**Terrain Draping and Following Using Low-Cost Remotely
Piloted Aircraft Systems for Geophysical Survey
Applications**

by
Salman Shafi

A thesis submitted to the Faculty of Graduate and Postdoctoral Affairs
in partial fulfillment of the requirements for the degree of

**Master of Applied Science
in
Aerospace Engineering**

Carleton University
Ottawa, Ontario

© 2019
Salman Shafi

Dedicated to the loving memory of my Father, Ahmed Shafi.

Abstract

Collecting high-resolution aeromagnetic data require sensors to be active at lower above ground level altitudes. Cost associated is the driving factor for pursuing remotely piloted aircraft systems. Operators have been considering these systems to complement manned aircraft surveillance missions. To provide accurate aeromagnetic readings, remotely piloted aircraft must fly low at constant above ground level altitudes and therefore follow the terrain.

A low-cost, non-proprietary terrain following system for remotely piloted aircraft is being developed to measure ground and surface altitude, fly at specific above ground level altitudes, and follow preloaded flightpaths from a smoothed terrain drape to maximize the quality of aeromagnetic data. Using digital elevation models, a smooth flightpath is predetermined so remotely piloted aircraft can follow the terrain without exceeding its structural loads or flight envelope; this process creates a terrain drape profile, which is loaded onto the autopilot system to follow the ground at the desired altitude.

Acknowledgements

I want to start by thanking NSERC and our industry partner Sander Geophysics Ltd. for the financial support that they provided for my research.

Thank you to everyone in the office of the Department of Mechanical and Aerospace Engineering, which includes Ron Miller, Janet Perras, Dan Premachuk, and Allyson Fitch, your help has been invaluable to my success, academically and professionally.

Thank you to the MAE lab techs, Steve Truttmann, David Raude, Stephan Biljan, Kevin Sangster, and Alex proctor. Your professionalism, knowledge, and expertise exceed all expectations.

To my family, you have my deepest gratitude for the continuous support and encouragement throughout my undergraduate and graduate studies.

To my wonderful girlfriend, Lindsay Kearnan, thank you for relentlessly motivating me, showing compassion when I needed it, and making me a better person throughout this process.

To my friends and colleagues in my office, thank you for putting up with and accepting my quirky personality. I've made some wonderful memories in that office that I will always cherish.

Zach Copeland, thank you for guiding me as an academic, pushing me at the gym, and putting up with my mental state at the tail end of my thesis.

A special thanks to the members of my research group, Brendan Ooi, Loughlin Tuck, Niall McCallum, Jason Hlaing, and Darren Penley. I learned so much from all of you and thanks for making this project so much fun!

My most sincere gratitude goes to my supervisor, Professor Jeremy Lalibert. I do not have the words to express how grateful I am for your guidance. You have been an exceptional teacher and mentor – I could not have wished for anyone better. You are an eternal optimist that recognized potential in me that I could not see. With humility, I humbly thank you and appreciate everything you have done for me.

One final shout out to my dear friend Darren Penley. If it wasn't for you, I may not have pursued graduate studies. For that, you have my sincerest gratitude.

Table of Contents

Abstract	iii
Acknowledgements	iv
List of Tables	viii
List of Figures	ix
List of Acronyms	xiii
List of Symbols	xvi
Chapter 1 Introduction	1
1.1 Manned Aeromagnetic Surveys	2
1.2 Thesis Motivation	3
1.3 Thesis Overview	5
1.4 Summary of Contribution	5
Chapter 2 Background	7
2.1 Terrain Following Technology for Manned Missions	7
2.1.1 A Brief History of Radar	9
2.1.2 Terrain Following Radar	11
2.2 Path Following Algorithm for Remotely Piloted Aircraft Systems . . .	16
2.2.1 Straight-Line Following Vector Field Based Path Following Al- gorithm	17
2.2.2 Circular Orbit Following Vector Field Based Path Following Algorithm	20
2.2.3 Combining Straight-Line & Circular Orbit Following Vector Field Based Path Following Algorithm	22
2.3 State-of-the-Art Terrain Following for Remotely Piloted Aircraft Systems	24

2.4	Review of Digital Elevation Models for Uninhabited Aircraft System Applications	26
2.5	Review of Mission Planner Mission Planning Software	33
2.6	Overview of Laser Altimetry Technology	34
2.6.1	Laser Altimetry Overview	34
2.6.2	Laser Classification	36
2.7	Qualitative Overview of Global Navigation Satellite System	36
2.7.1	Global Positioning System Services and Signals	37
2.7.2	Standard Positioning Service and Precise Positioning Service	38
2.7.3	Global Navigation Satellite System Receiver Position in Three-Dimensional Space	39
2.7.4	Global Positioning System Sources of Error	41
2.7.5	Differential Global Positioning System and Real Time Kinematics	44
Chapter 3	Proposed Solution & System Architecture	49
3.1	Platform: 3D Robotics 3DR Iris ⁺	50
3.2	Aeromagnetic Terrain Following System Requirements	51
3.3	Remotely Piloted Aircraft System	52
3.4	3D Robotics 3DR PX4 Pixhawk Autopilot System	54
3.5	Garmin Lidar Lite V3	54
3.5.1	Garmin Lidar Lite V3: Hardware Integration	55
3.5.2	Garmin Lidar Lite V3: Iris Modification	58
3.5.3	Garmin Lidar Lite V3: Software Integration	62
3.6	Emlid Reach RTK GNSS System	63
3.6.1	Emlid Reach RTK GNSS RPAS System: Hardware Integration	64
3.6.2	Emlid Reach RTK GNSS RPAS System: Base Station Setup & Assembly	68
3.6.3	Emlid Reach RTK GNSS RPAS System: Software Integration	69
3.7	Modified Iris ⁺ Architecture	74
3.8	Ground Control Station	75

3.9	Terrain Following Remotely Piloted Aircraft System Architecture . . .	76
Chapter 4	Mission Setup & Methodology	78
4.1	Mission Setup	78
4.1.1	Altimetry & Standalone GNSS Test Setup	81
4.1.2	RTK GNSS & NTRIP Test Setup	83
4.2	Post-processing Methodology	86
4.2.1	Laser Altimetry Post-processing Methodology	86
4.2.2	GNSS Post-processing Methodology	89
Chapter 5	Discussion of Results	93
5.1	Altimetry Results & Discussion	93
5.1.1	Barometric Altimetry Results & Discussion	93
5.1.2	Lidar Lite Altimetry Results & Discussion	97
5.1.3	Average Altimetry Difference Trend	99
5.2	GNSS Test Results & Discussion	100
5.2.1	Ublox NEO-7M GNSS Test Results & Discussion	100
5.2.2	Emlid Reach RTK GNSS Test Results & Discussion	103
5.2.3	NTRIP RTK GNSS Test Results & Discussion	106
Chapter 6	Conclusions	108
6.1	Summary	108
6.2	Future Work	109
Bibliography		112
Appendix A	Additional Figures for Altimetry and GNSS Results	118
A.1	Additional Barometric Results and Figures	118
A.2	Additional Lidar Lite Results and Figures	119
A.3	Additional Ublox NEO-7M GNSS Test Result Figures	121
A.4	Additional Emlid Reach RTK GNSS Test Result Figures	123

List of Tables

2.1	Sources of error.	41
3.1	Garmin Lidar Lite V3 system specifications.	55
3.2	Mission Planner CONFIG/TUNING parameter settings for the Lidar Lite.	62
3.3	Emlid Reach RTK GNSS system specifications.	63
3.4	Emlid Reach RTK GNSS system parameter settings.	71
3.5	Mission Planner CONFIG/TUNING parameter settings for the Reach.	72
3.6	Base mode parameters for the base station Reach to inject cor- rections through telemetry.	72
3.7	Base mode parameters for the base station Reach to inject cor- rections via Wi-Fi.	73
3.8	Base mode parameters for the base station Reach using NTRIP corrections.	74
4.1	Geographical LLH coordinates for the barometer, laser altime- ter, and standalone GNSS tests.	82
4.2	Geographical LLH coordinates for the RTK and NTRIP GNSS tests.	85
5.1	Average values of the barometric test results.	96
5.2	Average values of the Lidar Lite test results.	98
5.3	Ublox GNSS test results, including test and waypoint average and standard deviations.	102
5.4	Reach RTK GNSS test results, including test and waypoint av- erage and standard deviations.	104
5.5	NTRIP GNSS test results, including waypoint average and stan- dard deviation.	107

List of Figures

1.1	General Dynamics F-111 Aardvark [2].	1
1.2	Aeromagnetic survey workflow.	3
1.3	Total magnetic intensity based on altitude (image provided by Sander Geophysics Ltd.)	4
2.1	McDonnell F-4 Phantom II [10].	8
2.2	(a) Illustration of VF PFA flow, red line represents the flight path, and distance of τ was arbitrarily chosen and is not to scale, and (b) labeled straight-line following illustration of RPA with respect to the flight path. <i>Image (a) adapted from Figure 9 (a) in [20].</i>	19
2.3	(a) Illustration of circular VF PFA flow, and (b) labeled circular orbit following illustration of RPA with respect to the flight path. <i>Image (a) adapted from Figure 9 (b) in [20].</i>	21
2.4	Illustration of the three common methods used for combining straight-line and circular orbit VF PFAs [22]; Top: equal length method; Middle: through waypoint method; and Bottom: minimum time method.	23
2.5	(a) Digital terrain model of the Upper British Columbia River Basin, and (b) digital surface model of the Upper British Columbia River Basin.	27
2.6	The difference between DSMs and DTMs.	27
2.7	Following terrain with a contoured flight path (not to scale). . .	29
2.8	(a) Digital elevation model of Plevna, ON, and (b) Draped surface of Plevna, ON, with a 10% gradient and a clearance offset of 150 m AGL. <i>Images provided by Sander Geophysics Ltd.</i> . .	31
2.9	Sample survey coordinates data for Plevna, Ontario [6].	32
2.10	Following the terrain with a smoothed flight path (not to scale). .	32

2.11	Laser altimeter beam (a) exiting the emitter (Ex) scattering off the surface, and (b) being detected by the receiver (Rx). . . .	35
2.12	The receiver can exist: (a) anywhere on the surface of the sphere; (b) anywhere limited to the area of the two intersecting sphere; (c) on one of two points of the three intersecting spheres; and (d) at a single logical point selected based on time and range corrections.	40
2.13	(a) GNSS receiver that has a poor GDOP, and (b) GNSS receiver that has a good GDOP [60].	43
3.1	High-level block diagram of the terrain following RPAS.	50
3.2	(a) A one-third scale electrically powered Piper Pawnee fixed-wing RPAS, and (b) a 3DR Iris ⁺ quadrotor RPAS	51
3.3	RPAS Geophysics system architecture.	53
3.4	(a) Emlid Reach RTK GNSS receiver, (b) Garmin Lidar Lite V3, and (c) Pixhawk autopilot system.	54
3.5	Lidar Lite connection diagram.	57
3.6	YEP 20A SBEC.	57
3.7	XT60 modification on the power distribution and 4-in-1 ESC board.	59
3.8	Starboard side pass-through cutout of the Iris ⁺ 's ventral plate.	60
3.9	Lidar Lite connection wire.	60
3.10	3D CAD of the Lidar Lite attachment plate.	61
3.11	Ventral side of the modified Iris ⁺ with the Lidar Lite installed.	62
3.12	Tallysman Wireless TW4721 antenna [75].	64
3.13	(a) Reach and TW4721 Pixhawk connection diagram, and (b) actual Reach connection inside the Iris ⁺ RPA.	65
3.14	Emlid's antenna placement recommendations [74].	66
3.15	Tallysman TW4721 antenna placement adjacent to the NEO-7M module on the 3DR Iris ⁺ 3D printed dorsal plate.	67

3.16	(a) Block diagram of base station assembly, and (b) picture of base station assembly.	69
3.17	Lidar Lite and Reach connection diagram.	74
3.18	Iris ⁺ terrain following block diagram.	75
3.19	Ground control station block diagram.	76
3.20	Low-level terrain following RPAS architecture block diagram. .	77
4.1	Stanley's Olde Maple Lane Farm location, encircled in black; Ottawa International Airport, encircled in blue; and Carleton University encircled in red.	79
4.2	Stanley's Olde Maple Lane Farm (yellow), Christmas farm (white), and RTK/NTRIP flight test area (green).	80
4.3	Multipurpose land at Stanley's Olde Maple Lane Farm (yellow), water filled quarry (white), and altimetry and Ublox flight test area (green).	81
4.4	Altimetry and Ublox flight path near water filled quarry. . . .	83
4.5	Image of RPAS launch pad.	84
4.6	RTK/NTRIP flight path over the Christmas tree farm.	86
4.7	Iris ⁺ roll and pitch axes with laser illustration.	88
4.8	Iris ⁺ roll angles (top), pitch angles (middle), and raw Lidar Lite measurements (bottom).	88
4.9	Iris ⁺ raw Lidar Lite altitude measurements (above) and Lidar Lite altitude measurements corrected for roll and pitch angles (below).	89
5.1	Lidar Lite altitude measurements from the first barometric flight test.	94
5.2	Average difference between prescribed and measured altitude for barometric flight tests (error bars included).	96
5.3	Lidar Lite altitude measurements from the first Lidar Lite flight test.	97

5.4	Average difference between prescribed and measured altitude for Lidar Lite flight tests (error bars included).	99
5.5	Decreasing trend for average difference of AGL altitude measurements.	100
5.6	RTK measurements from the first Ublox flight test.	101
5.7	RTK measurements from the first RTK flight test.	103
5.8	RTK measurements from the NTRIP flight test.	106
A.1	Lidar Lite altitude measurements from the second barometric flight test.	118
A.2	Lidar Lite altitude measurements from the third barometric flight test.	119
A.3	Lidar Lite altitude measurements from the forth barometric flight test.	119
A.4	Lidar Lite altitude measurements from the second Lidar Lite flight test.	120
A.5	Lidar Lite altitude measurements from the third Lidar Lite flight test.	120
A.6	Lidar Lite altitude measurements from the fourth Lidar Lite flight test.	121
A.7	Lidar Lite altitude measurements from the fifth Lidar Lite flight test.	121
A.8	RTK measurements from the second Ublox flight test.	122
A.9	RTK measurements from the third Ublox flight test.	122
A.10	RTK measurements from the fourth Ublox flight test.	123
A.11	RTK measurements from the second RTK flight test.	123

List of Acronyms

AC	Alternating Current
ADLAT	Advanced Low altitude Algorithm
AFSCN	Air Force Satellite Control Network
AGL	Above Ground Level
ASL	Above Seal Level
AMCS	Alternate Master Control Station
BEC	Battery Eliminator Circuit
C/A	Coarse/Acquisition
CACS	Canadian Active Control System
CAD	Computer Aided Design
CORS	Continuous Operating Reference Station
CSF	Compagnie Générale de Télégraphie Sans Fil
CW	Continuous Wave
DC	Direct Current
DEM	Digital Elevation Model
DGPS	Differential Global Positioning System
DIY	Do-it-yourself
DOP	Dilution Of Precision
DSM	Digital Surface Model
DTM	Digital Terrain Model
ECI	Earth-Centred Inertial
EGNOS	European Geostationary Navigation Overlay Service
ERB	Emlid Reach Binary
FAA	Federal Aviation administration
GAGAN	GPS Aided Geo Augmented Navigation
GBAS	Ground Based Augmentation System
GCS	Ground Control Station

GDOP	Geometric Dilution Of Precision
GIS	Global Information System
GLONASS	GLobal Orbiting NAvigational Satellite System
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HARV	High Alpha Research Vehicle
HDOP	Horizontal Dilution Of Precision
ICAO	International Civil Aviation Organization
IMU	Inertial Measurement Unit
INS	Inertial Navigation System
LANTIRN	Low Altitude Navigation and Targeting InfraRed for Night
LiDAR	Light Detection And Ranging
LiPo	Lithium-Polymer
LLH	Latitude Longitude Height
MSAS	Multi-functional Satellite Augmentation System
MSL	Mean Sea Level
NAVSTAR	NAVigation Satellite Timing And Ranging
NMCS	New Master Control Station
NRCan	Natural Resources Canada
NTRIP	Network Transport of RTCM via Internet Protocol
OCS	Operational Control Segment
OW	Obstacle Warning
P-code	Precision code
PDOP	Position Dilution Of Precision
PFA	Path Following Algorithm
PIC	Pilot in Command
PID	Proportional-Integral-Derivative
PPP	Precise Point Positioning
PPS	Precise Positioning Service
PRN	PseudoRandom Noise

RINEX	Receiver INdependent EXchange format
RPA	Remotely Piloted Aircraft
RPAS	Remotely Piloted Aircraft System
RTCM	Radio Technical Commission for Maritime services
RTK	Real-Time Kinematic
SA	Selective Availability
SBAS	Satellite Based Augmentation Systems
SGL	Sander Geophysics Ltd.
SIM	Subscriber Identity Module
SPS	Standard Positioning Service
SRD	System Requirement Document
TCP	Transmission Control Protocol
TDOP	Temporal Dilution Of Precision
TFR	Terrain Following Radar
TIN	Triangular Irregular Networks
UART	Universal Asynchronous Receiver/Transmitter
USAF	United States Air Force
USB	Universal Serial Bus
UTM	Universal Transverse Mercator
VDOP	Vertical Dilution Of Precision
VTOL	Vertical TakeOff and Landing
WAAS	Wide Area Augmentation System
WWII	World War II

List of Symbols

α	Roll angle [deg]
β	Convergence space control
c	Speed of light [m/s]
χ_e	Heading entry parameter [rad]
D	Distance between two waypoints [m]
d	Arc length [m]
δ	Distance from the circumference of an orbital flight path [m]
f	Frequency [Hz]
H_{ASL}	Height above sea level [m]
h	Height above ground level [m]
h_c	Corrected height above ground level [m]
h_r	Raw height above ground level [m]
k	Proportionality constant\transition gain
λ	Wavelength [m]
λ_1	Desired longitude [rad]
λ_2	Measured longitude [rad]
O	Central location of an orbital flight path
Ω	Flight path angle [rad]
p	Location
ϕ	Latitude [deg]
ϕ_1	Desired latitude [rad]
ϕ_2	Measured latitude [rad]
ψ	Heading angle [rad]
ψ_c	Commanded flight path angle [rad]
ψ_d	Desired heading angle [rad]
ψ_w	Wind direction [rad]
R	Radius [m]

r_1	Radius at the equator [m]
r_2	Radius at the pole [m]
ρ	Sign function for Vector Field Path Following Algorithm
σ	Central angle between two points [rad]
θ	Pitch angle [deg]
t_0	Initial time [sec]
t_1	Current time [sec]
τ	Flight path boundary [m]
u	Lateral acceleration constraint [m/s ²]
V_a	Air velocity [m/s]
V_{gx}	Ground velocity in the x-direction [m/s]
V_{gy}	Ground velocity in the y-direction [m/s]
V_w	Wind velocity [m/s]
W_i	Initial waypoint
W_{i+1}	Destination waypoint
ζ	Cross-track error [m]

Chapter 1

Introduction

Terrain following was first developed for General Dynamics' F-111 *Aardvark* low altitude strike aircraft, see Figure 1.1. Prior to stealth technology, aircraft would have to be flown below enemy radar to avoid detection. Additionally these tactical flights could only be done at night so to not be visually seen by enemy ground or airborne units. The F-111 was equipped with a terrain following radar so that a pilot could fly close to the ground at night, avoiding enemy radar [1]. Currently, terrain following systems are being developed by remotely piloted aircraft system (RPAS) enthusiasts and researchers. These systems are being developed for low-cost RPAS using low-cost open source sensors; however, there is a lack of prior published work from the "do-it-yourself" (DIY) RPAS community. Thus, there is a lack of aviation-quality tested documented solutions using low-cost and non-proprietary methods.

Figure 1.1: General Dynamics F-111 Aardvark [2].

1.1 Manned Aeromagnetic Surveys

Aeromagnetic surveying is a geophysics technique that uses sensitive magnetometers to map geological trends and identify magnetic anomalies that may be associated with rare earth metals [3]. Magnetometers may be carried on aircraft, by operators on the ground, or towed beneath a ship.

Airborne surveys offer the benefit of rapidly covering large areas while also being able to access regions that may be difficult to reach through other means. Since the magnetic field intensity drops with the cube root of the distance, it is important to fly as close to the ground as possible to maximize sensitivity [4]; however, this presents a safety hazard for manned aircraft. As a result, most manned airborne surveys are conducted at a minimum altitude of 150 m above ground level (AGL) to minimize these risks. It is also desirable to drape a flight path over a terrain to maintain a constant AGL altitude; any deviations must be corrected in the final processing using high-precision altitude data collected. The shape of this draped profile is determined by the aircraft handling characteristics, air frame, occupant load limits, and the proficiency of the pilots.

The flight paths are determined in advance of the surveys using digital terrain elevation data during the flight planning phase. The pilots manually fly the aircraft along survey lines using global navigation satellite system (GNSS) technology and other sensors to maintain straight flight paths and equal spacing between the lines. The orientation and spacing of the survey lines are determined by the underlying geology, survey resolution requirement, and cost [5].

There exist general guidelines on what aeromagnetic workflows should look like. Figure 1.2 is an example of such a workflow, where a mission begins with the survey requirements and ends with synthesizing waypoints to be loaded onto a flight computer or autopilot system.

Figure 1.2: Aeromagnetic survey workflow.

1.2 Thesis Motivation

Currently, aeromagnetic surveys are traditionally performed by fixed-wing aircraft and helicopters with expensive sensors. To record high-resolution magnetic data with lower cost sensors, a pilot is required to fly an aircraft as close to the ground as possible. Flying close to the ground can be done safely with manned fixed-wing aircraft at moderate altitudes (~ 100 m AGL), but it cannot be done safely at lower altitudes (~ 10 m AGL); however, it can be done with helicopters, but this is prohibitively expensive [6].

To fly safely at low altitudes, acquire high-quality geomagnetic data, while reducing survey costs, RPAS are being evaluated as an alternative to manned aeromagnetic surveys. For example, the cost for these surveys using fixed-wing aircraft exceed \$1000/line·km [7]. Additionally, manned aeromagnetic surveys require a crew, which further increases the burden of cost. The growing demand for high-resolution,

small-size surveys ($<1 \text{ km}^2$) to be flown at lower altitudes and the associated cost is the driving factor for pursuing remotely piloted aircraft (RPA) [4, 5].

Figure 1.3 illustrates the effects altitude has on magnetic data. The image on the top left is data taken at low altitude, the other images were simulated to represent the expected signals that would be obtained from data taken at 200 m, 600 m, and 1000 m AGL. To obtain high-resolution data an aircraft must fly low, and to reduce errors in the data the terrain must be followed.

Figure 1.3: Total magnetic intensity based on altitude (image provided by Sander Geophysics Ltd.)

RPAS are capable of flying aeromagnetic survey missions at low altitudes safely, and at a relatively low-cost compared to manned aircraft. There are many RPAS companies that are currently developing or have developed terrain following systems; however, these systems are expensive, proprietary, and not freely available to the public. Therefore, investigating and developing a low-cost, non-proprietary terrain following solution was required.

1.3 Thesis Overview

This thesis presents the results of the investigation and development of a low-cost, non-proprietary terrain following system for low-cost RPAS used to complement manned aeromagnetic surveys. The need to develop a low-cost solution was identified by Sander Geophysics Ltd. (SGL) in the first quarter of 2008. SGL identified capability gaps when performing high resolution, low altitude geomagnetic surveys [8].

This thesis contains a review of relevant literature and the state-of-the-art; a qualitative overview of the technologies used; implementation of those technologies; and the results of the experiments that were undertaken. This thesis is organized into the following chapters:

Chapter 2: background overview of terrain following technologies, digital elevation models, and draping methodologies; and an overview of the software and hardware used.

Chapter 3: the terrain following system requirements, proposed solution and methodology, and the platform selection and sensor integration.

Chapter 4: results of altimetry and horizontal positional tests, and discussion of the results.

Chapter 5: conclusions and recommendations for future work.

1.4 Summary of Contribution

This thesis contributes to the RPAS and geophysics industry. The novelty of this terrain following system being proposed uses low-cost, non-proprietary, off-the-shelf, and sometimes, open-source technologies. This system also implements the use of

Real-Time Kinematic (RTK) GNSS and laser altimetry to complement or take over primary functions of standalone GNSS receivers and barometers, respectively. This approach of combining these two sensor types for terrain following had not been explored.

There have been RPAS enthusiasts developing terrain following systems with low-cost open-source sensors to low-cost RPAs, but there was a lack of published work during the outset of this research. Specifically, there was a lack of aviation quality tested peer-reviewed documented solutions in the low-cost and non-proprietary space; however, the RPAS community has been growing ever since.

During the literature study and experimental research conducted, the work outlined in this thesis were presented in the following conference proceedings:

Shafi, S., & Laliberte, J. (2016, May). *Terrain Following and Draping for Geophysical Survey Missions with Uninhabited Aerial Vehicles*. Abstract presented at the annual joint congress of the Canadian Meteorological and Oceanographic Society and Canadian Geophysical Union, Fredericton, NB.

Shafi, S., & Laliberte, J. (2016, November). *Terrain Following and Surface Avoidance for Geophysical Survey Missions with Uninhabited Aerial Vehicles*. Paper presented at the Unmanned Systems Canada Student Paper Competition (placed third), Edmonton, AB.

Shafi, S., & Laliberte, J. (2017, November). *Terrain Following and Avoidance for Geophysical Survey Missions with Uninhabited Aerial Vehicles*. Abstract presented at the Unmanned Canada 2017 Conference & Trade Show, Toronto, ON.

Chapter 2

Background

This chapter includes the background information that was required for the development of a low-cost, non-proprietary terrain following system for low-cost RPAS. This section covers:

- the traditional technology concerning terrain following for manned missions;
- state-of-the-art terrain following techniques for both manned and RPAS missions;
- a review of digital elevation models required for aeromagnetic surveys;
- an example of creating a mission profile using 3D point cloud data; and
- the qualitative overview of both laser altimetry and GNSS technologies.

2.1 Terrain Following Technology for Manned Missions

Terrain following refers to the ability of an aircraft to follow the spatial distribution and elevation of terrain landform at a prescribed altitude. Historically, terrain following radar (TFR) was a complex class of airborne radar used at low to very low altitude flights, specifically ranging from 30 m to 250 m AGL [1]. This radar technology was developed over 50 years ago under what was known as *Project 666A*. McDonnell Aircraft Corporation, General Electric, and Texas Instruments Defense

Electronics Systems were selected by the United States Air Force (USAF) to participate in this project, which was an automatic terrain following program that took place in St. Louis, Missouri, near McDonnell Aircraft Corporation's headquarters from June 1965 through to December 1966. The goal of Project 666A was to develop and demonstrate the automatic terrain following capability and to provide precise control for guidance and navigational course direction of the McDonnell F-4 Phantom II, a high-performance fighter-bomber aircraft [9] (Figure 2.1). This technology was later equipped into the F-111 Aardvark.

Figure 2.1: McDonnell F-4 Phantom II [10].

The goal of a successful mission is to complete a sortie without detection by flying low enough to avoid enemy radar while avoiding the terrain and any surface objects. To do this, the radar would connect to a flight computer that provides a pilot or on-board flight control system of a specified AGL altitude. TFR was used to covertly penetrate opponent's airspace by flying under enemy radar at high speeds; usually below 150 m AGL at approximately 600 kts airspeed [11].

2.1.1 A Brief History of Radar

Radar stands for "radio detection and ranging". Radar systems use electromagnetic waves to detect and locate objects and operates on a time-of-flight principle. These systems work by transmitting a predefined waveform signal, detects its echo, and measures the time from which it takes the signal to be transmitted and detected to determine the distance of an object (or in this case, terrain) with respect to the transmitter.

In 1886, Heinrich Hertz tested James Clark Maxwell's theory of electromagnetism predicted that electric and magnetic fields are coupled and would travel through space as electromagnetic waves. The equations that predicted this coupling are now known as Maxwell's equations. Hertz leveraged Maxwell's work to demonstrate the similarities between radio and light waves by showing that metallic and dielectric bodies could reflect radio waves [12].

In 1904, a German scientist by the name of Christain Huelsmeyer developed an instrument called the *Telemobiloscope*. The telemobiloscope demonstrated that it could reflect radio waves that could detect the presence of an object; however, it could not directly measure the distance to a target [13].

In 1915, British scientist Robert Watson-Watt became an expert on the use of radio direction finding. He developed a technique that used two antennas to locate a transmission source via triangulation (would later become known as radiotriangulation). He used this technique as an advanced warning to airmen during the First World War [14].

In 1922, during a regular entertainment broadcast that commenced from the Marconi Research Centre at Great Baddow, England, Italian scientist Guglielmo Marconi spoke about the close association between aviation and wireless telephony. In addition, Marconi also discussed how it was possible to design an apparatus that could

transmit radio waves at a ship and receive the reflected radio waves that would reveal the ship's presence, range, and bearing attributes. In the same year, two U.S. Navy researchers, Albert Hoyt Taylor and Leo C. Young placed a transmitter and receiver at opposite ends of the Potomac River and discovered that ships passing through caused the receiver signal to fade. Eight years later, Lawrence A. Hyland, and American electrical engineer at the Navel Research Laboratory (NRL), observed a similar phenomenon from passing aircraft [11].

Just before the World War II (WWII), researchers from all over the world – United Kingdom, France, Germany, Italy, Japan, the Netherlands, the Soviet Union, and the United States – were developing radar technology. In 1934, Maurice Ponte at the Compagnie Générale de Télégraphie Sans Fil (CSF) in France, began developing and obstacle locating radio apparatus. In that same year, the Soviet Leningrad Electrophysical Institute produced an apparatus called RAPID that was capable of detecting the presence an aircraft within 3 km of a receiver [15].

By the end of 1934 full radar evolved as a pulsed system. American engineering Robert M. Page from the Navel Research Laboratory in Washington, D.C., demonstrated the detection of an aircraft using a 60 MHz pulsed radar. The following year this pulsed radar design was also demonstrated by Rudolf Kühnhold in Germany and Robert Watson-Watt in Great Britain [11].

In 1940, Robert Watson-Watt patented his radar unit, which was based on the radar system used during the *Battle of Britain*. By late 1940, Watson-Watt was sent to the United States to advise on air defence after Japan's attack on Pearl Harbor. After being given a knighthood in 1942 and awarded the U.S. Medal for Merit in 1946, Watson-Watt became well regarded and known as the father of radar [15].

2.1.2 Terrain Following Radar

The first TFR system was invented by naval engineer Bert Bechtel at Texas Instruments. This TFR system was designated as the AN/APQ-101, the technology was patented in 1959, and Texas Instruments would produce the majority of U.S. military TFR systems until they were bought out by Raytheon, who would continue producing these systems [11].

The Goal of Terrain Following Radar Systems

Traditional methods of surveillance was used to avoid enemy countermeasures. These methods include the ability to fly as high as possible to avoid immediate detection or faster than the enemy's ability to get a missile lock on and shoot down the aircraft. The former was conducted by the Lockheed U-2 reconnaissance aircraft until it was shot down by Soviet forces on 1 May 1960, which lead to the development of Lockheed Martin's SR-71 Blackbird. The SR-71 was capable of flying faster than Soviet missiles; however, it required long runways that restricted where it could takeoff and land [16]. The requirement of a short takeoff and landing meant that the aircraft would have to fly low to avoid enemy radar; therefore, a TFR was required to fly at low altitudes.

Due to the required nature of short takeoffs and landings meant that the TFR system had two primary objectives it had to accomplish. The first objective is that aircraft detection must be minimized; the second objective is that the aircraft must be able to avoid obstacles safely while detection is minimized [11].

To successfully complete the first objective, the TFR system can minimize detection by minimizing altitude, minimizing time of flight, minimizing radio frequency (RF) signature, maximizing terrain masking, operating at night, and operating in adverse weather. To successfully complete the second objective – in addition for

completing the first objective – the TFR system can avoid obstacles while maximizing flight safety by maintaining a safe AGL altitude and avoid unexpected obstacles and/or weather [11].

Terrain Following Radar Scan

TFR systems use scanning radar technology to scan the airspace in front of the aircraft with vertical scans to obtain height information of obstacles in the flight path trajectory. This system scans the terrain ahead using a vertically sweeping pencil beam. The TFR scans in both the altitude and azimuth directions to gather all terrain and surface obstacle data that is gathered and collected for the aircraft's onboard computer for measurement [17].

Obstacles in the flight path results in a command to the pilot or flight control system to initiate a pull-up manoeuvre. The command to push down is issued once the obstacle is cleared to maintain an appropriate AGL. Since traditional military aircraft were manually flown, algorithms used had safety margins built in to account for pilots' delayed reactions for late pull-up manoeuvre; the trade-off being that the set clearance may often be exceeded and therefore increased the risk of detection. During turns the TFR system will look for possible obstacles that could penetrate the direction of the aircraft's flight path by creating a virtual obstacle warning (OW) line in the direction of flight. When the OW line is penetrated, a warning is issued to the pilot or the onboard computer to initiate a pull-up command [11].

Terrain Following Radar Interface with Other Aircraft Systems

TFR interfaces with multiple aircraft systems. The radar is the input of the TFR system, where the pilot or flight control system would be the output. The TFR generates commands based on radar return about the composition of the terrain and

inputs from other sensors that measure the aircraft speed, attitude, altitude, and acceleration. These inputs determine the aircraft's current state and compares this state with the desired one. To maintain clearance above the terrain, the onboard computer generates appropriate pull-up and push-down commands to the pilot or flight control system [11].

It is worth noting that TFR systems are designed on a per aircraft fleet basis. Since the TFR system is dependent on the current state of the aircraft and compares it with the desired one, the system must be tuned based on the performance of the aircraft during flight tests [11].

Terrain Following Radar Evolution

TFR systems have evolved since the inception of the technology in the 1960s. Earlier analogue systems were slow, made of heavy components, and used vacuum tubes. Later renditions of the technology became more reliable, used lighter components, and had faster processing power with increased hardware and algorithmic complexity [11].

There are four types of algorithms that are used in various types of TFR systems: *Template*, *Angle*, *Advanced Low Altitude*, and *Path Following Algorithms* [11]. Those algorithms can be processed using two different methods: *pulse-by-pulse processing*, which is a method of detecting and reacting to changes in the terrain; and *select point processing*, which relies on an aircraft following historical terrain data stored on an onboard computer.

The **Template Algorithm** was an analogue pulse-by-pulse processing TFR system that was patented by Bert Bechtel in 1959. During flight, this algorithm creates a two-part virtual line between the aircraft and obstacle. The TFR scans and monitors the terrain it sees, the range and angle data of the terrain is collected, and if the terrain or other surface object crosses this virtual line, a pull-up command is

initiated proportional to the range of the obstacle that is in front of the aircraft. As the terrain or object is cleared, the system sends a push-down command until the aircraft reaches its prescribed altitude. The McDonnell Douglas F-4 Phantom II and Ling-Temco-Vought A-7 Corsair II used Bert Bechtel's Template Algorithm TFR system [11, 18].

The **Angle Algorithm** is a more sophisticated version of the Template Algorithm in that it improves short-range manoeuvres. Originally, Angle Algorithm predated digital computing and used analogue electronics; later versions leveraged digital computers as they replaced older analogue ones. There are two variants of the Angle Algorithm: one that relies on pulse-by-pulse processing, and the other on selected point processing; the latter relying on digital computing technology. Angle Algorithm combines antenna scan angle and aircraft pitch angle to determine the relative angle to an object. Clearance angles are approximated by finding the quotient of the desired set clearance and range to the object. A margin factor – tuned to the aircraft's response characteristics – is added to the clearance angle to allow for the push-over point at the peak of the climb so to not drop below the desired set clearance above the terrain. The General Dynamics F-111 Aardvark and Lockheed C-130 Hercules used the Angle Algorithm pulse-by-pulse processing TFR system. Later, the F-111 Aardvark's Angle Algorithm TFR system was upgraded to use selected point processing, which could enable the TFR system to feed pull-up and push-down manoeuvres – typically to the aircraft head-up display – based on terrain data [11].

The **Advanced Low Altitude Algorithm** (ADLAT) was developed at the start of the digital computing age. This algorithm uses complex calculations, such as square root functions, to compute parabolas or high-order polynomials at a respective peak or peaks of points of interest, and continuously calculates as the aircraft approaches these points. The disadvantage of this algorithm is that the aircraft cannot

make instantaneous flight angle changes; therefore, the aircraft tends to exceed the desired set clearance when passing over an object [11]. This algorithm is part of the *Low Altitude Navigation and Targeting Infrared for Night* (LANTIRN) system that combines ADLAT and a targeting system used on the McDonnell Douglas F-15E Strike Eagle and General Dynamics F-16 fighting Falcon. LANTIRN increased the combat effectiveness of aircraft allowing them to fly at low altitudes, at night, and under the weather to attack ground targets [19].

The **Path Following Algorithm** (PFA) requires the most computational power as compared to the previous methods. This algorithm has the ability to track a large number of terrain points to follow the ground more closely and accurately [11]. It relies solely on digital computing and it can process information pulse-by-pulse or through selected point, simultaneously. PFAs are integrated into many autopilot systems and has built in nonlinear control techniques to add robustness to wind disturbances, perturbations, and other environmental effects. These nonlinear control techniques have been developed for path following problems differently for different aircraft. Some of the known techniques are linear quadratic regulator, sliding mode control, model predictive control, back-stepping control, gain scheduling theory, adaptive control, dynamic programming, and the most common approach used in path following is based on proportional-integral-derivative (PID) control [20]. A PFA – using a PID controller – called the *Nonlinear Guidance Law* was tested on the McDonnell Douglas F-18 High Alpha Research Vehicle (HARV) in 1987 [21]. PFA technology is also used in RPAS, autonomous surface vehicles, autonomous underwater vehicles, and unmanned ground vehicles [20].

2.2 Path Following Algorithm for Remotely Piloted Aircraft Systems

For RPA there are several different types of path following algorithms (PFA) that are considered appropriate to use. Some of which include and are not limited to Carrot-chasing, Nonlinear Guidance Law, Pure Pursuit and Line-of-Sight, Vector Field, and Linear Quadratic Regulator based path following algorithms [20].

To follow a path as accurately as possible it is important to understand an RPA's location and trajectory relative to the target waypoint and flight path. The RPA is at a location, $p(x, y)$, heading at an angle of ψ . The distance, D , is calculated by finding the difference between $p(x, y)$ and destination waypoint, W_{i+1} . The flight path angle, Ω , measured by the line that joins the initial waypoint, W_i , with W_{i+1} is used to help determine the heading error, which is the absolute difference between the flight path and heading angle, $|\Omega - \psi|$. The cross-track error, ζ , is the shortest path between the RPA and the flight path. The objective here is to reduce the cross-track error and the difference between the flight path and heading angle during flight.

Aerial path following should not only be accurate to the RPA location and trajectory, but it should also be accurate and robust to wind disturbances [20, 22]. The equations of motion in two dimensions can be described by the following:

$$V_{gx} = V_a \cos \psi + V_w \cos \psi_w \quad (2.1)$$

$$V_{gy} = V_a \sin \psi + V_w \sin \psi_w \quad (2.2)$$

$$V_g = \sqrt{V_{gx}^2 + V_{gy}^2} \quad (2.3)$$

Where:

- V_{gx} is the RPA's ground velocity in the x-direction;
- V_{gy} is the RPA's ground velocity in the y-direction;

- V_a is the air velocity of the RPA;
- V_w is wind velocity;
- V_g is the RPA's ground velocity;
- ψ is the RPA heading angle; and
- ψ_w is the wind direction.

Although any of the previously mentioned PFAs can be used, ArduePilot – which is the flight stack used in the Pixhawk autopilot system (see Section 3.4) – uses a Vector Field (VF) based PFA implementation for both fixed-wing and multirotor RPAs [20].

The most commonly used flight paths are straight lines, circular orbits, or a combination of the two. The objective of path following is to follow a predefined path in two or three dimensions; the former with a constant above mean sea level (MSL) altitude. Therefore, the following sections focuses on the kinematics involving VF PFAs in two spatial dimensions with a constant MSL altitude. Refer to [23] for a detailed overview of VF based PFA implementation of RPAs in three spatial dimensions for variable altitude manoeuvres.

2.2.1 Straight-Line Following Vector Field Based Path Following Algorithm

The idea behind VF PFAs are to indicate the direction of flow with regards to a close-to-optimal path an RPA would take to reach its next waypoint, and not necessarily the flight path that joins the two waypoints (i.e. W_i and W_{i+1}). VF PFAs have two modes:

1. When the RPA is far from the desired flight path; and

2. When the RPA is close to the desired flight path.

The distance between the two is measured by the transition boundary, τ . If the RPA is outside of τ , then the VF PFA is in the first mode, otherwise it is in the second mode. For example, if the first mode is true, the RPA flies towards the path at a desired heading angle, ψ_d . ψ_d is a function of the heading entry parameter, χ_e , which determines time at which the RPA will travel towards the flight path. This function is as follows:

$$\psi_d = \Omega - \rho \chi_e \quad (2.4)$$

Where:

- ρ is a sign function used to determine on what side of the VF path the RPA occupies at that particular moment.

For straight-line following, the performance of the VF PFA varies with different values of χ_e , k , τ , and β . The higher the χ_e , the quicker the RPA will attempt to travel towards the flight path. k is called the proportionality constant [20] or transition gain [23] that is commonly set to a value of 1 [20] and is constrained to $0 < k \leq 1$ [22–24], it characterizes the response time of how the autopilot will maintain RPA's course-hold [22]. τ is a boundary that surrounds the flight path and is a distance that defines whether the RPA is far from or close to the desired path, see Figure 2.2 (a). β controls the convergence space; the higher the value, the closer the RPA will attempt to converge with the flight path regardless the length of the transition boundary [20].

Figure 2.2: (a) Illustration of VF PFA flow, red line represents the flight path, and distance of τ was arbitrarily chosen and is not to scale, and (b) labeled straight-line following illustration of RPA with respect to the flight path. *Image (a) adapted from Figure 9 (a) in [20].*

The following section outlines the pseudocode for a straight-line VF PFA algorithm that is summarized in [20, 22–24]. There are two primary outputs of the algorithm: the commanded flight path angle, ψ_c , and lateral acceleration constraint, u . The former commands the RPA to change its heading towards the flight path, while the latter commands the RPA to either decrease, increase, or maintain its acceleration based on the RPA's current ground velocity and flight path length, D , see Figure 2.2 (b).

Vector Field Straight-Line Following Algorithm (Pseudocode)

Inputs: $W_i(x_i, y_i)$, $W_{i+1}(x_{i+1}, y_{i+1})$, $p(x, y)$, χ_e , τ , V_a , k , β , D

Outputs: ψ_c , u

$$\Omega = \arctan 2(y_{i+1} - y_i, x_{i+1} - x_i)$$

$$s^* = \frac{(p - W_i)^T (W_{i+1} - W_i)}{\|W_{i+1} - W_i\|^2}$$

$$\epsilon = \|p - (s^*(W_{i+1} - W_i) + W_i)\|$$

$$\rho = \text{sign}((W_{i+1} - W_i) \times (p - W_i))$$

$$\epsilon = \rho\epsilon$$

if $|\epsilon| > \tau$, then

$$\psi_d = \Omega - \rho\chi_e$$

$$\psi_c = \psi_d$$

else

$$\psi_d = \Omega - \chi_e\left(\frac{\epsilon}{\tau}\right)^k$$

$$\psi_c = \psi_d - \left(\frac{k\chi_e V_a}{\beta\tau^k}\right)\epsilon^{k-1} \sin \psi$$

end if

$$u = \begin{cases} \frac{-V_g^2}{D} & \text{if } u < 0 \text{ and } |u| > \frac{V_g^2}{D} \\ \frac{V_g^2}{D} & \text{if } u > 0 \text{ and } |u| > \frac{V_g^2}{D} \\ u & \text{otherwise} \end{cases}$$

2.2.2 Circular Orbit Following Vector Field Based Path Following Algorithm

For circular orbit following, the performance of the VF PFA causes the RPA to converge on the flight path circumference. Circular following flight paths are normally used for loitering, or merged with the straight-line following to handle RPA turns from one waypoint to the other. The RPA performance while tracking a circular flight path varies with different values of k and β . The response time sensitivity with respect to k in a circular orbit, so its suggested that $k = 1$ is kept constant. The convergence time to the circular orbit decreases with an increasing β ; however, increasing β does not decrease the convergence time significantly, and it increases the control effort exerted to the RPA [20].

Figure 2.3: (a) Illustration of circular VF PFA flow, and (b) labeled circular orbit following illustration of RPA with respect to the flight path. *Image (a) adapted from Figure 9 (b) in [20].*

The following section outlines the pseudocode for a circular orbit VF PFA algorithm that is summarized in [20, 22, 24]. As it was seen in the straight-line VF PFA (see Section 2.2.1), the circular VF PFA has two primary outputs for the algorithm: the commanded flight path angle, ψ_c , and lateral acceleration constraint, u . The algorithm for the circular orbit is not concerned with the initial and destination waypoint inputs, instead it is interested in the centre location, $O(x, y)$, and radius, R , of the orbit, and the distance, δ , the RPA is from the circumference of the orbit.

Vector Field Circular Following Algorithm (Pseudocode)

Inputs: $O(x, y), p(x, y), x_i, y_i, x_{i+1}, y_{i+1}, R, \delta, V_a, \beta, k, \psi$

Outputs: ψ_c, u

$$\delta = |p - O|$$

$$\Omega = \arctan 2(y_{i+1} - y_i, x_{i+1} - x_i)$$

if $\delta > 2R$, then

$$\psi_d = \Omega - \pi + \sin^{-1}\left(\frac{r}{\delta}\right)$$

$$\psi_c = \psi_d + \frac{V_a}{\beta \delta} \sin(\psi - \Omega)$$

else

$$\begin{aligned}\psi_d &= \Omega - \frac{\pi}{2} - \frac{\pi}{3} \left(\frac{\delta - R}{R} \right)^k \\ \psi_c &= \psi_d - \frac{V_a}{\beta \delta} \sin(\psi - \Omega) - \frac{k V_a \pi d^{k-1}}{3 R^k \beta} \cos(\psi - \Omega)\end{aligned}$$

end if

$$u = \begin{cases} \frac{-V_g^2}{D} & \text{if } u < 0 \text{ and } |u| > \frac{V_g^2}{D} \\ \frac{V_g^2}{D} & \text{if } u > 0 \text{ and } |u| > \frac{V_g^2}{D} \\ u & \text{otherwise} \end{cases}$$

2.2.3 Combining Straight-Line & Circular Orbit Following Vector Field Based Path Following Algorithm

Straight-line paths and circular orbits can be combined to produce a variety of paths. By combining both algorithms, straight-line segments and circular arcs can be approximated to allow the RPA to conduct a mission with multiple turns. Missions like aeromagnetic surveys require an RPA to follow both survey and tie lines to successfully complete the mission. VF PFA handles flight path turns using one of many different methods. Three common methods used however are equal length, through waypoint, and minimum time [22], see Figure 2.4.

Figure 2.4: Illustration of the three common methods used for combining straight-line and circular orbit VF PFAs [22]; **Top:** equal length method; **Middle:** through waypoint method; and **Bottom:** minimum time method.

The equal length method arranges the orbits so that the desired path transitions just before the waypoint. The through method arranges the orbits so that the desired path transitions over the waypoint. The minimum time method uses a single orbit to transition between straight-line segments [22].

The ArduPilot flight stack would have one of the above or its own approach for constructing the vector field to combines straight-line and arc segments. Other than meticulously sorting through the ArduPilot flight stack firmware to determine which approach is used, experimental results show that ArduPilot uses the minimum time method or a method similar to it, see Section 5.2.2 and Section 5.2.3.

2.3 State-of-the-Art Terrain Following for Remotely Piloted Aircraft Systems

There have been several academic studies that have investigated different methods for terrain following and obstacle avoidance that include simulations, trajectory planning, and optical flow for RPAS.

Studies regarding simulations and trajectory planning were important for the practical development and advancement of terrain following and obstacle avoidance technology for RPAS. These studies include:

- Autonomous obstacle avoidance for fixed-wing RPAS, utilizing potential fluid flow theory. Reactively avoiding obstacles by computing the instantaneous local potential velocity vector to change the RPAS trajectory in real-time [25].
- Utilizing fuzzy logic to determine the relationship among the slope of the terrain, aircraft AGL altitude, and speed to perform a two-dimensional terrain following flights [26].
- Utilizing cost and terrain masking functions for real-time terrain following and avoidance. Optimal trajectory is generated by considering the terrain and obstacles, developing manoeuvring constraints, and matching sensor data with onboard terrain data [27].
- Trajectory planning using fuzzy logic and pre-programmed flight plans to compute an optimal path while satisfying RPAS dynamic constraints and safety considerations [28].
- Automatic generation of a terrain following controller using a self-learning terrain following method. This method is based on the markup decision process

machine learning model, which utilizes learning algorithms to optimize RPAS trajectory [29].

Optical flow and vision-based systems were the sought after terrain following sensor due to their cost and weight savings. Although the technology is improving, vision based systems required more computing power than other types of low-weight RPAS friendly sensors such as LiDAR (light detection and ranging) and GNSS receivers. The optical flow and vision based studies include:

- The development of a non-linear terrain following controller for a vertical take-off and landing (VTOL) RPAS that utilizes optical flow with spatially separated non-collinear cameras [30–32].
- Combining a GNSS receiver with a camera to measure the ground speed and AGL altitude of a helicopter RPA [33].
- Using a vision-based height estimation algorithm for terrain following flights by combining a single lens camera with a GNSS and inertial measurement unit (IMU) [34].

Although there is no peer-reviewed literature outlining the use of LiDAR for terrain following, there have been studies surrounding LiDAR use for manned aviation. LiDAR was used to mimic the older radar-based terrain following system used by the military in the 1960s. Similar to radar, this system scans the terrain ahead by using a vertically sweeping pencil beam that scans in both the altitude and azimuth directions to gather all terrain and surface obstacle data. With modern technology, the aircraft flight controller can automatically pull-up or pull-down without a pilot's input [35].

There were no studies that were concerned with GNSS as a primary means for terrain following, specifically for AGL altitude trajectory planning. However, RTK GNSS were used for accuracy assessment of digital terrain models and advanced mission planning for aeromagnetic surveys [36, 37]. Also, GNSS receivers were explicitly used in combination with optical flow devices for RPAS terrain following [33, 34].

2.4 Review of Digital Elevation Models for Uninhabited Aircraft System Applications

Digital elevation models (DEMs) are three-dimensional representations of a terrain's surface created from terrain elevation data. There are two types of DEMs: digital terrain models (DTMs) and digital surface models (DSMs). The former refers to DEMs that represent the bare ground terrain without any objects such as trees and building, and the latter refers to DEMs that represents the earth's surface including all the objects on it. Figure 2.5 contains topographic maps of the Upper British Columbia River Basin – Figure 2.5 (a) on the left is a DSM, and Figure 2.5 (b) on the right is a DTM. Both images are very similar; however, it can be seen that Figure 2.5 (a) has surface objects on top of the terrain. Figure 2.6 is a side view that better illustrates the difference between DSMs and DTMs when concerned with geophysical survey flights.

Figure 2.5: (a) Digital terrain model of the Upper British Columbia River Basin, and (b) digital surface model of the Upper British Columbia River Basin.

Figure 2.6: The difference between DSMs and DTMs.

Both types of DEMs are important for terrain following. Since geophysics is concerned with what is under the ground's surface, it is important to use DTMs to build the flight path and determine the AGL that the RPA should be flying at; however, DSMs are used to determine if there are any surface objects that may exceed the desired AGL – if so, then the flight path or altitude near the surface object may

require adjustment.

As mentioned in Section 2.1, terrain following refers to the ability of an airborne vehicle to follow the spatial distribution and elevation of terrain landform at a prescribed altitude [1]. This prescribed altitude is determined with respect to the terrain elevation above sea level, and not sea level itself. Following an exact contour of the terrain with a fixed-wing aircraft is impractical, and for geophysical applications, it is more effective to employ fixed-wing aircraft; their distance-to-endurance ratio far exceeds that of a rotary wing aircraft.

Fixed-wing aircraft can only manoeuvre over the elevation of the terrain based on the aircraft's flight envelope; more specifically, the aircraft's maximum rates of climb and decent. These rates determine how quickly the aircraft can change its elevation; the higher they are, the more accurately the aircraft can follow the terrain.

If an aircraft were to attempt to follow a flight path that exceeds its flight envelope, it is likely to overshoot or undershoot its desired altitudes and may potentially enter aerodynamic stall. There are no known conventional fixed-wing RPAs that can handle the extremes of following the terrain with sudden peaks and valleys, their aerodynamic limitation would prevent them from instantaneously pitching up or down. Although documentation suggests that the limitation of a percent gradient value is approximately 5% for manned fixed-wing aircraft and 30% for manned helicopters [38], RPAs can have much more aggressive values since they will be uninhabited and can be designed to handle higher rates of climb and descent. Figure 2.7 is an illustration of a flight path an aircraft may take attempting to follow a flight path that contours the terrain.

Figure 2.7: Following terrain with a contoured flight path (not to scale).

Note that in this example, the aircraft is unable to precisely follow the contoured flight path. Although, Figure 2.7 illustrates a generalization of what is to be expected from a fixed wing aircraft, it can be assumed that most fixed-wing RPA would perform similarly.

To accurately collect magnetic data, more specifically the total magnetic intensity readings, the RPA must be capable of closely following the terrain as best as it can, and to do so within its own flight limitations; this can be done by smoothing the flight path [6], and it cannot be any flight path. The flight path rate of climb and descent is limited before the start of the survey operations to which it can be safely maintained by the RPA [39], and the aircraft must follow the elevation of the terrain to maximize the integrity of the data. To do this, it is important to make use of high-resolution DEMs.

Terrain elevation data is made up of point cloud data. Once this data is obtained, a DEM can be constructed using a global information system (GIS) software, such as QGIS, ArcGIS, Global Mapper, or similar GIS packages that may be licensed, proprietary, or open-sourced. Some of these GIS software packages have the capability

of using terrain draping methods to smooth terrain elevations to create a surface that can help build flight paths for which RPAs are capable of flying. Terrain draping is a method used to manipulate the topography of a DEM. A virtual two-dimensional mesh is placed on top of the DEM so that it can be manipulated to serve a purpose. For terrain following, the purpose is to smooth the terrain elevation so that an RPA can follow the terrain without exceeding its structural loads or flight envelope. It is important to note that there are some errors associated with the draping process itself. That is why it is important to use high-resolution DEMs for aeromagnetic operations.

In this regard, creating a smooth drape surface of a DEM depends on two factors: the RPA's rate of climb and descent, and the DEM of the survey area [38]. This implies that a smooth drape surface is unique to both survey area and aircraft. For example, Plevna, Ontario has been of interest to SGL because of its special magnetic gradient. This is a location with folded magnetic metasedimentary rocks that is also an area of considerable mining activity [4]. It makes it an excellent location for aeromagnetic test flights. A sample of a high-resolution DEM and a smoothed draped version with a 150 m offset of Plevna was provided by SGL, see Figure 2.8 (a) and Figure 2.8 (b). The draped version of the DEM was smoothed using rate of climb and descent angles that the *Cessna 208B Grand Caravan* handle – the primary aircraft SGL uses for aeromagnetic surveys. These images were constructed using high and low altitude airborne magnetic data, and magnetic data that was collected by a ground crew [39].

Figure 2.8: (a) Digital elevation model of Plevna, ON, and (b) Draped surface of Plevna, ON, with a 10% gradient and a clearance offset of 150 m AGL. *Images provided by Sander Geophysics Ltd.*

Data can be extracted from the draped image and used to construct survey lines with flight paths that will conform with the RPA's flight envelope. An example of survey lines created using the draped surface model of Plevna, Ontario can be seen in Figure 2.9. It is important to note that most aircraft have a better rate of climb than descent; its rate of climb performance would determine the direction that survey lines would be placed, and the direction an aircraft would traverse through those survey lines.

All encircled numbers within the survey lines represent a waypoint. Depending on the mission planning software being used, each waypoint can contain the position and altitude associated with it, and the percent gradient, angle, and distance from the previous waypoint. This data is loaded on an onboard flight computer for a pilot to follow or loaded on the autopilot of an RPAS for automatic terrain following flights.

Figure 2.10 illustrates an example of the expected behaviour of an aircraft when flying a smoothed flight path; this approach will prevent the RPA from overshooting

or undershooting its desired AGL, and will maximize the quality of the magnetic data.

Figure 2.9: Sample survey coordinates data for Plevna, Ontario [6].

Figure 2.10: Following the terrain with a smoothed flight path (not to scale).

2.5 Review of Mission Planner Mission Planning Software

Mission Planner is a ground control station (GCS) software that is used for fixed-wing and multirotor RPAs. This software is used as a configuration utility or as a dynamic control supplement for automatic flight RPAs. Mission Planner is capable of:

- loading firmware onto an autopilot board that controls the RPA;
- optimizing performance by setting up, configuring, and tuning the RPA;
- planning, saving, and loading automatic missions onto the autopilot with simple point-and-click way-point entry on Google or other maps;
- downloading and analyzing mission logs created by the autopilot;
- interfacing with flight simulators to create a hardware-in-the-loop RPAS simulator;
- monitoring the RPA’s status while in operation;
- recording, view, and analyze telemetry and autopilot logs; and
- enabling first person view RPA operations.

Mission Planner uses the ArduPilot flight stack. ArduPilot is an open source, RPAS autopilot software suite, capable of automatically controlling:

- multirotor RPAs;
- fixed-wing short, vertical, and long take-off and landing RPAs;
- ground rovers;

- antenna trackers;
- remotely controlled helicopters;
- remotely controlled boats; and
- remotely controlled submarines.

2.6 Overview of Laser Altimetry Technology

Most off-the-shelf RPAs use either barometric, ultrasonic, optical flow, or a combination of all three readings to determine the AGL (or above sea level) altitude. On the other hand, if RPAs utilized laser altimeters for measuring altitude, it should theoretically perform better since the other sensors have a shorter operational range (i.e. ultrasonic sensors) or are prone to larger errors (i.e. barometers and optical cameras).

2.6.1 Laser Altimetry Overview

Laser – an acronym for Light Amplification by Stimulated Emission of Radiation – is a collimated beam of light which has a low beam divergence, meaning the beam radius of the light will undergo minimal changes as it propagates. A light source can be collimated with a combination of lenses and curved mirrors to flatten the curve wave fronts of the light; in other words, the uses these lenses and curved mirrors causes light to focus [40].

Laser altimeters are rangefinders that use beams of light to measure the height AGL altitude of aircraft and RPAS. The most common forms of laser altimeters operate on the principle of time-of-flight; this is done by sending a narrow beam towards an object and measuring the time it takes a pulse or continuous wave (CW) of light to reach its destination and return [41]. Most laser altimeters have one emitter

and one receiver ; the emitter shoots out beams of light onto a surface for which the light then scatters (Figure 2.11 (a)); some of that scattered light is detected by the receiver, and the time of which the light left the emitter and detected by the receiver is measured (Figure 2.11 (b)), and as a result the height above ground can be calculated with following equation:

$$h = (t_1 - t_0) \times c \quad (2.5)$$

Where:

- h is the height above ground level;
- t_0 is the initial time of which the laser light/pulse leaves the emitter;
- t_1 is the time of which the laser light/pulse enters the receiver; and
- c is the speed of light.

Figure 2.11: Laser altimeter beam (a) exiting the emitter (Ex) scattering off the surface, and (b) being detected by the receiver (Rx).

2.6.2 Laser Classification

Light that exits a laser emitter is non-ionizing radiation that can be used for a range of applications, and their use is quite widespread; however, lasers can pose significant hazards that include eye injury, burns, and fire. Due to these hazards, control measures must be in place to mitigate these associated risks; therefore, international laser classifications have been put in place as a measure of control and safety [42, 43]. Seven classes of lasers are recognized: Class 1, 1M, 2, 2M, 3R, 3B, and 4 [43].

Class 1 and 1M lasers are the most appropriate out of the other class of lasers for RPAS application. Lasers in this class exist in the red to infrared light spectrum (>700 nm) and have a CW power of <1 mW. These lasers are considered to be safe when used under normal conditions, and are considered incapable of causing injury. Class 1 lasers are typically low powered where even telescopes or microscopes of normal power can be used to collect the beam without harm to the eye or skin; however, class 1M lasers that are collected can magnify the light being emitted, which can damage the eye. [42, 43]. Other more powerful classes of lasers are not appropriate for use with RPA and will therefore not be discussed. Refer to [42, 43] for more information on these classes of lasers.

2.7 Qualitative Overview of Global Navigation Satellite System

The size of the RPAS market has been growing fast. Globally, RPAS unit sales grew an estimated 60% to 2.2 million units from 2015 to 2016, and that number is expected to triple by 2021 [44]. With increasing demand for this technology and regulatory and airspace access rules, the accuracy requirement to determine the position of RPAS have become more critical in the commercial market, especially in the geophysics industry. In a typical outdoor environment, consumer grade Global Navigation Satellite

Systems (GNSS) can provide an average of 10 m to 15 m of real-time point position solution. Small RPAS – between 250 g and 1 kg – equipped with RTK GNSS technology can potentially achieve centimetre-level accuracy for low-altitude aeromagnetic survey missions. Level of accuracy can be improved even further with Precise Point Precision and Satellite Based Augmentation Systems, which are covered in Section 2.7.2 and Section 2.7.5, respectively.

This section will focus on GNSS technologies offered by the United States, known as the Global Positioning System (GPS). The Global Orbiting Navigational Satellite System (GLONASS), offered by the Russia, and Galileo, offered by the European Union will not be discussed in detail since they are very similar to GPS. Most commercially available GNSS receivers in North America are GPS receivers that are also compatible with GLONASS and Galileo.

The first GNSS technology was designed, financed, deployed, and operated by the *United States Department of Defense*. It was originally called *The Navigation Satellite Timing and Ranging (NAVSTAR) Global Positioning System*; now it is popularly known as GPS. This system is a satellite-based one-way ranging radio-positioning system that was designed as an all-weather, continuous, global radio-navigation system [45].

2.7.1 Global Positioning System Services and Signals

GNSS satellites transmit microwave carrier signals to enable GNSS receivers to determine its location, velocity, and time. These signals carry the navigation message that measures the distance the receiver is with respect to a GNSS satellite.

For GPS, there are four microwave carrier signals available for civilian use: L_1 C/A, L_1 C, L_2 C, and L_5 [47]. The two more frequently used signals are L_1 C (1575.42 MHz) and L_2 C (1227.60 MHz) [46]. The L_1 C and L_2 C signals carry the navigation

messages, which include satellite clock corrections; ephemeris data that provides information about the time and status of the entire satellite constellation (known as the *almanac*); and pseudorandom noise (PRN) codes, such as Coarse/Acquisition code (C/A) code and Precision code (P-code). The C/A and P-codes are so complicated that they appear to be noise at first, but they are PRN codes. PRN consists of a deterministic sequence of pulses that will repeat itself after its period [46, 48].

2.7.2 Standard Positioning Service and Precise Positioning Service

The GPS Standard Positioning Service (SPS) is a positioning, navigation, and timing service that broadcasts at the L_1 frequency. The L_1 C/A carrier signal, that is known as the *legacy signal*, contains the C/A code that is freely available to the public, and the restricted P-code that is reserved for authorized use. In 2000, the United States Congress began its GPS modernization effort to introduce the other carrier signals (L_1C , L_2C , and L_5). These *modernized signals* are used for the GPS Precise Positioning Service (PPS) that broadcasts at L_1C , L_2C , and L_5 . Only L_1C and L_2C are available for the public; L_5 is used to provide the means of radio navigation that is secure and robust enough for life critical applications. Precise Point Positioning (PPP) is a technique that utilizes GPS PPS that removes or models GPS system errors to provide a high level of position accuracy from a single receiver. PPP can deliver an accuracy close to ± 3 cm [51].

With real time or post-processing differential correction, the accuracy can improve by orders of magnitude. C/A code is used by 99% of users that can be found in most GPS enabled mobile devices such as smartphones, and other Subscriber Identity Module (SIM) enabled devices. PPS provides decimetre to millimetre level positioning accuracy, but it can take time for the receiver to converge and achieve a steady state solution. Relative positioning involves the determination of a vector between a known

and unknown point. Raw data from a moving rover is combined in an RTK solution through a communication link with raw data from a static base station to improve the rover's position. Assuming the base station is at a known position, the rover can provide centimetre level accuracy with differential correction [45].

2.7.3 Global Navigation Satellite System Receiver Position in Three-Dimensional Space

GNSS satellites exist in three-dimensional space that orbits the Earth. For GPS there consists of at least 24 operational satellites, which four exists in each of six orbital planes [45, 57].

GNSS uses a technique called trilateration to determine the location of its receivers. Trilateration is the process of determining absolute or relative locations of points by measurement of distances using the geometry of triangles, circles, or spheres. With respect to GNSS satellite locations, this trilateration technique leverages the geometry of spheres [48].

Assuming that the location of GNSS satellites with respect to a receiver are known, if one satellite is at a specified distance from the receiver, then it can be inferred that the position of the receiver can exist anywhere on the surface of a sphere that is formed around that satellite [48, 51] (Figure 2.12 (a)).

If a second satellite is at a specified distance from the receiver, then the position of the receiver will be limited to the area of a circle formed by the two intersection spheres [48, 51] (Figure 2.12 (b)).

If a third satellite is at a specified distance from the receiver, then the position of the receiver will be limited to the two intersecting points of all three spheres [48, 51] (Figure 2.12 (c)).

Any additional satellites are unlikely to intersect through the two intersecting

points. Instead, the fourth satellite helps calculate a timing location correction and pseudorange to select one of the remaining two points as the correct position [48, 51] (Figure 2.12 (d)).

Figure 2.12: The receiver can exist: (a) anywhere on the surface of the sphere; (b) anywhere limited to the area of the two intersecting sphere; (c) on one of two points of the three intersecting spheres; and (d) at a single logical point selected based on time and range corrections.

In practice, GNSS works such that at least six satellites are always visible to a receiver located anywhere on Earth [51].

2.7.4 Global Positioning System Sources of Error

There are several sources of error that degrade the quality of GPS solutions which must be considered:

Table 2.1: Sources of error.

Source of Error	Approximate Error Magnitude (m rms)
Ionospheric Effects (~ 50 km to ~ 1000 km)	≤ 30
Tropospheric Effects (≤ 50 km)	≤ 25
Satellite Orbit (Sagnac Effect)	≤ 10
Satellite Clock (Relativity)	≤ 3
Multipath Effects	≤ 5
Dilution of Precision (DOP)	Variable

Ionospheric Effects

The Ionosphere is part of Earth's upper atmosphere that covers an region from approximately a 50 km to 1000 km altitude, which includes part of the Mesosphere, Thermosphere, and part of the Exosphere. This region of atmosphere is mostly composed of weakly ionized plasma or gas. The presence of charged particles due to ionization makes the upper atmosphere an electrical conductor and influences the passage of radio waves causing them to diffract, to be out of phase, or both. Within the Ionosphere, the density of the atmosphere and ionized particles varies with altitude, time of day, location, and season [45, 48, 58]. Errors associated with ionospheric effects are larger for low elevation satellites, which can become problematic when operating GPS at higher latitudes [59].

Tropospheric Effects

"Tropospheric effects" exist in a region that extends up to 50 km of our atmosphere that includes both the Troposphere and Stratosphere. This region of atmosphere

is electrically neutral and consists of dry gasses and water vapours. The wet and dry constituents of the atmosphere, which have different pressure profiles, affect the propagation delay of the radio frequency signals quite differently. The dry gasses causes 90% of tropospheric refraction, whereas the wet portion only contributes to 10% [45,48,58]. Errors associated with tropospheric effects are larger for low elevation satellites, which can become problematic when operating GNSS at higher latitudes [59].

Satellite Orbit (Sagnac Effect)

GNSS satellite positions are calculated using the Earth-Centred Inertial (ECI) frame of reference. The ECI frame is a freely falling, local, non-rotating inertial frame with its origin at Earth's centre. The Sagnac delay effect is caused by the Earth's rotation during transit time of the satellite signal from the satellite to the ground receiver – the reception signal from the satellites travel an extra distance during the propagation time due to Earth's rotation [45,48].

Satellite Clock (Special and General Relativity)

Relativity errors occur due to time dilation from relative satellite velocity (Special Relativity) and Earth's gravity (General Relativity). Due to GNSS satellite orbital speeds, their clocks tick slower relative to a stationary clock on the ground; and, due to Earth's mass, clocks on the surface tick slower than the clocks in orbit. Additionally, receiver clocks are not as accurate as atomic clocks used in GNSS satellites. Both receiver and satellite clock error components are multiplied by the speed of light. For example, a clock error of 1 ns can translate into a 30 cm range error. If not corrected, receiver clock errors will increase over time, which would increase the range error even further [45,48].

Multipath Effects

Multipath is phenomenon whereby a signal arrives at a receiver via multiple paths attributed to reflection and refraction; this is caused by structures such as buildings, cliffs, hills, mountains, etc., before reaching the receiver. Signal multipath errors are larger for low elevation satellites, which can become problematic when operating GNSS at higher latitudes [59]

Dilution of Precision

Dilution of Precision (DOP) is concerned with a receivers positional accuracy as a function of the geometry of the satellites it is connected to. DOPs are dependent on the directions of arrival of the satellite signals, which means it is a function of the geometry of the visible satellites [45, 48]. When visible GNSS satellites that are connected to a receiver are close together, the geometry of the connected satellites are considered to be weak (Figure 2.13 (a)); if the GNSS satellites are far apart, the geometry is considered to be strong [48] (Figure 2.13 (b)).

Figure 2.13: (a) GNSS receiver that has a poor GDOP, and (b) GNSS receiver that has a good GDOP [60].

Corrections for the DOPs, Sagnac effect, and satellite clocks are built into the

GNSS system. Since the position of a receiver is calculated using trilateration, a good geometric spread of satellites is a key factor to achieving more accurate positional solutions to reduce errors associated with DOP. Both the Sagnac effect and satellite clocks are corrected by the satellites broadcasting navigation messages used to correct the receiver clocks and relativistic errors caused by the Sagnac delay. [45].

Mitigating Sources of Error

There are ways to mitigate the sources of error in single band GPS SPS receivers. For example, GPS receivers found in modern cellphones use sophisticated prediction algorithms to reduce the magnitude of error to lower than 10 m. Additional location algorithms are used in GNSS applications to reduce those errors even further by triangulating a user's position based on the cellphone towers they are connected to.

Dual band GPS PPS receivers operate at both the L_1 and L_2 frequencies, can correct for ionospheric errors by taking advantage of the dispersive nature of ionospheric delay by combining the P-code pseudorange measurements on both frequencies. Another method is to use correction data for post-processing – accurate ionospheric correction, tropospheric correction, satellite ephemeris, and satellite clock data is published by multiple sources several days post factum. Two primary means of improving real-time GPS solution quality is through *Differential GPS* (DGPS) and RTK GPS, where there is a moving receiver and a fixed receiver at a known point [45, 48].

2.7.5 Differential Global Positioning System and Real Time Kinematics

Both DGPS and RTK GPS use two receivers simultaneously: one for the base station, and the other for the rover. It is assumed that both receivers will be relatively close to each other, and both will experience similar atmospheric effects and be affected by the same variability in satellite ephemeris and clock data to mitigate some of the errors.

Ephemeris and clock data is collected by the base station, which is setup at a fixed location that is either known or could be determined via post-process. Corrections from the base station are sent to the rover in real-time via communication link, or stored to be post-processed later [45, 61]. This is where the similarity ends between these two types of GNSS systems.

Due to atmospheric effects there are going to be errors associated with the computation of pseudoranges due to phase delays. Pseudorange is used to compute the position of a GNSS receiver [45], it is an estimated distance between a navigation satellite transmitter and the navigation satellite receiver, which is determined by the amount of time it takes the signal to travel from the transmitter to the receiver and back [52].

DGPS circumvents errors associated with the computation of pseudoranges by placing the base station at a known position, therefore the correction for these errors can be estimated. If the roving receiver is near the base station, it assumes that the pseudorange errors will be the same. The roving receiver then applies the corrections for its own pseudorange errors to give it a more accurate position [51]. In theory, the accuracy for this technique should be less than 1 m. The computations required can be done in real-time or post-processed.

RTK GPS is a type of DGPS; however, it not only uses pseudoranges for computing position, but it also uses carrier phase tracking for more accurate measurements. Carrier phase tracking is an accurate mean of positioning used in GNSS surveying applications. The wavelength of the carrier phase is equal to the product of the period of the carrier frequency times the speed of light ($\lambda = fc$). For the GPS L_1 C carrier signal, and with a 1% wavelength accuracy, the error of the pseudorange can be as little as 2 mm [62].

To utilize carrier phase tracking and to leverage accurate pseudorange solutions,

a specifically equipped receiver is required that can measure the total phase. At least two receivers are needed, one for the base station and the other for the rover, to track carrier signals at the same time. The carrier phase is tracked by both receivers, and the changes in the tracked phase are recorded over time. The phase difference changes in both receivers are reduced using software to differences in the three spatial dimensions between the base station and rover [62]. Since a base station is required for RTK GPS, there are a few choices regarding the selection of a reference base station:

Local Base Station at a Known Location

To leverage RTK solutions, a base station can be setup at a known location. Survey markers can be found all over the world. In Ottawa and throughout Canada, there are several survey markers that have been embedded into the ground in different locations that have geographic coordinates are engraved into them. Theoretically, a base stations can be placed at one of these markers and its GPS location can be manually changed to reflect its actual location. Knowing the actual location can allow the base station to generate atmospheric and satellite error corrections to send to a rover; how it generates these corrections all depends on the quality of the GPS unit being used. A major caveat to this method is based on the location of these survey markers – most of them are within city limits, outside where most airborne geophysical survey missions would occur, and it is likely be surrounded by surface objects such as trees, building, and other objects that could obstruct satellite line of sight. For example, survey markers in Ottawa happen to be in areas with either a lot of foliage cover or surrounded by buildings; this reduces the area of satellites the GPS can connect to, which in turn could increase the DOP significantly.

Network Transport of RTCM via Internet Protocol

Network Transport of RTCM via Internet Protocol (NTRIP) is a non-proprietary protocol, created by the German Federal Agency for Cartography and Geodesy, for streaming DGPS and RTK GPS data over the Internet in accordance with specifications published by the Radio Technical Commission for Maritime Services (RTCM). It is a protocol based on the Hypertext Transfer Protocol HTTP/1.1, which is enhanced to handle GNSS data streams. NTRIP is a standard designed for disseminating differential GNSS correction data to GNSS receiver equipped base stations and rovers over the Internet. NTRIP corrections can be sent simultaneously to multiple mobile devices to act as *NTRIP casters*. Those mobile devices can cast corrections to multiple base stations, rovers, or both [63].

NTRIP uses a fixed nearby user-selected reference station from a network of reference stations. A reference station that is part of an NTRIP network is known as a continuously operating reference station (CORS) that constantly receives observation data from available satellites to more accurately correct for atmospheric and satellite orbit errors [45, 63].

To use this service, a receiver needs to have the capability to connect to the Internet, usually through a SIM activated device that can connect directly to the internet. Although there are some NTRIP service providers that offer a free service, most reliable service providers have a fee associated with their service. With NTRIP registration, a username, password, IP address, and port number is given to the NTRIP client to access the network through NTRIP servers to obtain real-time corrections [45, 63].

A rover using NTRIP can take advantage of RTK corrections without having to setup a base station. Alternatively, NTRIP can also be used to determine the absolute location of a base station. In turn, that base station can send reliable corrections to

one or multiple rovers in real-time.

NTRIP accuracy varies depending on the DGPS or RTK GPS modules being used. For example, the *Emlid Reach* RTK GPS modules specify a minimum static horizontal and vertical accuracy of 5 mm and 10 mm, respectively; and a minimum kinematic horizontal and vertical accuracy of 7 mm and 14 mm, respectively. However, for every additional kilometre a client is away from the NTRIP station, the horizontal and vertical accuracy is reduced by an additional 1 mm and 2 mm, respectively. For acceptable performance in static mode the recommended baseline (separation distance) is 20 km, and in kinematic mode the recommended baseline is 10 km [64]. Theoretically, if a user is sending real-time corrections to a rover 5 km away from the NTRIP station, then that user should expect horizontal and vertical accuracy corrections no better than 12 mm and 24 mm, respectively.

Chapter 3

Proposed Solution & System Architecture

As outlined in Section 2.7, technology within the RPAS industry has been advancing at a geometric rate [44]; this includes both follow-me and terrain following technologies. Automatic terrain following is nothing new. Many companies – such as DJI – have already developed it, but they keep their intellectual property a guarded secret.

This chapter presents an overview of the research and development of a non-proprietary open-sourced terrain following system for low-cost RPA using easy-to-access, simple-to-purchase, off-the-shelf parts.

Based on the best practices for RTK GNSS surveys found in the *Guidelines for RTK/RTN GNSS Surveying in Canada* [68] written by Natural Resources Canada and the Ministry of Transportation, this section also discusses the:

- selection of an appropriate test-bed platform for terrain following tests;
- the RPAS aeromagnetic system requirements;
- selection of an appropriate open-source, low-cost, off-the-shelf RPAS autopilot system;
- platform modification and integration of a low-cost, off-the-shelf laser altimeter;
- assembly and integration of an RTK base station and RPA receiver using low-cost, off-the-shelf technology;
- assembly of the GCS; and

- terrain following RPAS architecture.

Figure 3.1 is a high-level block diagram of the terrain following RPAS being implemented.

Figure 3.1: High-level block diagram of the terrain following RPAS.

3.1 Platform: 3D Robotics 3DR Iris⁺

The proposed platform to be used for aeromagnetic survey flight tests is a one-third scale electrically converted *Piper Pawnee* made mostly of balsa wood (Figure 3.2 (a)); however, this platform was not chosen to test the terrain following system because the cost of this RPA exceeds \$10,000 CAD; an alternative platform – 3D Robotics’ 3DR Iris⁺ – was selected (Figure 3.2 (b)). This RPA was designed and manufactured by 3D Robotics, which was a relatively low-cost ($\sim$ \$1000) off-the-shelf RPA that is well-built. Due to the result of mismanagement and stiff competition, 3D Robotics had to discontinue manufacturing RPAs and instead focus on software and service provision [69]. Despite the fact that the Iris⁺ was discontinued, 3D Robotics shared all of their engineering drawings and computer aided design (CAD) files for the Iris⁺

so that users can construct the RPA for themselves.

Figure 3.2: (a) A one-third scale electrically powered Piper Pawnee fixed-wing RPAS, and (b) a 3DR Iris⁺ quadroter RPAS

Although the Iris⁺ is not a fixed-wing RPA, automatic flight tests were setup such that Iris⁺ flew continuously through waypoints as if it were a fixed-wing RPA. The advantage of using a multirotor RPA for terrain following tests is the ability to stop at a fixed position during mid-flight. If anything were to go wrong during an automatic flight, the pilot in command (PIC) can take control of the RPA at any time.

The advantage the Iris⁺ has over other off-the-shelf platforms is its modular design. The motor arms and bottom, interior, and top plates can all be remove, replaced, or modified. The motors, GPS modules, antennas, receiver, and *Pixhawk* autopilot system are all off-the-shelf, non-proprietary components. This lack of technical proprietorship, makes swapping, repairing, and replacing parts easy. The Iris⁺ was appropriate for terrain following tests because of its robustness and ability to handle impact better than most RPAs its size.

3.2 Aeromagnetic Terrain Following System Requirements

The aeromagnetic system requirements established for the Pawnee RPA was outlined in the *GeoSurv II System Requirements Document* that was published for a Carleton University built fixed-wing aeromagnetic RPA in 2008 [8]. Those requirements are still relevant for the Pawnee and Iris⁺. However, a new set of system requirements

were developed for Iris⁺, since the terrain following system will be utilizing low-cost, non-proprietary parts. This system requires that:

- the RPA position be accurate to within 30 cm;
- the RPA is capable of maintaining a minimum altitude of 10 m; and
- the terrain following system cost less than \$2000 CAD;

There were a few changes from the original system requirement document (SRD). The horizontal position and altimetry accurate to within 60 cm. 30 cm was chosen because the Iris⁺ was a low weight multirotor RPA with better manoeuvrability than GeoSurv II or Pawnee. Also, there was no cost ceiling in the original SRD; \$2000 CAD was chosen because many off-the-shelf RPAs (e.g. DJI Phantom) fall into this price range.

3.3 Remotely Piloted Aircraft System

As it was explained in Section 3.1, The 3DR Iris⁺ was selected as the terrain following aircraft. The goal was to develop a terrain following system for fixed-wing RPAS equipped with appropriate geophysical survey grade magnetometers. This fixed-wing RPAS would contain two primary systems: the *Geophysics RPA* and a *Ground Control Station*. The Geophysics RPA contains four subsystems: the Magnetometer, Data Logger, and Aircraft Flight Control Subsystem. The Magnetometer Subsystem is responsible for collecting magnetic readings; the Data Logger subsystem is responsible for storing crucial data and time stamping it from a GNSS unit; and the Aircraft Flight Control Subsystem is responsible for aircraft and automatic flight controls. The Terrain Following System lies within the Aircraft Flight Control Subsystem. Figure 3.3 is a block diagram that illustrates the *RPAS Geophysics System* architecture.

This section will focus on the terrain following system, the GCS required to operate the system, and the 3DR Iris⁺ as its platform.

Figure 3.3: RPAS Geophysics system architecture.

As it can be seen in Figure 3.3, the three main components of the Terrain Following System are the RTK GNSS module/receiver, laser altimeter, and autopilot system. The RTK GNSS module, laser altimeter, and autopilot selected for the terrain following system are the *3D Robotics 3DR PX4 Pixhawk* (version 1) autopilot system (Figure 3.4 (a)), *Emlid Reach RTK GNSS* receiver (Figure 3.4 (b)), and *Garmin Lidar Lite V3* (Figure 3.4 (c)).

Figure 3.4: (a) Emlid Reach RTK GNSS receiver, (b) Garmin Lidar Lite V3, and (c) Pixhawk autopilot system.

3.4 3D Robotics 3DR PX4 Pixhawk Autopilot System

The Pixhawk is an independent open-source autopilot system that provides a standard for low-cost (under \$300 USD), off-the-shelf, non-proprietary, and quality designs for academics, hobbyists, and developers. It can be used as a remote or automatic control system for remote ground, water, underwater, and aircraft systems. For RPAS, Pixhawk supports both PX4 and ArduPilot flight stacks (autopilot software). There are many variations of autopilot systems that are part of the Pixhawk brand; each of which are compatible with several open-source mission planning software packages. This autopilot system was also selected because it integrates easily with low-cost, off-the-shelf sensors such as the Reach and Lidar Lite. Additionally, the Iris⁺ comes equipped with an included Pixhawk as its autopilot and flight control system.

3.5 Garmin Lidar Lite V3

The Lidar Lite was designed to act as a low-cost laser rangefinder used for distance measuring, obstacle avoidance, object detection, or aircraft altimetry. For terrain

following, RPAS altitude accuracy needs to depend on more accurate altimetry measurements than it would be provided by the onboard Pixhawk barometer, or any small scale solid-state barometer built for small scale remotely piloted vehicle. Barometer readings are susceptible to errors caused by sudden changes in air pressure and temperature, where as laser rangefinders are not affected by such environmental changes.

The Lidar Lite is a non-proprietary off-the-shelf pulsed, class 1, topographic laser rangefinder solution with a 40 m range under most operating conditions, and capable of measuring ranges with at a 1 cm resolution. The Lidar Lite system specifications are as follows:

Table 3.1: Garmin Lidar Lite V3 system specifications.

Cost:	\$150 USD
Wavelength:	905 nm (near IR)
Range:	0 - 40 m
Laser Power (peak):	1.3 W, Class 1
Sample Rate:	270 Hz
Accuracy < 5 m:	± 2.5 cm
Accuracy ≥ 5 m:	± 10 cm
Resolution:	1 cm
Power Supply Voltage:	$5.0 \pm$ VDC
Power Supply Current:	135 mA (max)
Dimension:	20 x 48 x 40 mm
Weight:	22 g
Beam Divergence:	0.46 degrees
Operating Temp.:	-20 to 60°C
Interface:	I ² C, PWM

3.5.1 Garmin Lidar Lite V3: Hardware Integration

The Lidar Lite was designed to integrate with several types of devices, and it can be used as a rangefinder or altimeter depending on its installation and orientation. Also, this product has the capability of integrating with many off-the-shelf autopilot systems such as the Pixhawk. The Lidar Lite has two connection options, both of

which are compatible with the Pixhawk: I²C and pulse-width modulation (PWM). Although PWM would work, I²C was chosen because in Mission Planner it is a supported protocol for the Lidar Lite. With this support, the Lidar Lite can be selected and configured directly within the Mission Planner software.

The Lidar Lite cannot simply connect to the Pixhawk I²C bus. The I²C port cannot supply enough power to the Lidar Lite for it to work properly; therefore, a battery eliminator circuit (BEC) was required. Additionally, Garmin recommends some modification to the I²C connection wire prior to installation. A 680 μ F capacitor was installed between the ground and a 5 V lead of the BEC, and two 47 pF capacitors were installed between the SDA signal wire and ground and between the SCL signal wire and ground, respectively [70–72]. The 680 μ F capacitor acted as a shunt to reduce the current being drawn from the Lidar Lite; without the capacitor, the BEC will have attempted to draw too much current, causing the Lidar Lite to not function. The 47 pF capacitors were used to reduce the variable noise of the signals and to reduce hysteresis looping [71, 72]. Figure 3.5 illustrates how the Lidar Lite interfaces with the Pixhawk.

Figure 3.5: Lidar Lite connection diagram.

The BEC used was connected to the Lidar Lite with the Pixhawk was the YEP 20A SBEC (see Figure 3.6). This BEC has jumpers to configure the voltage that is connected to the Lidar Lite, which was set to 5 V since the potential of the 3S Lithium-Polymer (LiPo) battery used in the Iris was rated at 11.1 V.

Figure 3.6: YEP 20A SBEC.

3.5.2 Garmin Lidar Lite V3: Iris Modification

For the Lidar Lite to function properly, some modifications to the Iris fuselage and internal components was required. These modifications included:

- Attaching a power and ground wire with an attached female XT60 connector to the power distribution and 4-in-1 ESC board;
- cutting out a pass-through for the XT60 connector on the ventral plate of the Iris⁺;
- assembling the Lidar Lite connection wire; and
- designing and manufacturing a Lidar Lite attachment plate for the Iris⁺.

To wire the XT60 connection for the BEC, the ventral plate of the Iris⁺ was removed to expose the power distribution and 4-in-1 ESC board. This board connected directly to the battery and provided power to the motors. The battery and power connections were soldered directly onto the board's power leads. The XT60 wire was soldered directly to these leads, which gave the BEC direct access to the battery. The power distribution and 4-in-1 ESC board with the XT60 modification can be seen in Figure [3.7](#) below.

Figure 3.7: XT60 modification on the power distribution and 4-in-1 ESC board.

A pass-through was cut out for the XT60 connector on the ventral plate of the Iris⁺. Using a handheld rotary saw (the Dremel 4000), a 21.5 mm x 11.0 mm pass-through was cut out of the starboard side of the battery installation bay, see [Figure 3.8](#).

Figure 3.8: Starboard side pass-through cutout of the Iris⁺’s ventral plate.

Assembling the Lidar Lite connection wire involved soldering – in parallel – the 680 μ F capacitor to the power and ground wire of the BEC servo connector; and soldering the 47 pF capacitors to between the SDA and ground and the SCL and ground to the wire of the I²C connector. The SDA and SCL wires were from the Lidar Lite connector was connected to their respective 47 pF capacitor leads. The power wire from the Lidar Lite connector was soldered onto the positive lead of the 680 μ F capacitor. All three connectors share the same ground and were soldered together. Figure 3.9 is a picture of the assembled Lidar Lite connection wire.

Figure 3.9: Lidar Lite connection wire.

The Lidar Lite attachment plate (see Figure 3.10) was designed using Tinkercad, a simple online web-based 3D CAD program. Each hole has narrow spacing for M4 machine screws, which are the screw sizes used to assemble and attach a gimbal to the Iris⁺. The attachment plate was built to fit the gimbal installation holes.

Figure 3.10: 3D CAD of the Lidar Lite attachment plate.

After modification, assembly, and manufacturing were completed, all components were connected and the Iris⁺ was reassembled. The connection wire was connected to the I²C bus, and both the BEC servo wire and Lidar Lite connector was fished out of the ventral ventilation grill to connect the Pixhawk and power distribution board with the Lidar Lite and BEC, respectively. Figure 3.11 shows a ventral view of the Iris⁺ with the Lidar Lite attachment. Note that there is a 5 V, 1 A lithium ion battery pack attached. This battery was used to power the installed Reach receiver for non-RTK flight tests; this is explained in Section 4.1.1.

Figure 3.11: Ventral side of the modified Iris⁺ with the Lidar Lite installed.

3.5.3 Garmin Lidar Lite V3: Software Integration

For terrain following, RPA AGL altitude accuracy depends on accurate altimetry to make sure that the RPA is capable of reaching a prescribed waypoint altitude. To configure the Lidar Lite to act as an altimeter on the Iris⁺, several parameters need to be changed to the following:

Table 3.2: Mission Planner CONFIG/TUNING parameter settings for the Lidar Lite.

Parameter	Setting
RNGFND_TYPE:	15
RNGFND_MIN_CM:	20
RNGFND_MAX_CM:	4000
RNGFND_OFFSET:	0
RNGFND_GNDCLEAR:	10
RNGFND_SCALING:	1
RNGFND_GAIN:	0.5
EK2_RNG_USE_HGT:	70
EK2_ALT_SOURCE:	1

The above settings assigned Lidar Lite readings as a rangefinder input; it set the minimum and maximum readable value to 20 and 4000 cm, respectively; it configured the Pixhawk to recognize that the Lidar Lite was pointing in the downward position; it set the elevation distance between the Lidar Lite the bottom of the Iris⁺ landing legs to 10 cm; and set the Lidar Lite as the primary altimeter from 20 cm to 2800 cm, where the barometer would take over for any AGL altitude above 2800 cm. Since the Lidar Lite was attached in a fixed position, it was more susceptible to roll and pitch effects where a small change in angle can have more drastic effects on the distance measured than it would at a lower altitude. Definitions for the parameters seen in Table 3.2 can be found in [73].

3.6 Emlid Reach RTK GNSS System

The Reach receivers were used for RTK positioning and navigation. Emlid advertises the Reach's capability of calculating real-time coordinates with centimeter accuracy [74]. The Reach system specifications are as follows:

Table 3.3: Emlid Reach RTK GNSS system specifications.

Cost:	\$570 USD
Receiver Type:	L ₁ C/A, L ₁
Supply Voltage:	2.6 V to 3.6 V
Sample Rate:	10 Hz
Positional Accuracy:	± 2 cm (horizontal); ± 10 cm (vertical)
Processing Unit:	Intel Edison dual-core
Dimension:	26 x 45 x 5 mm
Weight:	12 g
Operating Temp.:	-20 to 65°C
Interfaces:	UART, USB, SPI, I ² C, Wi-Fi

To obtain proper positioning, two Reach receiver modules were required: one for the 3DR Iris⁺ RPA, and the other for the base station. Each module was equipped

with a 72 channel u-blox NEO-M8T receiver that came with their own Tallysman TW4721 antenna (Figure 3.12).

Figure 3.12: Tallysman Wireless TW4721 antenna [75].

3.6.1 Emlid Reach RTK GNSS RPAS System: Hardware Integration

The Reach was designed to integrate with several types of devices, two of which are off-the-shelf autopilot systems: the Pixhawk through a DF13 connection, which uses the UART protocol; and the Emlid Navio over UART or USB. Since the Pixhawk is the autopilot system on board the Iris⁺, the DF13 port was used to connect the Reach with the Pixhawk. There are many versions of Pixhawk made by many manufacturers in the market; since, the Pixhawk used in the Iris⁺ was the first version produced by 3D Robotics, it happened to use standard DF13 connectors. The Reach receiver connected to the *SERIAL 4/5* male input pins of the Pixhawk through a DF13 cable located above the *GPS* input pins. A standalone Ublox NEO-7M GNSS with compass module was connected to the GPS input since it would be used in the terrain following system as a fallback in case the RTK system disconnected, experienced a

failure, or had a less accurate GNSS solution. The NEO-7M module is a standard plug-and-play GNSS receiver that is manufactured to be integrated with a Pixhawk, and it is included with many Pixhawk autopilot kits. The TW4721 antenna connected directly to the Reach module through a coaxial cable. Figure 3.13 (a) illustrates how the Reach interfaced with the Pixhawk, and Figure 3.13 (b) shows how it was installed inside the Iris⁺.

Figure 3.13: (a) Reach and TW4721 Pixhawk connection diagram, and (b) actual Reach connection inside the Iris⁺ RPA.

Unlike standalone GNSS receivers found in most smartphones, RTK GNSS have special requirements for antenna placement that are more strict than most standalone GNSS systems. These antennas need to have a clear sky view of at least 30 degrees above the horizon; for RTK surveys, a 15 degree elevation mask is recommended [68]. There should be no obstacles that could block the view; this includes buildings, trees, cars, and people.

Emlid recommends that the Tallysman TW4721 antenna should be placed 15 cm to 20 cm above the RPAS dorsal section [74], see Figure 3.14; however, due to concerns that the Iris⁺ would be unstable during flight if the antenna was placed too high – potentially elevating its centre of gravity – it was attached right on the dorsal frame. Since 3D Robotics offers the CAD files for the Iris⁺, as mentioned in Section 3.1, a new dorsal frame was printed so that the original frame was not damaged when the antenna was installed.

Figure 3.14: Emlid’s antenna placement recommendations [74].

Electronic devices can sometimes produce radio frequency (RF) noise that could

affect the reception of GNSS signals; it is recommended that all electronics – including the Reach module itself – be placed as far as possible from the antenna. Additionally, the antenna has to be placed on a ground plane to reduce multipath effects, provide shielding, and improve signal reception [68, 74]. The ground plane has to be made of a conductive material, such as an aluminum or copper plate, and must be no less than 70 mm x 70 mm [74]. Since this the Iris⁺ was being used as a test bed for a terrain following system that was being developed for geophysical survey RPAS applications, aluminum was chosen due to its low paramagnetic properties. Figure 3.15 illustrates the TW4721 antenna placement on the Iris⁺'s 3D printed dorsal plate adjacent to the NEO-7M module. Although, the NEO-7M can cause some interference with the TW4721 antenna, the Reach was still capable of obtaining a fixed RTK position.

Figure 3.15: Tallysman TW4721 antenna placement adjacent to the NEO-7M module on the 3DR Iris⁺ 3D printed dorsal plate.

3.6.2 Emlid Reach RTK GNSS RPAS System: Base Station Setup & Assembly

For RTK GNSS positional accuracy, a second standalone static Reach receiver at a known location was required to send its GNSS correction to the receiver on the Iris⁺. This Reach was part of the base station and consisted of a:

- TW4721 antenna,
- conductive aluminum plate,
- telescoping tripod,
- Emlid Reach RTK GNSS receiver, and
- 12,000 mAh (44.4 Wh) *iStart* lithium-ion power pack.

The tripod was used as the primary structure for the base station assembly. Fixed on the top of the tripod was the TW4721 antenna adhered to the conductive aluminum plate; the antenna was attached via coaxial cable to the Reach located near the base of the tripod; and, the iStart power pack was fastened on the base of the tripod and was connected to the Reach module through a micro universal serial bus (USB) cable. Note that any 5 V, 1 A battery pack with a USB out connection could have been used to power the Reach; however with 44.4 Wh, the Reach could theoretically be powered for over 40 hours. A block diagram and picture of the base station assembly can be seen in Figure 3.16 (a) and Figure 3.16 (b), respectively.

Figure 3.16: (a) Block diagram of base station assembly, and (b) picture of base station assembly.

3.6.3 Emlid Reach RTK GNSS RPAS System: Software Integration

The Reach was designed to be a low-cost survey grade RTK GNSS system that is capable of using standalone, differential, kinematic, and static survey techniques. For terrain following, RPAS positional accuracy depends on kinematic techniques so that the RPA can accurately plot its course to any given waypoint position.

The Reach supports RTK-enhanced coordinates that can output to autopilot systems using the ReachView App. ReachView is a web-based application that allows a user to take control of the Reach receivers. The ReachView App is hosted on the Reach modules themselves and is accessible via Wi-Fi. This application is compatible with Windows, OSX, Linux, Android, and iOS; it is compatible with most mainstream browsers, such as Mozilla Firefox, Google Chrome, Opera, Microsoft Edge, and Safari.

Both base station and RPAS reach units was initialized with one another via Wi-Fi through a common Wi-Fi network. The process on how to do this is described on Emlid’s website [76].

ArduPilot Integration

To make ArduPilot integration possible, Emlid implemented a custom GNSS protocol called the Emlid Reach Binary (ERB) protocol. The ERB protocol is an efficient binary protocol for communication between the Reach receiver and its user. ERB is used by the Reach receiver for transmitting various GNSS messages such as navigation solution information, receiver status, speed values, precision, and detailed information about the satellites its connected to; some auxiliary messages – such as version protocol – are also transferred [77]. To integrate the Reach system with the Pixhawk autopilot system on the Iris⁺, the Pixhawk had to have ArduCopter version 3.4 or newer firmware loaded onto it. The version of ArduCopter used in the Iris⁺ was version 3.6.9.

The Reach is capable of connecting to several types of computing and controlling devices, such as autopilot systems, microcontroller boards, and microcomputers; it is capable of doing this via Wi-Fi, Bluetooth, universal serial bus (USB), universal asynchronous receiver/transmitter (UART), or DF13. The Reach was designed to integrate with ArduPilot systems.

To configure the Reach on the Pixhawk, the *Correction input* and *Position output settings* was configured within the ReachView App to the following parameter settings:

Table 3.4: Emlid Reach RTK GNSS system parameter settings.

Correction input		Position output	
Base correction type:	Serial	Output 1:	Serial
Device:	UART/USB-to-PC	Device:	UART/USB-to-PC
Format:	RTCM3	Baud rate:	38400
		Format:	ERB

Injecting RTK Base Corrections

There are several methods of injecting RTK base corrections to the Reach; three methods can be used: (1) Configure Mission Planner to inject RTK corrections into telemetry; (2) configure the ReachView App to inject RTK corrections via Wi-Fi; and (3) send corrections directly to the RPAS Reach from a local (non-Reach) base station through NTRIP.

The first method – **injecting RTK corrections into telemetry** – is what Emlid recommends and claims that the most effective way is to use the Iris⁺ telemetry radio as a carrier for the RTK corrections [78]. The GCS can pass corrections to the autopilot with a feature called *Inject GPS*; this functionality is available in Mission Planner, only.

With default settings, the radio telemetry is not optimized for sending RTK corrections. The default settings can telemetry data delivery delays and losses. These delays will deteriorate the RTK solution quality and therefore must be minimized. To minimize the deterioration of RTK solution quality, the *Sik Radio* settings during initial setup need to be changed. Both the *Local* and *Remote* parameters need to be changed; *ECC* needs to be unchecked, and *Mavlink* needs to be changed to *RawData*.

To configure the Pixhawk to enable the use of the Reach as an external GNSS, ArduPilot will require setting some parameters through Mission Planner. After connecting, the following parameters within the *CONFIG/TUNING* menu must be set

to the following:

Table 3.5: Mission Planner CONFIG/TUNING parameter settings for the Reach.

Parameter	Setting
GPS_TYPE2:	1
SERIAL4_BAUD:	38
GPS_AUTO_SWITCH:	1
GPS_INJECT_TO:	1

Definitions for the parameters seen in Table 3.5 can be found in [73].

The Inject GPS option in Mission Planner is found in the advanced GCS settings. This feature is used to enable and configure RTK corrections. These RTK corrections come from the base station, which can support transmission control protocol (TCP) and serial protocol modes. TCP mode was chosen because that was the protocol that Emlid tested successfully with their own equipment [78].

To configure the Reach device on the base station, *Base mode* using the ReachView App needs to be turned on. Turning on the *Corrections output* in Base mode causes the Reach to constant broadcast its RTK correction based on the Corrections output mode selected. *TCP* mode is selected and the parameters are set to the following:

Table 3.6: Base mode parameters for the base station Reach to inject corrections through telemetry.

Parameter	Setting
Role:	Server
Address:	localhost
Port:	9000

To connect the base station to the telemetry modem, in the Inject GPS window of the of advanced GCS menu of Mission planner, *TCP Client* mode is selected, the assigned Internet protocol (IP) address and port number assigned to the base station Reach are entered into the *remote host* window, after which corrections will be accepted by the Iris⁺ through the telemetry radio.

The second method – **injecting RTK correction via Wi-Fi** – is the simplest of the three; however, its range is limited not by the telemetry modem, but by the device responsible for routing the corrections; this can include either a tether enabled cellphone or broadband router.

The difference between the two methods is minimal. Instead of using Mission Planner to send the corrections through the telemetry modem, the corrections are sent directly through the router. No setup in Mission Planner is required; ReachView App is used to set the Correction input of the RPAS Reach to TCP. In TCP mode, the parameters are set to the following:

Table 3.7: Base mode parameters for the base station Reach to inject corrections via Wi-Fi.

Parameter	Setting
Role:	Client
Address:	<i>IP address of base station</i>
Port:	9000 (or port number set for base station)
Format:	RTCM3

The third method – **sending the RPAS RTK corrections using NTRIP** – was the only method of the three that did not require a base station to send RTK corrections; however, to gain access to an NTRIP-capable RTK base station, a subscription with an NTRIP service provider was required. Service providers with RTK networks that have entered into compliance agreements with the Government of Canada are *LEWIS*, *BRANDT*, *CANNET*, *TOPNET*, and *SMARTNET* [79, 80]. CANNET, for example, has the most service in Eastern Ontario; they provide their service at a price tag of \$450 CAD monthly or \$3300 CAD annually, with a \$300 CAD activation fee.

Similar to the second method, the ReachView App is used to set the Correction input fo the RPAS Reach to NTRIP mode. In NTRIP mode, the parameters are set

to the following:

Table 3.8: Base mode parameters for the base station Reach using NTRIP corrections.

Parameter	Setting
Address:	<i>IP address of RTK network</i>
Port:	<i>Port number provided by NTRIP service provider</i>
Username:	<i>Psername provided by NTRIP service provider</i>
Password:	<i>Password setup by user</i>
Mount point:	<i>Name of NTRIP base station</i>
Format:	RTCM3

For all terrain following tests, only the first and third methods were used.

3.7 Modified Iris⁺ Architecture

Both the Lidar Lite and Reach were integrated onto the Pixhawk to measure Iris⁺'s flight AGL altitude and position, simultaneously. Figure 3.17 illustrates how the Lidar Lite and Reach interfaces with the Pixhawk.

Figure 3.17: Lidar Lite and Reach connection diagram.

A block diagram of the terrain following system integrated within the Iris⁺ RPA can be seen in Figure 3.18.

Figure 3.18: Iris⁺ terrain following block diagram.

3.8 Ground Control Station

The GCS took on critical functions of the RPAS. These functions included:

- the radio link between the Reach modules to provide RTK corrections to the Iris⁺ from the base station;
- corrections sent from CANNET’s RTK network to the Iris⁺;
- a telemetry link between Mission Planner and the Iris⁺; and
- a satellite monitoring station for the base station and Iris⁺ RTK GNSS.

The GCS included a laptop computer that ran both ReachView App and Mission Planner. This computer was connected to a Linksys WRT54G v5 Wireless-G

Broadband Router, which links together the base station and Iris⁺ Reach modules, and it was connected to the telemetry radio (Telem01), which communicates with the telemetry radio on the Iris⁺ (Telem02).

A 12 V lead-acid car battery attached to a power inverter to convert the 12 V direct current (DC) to a 110 V alternating current (AC) potential. The battery and inverter was used to power the laptop. A block diagram of the GCS can be seen in Figure 3.19.

Figure 3.19: Ground control station block diagram.

3.9 Terrain Following Remotely Piloted Aircraft System Architecture

The Iris⁺ had to complete its positional tests by staying within the required 30 cm AGL altitude and horizontal position threshold outlined in Section 1.1. This was done by linking three systems – the base station, GCS, and Iris⁺ – together to assemble a terrain following RPAS test bed to be implemented into a geophysical survey RPAS. Figure 3.20 is a block diagram of the low-level terrain following RPAS architecture.

Figure 3.20: Low-level terrain following RPAS architecture block diagram.

Chapter 4

Mission Setup & Methodology

Accurate terrain following is dependent on two factors: accurate and precise AGL altitude and horizontal position. These factors are important for the flight control system to achieve the desired trajectory on the flight path towards a prescribed waypoint. To achieve these measurements, two sensors – the Garmin Lidar Lite V3 and Emlid Reach RTK GNSS system – were installed on a modified 3D Robotics 3DR Iris⁺ RPAS equipped with a 3D Robotics PX4 3DR Pixhawk autopilot system.

4.1 Mission Setup

To determine Iris⁺ would perform with these sensors, two sets of tests were required: an altitude and standalone GNSS test; and an RTK GNSS test with and without NTRIP corrections. The first set of tests were used to achieve three goals:

- To utilize the onboard barometer as the primary altimeter and to measure its performance using the Lidar Lite;
- to utilize the Lidar Lite as the primary altimeter and to measure its own performance; and
- to measure the performance of the Ublox by measuring the distance between Iris⁺ and a prescribed waypoint.

The second set of tests were used to achieve two goals:

- To use the Reach as the primary navigation system in real time, and measuring its performance; and
- to inject NTRIP corrections directly to the Reach equipped inside the Iris⁺.

Data collected from these flight tests were post-processed to compare the measured results with the prescribed flight paths. Post-process, briefly discussed in Section 2.7.4, refers to the processing technique that uses multiple fixed base stations to help acquire accurate GNSS data. This technique was used to measure the real-time performance for both the Ublox and Reach.

All flight tests took place at *Stanley's Olde Maple Lane Farm* (Stanley's Farm) that is located at 2452 Yorks Corners Road in Edwards, Ontario. Stanley's Farm is located southeast of Ottawa (Figure 4.1), and it consists of 250 acres of developed, undeveloped, and crop land. The geographical location to the main entrance of the farm is $45.2626111^{\circ}\text{N}$ $75.4343333^{\circ}\text{W}$.

Figure 4.1: Stanley's Olde Maple Lane Farm location, encircled in black; Ottawa International Airport, encircled in blue; and Carleton University encircled in red.

Stanley's Farm is a convention facility designed to host events, and therefore farm production is limited and allowed its operations to be predictable. The facilities included the farmland itself, a multipurpose lot, and the owner's personal residence, see Figure 4.2. The residence included a workshop that served as a local base of operation that was suitable for assembly, indoor bench testing, and other preparations required for the flight tests.

Figure 4.2: Stanley's Olde Maple Lane Farm (yellow), Christmas farm (white), and RTK/NTRIP flight test area (green).

The farm and multipurpose land consisted of empty grass fields, wooded areas, a water filled quarry, and a Christmas Tree farm. The geographical coordinates to the main entrance of the multipurpose land is $45.2590000^{\circ}\text{N}$ $75.4358333^{\circ}\text{W}$, see Figure 4.3.

Figure 4.3: Multipurpose land at Stanley's Olde Maple Lane Farm (yellow), water filled quarry (white), and altimetry and Ublox flight test area (green).

4.1.1 Altimetry & Standalone GNSS Test Setup

The altimetry and standalone GNSS tests consisted of nine automatic flight tests that took place near the water filled quarry. Nine out of nine flight tests were successful without incident. The quarry was selected because it is located on an open flat field with no built up or natural obstacles. This field was ideal because it gave the desired elevation mask for both the base station and the Iris⁺; with no built up or natural structures, there was little chance of experiencing errors due to multipath effects.

The first four flight tests were used to measure the performance of the barometer and Ublox GNSS; the final five flight tests were used to measure the performance of the Lidar Lite. The Reach was used in post-process to measure the performance of the Ublox. The Reach was disconnected from the Pixhawk and powered directly from the 5 V, 1 A lithium ion battery pack, since the Reach is capable of logging its own data.

All three goals of the first test, outlined in Section 4.1, were achieved by flying the exact same mission. Each waypoint had the same latitude and longitude coordinates with the same prescribed AGL altitude; all flight characteristic parameters were left at the stock configuration. The geographical coordinates for the flight tests were broken into 13 waypoints that are tabulated below, see Table 4.1. From those 13 waypoints, five survey lines were produced to simulate a land survey, see Figure 4.4.

Table 4.1: Geographical LLH coordinates for the barometer, laser altimeter, and standalone GNSS tests.

Waypoint	Latitude (decimal degrees)	Longitude (decimal degrees)	Altitude (m)
1	45.2612505°N	75.4219244°W	3
2	45.2612137°N	75.4220451°W	6
3	45.2611835°N	75.4220156°W	9
4	45.2612222°N	75.4219016°W	12
5	45.2612619°N	75.4217863°W	9
6	45.2612298°N	75.4217622°W	6
7	45.2611977°N	75.4218802°W	3
8	45.2611580°N	75.4219969°W	6
9	45.2611278°N	75.4219714°W	9
10	45.2611684°N	75.4218587°W	12
11	45.2612024°N	75.4217407°W	9
12	45.2611703°N	75.4217099°W	6
13	45.2611335°N	75.4218332°W	3
14	45.2610948°N	75.4219486°W	0

Figure 4.4: Altimetry and Ublox flight path near water filled quarry.

4.1.2 RTK GNSS & NTRIP Test Setup

The RTK GNSS and NTRIP tests consisted of nine automatic flight tests in total; seven to test Iris⁺'s performance when using the Reach, and another two to test its performance when injecting NTRIP corrections. However, only two of the seven tests with the Reach were successful, and only one of the tests with NTRIP corrections were successful. The lack of successful flight tests were due to a brief loss of attitude control that is discussed in Section 5.2.2 and Section 5.2.3.

These flight tests took place on the Christmas farm (used for growing Christmas trees). The Christmas farm was selected because the area near the water filled quarry was rented out by the landowner; it too is a flat field with no built up or natural obstacles. Although the field contained sapling pine trees, they were too short to cause any multipathing effect. After conducting preliminary RTK tests, the Christmas farm presented an unforeseen consequence; the RTK fix between Iris⁺ and the base station

was not only obtained in less time than it did at the water filled quarry, but it also maintained a fix at much longer distance – approximately 40 m at the Christmas Tree farm, versus 20 m at the water filled quarry. This was an important benefit because the distance from the base station to Waypoint 2 was about 30 m.

Due to the requirements for conducting RTK GNSS and NTRIP tests, both the Iris⁺ and base station were required to receive signals from the same (or as many of the same) GNSS satellites to obtain a fixed solution. It was observed that when Iris⁺ would take off at a different location, it would not be able to achieve a fixed solution. This could be a limitation to this version of the Reach. So to ensure that a fixed solution was possible, the Iris⁺ would take off close to the base station location, at the same height AGL. To accomplish this, an RPAS launch pad was constructed for multirotor RPAs, specifically the Iris⁺, see Figure 4.5. This launch pad can telescope to 2 m and has a 77 cm takeoff surface.

Figure 4.5: Image of RPAS launch pad.

The first two flight tests were used to measure the horizontal positional performance of the Reach; the final two flight tests were used to measure the positional

accuracy of Iris⁺ while injecting NTRIP corrections directly to it without the use of the base station. Unlike the tests outlined in Section 4.1.1, the Reach will be directly connected to and powered from the Pixhawk; both the Reach itself and Pixhawk are capable of logging data.

All two goals of the second test, outlined in Section 4.1, were achieved by flying the exact same mission. The second test had the same flight profile as the first test, where each waypoint was located in the same position relative to all the other waypoints; however, the attitude of each waypoint was increased by 2 m to remove any possibility of the Iris⁺ striking a sapling. Each waypoint had the same latitude and longitude coordinates with the same prescribed AGL altitude; all flight characteristic parameters were left at the stock configuration. The geographical coordinates for the flight tests were broken into 13 waypoints that are tabulated below, see Table 4.2. From those 13 waypoints, five survey lines were produced to simulate a land survey, see Figure 4.6.

Table 4.2: Geographical LLH coordinates for the RTK and NTRIP GNSS tests.

Waypoint	Latitude (decimal degrees)	Longitude (decimal degrees)	Altitude (m)
1	45.2587055°N	75.4377602°W	5
2	45.2586687°N	75.4378809°W	8
3	45.2586385°N	75.4378514°W	11
4	45.2586772°N	75.4377374°W	14
5	45.2587169°N	75.4376221°W	11
6	45.2586848°N	75.4375980°W	8
7	45.2586527°N	75.4377160°W	5
8	45.2586130°N	75.4378327°W	8
9	45.2585828°N	75.4378072°W	11
10	45.2586234°N	75.4376945°W	14
11	45.2586574°N	75.4375765°W	11
12	45.2586253°N	75.4375457°W	8
13	45.2585885°N	75.4376690°W	5
14	45.2585498°N	75.4377844°W	0

Figure 4.6: RTK/NTRIP flight path over the Christmas tree farm.

4.2 Post-processing Methodology

This section outlines the methods taken to post-process results acquired from all tests conducted. Range measured using the Lidar Lite needed to be corrected to determine that actual AGL altitude. These correction methods are outlined in Section 4.2.1 below. The actual horizontal location of Iris⁺ during the GNSS tests had to be post-processed using RTKLIB. The processing methods conducted are outlined in Section 4.2.2.

4.2.1 Laser Altimetry Post-processing Methodology

To test the performance of the barometer and Lidar Lite and compare it with the desired altitude, flight tests with the AGL altitude value oscillating from 3 m to 12 m were conducted. The flight test is outlined and can be seen in Table 4.1 found in Section 4.1.1.

As seen in Table 3.1 and Section 3.5, the Lidar Lite is capable of a sampling rate of 270 Hz. The Pixhawk's I²C port – for which the Lidar Lite was connected to – samples at a rate of 5 Hz, which is under 2% of the data the Lidar Lite is capable of reading. That data was used to measure Iris⁺'s altitude.

Iris⁺'s altitude performance was measured by the Lidar Lite regardless of whether the barometer or Lidar Lite was used as the primary altimeter. Since the Lidar Lite was attached in a fixed position, measurements from it had to be adjusted based on the roll and pitch angles experienced by Iris⁺ while the Lidar Lite was measuring the AGL altitude, see Figure 4.7. In addition to the attitude correction, the Pixhawk accelerometer sampling rate was 10 Hz and not synchronized with the I²C bus the Lidar Lite was connected to. To properly analyze the data post factum, the Lidar Lite data had to be linearly interpolated to fill in the missing data. Linearity was assumed since Iris⁺'s average velocity was 2.33 m/s, and no significant change of altitude was observed within any 200 millisecond interval during flight. The height AGL was corrected by the following equation:

$$h_c = h_r \cdot |\cos(\alpha)| \cdot |\cos(\theta)| \quad (4.1)$$

Where:

- h_c is the corrected height above ground level;
- h_r is the raw height above ground level;
- α is the roll angle of the Iris⁺; and
- θ is the pitch angle of the Iris⁺.

Figure 4.7: Iris⁺ roll and pitch axes with laser illustration.

For example, Figure 4.8 contains the roll, pitch, and raw Lidar Lite measurement results for the first barometric altitude test.

Figure 4.8: Iris⁺ roll angles (top), pitch angles (middle), and raw Lidar Lite measurements (bottom).

Figure 4.9 shows the altitude for the first barometric altitude test prior implementing Equation 4.1; for comparison, the corrected altitude after implementing Equation 4.1 can be seen below. These corrections were calculated for every flight test.

Figure 4.9: Iris⁺ raw Lidar Lite altitude measurements (above) and Lidar Lite altitude measurements corrected for roll and pitch angles (below).

4.2.2 GNSS Post-processing Methodology

To test the performance of the Ublox and Reach systems, flight tests simulating survey lines were conducted. The flight test for the Ublox is outlined and can be seen in Table 4.1 found in Section 4.1.1. The flight test for the Reach is outlined and can be seen in Table 4.2 found in Section 4.1.2.

Iris⁺'s real-time position was measured for both the Ublox and Reach itself, and it was calculated relative to the base station. To get the correct absolute coordinates, the exact position of the base station needed to be known. That meant the base station had to be placed on a point with known coordinates, or determined by post-processing the base station against a reference station in static mode; the latter method was selected. The reference station selected belongs to NRCan; it is located

in Vanier, Ottawa, approximately 30 km north-west of Stanley's Olde Maple Lane Farm.

The Reach base station provided a raw observation file to help determine the relative location of Iris⁺. NRCan's reference station provided observation and navigation files that contained clock and ephemeris data corrections, which was used to determine the absolute location of the base station.

For both the base station and Iris⁺ Reach receivers, the raw observation files were proprietary and used a *.UBX* file extension. Although the file type was proprietary, it was converted into RINEX log files using RTKLib. RTKLib is an open-source software package that has many functions that specialize in GNSS positioning. The functions required for post-processing the GNSS tests is the conversion tool, *RTKCONV*, to convert the raw log file (*.UBX*) provided by the Reach to RINEX observation (*.obs*) and navigation (*.nav*) files; and the position calculation tool, *RTKPOST*, calculates the absolute and relative position of the base station and Iris⁺ receivers, respectively.

With the positions known, the distance, or arc length, between the desired and post-processed measured location of Iris⁺ at a given waypoint, was calculated by finding the product of the central angle of the two points with the radius of Earth plus the height above sea level (ASL) of Stanley's Olde Maple Lane Farm. Equation 4.2 – the *Spherical Law of Cosines* – was used to calculate the central angle:

$$\sigma = \arccos(\sin \phi_1 \sin \phi_2 + \cos \phi_1 \cos \phi_2 \cos(|\lambda_2 - \lambda_1|)) \quad (4.2)$$

Where:

- σ is the central angle between two points in radians;
- ϕ_1 is the desired latitude of the waypoint in radians;
- ϕ_2 is the measured latitude of Iris⁺ in radians;

- λ_1 is the desired longitude of the waypoint in radians; and
- λ_2 is the measured longitude of Iris⁺ in radians.

Since Earth is a spheroid, the radius of Earth changes as the latitude changes. That is, Earth's radius is larger closer to the equator than it is at the pole. The radius required to calculate the arc length is the sum of Earth's radius located at the latitude Edwards, Ontario crosses and the height ASL of Stanley's Olde Maple Lane Farm; the latitude and height ASL are 45.2612°N and 80 m, respectively. Equation 4.3 was used to calculate the required radius:

$$R = \sqrt{\frac{[(r_1^2 \cos \phi)^2 + (r_2^2 \sin \phi)^2]}{[(r_1 \cos \phi)^2 + (r_2 \sin \phi)^2]}} + H_{ASL} \quad (4.3)$$

Where:

- R is the radius;
- ϕ is the latitude Edwards, Ontario crosses;
- r_1 is the radius at the equator;
- r_2 is the radius at the pole; and
- H_{ASL} is the height ASL of Stanley's Olde Maple Lane Farm.

Given the central angle and radius, the arch length can be computed as:

$$d = R \cdot \sigma \quad (4.4)$$

Where:

- d is the arc length;
- R is the radius; and

- σ is the central angle between two points in radians.

Similar to the noteworthy observations that were made during the RTK test flights, Iris⁺ also appeared to randomly lose attitude control for short periods of time that also occurred only once per flight test. The loss of control for the second flight test was so significant that the pilot in command was unable to recover control of Iris⁺, and thus resulted in its crash.

Chapter 5

Discussion of Results

As outlined in Section 4.1, missions took place at Stanley’s Olde Maple Lane Farm to predict the respective performance of the Lidar Lite and Reach for improved altimetry and horizontal positional accuracy for terrain following applications. An extensive series of experimental tests were conducted to measure Iris⁺’s performance when implementing the proposed terrain following architecture discussed in Chapter 3. To measure Iris⁺’s performance, the Lidar Lite and Reach took over altimetry and navigation functions to determine how well the RPA can follow the terrain.

5.1 Altimetry Results & Discussion

This section discusses Iris⁺’s altitude performance using the on-board barometer as the primary altimeter. Those results are contrasted to Iris⁺’s altitude performance when the Lidar Lite as the primary altimeter while the on-board barometer was used as its backup. In addition to Iris⁺’s altitude performance results, a trend was observed where the altitude performance improved on a single battery charge.

5.1.1 Barometric Altimetry Results & Discussion

Figure 5.1 illustrates the Lidar Lite altitude measurements for the first barometric flight test conducted, and contrasts the result with the desired waypoint locations. As it can be observed in Figure 5.1, the "×" represents the exact desired waypoint locations, each waypoint is denoted with the letters "wp" followed by the waypoint

number; the inner circle illustrates the 30 cm positional threshold outlined in the mission requirements found in Section 3.2; the outer circle illustrates a 1 m waypoint radius; and the shaded region represents the ± 2.5 cm and ± 10 cm accuracy limits outlined in Table 3.1 of the Lidar Lite system specification in Section 3.5. This waypoint radius represents the minimal distance from the waypoint that the Iris⁺ must cross to successfully reach its waypoint. Although this value is greater than 30 cm, 1 m is the smallest value that can be set inside Mission Planner.

Figure 5.1: Lidar Lite altitude measurements from the first barometric flight test.

Figure 5.1 has noteworthy features: during any manoeuvres where Iris⁺ produces trajectories that concave upward – seen in wp1 and wp7 – Iris⁺ appears to have missed its target more than any other waypoint; in contrast, the waypoints where Iris⁺ produces trajectories that concave downward – seen in wp4 and wp10 – Iris⁺ did not miss its target. This behaviour can be seen in all four flight tests, see Appendix A.1.

There are three possible reasons why the Iris⁺ misses its wp1 and wp7 targets. One could be due to ground effects. As Iris⁺ descends closer to the ground, the

downward airflow from the propellers causes the air to reflect off the ground. This reflected airflow pushes up against Iris⁺, causing it to ascend before reaching its target waypoint. The second possible reason could be a built-in safety measure where the motors ramp up early to prevent Iris⁺ from descending too low, which would cause it to ascend before reaching its target. It is difficult to know for sure if the motors are ramping up early since Iris⁺'s ESC does not log the rotational speed of the motors during flight. The third cause could be due to the minimum default AGL altitude being set to 5 m. It is possible the the Iris⁺ automatically fights to climb to 5 m whenever it is below that threshold during automatic flights.

The average results of all four barometric flight tests can be seen in Table 5.1. The *Prescribed Barometric Altitude* is the prescribed altitude Iris⁺ will attempt to reach while using the barometer as its primary altimeter; the *Measured Lidar Lite Altitude* is the corrected AGL altitude measured by the Lidar Lite, which includes precision values that are the standard deviation calculated from all four flights for each given waypoint; the *Difference* is the difference between the Prescribed Barometric Altitude and the Measured Lidar Lite Altitude; and the *Percent Difference* is the percentage difference between the Prescribed Barometric Altitude and the Measured Lidar Lite Altitude. Figure 5.2 illustrates the average difference between prescribed and measured altitudes for each waypoint for all four barometric flight tests.

Table 5.1: Average values of the barometric test results.

Waypoint	Prescribed Barometric Altitude (m)	Measured Lidar Lite Altitude (m)	Difference (m)	Percent Difference
1	3	4.24 ± 0.09	1.24	41.21%
2	6	6.27 ± 0.22	0.27	4.58%
3	9	9.62 ± 0.14	0.62	6.91%
4	12	12.39 ± 0.11	0.39	3.27%
5	9	9.25 ± 0.25	0.25	2.74%
6	6	6.28 ± 0.18	0.28	4.65%
7	3	3.73 ± 0.14	0.73	24.17%
8	6	6.18 ± 0.21	0.18	3.00%
9	9	9.14 ± 0.25	0.14	1.52%
10	12	12.15 ± 0.11	0.15	1.24%
11	9	9.32 ± 0.22	0.32	3.60%
12	6	6.35 ± 0.03	0.35	5.82%
13	3	2.95 ± 0.12	-0.05	-1.53%
Average:			0.37	7.78%
Standard Deviation:			0.31	11.78%

Figure 5.2: Average difference between prescribed and measured altitude for barometric flight tests (error bars included).

The average difference and standard deviation for all four flight tests are 0.37 m and 0.31 m, respectively. The average deviates by 7 cm beyond the acceptable system requirement accuracy value. 42.3% of waypoints that Iris⁺ crossed for all flight tests successfully met the 30 cm altimetry requirement. The respective average percent difference and standard deviation percent for all four flight tests are 7.78% and 11.78% with Waypoint 1 and Waypoint 7 having the largest percent difference values, which was consistent for each flight test. Although Waypoint 1 and Waypoint 7 had the smallest prescribed altitude value, its absolute difference were consistently larger than any other waypoint for 100% of the flight tests.

5.1.2 Lidar Lite Altimetry Results & Discussion

Figure 5.3 illustrates the Lidar Lite altitude measurements for the first Lidar Lite flight test conducted, and contrasts the result with the desired waypoint locations.

Figure 5.3: Lidar Lite altitude measurements from the first Lidar Lite flight test.

Figure 5.3 has the same noteworthy features found in the barometric altimetry tests; however, the deviations are not as pronounced, and although Iris⁺ met the 1

m waypoint radius at wp1 and wp7, it did not meet the 30 cm (0.30 m) requirement. Additionally, there seemed to be a lag between wp2 and wp3 which did not occur in any of the barometric tests. This lag appeared on all five Lidar Lite tests, but seemed to diminish with each subsequent test. This behaviour could be due to localized thermals or cross winds. Graphical results for all five flight tests can be seen in Appendix A.2.

The average results of all five Lidar Lite flight tests can be seen in Table 5.2. The *Prescribed Lidar Altitude* is the prescribed altitude Iris⁺ will attempt to reach while using the Lidar Lite as its primary altimeter; the Measured Lidar Lite Altitude, Difference, Percent Difference conduct the exact same measurements conducted for the barometric altimetry tests described in Section 5.1.1. Figure 5.4 illustrates the average difference between prescribed and measured altitudes for each waypoint for all five Lidar Lite flight tests.

Table 5.2: Average values of the Lidar Lite test results.

Waypoint	Prescribed Barometric Altitude (m)	Measured Lidar Lite Altitude (m)	Difference (m)	Percent Difference
1	3	3.47 ± 0.31	0.47	15.82%
2	6	5.84 ± 0.10	-0.16	-2.65%
3	9	9.27 ± 0.03	0.27	3.02%
4	12	12.10 ± 0.05	0.10	0.86%
5	9	9.17 ± 0.44	0.17	1.87%
6	6	5.95 ± 0.22	-0.05	-0.86%
7	3	3.51 ± 0.10	0.51	16.97%
8	6	5.88 ± 0.38	-0.12	-1.98%
9	9	9.05 ± 0.29	0.05	0.52%
10	12	11.97 ± 0.17	-0.03	-0.23%
11	9	9.21 ± 0.29	0.21	2.36%
12	6	6.01 ± 0.26	0.01	0.20%
13	3	3.08 ± 0.14	0.08	2.69%
Average:			0.12	3.48%
Standard Deviation:			0.20	4.80%

Figure 5.4: Average difference between prescribed and measured altitude for Lidar Lite flight tests (error bars included).

The average difference and standard deviation for all five flight tests are 0.12 m and 0.20 m, respectively. On average, Iris⁺ is under by 18 cm of the system requirement accuracy threshold. 66.2% of waypoints that Iris⁺ crossed for all flight tests successfully met the 30 cm altimetry requirement. The respective average percent difference and standard deviation percent for all five flight tests are 3.48% and 4.80% with Waypoint 1 and Waypoint 7 also having the largest percent difference values, which was consistent for each flight test. Although Waypoint 1 and Waypoint 7 had the smallest prescribed altitude value, again its absolute difference were consistently larger than any other waypoint for 100% of the flight tests.

5.1.3 Average Altimetry Difference Trend

Regarding the respective barometric and Lidar Lite altimetry results outline in Section 5.1.1 and Section 5.1.2, Iris⁺ appeared to perform better as the same mission was repeated on a single charge of a battery. This was observed in both the barometric

and Lidar Lite flight tests. Figure 5.5 illustrates this trend. When the autopilot was powered down and a new battery was installed, it appeared that the improved performance reset.

Figure 5.5: Decreasing trend for average difference of AGL altitude measurements.

5.2 GNSS Test Results & Discussion

This section discusses Iris⁺'s horizontal positional performance using the Ublox as the primary GNSS. Those results are contrasted to Iris⁺'s horizontal positional performance when the Reach was used as the primary GNSS while the Ublox was used as its backup. An additional test was conducted to see how well Iris⁺ would perform while the Reach received corrections via NTRIP.

5.2.1 Ublox NEO-7M GNSS Test Results & Discussion

Figure 5.6 illustrates the Ublox GNSS measurements for the first standalone GNSS flight test conducted, and contrasts the result with the desired waypoint locations. The data presented was independently measured by the Reach and post-processed

using the base station and fixed reference station located in Vanier, Ottawa. As it can be observed in Figure 5.6, the "x" is the exact desired waypoint location, each waypoint is denoted with the letters "wp" followed by the waypoint number. The cross on the waypoint locations illustrates the 1 m waypoint threshold that was set inside Mission Planner; as it was discussed in Section 5.1.1, 1 m is the smallest value that can be set inside Mission Planner. The distortion seen with the cross is caused by the same distortion seen in maps at higher latitude, which happens when a spherical image is projected onto a flat surface. The dashed black lines represent the survey lines and prescribed flight path. The dotted red lines connect the desired waypoint location to the actual location Iris⁺ was as it crossed the waypoint location assigned to the Pixhawk.

Figure 5.6: RTK measurements from the first Ublox flight test.

Unlike the results seen in Section 5.1, Iris⁺ missed all the prescribed waypoint locations for all four flight tests. The graphical results of the other three flight tests

can be seen in Appendix A.3. The reasons why Iris⁺ missed its targets is likely due to it relying on a standalone GNSS receiver that has decametre to sub-decametre accuracy. As it can be seen in Table 5.3, the average deviation from the target waypoints is 4.52 ± 0.21 m; Iris⁺ missed every waypoint for 100% of the flights. As described in Section 2.7, the expected accuracy for standalone GNSS systems is between 10 to 15 m; however, the Ublox performed better than what was expected. This improved performance is due to the fact that the Ublox and IMU are part of the Iris⁺'s inertial navigation system (INS). The IMU is an integrated sensor package that combines onboard accelerometers and gyroscopes to produce a three-measurement of both specific force and angular rate, with respect to an inertial reference frame; however, the IMU is prone to drift errors, and therefore the INS relies on the GNSS system to correct for those errors.

Table 5.3: Ublox GNSS test results, including test and waypoint average and standard deviations.

Waypoint	Test 1 (m)	Test 2 (m)	Test 3 (m)	Test 4 (m)	Absolute Average Difference (m)
1	5.24	4.37	3.95	5.17	4.68 ± 0.54
2	3.66	2.89	2.66	3.56	3.19 ± 0.43
3	3.81	3.22	3.52	4.44	3.75 ± 0.45
4	4.17	3.91	4.37	5.99	4.61 ± 0.81
5	5.11	4.48	4.98	5.61	5.05 ± 0.40
6	6.25	5.18	5.26	5.65	5.59 ± 0.42
7	5.87	5.24	5.44	5.30	5.46 ± 0.25
8	2.75	2.64	3.21	2.41	2.75 ± 0.29
9	2.12	2.92	3.42	2.14	2.65 ± 0.55
10	4.14	4.42	4.97	5.37	4.72 ± 0.48
11	4.95	4.88	5.85	6.08	5.44 ± 0.53
12	5.79	5.04	5.49	5.92	5.56 ± 0.34
13	6.45	5.40	5.37	4.20	5.36 ± 0.80
Average	4.64	4.20	4.50	4.76	4.52 ± 0.21
Standard Deviation	1.28	0.95	1.00	1.27	1.04

5.2.2 Emlid Reach RTK GNSS Test Results & Discussion

Figure 5.7 illustrates the Reach measurements for the first RTK GNSS flight test conducted, and contrasts the results with the desired waypoint locations. The data presented was post-processed using the base station and fixed reference station located in Vanier, Ottawa. The graphical result for the other flight test can be seen in Appendix A.4.

Figure 5.7: RTK measurements from the first RTK flight test.

Iris⁺ missed all the prescribed waypoint locations for both flight tests, just as it did with the Ublox equipped; however, there was a measurable improvement in the horizontal positional performance. As it can be seen in Table 5.4, the average deviation from the target waypoints is 1.49 ± 0.26 m; Iris⁺ missed the 30 cm threshold for every waypoint for 100% of the flights. On the other hand, Iris⁺ did manage to reach the 1 m threshold imposed by Pixhawk for 34.62% of the waypoints for both flight tests.

Table 5.4: Reach RTK GNSS test results, including test and waypoint average and standard deviations.

Waypoint	Test 1 (m)	Test 2 (m)	Absolute Average Difference (m)
1	1.95	2.23	2.09 ± 0.14
2	1.71	1.47	1.59 ± 0.12
3	1.90	2.12	2.01 ± 0.11
4	0.78	1.68	1.23 ± 0.45
5	1.41	1.76	1.59 ± 0.17
6	0.42	0.72	0.57 ± 0.15
7	0.45	1.21	0.83 ± 0.38
8	2.59	2.58	2.59 ± 0.00
9	0.52	0.47	0.50 ± 0.02
10	1.04	1.33	1.19 ± 0.14
11	1.80	3.99	2.89 ± 1.10
12	0.79	0.84	0.82 ± 0.02
13	0.64	2.41	1.53 ± 0.88
Average	1.23	1.75	1.49 ± 0.26
Standard Deviation	0.67	0.90	0.72

As described in Section 2.7.5, centimetre accuracy is expected while using RTK GNSS and the expected precision should be as little as 2 mm; however, the results show metre to sub-metre accuracy with an average precision of 0.26 m. There are three possible explanations for why the Iris⁺ performed the way it did:

1. Iris⁺ is an aircraft that has to maintain stability and control in three-dimensional space; its flight dynamics are influenced by its environment such as local airflow, air pressure, and temperature. Although Iris⁺ was never 2 mm away from its desired waypoint, it does not mean that the data recorded was not within 2 mm.
2. The Reach is a single-frequency RTK GNSS system; as it was explained in Section 2.7.1 and Section 2.7.2, dual-frequency survey grade receivers can provide

centimetre to millimetre accuracy, which provides navigation transmissions that correct for atmospheric effects.

3. Iris⁺ may have performed better for these tests simply because it had two GNSS receivers. Since Iris⁺ will utilize the GNSS signal that has the best solution, it is possible that Iris⁺ would have performed just as well with a second standalone GNSS receiver.

In addition to the results presented, there were some noteworthy observations that were made during flight tests. For each RTK flight test Iris⁺ appeared to randomly lose attitude control for a short period of time (< 1 sec.); this only occurred once per flight test. These brief losses of attitude control may have occurred while Pixhawk was switching between the Ublox and Reach GNSS receivers; Pixhawk depends on the GNSS receivers as part of its INS, which also depends on the IMU. All the INS sensors feed into the EKF, so it is possible that the glitches occurred by large errors being fed into the EKF while Pixhawk was switching from one GNSS receiver to the other.

Other than brief losses of attitude control, automatic flights of Iris⁺ with the Reach as the primary GNSS receiver showed evidence of what VF PFA method ArduPilot uses. It appears that the method used is the minimum time method, or something very similar. It was observed that Iris⁺ moved from one line-segment to the next – missing its connecting waypoint – at WP1, WP5, WP8, and WP11 for both flights. However, this was not observed at other waypoints, possibly because the waypoints were too crowded. Iris⁺ did not have a chance to go directly from one waypoint to the next. It is important to note that this behaviour did not present itself when the Ublox was the only GNSS receiver used, possibly because the accuracy of the Ublox inferior to that of the Reach.

5.2.3 NTRIP RTK GNSS Test Results & Discussion

Figure 5.8 illustrates the Reach measurements for the first RTK NTRIP GNSS flight test conducted, and contrasts the results with the desired waypoint location; however, the second flight test resulted in a crash. This crash was caused by the same loss of attitude control observed while Iris⁺ was conducting its automatic flight tests with the Reach, see Section 5.2.2. The data presented was post-processed using the base station and fixed reference station located in Vanier, Ottawa.

Figure 5.8: RTK measurements from the NTRIP flight test.

The advantage NTRIP had over traditional RTK surveys was the lack of a base station requirement. As it can be seen in Table 5.5, was 1.25 m; precision was not calculated since only one NTRIP test was successfully conducted. Similar to the RTK results (outlined in the previous section), Iris⁺ missed the 30 cm threshold for 100% of the flights and managed to reach the 1 m threshold imposed by Pixhawk for 69.23% of the waypoints. Although the results were an improvement to the previous RTK

tests, they are not conclusive since only one flight test was conducted.

Table 5.5: NTRIP GNSS test results, including waypoint average and standard deviation.

Waypoint	Absolute Difference (m)
1	2.31
2	0.98
3	0.97
4	0.66
5	3.04
6	0.36
7	1.00
8	0.88
9	0.93
10	0.60
11	3.24
12	0.73
13	0.70
Average	1.25
Standard Deviation	0.92

As described in Section 2.7.5, NTRIP accuracy depends on how far the reference station is from the RPA. The CanNet reference station located in Russell, Ontario, which is approximately 8 km from Stanley’s Olde Maple Lane Farm. The distance between the reference station and the farm should have yielded a horizontal accuracy of approximately 15 mm. As it was mentioned in the previous in the previous section, although Iris⁺ was never 15 mm away from its desired waypoint, it does not mean that the data recorded was not within 15 mm.

As it was observed with the automatic flights with the Reach as the primary GNSS receiver, the Reach receiving NTRIP corrections also showed evidence that the VF PFA method used is a variation of the minimum time method. Iris⁺ also moved from one line-segment to the next, also missing its connecting waypoints.

Chapter 6

Conclusions

Terrain following was originally developed for military use. Today, this technology has applications for both commercial and civilian uses. To date, the geophysics industry has relied on both manned fixed-wing and rotary wing aircraft for aeromagnetic surveys, but terrain following RPAs offer a safer and more cost effective solution. Implementing RPAS with reliable off-the-shelf parts not only allow geophysicists to conduct these surveys missions safely, but it also opens the door for RPAS enthusiasts, amateur geophysicists and surveyors, and other survey dependent industries and professions.

6.1 Summary

This thesis presented the proposed solution and system architecture of a low-cost, non-proprietary terrain following system for small RPAS for geophysical survey applications. Cost and safety were the driving factors for pursuing RPAS technology to complement existing manned aeromagnetic surveys. Using the Reach, Lidar Lite, and Mission Planner, a novel approach to assemble and modify the Reach base station and Iris⁺ was outlined.

Background information for existing manned and remotely piloted terrain following system for aircraft was presented. This information covered traditional and known state-of-the-art methods of terrain following. A study of laser altimetry, GNSS technology, and terrain draping methods were detailed.

There was a measurable performance gain in altimetry when Iris⁺'s onboard barometer was switched to the Lidar Lite. Altimetry test flights utilizing the barometer and Lidar Lite yielded average differences of 0.37 ± 0.31 m and 0.12 ± 0.20 m, respectively. Iris⁺ was 67.57% closer to reaching its prescribed altitude when the Lidar Lite acted as the primary altimeter sensor. Iris⁺ met the required altitude with the barometer and Lidar Lite for 42.3% and 66.2% of the waypoint for all flight tests, respectively. Iris⁺ reached its prescribed 30 cm altitude 44.06% more often with the Lidar Lite than it did with the barometer.

There was a measurable performance gain in horizontal position when the Reach RTK system was integrated into the Iris⁺ RPA. GNSS test flights utilizing the Ublox, Reach, and Reach with NTRIP corrections yielded differences of 4.52 ± 0.21 m, 1.49 ± 0.26 m, and 1.25 m, respectively. Compared to using the Ublox as a standalone GNSS, Iris⁺ was 67.04% closer to reaching its prescribed horizontal position when the Reach was being used as the primary GNSS receiver with base station corrections; Iris was 72.35% closer to reaching its prescribed horizontal position when the Reach was being injected with NTRIP corrections. Iris⁺ was unable to meet the 30 cm horizontal position requirement for any of the GNSS tests; however, when Iris⁺ utilized RTK and NTRIP, it reached its waypoint destinations within 1 m for 30.77% and 69.23% of the waypoints, respectively.

6.2 Future Work

The Lidar Lite and Reach presented quantitative improvements for the prescribed positional accuracy and trajectory for the Iris⁺ RPA when simulating automatic terrain following conditions for an aeromagnetic survey; nevertheless, there remains several avenues of additional work.

During the altimetry tests, Iris⁺ missed the desired AGL altitude by a measurable

margin. The likely cause for this are due to ground effects. More altimetry tests may be required at higher altitudes to see if manoeuvres that produce trajectories that concave upward are in fact influenced by ground effects. Otherwise, the ArduPilot flight stack firmware should be reviewed carefully to find why Iris⁺ would keep missing its target during these types of manoeuvres.

As it was discussed in Section 5.1.3, both barometric and laser altimetry performance would improve as tests were conducted on a single battery charge. A method for saving the Pixhawk accuracy state needs to be investigated. The more often the same mission is flown, the better the prescribed AGL altitude accuracy should be. Alternatively, machine learning could be another method of improving the AGL altitude. The Lidar Lite itself captures data at 270 Hz; however, the I²C protocol only transmits at 5 Hz. There is little reason to not have a machine learning algorithm be an intermediary between the Lidar Lite and flight control system to get more accurate AGL altitudes throughout the flight and not only a prescribed waypoint.

Using the Lidar Lite as the primary altimeter performs well on flat terrain with little to no surface objects; however, it may not perform as expected if there were surface objects that had many gaps in it, such as trees, bushes, and electrical wires. Tests over different types of shrubs should give a good indication of how an RPA would perform using laser as the primary altimeter. In addition, tests on non-flat terrain should also be conducted.

The Lidar Lite was fixed on the ventral portion of Iris⁺'s fuselage. As a result, altimetry measurements had to be corrected based on the relative aircraft attitude recorded by Pixhawk. The Lidar Lite should be equipped onto a stabilized multi-axis gimbal to ensure that it is always pointing down. Alternatively, the Lidar Lite can be used as a look-ahead for obstacle detection and avoidance.

Test results not only need to be verified, but both standalone, RTK, and NTRIP

GNSS tests need to be conducted in the same location. Not only do these tests need to be conducted in the same location, but they need to cover a larger area with the same number of waypoints to confirm if ArduPilot's VF PFA uses the minimum time method. Conducting flight tests over a larger area may also improve Iris⁺'s ability to stay on its desired flight path. Flying over a large area would give Iris⁺ an opportunity to adjust its heading to reach each desired waypoint.

There were few RTK and NTRIP GNSS tests resulting in a smaller than acceptable amount; this was due to a consistent loss of attitude control that forced the PIC to regain control of the RPA to prevent a crash. The second NTRIP GNSS test resulted in a crash that prevented additional tests to be conducted. The flight logs recorded a "GPS glitch" for each of the RTK and NTRIP GNSS flight tests. A thorough examination is required to investigate the cause of the glitch, which may reveal why there were brief losses of attitude control.

The investigation for a low-cost, non-proprietary terrain following system began in September, 2015. At the time, optical flow was difficult to implement with the technology available at the time; its computational power and power supply requirements exceeded what could be feasibly equipped into a small RPA. With the continued miniaturization and improved power efficiency of modern electronics, optical flow is becoming more attractive in the small RPAS industry and should be investigated further for terrain following applications.

Lastly, terrain following tests should be conducted on a low-cost fixed-wing RPA with both the Lidar Lite and Reach acting as primary navigation sensors. Most aeromagnetic surveys missions utilize fixed-wing platforms because of the area it can cover. Equipping a fixed-wing RPA with the proposed terrain following system would demonstrate how well it would perform for real-world geophysical survey applications.

Bibliography

- [1] Starling R.J., S. C., “The Development of Terrain Following Radar: An account of the progress made with an airborne guidance system for low flying military aircraft,” *Aircraft Engineering and Aerospace Technology*, Vol. 43, No. 4, 1971, pp. 13–15.
- [2] Guenwald, K., “An F-111C of the Royal Australian Air Force in 2006,” 2006, https://en.wikipedia.org/wiki/File:General_Dynamics_F-111C#/media/File:RAAF_F111.jpg.
- [3] Elebiju, O., Keller, R., and Marfurt, K., “Investigation of linkages between Precambrian basement structure and Paleozoic strata in the Fort Worth Basin, Texas using high-resolution aeromagnetic data and seismic attributes,” *Geophysics*, 2009, pp. 2–4.
- [4] Tuck, L., “Characterization and compensation of magnetic interference resulting from unmanned aircraft systems,” Tech. rep., Carleton University, Ottawa, 2019.
- [5] Wood, A., Cook, I., Doyle, B., Cunningham, M., and Samson, C., “Experimental aeromagnetic survey using an unmanned air system,” *Leading Edge*, Vol. 35, No. 3, 2016, pp. 270–273.
- [6] Cho, T., “Drape Surface Analysis and Determination of the Flight Path,” Tech. rep., Carleton University, Ottawa, 2016.
- [7] Urquhart, T., “General Introduction to Airborne Magnetic Surveys,” 2013, https://www.geoexpl.com/airborne_survey_workshop.html.
- [8] James, T., “GeoSurv II System Requirements Document,” Tech. rep., Carleton University, Ottawa, 2008.
- [9] Krachmalnick, F. M., Vetsch, G. J., and Wendl, M. J., “Automatic flight control system for automatic terrain-following,” *Journal of Aircraft*, Vol. 5, No. 2, 2008, pp. 168–175, <https://doi.org/10.2514/3.43925>.
- [10] Department of Defense, “F-4 Phantom II,” 2008, <https://www.holloman.af.mil/News/Photos/igphoto/2000452437/>.
- [11] Penn, T., “A History of Terrain-Following Radar,” *Masters thesis, College of Engineering, Texas Tech University*, 2005, pp. 1–89.
- [12] Skolnik, M., *Introduction to Radar Systems*, McGraw-Hill Education, New York, 3rd ed., 2008.

- [13] Bauer, A. O., “Christian Hülsmeyer and about the early days of radar inventions, sense and nonsense,” *Science*, , No. January, 2005, pp. 1–74.
- [14] Sim, P., “Making waves: Robert Watson-Watt, the pioneer of radar,” 2014, <https://www.bbc.com/news/uk-scotland-tayside-central-27393558>.
- [15] Watson, R., *Radar Origins Worldwide: History of Its Evolution in 13 Nations Through World War II*, Trafford Publishing, Bloomington, 2009, <https://books.google.ca/books?id=g-rQQgAACAAJ>.
- [16] Gunston, B., *F-111*, Scribner, New York, 1978.
- [17] Jiang, W., Huang, Y., Junjie, W., Li, W., and Yang, J., “A New Approach for Terrain Following Radar Based on radar Angular Superresolution,” *The proceedings of the third international conference on communications, signal processing, and systems*, Vol. 322, 2015, pp. 223–231.
- [18] Woodward, A. C. and Lagrange, J. B., “Terrain-following radar: key to low-altitude flight,” *IEEE Proc Natl Aerosp Electron Conf NAECON '79*, Vol. v, No. 3, 1979, pp. 1089–1096.
- [19] U.S. Air Force, “LANTIRN,” 2001, <https://www.af.mil/About-Us/Fact-Sheets/Display/Article/104582/lantirn/>.
- [20] Sujit, P. B., Saripalli, S., and Sousa, J. B., “Unmanned aerial vehicle path following: A survey and analysis of algorithms for fixed-wing unmanned aerial vehicles,” *IEEE Control Systems*, Vol. 34, No. 1, 2014, pp. 42–59.
- [21] Ene, C., “Path following for the F18-HARV aircraft,” *UPB Scientific Bulletin, Series D: Mechanical Engineering*, Vol. 79, No. 1, 2017, pp. 67–78.
- [22] Nelson, D. R., Barber, D. B., McLain, T. W., and Beard, R. W., “Vector field path following for miniature air vehicles,” *IEEE Transactions on Robotics*, Vol. 23, No. 3, 2007, pp. 519–529.
- [23] Meenakshisundaram, V. S., Gundappa, V. K., and Kanth, B. S., “Vector field guidance for path following of MAVs in three dimensions for variable altitude maneuvers,” *International Journal of Micro Air Vehicles*, Vol. 2, No. 4, 2010, pp. 255–265.
- [24] Wilhelm, J. P. and Clem, G., “Vector field UAV guidance for path following and obstacle avoidance with minimal deviation,” *Journal of Guidance, Control, and Dynamics*, Vol. 42, No. 8, 2019, pp. 1848–1856.
- [25] De Ruiter, A. H. and Owlia, S., “Autonomous obstacle avoidance for fixed-wing unmanned aerial vehicles,” *Aeronautical Journal*, Vol. 119, No. 1221, 2015, pp. 1415–1436.

- [26] Rahim, M. and Malaek, S. M., “Intelligent operation using terrain following flight in unmanned aerial vehicles,” *IEEE Aerospace Conference Proceedings*, 2007, pp. 1–8.
- [27] Choi, M., Lee, W., and Bang, H., “Trajectory of Terrain-Following/Terrain-Avoidance Flights for Real-Time Implementation,” *11 th International Conference on Control, Automation and Systems*, Korea Advanced Institute of Science and Technology, Gyeonggi-do, 2011, pp. 286–290.
- [28] Bagherian, M., “Unmanned Aerial Vehicle Terrain Following/Terrain Avoidance/Threat Avoidance trajectory planning using fuzzy logic,” *Journal of Intelligent and Fuzzy Systems*, Vol. 34, No. 3, 2018, pp. 1791–1799.
- [29] Li, S., Liu, G., and Wu, J., “A self-learning terrain-following method for aircrafts,” *Chinese Control Conference, CCC*, Vol. 100190, No. 5, 2017, pp. 3437–3442.
- [30] Herisse, B., Hamel, T., Mahony, R., and Russotto, F.-X., “A nonlinear terrain-following controller for a VTOL unmanned aerial vehicle using translational optical flow,” 2009, pp. 3251–3257.
- [31] Herisse, B., Oustrieres, S., Hamel, T., Mahony, R., and Russotto, F. X., “A general optical flow based terrain-following strategy for a VTOL UAV using multiple views,” *Proceedings - IEEE International Conference on Robotics and Automation*, 2010, pp. 3341–3348.
- [32] Hérissé, B., Hamel, T., Mahony, R., and Russotto, F. X., “A terrain-following control approach for a VTOL Unmanned Aerial Vehicle using average optical flow,” *Autonomous Robots*, Vol. 29, No. 3-4, 2010, pp. 381–399.
- [33] Garratt, M. and Chahl, J., “Vision-Based Terrain Following for an Unmanned Rotorcraft,” *Journal of Field Robotics*, Vol. 25, No. 4-5, 2008, pp. 284–301.
- [34] Campos, I. S., Nascimento, E. R., Freitas, G. M., and Chaimowicz, L., “A height estimation approach for terrain following flights from monocular vision,” *Sensors (Switzerland)*, Vol. 16, No. 12, 2016.
- [35] Stal, C., Nuttens, T., Bourgeois, J., Carlier, L., De Maeyer, P., and De Wulf, A., “Accuracy assessment of a LiDAR digital terrain model by using RTK GPS and total station,” *Earsel Eproceedings*, Vol. 10, No. 8, 2011, pp. 1–8.
- [36] Hogan, M. K. and Santos, M. C., “Advanced mission planning tool for Real-Time Kinematic (RTK) GPS surveying,” *Proceedings of the Institute of Navigation, National Technical Meeting*, 2005, pp. 480–488.

- [37] Chang, H.-C., Ge, L., and Rizos, C., “Assessment of digital elevation models using RTK GPS,” *Journal of Geospatial Engineering*, Vol. 6, No. 1, 2004, pp. 1–8.
- [38] Dumont, R. and Bardossy, Z., “Geological Survey of Canada Open File 7690,” Tech. rep., Natural Resources Canada, 2014, <http://geoscan.nrcan.gc.ca/>.
- [39] Sander Geophysics Ltd., “Worldwide Services,” <http://sgl.com/services.html>.
- [40] National Ignition Facility & Photon Science, “How Lasers Work,” 2016, https://lasers.llnl.gov/education/how_lasers_work.
- [41] Zant, C., “How do Rangefinders Work?” 2013, <https://precisionrifleblog.com/2013/10/29/how-do-rangefinders-work/>.
- [42] Environmental Health and Safety, “Laser Safety,” 2019, <https://carleton.ca/ehs/programs/working-lab/laser-safety-program/>.
- [43] Ministry of Labour, “Lasers in Ontario Workplaces,” 2017, https://www.labour.gov.on.ca/english/hs/pubs/gl_lasers.php.
- [44] Meola, A., “Drone market shows positive outlook with strong industry growth and trends,” 2017, <https://www.businessinsider.com/drone-industry-analysis-market-trends-growth-forecasts-2017-7>.
- [45] Xinheng Du, E., “Integrating RTK Positioning with Small UAV for Precise Trajectory Determination,” Tech. rep., York University, Toronto, 2017.
- [46] Parkinson, B. and Spilker Jr., J., *Global Positioning System: Theory and Applications Volume II*, American Institute of Aeronautics and Astronautics, Inc., Washington, 1996.
- [47] National Coordination Office for Space-Based Positioning, Navigation, and Timing, “New Civil Signals,” 2016, <http://www.gps.gov/systems/gps/modernization/civilsignals/>.
- [48] Parkinson, B. and Spilker Jr., J., *Global Positioning System: Theory and Applications Volume I*, American Institute of Aeronautics and Astronautics, Inc., Washington, 1996.
- [49] U.S. Department of Defense, “Global Positioning System Standard Positioning Service,” Tech. rep., 2008, <http://www.gps.gov/technical/ps/2008-SPS-performance-standard.pdf>.
- [50] U.S. Department of Defense, “Precise Positioning Service,” Tech. rep., 2007.
- [51] El-Rabbany, A., *Introduction to GPS: The Global Positioning System*, Artech House, Norwood, 2nd ed., 2006.

- [52] Teunissen, P. and Kleusberg, A., “GPS Observation Equations and Positioning Concepts,” *GPS for Geodesy*, edited by P. Teunissen and A. Kleusberg, Springer, Berlin, Heidelberg, 1996, pp. 187–229.
- [53] National Coordination Office for Space-Based Positioning, Navigation, and Timing, “GPS Accuracy,” 2017, <https://www.gps.gov/systems/gps/performance/accuracy/>.
- [54] Prim, A., Naidu, C. R., Cariappa, K., Tripathy, G., Mandla, V. R., K, R., Vittal, T. R., and Kondepati, V., “No Title,” 2014, <http://www.gisresources.com/rinex-receiver-independent-exchange-format/>.
- [55] Souliman, S., “RINEX Files and Differential Corrections in Post-Processing,” 2019, <https://support.oxts.com/hc/en-us/articles/115003212489-RINEX-files-and-differential-corrections-in-post-processing>.
- [56] Natural Resources Canada, “Canadian Active Control System (CACS),” 2018, <https://webapp.geod.nrcan.gc.ca/geod/data-donnees/cacs-scca.php?locale=en>.
- [57] National Coordination Office for Space-Based Positioning, Navigation, and Timing, “Space Segment,” 2019, <https://www.gps.gov/systems/gps/space/>.
- [58] MacDonald, A. F., *From the Ground Up*, Aviation Publishers Co. Ltd., Ottawa, 29th ed., 2019.
- [59] Trimble, “Critical factors affecting RTK accuracy,” 2019, https://www.trimble.com/OEM_ReceiverHelp/V4.44/en/PositionModes_CriticalFactorsRTK.html.
- [60] GISGeography, “GPS Accuracy: HDOP, PDOP, GDOP, Multipath & the Atmosphere,” 2018, <https://gisgeography.com/gps-accuracy-hdop-pdop-gdop-multipath/>.
- [61] Deere, J., Ess, D., and Morgan, M., *The Precision Farming Guide for Agriculturists*, University of Wisconsin, Madison, 2nd ed., 2003.
- [62] Press, W., Teukolsky, S., Vetterling, W., and Flannery, B., *Numerical Recipes in C: The Art of Scientific Computing*, Press Syndicate of the University of Cambridge, New York, 2nd ed., 2002.
- [63] Weber, G., Dettmering, D., and Gebhard, H., “Networked transport of RTCM via internet protocol (NTRIP),” *International Association of Geodesy Symposia*, Vol. 128, 2005, pp. 60–64.
- [64] Emlid, “FAQ,” 2019, <https://emlid.com/reachrs/#nav-faq>.
- [65] Stanford Engineering GPS Lab, “WAAS/SBAS,” 2019, <https://gps.stanford.edu/research/currentcontinuing-research/waas-sbas>.

- [66] Federal Aviation Administration, “GNSS Frequently Asked Questions - WAAS,” 2019, https://www.faa.gov/about/office_org/headquarters_offices/ato/service_units/techops/navservices/gnss/faq/waas/.
- [67] Stanford Engineering GPS Lab, “LAAS/GBAS,” 2019, <https://gps.stanford.edu/currentcontinuing-research/laas-gbas>.
- [68] Donahue, B., Wentzel, J., and Berg, R., “Guidelines for RTK / RTN GNSS Surveying in Canada,” , No. July, 2013, pp. 0–26.
- [69] Mac, R., “Behind The Crash of 3D Robotics, North America’s Most Promising Drone Company,” 2016, <https://www.forbes.com/sites/ryanmac/2016/10/05/3d-robotics-solo-crash-chris-anderson/#40caa6883ff5>.
- [70] Garmin Ltd., “Lidar Lite v3 Operation Manual and Technical Specifications,” 2016, https://static.garmin.com/pumac/LIDAR_Lite_v3.Operation_Manual_and_Technical_Specifications.pdf.
- [71] ArduPilot, “LIDAR-Lite Rangefinder,” 2016, <http://ardupilot.org/copter/docs/common-rangefinder-lidarlite.html>.
- [72] Lamb Drive, “Garmin LidarLite V3,” 2017, <https://www.lambdrive.com/depot/Robotics/Controller/Firmware/ArduPilot/LIDAR-Lite.html>.
- [73] ArduPilot, “Complete Paramter List,” 2019.
- [74] Emlid, “Antenna Placement,” 2017, <https://docs.emlid.com/reach/antenna-placement/>.
- [75] Tallysman, “TW4721 Single Band GNSS Antenna,” 2019, <https://www.tallysman.com/product/tw4721-single-band-gnss-antenna/>.
- [76] Emlid, “Reach RTK docs,” 2017, <https://docs.emlid.com/reach/>.
- [77] Emlid, “Emlid Reach Binary (ERB) Protocol,” 2016, <https://files.emlid.com/ERB.pdf>.
- [78] Emlid, “ArduPilot integration,” 2017, <https://docs.emlid.com/reach/ardupilot-integration/>.
- [79] Natural Resources Canada, “Data,” 2019, <https://www.nrcan.gc.ca/maps-tools-and-publications/tools/geodetic-reference-systems-tools/data/10923#rtk>.
- [80] Natural Resources Canada, “RTK Networks,” 2019, <https://webapp.geod.nrcan.gc.ca/geod/data-donnees/rtk.php?locale=en>.

Appendix A

Additional Figures for Altimetry and GNSS Results

This appendix includes all the results to support the discussions outlined in Section ???. The following graphs illustrate additional flight tests conducted for barometric and Lidar Lite altimetry tests and the Ublox and Reach GNSS tests.

A.1 Additional Barometric Results and Figures

This section of Appendix A illustrates how well the Iris⁺ performed using the onboard barometer as its primary altimeter.

Figure A.1: Lidar Lite altitude measurements from the second barometric flight test.

Figure A.2: Lidar Lite altitude measurements from the third barometric flight test.

Figure A.3: Lidar Lite altitude measurements from the fourth barometric flight test.

A.2 Additional Lidar Lite Results and Figures

This section of Appendix A illustrates how well the Iris⁺ performed using the Lidar Lite as its primary altimeter.

Figure A.4: Lidar Lite altitude measurements from the second Lidar Lite flight test.

Figure A.5: Lidar Lite altitude measurements from the third Lidar Lite flight test.

Figure A.6: Lidar Lite altitude measurements from the fourth Lidar Lite flight test.

Figure A.7: Lidar Lite altitude measurements from the fifth Lidar Lite flight test.

A.3 Additional Ublox NEO-7M GNSS Test Result Figures

This section of Appendix A illustrates how well the Iris⁺ performed using the Ublox as its primary GNSS to resolve its horizontal position during flight.

Figure A.8: RTK measurements from the second Ublox flight test.

Figure A.9: RTK measurements from the third Ublox flight test.

Figure A.10: RTK measurements from the fourth Ubx flight test.

A.4 Additional Emlid Reach RTK GNSS Test Result Figures

This section of Appendix A illustrates how well the Iris⁺ performed using the Emlid Reach RTK as its primary GNSS to resolve its horizontal position during flight.

Figure A.11: RTK measurements from the second RTK flight test.