A Comparative Study of Single and Dual-Wavelength Laser Doppler Vibrometry for Speckle Noise Reduction in Real-Time Dead Reckoning within GNSS-Denied Environments

Research Proposal

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Course:
41029 Engineering Research Preparation

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Date:
18th May 2025

Contents

Introduction

Accurate navigation in Global Navigation Satellite System (GNSS) denied environments is a significant challenge for industries in mining, military operations, and civilian navigation, where reliable positioning and navigation is essential. In these scenarios, Inertial Navigation Systems (INS) use dead reckoning to navigate, but suffer from drift over time without GNSS correction due to unavoidable sensor errors. To address this limitation, Laser Doppler Vibrometers (LDVs) have been explored as a high accuracy velocity sensor that can mitigate this drift. Despite their accuracy, their effectiveness is still degraded due to speckle noise, particularly during continuous movement. To combat speckle noise, dual-wavelength LDV systems have been developed and show potential for speckle noise reduction in laboratory settings, but their real-time performance in dynamic environments remains underexplored.

The research proposed in this report will compare single and dual-wavelength LDV systems for real-time dead reckoning, evaluating their effectiveness in speckle noise reduction and navigation accuracy within GNSS-denied environments. The report includes an analysis of previous research into these topics, highlighting gaps in the literature and giving necessary background to show its significance in mining, military and civilian applications. From the literature review, a research question and sub questions has been developed, with a research methodology and timeline proposed.

Literature Review

This literature review aims to explore the breadth of existing knowledge on INS in combination with LDV's for enhancing velocity and displacement measurements in GNSS denied environments. It examines current research on both INS and LDV individually, as well as studies that integrate these technologies, to identify prevailing methodologies, technological developments, and gaps in the literature.

This review does not aim to provide a comprehensive historical overview of INS, GNSS, LDV, nor does it cover the full range of available technologies. For a more detailed background on these topics, the reader is referred to [1] [2] .

INS and Dead Reckoning

INS enable users to estimate their position and navigate from one point to another using dead reckoning [2].Dead reckoning is the process of position estimation relying on a known initial position, along with continuous measurements of velocity, heading, and elapsed time to update the position incrementally [2] [3]. This allows for position tracking relative to a known starting point without the need for external references such as GNSS or visual environmental features.

INS incorporate Inertial Measurement Units (IMU), which consists of various sensors, commonly accelerometers, and gyroscopes, paired with others depending on the specific implementation [3] [4]. These sensors typically measure linear acceleration and angular velocity, providing the motion data required to perform the calculations for estimating position and orientation. High-frequency updates, often in the range of hundreds to thousands of times per second, enable real-time navigation depending on the device specifications.

However, a significant limitation of inertial navigation is the phenomenon of 'drift', where minor sensor errors accumulate over time, resulting in increasingly inaccurate position estimates [5] [6]. This drift leads to large deviations in positional accuracy over long-duration trips especially for low-cost INS units with worse accuracy. This is where the need for high resolution measurement devices such as LDV are needed to reduce the growth of positional error over time.

GNSS and its role

GNSS offers continuous, low-accuracy (typically within a few meters) 3D position updates under all weather conditions and at all times, without experiencing drift. When combined with an INS, the two technologies complement each other effectively, each compensating for the other's limitations. While INS delivers high-accuracy measurements over short durations but suffers from drift over time, GNSS provides long-term stability with lower precision [4]. Together, they enable highly accurate, drift-free navigation, with positional estimates reaching centimetre level accuracy with the most accurate INS and GNSS systems regardless of travel distance or duration [7].

One of the primary challenges with GNSS-aided navigation is its vulnerability to interference. GNSS signals can be intentionally denied or spoofed across the space, ground, or receiver segments of its signal, posing serious risks to reliability. In addition, unintentional disruptions, such as signal blockage in tunnels, urban canyons, or dense foliage, can degrade performance due to multipath effects where signals reflect off surfaces before reaching the receiver [8] [9] [10]. Due to these limitations, advancing the accuracy and reliability of INS technology remains essential, particularly for military applications where GNSS spoofing is prevalent, mining operations where signals are naturally obstructed, urban environments with frequent satellite occlusion, and indoor settings such as large buildings and tunnels.

Benefits of LDV

To overcome these limitations of GNSS, sensors with high accuracy are required to reduce the drift associated with INS. Among these sensors, LDV are utilized to measure velocity by exploiting the Doppler effect, specifically, the frequency and phase shift that occurs when waves reflect off moving surfaces. Heterodyne detection is employed to determine the direction of velocity by introducing a known frequency shift to the reference beam using a Bragg cell. This frequency-shifted beam interferes with the backscattered light from the moving target, producing a beat frequency at the optical detector. By analysing the frequency and phase of this beat signal, both the magnitude and direction of the velocity can be determined.

Integrating LDV with INS on land vehicles has demonstrated exceptional positioning accuracy, typically ranging from 0.05% to 0.01% of the distance travelled [11] [12] [13]. These systems often utilize a one-dimensional LDV (1D-LDV) to measure forward velocity or, in some cases, a two-dimensional LDV (2D-LDV) to also capture vertical (upward) velocity. When these LDV configurations are combined with known non-holonomic constraints (NHCs), it becomes possible to infer three-dimensional (3D) velocity data [14] [13].

Speckle

Although LDV systems are highly accurate, they remain susceptible to noise, most notably speckle noise. Optically rough surfaces produce a phenomenon known as speckle when illuminated by highly coherent light (like a laser from an LDV). This results in a granular pattern of bright and dark spots of varying size and shape, caused by scattered light interfering constructively (bright spots) and destructively (dark spots) [15]. Moving LDV systems, such as those mounted on vehicles, experience degraded measurement accuracy due to the speckle pattern shifting across the optical receiver, which quickly becomes the dominant source of noise as these speckle transitions occur [16]. The speckle causes slight variations in the frequency and phase of the light being received, leading to fluctuations in the LDV output, furthermore the constantly changing signal intensity can result in signal dropouts [1] [17].

Several techniques have been developed to reduce speckle noise, including signal averaging over repeated measurements of the same surface [18], ensemble empirical mode decomposition (EEMD) [17], and spatial averaging [19]. However, these methods rely on either multiple measurement of a fixed location or knowledge of the surrounding vibration field conditions, which is impractical for an LDV system passing over an area once during travel.

Jin et al. proposed a dual-wavelength LDV method that suppresses spike noise and reduces the frequency of signal loss caused by continuous full speckle transitions during measurements [20]. Their method employs envelope weighting, calculating a weighted average of the velocity estimates from both channels. This ensures that the channel with a stronger and more reliable signal has greater influence on the final velocity output, effectively mitigating spike noise and reducing the impact of signal dropouts.

Similarly, Lu et al. presented a dual-wavelength LDV system that also addresses speckle noise and signal dropouts but takes the approach further by substituting the signal envelopes with the Carrier-to-Noise Ratio (CNR) as the weighting factor [21]. This allows the system to directly account for both signal strength and noise levels, providing a more accurate weighting mechanism based on signal quality.

Literature Review Outcome

Current research has demonstrated the effectiveness of LDV-INS systems in ground-based applications, however, there is limited exploration of speckle noise mitigation during motion, where speckle transitions become the dominant noise source. Pairing this with the promising speckle noise reduction achieved by dual-wavelength LDV systems in laboratory settings, combined with their potential for real-time implementation, highlights a clear opportunity for further investigation.

Research Question

How does a real-time dual-wavelength Laser Doppler Vibrometer (LDV) system compare to a conventional single-wavelength LDV in terms of speckle noise suppression and dead reckoning accuracy for GNSS-denied inertial navigation

- ***Drift Reduction:***
  To what extent does the dual-wavelength LDV system reduce accumulated velocity drift during dead reckoning compared to a single-wavelength LDV?
- ***Noise and Dropout Suppression:***
  How effectively does the dual-wavelength LDV system mitigate spike noise and reduce signal dropouts caused by irregular surface materials, and what impact does this have on overall navigation stability?
- ***Industry Viability:***
  Based on the results from the experiment, does integrating a dual wavelength LDV over a single wavelength LDV offer significant advantages to warrant the increased costs, complexity and processing power required.

Research Methodology

To answer the research question, an experiment will be conducted to collect quantitative data including measurements of drift for both individual laser wavelengths channels and the combined dual-wavelength system. Each individual velocity output and the combined velocity output will also be saved over the duration of the experiment for further investigation to assess speckle suppression effectiveness of the combined output.

Data collection method

The data will be collected through direct observation during an experimental trial. A dual-wavelength LDV system, based on the setup described in *"Research on the Speckle Effect Suppression Technology of a Laser Vibrometer Based on the Dual-Wavelength Detection Principle"* [20] will be mounted inside a vehicle, with the optical head attached externally and angled forward toward the ground. The LDV's velocity readings will be captured in real time and processed by an onboard computer paired with a MEMS IMU. Three separate velocity inputs will be recorded, one from each photodetector and one combined velocity estimate following the same method as shown in the previously mentioned paper.

Three identical dead reckoning (DR) algorithms will be run in parallel, each using a different velocity input, while maintaining the same gyroscope data, and sampling rates. This ensures that the only changing variable affecting the results is the velocity input from the LDV. Simultaneously, GNSS data will be collected to serve as the ground truth for the vehicle's position. At the end of the experiment, the final drift and positional errors from each DR estimate will be calculated and compared against the GNSS data to determine which velocity input produces the most accurate position estimates (i.e. least drift). Additionally, all velocity readings over time will be logged for post-experiment analysis to identify spikes, anomalies, and dropout events.

The MEMS IMU will provide gyroscope data, while the exact model is yet to be determined, all DR calculations will share the same IMU output to ensure consistency. It's important to note, a higher-grade IMU, such as a Fiber Optic Gyroscope (FOG), would provide improved positional accuracy, but this experiment focuses solely on comparing the relative performance of dual-wavelength versus single-wavelength LDV velocity measurements, not on achieving the highest navigation accuracy.

Finally, the LDV can only measure forward velocity (in line with the laser), with no lateral or vertical displacement data collected. As a result, a Non-Holonomic Constraint (NHC) will be applied to constrain motion to a 2D plane. Although this limits the experiment to planar motion estimation, any errors introduced by lateral vehicle motion will be consistent across all sensors and will not affect the comparative results.

Practicalities

Equipment

All equipment required for this experiment will be sourced from the UTS Vibration and Photonics Laboratories. Any components not available, such as the IMU, will be personally purchased to ensure the project remains on schedule.

Software

This project does not aim to develop or propose a new dead reckoning or data processing method. Instead, open-source software will be used for the dead reckoning algorithm, data analysis, and presentation to streamline the experimental setup and reduce the required workload.

Preliminary Testing

Preliminary tests will be conducted to verify the correct operation of the IMU, dead reckoning algorithm, and LDV system before the final experiment. The dead reckoning algorithm will initially be tested using IMU velocity and gyroscope readings while driving through the local neighbourhood. This will ensure the IMU and dead reckoning algorithm work as intended before connecting the LDV.

The LDV system will be assembled and validated in the laboratory to ensure correct assembly of all components and accurate velocity outputs. The LDV will then be connected to the IMU in the laboratory and tested together to ensure correct data transmission to the dead reckoning algorithm, and to catch any unforeseen issues before the final experiment.

Once all components are functioning correctly in the lab, the output data will be processed using the same software tools and visualization methods planned for the final experiment. This will validate appropriate data storage formats and file types have been selected, helping to identify and resolve any compatibility issues in advance. By doing so, the risk of having to repeat the final experiment due to unforeseen data handling problems will be avoided.

Data Analysis & Presentation

Analysis

At the conclusion of the experiment, the final position estimates from each of the three channels will be compared against the ground truth. The positional error in meters will be recorded, and drift as a percentage of total distance travelled will be calculated. While this drift value accounts for all sources of error in the system, including gyroscope inaccuracies and LDV measurement noise, only the velocity input differs between the three channels. Therefore, the channel with the lowest drift percentage will be considered as the most accurate LDV. In addition to positional analysis, the velocity data from each channel will be recorded and analysed post-experiment using statistical analysis methods such as standard deviation and root mean square (RMS) of velocity to compliment the drift analysis.

Presentation

To help visualise the route taken, and positional errors compared to GNSS, displacement estimates obtained from the dead reckoning (DR) algorithm will be converted from meters into GPS coordinates for all channels using the known initial position and heading. These paths will be plotted on a map of the driving area using the Folium library in Python, providing a clear visual representation of each channel's position estimates over time and their deviation from the GNSS ground truth. Furthermore, Velocity-over-time plots will be generated to visually assess spikes, anomalies, and dropout events.

Ethical and Indigenous Considerations

This research is entirely based on technical experimentation and does not involve human participants, personal data collection, or engagement with Indigenous communities or cultural knowledge. All data collected will be handled objectively, and results will be reported accurately and transparently, free from bias or external influence.

Research Milestones & Timeline

Setting a timeline and milestones is an essential way to monitor progress towards completing the research required for the capstone project. It helps to build momentum and removes the burden of remembering tasks, allowing focus on completing the tasks [22].

Research Phase	Objectives	Deadline (2025)
Resource & Software Preperation	Select and source all hardware components required for the experiment Selecting and configuring the software packages required for dead reckoning and data visualization Write software to convert photodetector outputs from LDV into velocity Determine the most suitable method for securely mounting the final system to the vehicle with minimal vibration interference, and ease of installation.	15th June
Preliminary Tests	Run a mock experiment using the IMU sensors with the dead reckoning algorithm to validate both components Setup dual-wavelength LDV in lab to validate LDV configuration and velocity output software. Combine all components to ensure full software compatibility, validate system configuration, confirm sufficient processing power for parallel dead reckoning, and verify that the data storage method supports the required post-experiment analysis. This process will also help identify and resolve any errors before deploying the system outside the lab.	13th July
Final Experiment	Conduct final experiment over the course of a day. Run the experiment multiple times if required and collect as much data as possible Resolve any errors which occur during final experiment	28th July
Data Analysis	Convert all stored data into desired plots for visualization Analyse data and come to conclusions based on the results	25th August
Write Report	Prepare a comprehensive report detailing all steps undertaken to achieve the final experimental results, including the outcomes and their implications for GNSS-denied navigation using LDV technology.	22nd November

Contribution to Knowledge

This research will demonstrate whether dual-wavelength LDVs are a viable solution for improving velocity measurements in INS systems used for navigation in GNSS-denied environments. It will quantify how much positional drift, signal dropout, and noise can be reduced compared to single-wavelength LDVs, providing clear data to assess if this is a practical direction for improving INS technology. These findings will be useful for companies developing high-end INS systems for mining, military, and civilian applications, helping guide future product development based on real-world performance improvements.

References

[1] S. Rothberg, M. Allen, P. Castellini, D. Di Maio, J. Dirckx, D. Ewins, B. Halkon, P. Muyshondt, N. Paone, T. Ryan, H. Steger, E. Tomasini, S. Vanlanduit and J. Vignola, “An international review of laser Doppler vibrometry: Making light work of vibration measurement,” *Optics and lasers in engineering,* vol. 99, pp. 1 - 23, 2017.

[2] M. Braasch, Fundamentals of Inertial Navigation Systems and Aiding, Institution of Engineering and Technology (The IET), 2022.

[3] A. P. A. C. G. B. Mohinder S. Grewal, Global Navigation Satellite Systems, Inertial Navigation, and Integration, John Wiley & Sons, Incorporated, 2013.

[4] M. S. A. A. P. W. L. R. Grewal, Global Positioning Systems, Inertial Navigation, and Integration, A John Wiley & Sons, Inc.,, 2007.

[5] W. W. J. L. F. W. L. Z. A. Z. C. PEI YU, “An Improved Autonomous Inertial-Based Integrated Navigation Scheme Based on Vehicle Motion Recognition,” *IEEE Access,* vol. 11, pp. 104806 - 104816, 2023.

[6] Z. L. a. X. M. Henghao Zhang, “The D-S theory algorithm with application in the strap-down inertial navigation system,” *Int. J. Modelling, Identification and Control,* vol. 16, pp. 259 - 263, 2012.

[7] Y. C. Q. M. P. W. B. X. L. G. W. G. a. Z. L. Changhui Jiang, Advanced Technologies for Position and Navigation under GNSS Signal Challenging or Denied Environments, 2023.

[8] a. E. J. B. Gregory L. Duckworth, “Navigation in GNSS-Denied Environments: Signals of Opportunity and Beacons,” in *NATO*, France, 2007.

[9] L. Kim, Y. Lee and H. K. Lee, “Kalman–Hatch dual-filter integrating global navigation satellite system/inertial navigation system/on-board diagnostics/altimeter for precise positioning in urban canyons,” *IET radar, sonar & navigation,* vol. 16, no. 2, pp. 379 - 397, 2022.

[10] J. J. Y. T. a. J. L. Jiaji Wu, “Gaussian–Student’s t Mixture Distribution-Based Robust Kalman Filter for Global Navigation Satellite System/Inertial Navigation System/Odometer Data Fusion,” *Remote sensing,* vol. 16, p. 4716, 2024.

[11] Y. L. Z. L. ,. S. L. ,. a. B. G. Qiangwen Fu, “High-Accuracy SINS/LDV Integration for Long-Distance Land Navigation,” *IEEE/ASME TRANSACTIONS ON MECHATRONICS,* vol. 23, no. 6, pp. 2952 - 2961, 2018.

[12] Z. X. J. Z. X. N. a. Q. W. Tao Zhang, “Vehicle-mounted SINS/Dual LDV Integrated Navigation Method Based on Sequential Residual Chi-square Detection,” in *3rd International Symposium on Sensor Technology and Control (ISSTC)*, 2024.

[13] J. Cheng, C. Hou, X. Zhu, M. Chen, G. Wei, J. Zhou, X. Yu, Y. Tian and C. Gao, “Vehicle Dynamic Continuous Gravimetry Technology Based on High-Precision 2-D LDV and GNSS,” *IEEE geoscience and remote sensing letters,* vol. 21, pp. 1 - 5, 2024.

[14] T. Z. Q. W. S. J. a. X. N. Zhiyi Xiang, “A SINS/GNSS/2D-LDV integrated navigation scheme for unmanned ground vehicles,” *Measurement science & technology,* vol. 34, no. 12, p. 125116, 2023.

[15] R. A. B. J. Hector J Rabal, Dynamic Laser Speckle and Applications, Taylor & Francis Group, LLC, 2009.

[16] B. H. Steve Rothberg, “Laser vibrometry meets laser speckle,” in *The International Society for Optical Engineering 5503*, 2004.

[17] Y. Jin and Z. Li, “A new method for eliminating speckle noise from Laser Doppler Vibrometer signals,” *Journal of physics,* vol. 2041, no. 1, p. 12007, 2021.

[18] Y. L. a. R. B. Jinghao Zhu, “Mitigation of speckle noise in laser Doppler vibrometry by using a scanning average method,” *Optics Letters,* vol. 44, pp. 1860 - 1863, 2019.

[19] P. Martin and S. Rothberg, “Introducing speckle noise maps for Laser Vibrometry,” *Optics and lasers in engineering,* vol. 47, no. 3, pp. 431 - 442, 2009.

[20] X. Jin, Y. Shen, Y. Wang, X. Kong and W. Zhang, “Research on the Speckle Effect Suppression Technology of a Laser Vibrometer Based on the Dual-Wavelength Detection Principle.,” *Applied Science,* vol. 15, p. 4858, 2025.

[21] C. Lu, Z. Xu, J. Liu, B. Lu, Z. Yu, L. Zou and G. Liu, “Reducing decoherence introduced by a rough target in laser Doppler vibrometry using a dual-wavelength structure,” *Measurement : journal of the International Measurement Confederation,* vol. 247, p. 116743, 2025.

[22] D. Deb, R. Dey and V. E. Balas, Engineering Research Methodology A Practical Insight for Researchers, Springer, 2019.

[23] P. W. M. G. D. L. R. Dr. David McManus, “Laser Velocity Sensor (LVS): A High-Accuracy Velocity Aid for GNSS-Denied Navigation,” Advanced Navigation, 30 March 2025. [Online]. Available: https://www.advancednavigation.com/tech-articles/laser-velocity-sensor-lvs-high-accuracy-velocity-aid-gnss-denied-navigation/. [Accessed 11 April 2025].

[24] R. S. R. R. P. S. C. C. B. T. J. Vass, “Avoidance of speckle noise in laser vibrometry by the use of kurtosis ratio: Application to mechanical fault diagnostics,” *Mechanical systems and signal processing,* vol. 22, no. 3, pp. 647 - 671, 2008.

[25] C.-H. Cheng, C.-W. Lee, T.-W. Lin and F.-Y. Lin, “Dual-frequency laser Doppler velocimeter for speckle noise reduction and coherence enhancement,” *Optics express,* vol. 20, no. 18, pp. 20255 - 20265, 2012.

[26] R. D. Z. L. Yang Jin, “Numerical simulation and characterization of speckle noise for laser Doppler vibrometer on moving platforms (LDVom),” *Optics and Lasers in Engineering,* vol. 158, p. 107135, 2022.

[27] B. J. H. a. M. A. I. Christian Rembe, “Measuring Vibrations in Large Structures with Laser-Doppler Vibrometry and Unmanned Aerial Systems: A Review and Outlook,” 2025.

[28] A. Darwish, “Mobile laser Doppler vibrometry motion tracking and vibration compensation for in-field vehicular deployments,” 2022.

Appendix A: Supervisor Communication Log

The following screenshots are the meeting minutes and weekly meeting scheduled with my supervisor. You will notice we did not have a meeting every week, this is due to Ben Halkon being busy most week with illness, overseas travel, course preparation, and hospitalization. Attached is a screenshot of an email from him detailing this himself to confirm these reasons as to why there has been little feedback:

Ben Halkon 24/02 7:00 pm

BH Capstone Projects peer-review weekly meeting
Occurs every Tuesday 12:30 PM

... Join

Dear all, As promised, here's a meeting to get together regularly to talk about your progress on your capstones and share ideas/benefit from my feedback. Please expect to contribute and come prepared to do so (make a few slides to show something that you've been working on e.g.).
Remember that this is a different mode of engagement to what you're used to on taught subjects - here, there are no set objectives, you define those. I will give you opps. to do things but do not require anything. It's up to you to define deliverables and drive progress. Those joining 41039 this session have been provided the "Capstone Expectations" doc. to work thro' with me; let's start with that when we meet (please prepare yours and I will share mine).
I hope the timing works. I previously suggested a different slot. I know that some of you are working and some are studying. I hope that, by scheduling at lunch time and on the half hour, most if not all of you will be able to drop in for at least 30 mins every other time (try to come more often than not would be a good target). Kind regards, Ben

SUPERVISION MEETING NOTES

Meeting date: 04/02/2025

Attendees: Liam Faulkner-Hogg, Suraj, Ella Covington, Oscar Eastwood, Ben Halkon, Mahdi Mohammadi

Agenda – must be prepared before the meeting

- Questions about the final goal of the “Research Preparation” course
- Questions about lab equipment & procurement
- Questions about LDV Fundamentals

Action List – prepared after the meeting

Who is responsible for the action?	*When does the action need to be completed?*	*What is the action?*
Suraj	Unknown	Secure SPOT
Liam, Ella, Oscar, Mahdi	ASAP	Book a meeting with Michael and Ben to tour their respective labs

Key ideas discussed in the meeting – must be prepared after the meeting

- BH suggested that, where a capstone has multiple experiments, methodologies, results, etc. should be separated per experiment. Numbering methodology is also uncommon.
- Suraj would like to do testing with SPOT the robot dog
- Use ABAQUS (software) for FEA (well-regarded for material models)
- Axis symmetric structures are important and easy to manufacture. BH is currently looking into dynamics of rings. BH to provide recent documentation to EC
- Capstone preparation assignment 1 research question should be open ended and will be iterated upon through the semester

SUPERVISION MEETING NOTES

Meeting date: 25/02/2025

Attendees: Ben Halkon, Liam Faulkner-Hogg, Ella Covington, Oscar Eastwood, Bryaden Roeger, Chad Mackinlay

Agenda – must be prepared before the meeting

- Discussion of "Capstone Expectations"
- Introduction to the team and other capstone students

Action List – prepared after the meeting

Who is responsible for the action?	*When does the action need to be completed?*	*What is the action?*
Liam, Oscar, Chad, Ella	No Due Date	Meet with Michael Lee for a walk around the photonics lab

Key ideas discussed in the meeting – must be prepared after the meeting

- Bryaden gave an overview of his research during his capstone preparation and talked about modal measurements of axis symmetrical structures.
- Ben mentioned he might give a weekly update on his locations each week so that students can drop in and meet him when possible.
- Ben gave insight into how all variables in an experiment must be controlled by the engineer. Without measured control over all variables your results cannot be trusted.
- Talked about entering the labs and all of the documents which must be complete such as safety and riask assessment documents.
- The highest risk level allowed during a task in the labs is **MEDIUM.**
- Talked about how to correctly write a risk assessment and how to reduce the danger level of risks associated with lasers.
- Talked about how the "SJRlabscomplete2015" document is for a regular LDV not a two colour laser vibrometer, and how we will first make a regular LDV before diving deeper into the two colour version.
- Went through the students and supervisors "Discussioon of Capstone Expectations" document and we all agreed on most things.

SUPERVISION MEETING NOTES

Meeting date: 29/04/2025

Attendees: Oscar Eastwoods, Liam Faulkner-Hogg, Ella Covington, Chad Mackinlay, Ben Halkon

Action List – prepared after the meeting

Who is responsible for the action?	*When does the action need to be completed?*	*What is the action?*
Oscar & Liam	ASAP	Build a simple vibrometer in the lab
Liam	ASAP	Finalise research question

Key ideas discussed in the meeting – must be prepared after the meeting

- IEEE reference style is accepted by Ben Halkon
- An abstract should mention the outcomes of the report, NOT what's in the report (this should be introduction). To give people an understanding of what will be uncovered while they read.
- Get together with Oscar and build the simple vibrometer
- Work can be done at Techlabs during the semester break, with limited academic help

VL

Ben Halkon on behalf of Vibration Lab

To: Ben Halkon; Liam Faulkner-Hogg; Oscar Eastwood; Suraj Kattera; **+4 others**

Tue 5/13/2025 10:31 AM

Cc: Zimu Guo; Mahdi Mohammadi; Seetha Mahadevan

Canceled: BH Capstone Projects peer-review weekly meeting

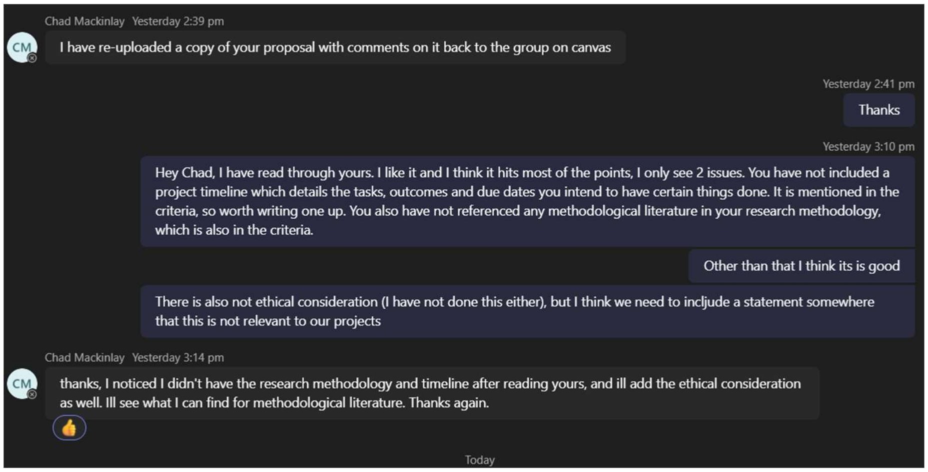
~~Tue 5/13/2025 12:30 PM - 1:30 PM~~

~~Microsoft Teams Meeting~~

Remove from calendar

Dear all, Sorry, I have been in hospital over the weekend and have been signed off work. Sorry. I have been really sick with flu-like symptoms (again) and swellings on my lower legs (suspected erythema nodusum?!) which will take weeks to settle. Possibly adverse reaction to flu shot on Wed. I would support you submitting special considerations on the basis that you have not been able to get reasonable access to regular supervision (and resources) during the course of the session due to lack of supervisor availability due to UTS excessive workload on other projects, business travel, and extended illness. You can use these words. Kind regards, Ben

Appendix B: Peer Reviews



Appendix C: Literature Review Updates

Due to Ben Halkons sickness and unavailability for supervision, my literature review for assignment 2 has not been marked, nor feedback given by the due date of assignment 3, so I cannot show any direct improvements based on feedback from my supervisor. This being said, I have heavily updated the speckle section of the review and changed the focus of my research question based on further reading after the submission of assignment 2. The sections which have been changed are highlighted in the below screenshots, red text indicates what has been removed due to it not being relevant to the updated research question, and blue text shows what has been added:

Benefits of LDV

To overcome these limitations of GNSS, sensors with high accuracy are required to reduce the drift associated with inertial navigation systems (INS). Among these sensors, laser Doppler vibrometers (LDVs) are utilized to measure velocity by exploiting the Doppler effect, specifically, the frequency and phase shift that occurs when waves reflect off moving surfaces. Heterodyne detection is employed to determine the direction of velocity by introducing a known frequency shift to the reference beam using a Bragg cell. This frequency-shifted beam interferes with the backscattered light from the moving target, producing a beat frequency at the optical detector. By analysing the frequency and phase of this beat signal, both the magnitude and direction of the velocity can be determined.

Integrating LDV with INS on land vehicles has demonstrated exceptional positioning accuracy, typically ranging from 0.05% to 0.01% of the distance travelled [11] [12] [13]. These systems often utilize a one-dimensional LDV (1D-LDV) to measure forward velocity or, in some cases, a two-dimensional LDV (2D-LDV) to also capture vertical (upward) velocity. When these LDV configurations are combined with known non-holonomic constraints (NHCs), it becomes possible to infer three-dimensional (3D) velocity data [14] [13].

While this approach proves highly effective for terrestrial vehicles, it is not easily transferable to aircraft applications. This is due to the variability of NHCs for drones and fixed-wing aircraft, as well as the lack of constraints in vertical motion. Additionally, aircraft introduce several unfavourable conditions for LDV systems, including idle sway, high-frequency vibrations, longer target distances, dynamic roll, pitch, and yaw behaviour, as well as strict weight and power limitations [15]. Darwish simulated an LDV-INS drone system incorporating a steering mirror to counter-rotate the LDV beam and compensate for roll and pitch movements during hover [16]. The setup demonstrated a 68% reduction in beam motion, which is a great step towards fusion with drones.

Advanced Navigation, an Australia-based manufacturer of inertial navigation systems, has developed its own Laser Velocity System (LVS), which employs a tri-beam LDV to deliver full 3D body velocity measurements. This system is integrated with a high-precision fibre-optic gyroscope INS and is designed for both ground and airborne applications. According to the company, the system achieves "GNSS-denied navigation performance with an error of approximately 0.05% relative to the total distance travelled," aided by their proprietary advanced noise filtering algorithms [17]. However, specific details regarding the filters used, encountered challenges, and comprehensive performance data remain undisclosed.

Currently, there is limited publicly available research on the integration of LDV and INS systems for aerial platforms, particularly regarding their performance, noise characteristics, filters and overall system behaviour under flight conditions.

Speckle

One major sources of noise, present in all LDV is speckle. Optically rough surfaces produce a phenomenon known as speckle when illuminated by highly coherent light (like a laser from an LDV). This results in a granular pattern of bright and dark spots of varying size and shape, caused by scattered light interfering constructively (bright spots) and destructively (dark spots) [18]. Moving LDV systems, such as those mounted on aircraft, often experience degraded measurement accuracy due to the speckle pattern shifting across the optical receiver. The speckle has slight variations in frequency and phase, leading to fluctuations in the LDV output, furthermore the constantly changing signal intensity can result in signal dropouts [1] [19].

Several techniques have been developed to reduce speckle noise, including signal averaging over repeated measurements of the same surface [20], ensemble empirical mode decomposition (EEMD) [19], and spatial averaging [21]. However, these methods rely on either multiple measurement of a fixed location or knowledge of the surrounding vibration field conditions, which is impractical for an LDV system passing over an area once during travel.

Vass et al. demonstrated a statistical technique for detecting the presence of speckle noise [22], but Jin et al. challenged its effectiveness, arguing that it performs poorly in removing speckle noise with typical amplitude levels [23].

Cheng et al. proposed a dual-frequency LDV method to reduce speckle noise by locking the optical phases through microwave modulation [24]. This solution is better suited for airborne applications with an improved detection range and high velocity resolution.

Conclusion

Current research has demonstrated the effectiveness of LDV-INS systems in ground-based applications, but significant challenges remain in adapting these systems for airborne use. Issues such as unrestrained movement for drones, power and weight efficiency, and speckle noise introduce technical hurdles that are not yet fully addressed in the literature. Although commercial systems like Advanced Navigation's LVS suggest the feasibility of high-performance LDV-INS integration in flight, detailed performance data and noise mitigation strategies remain scarce. This gap highlights a clear opportunity for further investigation, particularly into noise suppression techniques, lightweight system integration, and ideal LDV setups optimized for aerial platforms. Realizing this gap has allowed me to further refine my research question into the following:

Speckle

Although LDV systems are highly accurate, they remain susceptible to noise, most notably speckle noise. Optically rough surfaces produce a phenomenon known as speckle when illuminated by highly coherent light (like a laser from an LDV). This results in a granular pattern of bright and dark spots of varying size and shape, caused by scattered light interfering constructively (bright spots) and destructively (dark spots) [15]. Moving LDV systems, such as those mounted on vehicles, experience degraded measurement accuracy due to the speckle pattern shifting across the optical receiver, which quickly becomes the dominant source of noise as these speckle transitions occur [16]. The speckle causes slight variations in the frequency and phase of the light being recieved, leading to fluctuations in the LDV output, furthermore the constantly changing signal intensity can result in signal dropouts [1] [17].

Several techniques have been developed to reduce speckle noise, including signal averaging over repeated measurements of the same surface [18], ensemble empirical mode decomposition (EEMD) [17], and spatial averaging [19]. However, these methods rely on either multiple measurement of a fixed location or knowledge of the surrounding vibration field conditions, which is impractical for an LDV system passing over an area once during travel.

Jin et al. proposed a dual-wavelength LDV method that suppresses spike noise and reduces the frequency of signal loss caused by continuous full speckle transitions during measurements [20]. Their method employs envelope weighting, calculating a weighted average of the velocity estimates from both channels. This ensures that the channel with a stronger and more reliable signal has greater influence on the final velocity output, effectively mitigating spike noise and reducing the impact of signal dropouts.

Similarly, Lu et al. presented a dual-wavelength LDV system that also addresses speckle noise and signal dropouts but takes the approach further by substituting the signal envelopes with the Carrier-to-Noise Ratio (CNR) as the weighting factor [21]. This allows the system to directly account for both signal strength and noise levels, providing a more accurate weighting mechanism based on signal quality.

Conclusion

Current research has demonstrated the effectiveness of LDV-INS systems in ground-based applications, however, there is limited exploration of speckle noise mitigation during motion, where speckle transitions become the dominant noise source. Pairing this with the promising speckle noise reduction achieved by dual-wavelength LDV systems in laboratory settings, combined with their potential for real-time implementation, highlights a clear opportunity for further investigation. Recognizing this gap has allowed me to refine my research question into the following:

How does a real-time dual-wavelength Laser Doppler Vibrometer (LDV) system compare to a conventional single-wavelength LDV in terms of speckle noise suppression and dead reckoning accuracy for GNSS-denied inertial navigation

- ***Drift Reduction:***
  To what extent does the dual-wavelength LDV system reduce accumulated velocity drift during dead reckoning compared to a single-wavelength LDV?
- ***Noise and Dropout Suppression:***
  How effectively does the dual-wavelength LDV system mitigate spike noise and reduce signal dropouts caused by irregular or non-cooperative surface materials, and what impact does this have on overall navigation stability?