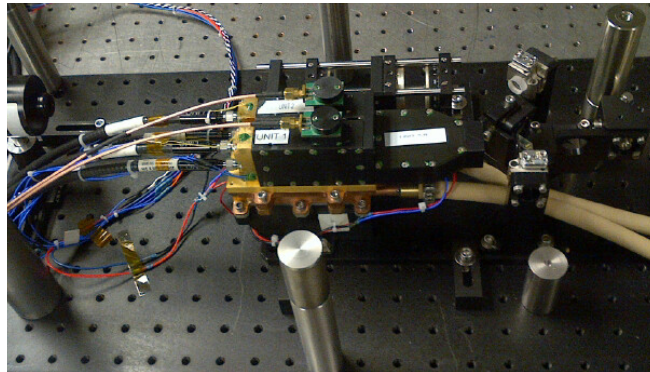


Figure 6 - Laser on optical bench

8.2.2 Detector Subsystem

The detector consists of an array of 64x256 (16,384) Avalanche Photo Diodes (APDs) that are mated to an array of CMOS circuitry, which digitally encodes the time of arrival of each photon. Each APD device is fabricated on an InP substrate by creating an InP multiplier layer and an InGaAsP absorptive layer. The device is then etched to create mesas, and an electrical contact is made to the top of each mesa. The detector is operated in what is called, “Geiger mode”, which means that it is operated at a few volts above breakdown. The breakdown voltage is the voltage at which the multiplicative gain matches the carrier recombination rate. When an incident photon hits the substrate, it generates carriers in the absorber. A small current sweeps the carriers into the avalanche region, where the electric field is so high that the multiplication rate overwhelms the intrinsic carrier loss rate, so the electric current grows exponentially. A single generated electron-hole pair is enough to trigger an avalanche, which persists until the self-capacitance of the APD is discharged, and its bias voltage falls back to the breakdown voltage. Although the digital readout is noiseless, thermal fluctuations can

similarly generate carriers in the absorber, which can register as false detections. These false detections establish a noise floor known as the dark count rate, which is discussed later in this section.⁸

Once the APD is discharged, the time it takes to re-arm the self-capacitance is known as dead time, which is a significant limitation of these devices. The benefit of using these detectors is that they are sensitive enough to detect single photons, and can be used to directly trigger digital readouts. Because of their small footprints and simple circuitry, large arrays can be fabricated. Compared to linear mode lidar, the significantly higher increase in detector sensitivity enables higher area collection rates (ACR), lower overall costs, and the ability to perform foliage penetration.

8.2.3 Pointing Subsystem

The pointing and scanning system used on AOSTB consists of a high performance scan mirror assembly (RSMA), a custom scan mirror control generator (SMCG), and a GNSS unit built by Applanix. These legacy systems were originally developed for the ALIRT program, but have been incorporated into the updated AOSTB platform. In order to optimize the scanning capability for foliage penetration (FoPen), as opposed to mapping, the x- and y- axes have been rotated by 90 degrees about the z-axis. This rotation takes advantage of the increased maximum acceleration about the short axis of the mirror, and allows the sensor to achieve a larger number of “looks” over a target. Each “look” of the target is a single sinusoidal scan pattern that travels once across the target (typically from a 250x250m to 1x1km box on the ground). With the increased looks that the sensor can achieve, we can obtain the angular diversity of reflected photons that is required for foliage penetration. These physical modifications also required some extensive software modification to our SMCG.

The SMCG records the GPS position from an Applanix GPS/IMU and precise RSMA angle encoder values corresponding to where the scan mirror is pointing for each frame of range data. In order to be able to match the timestamps between the scan system and detector system, the team used the GPS’s TTL pulse-per-second (PPS) signal as a synchronization pulse, and used internal high-frequency oscillators on the SMCG and GMAPD FPGA for further precision.

8.2.4 Hardware Racks and Integration

With the original goal of enabling a roll-on/roll-off sensor capability for multi-sensor fusion, the team had to address the problem of space and power constraints on a DHC-6 Twin Otter aircraft. A Twin Otter aircraft was chosen as the operating platform of choice due to its relatively low cost, its 36”x23” hole in the bottom of the fuselage (wildcat hole), and ease of integration into an unpressurized cabin. Though the aircraft does have many limitations, such as limited range, speed, and not being pressurized, it is an excellent

⁸ https://www.rp-photonics.com/avalanche_photodiodes.html

platform for budget conscious research projects. Specifically for ladar, the slow speed of the aircraft allows the sensor to achieve an increased number of looks over a target as the aircraft passes over it, resulting in higher point densities in the generated data products.

The aircraft provides two 2300W power inverters, and enough space to position an optical bench and up to 2-3 racks, depending on rack configuration. Due to space and power constraints on a Twin Otter, our goal was to consolidate as much of the hardware as possible into a single rack, and install a second empty rack that would be made available for the hardware of a second or third sensor. A block diagram of the system can be seen in Figure 7.

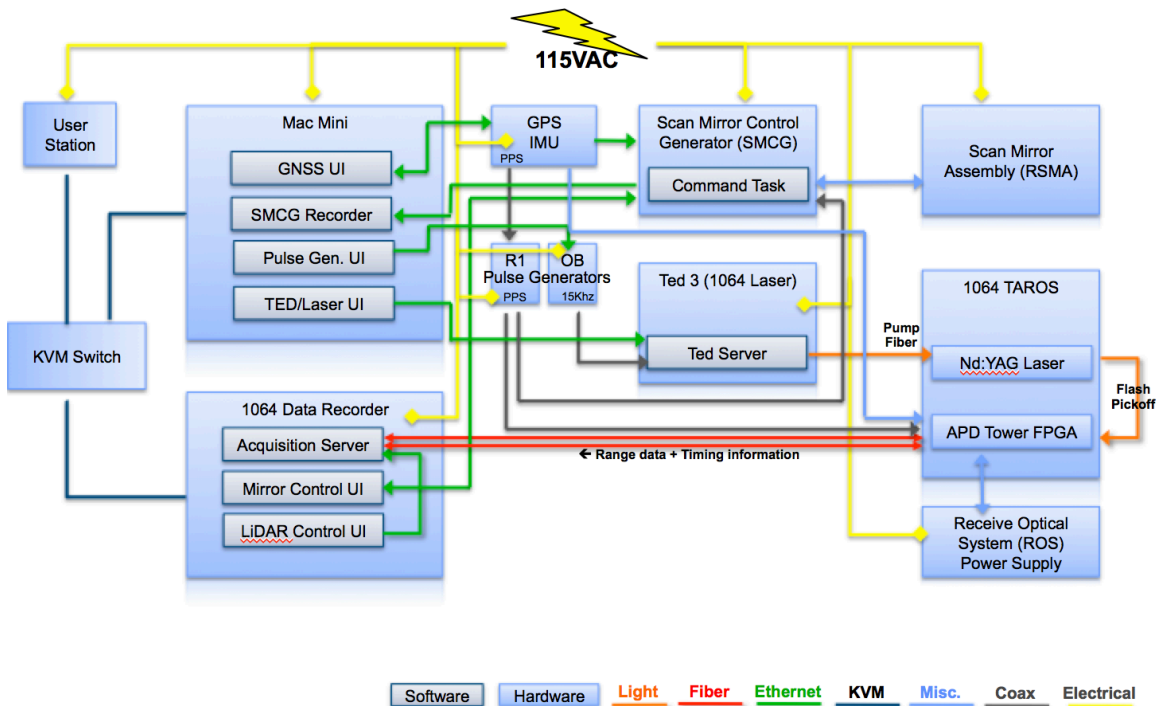


Figure 7 - AOSTB Ladar Schematic

The ladar system consists of the ladar sensor (situated on a 64x40x6in custom optical bench) and an electronics rack. The electronics rack houses: a data recording server, an Applanix POS AV GNSS unit; a BAE scan mirror controller (RSMA controller), a custom-built scan mirror control generator (SMCG), a 1GbE network switch, a Mac Mini computer for laser control, the receive optical system (ROS) power supply, a two-port KVM, a K-O Concepts DMC-14 chiller for cooling the laser and detector subsystems, and an LCD display for the operator. The data recorder / acquisition server (DR) has a built-in 4.5TB of local storage that doubles as a storage device for the recorded raw range data, which allowed our team to leave off an additional external storage device, and ultimately save 2U worth of space in the rack. The data are recorded at ~250MB/s, and typically total 0.5-1.5TB per sortie. Offloading data is performed by physically

removing the three data drive sleds, or by copying to an external drive via USB3, Ethernet, or MiniSAS. The server also contains all the software for controlling the interface adapter board (IAB), the readout electronics module (REM), and the SMCG.

The Applanix POS AV GNSS system is responsible for providing position and time data to our SMCG, as well as a GPS time source for our IAB. It is also responsible for triggering a pulse generator with a 1 pulse-per-second (PPS) TTL signal, which synchronizes the SMCG with the detector control system (IAB).

The optical bench hardware consists of a 1064nm TED laser driver, a Honeywell IMU, the fast scan mirror assembly (RSMA), a TX/RX covered enclosure, with the laser and detector separated by a baffle, and various optical components including a safety shutter.

A CAD model of the system, as integrated onto the optical bench, can be seen below in Figure 8. The rear of the optical bench is elongated to accommodate a secondary sensor payload (shown as an orange envelop in the figure below).

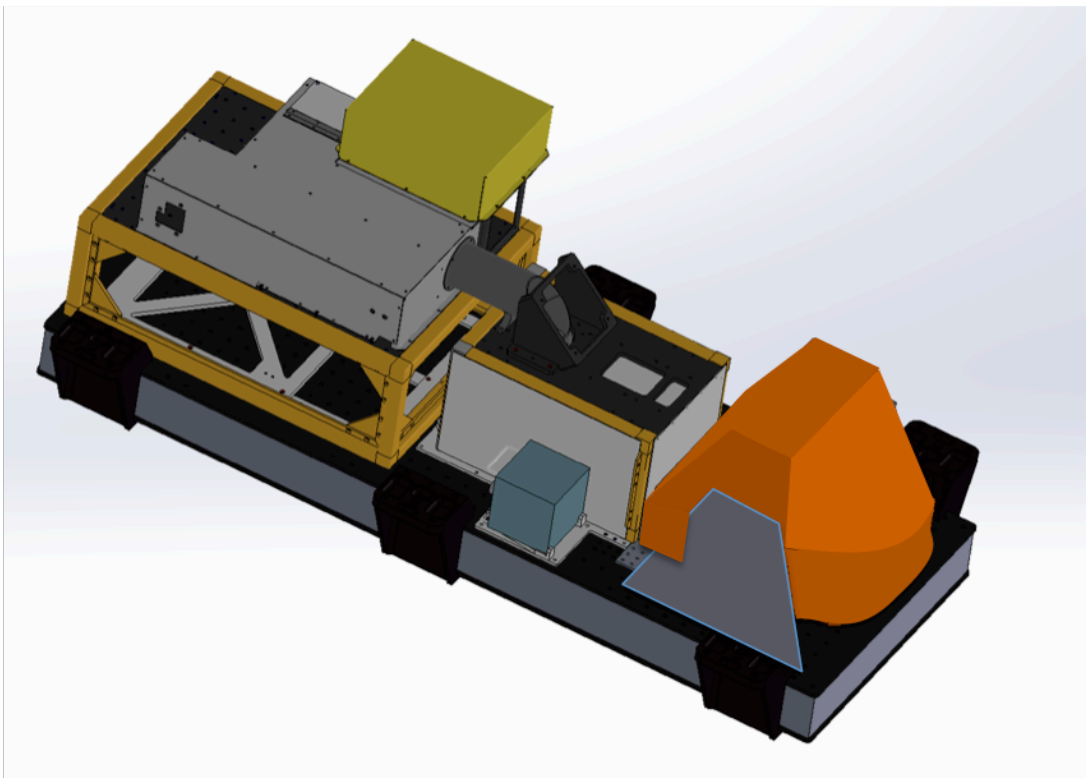


Figure 8 - CAD Model of AOSTB + Secondary Sensor

8.2.5 Optical System Design

The laser exits the enclosure through a 10cm aperture, off of a gold-coated broadband mirror, and is directed by a periscope downwards and to the RSMA scan mirror. A safety shutter exists on a motorized flip mount, which can be flipped into the beam to prevent the beam from exiting the enclosure, and rerouting it to a power meter. The returning light is collected by a custom-built centrally obscured telescope assembly and focused onto the detector array by adjusting the spacing between a pair of achromatic lenses using a micrometer stage. The ability to easily adjust the focus with the micrometer stage made it easy for the team to switch between imaging targets at a 90-m range (in the near field), as well as adjusting for flight altitude (far-field). For daytime flights, an additional filter is inserted before the focusing lenses in order to reduce the amount of solar background noise, and maintain a high SNR. The spectral filter that we used for this was a 1nm FWHM narrowband optical filter, with a peak transmission of 80% at 1064.5nm. This filter reduces the amount of background incident onto the GMAPD during daytime measurements, but can be removed for nighttime collections. The laser and detector subassemblies are situated inside an enclosure equipped with temperature and humidity sensors. Dry air is also directed into both the TX and RX sides of the enclosure through a tube of desiccant, in order to control the dew point inside the enclosures. The optical design can be seen below in Figure 9.

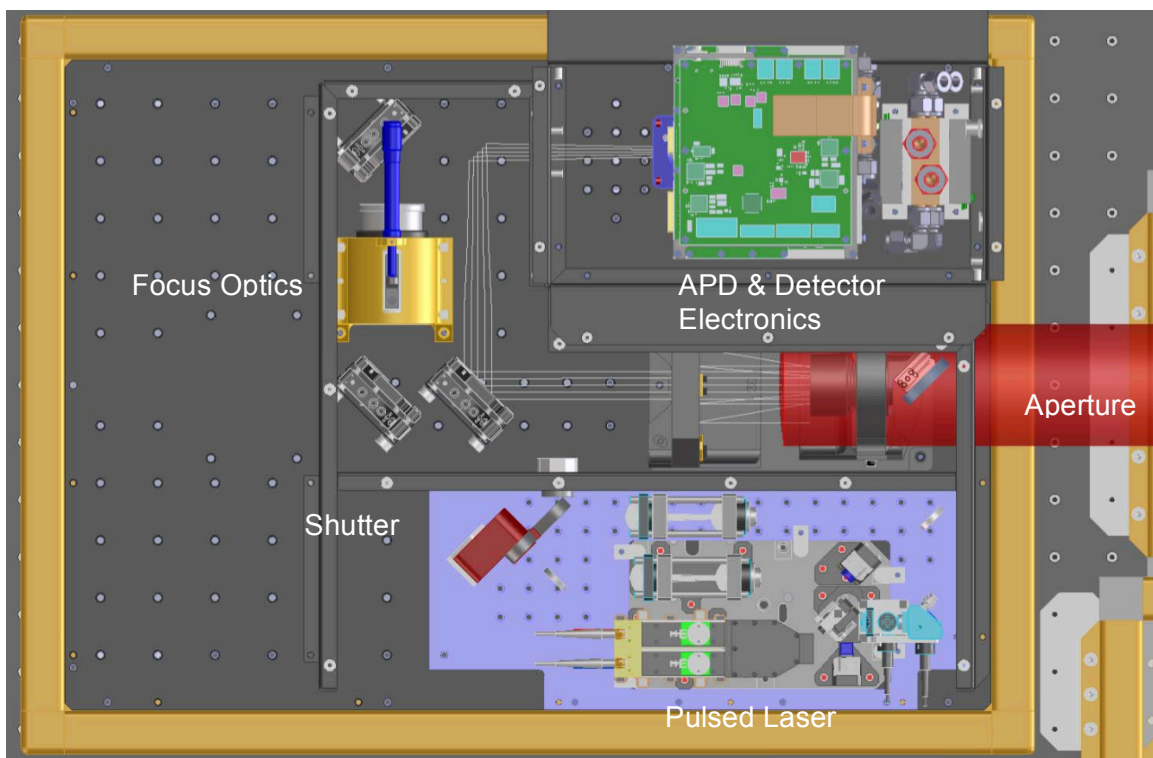


Figure 9 - Optical Layout of the AOSTB Ladar

8.3 Scientific Principles Applied

High power lasers, photon-counting detectors, and precise pointing and scanning systems are some of the key technologies that enable this new generation of lidar sensors. Conceptually, a high power laser sends out fast, short pulses of light that flood illuminate a scene on the ground at a rate of many thousand pulses per second (15Khz). As soon as the laser sends out a single pulse, a focal plane array of timers, which make up the detector, start their clocks. In the time between pulses, the laser light travels down to the illuminated scene, partially reflects back (amount reflected determined by surface reflectivity), and is detected by the individual photon-sensitive avalanche photodiodes (APDs). As soon as a photon detection is made, the timer stops and records a “time-of-flight” or “round-trip-time” for the photon. This array of data is then written on a per-pulse basis as a “frame” of range data, with range extrapolated from the time-of-flight data (using the known speed of light), and each detection corresponding to a pixel within that frame. Because the data readouts are synchronized with the laser pulses, the data are recorded at the same rate of 15Khz. Frames are then aggregated together to determine whether a certain pixel’s detections are statistically significant to indicate returns from a surface, or indicative of false detections below the noise floor.

In order for such a lidar system to be useful, we must also have the ability to steer the pulsed laser beam to illuminate various targets that may be under or around the aircraft. The pointing and scanning system enables fast and precise control of a scanning mirror, and allows us to maximize area coverage rate (ACR), as well as perform foliage penetration (FoPen) by obtaining multiple views of the same scene from different view angles. The precise pointing direction of the mirror is digitally encoded using rotary encoders on two axes, and recorded along with the precise GPS coordinates for each frame of range data. The separate streams of position, pointing, and range data, known collectively as L0 data, are fused together, while being separated into smaller tiles (for parallel processing), in order to create “angle-angle-range” files, which are known as L1 data. This L1 data is fundamentally a 3-dimensional product, however contains a large amount of noise from false detections, mostly thermal in nature. The angle-angle-range data then goes through a series of algorithms, such as coincidence processing (the algorithm that determines which recorded values have a high probability of coming from an actual surface vs. being noise), and eventually produces a clean 3-dimensional data product known as L2. Finally, the tiles of clean point clouds are intelligently aggregated and geo-registered to each other in order to create large 3D point clouds, known as L3. Depending on the specific customer requirements, the L3 products can be further analyzed or filtered to produce custom data products that may contain information such as flood maps, helicopter landing zones, etc. These finished and analyzed products are known as L4 products. A diagram of the various levels of data processing can be seen below in Figure 10.

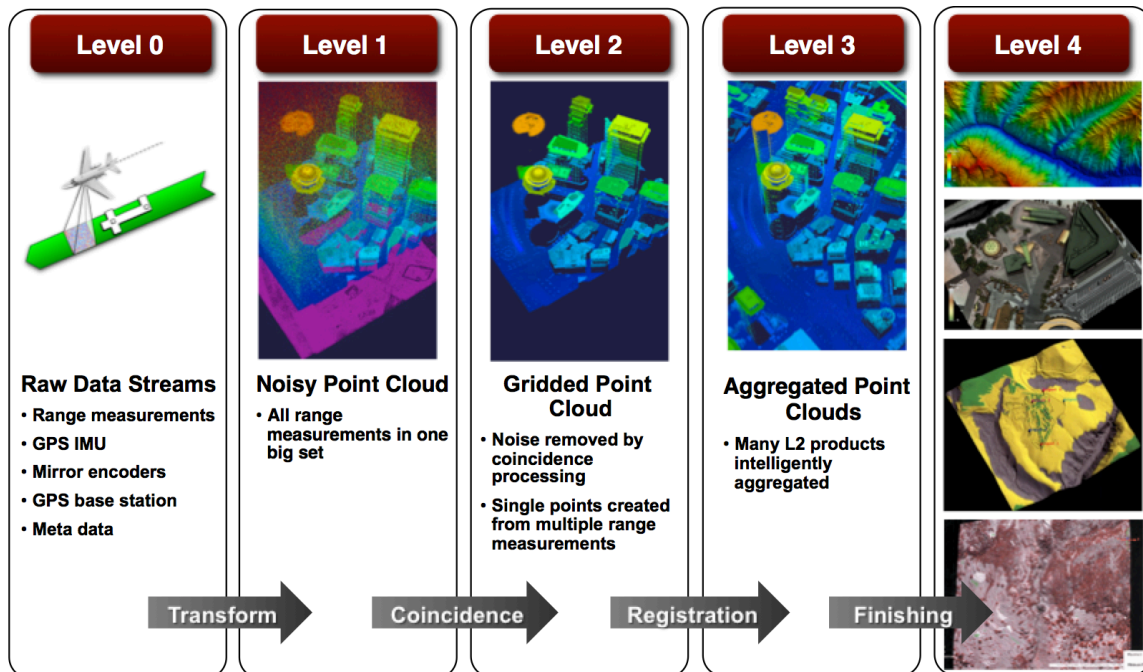


Figure 10 - Data Processing Levels

The scope of this challenge project involved studying the underlying scientific principals of this technology in detail, and the deliverable was the creation and integration of a photon-counting lidar into an airborne platform, alongside a sponsor-provided secondary imaging sensor. The scientific principals that were further assessed, analyzed, learned, and mastered, involve optics and E-M waves (for understanding beam propagation and laser link budget), quantum statistics (used for understanding the detector array), and to a lesser extent, rotated coordinate systems (for manipulating the pointing and scanning system), frictional forces, rotational motion, and elasticity (for analyzing strain and stresses on the equipment racks and hardware in flight).

9 TECHNOLOGY APPROACH AND RESULTS

9.1 Development Approach and Methods

The first step was to start building the lidar sensor in a laboratory environment and to get it to a working state while on the ground and in an accessible lab space. A model of the sensor (Figure 8) was first created in CAD and analyzed for flight, which included finite element analyses (FEA) of the vibration isolators and mounting plates (Figure 11). Though not shown, all mounting hardware was analyzed through FEA to ensure that it would be able to withstand a 9G forward crash.

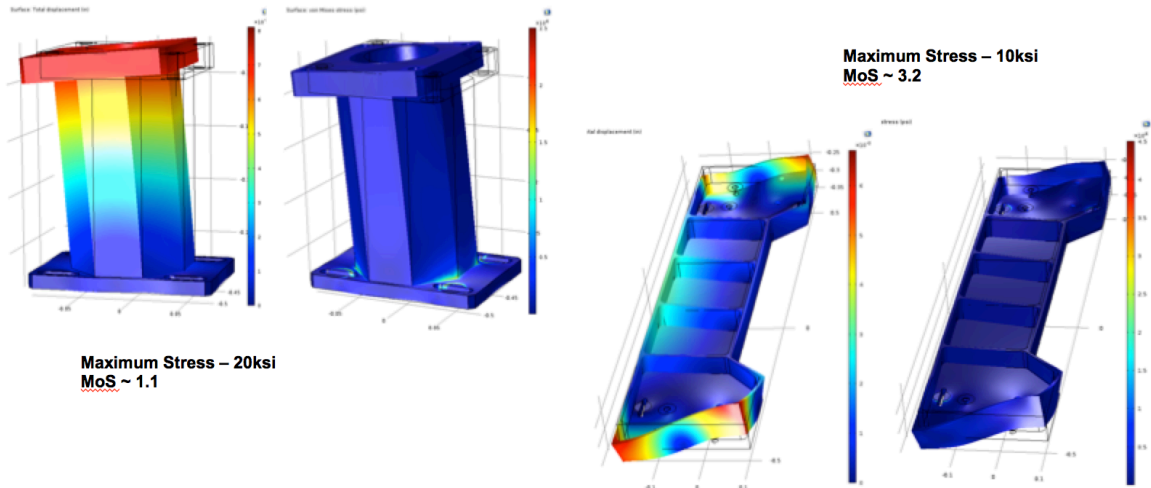


Figure 11 – Finite Element Analysis of Loads on Isolators (9G Forward)

Building the sensor involved modifying certain hardware components and making them compatible with legacy and/or newer hardware. One example is the modification of the Interface Adapter Board (IAB) FPGA, which we obtained from a spare of another sensor, to accept the GPS and timing inputs from a legacy GNSS. The firmware was specially modified for this purpose, and an RS232 connector was soldered to provide the hardware interface. The Scan Mirror Control Generator (SMCG) also had to be modified to account for the scan mirror’s rotated coordinate plane, which was offset by 90° about the Z-axis from the way it was mounted in its original configuration on the legacy ALIRT sensor.

A second pulse generator (depicted as R1 in Figure 7) was added into the schematic to provide a 5V TTL synchronization pulse to the SMCG and IAB, which ensured that the scan frames would align with the range data frames.

One of the team’s development and integration constraints was to preserve the current state of the laser, as installed on an optical breadboard, with all of its affixed optics intended for the ALIRT sensor. Taking this constraint into consideration, we installed the entire laser breadboard into our setup, and through various folding and beam-shaping optics, were able to route a properly shaped beam through our aperture (Figure 9). The beam shape was such that it expanded at an angle that matched the IFOV of the detector array (4-to-1 aspect ratio). It was important to not have the beam expand too fast to avoid losing photons outside the IFOV of the detector. Similarly, it was important to not have the beam be too narrow, to avoid a poorly illuminated scene, and a partially saturated detector.

Another important consideration for our design was the desire to have a safety shutter and power meter. A safety shutter was built in and wired such that both sensor operators and pilots had emergency switches that would flip the shutter into a blocking position in case of an emergency. The shutter consists of a motorized flip mount with a flat mirror

that is out of the beam path for propagation, and in the beam path when blocking. With the mirror blocking propagation, the beam is redirected into a power meter, simultaneously satisfying both of our design requirements.

9.2 Testing, Verification and Validation Implementation

Once built, the lidar sensor was tested and calibrated on the ground, prior to integrating into the aircraft, in order to ensure that time on the aircraft and/or flight time is not wasted. Care had to be taken with the optical pump fibers to preserve the polarization state required for the oscillators. Once an optimal position was found for the fibers experimentally, they were tied down to avoid any changes in bend radius, or other perturbations.

Measurements were taken to determine the detector's dark count rate (DCR), per-pixel range bias (range measurement offsets on a per pixel basis), range resolution calibration, angular resolution calibration, and timing synchronization. The DCR was determined by covering up the sensor to block entry of light, and then measuring the rate at which pixels fire on the array. This rate of falsely firing pixels determines the dark count rate and establishes a baseline for false alarm detections. Additionally, it shows which pixels may be stuck firing at all times, which allows us to mask those pixels out and ignore their data. For per-pixel range bias calculations and range resolution calculations, the team set up a flat plate at the end of the lab (>80m away), and measured the precise range from the sensor to the plate with a measuring wheel. We then collected data and applied an overall detector offset to ensure that the reported range value matches the actual range value. This process was also done on a per-pixel basis to address the individual pixel variations, which further ensures that surfaces are recorded correctly. Accurate angular range is dependent on timing synchronization between the detector and scanning system, so it was important to exercise the scan mirror. Matrix transformations were implemented in order to accommodate the different sensor modalities (down-looking and side-looking).

For sensor testing and calibration, various measurements were taken, including dark count rate (DCR) measurements, flat plate measurements, knife-edge measurements, and finally from flight, spatial resolution and pointing accuracy measurements. The DCR was measured by covering the photon-sensitive detector in order to prevent any light from landing on it. With the detector completely covered, it still registered an average rate of detections, or counts. This average rate of false detections, established a noise floor for photon detections (not including background noise). Our measured DCR was 10Khz.

The team also performed range resolution measurements by imaging a flat plate across the full field of view of the detector. The flat plate is set up perpendicular to the beam, and integrated over a number of frames. The photon detections are computed for each individual pixel, which can vary due to some pixels firing earlier than others. As seen in Figure 12, the largest rates of detections come from the actual surface, or flat plate. The

range resolution can also be computed by obtaining the full width at half maximum (FWHM) value of the detection statistics from the flat plate.

With this knowledge, and the known true distance between the detector and plate, we were able to establish an overall range offset for each pixel, as well as a calculated range resolution of 38cm.

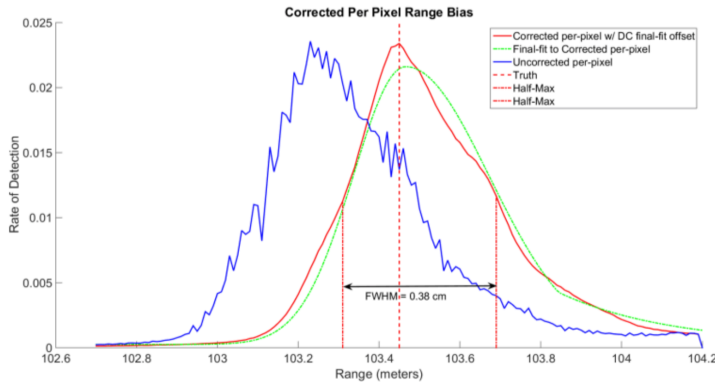


Figure 12 – Flat Plate Measurement

Spatial resolution was measured by flying over a modulation transfer function (MTF) target, shown in Figure 13, that was set up in the parking lot of our flight facility.

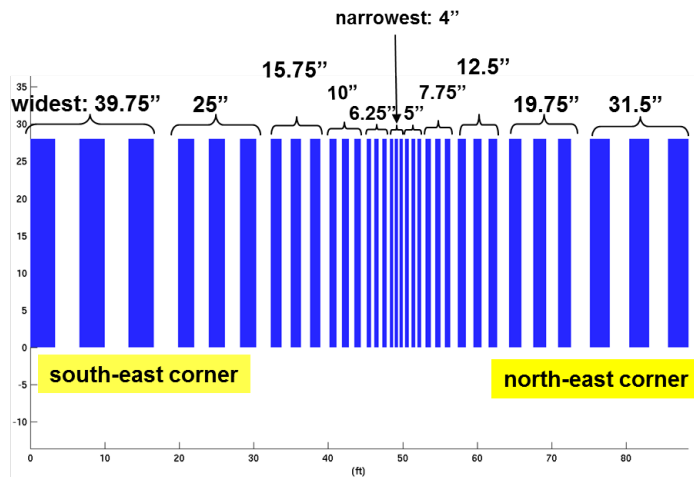


Figure 13 - MTF Target Dimensions

Looking at the imagery collected of the MTF target in Figure 14, we are able to clearly see the separation of bars up to the 9th bar. This demonstrates that we achieved a special resolution of roughly 32cm, though this was not the smallest resolvable object that we were able to make out. We were also able to see the parking lines, which are roughly 10-15cm in diameter, though spaced 1m apart.

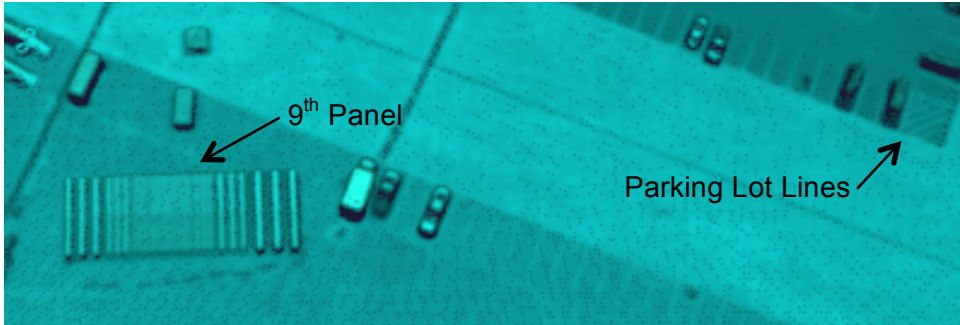


Figure 14 - MTF Target

9.3 Results and Technical Conclusion

For this challenge project, we were able to successfully deliver on developing an Airborne Optical Systems Test Bed with sufficient infrastructure to support a base ladar configuration with ~30cm resolution alongside a secondary sensor. We performed calibration of the ladar sensor, which ensured that our pointing was accurate, timing synchronization was functional, and our spatial and range resolutions were as originally expected. All components were also individually secured and verified through FEA to withstand a 9G forward crash to ensure maximum crew safety. By designing the model to support roll-on/roll-off capability, future programs looking to leverage the AOSTB will be able to use all parts of the ladar and scan system, limited individual subsystems, or simply the general infrastructure to perform data collections with one or more sensors. The team's ability to create this sensor from legacy and spare components proved that we were able to make a low-cost sensor platform that is already being leveraged by external programs for significant cost savings.

9.4 Scientific and Technical Challenges

The major technical hurdles of this project were to successfully produce quality imagery from this collection of spare parts (which was previously attempted unsuccessfully). Since all of the electronics and firmware were custom made for their respective sensors, enabling communication and synchronization was an interesting and predictable challenge. Sensor calibration was also a key technical challenge that was essential to overcome in order to produce good imagery. On the hardware side, in order to reduce SWaP, we were required to consolidate certain hardware components, and minimize the sensor's footprint as much as possible. This was essential to creating the envisioned roll-on/roll-off capability. Finally, in order to maintain crew safety, the system as a whole was modeled and analyzed in order to measure the forces that may affect the hardware in flight.

10 PROJECT PLAN

10.1 Statement of work

The project proposed was an Airborne Optical Systems Test Bed (AOSTB) that would provide The Laboratory with a resident platform, or “facility”, to enable development of novel sensors and phenomenology exploration. In order to successfully build this sensor within temporal and budgetary constraints, the team had to leverage existing sensor spare parts and interconnect them. By the end of the project, we successfully produced nearly 30cm resolution 3D ladar data, and had a number of successful local test flights with a secondary sensor, along with an operational data collection campaign for an external sponsor.

10.2 Schedule

10.2.1 Work Breakdown Structure

WBS	Task Name	Outcome	WBS Predecessor
1	Challenge Project	Roll-on/Roll-off Ladar sensor platform	
1.1	Market Research		
1.1.1	Develop interview questionnaire		
1.1.2	Contact stakeholders	Customer visits	1.1.1
1.1.3	Interview stakeholders	Customer data	1.1.2
1.1.4	Analyze customer data	Customer needs	1.1.3
1.2	Ladar OSTF		
1.2.1	Parts Fabrication	Base plates, ladar enclosure	
1.2.2	Create optical setup	Functional & mounted optical setup	1.2.1
1.2.3	Configure pointing system	Calibrated pointing system that point N/S/E/W and working scan modes.	1.2.1
1.2.4	Configure data recorder	Functional data recorder with required software	
1.2.5	Ladar assembly	Fully assembled ladar sensor ready for debugging	1.2.3, 1.2.4
1.2.6	End-to-end (E2E) testing	Functional ladar sensor ready for aircraft integration	1.2.5
1.2.7	Write processing software	Processing chain that is capable of processing 3D data	
1.4	Twin Otter		
1.4.1	Lease aircraft	Completed and submitted paperwork for aircraft lease	
1.4.2	Perform system analysis	Generate sensor SWaP, CG, weight and balance lists	
1.4.3	Safety + Permissions	Obtain permission from FAA, NavCanada, and EHS to fly	
1.4.4	Aircraft ferry/delivery	Delivered Twin Otter aircraft to Bedford, MA	1.4.1
1.4.5	Sensor integration	Integrated ladar+secondary into Twin Otter aircraft	1.4.4
1.4.6	Hangar testing	Generated ground imagery	1.4.5
1.4.7	Local flight testing	Aligned and focused sensor with generated 3D imagery	1.4.3, 1.4.5, 1.4.6
1.4.8	Field deployment	Generated 3D data products for customers	1.4.7

10.2.2 Gantt chart

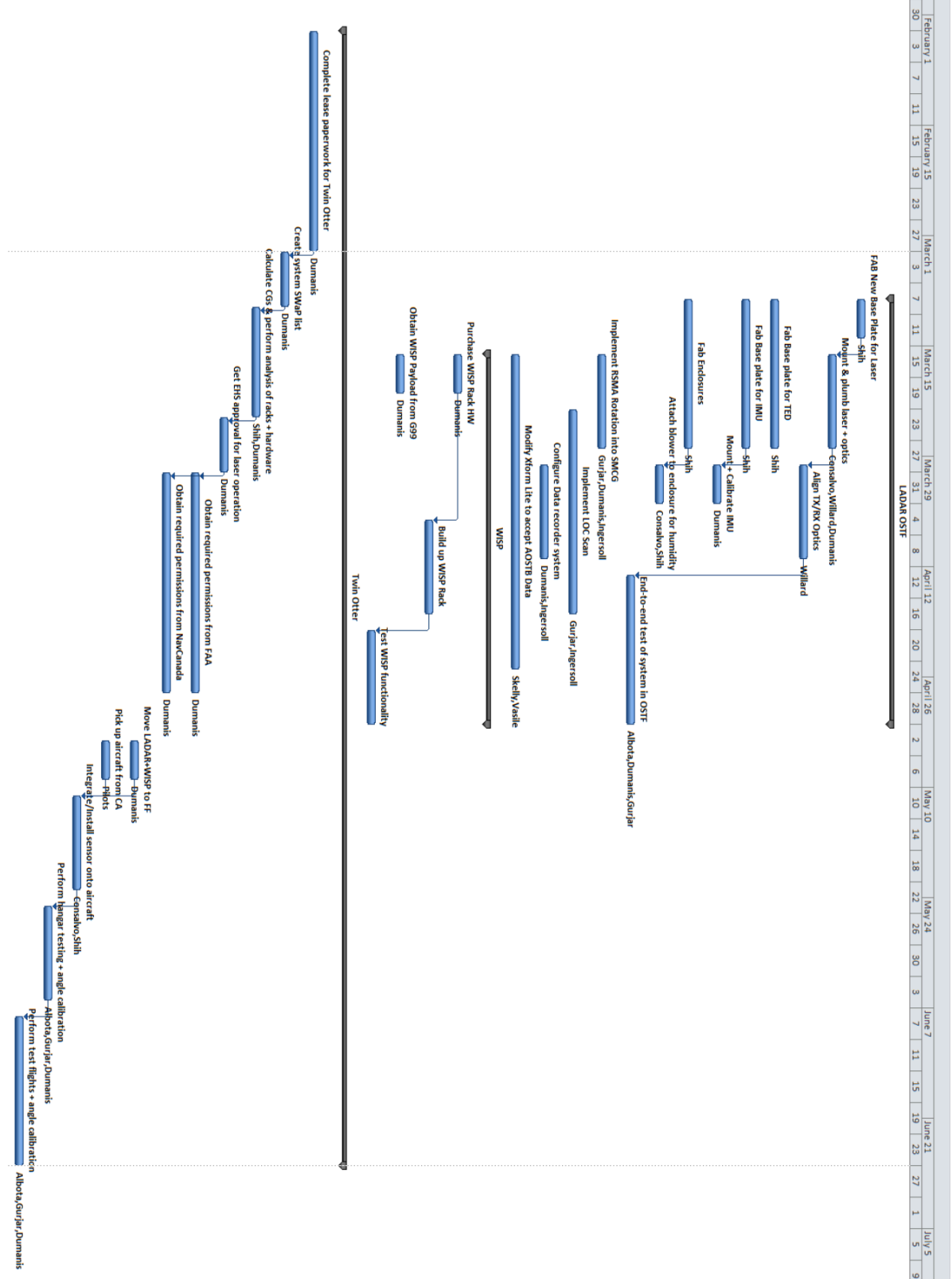


Figure 15 - Gantt Chart

10.2.3 Project Planning Assessment

After the first few weeks of working with other groups, it became apparent that the WISP sensor was committed to another externally funded program, and that we would not be able to use it for this project. A communication breakdown during the very initial project planning stage led to this issue that was ultimately unable to be rectified. This required a change in the scope of the project, and the WISP sensor was removed from plans.

In order to still attempt an integration of a secondary sensor, for the scope of this challenge project, we worked with another group who had a sponsor interested in flying a different type of imaging sensor to produce a fusion data product with ladar imagery. This externally funded project was enabled by the promise that AOSTB would be a reality, and provided funds for the design of our new elongated optical bench. Due to what seemed to be conflicting requirements between this program and other users, we had to organize multiple meetings to objectively look at the requirements, and determine how to proceed. Through the use of decision matrices, I was able to steer the different projects to agree to mutually beneficial configurations. Although I do believe that I underestimated the effort involved (further described in the budget and cost assessment), I am satisfied with the outcome of the project. Important lessons learned were the importance of a program manager being involved in the capture stage of a project, as well as the importance of properly estimating levels of effort.

10.3 Budget and Costs Assessment

The budget estimated to be required for building and integrating the ladar sensor onto a Twin Otter aircraft was \$497,000. This assumed that most materials were available and did not need to be specially procured. Items that did need to be separately purchased (supplies and incidentals) were estimated to cost roughly \$20,000. An overview of the labor time allotments can be seen in Table 16, with a rough estimate of \$25,000 per man-month. Although we were officially under budget (Spent ~\$475K out of estimated \$497K), the tight schedule and short timelines forced us to work longer hours, including some nights and weekends. Ultimately, this suggests an underestimation of resources and time required and is not a sustainable workload balance in the long-term.

Table 16 – Labor Allotments

	March	April	May	June	July	August
Senior Lidar Scientist	50%	50%	70%	20%	20%	20%
Senior Opto-Mechanical Manager	40%	20%	35%	0%	0%	0%
Optical Engineer	20%	10%	10%	0%	0%	0%
IT Systems Specialist	20%	20%	0%	0%	0%	0%
Lidar Scientist	40%	40%	40%	20%	20%	20%
Program Manager	30%	30%	50%	20%	20%	20%
Lead Technician	20%	20%	50%	0%	0%	0%
Assistant Technician	25%	25%	0%	0%	0%	0%
Computer Scientist 1	0%	10%	10%	10%	10%	15%
Computer Scientist 2	0%	15%	0%	0%	0%	0%
Data Analyst	0%	0%	0%	0%	50%	50%
Flight Facility	0%	0%	100%	0%	0%	0%

10.4 Risk Plan and Mitigation Assessment

Risk	Risk Level	Actions to Minimize Risk
-Insufficient resources to complete tasks	Medium	-Plan ahead and engage group leadership support early on -Meet with all team members early on to help them plan time and schedules in advance
-Unable to meet timeline	High	-Separate out hardware/software tasks and work on in parallel. -Dependent on all other risks
-Can not make components interoperable	Low	-Firmware has been verified modifiable, and only issue may be timing. If necessary, synchronize with external pulse generator.
-Can not produce 3D imagery	Medium	-Ensure adequate resources allocated to software tasks well enough ahead of time -Collect ground imagery and provide to software team as early as possible
-Damage to sensor through user error	Low	-Create standard operating procedure to mitigate risk by operator error
-Scan mirror damaged by flying debris	Low	- Install scan mirror recessed enough into the window that avoids debris trajectories -Took advantage of new bench to design protective cover

11 LEADERSHIP

The GEL challenge project has pushed the boundaries of my previous roles at The Laboratory, and required that I work more directly with group leadership and management. Over the course of the project, I demonstrated leadership qualities by leading the project from the initial planning stages through success. I demonstrated initiative through starting the GEL program and having an initial conversation with my group leadership about this, but success required resourcefulness and actionable goal setting in order to realize the vision. The project challenged me in connecting across multiple disciplines, communicating effectively, and showing the courage to take charge. I was responsible for critical decision-making, and had to maintain the trust and loyalty of my team, despite being the least technically educated and youngest person on it.

11.1 Leadership Capabilities Assessment

When completing the spider chart assessment in the beginning of the year, I identified three skills that I would most like to improve: Communication and Advocacy, Inquiry, and Realizing the Vision. In working on this project, I increased my leadership core competencies and improved in all aspects, as depicted in Figure 17 below.



Figure 17 - Leadership Spider Chart

11.1.1 Communicating and Advocacy / Interpersonal Skills

This project required acknowledgment of feasibility, and buy-in from all parties. Due to the previous failures of AOSTB, many key stakeholders harbored negative associations with the concept, and were hesitant to commit themselves. I needed to clearly communicate to the team, as well as the stakeholders, why this renewed effort would be successful. I organized and led monthly stakeholder meetings, which kept all of the stakeholders apprised and interested, in order to partially address this goal. My age and relative inexperience was a significant hurdle to gaining my team's confidence.

11.1.2 Inquiry

In the past, I have hesitated to ask questions that make me sound inexperienced, thus inquiry was an important leadership challenge for me to work on. Situational awareness was also critical to asking relevant questions that led to good decision-making. This required leaning on more senior team members with significant experience. Additionally, I strived to make myself available, and encourage inquiry within the team as much as possible. One of the central goals of the project was to regain institutional knowledge in lidar systems, which required extensive teamwork and knowledge sharing.

11.1.3 Realizing the Vision / Resourcefulness

Developing a vision has always come easily to me, but realizing it has been a challenge. While the vision and end goal were fairly clear, when certain issues arose, it took resourcefulness and determination to circumnavigate obstacles. My role as program manager was central to enabling my team members to complete their work in the face of any challenges that surfaced. Our successful outcome depended on my willingness to confront and deal with uncomfortable situations, such as seemingly conflicting program requirements. Leveraging some of the product development tools learned in class, such as decision matrices, I was able to facilitate objective discussions that helped all parties achieve optimal configurations and schedules.

11.1.4 Negotiation and compromise

In order to establish a base for negotiation and compromise, I had to show that as a program manager I had my team's back, but was also objective in discussing various program needs. There was a widely held opinion that our group was difficult to work with, and so I took it upon myself to dispel this notion. There was a set of discussions held over the course of weeks about where on the optical bench to install middle bench legs (structural vs. functional). This decision had two groups heavily debating with no end in sight, and so I volunteered to get in the middle of this debate, and hold an objective discussion with the goal of coming to a decision by the end of the meeting. Using decision matrices learned in product development class, I came into the meeting with a clearly defined meeting goal of objectively coming to a decision within the hour. As a team, we finished populating the decision matrix that I had started. Although the decision was not made right then and there, it provided group leaders the objective inputs they required to reach the decision within minutes after the discussion.

11.2 Team staffing and organization

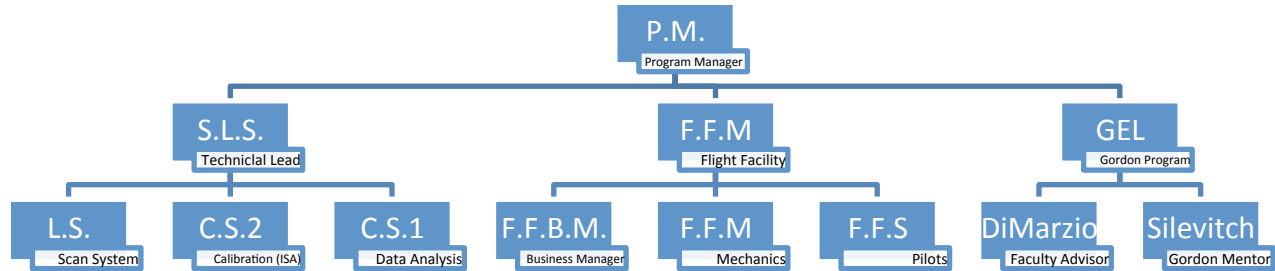


Figure 18 - AOSTB Organizational Structure

The project team consisted of a few core team members, and a much larger extended team. As Program Manager (PM), I was responsible for all day-to-day operations, scheduling, budgeting, and key decision-making. I was also the point of contact (POC) between the various team members and upper management, as well as the POC with all the stakeholders. The sub-teams were characterized as technical (sensor and software), and flight facility (maintenance and pilots).

11.2.1 Technical Sub-Team

Marius Albota was selected to be the Technical lead on the project, since he had the most experience, of the remaining staff, working with Geiger-mode APDs and laser systems in general. He has a lot of technical depth when it comes to the individual ladar components, but has not worked with them much as a system. Though I was the least technically educated person on the team, I had the most experience of anybody with ladar systems as a whole, so was very heavily involved on the technical sub-team, as well as the overall management of the project. Tina Shih was asked to lead the engineering design portion of this project, and brought years of experience in design work to the team.

11.2.2 Sensor Team

Under the sensor portion of the technical work, Rajan Gurjar was heavily involved in scan system operation and modification, and was responsible for putting in new scan modes (map-mode, LOC, etc), as well as optimizing scan parameters. Rajan also helped out in overall sensor testing and fine-tuning, was one of the sensor operators in flight, and was my ISA for the project. Anthony Mangogna was also an invaluable asset on the program, and helped with all stages of ground testing, aerial data collections, and post-flight data analysis.

11.2.3 Software Team

The software team consisted of a few key software players in our group. Luke Skelly is the lead software engineer in our group, and was responsible for writing most of the back-end transformation and processing algorithms that are used by our lidar sensors. He made modifications to his code in order to accept the hardware variations we implemented, as well as the modified optical geometry. Luke was an invaluable resource and team member for this project. Similarly, Alexandru Vasile is another key software developer in our group, and is the author of numerous coincidence processing algorithms and near-real-time processing chains. His expertise in sensor calibration also proved critical for the project. Alex is a PM for another program that ultimately envisions leveraging the AOSTB platform for their testing.

11.2.4 Project Team

Gordon Candidate: Daniel Dumanis (Program Manager)

ISA: Rajan Gurjar

Gordon Mentor: Michael Silevitch

Faculty Advisor: Charles Dimarzio

Others: M.A (Tech Lead), R.G (Scan system work and operator), P.C. (Technician), T.S (Engineering), B.W (Optics), K.I (Software), L.S (Data Processing), A.V (Calibration), A.M. (Data analysis and operator)

12 SUMMARY

With the AOSTB challenge project, the team successfully completed our objective of creating a resident airborne test platform with a fully functional lidar sensor. Various modern and legacy components were combined, made compatible, and integrated into a Twin Otter aircraft, which made over \$3,500,000 in lidar technology available to the wider Laboratory community for development of novel sensors and phenomenology exploration

This AOSTB “facility” is equipped with basic infrastructure (power, cooling, optical bench, racks, etc.) to support ‘roll-on, roll-off’ capability of different sensors at low cost and modest time frames. Additionally, a key unique Lincoln Laboratory developed technology, the Geiger-mode 3D imaging lidar (based on the MACHETE design), is integrated and made available as a roll-on/roll-off capability as a laboratory-wide asset to support both internal and external efforts. This test bed facility is the airborne counterpart to the highly successful and highly utilized infrastructure asset known as the Optical Systems Test Facility (OSTF).

The engineering development of this project was broken down into hardware and software challenges that were executed in parallel in order to satisfy our short timeline. The technical challenges of this project involved 1.) creating a usable and functional optical design, 2.) designing the core sensor payload with minimized SWaP, 3.) modeling the sensor payload and verifying flight-worthiness, modifying the scanning system to accommodate various orientations and new scan patterns, 4.) producing high-quality data products and 5.) performing various sensor measurements and calibrations to produce high-quality 3D imagery.

The project challenged me as a leader, and required me to connect across multiple disciplines, communicate effectively, and to show the courage to take charge. I was responsible for critical decision-making, objective compromising, and maintaining the trust and loyalty of my team by never compromising my integrity, or my team’s safety.

12.1 Recommendations for future work

A path forward for AOSTB includes upgrading some of the legacy hardware, including a more powerful laser, an updated SMCG, and an optical window to seal the cabin and allow for comfortable winter flights. Ideally, such a platform can be leveraged for humanitarian aid and disaster relief missions, which would require a faster and more capable platform. As technology evolves, the capabilities available on this laboratory test bed will have to evolve with it, if the platform is to remain a relevant and important asset to The Laboratory.

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