Drone Navigation in Polar and Cryospheric Regions

Iain Sheridan

Scott Polar Research Institute

University of Cambridge

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This thesis is dedicated to my father, an exceptional engineer of Da Vincian ingenuity. For the many lessons you have taught me about problem solving.

ABSTRACT

Aerial and underwater drones present a paradigm shift away from the long term use of manned airplanes, helicopters and mini-submarines. This is evident from the number of scientific research articles that focus on research data obtained with drones. For instance, a special edition of the *International Journal of Remote Sensing* consists of 65 articles focused solely on aerial drone research (*Remote Sensing*, Vol 38, 2017). A second special edition consists of another 36 aerial drone articles (Remote Sensing, Vol 39, 2018).

While less prevalent, underwater drones are also playing an ever increasing role in scientific research and proving to be effective contributors in many contexts (Harris, 2018; Zhou et al 2019). For example, if a typical daily drop camera productivity rate is 700 images per day, underwater drones can already achieve 15,000 images per day (Smale *et al* 2012).

This study predominantly examines the use of aerial drones at high latitudes and in cryospheric regions. The study aims to provide insights into the navigation accuracy of Global Navigation Satellite Systems (GNSSs) use for drones, and the accuracy levels of drone positioning data achieved by GNSS augmentation.

Currently, drone use in the global polar and cryospheric community is limited, and there is a scarcity of data on drone GNSS navigation and augmented measurements. The drone use survey in this study attempted to gain insights on general GNSS accuracy and augmented GNSS.

The drone survey data obtained is the first representative sample from this close-knit community across the specialisms of climatology, ecology, geology, geomorphology, geophysics and oceanography. The drone survey data revealed that many different combinations of augmentation were used to obtain sub-metre and even sub-decimetre accuracy.

DECLARATION

This dissertation is the result of my own work and includes nothing which is the outcome of work done in collaboration except where specifically indicated in the Acknowledgements and text.

The length of this study does not exceed 20,000 words. The word count excludes this Declaration, Acknowledgements, Appendices 1-3, captions, figures, References and tables.

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List of Nomenclature

Mathematics and Physics Symbols

a – Major axis

C – Speed of sound in water (1461 m s^{-1} at 20°C)

c – Speed of light (2.997 924 58 x 10^{8} m s^{-1})

Cd – Candela

dB – Decibel

F – Gravitational Force

Fd – Doppler Shift Frequency

G – Gravitational constant (6.672 59(85) x 10^{-11} N m^2 kg^{-2})

lm – Lumen

M or *m* – Mass

m/s – metres per second

nm – Nanometers

λ – Wavelength

mAh – Milliamp hour

Ω – Ascending node

ω – Perigee

∑ – Sum

σ – Sum

μT – Tesla Units

V – Voltage

Abbreviations / Accronyms

AI – Artificial Intelligence
ANO – Air Navigation Order
ATC – Air Traffic Control
BAS – British Antarctic Survey
BEIDOU – Chinese Satellite Navigation System
BVLOS – Beyond Visual Line of Sight
CAA – Civil Aviation Authority
C/A – GPS Course Acquisition Code
CAP – Civil Aviation Procedure
CDMA – Code Division Multiple Access
COMNAP – Council of the Managers of National Antarctic Programs
CTD – Conductivity, Temperature and Depth
DGC – Defence Geographic Centre
DVL – Doppler Velocity Log
EASA – European Aviation Safety Agency
ESA – European Space Agency
FDMA – Frequency Division Multiple Access
GALILEO – European Satellite Navigation System
GCPs – Ground Control Points
GDGPS – NASA Global Differential GPS System
GDOP – Geometric Dilution of Precision
GEO – Geosynchronous Equatorial Orbit
GLONASS – Russian Global Navigation Satellite System
GNSS – Global Navigation Satellite System
GPS – US Global Positioning System
IFR – Instrument Flight Rules
ICAO – International Civil Aviation Organization
IERS – International Earth Rotation Service
IGS – International GNSS Service
IGSO – Inclined Geo-Synchronous Orbit
IMU – Inertial Measurement Unit
ITRS – International Terrestrial Reference System

KF – Kalman Filter

L1 C/A – GPS Course Acquisition Code at 1.57542 GHz

L1 – GPS signals at 1.57542 GHz

L1C – New GPS code planned for L1 signal

L2 – GPS signals at 1.22760 GHz

L2C – New GPS code on L2 signal

L5 – New GPS signals at 1.17645 GHz

LAAS – Local Area Augmentation System

LOL – Loss of Lock

MB – Magnetic Bearing

MD – Magnetic Declination

MEO – Medium Earth Orbit

MOR – Mandatory Occurrence Reporting

MTOM – Maximum Take-Off Mass

NAA – National Aviation Authority

NASA – National Aeronautics and Space Administration

NGC – National Geospatial Intelligence Agency

NOAA – National Oceanic and Atmospheric Administration

NOTAM – Notice to Airmen

OM – Operations Manual

PE – Purkinje Effect

PfCO – Permission for Commercial Operation

PNT – Position, Navigation, and Timing

PPK – Post Processed Kinematic

PPP – Precise Point Positioning

PRN – Pseudo-Random Noise

P(Y) – GPS precision code

QZSS – Japanese Quazi-Zenith Satellite System

RNSS – Radio Navigation Satellite Service

RPA – Remotely Piloted Aircraft

RPAS – Remotely Piloted Aircraft System

RTK – Real-Time Kinematic

SAR – Search and Rescue

SARG – Safety and Airspace Regulation Group

SARPs – Standards and Recommended Practices

SBAS – Satellite Based Augmentation System

SNU – Scintillation Nerve Unit

SOP – Standard Operating Procedures

SPRI – Scott Polar Research Institute

SRP – Scientific Research Pilot

SUA – Small Unmanned Aircraft

SUSA – Small Unmanned Surveillance Aircraft

SV – Support Vector

SVM – Support Vector Machines

TB – True Bearing

UA – Unmanned Aircraft

UAS – Unmanned Aircraft System

UAV – Unmanned Aerial Vehicle

VFR – Visual Flight Rules

VLOS – Visual Line of Sight

WMM – World Magnetic Model

Chapter 1

Introduction

1.1 Justification for the Study

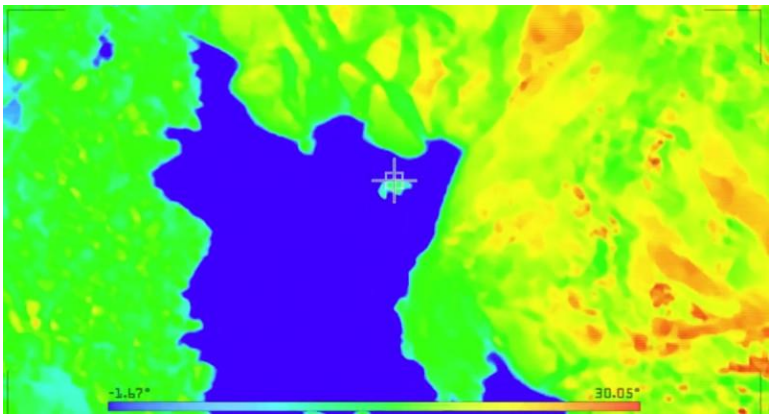
Unmanned Aerial Vehicles (UAVs) and Unmanned Underwater Vehicles (UUVs) (singularly and collectively 'drones') are already a crucial instrument of scientific research. This is evident from the rapid increase in the number of articles that focus on research data obtained with drones. For instance, a whole edition of the International Journal of Remote Sensing, comprising of 65 articles, has focused solely on aerial drone research (Remote Sensing, 2017, Vol 38). Shortly after the same journal published another special edition also dedicated to drone research, comprising of 36 articles (Remote Sensing, 2018, Vol 39). In sum, 101 drone articles in less than 24 months.

Drones are also increasingly assisting research not only at high latitudes (Bernard et al, 2017; Chudley et al, 2017; Hawley and Millstein 2019), but also in cryospheric regions (Bühler et el, 2017; Kraaijenbrink, P. et al 2017). In both these locations drones support important research on climatology, ecology, geology, geomorphology, geophysics and oceanography.

Whatever the precise research, all scientists need to navigate a drone from a known point of departure to perform specific research tasks. The drone has to then return safely with data or samples or both. For example, Figure 1.1 (Intel, 2019) shows an infrared sensor attached to an aerial drone locating a polar bear in a remote part of Svalbard. The small green patch in the cross hair surrounded by a large blue patch is an adult polar bear sleeping in >1m of snow.

In the atmosphere of Earth, aerial drones navigate and verify accurate positioning based on one or more Global Navigation Satellite Systems (GNSSs). Furthermore, other satellite systems and diverse augmentation methods refine the accuracy of GNSS measurements. Therefore, a common denominator of drone navigation is to understand how each GNSS operates.

Fig 1.1 Drone Locating Polar Bear Sleeping in Snow



Turning to underwater drones, while less prevalent, they are also playing an ever increasing role in scientific research and are proving to be effective contributors in many research contexts. For example, one team of scientists recorded that their daily image collection rates for drop cameras was 700 images per day compared with underwater drones achieving 15,000 images per day (Smale et al 2012). Figure 1.2 (UC Davis, 2017) shows a typical underwater drone used for polar science.

Fig 1.2 Drone in Antarctica

When they are submerged GNSS signals suffer from attenuation. However, underwater drones can still measure accurately their submerging and surfacing positions with GNSS. Further, based on water surface GNSS signals these drones can validate their underwater doppler sonar and inertial measurements.

Further, it cannot be assumed that aerial or underwater drones are used solely for GNSS-based data collection. For example, ecologists are increasingly collecting physical samples that are supported with GNSS data. For example, this dual role could potentially include future sample collections from whales and other mammals as has already been achieved at lower latitudes (Apprill et al, 2017).

It is timely to assess the location finding, measuring ability and other navigational limitations placed on drones. Hereafter in this study, a scientist operating a drone, whether aerial or underwater or both, is referred to as a Scientific Remote Pilot (SRP).

1.2 Aims and Objectives

The key aims of this study are four-fold. First, to present and analyse the data provided by a drone use survey of respondent SRPs, with special focus on their GNSS choices, measurement accuracies achieved and selected augmentation methods.

To succeed, the drone use survey must show the GNSS choices of SRPs for navigation in the traditional sense of moving from a base to the research subject matter. Further, the drone use survey must reveal the more precise positioning data achieved by one of numerous augmentation methods. These augmentation methods may be physical such as Ground Control Points (GCPs) or water surface buoys, but are mainly based on electronic receivers, sensors or transmitters.

Second, to assess the operational planning and visual navigation variables relevant to aerial drones. This includes pre-mission risk assessment, fuselage design, wing design, the use of LEDs, and also careful reliance on magnetometers at high latitudes.

Third, to assess the operational planning and navigation variables relevant to underwater drones. This includes pre-mission risk assessment, the use Doppler Velocity Log (DVL) and other ways to improve underwater navigation systems bereft of GNSS.

Fourth, to critically interpret aviation law most relevant to SRPs in a number of the most researched polar and cryospheric regions, including Antarctica, Greenland, Nepal and Svalbard.

1.3 Overall Approach

To attempt to achieve the most important aims of this study, in March 2019 a global drone survey of SRPs was completed (hereafter ‘the drone survey’). The target sample of 211 scientists was a balanced international mix. Asian, European, Latin American, North American and Russian institutions.

The survey questionnaire was drafted so that aerial-only and underwater-only SRPs were presented with 10 focused questions. SRPs operating both aerial and underwater drones were presented with 17 questions. The logic of a succinct questionnaire approach was to maximise the number of respondents. Additionally

each respondent was also given the option of providing a short note at the end of the survey. A sample questionnaire is attached as Appendix 1.

The second approach is to make a multi-disciplinary analysis of operational planning and navigation decisions. This analysis is based on established (i) risk analysis methods and (ii) physics. Authoritative sources include the Antarctic Remotely Piloted Aircraft Systems Operators' Handbook (COMNAP, 2017) and NASA. Further, the physical principles of aerodynamics, classical mechanics, electroluminescence, electromagnetism, gravity and light all influence the flying and retrieval of drones.

The third approach is to establish the legal context in which SRPs will operate drones. Showing competence, gaining permission to operate drone missions and avoiding law suits are three increasing challenges for all SRPs. The legal context is best understood on the foundations of one jurisdiction's aviation law. In this study UK law (English law) is chosen. However, the analysis and summaries on aviation laws from five polar and cryospheric regions where drone missions are likely to occur are structured to enable an SRP from any country to read everything in the context of their home jurisdiction.

1.4 Thesis Structure

This study is divided into six chapters. This chapter summarised its basic aims and motivations. The second chapter covers the background evolution of Global Navigation Satellite Systems (GNSS) and location errors typically experienced in polar regions. Further, it summarises the theory of a Scintillation Nerve Unit (SNU) chip that receives short Support Vector Machines (SVM) messages from ground level GNSS ionospheric monitoring equipment.

The third chapter provides an assessment of the main operational planning and visual navigation factors relevant to aerial drones in polar and cryospheric regions. This chapter also assesses the operational planning and navigation factors relevant to underwater drones in polar regions.

The fourth chapter moves away from science to analyse aviation law governing drone use in Antarctica, Greenland, Nepal, Norway and the UK. The fifth chapter

presents and discusses the statistical results of the drone survey. Finally, chapter 6 provides conclusions and proposes future research areas.

The predominant focus of this study is aerial drones. The drone survey results showed that 78.57% of scientists used aerial drones compared with 4.76% who used underwater drones. The remaining 16.67% used both types of drone.

One final introductory matter concerns terminology. Navigation and positioning have always been imbued heavily with abbreviations, and this tendency is multiplied by quite a factor when discussing GNSS, aerial drones and underwater drones. The Glossary is found at the start of this thesis after the Index. However, to aid fluidity of reading less well known abbreviation explanations are repeated throughout.

Chapter 2

Global Navigation Satellite Systems

2.1 Aims and Structure

All aerial drones used at high latitudes and in cryospheric regions rely on Global Navigation Satellite Systems (GNSS). While not the only basic navigation or data positioning systems available, GNSS are the primary means of both navigation and positioning for scientists.

This chapter explains how GNSS functions. It also analyses the constraints, errors and limitations of GNSS in the context of high latitudes. The US Global Positioning System (GPS) has been at the forefront of polar research for more than three decades. Consequently, there is significantly more research on GPS errors and performance. However, it will become clear that access to all GNSS can be important, and these alternatives to GPS are also assessed, especially GLONASS.

2.2 Background Evolution of Satellites

The origins of GNSS can be traced back to both Isaac Newton and Johannes Kepler. Published in 1726, Newton's third book of the *Principia Mathematica* has a section entitled *A Treatise of the System of the World*. In this section he reasoned that:

'bodies to be projected in the directions of lines parallel to the horizon from greater heights…will describe arcs either concentric with the Earth, or variously eccentric, and go on revolving in the heavens in those trajectories, just as the Planets do their orbs [orbits]' (Millard, 2017:p.19).

Second, Johannes Kepler's three planetary laws of motion (published 1609-1619) apply equally to satellites orbiting the Earth when applying Newton's inverse square law ($F = G\ Mm / (d^2)$) and law of gravitation. These are (Wiley and Larson, 2000):

(1) The orbit of each planet is an elipse;

(2) The line connecting the planet to the Sun sweeps out equal areas in equal times;

(3) The square of the period of a planet is proportional to the cube of its mean distance from the Sun.

The contributions of Kepler and Newton allowed many subsequent scientists to ultimately advance physics towards satellite technology. In this respect special credit must go to Konstantin Tsiolkovsky and Robert Esnault-Pelterie.

Then in 1957 the Soviet Union's successful launch of *Sputnik I* dramatically changed the science of navigation. Sputnik I was monitored by Bill Guier (mathematician), Frank McClure (John Hopkins Applied Research Laboratory research director) and George Weiffenbach (physicist). In less than six months the genesis of GNSS is seen in a 1958 memorandum from McClure:

'*Guier, Weiffenbach et al have been analysing the shape of the doppler signals from the Sputniks…They have found they were able to establish the parameters [eight] of a satellite's orbit with surprising accuracy…the doppler information received from a single pass seems to be sufficient to determine all these parameters…It occurred to me that the inverse problem, namely that of locating the observing station by analysis of the doppler signal of a well-established satellite, would be much simpler...In such a system one would use quite sophisticated equipment on land to determine the satellite orbit parameters...A receiving station would have knowledge of these orbit parameters and then doppler observation of a pass would leave the receiving station with the problem of determining…its coordinates on the surface of the Earth...*' (May, 2019: pp.10-11).

2.3 Satellite Orbiting

As represented in Equation 2.1 (Cojocaru, 2009; Larson and Wertz, 2000), a satellite is launched into orbit relying on the well-established six *Keplerian* parameters of integration:

$$Pi\ (i\ldots 6) = \{a,e,i,\Omega,\omega,v\} \qquad \textbf{[Equation 2.1]}$$

Where a is the semi-major axis, meaning the size of the ellipse; e is the eccentricity, which refers to the shape of the ellipse where a perfect circle = 0 and a highly eccentric shape has a value of 0.77; i is the inclination; Ω is the right ascension of the ascending node; ω is the perigee, meaning the angle from the ascending node to the eccentricity vector; and v is the true anomaly, referring to the angle from the eccentricity vector to the satellite position vector.

These six unperturbed variables are affected by a number of perturbing accelerations, namely: an oblate Earth; the direct gravity of the Moon and Sun; acceleration produced by tides as an indirect effect of Moon and Sun; and the acceleration caused by direct radiation from the Sun (Cojocaru *et al*, 2000). Ephemeris[1] data corrections to account for these perturbations are then updated in each satellite at four hour intervals (Parkinson, 1996).

In combination, these constants and variables affecting an orbiting satellite highlight the considerable technical challenges in maintaining a consistent orbit fundamentally required in satellite management. Software tools allow for simulations to assist this task, and allow for visualization. For instance, the program SaVi allows two and three dimensional simulations of satellite orbits and coverage.[2]

[1] Ephemeris has several meanings. In the context of satellites it refers to "predictions of current satellite
[2] The Savi software can be downloaded at https://savi.sourceforge.io/

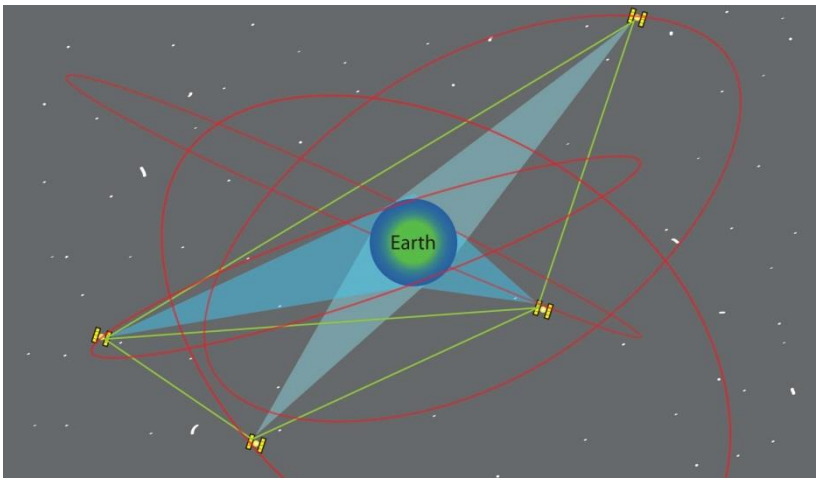
2.4 Geographic Satellite Coverage

In addition to Newton's laws and Kepler's parameters and perturbing accelerations, a fourth essential aspect to understanding GNSS is that satellite constellation design is based on advanced geometry. The fundamental question challenging satellite designers is 'what is the minimum number of satellites required to provide continuous geographic coverage of the Earth?' By which is meant being certain that any point on Earth has at least one satellite pointing at it. Any reliable navigation satellite constellation requires more than 20 satellites, but starting with the theoretical minimum for any signal beaming onto Earth assists in grasping the complex multi-variables of GNSS discussed later in this chapter.

In the evolution of satellites, the theoretical minimum question has produced several convincing answers (Larson and Wertz, 2000). Ultimately, the settled answer is four satellites (Draim, 1987; and Draim, US Patent No 4,854,527 1985). More recently Draim and others have re-endorsed that the theoretical '*Tetrahedral Multi-Satellite Continuous-Coverage Constellation minimum'* still applies. The satellite to Earth coverage is captured by the light blue beams in Figure 2.1 (Draim et al, 2012: p.6).

The original patent abstract states 'Each of the satellite orbits is made elliptic…the ellipses are so arranged that two opposing satellites have their perigees in the Northern Hemisphere, while the other two have their perigees in the Southern Hemisphere. Additionally, the mean anomalies for the starting positions of the satellite orbits are selected so that one opposing satellite pair has one satellite at perigee and the other at apogee. The other pair are placed midway (in time) between apogee and perigee (i.e., one at 90° mean anomaly and the other at 270° mean anomaly)' (Draim, 1985; US Patent No 4,854,527 1985).

Fig 2.1 Four SatelliteTetrahedral Constellation

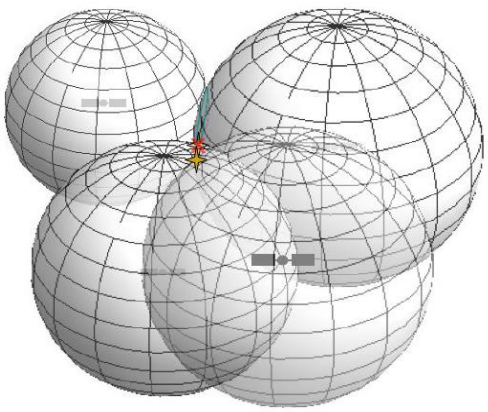


2.5 GNSS Positioning Requirements

The geometry of GNSS satellites varies between designers, but what they all share in common is that to achieve an accurate position, that is ≈10 metres, the receiver on the ground has to lock onto four satellites.

By applying trilateration the position of the receiver at a precise point in time is known (Larson et al., 2000). Figure 2.2 (Chong, 2013: p.11), illustrates that at least four satellites are above the horizon anywhere on Earth is required to obtain an accurate position. When a third satellite, the lower left one, is added the location can be either of the two starred points. If the lower right fourth satellite is added then the location can only be the lower yellow star point.

Fig 2.2 GNSS Trilateration



As the original US government technical briefing on GPS explained ‘a minimum of four satellites are normally required to be simultaneously ‘in view’ of the receiver, thus providing four pseudorange and four delta range measurements…Less than four satellites can be used by a receiver if time or altitude are precisely known or if these parameters are available from an external source’ (Navstar GPS, 1996).

GNSS signal availability is determined by three key factors: the altitude of the orbit, the inclination angle of the satellite and the Earth ground level ‘field of view’ width of the signal transmitter attached to the satellite.

Each satellite is transmitting two pieces of information: (a) its position in space, and (b) its clock time. All satellite clocks are synchronised and accurate to one millionth of a second. Applying the equation *distance = speed x time*, the speed of light (2.997 924 58 x 10^8 m s^{-1}) multiplied by the time taken for a satellite signal to arrive at a GNSS receiver, provides the altitude (distance) of the satellite from the user. The example in Equation 2.2 (adapted from Parkinson, 1996) based on the known orbit altitude of the US GPS satellites, underlines that each signal reaches a GNSS receiver in a millionth of one second.

$$t = d/s \qquad \textbf{[Equation 2.2]}$$

$$t = 26{,}600\ (km) / 2.997\ 924\ 58 \times 10^8\ ms\text{-}1$$

$$t = 26{,}600{,}000 / 299{,}792{,}458$$

$$t = 8.8728E\text{-}5s$$

$$t = 0.000088728s$$

The concept of pseudorange is critical to explaining how GNSS works with such high precision. Pseudorange refers to the difference between the satellite clock time and the user clock time when the user clock time is always relatively imprecise (Parkinson, 1996). The Achilles heel of GNSS is the inaccuracy of the receiver. The fourth satellite in any position fix is required to determine how far off precisely the receiver clock is compared with the satellite clocks. To underline how important this is, if the receiver clock is off by 1.25 seconds (≈300,000 x 1.25) the position would be in inaccurate by 375,000km - the same distance as the moon’s orbit from Earth.

In Equation 2.3 (Parkinson, 1996) the pseudorange is expressed as

$$\boldsymbol{\rho_i} = |\boldsymbol{r_i} - \boldsymbol{r_u}| + \boldsymbol{c} \cdot \boldsymbol{b_u} + \boldsymbol{\varepsilon_{pi}} \qquad \textbf{[Equation 2.3]}$$

Where r_i is the satellite position at transmit time; r_u is the receiver position at receive time; b_u is the receiver clock bias expressed in seconds; and $\boldsymbol{\varepsilon_p}$ the combined calculation for all the estimated or measured ionosphere and troposphere delays, clock mis-modelling, ephemeris and multipath.

2.6 Minimising GPS Error with Optimum Satellite Geometry

From the leading text on space mission analysis and design it is clear that the task of maximising the precision of a satellite constellation is a daunting one requiring highly detailed budget, equipment and orbit calculations (Larson and Wertz, 2000). However, three common denominator components are critical to minimising errors created because of the geometry of satellites. These are the spacing, altitude and attitude of the satellites.

The quality of spacing of satellites has been termed as the Geometric Dilution of Precision (GDOP). The errors experienced by GPS users at high latitudes can significantly depend upon GDOP. Equation 2.4 expresses how GDOP performance measurement is calculated, based on the variables of three dimensions plus time (Parkinson, 1997).

$$\boldsymbol{GDOP} = \frac{\boldsymbol{1}}{\boldsymbol{\sigma}} \sqrt{\boldsymbol{\sigma_x^2} + \boldsymbol{\sigma_y^2} + \boldsymbol{\sigma_z^2} + \boldsymbol{\sigma_b^2}} \qquad \textbf{[Equation 2.4]}$$

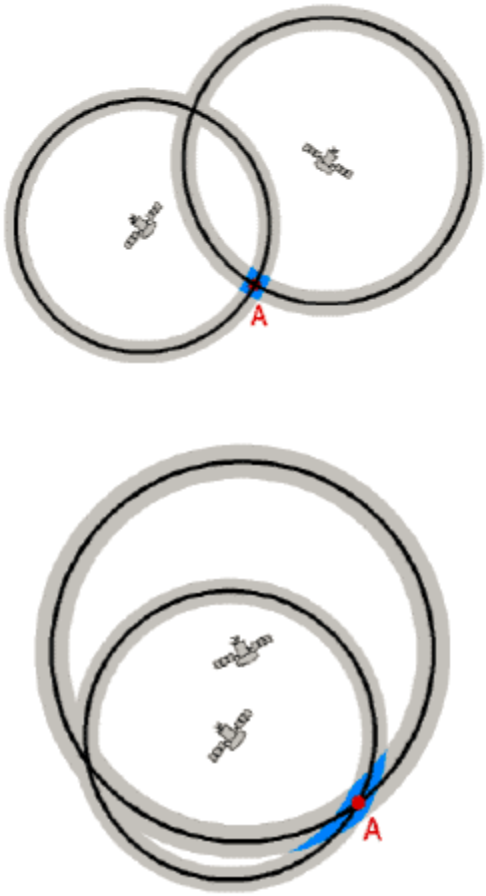
As a general rule the wider the spacing of satellites the higher the quality of signal consistency. Figure 2.3 shows two dimensional representations where the uncertainty on the range of measurement is indicated by the grey shading on either side of each circle. The receiver is assumed to be located anywhere on the intersection of area A in each.

In the theoretical first constellation in Figure 2.3 (Sunehra, 2013; p.76) the satellites have good geometry because they are spread out. The light blue coloured area indicates minimal GDOP – the lower the GDOP, the better the accuracy. In contrast, in the second constellation the satellites have poor geometry because they are close

together. As a consequence, the positioning area (coloured light blue) over the receiver position is far larger. Therefore, the GDOP is higher (Sunehra, 2013).

For any SRP operating in high latitudes or cryospheric regions the task of determining GDOP before drone use may make sense because the drone can then be switched to the GNSS with the lowest GDOP. A GDOP between 2 and 5 is good and a GDOP of 1 is excellent. A website exists that allows this calculation to be made (www.calsky.com/cs.cgi/Satellites). For example, on 22nd May 2019 at 1800 hours at Ny-Ålesund, for the 13 GALILEO and GPS satellites in view, the GDOP is 4.52. For the seven GPS satellites in view the GDOP was 4.8. On that date, any SRP was served almost equally well by either of these GNSS.

Fig 2.3 Dilution of Position



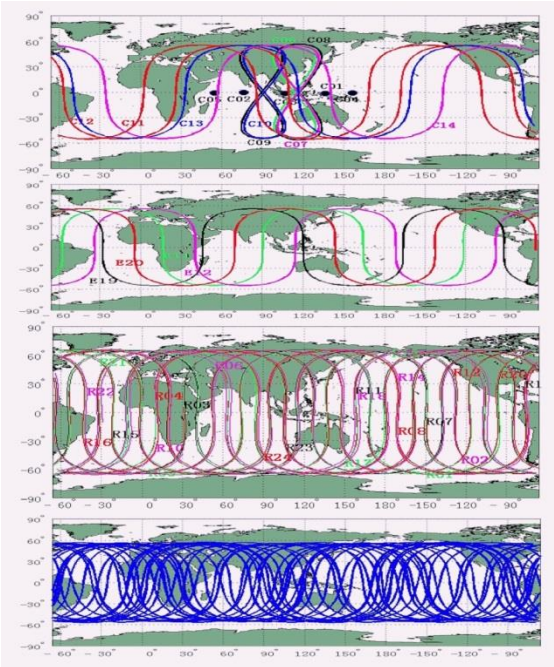
2.7 Polar GNSS

It is insufficient to explain GNSS without a comparison of the leading systems in the context of high latitudes. No SRP needs to rely solely on GPS. **Appendix 2** at the

back of this study summarises GNSS relevant to not only polar scientists, but also a regional satellite system, namely India's IRNSS relevant to cryospheric scientists researching in the Himalayas.

Figure 2.4 (Li et al, 2016: p.610) records the ground tracks of the four main GNSS recorded in September 2013. Top to bottom, these are BEIDOU, GALILEO, GLONASS and GPS. What is apparent from all four is that high latitudes are less well served compared with equatorial regions. The BEIDOU tracks in the top graph show that these are confined to latitudes 55°N and 55°S. The third graph shows that GLONASS is the most likely to best serve an SRP operating in polar regions.

Fig 2.4 Four GNSS Ground Tracks



Loss of GNSS signals is most evident when analysing how GPS performs at high latitudes compared with the Russian GLONASS system and the EU Galileo system. At first glance, these three systems seem similar. GPS functions with 31 operational satellites, GLONASS 24 and Galileo 24 (RIN, 2018). The flight altitude of each are GPS at 20,180km, GLONASS at 19,100km and Galileo at 23,222km. So each individual satellite in each constellation has a similar fraction of the Earth in view (Parkinson, 1996). Thirdly, the attitude, by which is meant the satellite orbital inclination angle of each system are GPS at 55°, GLONASS at 64.8° and Galileo at 56°.

The differences between these three constellations are clearly of importance based on these variables alone. With reference to Galileo, it has been observed that factoring in its different 'orbital inclination and the flight altitude of the satellites will considerably increase the coverage of the polar regions, not so well achieved by GPS' (Cojocaru, 2009). Further, although GLONASS orbits at a similar altitude to GPS, its higher altitude orbit coverage over different higher latitudes is superior as shown in Table 2.5 (extracted from Januuszewski, 2016: p.96).

Table 2.5 Percentage of Visible Satellites Above Angle H Degrees

LATITUDE RANGES	SYS	40°H	50°H	60°H
70-75°	GLONASS	34.4	20.2	11.7
	GPS	27.1	16.1	4.4
75-80°	GLONASS	37.2	**20.9**	9.2
	GPS	26.0	**11.0**	1.1
80-85°	GLONASS	40.2	19.9	19.9
	GPS	24.8	4.5	4.5
85-90°	GLONASS	26.6	1.3	1.3
	GPS	21.8	0.4	0.4

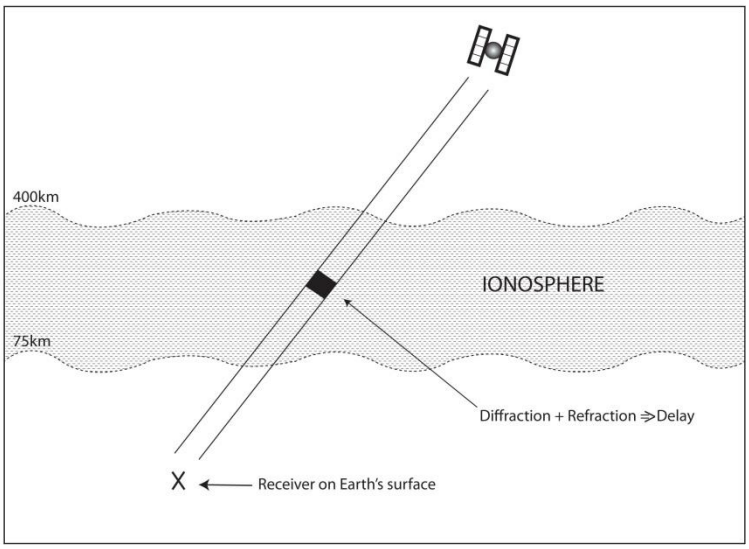
From Table 2.5 it can been deduced that GPS is not performing well at a ≥50° degrees angle from 75° degrees latitude. At the 75-80° latitude range the percentage of GPS satellites is nearly half of the number of GLONASS satellites. Further, applying the minimum four satellite principle, at the 75-80° latitude range, GLONASS would still achieve a full position fix with five visible satellites[3], but GPS would provide just three[4]. Therefore, taking just two important high latitude location examples, an SRP on Svalbard (+78°N) or Ellesmere Island (+76°N) would be better served by ensuring GLONASS is included as part of their navigation choices. In sum, in combination these two GNSS have played and logically will continue to play navigation and positioning data at the poles.

[3] 20.9 per cent of the 24 GLONASS satellites = 5.0.
[4] 11.0 per cent of the 31 GPS satellites = 3.41. Require at least four satellites for a full position fix; and time or altitude fix.

2.8 Scintillation Effects

At high latitudes both the amplitude and phase of the received GNSS signal can be affected by scintillation. Amplitude scintillation occurs less frequently compared with phase scintillation (Jacobson and Dahn, 2014). At high latitudes, scintillation effects can last for many hours, even days (Parkinson, 1996). Phase scintillation is important to polar scientists relying on GNSS. Receiver measurements can result in '…positioning errors of tens of metres or, in the most severe cases, in complete outages due to Loss of Lock (LOL). Such a threat has a disruptive impact on sub-metre navigation and precise positioning' (Linty et al., 2016: p.1). Figure 2.6 (adapted from Parkinson, 1996: p.50) shows how scintillation effects GNSS signals.

Fig 2.6 Ionospheric Scintillation



Phase scintillation research reveals specific patterns that correlate with GNSS errors. For example, Pan and Yin published an '*Analysis of Polar Ionospheric Scintillation Characteristics Based on GPS Data*', derived from a 12 month, daily observation of scintillation in 2011 at the South Pole (Pan et al, 2014).

Their results revealed that phase scintillation followed a pattern of seasonal variation with two low periods starting in January and June. In April and October it peaks (Pan *et al,* 2014). For SRP researching with drones at high latitudes, these findings may point to the need to make most use of drones for research in the low phase scintillation months.

Ionospheric phase scintillation disturbance predominantly caused by aurora occur not just in high latitudes, but are most visible in the latitude bands ±60° degrees of the Northern and Southern Hemisphere. From data derived from the International Polar Years 1882-3 and 1932-3, scientists have long known that above 60° degrees latitude North or South the complexity, intensity and variability in time of magnetic disturbance is most great (Chapman, 1951: p89).

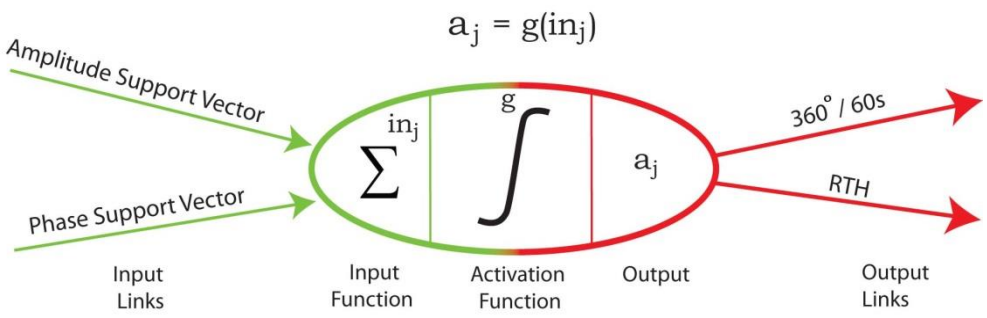
At high latitudes, strong ionospheric storms can persist for many hours (Parkinson, 1996). Based on research by the US Space Weather Division, GNSS signal errors strongly correlate with the auroras (Viereck, 2014). The aurora sub-storms are typically around 60° degrees in the Northern Hemisphere. Ionospheric irregularities tend to occur within 90 minutes of a sub-storm onset. The irregularities typically occur within the auroral oval and not outside of it. To clarify, dayside aurora exist as well (Lorentzen and Egeland, 2011), and it is likely that awareness of the location of the dayside aurora is relevant to most SRP given they will plan to or may only be permitted to fly in daylight hours.

2.9 Scintillation Nerve Unit

Collectively, all the above research highlights the risk of GNSS signal delay disruption from scintillation. Theoretically, it may be possible to mitigate this effect by inserting new artificial intelligence (AI) electronic components into the drone.

Specifically, a Scintillation Nerve Unit (SNU) electronic chip can be logically added as a parallel control to an aerial drone's main flight control platform. Figure 2.7 (my adaption from Russell and Norvig, 2010: p.728) shows a mathematical model of a neuron invented by McCulloch and Pitts in 1943 on which an SNU could function in a drone.

Fig 2.7 Scintillation Nerve Unit



My concept of an SNU is beyond the scope of this study, but it is theory worth summarising because its possible implementation mitigates the problem of delayed GNSS reception for drones at high latitudes. In Equation 2.5 (Russell and Norvig, 2010: p.728) the SNU nervous reaction is based on:

$$\boldsymbol{a_{j=}\, g(in)_j} \qquad \textbf{[Equation 2.5]}$$

*Where **a** is the outputs, meaning the neural action to circle 360° for 60 seconds or Return To Home (RTH); **g** is the activation function; and **in** are inputs, meaning the scintillation data message received every 60 seconds.*

The SNU would be supported by a base station operated on a rugged low temperature-tolerant laptop. At the base station there would be a multi-frequency, multi-constellation GNSS ionospheric receiver[5] and antenna capable of monitoring local amplitude and phase scintillation.

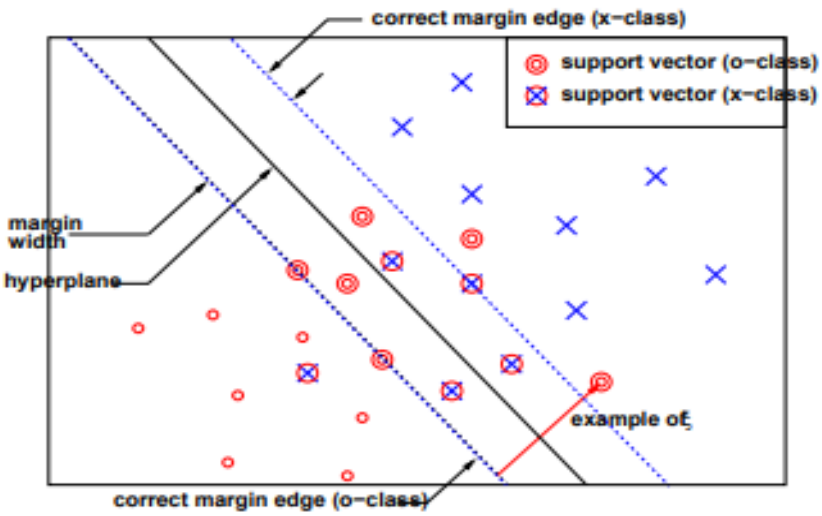
The GNSS ionospheric receiver is connected to the laptop that runs machine learning software. Regression calculations would be made to determine the margin of amplitude and phase scintillation levels that are likely to cause (a) disruption to GNSS signal sufficient to push positioning accuracy >10m; or (b) result in loss-of-lock (LOL) meaning the GNSS signal is lost.

[5] An example is the Novatel GP Station-6. See www.novatel.com/products/scintillation-tec-monitor/gpstation-6/.

Increasingly, machine learning has shown it has the potential to improve phase scintillation prediction (McGranaghan *et al*, 2018). However, models to date rely on huge amounts of data. Latency and substantial energy use mean that a drone cannot efficiently process large amounts of data whilst in flight. With an SNU the need for large amounts of data processing and transfer is removed, because the laptop transmitter is simply forwarding two inputs simultaneously every 60 seconds. The message (Input Links) sent from the laptop to the drone SNU contains information on scintillation relevant only to the latest Support Vector (SV) classification examples stored in the SNU.

The Support Vector Machines (SVM) data is formed on a “model of learning from examples” (Vapnik, 1998: p.19). As Figure 2.8 (Gales, 2019: p.8) illustrates, SVM are based on the idea of creating a hyperplane that divides a dataset into two classes with the widest margin – the wider the margin the more accurate the classification of data points.

Fig 2.8 Support Vector Classification



The key benefit of SVM is that the hyperplane provides an efficient means of classifying with previously unobserved data points (Russell and Norvig, 2010). This is achieved by factoring in only new data points compared with the existing Support Vectors as marked in Figure 2.8. Here, the new data points are the latest scintillation levels to determine if the drone will in under 60 seconds experience significant signal disruption resulting in greater than GNSS 10m accuracy or even LOL.

The laptop transmits every 60 seconds. The transmission provides just two inputs: (i) phase scintillation levels; and (ii) amplitude scintillation levels. Collectively these are SV Input Functions. The SNU cannot directly receive non-linear SVM because this is computationally burdensome. Instead the laptop performs regression calculations, including where necessary Kernel functions (Vapnik, 2018), then transmits to the drone a short compressed data message.

The SNU is using minimal energy because it only consumes battery power (i) when the drone antenna receives the combined code of the two inputs, and (ii) at the point of excitation when the combination of the two inputs exceeds a hard threshold that requires specified outputs. For fixed wing drones there would be the added opportunity to make the SNU fully-energy independent by grafting photovoltaic outer skins on the top wing surfaces.

If the activation function results in LOL categorisation of GNSS interference the SNU ‘fires’ an overriding instruction to the drone’s flight control module to Return To Home (RTH) – the drone flies back to the SRP. As the original neural network theorists put it “at any instant a neuron has some threshold which excitation must exceed to initiate an impulse” (McCulloch and Pitts, 1943: p.115).

If the activation function results in predicted GNSS measurements >10m, the neural SNU ‘fires’ an overriding instruction to the drone’s flight control module to maintain a 360° holding pattern for 60 seconds (360° Circle for 60s). If the drone has been placed in a 360° Circle for 60s holding pattern, the next message sent from the base station to the SNU determines if the drone remains circling for another 60 seconds or continues on the pre-programmed mission flight pattern. SVM models often predict false alarm scintillation events (McGranaghan et al, 2018), so the 360° Circle for 60s impulse output minimizes the number of aborted drone missions. Further, if there is a reduction in scintillation after 60 seconds the drone quickly resumes its mission flight pattern.

The inclusion of an SNU component that can override the drone’s flight control platform potentially solves the challenge scintillation presents to accurate drone missions at high latitudes. In the event that the drone malfunctions and is unable to move out of the 360° holding pattern, the drone eventually loses all power and glides or drops down to the ground. The drone is recoverable when calculating the most

likely circumference of its landing based on the gravitational constant, mass, velocity and wind vectors.

Introducing a new component into the control platform of a drone requires an open-source main hardware board of which there is a significant selection (Ebeid et al, 2017). Put another way, an SRP would be unable to incorporate an SNU into an off-the-shelf manufactured drone.

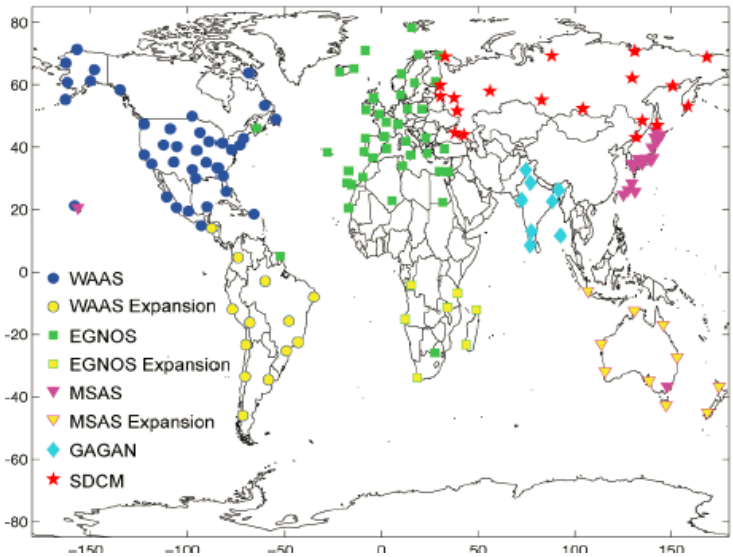
In sum, by only receiving minimal Support Vector data messages every 60 seconds, the neural nature of the SNU provides a potentially superior solution. Further, based on logic it would potentially place no extra or minimal extra processing power demands on the main Inertial Measurement Unit (IMU).

2.10 Augmentation of GNSS

High latitude errors in GNSS accuracy are a significant weakness to manage. Currently and for the medium-term, existing augmentation systems provide a scientifically proven gap-filling service to mitigate GNSS errors.

A Satellite-Based Augmentation System (SBAS) is designed for all flight phases of commercial aircraft navigation. In each geographical region the relevant SBAS provides the accuracy, availability and integrity needed to rely on a GNSS. This is achieved by providing, via a separate constellation of geostationary satellite signals, a set of positioning and time to the user's GNSS receiver (GSA, 2019). As Figure 2.9 (SBAS Interoperability Working Group, 2012: p.24) shows, there are SBAS operating that cover GPS in North and South America including Southern Patagonia (WAAS and WAAS expansion), Galileo in Europe including Iceland and Svalbard (EGNOS), and GLONASS across all Russia (SDCM).

Figure 2.9 SBAS With ≤3m Accuracy



The use of a SBAS at high latitudes and in cryospheric regions is addressed again in Chapter 5 of this study. Chapter 5 covers the drone survey which included a question put to the SRPs about what, if any, SBAS they use.

Turning specifically to a service of relevance only to GPS, the Global Differential GPS (GDGPS) System is a network of 75 geodetic quality triple frequency (L1, L2 and L5) receivers positioned globally (www.gdgps.net/system-desc/network.html). GDGPS has a latency level of approximately five seconds[6] from receiving a navigation signal to dispatch of the differential corrections.

NASA ultimately controls GDGPS and claims it 'provides sub-decimetre (<10 cm) positioning accuracy and sub-nanosecond time transfer accuracy anywhere in the world, on the ground, in the air, and in space, independent of local infrastructure' (GDGPS, 2018). It is evident that GDGPS receivers are located in several key high latitude locations, including the Antarctic Peninsula, Greenland and Svalbard. The British Antarctic Survey, among other research organisations, uses this service (British Antarctic Survey, 2018).

[6] NASA states that even lower latency levels are available for GDGPS real-time integrity monitoring services.

While acknowledging the positive role of GDGPS and other augmentation systems, there is also a common denominator weakness, namely they all[7] still rely on GNSS signals. Therefore, when there is no GNSS the SBAS is useless (Spaans, 2000).

[7] An exception was Eurofix. However, since 2016 Eurofix is not operational.

Chapter 3

Operational Planning and Navigation

3.1 Introduction

This chapter addresses the risk management, scientific principles and technical factors to consider when navigating drones for scientific research purposes at high latitudes and in cryospheric regions. Operational planning has a very wide application, because safe drone use requires decision making on exact design specifications and precise electronic components to minimise damage and loss of expensive research equipment. Thorough planning and decision making also mitigate risks linked to taking-off, flying and landing a drone near humans, animals and property. In short, the drone needs to perform and return with data without high cost or damage in often extreme environments.

In the context of general aviation pilots, the use of GNSS has an added weakness of making pilots overconfident about the aircraft's position without reference, to among other things, ground-based navigation methods (Psyllou, 2018). The risk of SRPs behaving in the same way is very likely, because a drone under good GNSS conditions performs reliably. However, both polar and cryospheric locations share in common a high likelihood of unreliable GNSS signals or even LOL.

There are many SRP risk management issues. These include aerial line of sight, differentiating drone landing from background snow, and coping with moving platforms floating on ice or water. The selection of appropriate Light Emitting Diodes (LEDs) on the drone to aid competent and safe drone piloting and ground level retrieval (Grundmann, 2010). Minimizing environmental impact of route, especially *dB* levels of unmanned aerial drones both above the ground and underwater (Erbe et al, 2017) based on up to date scientific evidence of wildlife responses to drone activity (Mustafa et el, 2018).

The rest of this chapter 3 addresses these key issues. The structure is to first cover general risk management matrices to aid pre-planning risk mitigation. Thereafter, design and electronic components are discussed.

3.2 Risk Management in Polar and Cryospheric Areas

The Council of Managers of National Antarctic Programs (COMNAP) has produced a cause-consequence matrix, Table 3.1 (COMNAP, 2017: p.9) which uses a vertical axis based on Likelihood of event occurrence, namely ‘Probable’, ‘Remote’, ‘Extremely Remote’ and ‘Extremely Improbable’. Each Likelihood categorisation is a qualitative measurement based on the lifetime of one drone. By which is meant an event occurring is Probable when it is anticipated to occur at least once in the operational lifetime of a drone.

An event occurring is Remote when it is unlikely to occur in the operational lifetime of a drone. An event is Extremely Remote when it is not anticipated to occur in the operational lifetime of a drone. An event is Extremely Improbable when it is not anticipated to occur throughout the operational lifetime of an entire fleet of drones (COMNAP, 2017).

For instance, drone icing, typically on the wing surfaces, can result in maximum lift decreasing by up to 80% and drag can increase by up to 60% (Sørensen, 2016). Therefore, ice forming on wings could cause the drone to crash. Subject to planning and mitigation, the risk of drone icing causing the drone to crash is Probable or Remote.

Table 3.1 Cause-Consequence Matrix

Severity Level	**No Safety Effect**	**Minor**	**Major**	**Hazardous**	**Catastrophic**
Likely Occurrence					
Probable	Nav sys malfunc causes loss on tundra in daylight. Need to retrieve.	Nav sys malfunc causes loss on snow in daylight. Need to retrieve.	Nav sys malfunc causes loss on tundra at dusk. Need to retrieve.	Ice on wings causes drone to crash near SRP or ground support staff.	Nav sys malfunc causes crash in crevasse. Need to retrieve.
Remote				Drone crashes through the roof of an occupied building.	On take-off drone catches fire caused by exploding lithium battery.
Extremely Remote					Drone collides with helicopter causing both to crash.
Extremely Improbable					Drone battery explosion causes research boat to sink.

Turning to the horizontal axis of the Cause-Consequence Matrix, the Severity Level is based on definitions provided by NASA as a risk analysis structure specifically for drone pilots.

In Table 3.2 (COMNAP, 2017: pp.9-10), these Severity Levels has been adapted and made relevant and succinct to an SRP. By reading Table 3.1 and Table 3.2 together an SRP can assess and seek to lower risks for each mission.

Table 3.2 NASA Severity Definitions for SRPs

Severity Level	Definition
Catastrophic Failure	Failure of a drone would result in loss of life or serious injury.
Hazardous	The SRP would be unable to perform his or her flying or research tasks, distress to persons and injury to persons.
Major	Reduced capability or functional safety margins of the SRP or other ground crew to cope with adverse operating conditions, potential injuries or potential physical discomfort to persons.
Minor	No significant reduction to human safety. Minor failure conditions may include a slight reduction in safety margins or functional capabilities or a slight increase in the workload of ground crew.
No Safety Effect	Would have no effect on safety, meaning there would be no effect on operational capability of the drone or any increase in ground crew workload.

Referring back to the Table 3.1 Cause-Consequence Matrix, an SRP planning a drone flight has to first identify hazards and risks, and then decide how they can mitigate each risk to a lower or low level. In Table 3.1, green indicates a low risk, yellow a medium risk and red a high risk.

For example, imagine the navigation systems of a drone malfunction in flight with complete loss of SRP control. The drone crashes BVLOS into a crevasse approximately 500m from the side of the glacier where the SRP controlled its take-off. Attempting to retrieve the drone has the potential of being a Catastrophic Failure Severity Level consequence and is initially coded a high risk (coloured red) situation. In this crash scenario the SRP would assess how to mitigate the mission to move from high risk to ideally a low risk (green) or perhaps a medium (yellow) risk. Mitigating the high risk (red) of attempting retrieval to one of medium or low risk would include:

(a) working out how to lessen the chance of the drone crashing in the first place based on thorough drone navigation system operational checks before each flight;

(b) applying standard safety procedures for locating any crashed drone;

(c) applying local expert knowledge safety procedures for locating any crashed drone on the specific glacier taking into account its dynamics, the time of day and the time of year;

(d) the procedure for safe retrieval based on the SRP and ground crew roping up to retrieve the drone.

3.3 Environmental Challenges

One way of analysing the use of lightweight drones in demanding environments is set out in Table 3.3 (Duffy et al, 2017: p.7). While Table 3.3 provides a useful structure to start planning SRP drone flights, it has three omissions, because in both polar and cryospheric regions there can be both challenges from fine particles and telemetry issues.

First, previous studies have indicated that high altitude cryospheric regions, such as the Himalayas, have been subject fine particles in the form of episodic dust plumes that travel over the mountains (Gautam et al, 2013). High altitude plateaus can also be affected. For example, studies indicate black carbon is prevalent in the air on the Himalayan-Tibetan Plateau glaciers (Chaoliu et al, 2016). Second, both polar and cryospheric regions can experience difficulties deploying and locating GCPs (Chudley et al, 2018). For each area in different conditions a specific challenge chart can be produced on a mission to mission basis.

Third, high altitude environments are often exposed to telemetry issues, because high peaks can create multipath errors (Parkinson, 1996). Further, the aurora at both poles can lead to extreme interference with GNSS signals (Lorentzen and Egeland, 2011).

Table 3.3 Environmental Challenges

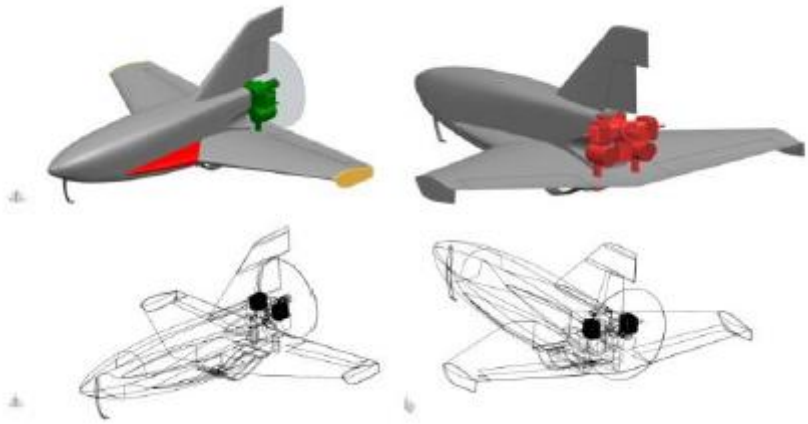
	Specific Challenge							
Operating environment	Safety and regulation	Societal considerations	Wind	Fine particles	Solar effects (glint, shadows, albedo)	Spatial constraint of data products (Difficulties deploying/locating GCPs)	Telemetry issues	Topography issues
Coastal	■	■	■	■	■	■		■
Dryland	■	■	■	■				■
Polar	■	■	■		■			■
Dense forest	■	■	■			■	■	■
High altitude	■	■	■					■

3.4 Katabatic and other High Wind Forces

Katabatic winds are often most fierce and persistent when developing off large ice sheets (Strahler 2013; Grazioli et al, 2017). This affects not only polar regions, but also the Himalayas and the Patagonic Andes. Use of an anemometer will prevent starting missions that have a high risk of a crash, but such devices are not a panacea. A more important planning decision for drone research by an SRP is a fuselage and wing design that copes well with these sudden and often extreme conditions. Conversely, inadequate aerodynamic design will result in more drone losses.

Researchers have recently analysed that high wind loading design of both the fuselage and wings copes best with the turbulent environment of the Antarctic coast in the context of a drone for monitoring penguins. High wind loading is '*responsible for low sensitivity to gust and low weight-to-power ratio – important for high excess of power and quicker recovery from diving, pull-up and other manoeuvres*' (Goraj, 2014: p.1). Visually, Figure 3.4 (Goraj, 2014: p.9) shows the end product of high wind loading calculations - not a delta-shaped wing but a stocky NASA Space Shuttle-like fuselage with a short wingspan.

Fig 3.4 High Wind Loading Design



3.5 Mitigating Drone Loss with Light Emitting Diodes

It is timely to first explain what a Light Emitting Diode (LED) is, then in the next section address factors relevant to the properties of LEDs in the context of human vision. An LED is a pn-junction semiconductor. As for any electric light, the efficiency is measured in lumen (*lm*)[8], indicating the amount of light produced. Technical explanations on how a pn-junction works is beyond the scope of this chapter, but are provided succinctly elsewhere (Tipler and Mosca, 2008; Grundman, 2010; Galvez, 2013).

LEDs work by a process known as injection electroluminescence. An electric current injection mechanism produces photons – luminescence. The more photons that can be produced the brighter the light, which is achieved by electric current passing through the energy gap of the semiconductor (Parker, 2004).

LEDs are essential components to have on a drone in remote, often featureless and predominantly white environments.

Even in lower high latitude boreal forest regions where in spring, summer and autumn there is less or no snow, the costs and inconvenience of lost drones has to be thoroughly thought through.

The drone has to leave point A where the SRP stands, fly over or hover near the subject matter of research, then return to the same take-off point or land at a safe

[8] Oxford Dictionary of Physics defines lumen (*lm*) as the SI unit of luminous flux equal to the flux emitted by uniform point source of 1 candela in a solid angle of 1 steradian.

short distance from the take-off point. Therefore, the basic risk mitigation of the drone is achieved in daylight by LEDs attached to the drone. At dusk LEDs are vital. In the event of a drone crashing or landing Beyond Visible Line of Sight (BVLOS), still working LEDs may be pivotal to finding it. In short, one of the simplest semiconductors that a drone can have is the most practical mitigant to avoid loss.

Choice of LEDs have to centre on specifications that mean natural human vision has the best chance of seeing a drone, whether in the air or on the ground. Any assessment of LED colour choices also has to be based on recent colour-blindness tests by the relevant SRP.

Manufactured drones are not generally built for a specific climate in mind, but there are exceptions. For instance, as shown in Figure 3.5 (GPS World, 2018) the Russian *Zala* series of drones, 421-08M and 421-16E, are both designed for use at freezing temperatures (GPS World, 2018). An SRP with a self-made drone with the relevant selection of LEDs attached can see the drone in flight all of the time. If unexpectedly there is a loss of altitude and fall to the ground, there is a higher likelihood of searching the correct crash area and locating the fuselage along with its main electronic components.

Fig 3.5 Russian High Latitude Drone

3.6 LED Colour Compatible with Human Vision

In Figure 3.6 (my colour adaption from Lynch and Livingston, 1995: p.720) are aspects relevant to an SRP choosing LEDs to assist seeing a drone during flying, and for ground level retrieval of a drone. It is vital to choose the best LED colour to maximise (a) inflight sight of the drone, and (b) relocate a drone that has landed or

crashed out of sight. The boundaries of the eye's sensitivity are from 310 to 1050 nanometers (nm) (Lynch and Livingston, 1995). This sensitivity is based on a trichromatic receptor that has colour sensors called retinal cones, coated with blue, green and red pigments. Red and green cones are close in wavelength.

Fig 3.6 Photonic Cones and Scotopic Rods

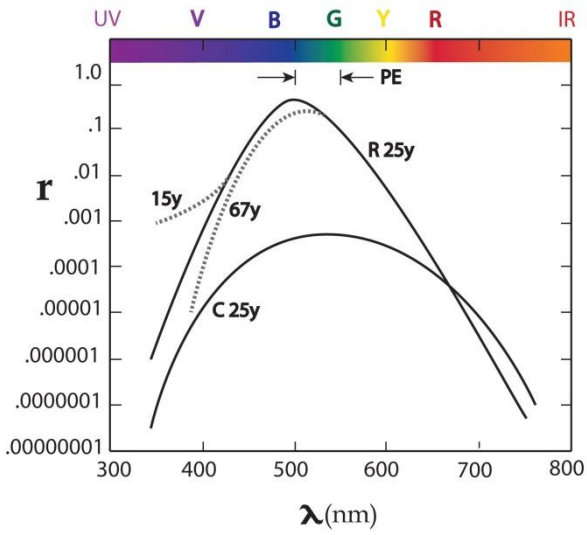


Figure 3.6: Relative response (*r*) of the eye for the photopic (high light level) cones (C) and scotopic (darkness functioning) rods (R) based on wavelength (λ). Scotopic sensitivity in the blue-violet weakens with age and the applicable age in years (y) is shown. The Purkinje Effect (PE) takes place in going from cone to rod vision. UV = Ultra-Violet; V = Violet; B = Blue; G = Green; Y = Yellow; R = Red; IR = Infra-Red.

The challenge for SRPs is to factor in three aspects to their LED decision making – the limitations of blue, green or red LEDs. First, eye sensitivity to brightness of LEDs is greatest in the visible spectral range of green (Lynch and Livingston, 1995). Therefore, green LEDs have the greatest chance of being seen by scientists across age groups. However, the background landscape context matters as well. For instance, green LEDs can be a risk, because polar open water, glacier surfaces and cryospheric glacial lakes are often, but not exclusively green.

Second, the Purkinje effect means that after sunset peak eye sensitivity to colour results in red objects appearing very dark, and green-blue becoming more visible in the landscape, because peak colour sensitivity decreases from 560 to 500 nm

(Lynch and Livingston, 1995). Therefore, after sunset, red LEDs are a risk. Further, green LEDs in a foliage landscape will be challenging to see.

Third, middle age results in blue and violet colours being fainter (Lynch and Livingston, 1995). Many chief and senior researchers will be middle-aged or approaching it, so this fact cannot be ignored. An SRP in the 25 years of age range has the wider flexibility to choose blue, green or red. (Lynch and Livingston, 1995). However, blue LEDs are not a good choice if the chief scientist or senior researcher is also the SRP.

Fourth, given the limitations of blue, green or red LEDs, all LEDs need to flash or vary in brightness to be consistently spotted by the SRP and any ground crew. It is proven that image fluctuations are required to stimulate a signal in either a photopic or scotopic context, or perception fades to a grey background (Pritchard, 1961). This risk of a faded background supports having some form of image fluctuation on a drone in the form of one or more flashing LEDs. Further, as covered in Chapter 4 (Regulation) of this study, there are already legal requirements in Norway for a drone used in Beyond Visual Line of Sight (BVLOS) flights to have flashing LEDs with a light intensity of not less than 10 candela (*Cd*).

Taking all the above factors into account, a lead SRP has to assess and decide the best choice of LEDs based on their unique research circumstances. Logically, the most efficient choice is to fly in the clearest daylight hours, but that is not going to maximise research output in all specialisms. For instance, some ecologists and oceanographers are going to want to use a drone at dusk when certain animals and birds are more active.

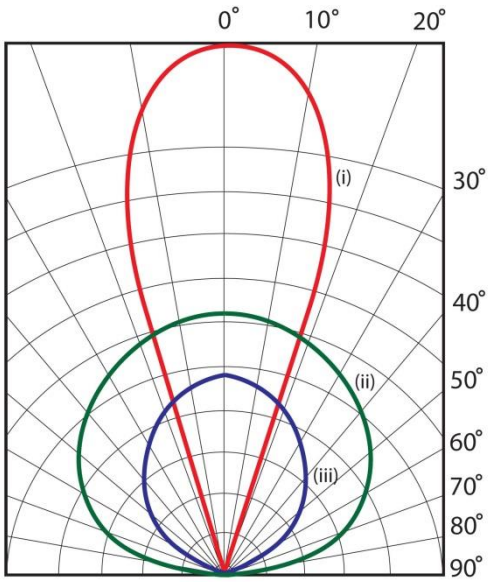
3.7 LED Lens Shape

There are several aspects that determine the angle of the external radiant output of an LED beam. These include the surface area of the p-n junction, the intrinsic semiconductor chosen, and any extrinsic impurity doping excitation (Parker, 2004). However, the shaping of the back surface of the LED has a very significant impact on external efficiency – the radiation pattern of light (Galginaitus, 1965).

Figure 3.7 (my adaption from Grundmann, 2010; p.664) is a comparison between three LED radiation patterns, expressed in degrees of radiance, namely: (i) parabolic reflector; (ii) hemispheric; and (iii) rectangular. Note the colours used in Figure 3.8 are just for ease of reference only and do not indicate the colour of the LED. As can be seen by comparing the three geometric patterns and their angles of light dispersion, the parabolic reflector pattern (i) is the superior choice. Based on the same amount of electrical energy, the parabolic pattern radiates a parallel beam of light (Galginaitus, 1965).

Whether the SRP chooses a bespoke or manufactured drone, it is logical to ensure parabolic reflectors are (a) selected; and (b) positioned on the drone to maximise seeing the drone whether inflight or stationary. The task of checking the parabolic qualities of LEDs is easier with self-made drones, because these can be ordered from manufacturers that provide detailed specification sheets showing key performance data, including a spatial distribution graph to check the precise lens shape including its view angle (RS, 2019). In sum, LED colour choice requires very careful planning.

Fig 3.7 Geometry of LED Radiance



3.8 LED Maintenance

Before each take-off, it is sensible for an SRP to check LEDs for any obstruction, dirt or malfunctioning. Further, the SRP needs to schedule at least annual testing of LED intensity. This test can be achieved with a digital light meter in an appropriate

scientific environment – indoors, away from shadows, reflective surfaces and with no external light affecting the light from each tested drone LED.

However, a note of caution is required when attempting to measure the light intensity of an LED. Traditionally, the inverse square law of the point source is applied, but an alternative method of calculation highlights that the specified luminosity value does not necessarily remain constant at varying distances (Manninen et al, 2007).

For all SRPs, the key radiance distance is going to vary based on when (i) the drone is in flight and (ii) seeking to retrieve the drone. The inverse square law method causes distance dependence errors of up to 47% (Manninen et al, 2007). However, to date the alternative method of calculation has been tested on only 17 LEDs. Therefore, while the alternative method's claimed reduction in statistical variation of less than 1% is impressive, it requires further research before concluding it can replace the inverse square law that is still used by all LED manufacturers (Manninen et al, 2007).

3.9 LED Longevity

Accepting the importance of LEDs as both an aerial indicator of position and a means of finding a drone that has flown out of sight, an unknown challenge is determining when these vital components should be replaced. Research shows that aging causes both a reduction in external efficiency (brightness) and colour offset. Although LED performance over a lifetime has found to be independent of its colour (Cuadras et al, 2017).

However, monitoring the predicted lifetime of each LED is complex, because long term studies conclude that many factors affect longevity, including electronic component temperature operation, external environment temperature, on-off switching patterns and discoloration or cracking of the lens casing (Cuadras et al 2017; Yang et al 2010). The industry standard provided by the Illuminating Engineering Society states that the threshold for use is 70% normal intensity – measured in lumens depreciation (IES, 2011).

3.10 Internal Drone Semiconductors

There are five essential flight control components found in nearly all aerial drones relevant to navigation and positioning. These are:

(a) a magnetometer that measures the magnitude and direction of a magnetic field, which in turn can be converted into a magnetic north, south, east and west bearing (OUP Dictionary of Physics, 2015);

(b) an accelerometer which measures changes in velocity and in turn distance travelled based on the time elapsed from one point to another (Feynman et al, 2013);

(c) a gyroscope that maintains the orientation of the drone keeping it upright in flight by maintaining a perpendicular direction to any force applied to it (Denny, 2012);

(d) a GNSS receiver;

(e) a barometer used to measure the drone's altitude by sensing even a centimetre change in atmospheric pressure (Ebeid et al, 2017);

Notably, (a) (b) and (c) are usually combined in the same component, namely the Inertial Measurement Unit (IMU).

Magnetometers in drones are vital navigation components, because they communicate how GNSS is functioning in terms of north, south, east or west movement when a drone is flying. More importantly when GNSS is unavailable or unreliable, magnetometers facilitate accurate drone flight research and as a means of locating a drone that has crashed out of sight of the SRP or support team. To explain the reasoning for this operational and planning importance it is necessary to briefly explain how magnetometers work.

3.11 Magnetic Fields in High Latitudes

Iron-rich liquid iron movement in the Earth's outer core produces a constant magnetic field over the Earth's entire surface (Backus et al 1996). Both the flow and the field are unstable resulting in both magnetic North and South moving several miles each year (Huth, 2015: pp.115-116). In high latitudes variation in the strength of this magnetic field is 'most intense, most variable in time, and most complex' (Chapman, 1951: p.89).

The established means of finding the magnetic variation in a research location has been to apply data from the World Magnetic Model (WMM) (NOAA, 2019). The WMM is a joint initiative of the United States' National Geospatial-Intelligence Agency (NGA) and the United Kingdom's Defence Geographic Centre (DGC).

Fig 3.8 WMM Declination Model 2015

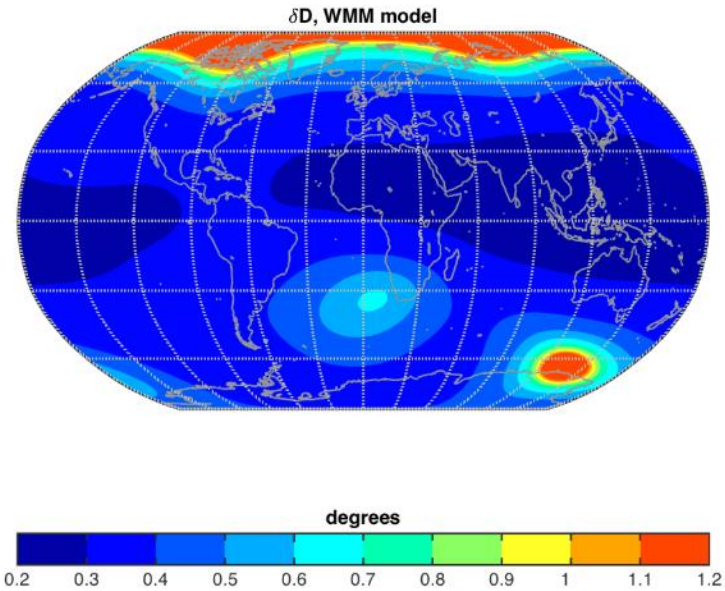


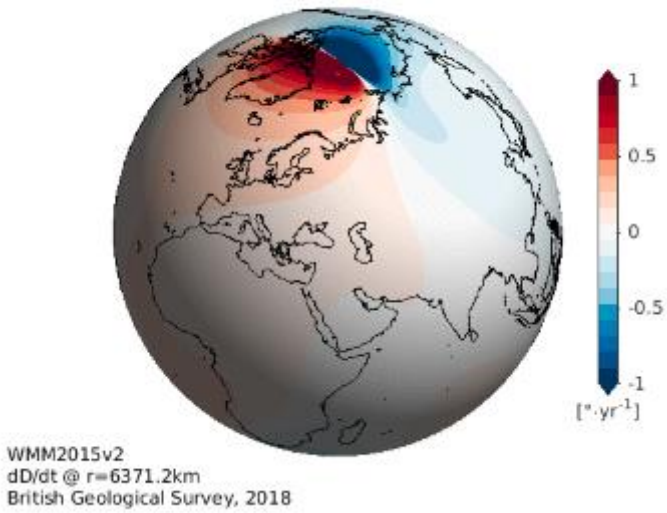
Figure 3.8 (NOAA, 2019) shows the five year WMM Declination Model 2015 which predicts that both the North and South Poles experience greater declination levels compared with anywhere else. The WMM is based on accurate five year predictions on the Earth's outer core magnetic field and its rate of change. However, there are other magnetic field influences from the Earth's crust and the ionosphere not factored in.

The consequence for magnetometers in drones is that a 'magnetometer may observe spatial and temporal magnetic anomalies when referenced to the WMM' (NOAA, 2019). In particular, certain local, regional, and temporal magnetic declination anomalies can in rare situations exceed 10 degrees, but more commonly range between 3-4 degrees.

The focus on the outer core magnetic field means important magnetic field variables in high latitudes are not included in the WMM calculations. Omissions include daily changes driven by the solar wind that change magnetospheric and ionospheric systems. Specifically relevant to high latitudes, these omissions include the North and South Polar auroral electrojet currents (NGA, 2019).

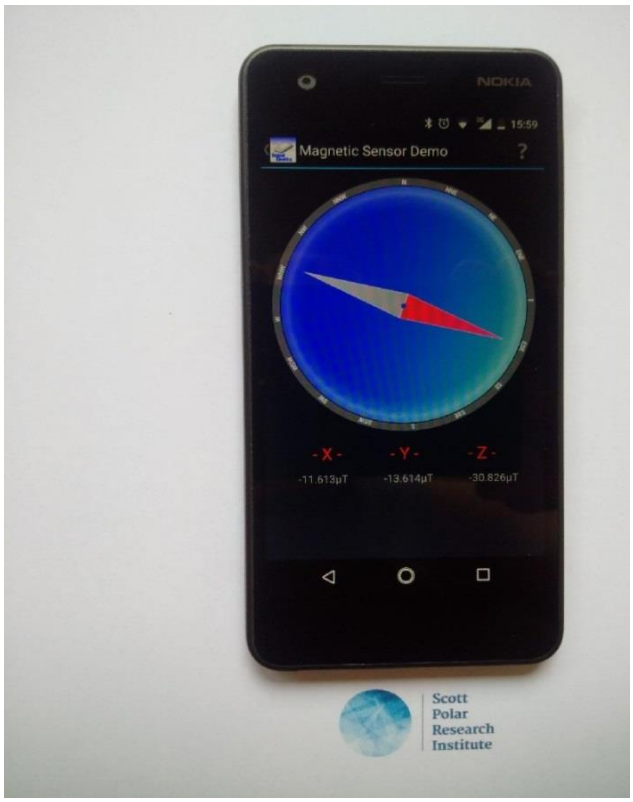
A further limitation of the WMM is that annually over each five year model lifespan its prediction loses accuracy. However, updates mitigate this weakness. For example, the WMM 2015 Model was updated to 2015 version 2, as shown in Figure 3.9 (BGS, 2019). The justification for this latest update was that since 2014 the core magnetic field had unpredictably varied ‘particularly at high northern latitudes’ (BGS, 2019). The next five year WMM Model will be released in late 2019.

Fig 3.9 WMM Model 2015 Version 2



Turning back to the pivotal magnetometer contained in every drone, the key question for SRPs is how can this component exploit the WMM data to provide precise navigation in high latitudes without relying on GNSS? Before answering this question, it is timely to briefly explain how a magnetometer functions.

Fig 3.10 Magnetometer Readings µT



A magnetometer works because of the Hall Effect. The Hall Effect is the electromotive force within a semiconductor through which an electric current is flowing when there is a strong magnetic field from a permanent magnet close by. The potential difference, called the voltage (*V*) produced develops at right angles to both the electric current and the permanent magnet (OUP Dictionary of Physics, 2015).

Figure 3.10 is a screen shot of the data produced from an Android App that is recording the magnetic field measured by a magnetometer chip operating in my Nokia smartphone. This magnetometer chip works on the exact same physical principles inside a drone. The Tesla Units (µT) measurements for three magnetic field forces can be seen: X 11.6; Y 13.6; and Z 30.8. The X, Y and Z measurements represent the Hall Effect voltage converted to a digital signal. In turn, these show the magnetic field strength on these three perpendicular axes.

When the drone turns, the X and Y axis will show significant changes in their data readings. This is because the X axis records changes in the magnetic field caused by movements toward or away from the Magnetic North Pole. The Y records

changes to the magnetic field caused by movements towards or away from East. Together, the X and Y provide an accurate 360° compass of the drone's orientation based on the magnetic field. The Z axis records the altitude difference of a drone compared with the Earth's surface. Finding degrees of direction on a level plane is a two dimensional task that relies on the X and Y axes

3.12 Magnetic Declination

In an operational and planning environment in which GNSS is working, the GPS or equivalent service would make automatic adjustments for the magnetic declination using the latest WMM data. However, that still presents two challenges for any SRP when there is no GNSS or GNSS is limited or unreliable.

First, when conducting research with drones in northern latitudes without GNSS, the SRP has to ensure the drone operates with an adjustment for declination, because it is the highest on Earth. Depending on precise location, the range is >6 to 15 degrees. Once the current declination is checked it can be programmed into the drone's flight operations. The benefit is that the flight path of sensor data would then more precisely correlate with ground truth evidence and the maps used to record positions of what is observed.

Second, an SRP needs to factor local declination in to know exactly where the drone is heading with reference to a map. If the drone crashes then the direction is clear based on current declination versus any potentially out of date declination recorded on the map.

My example Equation 3.1 shows a calculation that a SRP would make to ensure a drone with limited or without GNSS can fly with maximum accuracy. It would require a program that alters the magnetometer to include the WMM declination for the precise latitude and longitude together with a Kalman Filter that provides a value for daily ionospheric and local magnetic changes.

Equation 3.1 - Calculating True Bearing with WMM and a Kalman Filter

True Bearing (TB) = Magnetic Declination (MD) (GV grid = D-C) + Magnetic Bearing (MB) ± Kalman Filter (K)

$TB = MD + MB \pm K$

$MD\ (WMM)\ (version\ 2) = 6.8^{0}; MB = 270^{0}; K = +1°$

$MD + MB \pm K = TB$

$TB = 264.2^{0}\ (264'12'')$

Briefly a Kalman Filter is a computationally complex algorithm that can be use one known measurement to predict another unknown measurement (Grewal and Andrews, 2015; Valade et al, 2017). It has been described as a “predict-update” cycle, where predictions are updated based on observations - a continuous cycle of new predictions based on revised known data (Stutters et al, 2008).

3.13 Operational Planning and Navigation for Underwater Drones

The structure of this section follows, where relevant, the earlier thematic structure on aerial drones. Therefore, an SRP working only with underwater drones can choose to read just this section or supplement it with the whole chapter. Indeed, based on the international response of researchers to the survey results analysed in chapter 5 of this thesis, a significant percentage of SRPs use both aerial and underwater drones. Therefore, all of this chapter 3 may apply to some SRPs.

Many of the aspects covered so far in this chapter are also relevant to underwater drones. From a risk management viewpoint the Cause-Consequence Matrix and NASA Severity definitions covered earlier in this chapter can equally be adjusted to be valuable methods for an SRP to pre-assess underwater drone missions. However, there are notable differences. First, there is negligible visual line of sight navigation with an underwater drone, given an SRP only sees the drone when it is floating on the surface of the water. Figure 3.11 (NERC, 2018) is a typical example. Second, navigation accuracy is more challenging because GNSS signals do not penetrate water (Emami and Taban, 2018).

Fig 3.11 Glider-Shaped Drone

3.14 Quantitative Risk Management for Underwater Missions

Experts in underwater drones and risk analysis have adopted a Risk Management Process model called the RMP AUV process specifically for extreme environments. The RMP AUV focuses on risk of loss of the drone, but excludes financial loss and loss of scientific data (Brito et al 2010). The RMP-AUV process is sophisticated, relying on experts to provide quantitative value for risk based on many precise observed faults and successful missions. One model created using this method was based on four different underwater drone operating environments – coastal water, ice shelf, open water and sea ice (Brito et el, 2010).

In summary, the risk assessment process is split into three parts. First, the SRP specifies the probability of risk. Second, the SRP defines the minimum operational requirements, including the minimum number of missions and distances to be travelled by the underwater drone. Third, a risk assessor calculates the probability of losing a drone over the research campaign, meaning over the total number of missions. Based on the probability provided, the SRP can proceed. Alternatively, the SRP may need to work with technical support colleagues or external experts to mitigate and consequently obtain a revised probability of loss (Brito et al, 2010).

Statistics for the glider underwater drone in Figure 3.12 (data extracted from Rudnick et al, 2016: p.1116), covering 12 years (2004-2014) show that for thousands of missions of greater than five days in duration it is possible to have a relatively low loss rate of 12 per cent. However, this 12 year period needs to be treated with

caution in the context of SRPs in high latitude waters. First, it is based on one specific type of glider model, called the Spray (2m length, 50 kg mass). Second, the trajectories of the Spray missions were global and not focused on high latitude oceans where sea ice and ice bergs would increase risk of loss. Third, the SRPs of the Spray gliders were always expert users trained by the developers of Spray, rather than using a range of different gliders.

Fig 3.12 Glider Statistics for Missions >5 Days

Number of missions	297
Total duration (days)	28,091
Median duration (days)	100
Upper quartile (days)	119
Number of losses	9
Loss rate (per year)	0.12

3.15 Locating Drones on the Surface of Water

A brightly coloured underwater drone at the water surface is sufficient risk mitigation in daylight. However, there will be research missions that require operating a drone in the dark or recovering a malfunctioning drone in the dark. LED selection has already been covered earlier in this chapter. What is evident is that when using underwater drones the surfacing of the drone has to factor in a mainly green background. Therefore, a drone with green LEDs is going to be harder to pinpoint and easier to lose against mainly green or green-tinged ice or water backgrounds. Further, flashing LEDs that are not green in colour will assist against dark grey ocean backgrounds (Pritchard, 1961).

3.16 Electronic Components for Underwater Navigation and Positioning

The essential flight control components in underwater drones follow a similar format to aerial drones. That is they rely on an IMU made up of accelerometers, gyroscopes and magnetometers. There is also a GNSS module so that GPS or an equivalent fix is obtainable for localization on the water surface, and can also function with sonar components. In combination, these sensors: (a) calculate the position of the drone underwater in the context of where it submerges and surfaces; and (b) map or survey the research focus underwater using sonar or inertial measurements or both.

A key addition to an underwater drone's navigation systems is the Doppler Velocity Log (DVL) that uses active sonar. An active sonar device uses sound to detect and locate objects in water, where signals are transformed into either images or bathymetric maps (Paull et al, 2014).

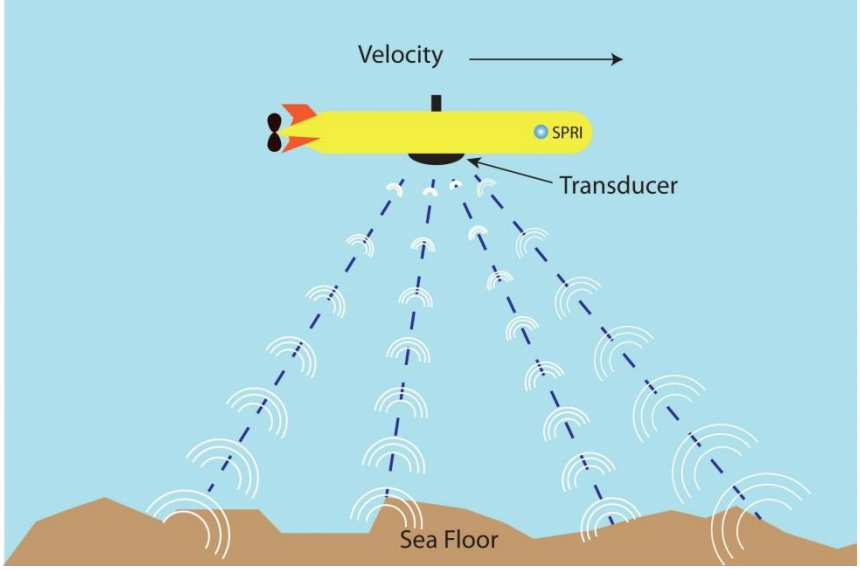
The DVL sensor, called a transducer (Nortek, 2019), uses the Doppler return signal from the bottom of the sea to calculate the velocity of the drone relative to the sea bottom. If the sea bottom is too far from the water surface then a DVL would be too imprecise to rely on. The DVL provides accurate data on velocity gained from four beam directions which can be added into inertial navigation measurements (Miller et al, 2010). In Equation 3.2 (Bowditch, 2017: p.416) the doubled Doppler shift is expressed as:

$$Fd = 2Fs\ (V/C) \qquad \textbf{[Equation 3.2]}$$

Where Fd is the Doppler shift frequency; Fs is the frequency of the sound when everything is still; V is the relative velocity between the sound source and the sound receiver (m/s); and C is the speed of sound in water (m/s).

The original patent summary by the inventors of the first digital sonar navigation sensor explain that the 'horizontal motion of a vessel through a body of water is determined by providing means to receive Doppler-shifted signals along the fore-aft and port-starboard axes of the vessel, digitizing the received Doppler-shifted signals…integrating the digitized signals…throughout a given period of time to obtain an indication of the incremental distance travelled along each axis during the given period of time' (Kritz and Lerner, 1972: p.1). Figure 3.13 (my adaption from Bowditch, 2017: p.417) shows how DVL works by constantly pinging signals to calculate velocity.

Fig 3.13 Doppler Velocity Log



3.17 Eclectic Navigation Systems

Underwater drone technology relevant to navigation is rapidly developing. The consequence is that both fundamental A to B navigation and the accuracy of measurements made for research purposes increasingly rely on eclectic solutions. Three examples are (a) Deep Ocean Gliders Using Sonar and Thrusters; (b) Sonar Combined with GNSS and Cameras; and (c) Simplifying Algorithms to Decrease Computational Load.

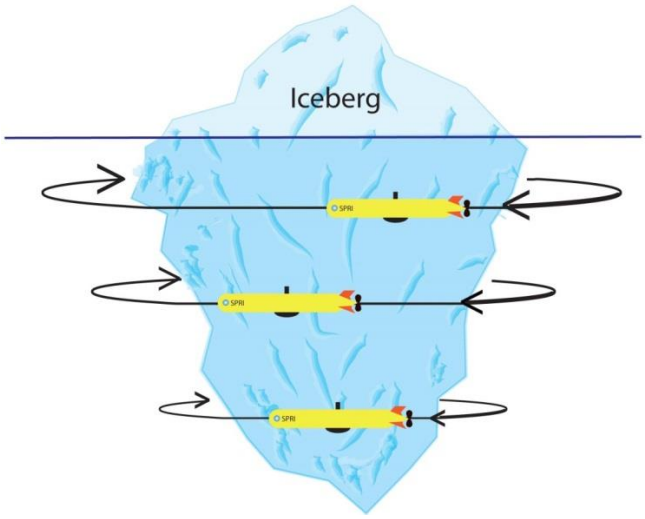
(a) Deep Ocean Gliders Using Sonar and Thrusters

The threat of icebergs occurs not only at the Poles, but also in cryospheric regions such as Southern Patagonia. Research on and near glaciers and icebergs are high risk for ship-based projects. Therefore, more underwater drones can be more safely better used to carry out research in such environments.

Recent using a hybrid underwater glider to measure the underwater shape of an iceberg using sonar shows that SRPs can successfully reconstruct icebergs (adapted from Zhou et al, 2019). Even deep sea optical mapping has included the use of underwater drones because of innovative acoustic systems (Iscar et al, 2017). The glider design, as shown earlier in Figure 3.11, is widely used by SRPs because they provide a low-powered drone well-designed for oceanography. The normal gliding path is a vertical zigzag pattern created by a buoyancy pump (Rudrick, et al, 2016).

SRPs can fit a thruster forward propulsion device to the back of the glider so that it can travel horizontally rather than only zigzag vertically at different depths. The consequence is that sophisticated mapping of the exterior of icebergs is now possible, as shown in Figure 3.14 (adapted from Zhou et al, 2019: p.3). Further, below ice shelves this same sonar and thruster combination is useful for mapping a variety of seafloor morphological features (Wynn et al, 2014).

Fig 3.14 Revolutions around an Iceberg



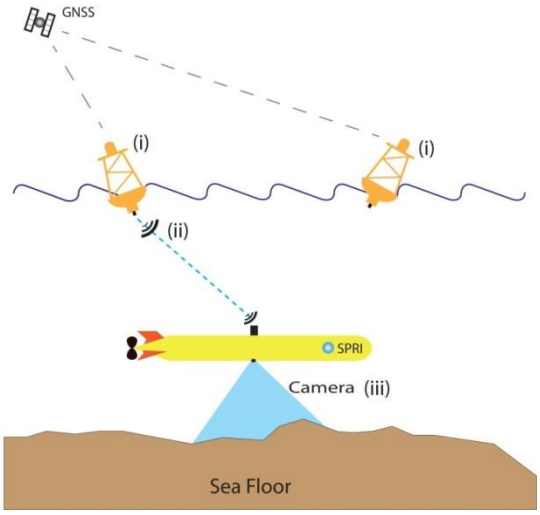
In this hybrid set-up, the glider receives a GPS or equivalent GNSS fix for localization on the water surface. Thereafter, the mission starts with the standard glider vertical buoyancy movement and relies on dead reckoning to reach the required initial depth. Then once at the required depth the thruster enables the glider to horizontally revolve around the iceberg taking continuous sonar measurements.

(b) Sonar Combined with GNSS and Cameras

A hybrid system based on an “instrumented workspace bound by the range of the acoustic transducers” has the effect of combining “odometry estimate with the range measurements for accurate localization” (Iscar et al, 2017). As shown in Figure 3.15 (adapted from Iscar et al, 2017: p.11), this is achieved by (i) GNSS localization based on two static beacons on the water surface. Then, (ii) sonar transducers are placed on the underside of each beacon. Further, dead reckoning provides distance information within the parameter of the two beacons. Finally, (iii) cameras attached

to the drone provide visual odometry when the drone is travelling near to the sea floor.

Fig 3.15 Sonar with GNSS and Cameras



(c) Simplifying Algorithms to Decrease Computational Load

Increasingly, algorithms are being used to reduce the computational load on all types of drones, including underwater drone navigation systems (Emami and Taban, 2018). The benefits of doing are reduced costs, less heat loss, improved performance and more efficient power consumption.

For instance, researchers have produced simplified algorithms to reduce the complexity of conventional Kalman Filter (KF) algorithms. In a recent underwater drone sea trial a low complexity KF algorithm was compared with a conventional system (Emami and Taban, 2018). The performance was similar. This result showed that underwater drone designers have greater choice of semiconductor processors, which will reduce costs, increase flexibility of drone design and improved reliability. The benefits for navigation are clear – comparable quality research output for less cost.

Further, in colder high latitude and cryospheric waters the reduced computational burden may decrease already weaker battery (measured in *mAh*) power longevity. Battery life is a vital variable that contributes to increases the probability of a lost drone trapped under ice potentially surfacing many months later (Harris, 2018).

Chapter 4

Drone Regulation for Scientists

4.1 Introduction to the Approach

It is vital that scientists taking control of drones accept the professional responsibilities of airmanship, airspace, navigation and safety. This requires complying with relevant laws even though the norm may be to research in locations distant from civilian populations and urban areas.

There are many aviation "laws" relevant to SRPs.[9] The tactical aim of this chapter is to cover aviation law[10] in a memorable and practical way most pertinent to SRPs navigating and positioning drones in key high latitude jurisdictions and in the Nepalese Himalayas. Inevitably with expensive, long range drones the task of flying will often be carried out by professional technicians. However, as evidenced by the Remote Sensing Volume 38 (2017) and Volume 39 (2018) drone-focused articles mentioned in chapter 1 of this study, many short and medium range aerial drones are operated by scientists.

While the following analysis is based on UK requirements, the structure of this chapter allows any SRP[11] from another country to read everything as it relates to their home jurisdiction. They just need to factor out UK law and factor in the law of their home jurisdiction.

[9] In contrast, a lawyer would take the exact opposite approach and absorb all the law, and then be well placed to analyse any specific application. For an SRP this would be unnecessary!

[10] English Law precisely includes statutes, secondary legislation and common law precedent, and until at least 2020 EU Law. However, laws in the context of aviation are best understood by references to all relevant law, guidance and policy.

[11] As in all chapters of this study the term Scientific Research Pilot (SRP) is used throughout chapter 4. SRP is not a legally defined term in the UK or under any other jurisdiction's aviation law. It merely serves to highlight the focus is aviation law relevant to scientists.

4.2 UK Aviation Laws Relevant to SRPs

In the UK, the Air Navigation Order (ANO), and all its subsequent amendments, is the key aviation law to apply. The Civil Aviation Authority (CAA), as the main UK aviation regulator of all aircraft including drones, also provides guidance in the form of Civil Aviation Procedure (CAP) documents that contain further detail, explanations and policy. Each CAP has a unique number so that there is no confusion when communicating or cross-referencing CAPs.

Drone regulations are contained within the Air Navigation Order 2016 (ANO 2016) and its subsequent amendments. To date, so June 2019, the most recent ANO 2016 amendment is CAP 393 (2019) the Air Navigation (Amendment) (No.2) Order 2018.[12]

Technically, any UK-based SRP can rely on Section 3.10 of the UK CAA Unmanned Aircraft System Operations in UK Airspace – Guidance (CAP 722) which exempts 'research' work conducted 'in-house' from the legal requirements to seek permission and undergo a flight competence test. The logic is that research is not commercial work because there is an absence of 'valuable consideration' (CAA, CAP 722). So researchers could communicate with and seek permission from the CAA on a mission by mission basis.

While, the ANO 2016 context of 'commercial' drone activity is based on for-profit activities, these terms have become increasingly relevant to research scientists because of the potential risk of injury caused by drones to persons and property and protected species. This risk is mitigated with insurance cover under UK law. Consequently, managers of research institutes are rapidly moving towards policies that ensure that all staff operating drones are competent at the commercial level of qualification. Without proof of this competence at the commercial level, insurance may be unobtainable or exorbitant (Cracknell, 2017).

It has been observed that 'increasingly, academic researchers utilizing remotely piloted aircraft systems [drones] may deem it necessary to obtain permission from

[12] See https://publicapps.caa.co.uk/docs/33/CAP393_Fifth_edition_Amendment_13_March_2019.pdf; also at http://www.legislation.gov.uk/uksi/2019/261/made

the CAA, codifying their operational competence' (Cunliffe et al, 2017: p.2739). The motivation to do so relevant to SRPs may include, the need to comply with institutional insurance requirements (Lloyd's, 2015), and to confirm professional competence to research collaborators. The consequences of meeting legal requirements and applying risk mitigation are that operating a drone in this context requires PfCO is in effect a licence to operate a drone. Table 4.1 sets out the three main requirements.

Table 4.1 Main PfCo Requirements

PfCo Requirement	Essential elements
Theoretical Examination	A theoretical examination based on Air Law, Airmanship, Map-reading & Navigation and Meteorology. Then a practical test to prove the remote pilot can take-off, fly, land and perform emergency procedures.
Operations Manual (OM)	SRP or research institute submits a very detailed operations manual recording all its administrative processes and risk assessment models for drone use.
Practical Examination	Practical flight tests to confirm the applicant pilot can safely take-off, fly, land and perform emergency procedures, all in the overarching context of thorough operational and safety planning.

Further, polar and cryospheric research institutions are likely to assess that the operational risk management of drones is mitigated by Standard Operating Procedures (SOPs). Any SOPs would rationally require a consistent approach and measurable level of pilot competence and legal knowledge. PfCO, especially the OM component of it, fulfil this role. Further, in the context of wildlife research an OM is strong evidence that all requirements of the PfCO are understood, and in turn it is evidence of best practice to manage operational risks (Hodgson and Koh, 2016).

Seeking a CAA PfCO is the most cost-effective and logical SOP to consistently minimise injuries, avoid law suits concerning damage to property, reduce lost drone costs and avoid fines from aviation authorities. Minimising insurance costs is not a legal requirement, but it presents the opportunity to negotiate insurance contracts that factor in a high level of SRP flying competence. A Lloyd's report on drones has specifically pointed out that 'commercial insurers have the opportunity to encourage

good practice in commercial operators by varying terms and conditions, risk retention (deductibles or excess) and premiums on the basis of the quality of clients' risk' (Lloyd's, 2015).

Analysed further, there are two separate elements that the SRP is satisfying – legal and risk. Law often merges legal and risk elements so it's important to clarify precisely the reasoning of each point in the context of the CAA Permission for Commercial Operation (PfCO) in Table 4.2, checked and updated to 1st June 2019.

Table 4.2 An SRP with CAA PfCo

Legal Requirement or Risk Mitigation	Advantages, Examples and Key Points
Legal Requirement - EC 785/2004[13] - Regulation (EC) No 785/2004 of the European Parliament and of the Council of 21 April 2004 on insurance requirements for air carriers and aircraft operators	Legal Requirement for third party public liability insurance at all times based on maximum take-off mass (MTOM). The insured risks must include force majeure and acts of sabotage. In the UK the pilot training provider check the applicant's insurance before recommending to the CAA whether a PfCO is granted.
Risk Mitigation - Potential Legal Cost attached to third party claims	Flying over private land for research purposes would in most instances not require a PfCO. Only the land owner's permission would be needed. However, possession of a PfCO would reduce insurance premiums. Large research institutions are likely to have public liability insurance policies that require renegotiating to include negligent damage cause by its drones.
Risk Mitigation - Independent testing of competency based on safe airmanship, airspace, navigation and safety	Proves drone pilot competence to research partners. Joint research projects create more risk which is mitigated by measurable pilot competence standards. Just institutional in-

[13] See https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:32004R0785. Available in 23 languages as a PDF format.

	house training is unlikely to be sufficient.
Risk Mitigation - Independent testing of competency based on safe airmanship, navigation, operational planning	Pilot is less likely to crash, damage or lose drones. Number of third party claims with the consequence of court enforced or settled damages would be reduced.
Risk Mitigation – Working with colleagues who also have PfCO.	PfCo pilot more likely to exercise good safety management and leadership when working with in-house or joint project colleagues who are operating drones to a commercial standard. For example, awareness about decision making under stress, fatigue, the effects of alcohol, illness and medication.

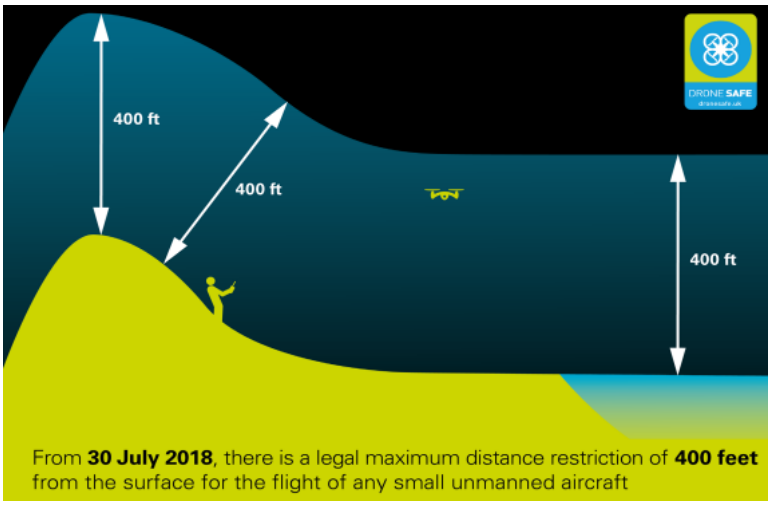
The exponential rise of drone use in all research has been matched by expanding legal requirements and risk management logic to seek PfCO from the CAA.

The 400 Feet Rule

The ANO 2016 was amended in May 2018 to require that all drones fly no higher than 400 feet from the ground. The application of the 400 feet restriction is indicated in Figure 4.3 (CAA, 2019). This shows that the maximum height rule applies regardless of how high the ground is compared with sea level. So subject to specific airspace restrictions indicated on CAA aviation maps, the UK rules would allow an SRP to fly a drone up to 400 feet above the summit of a mountain.

A small unmanned aircraft is defined as ‘any unmanned aircraft, other than a balloon or a kite, having a mass of not more than 20 kg without its fuel but including any articles or equipment installed in or attached to the aircraft at the commencement of its flight’ (CAP 722, 2015). Most polar and cryospheric scientists may have drones that qualify as a small unmanned aircraft. If the drone is more than 20kg the rules are far more onerous and the likelihood of the commensurately higher cost would make a professional drone pilot not an SRP the only rational choice.

Fig 4.3 The Meaning of 400 Feet



4.3 Other Relevant ANO Articles 2016

Given the constant changes to the legal treatment of drones, it is imperative to check aviation law statutes on a weekly basis. Conveniently, Article 23 allows an efficient, albeit not 100 per cent assessment of changes. Article 23 sets down which of the 275 Articles in ANO 2016 are relevant to drone use. The current applicable Articles are listed in Table 4.4 below.

Table 4.4 ANO Article 23 Provisions

Article	Relevance
2	Interpretation
91	Dropping of articles for agriculture etc.
92	Mooring, tethering, etc. (not related to small unmanned aircraft)
93	Release of small balloons (not related to small unmanned aircraft)
94	Small unmanned aircraft: requirements
94A	Small unmanned aircraft: height restrictions on flights (new)
94B	Small unmanned aircraft: restrictions on flights over or near aerodromes (new)
94C	Small unmanned aircraft: registration of SUA operator (new)

94D	Small unmanned aircraft: requirement for registration as SUA operator (new - not applicable until 30 November 2019)
94E	Small unmanned aircraft: competency of remote pilots (new)
94F	Small unmanned aircraft: requirement for acknowledgement of competency (new – not applicable until 30 November 2019)
94G	Meaning of ‘remote pilot’ and ‘SUA operator’ (new)
95	Small unmanned surveillance aircraft
239	Power to prohibit or restrict flying (Prohibited and Restricted Areas)
241	**Endangering safety of any person or property**
257	CAA’s power to prevent aircraft flying (except 257(2)(a))
253	Revocation, suspension, variation of certs, licences or other documents (new to this list)
265	Offences and penalties
266	Exemption from the ANO (new to this list)
269	Certificates, authorisations, approvals and permissions (new to this list)

4.4 SRP in Antarctica, Greenland, Nepal, Southern Patagonia or Svalbard

Having set down the minimum explanation and legal content relevant to a SRP based in the UK, hereafter this chapter focused on the applicable aviation laws of the specific jurisdiction that that a polar or cryospheric scientist would conduct research in. Given the importance of Antarctica, Greenland and Svalbard to polar scientific research, these three locations are covered. Nepal is also included because of given the increasing research focus on its cryospheric areas with drones.

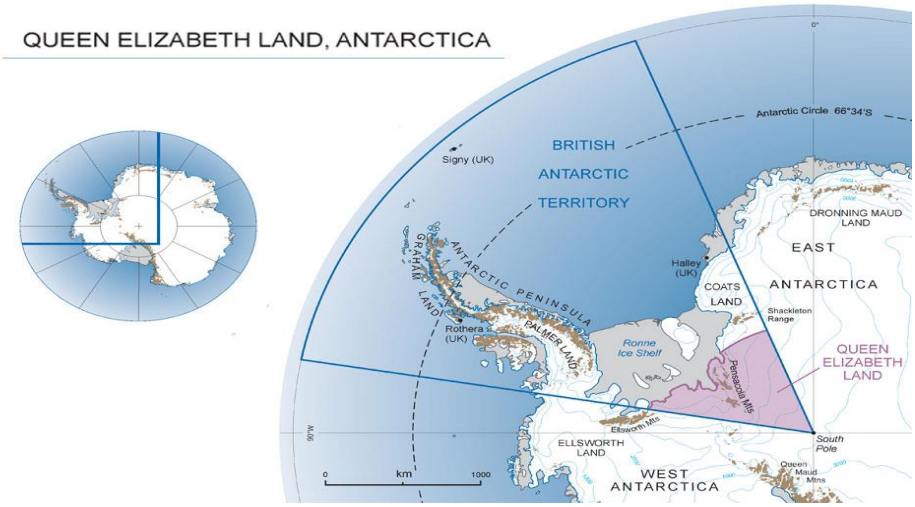
4.5 Antarctica

From an aviation law viewpoint, Antarctica is the most complex location to analyse. To provide a memorable contrast, if a scientist is dedicated solely to Arctic research, there are only eight jurisdictions to think about. On or above Antarctica, both its land

and coast[14], there is no single applicable jurisdiction, because currently there is no universally accepted sovereignty territory.

For example, Figure 4.5 (Foreign & Commonwealth Office 2012) illustrates the British Antarctic Territory claimed since 1908. On examining this Foreign Office map, anyone would be forgiven for deducing the governing law between longitude 20°W and 80°W is likely to be UK law. However, it is not. The reason is that governance of all Antarctica is based on the 1959 Antarctic Treaty (the "UN Treaty") which holds in abeyance all sovereign territorial claims (Foreign & Commonwealth Office 2012).

Fig 4.5 British Antarctic Territory



The basis of all legal analysis on what law should apply to any scientist on Antarctica is set out in Article 8 of the UN Treaty. Article 8 states that "each country [signatory] has legal jurisdiction over its own citizens and observers." Therefore, citizenship of an SRP is always relevant to his or her drone use. For a scientist who is a British citizen, UK aviation laws would apply.

In the scenario of an SRP with British citizenship working out of an Antarctic base not managed by British Antarctic Survey, the jurisdiction of the country managing that non-UK base station is going to have no legally enforceable relevant, but it certainly has political and practical relevance. For example, increasing numbers of

[14] Above and below the surface of water, congruent with public international law, the Antarctic Treaty extends 12 nautical miles from its coast. See Article 3, United Nations Convention on the Law of the Sea (United Nations, 2019).

scientists are likely to operate drones on the Fildes Peninsula, located at Latitude: 62° 13' and Longitude: 58° 59', on the western side of King George Island.[15]

Another important influential form of authoritative guidance for SRPs using drones on Antarctica is the Council of Managers of National Antarctic Program (COMNAP), *Antarctic Remotely Piloted Aircraft Systems (RPAS) Operator's Handbook (COMNAP, 2017).* Produced by the COMNAP drone working group, its full title is the COMNAP Unmanned Aerial Systems Working Group, from this detailed document three points are essential to factor in.

(a) **Point 8 (COMNAP, 2017)** – strongly recommends that all drone flights in Antarctica are notified to responsible officials in the relevant area. Table 4.6 is a crystallization of a very detailed Notice to Airman (NOTAM) or similar notification that would need to be made by an SRP, to be circulated via a website posting by a national Antarctic program air operations manager.

Table 4.6 Notice to Airman Details

NOTAM
Pilot Details:
Notam Details: New; Cancel; Update
Launch Location: [Latitude and Longitude]
Radius of Flight: [Latitude and Longitude]
Centre of Flight: [Latitude and Longitude]
Timeframe:

(b) **Point 9 (COMNAP, 2017)** – recommends that each national Antarctic program ensures each drone pilot is appropriately trained based on its national regulations. Therefore, an SRP who is not a British citizen but works with BAS who does not possess UK CAA PfCo logically needs to prove possession of a comparable national drone pilot qualification.

[15] Note Annex 3 in this study summarises the law and regulation applicable to a number of SRP situations, including drone use in Antarctica on or near King George Island (South Shetland Islands).

(c) Point 4 (COMNAP, 2017) – recommends that where manned operations exist, the use of geofences may be appropriate.

4.6 Greenland

Danish (2017), CAA Amendments, Order on flights with drones outside built-up areas, Order no. 788 applies ("Order 788"). Danish law has many similarities with the UK rules. Height restriction is slightly lower set at 100m. There is no specific distance limit, but VLOS is always required, except by special dispensation for research approved by prior application. Therefore an SRP can apply for a waiver to fly BVLOS (Aeronautical Information Circular B 08/14). The application fee for processing such applications is 150 Euro per hour so this cost needs to be included in projected research budgets.

4.7 Nepal

Flight Operations Directives No.7, May 2015 contains the core rules, conferred by Rule 82 of the Civil Aviation Authority Nepal (CAAN) of Nepal, Civil Aviation Regulation, 2058 (Directives No7). Nepalese law mirrors the UK rules with a VLOS required of 122m maximum height and 500m maximum range from the SRP. Note "Operations beyond these distances must be approved by the CAAN (the basic premise being for the operator to prove that he/she can do this safely)" (Rule 4.1, Directives No 7).

The second key document for guidance is the CAAN Procedure Manual for Flight Permission. In its Appendix G there is set out the Application for Drone Use. Further, Appendix – H lists the required documents for Drone Operation Permission. These include:

1) A Letter of Request;

2) A copy of Operation Specifications of Drone;

3) A copy of the Map of the Operation Area;

4) A document indicating the latitude and longitude box of the proposed Operation Area;

5) A “No Objection” or “Recommendation Letter” from the relevant private or public land owner, or military unit if in an operational military area;

6) Letter from the concerned authority for security clearance and or other clearance.

4.8 Svalbard

The Norwegian Civil Aviation Authority, via Norwegian Amendments (2016) to the Aviation Act 1993, The Regulation Drones - concerning aircraft without a pilot on board, applies (Drone Reg 2016). Note this is an English translation of the Norwegian text published by the Norwegian Civil Aviation Authority, https://luftfartstilsynet.no/en/drones/commercial-use-of-drones/. In the event of any deviation between the English and the Norwegian version the Norwegian would apply.

Section 51 of the Drone Regs 2016 requires drones to operate within VLOS during daylight hours. On Svalbard this is a most important rule, given its many months of darkness and short daylight hours. There is a no exception in Section 59 of the Drone Regs 2016 that allows BVLOS with drone lights. The drone must have white, low-intensity lights that have a light intensity of least 10 candela, where flashes are produced by rotating lights (strobe lights) at a rate of at least 20 flashes per minute.

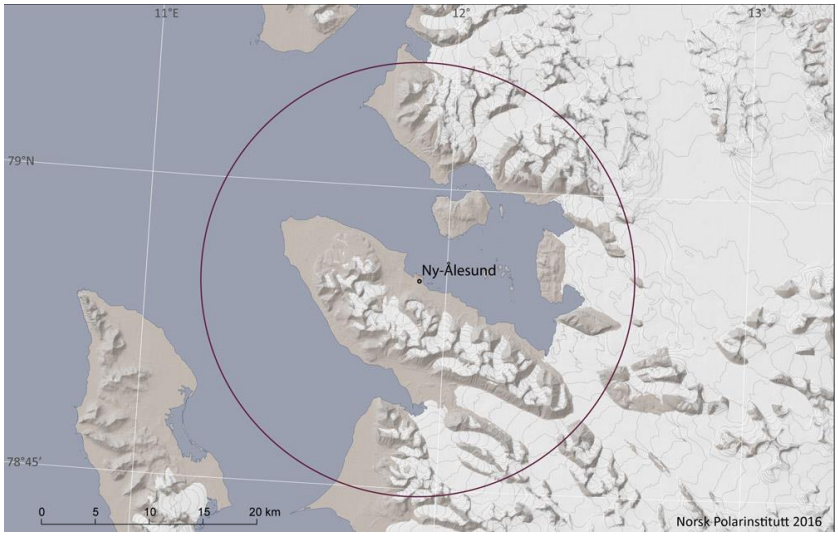
Once the SRP is in situ they would need to comply with local laws. Given Svalbard is part of Norway, the Norwegian laws concerning commercial drones apply along with the Svalbard Environmental Protection Act and local laws.

For example, at Ny-Ålesund (78°55’ N, 11°56’ E), there is the requirement to submit a signed agreement with the local Aerodrome Flight Information Service (AFIS). This signed agreement needs to set out the planned use. The SRP must sign an agreement with the local AFIS (Kings Bay) regarding use of Ny-Ålesund airspace. All

relevant permits, notice to authorities, drone pilot licence and proof of insurance have to be presented to Kings Bay AFIS before signing the contract.[16]

There is an application guide (Kings Bay ALIS, 2016) that sets out all details, including a reminder concerning the latest possible notice periods required before commencing BVLOS (three months) and VLOS (four weeks) flights, and as marked with a purple coloured circle on Figure 4.7 the 20km radio silence exclusion zone.

Fig 4.7 Ny-Ålesund Radio Silence Zone



4.9 Summary of jurisdictions

Appendix 3 of this study provides a route map for SRPs who are either UK CAA PfCo qualified or hold British citizenship. However, any SRP regardless of country of citizenship can make use of **Appendix 3**. In each jurisdiction the SRP would simply need to confirm the specific answers relevant to their home jurisdiction. Put another way they would replace all references to UK law with the law of their home jurisdiction and replace the words UK citizenship with that of their own.

4.10 International Recognition of Competence

For a SRP who has UK PfCO registration, a key recurring question will be ‘when I set up in Antarctica, Greenland, Nepal, Southern Patagonia or Svalbard, will the authorities in each of these remote locations recognise my UK drone pilot

[16] The email address for Kings Bay AFIS is airport@kingsbay.no.

competency?' First, international principles and policies cannot be ignored, and may facilitate quicker access to a research area. Specifically, all 192 member states of the United Nations are signatories to The Convention on International Civil Aviation met in 1944 in Chicago ('the Chicago Convention').

For each location the answer will be not only different but evolving. What is likely to play a constructive role is the ICAO's promotion of the Chicago Convention. Article 33 of the Chicago Convention covers, among other things, the recognition of licences and certificated of competency held by pilots, so that each pilot's competency can be recognised, subject to meeting minimum standards established by the Convention. In the context of drones this cross border recognition principle alone makes the Convention and its updates relevant to any SRP.

Second, the ICAO Manual on Remotely Piloted Aircraft Systems (ICAO RPAS, 2015), published in Arabic, Chinese, English, French and Russian, provides a detailed grounding in all the risk issues that drones present as aircraft that have to be integrated within a very established international framework of safe aviation principles.

4.11 Maritime Law Relevant to SRPs Operating Underwater Drones

The regulatory detail surrounding aerial drones is contrasted by the paucity of underwater drone regulation. This reflects the position that underwater drones are neither defined under English law as a "ship", nor are they a fixed structure, such as a buoy or jetty. Maritime law has unaffected core principles, but it has also continually adapted (Van Hooydonk, 2014). Therefore, changes usually occur with reference to established legal concepts and case law.

As underwater drone use increases, there is a need for greater legal clarity on their treatment (Wynn, R. 2014). Nevertheless it is still vital that SRPs taking control of underwater drones accept that such a research tool creates an extra role – to think simultaneously about navigation and safety. Therefore, the planning and operation of underwater drones requires the same level of thoroughness as aerial drones. Further, third party public liability insurance would mitigate risks, even if the risks are less than aerial drones.

Chapter 5

Data and Methods

5.1 Frame Sample Methodology

The fundamental aim of the drone survey was to target respondents that would meet the three quality survey implementation criteria of (i) reliability, (ii) validity and (iii) representativeness (Buckingham and Saunders 2004; Ritter, 2012). The criterion of representativeness was the most challenging of these three, because it involved attempting to avoid over-concentration on clusters of researchers, for example just geomorphologists or only Arctic researchers. To maximise representativeness, five specialisms were finally selected.

(a) Climate & Climate Change

(b) Ecology & Biodiversity

(c) Geomorphology

(d) Ice & Moving Ice

(e) Oceanography

Additional consultation within the SPRI resulted in the decision to broaden the survey coverage to not only aerial, but also underwater drones. The logic was that two of the five research groups, namely Ecology & Biodiversity (b) and Oceanography (e), would potentially reveal SRPs using only underwater; or both aerial and underwater drones.

5.2 Target Population of Scientists

With the framework of the above five research specialisms, a to e, the next task was to compile a list of polar and cryospheric institutions globally as the source of the potential SRPs. A former Head Librarian at BAS, Andrew Gray, has analysed the

statistical output of polar research globally on a country level (Gray, 2016). In his research, polar is broadly defined to include cryospheric research, so not just research focused at high latitudes.

Applying Gray's results for the highest national share of total polar publishing the relevant countries for both Antarctic and Arctic research could be targeted. For Antarctic research these were Australia, China, France, Germany, Italy, New Zealand, Russia, Spain, UK and USA. For Arctic research these were Canada, China, Denmark, Finland, France, Russia, Sweden, UK and USA.

While Argentina and Chile are not leading countries measured by national share of total global polar publishing, both have the highest number of polar publications as a percentage of their respective national output (Gray, 2016). Further, Switzerland-based researchers were included because there was strong publishing evidence that this community uses drones to support research in the European Alps and Himalayas.

The target respondents were selected from polar and cryospheric research journals and the leading polar and cryospheric institutions in the countries in the two aforementioned lists. Added to this were the national polar research institute or institutes for each of these countries.

5.3 Questionnaire Structure

The survey required asking sufficient questions to reveal SRP choices, and also brevity to facilitate its quick completion. The original plan was to ask not more than six questions. Ultimately, 10 questions were put to respondents answering the aerial-only or underwater-only questionnaire. SRPs using both aerial and underwater drones were asked 17 questions.

Four polar professionals, Gareth Rees (SPRI), Tom Chudley (SPRI), Tom Jordan (BAS) and Carl Robinson (BAS), were consulted on refining the survey questions to maximize the value of any responses based on asking ≤10 questions. The value of this feedback was that questions contained a more comprehensive list of (a) sensors, and (b) methods of augmentation.

5.4 Choice of Online Survey Platform

Cambridge University's Statistics Department was able to provide access to *Qualtrics*, a cloud-based survey solution (www.qualtrics.com). The *Qualtrics* software enabled a professional online questionnaire template to be developed.

In early March 2019 an initial preparatory exercise involved sending 144 emails to polar and cryospheric researchers to understand who would be relevant inclusions in the final sampling frame of researchers using drones. After this exercise, the final number of potential respondents emailed was 211. Table 5.1 shows the subsequent 42 responses from both the northern and southern hemisphere.

Table 5.1 Drone Survey Summary

Country of institute	No of researchers sent survey	No of researchers replying
Argentina	6	0
Australia	9	1
Brazil	5	1
Canada	9	1
Chile	7	1
China	7	1
Denmark	7	0
Finland	12	3
France	12	4
Germany	23	5
Italy	8	0
Japan	5	0
New Zealand	12	2
Norway	13	3
Russia	11	1
South Korea	5	1
Sweden	11	5
Switzerland	11	4
UK	20	5
USA	18	4
Total	211	42

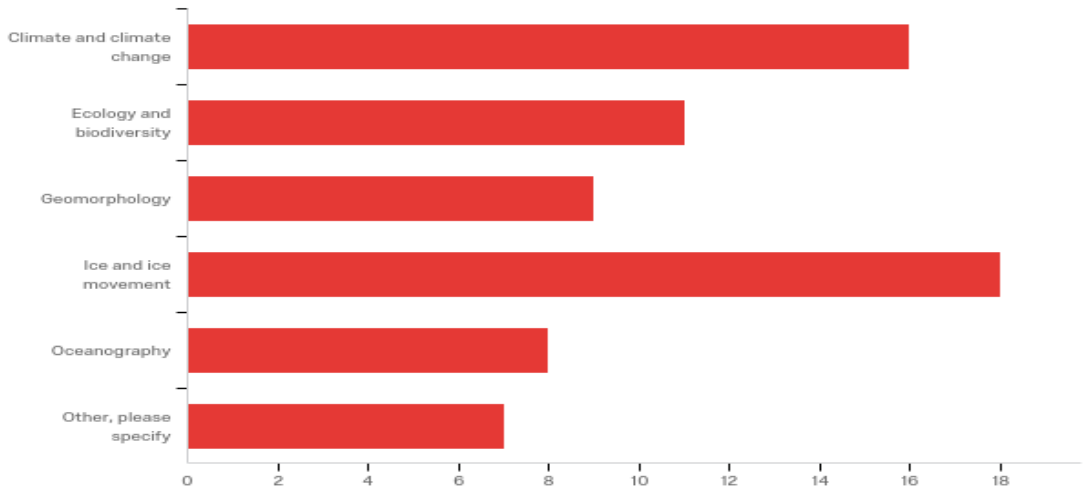
5.5 Survey Questions 1 to 3

This section deals with the first three questions of the drone survey. After this section, the remainder of chapter 5 applies a thematic approach that allows a succinct synthesising of the remaining questions. All 17 aerial and underwater

questions can be seen in an anonymous sample answer at the back this study (**Appendix 1**).

Question 1 of the drone survey asked SRPs to confirm the research areas in which they use drones. Based on 69 counts from the 42 respondents, Figure 5.2 shows that Ice & Ice Movement had 18 drone users (26.09%), followed by Climate & Climate Change with 16 drone users (23.19%). A total of 8 users (11.59%) recorded that their drones were used for Oceanography.

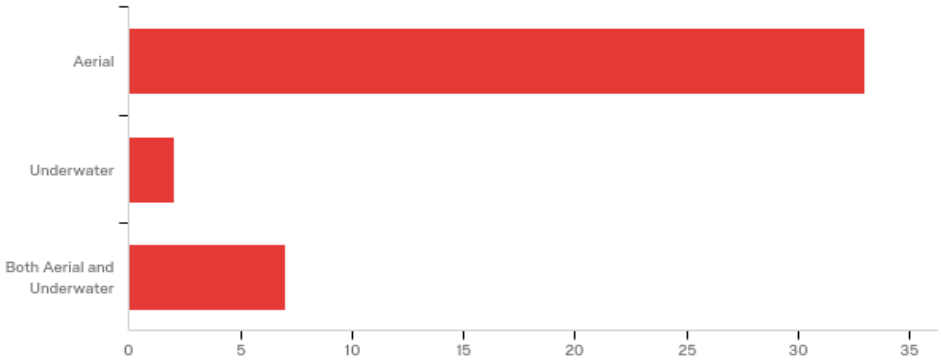
Fig 5.2 Research Areas



Question 2 concerned the types of drone used. The respondent would answer (a) aerial; or (b) underwater; or (c) both. Their answer to this question then determined which questions were relevant to put to them for the remainder of the survey.

As shown in Figure 5.3, 33 of the 42 respondents used only aerial drones. All 33 aerial-only SPRs answered all questions comprehensively. Seven respondents used both aerial and underwater, and just two respondents used only underwater drones. Only three of the aerial and underwater respondents provided detailed answers past question 4. This must in part be a result of the 17 questions that they were asked to answer covering both types of drone.

Fig 5.3 Types of Drones



The results indicated a dominant use of aerial drones (78.57%), and a minority using only underwater drones (4.76%). Significantly, a sizeable minority (16.67%) used both aerial and underwater drones. It is evident that aerial drones have an overwhelming exposure in geographical research. For example, as noted in the abstract of this thesis, the International Journal of Remote Sensing 2017 Volume 38 comprising of 65 articles focused solely on aerial drone research ("Remote Sensing, 2017, Vol 38").

Question 3 concerned drone sensor use. As shown in Table 5.4, there was the expected diverse range of sensors used, because of the broad research areas. Notably, because SfM achieves very accurate measurements at a reasonable cost compared with other methods (Chudley et al, 2018), it is unsurprising that this was a popular choice (9.09%).

Table 5.4 Aerial Drone Applications

Sensor type	Percentage
Collecting physical samples / physical retrieval of objects	18.18%
LiDAR	0.00%
Photogrammetry	0.00%
Photography	36.36%
Spectral / Hyperspectral measurement	0.00%
Structure from Motion (SfM) / orthophoto	9.09%
Other, please specify	27.27%
Don't know	9.09%

A weakness in the Question 3 answers emerged. First, there were gaps from some respondents that answered ‘Other please specify’ (27.27%), but then omitted to record any information. The result was that 15.58% stated they were using a sensor(s) not covered by one of the six broad categories in Table 5.4. An examination of all their typed answers revealed that a majority of these ‘Other please specify’ used aerial drones for atmospheric, gravity, magnetic and thermal measurements.

5.6 GPS Reliance

For the 33 SRPs using only aerial drone users, the breakdown of GNSS choices is shown in Table 5.5. An important aspect of this survey was the aim of establishing if there is an over reliance by SRPs on GPS (45.59%). At first glance, the 45.59% using GPS underlines that GPS is certainly important. However, for an inference to be drawn that there is an over reliance on GPS it was important to know what percentage of aerial-only GPS users were also using GPS and GLONASS; or GPS GLONASS and GALILEO.

Analysis of the 33 aerial-only SRP questionnaires showed that 12 (36.36%) relied solely on GPS. Nine relied on GPS and GLONASS (27.27%). Another nine (27.27%) relied on GPS, GLONASS and GALILEO. Only one SRP used GPS and GALILEO, but not GLONASS. In contrast, when the three per cent (3.03%) of SRPs who did not answer the GNSS survey question are factored-out, 60.61% of SRPs use more than one GNSS.

If the seven SRPs that used both aerial and underwater are added to these results, the answer is not more insightful on GPS reliance percentages. With the SRPs using both types of drone the sample size is 40 SRPs. Of these seven SRPs, two (27.57%) relied solely on GPS. However, because five of the seven (71.42%) provided a ‘Don’t know’ answer this makes the data provided by the seven SRPs using both aerial and underwater drones unreliable.

In sum, the 33 aerial-only SRPs showed no over reliance on GPS. The drone survey data on GNSS use for aerial-only SRPs appears to be reliable, because all but one of the 33 SRPs (96.96%) answered the GNSS use question with specific choices. One exception answered ‘Don’t know’.

Table 5.5 GNSS Choices by 33 Aerial-Only

Sensor type	Percentage
BEIDOU	5.88%
GALILEO	14.71%
GLONASS	27.94%
GPS	45.59%
IRNSS	1.47%
Other, please specify	1.47%
Don't know	2.94%
Total	100%

5.7 GNSS Combinations

Other results included the choice on GPS with GLONASS (27.27%). This is consistent with their established orbital operations for more than two decades over both polar regions.

Another aspect that points to increasing reliance on a trio of GNSS at high latitudes was the significant use of GALILEO (14.71%). As mentioned in chapter 2 of this study, the different "orbital inclination and the flight altitude of the [GALILEO] satellites will considerably increase the coverage of the polar regions, not so well achieved by GPS" (Cojocaru, 2009).

Further, the drone survey revealed low level use of both BEIDOU and IRNSS, which is consistent with the fact they both commenced operations as regional satellite systems rather than GNSS. Considerable expansion of BEIDOU means it is now a potentially valuable global satellite system (Navigation, 2019). However, it was used by only 5.88% of the SRPs.

5.8 Satellite Based Augmentation System Use

Turning to the enhancement of GNSS with geostationary Satellite Augmentation System (SBAS), a high percentage (38.89%) made no use of any SBAS. Further, an even higher percentage (41.67%) did not know what, if any, SBAS was used. The remaining respondents either used WAAS (13.89%) or EGNOS (5.56%). In sum, for this sample the use of any SBAS was an insignificant part of SRP missions, and many SRPs lacked awareness on whether any SBAS is relied on at all. One

explanation for the low level use is that at high latitudes geostationary satellites have poor visibility (Jensen, 2018).

5.9 Drone Precision Measurement Choices and Plans

SRPs were asked for information about (i) their current precise measurement choices, and (ii) future planned measurement choices. As shown in Table 5.6, the current and planned percentages changes are insignificant.

An exception was the planned use of the NASA GDGPS service. Subsequent to the survey, on 7th May 2019 an email was sent to the NASA Jet Propulsion Laboratory (JPL) to understand if there was any reason known to JPL for this increased interest among polar users for GDGPS. The JPL technical manager replied that there was no specific reason or reasons known to them.

Having checked all the individual questionnaires none of the current users intended to stop using it, so the real planned change (8.78%) indicated a significant increase in its use.

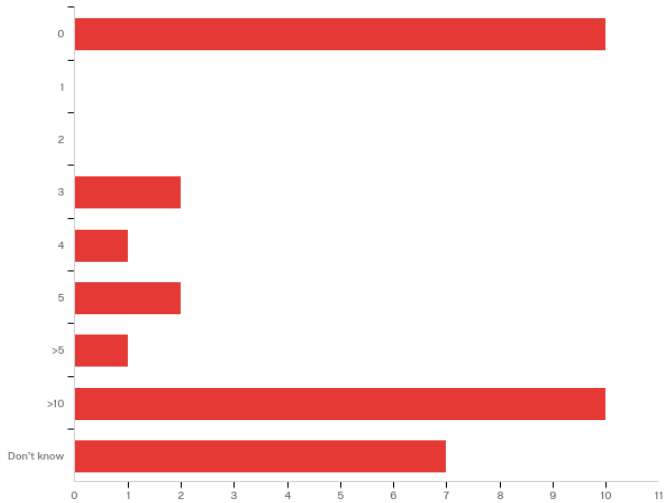
Table 5.6 Precision Measurement

Precision Research Method	Current	Planned
Differential GNSS using own base station	28.33%	23.88%
Geo-referenced Ground Control Points	26.67%	23.88%
Inertial Navigation System	11.67%	10.45%
Iridium satellite constellation	1.67%	2.99%
NASA Global Differential GPS (GDGPS)	1.67%	***10.45%***
Post-Processing Positioning	20.00%	16.42%
Other, please specify	5.00%	4.48%
Don't know	5.00%	7.46%
Total	100%	100%

5.10 Ground Control Points

The results on the precise average number of Ground Control Points (GCPs) used were half positive and half negative. The mean use was 5.61 GCPs with a standard deviation of 3.29.

Fig 5.7 Number of GCPs



As shown in Figure 5.7, 10 respondents (33.30%) stated “zero” to the use of GCPs in Question 9 of the drone survey, but in fact in one of these respondents indicated earlier in Question 6 they did use GCPs. An additional 7 respondents (21.21%) recorded “Don’t Know”, but 3 of these indicated in their earlier answers (Question 6) that they did use GCPs. Therefore, 8 out of 10 of the GCPs results need to be treated with caution. In retrospect asking the average number of GCPs deployed was too time-consuming a question for many respondents to answer. However, nearly half (16) provided a number ranging from 3 to >10.

It is logical to add in the four respondents that used GCPs, but erroneously recorded otherwise, to the total number of GCPs at the minimum of ≥1 GCPs level. The use of GCPs shown in Table 5.8 indicates that 20 SRPs (60.60%) currently use ≥1 GCPs.

Table 5.8 GCPs Used by the 33 SRPs

No of GCPs used	No of SRPs	No of SRPs as % of Sample	Ave Accuracy (m)	Range (m)
0	13	39.39	8.06	0.10-100
1	4	12.12	2.33	1-5
3	2	9.09	0.10	0.10-0.10
4	1	3.03	0.40	0.40-0.40
5	2	15.15	0.05	0.0001-0.10
>5	1	3.03	0.50	0.50-0.50
>10	10	30.30	1.38	0.0005-10
Totals	33	100	1.76	0.0001-100

5.11 Regression Calculations

The calculations sought to establish if there was a functional relationship between the accuracy of measurements obtained (the dependent variable or response variable) with the following individual and pairings of independent variables:

(i) Differential GNSS;

(ii) ≥1 GCPs used;

(iii) PPP;

(iv) Differential GNSS + ≥1 GCPs;

(v) Differential GNSS + PPP;

(vi) Differential GNSS + ≥1 GCPs + PPP;

(vii) Differential GNSS + ≥3 GCPs;

(viii) Differential GNSS + ≥3 GCPs + PPP.

Table 5.9 Regression Results

Accuracy relationship	R	Adj R^2	P-value	SRPs
Diff GNSS	0.20	N/A	0.07	33
≥1 GCPs	0.16	N/A	0.09	33
PPP	0.11	N/A	0.13	33
Diff GNSS + ≥1 GCPs	0.23	-0.007	0.14	33
Diff GNSS + PPP	0.23	-0.005	0.12	33
Diff GNSS + ≥1 GCPs + PPP	0.25	-0.03	0.05	33

Of these six relationship results in Table 5.9, only Diff GNSS + ≥1 GCPs + PPP had a significant p-value (0.05). A p-value needs to be ≤0.05 for the R value to be scientifically significant.

Of the six regression calculations, the R results for (i) the weak relationship between accuracy obtained and the use of differential GNSS (0.20), and (ii) accuracy obtained and the use of ≥1 GCPs (0.16), were the most surprising. A weak relationship is generally considered to be in the range 0.20 to 0.39. These two augmentation techniques are well established methods of increasing measurement accuracy.

Further, the pairings of (iv) Diff GNSS with ≥1 GCPs and (v) Diff GNSS with PPP would both logically expect to have yielded a stronger R. However, their respective results (0.23 and 0.23) were also both in the weak range.

The R value for (vi) differential GNSS, ≥1 GCPs plus PPP was 0.25. Its p-value was 0.05. Therefore, this is was a close result. Notably, GNSS, ≥1 GCPs plus PPP has only a marginally stronger relationship (0.25) when compared with Diff GNNS + ≥1 GCPs (0.23) or Diff GNSS + PPP (0.23). Based on a meaningful sample of 33 SRPs and a p-value at the statistically significant level, this is still the most valuable result of the six regression calculations.

An additional inference to be drawn from the three results (iv to vi) is that (i) Diff GNSS alone (0.20) is the most important augmentation method.

5.12 The 16 SRPs Using ≥3 GCPs

As shown in Table 5.10, additional regression calculations were performed concentrating on the 16 SRPs, therefore just under half of the original 33 aerial-only sample (48.48%), that all used differential GNSS and ≥3 GCPs.

Table 5.10 Results for Two Combinations

Accuracy relationship	R	Adj R^2	P-value	SRPs
Diff GNSS + ≥3 GCPs	0.39	0.025	0.27	16
Diff GNSS + ≥3 GCPs + PPP	0.43	-0.09	0.25	16

A sample of 16 respondents is insignificant from a statistical confidence view point. Nevertheless, the results provide an additional insight for future drone use surveys. In particular differential GNSS, ≥3 GCPs and PPP showed a moderate relationship between these three coefficients and accuracy achieved (0.43), albeit at the bottom end of the moderate category, which is generally considered to be in the range 0.40 to 0.59.

5.13 Validation of the Drone Survey Data against Published Research

The drone survey data was validated for accuracy of answers against published measurement data spread across the 65 articles focusing on drone research in the International Journal Remote Sensing, 2017, Vol 38 (‘Remote Sensing, 2017 Vol 38’). On examination, in fact only 53 of the articles concern GNSS or GNSS augmented measurements (see Table 5.11).

Table 5.11 Remote Sensing 2017 Data

Applications	Number of Articles	Accuracy Range (m)
Collecting physical samples	0 (0.0%)	N/A
LiDAR	6 (11.32%)	0.05-30
Photogrammetry	8 (15.09%)	0.015-5.82
Photography	8 (15.09%)	0.01-10
Spectral / Hyperspectral measurement	19 (35.8%)	0.0002-70
Structure from Motion SfM)/orthophoto	11 (20.75%)	0.015-5
Other, please specify	1 (1.88%)	N/A

Of the 53 relevant articles, one article is based on Arctic research (Bernard et al, 2017), and three concern cryospheric regions (Bühler et al, 2017; Seier et al 2017; and Yi, 2017). Three out of four of these researchers achieve sub-decimetre accuracy, and three out of four use SfM. A collective weakness of the 49 articles is that they deal with drone use globally not just high latitudes and cryospheric regions.

While the 49 SRPs in these 49 articles are not representative of polar and cryospheric SRPs, their published measurements still provide validation on the accuracy levels achieved by the 33 aerial-only respondents. Notably, 31 of the 53 (58.49%) use ≥1 GCPs as a part of their solution, a percentage in the same region as the drone survey (72.72%). Further, 20.75% use SfM which is similar to the drone survey percentage (22.08%).

5.14 Underwater Drone Use

As mentioned at the beginning of this chapter, only two SRPs used only underwater drones (6.06%), and a larger minority of 7 SRPs (21.21%) used both aerial and underwater drones. The general pattern of the 7 both aerial and underwater SRPs was that out of the 17 drone survey questions they had to answer, the first 7 to 10 questions were answered well, but later questions, for example covering number of baselines (nodes) used and accuracy achieved, were left unanswered. Of these nine SRPs using underwater drones (21.42% of the 42 sample), one third (33.33%) used the Iridium service. One third (33.33%) used DVL. The accuracy range achieved was 0.2m to 1,000m.

Positively, over half of these respondents (55.55%) provided details on their precise underwater research applications, as set out in Table 5.12. This also shows 33.33% use underwater drones for Conductivity, Temperature, and Depth (CTD).

Table 5.12 Underwater Drone SRPs

Research Areas	Underwater Applications
Oceanography and Ice Movement	‘Drone lands on the ice and transmits position updates to exactly measure the ice´s drift’
Oceanography and Ecology & Biodiversity	‘CTD, Turbulence, Fluorescence, PAR [Photosynthetically Active Radiation], Nitrate, Oxygen’
Oceanography, Climate & Climate Change and ‘Cloud microphysics, aerosol, hydrometeorology’	‘Temperature, salinity and depth measurements’
Oceanography	‘CTD, O2, turbidity measurements’
Oceanography	‘CTD and ocean currents’

5.15 Summary

Overall, the survey results illuminated the limitations on analysing the multifaceted nature of GNSS drone navigation and positioning augmentation.

The response to the survey by the 33 aerial-only SRPs was a representative sample of the SRP population using aerial drones in polar and cryospheric regions. SRPs from all five research areas answered along with a range of institutes from both the northern and southern hemispheres. In this context the sample was comprehensive and unbiased.

The sample of 33 aerial-only SRPs was relatively small, therefore the results have to be interpreted cautiously. However, the current total global population of polar and cryospheric SRPs is certainly less than 300 if not less than 200. Whatever, the precise total population, 33 SRPs is an insightful sample.

The detailed answers of all 33 aerial-only SRP respondents showed a complex, multifaceted list of methods used. Different combinations, some without differential GNSS or without the use of GCPs, provided measurements at the sub-metre level.

Further, it was not possible to establish a strong functional relationship between combinations of augmentation methods that predict navigation or positioning with

sub-metre accuracy. However, the drone survey revealed the combination of differential GNSS, ≥1 GCPs and PPP had a weak relationship (0.25). This finding provided an insight for future research. A different or larger sample may show that this combination provides a consistent chance of sub-metre accuracy.

Chapter 6

Conclusions, Implications and Further Research

6.1 Conclusions and Implications

The drone survey data revealed six important points.

1. No Common Augmentation Pattern

First, answers from all 33 aerial-only SRP respondents revealed that multi-faceted combinations of measurement methods are used to augment GNSS signals. It was not possible to establish a strong pattern from any specific combination of augmentation methods that correlate with sub-metre accuracy.

2. No Over-Reliance on GPS

Second, out of the 33 aerial-only SRP respondents just over one third (36.36%) used solely GPS. Nine used GPS and GLONASS (27.27%). A further nine (27.27%) relied on GPS, GLONASS and GALILEO. Therefore, the risk of over reliance on GPS does not apply to aerial-only SRPs operating in polar or cryospheric regions.

3. Projected Increase Use of NASA's GDGPS

Third, the chapter 5 drone survey revealed a marked projected increase in the use of the NASA Jet Propulsion Laboratory (JPL) GDGPS; from 1.67% to 10.45%. Subsequently, NASA JPL has offered no explanation for this significant projected increase. Therefore, it would be valuable for future drone research to look at how the NASA JPL GDGPS service improves research by polar and cryospheric SRPs. Specifically, the whole situation in Antarctica needs to be assessed, because the GDGPS augmentation network is prevalent on the Antarctic Peninsula, but not elsewhere (NASA, 2019).

Further, the drone survey included a questionnaire from an SRP who achieved a GDGPS accuracy of 3m. NASA JPL states the accuracy is <10cm. Therefore, more research is needed to understand the gap, if any, between actual averages and the NASA JPL represented accuracy.

4. Larger SRP Samples May Not Reveal Extra Insights

Fourth, the drone survey yielded a total of 42 respondents. Speculatively, it might be that a larger sample compared with the fully answered aerial-only 33 SRP sample, may show a stronger relationship between the accuracy of measurements achieved and a specific augmentation method. Conversely, expecting a larger aerial-only sample size ≥34 SRPs to provide superior results may be irrelevant in the context of a relatively small global community of polar and cryospheric SRPs.

5. Technological Change Rapidly Dates Drone Survey Data

Technology used to augment GNSS in drones is moving so rapidly that any drone survey results become quickly dated. Taking just one example, the drone survey results in this study showed that one fifth (20.75%) used SfM. This percentage compares with the SfM percentage (22.08%) from the data collected from the 49 SRPs that published in Remote Sensing, 2017 Vol 38. However, the risk mitigation benefits of SfM mean that 20.75% is likely to be imminently dated. SfM provides not only accurate measurements, but also lowers mission risk for SRPs because in both polar and cryospheric environments GCPs are often challenging or dangerous to position and retrieve (Chudley et al, 2018).

6. Dearth of Quality Data on Underwater Drones

Out of the total drone survey sample of 42 SRPs, seven respondents used both aerial and underwater, and just two respondents used only underwater drones. Nine responses is not a meaningful scientific sample.

Further, not all of the both aerial and underwater SRPs provided detailed questionnaires, including information on any baseline beacon use. A sample of ≥30 respondents is a minimum requirement for a 95% statistical confidence interval. A future drone survey that gains 30 plus respondent answers from dedicated underwater drone SRPs would be hugely valuable.

6.2. Further Research

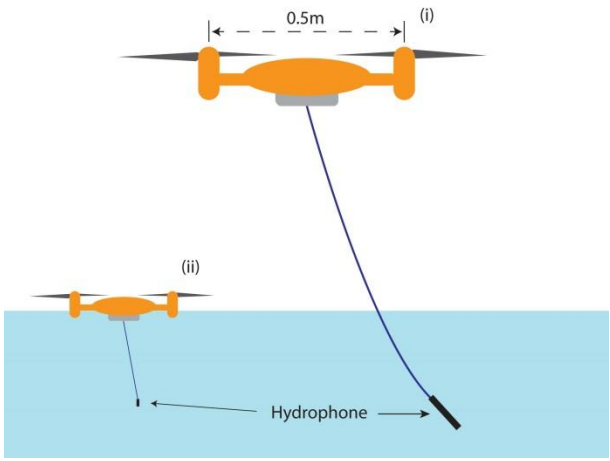
1. Aerial Drone GNSS Navigation for Underwater Research

A recent experiment used an aerial drone with an underwater acoustic sensor (Lloyd et al, 2017). This research shows an important innovation to avoid the challenges of weak GNSS attenuation. Aerial drones are manoeuvred onto water surfaces so that sensors can be dropped into the water, which simultaneously benefits from continuous GNSS coverage. Clearly, many research missions that require sensing at depth will not benefit from this approach. However, this approach has potential value for many just under the water surface missions.

To explain, the sensors perform accurate underwater research based on (a) above water surface GNSS augmented signals; (b) water surface GNSS signals; and (c) below the water surface acoustic survey data corroborated by GNSS augmented signals. Figure 6.1 (adaptation of Lloyd et al, 2017 photographic evidence: p.2810) illustrates (i) a fully waterproof drone lowering onto the water surface, then (ii) landing on the water surface.

Further research is needed in polar and cryospheric regions where weather and temperature put extra demands on drones. The drone used in the experiment could only tolerate winds of up to 21*m/s*, but even at that speed, waves can be 4m heigh. Therefore, a polar or cryospheric water proof drone may need a wide base surface to reduce the risk of capsize (Lloyd et al, 2017).

Fig 6.1 Waterproof Aerial Drone



2. Post-Processed Kinematic and Real-Time Kinematic Technology

The drone survey respondents covered in chapter 5 of this study included one SRP focused on biodiversity, ecology, hydrology and snow science. This SRP recorded constant sub-20cm measurement accuracy (5cm-15cm).

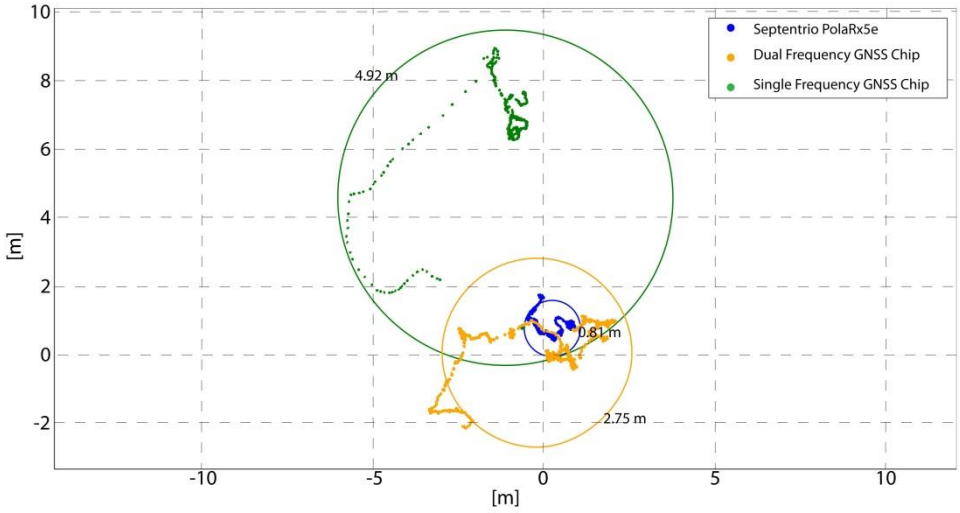
He or she also commented that ‘well distributed GCPs are often difficult to collect in mountain and glacier environments’, and that their measurements were achieved by ‘PPK with dual phase GNSS’. This ‘PPK with dual phase GNSS’ answer can be interpreted to mean that two sets of GNSS frequencies are checked against each other. These inflight GNSS signals are picked up by the drone. Thirdly, a more accurate base station records the drone flight with triangulation. Then after each mission, Post-Processed Kinematic (PPK) technology allowed the SRP to thoroughly augment positioning data from the drone mission by reference to data from the base station and data stored on past flights. Carl Robinson of BAS has pointed out that at high latitudes where signal loss is common, the use of PPK is valuable (BAS, 2019).

Real-Time Kinematic (RTK) technology is similar to PPK except that corrections to the GNSS signal data is made during the mission flight (BAS, 2019). The two technologies are not mutually exclusive. Further research is needed into how PPK and RTK technologies can be used more across the five polar and cryospheric areas.

3. Multi-Frequency GNSS Semiconductor Chips

Nottingham Scientific Limited, a professional GNSS testing company, has published field results comparing a geodetic class GNSS receiver (Septentrio PolaRx5e); with a dual-frequency (L1/L5) GNSS Broadcom 47755 single-chip inside a smartphone; with a second smartphone containing an older single frequency Broadcom 4774 chipset.

Fig 6.2 Broadcom 47755 Chip Accuracy



One test involved placing all three devices at a fixed Ground Control Point (GCP) for 10 minutes. The Figure 6.2 (NSL, 2018: p.1) position scatter graphically represents the accuracy of the distance from the origin. A radius containing 95% of solutions is recorded for each. Unsurprisingly, the Septentrio device, coloured blue, recorded an exceptionally high level of accuracy. However, what is equally impressive is that the horizontal accuracy of the dual-frequency Broadcom 47755 chip-set, coloured yellow, is nearly 50 per cent better than the Broadcom 4774 single-chip, coloured green, decreasing from 4.92m to 2.75m (NSL, 2018). The Broadcom 47755 chip is available for purchase to install in a bespoke drone.

Further, the software navigation company Swift Navigation ('Swift') has produced a software program called Starling, that enhances an integrated IMU and multi-GNSS Broadcom BCM 47755 chip. Swift's Starling program claims to offer multi-constellation interoperability, and to provide "centimetre-level accuracy and supports the calculation of integrity outputs to provide absolute position, velocity and time (PVT)" (GPS World, 2018). More research is needed to examine and test how the Starling program and equivalent software can better augment dual-frequency GNSS chips.

Another semiconductor company, u-blox (www.u-blox.com) has produced a multi-GNSS chip. The u-blox F9 chip uses GNSS signals in multiple frequency bands to correct ionospheric errors. To achieve centimetre-level accuracy, u-blox F9 chip also offers optional on-chip RTK technology (GPS World, 2018).

4. Open Source Drone Building for Polar and Cryospheric Regions

Finally, the opportunity to exploit multi-frequency chips can be most flexibly and cost-efficiently achieved with the use of open-source flight controller hardware boards. Open-source is valued for research because knowledge can be built upon in the long term without licensing constraints (Pope et al, 2014). A good example, is the *Raspberry Pi* based *Navio2* platform developed by a company called *Emlid* (Ebeid, 2017). *Navio2* has already been used in studies by many institutions including Cambridge, *ETH* Zurich and Stanford. Further research is required into exploiting open source hardware boards that include performance tests on multi-frequency chips at high latitudes and in cryospheric regions.

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Appendices

Appendix 1 Online Drone Survey Sample

UNIVERSITY OF CAMBRIDGE

Survey Questionnaire on Drone use for Polar or Cryospheric Research

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Survey Questionnaire on Drone use for Polar or Cryospheric Research

I'm conducting research into drone use by scientists working in Antarctic, Arctic or high mountains regions. This work is my thesis towards an MPhil in Polar Studies. The published statistical analysis will benefit scientists across all specialisms.

A significant challenge concerns how researchers increase the accuracy of data obtained from aerial drones or underwater drones.

The following survey will take less than 10 minutes to complete, but if you have time there is a small space at the end to add anything else you would like to contribute.

Q1. In which of the following research areas do you use drones?

- [ ] Climate and climate change
- [ ] Ecology and biodiversity
- [ ] Geomorphology
- [x] Ice and ice movement
- [x] Oceanography
- [ ] Other, please specify

Q2. Which types of drone do you use?

- ( ) Aerial

.....

Q4.
For what applications are you using your underwater drone? Tick all that apply.

- [x] Collecting physical samples / physical retrieval of objects
- [x] Doppler Velocity Log
- [x] Imaging Sonar
- [ ] LiDAR
- [ ] Photogrammetry
- [x] Photography
- [ ] Ranging Sonar
- [ ] Spectral / Hyperspectral measurement
- [ ] Structure from Motion (SfM) / orthophoto
- [ ] Synthetic Aperture Sonar (SAS)
- [x] Other, please specify: Biogeochemical Research: Fluorometry (Chl. a + CDOM), Nitrate and oxygen measurements, physical oceanography (Microstructure temperature + velocity shear + CTD), light measurements (PAR), gathering water samples
- [ ] Don't know

Q5. When using your aerial drone for research applications, which of the following GNSS do you use for its navigation and positioning?

- [ ] BEIDOU
- [ ] GALILEO
- [ ] GLONASS
- [x] GPS
- [ ] IRNSS
- [ ] Other, please specify
- [ ] Don't know

Q6. When using your underwater drone for research applications, which of the following GNSS do you use for its navigation and positioning?

- [ ] BEIDOU
- [ ] GALILEO
- [ ] GLONASS
- [x] GPS
- [ ] IRNSS

Q7. When using the aerial drone, which of the following regional geostationary Satellite-Based Augmentation Systems (SBAS) do you currently use to obtain greater accuracy?

- [ ] EGNOS
- [ ] GAGAN
- [ ] MSAS
- [ ] SDCM
- [ ] WAAS
- [ ] Other, please specify
- [ ] Don't know
- [x] Don't use any

Q8. When using the underwater drone, which of the following regional geostationary Satellite-Based Augmentation Systems (SBAS) do you currently use to obtain greater accuracy?

- [ ] EGNOS
- [ ] GAGAN
- [ ] MSAS
- [ ] SDCM
- [ ] WAAS
- [ ] Other, please specify
- [ ] Don't know
- [x] Don't use any

Q9. Currently, which of the following do you use to achieve greater accuracy from the aerial drone flight data?

- [ ] Differential GNSS using own base stations
- [ ] Georeferenced Ground Control Points
- [x] Inertial Navigation System
- [ ] Iridium satellite constellation
- [ ] NASA Global Differential GPS (GDGPS) System
- [ ] Post-Processing Positioning
- [ ] Other, please specify
- [ ] Don't know

Q10. In the future, when using your aerial drone to carry out precise research, which of the following do you plan to rely on to maximise drone accuracy?

- [ ] Differential GNSS using own base stations
- [ ] Georeferenced Ground Control Points
- [ ] Inertial Navigation System
- [ ] Iridium satellite constellation
- [ ] NASA Global Differential GPS (GDGPS) System
- [ ] Post-Processing Positioning
- [ ] Other, please specify
- [x] Don't know

Q11. Currently, which of the following do you use to achieve greater accuracy from the underwater drone dive data?

- [x] Acoustic Positioning Systems / baseline beacons
- [ ] Inertial-Doppler Navigation System
- [x] Inertial Navigation System
- [ ] Iridium satellite constellation
- [ ] NASA Global Differential GPS (GDGPS) System
- [x] Post-Processing Positioning
- [ ] Other, please specify
- [ ] Don't know

Q12. In the future, when using your underwater drone to carry out precise research, which of the following do you plan to rely on to maximise drone accuracy?

- [x] Acoustic Positioning Systems / baseline beacons
- [ ] Inertial-Doppler Navigation System
- [x] Inertial Navigation System
- [ ] Iridium satellite constellation
- [ ] NASA Global Differential GPS (GDGPS) System
- [x] Post-Processing Positioning
- [ ] Other, please specify
- [ ] Don't know

Q13.

Most research requires measurement accuracy below 10 metres. Some research requires accuracy to the centimetre level. Please specify in metres the average average accuracy level you achieve with your chosen augmentation systems for aerial drones?

- ○ Average aerial drone accuracy in metres = [ ]
- ◉ Don't know

Q14.
Most research requires measurement accuracy below 10 metres. Some research requires accuracy to the centimetre level. Please specify in metres the average average accuracy level you achieve with your chosen augmentation systems for underwater drones?

- ○ Average underwater drone accuracy in metres = [ ]
- ◉ Don't know

Q15. In the last 12 months, how many Ground Control Points (GCPs) per flight have been positioned to support or validate your aerial drone data?

- ◉ 0
- ○ 1
- ○ 2
- ○ 3
- ○ 4
- ○ 5
- ○ >5
- ○ >10
- ○ Don't know

Q16. In the last 12 months, how many baseline beacons (nodes) per dive have been positioned to support or validate your underwater drone data?

- ○ 0
- ◉ 1
- ○ 2
- ○ 3
- ○ 4
- ○ 5
- ○ >5
- ○ >10
- ○ Don't know

Q17. Finally, is there any other observation you would like to make about the challenges of drone navigation and positioning, please summarise your short message in the box below.

- ○ Observation
- ◉ Nothing to add

Appendix 2 Current and Planned GNSS

System	Accuracy and Coverage	Frequency	Number and Altitude	Regime	Additional Facts
BEIDOU *北斗卫星导航系统* China www.cnsa.gov.cn	10m	1.561098 GHz (B1) 1.589742 GHz (B1-2) 1.20714 GHz (B2) 1.26852 GHz (B3)	35 orbiting at 21,150 km based on 2020 schedule	GEO(5) IGSO(3) MEO(27)	Initially coverage was Long 70°E to 140°E; Lat 5°N to 55°N, so covers all Himalayas 35 scheduled to orbit by 2020 (RIN, 2019)
GALILEO EU www.gsa.europa.eu	1m Global	1.559–1.592 GHz (E1) 1.164–1.215 GHz (E5a/b) 1.260–1.300 GHz (E6)	26 orbiting at 23,222 km	MEO(26)	Hydrogen maser clock + reserve rubidium clock

GLONASS *ГЛОНАСС* *Russia* *www.roscosmos.ru*	4.5-7.5m Global	1.593–1.610 GHz (G1) 1.237–1.254 GHz (G2) 1.189–1.214 GHz (G3)	27 orbiting at 19,130 km	MEO(27)	Superior positioning where masking elevation >50° at latitudes >75°
GPS USA www.afspc.af.mil	15m Global	1.563–1.587 GHz (L1) 1.215–1.2396 GHz (L2) 1.164–1.189 GHz (L5)	31 orbiting at 20,180 km	MEO(31)	Continuously adapted with planned long term investment
IRNSS (NAVIC) India www.isro.gov.in	10m Regional, inc all Himalayas	1176.45 MHz(L5) 2492.028 MHz (S)	7 orbiting at 36,000 km	High Earth(7)	Long 30°E to 130°E; Lat 30°S to 50°N, so covers all Himalayas

Appendix 3 Regulation Applicable to a Scientific Research Pilot

Law, Regulation or Restriction	Max height	Max range	VLOS only	Max weight	3rd Party Insurance	Notes
UK English law (hereafter UK law)	122m (400ft)	500m	Yes	20kg	Yes Regulation (EC) No 785/2004	Applies to all pre-testing in the UK Would apply to insurance cover globally UK law standards would apply unless in direct conflict with law of specific airspace
Antarctica, Rothera UK law if SRP is a UK citizen. For risk management still need to know law of areas controlled by other national programs, especially air	122m (400ft)	500m	Yes, if jurisdiction of which SRP is a citizen requires	20kg if subject to UK law	Yes, if jurisdiction of which SRP is a citizen requires it. Practically, SRP likely to be breaching employment contract and employer SOPs for flying without	Mix of legal jurisdictions Missing drone policy requires reporting loses Effect on wildlife Antarctica (CONMAP)

traffic control stations.					insurance.	
Antarctica King George Island UK law if SRP is a UK citizen. For risk management still need to know law of areas controlled by other national programs, especially ATC stations.	122m (400ft) 400m above the ground if subject to Chilean law	500m	Yes, if jurisdiction of which SRP is a citizen requires	20kg if subject to UK law, but only 9Kg if subject to Chilean law	Yes, if jurisdiction of which SRP is a citizen requires. Practically, SRP likely to be breaching employment contract and organisation SOPs for flying without insurance.	Mix of legal jurisdictions Missing drone policy Effect on wildlife Maximum Take-off Mass is 9 kg, excluding parachute weight. Must have parachute. Only manufactured drones are allowed; no home-made Antarctica (CONMAP)
Greenland	100m	No specific	Yes, but for	25kg	Yes	

Danish Law		distance stated, but VLOS applies, except if have successful application for waiver	research can apply for waiver.		Regulation (EC) No 785/2004	Greenland issues its own Aeronautical Information Circulars so cannot just rely on Danish law Arctic Council Drone Operator's Handbook may provide useful updates on changes affecting Greenland.
Nepal Nepalese law	122m	500m	Yes	20kg	Yes	Flight Operations Directives No.7, May 2015 contains the core rules, conferred by Rule 82 of CAAN, Civil Aviation Regulation, 2058. Drone pilots should be proficient in flying and drone operation Research permission of from following required: Relevant Ministry/Department relating to the research subject matter; Ministry of Home Affairs; CAA Appendix G of the CAA Procedure Manual for Flight Permission is the Application for Drone Use.

Svalbard Norwegian Law	120m	500m	Yes	25kg	Yes	Section 59. Mandatory strobe lights for all BVLOS flying. Light intensity of at least 10 candelas, where flashes are produced by rotating lights (strobe lights) at a rate of at least 20 flashes per minute. Special rules apply to Ny-Ålesund, including at least 3 months' notice to apply for BVLOS.