Landing Unmanned Aerial Vehicles
using a Ground Based Augmentation System

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1 Introduction

This project assignment focuses on the possibilities of autonomous landing of commercial Unmanned Aerial Vehicles (UAV's) by integrating existing Ground Based Augmentation System (GBAS) signals with the UAV's avionics.

1.1 Motivation

GBAS aircraft hardware (avionics) have been developed by multiple companies, but at present it is intended for use in manned aircraft. The goal is therefore to develop a GBAS capable navigation platform suitable for use on board a UAV. This introduces multiple technical challenges, as a UAV imposes significant constraints on both cost, weight and size of such a platform. This also introduces safety related challenges, and while safety is a natural aspect of the problem, the main focus of this project assignment will be on the technical challenges.

Andøya Space Center

Andøya Space Center (ASC) is focusing heavily on the development and operation of drones and unmanned aircraft (Unmanned Aerial Vehicles, UAVs) for a variety of applications. They already run operations for customers like the Andøya Test Center and power delivery companies. One of the bases for their UAVs is Andøya Air Station (Andøya Flystasjon), and ASC is looking to expand its activities there to allow an even wider selection of test and mission services.

As Andøya Air Station is in close proximity to inhabited areas and due to challenges with weather, it would be an advantage to improve the positioning accuracy, and provide integrity support during landing operations. This would be beneficial for both safety and availability of ASC's services independent of weather conditions. This is especially critical for operations involving larger UAVs.

Some of the other GBAS features are also of interest, such as allowing to land their UAVs remotely on other airfields, enabling them to perform for instance the flight from Andøya to Svalbard.

Indra Navia

Indra Navia is a global supplier of landing systems for the aviation industry, both through the well established Instrument Landing System (ILS) and the more recently developed GPS based Special Category-I (SCAT-I).

The last few years Indra Navia has been developing the ground infrastructure for the Ground Based Augmentation System (GBAS), which will secure the safe landing of aircraft even in no-sight conditions. The development and testing of this system is now completed and after validation it will become Indra Navia's latest product for civil airport operations.

With this project, Indra Navia is looking for ways to expand the use of the GBAS product to UAVs as well, which represents a new market for the system.

1.2 Objectives

The main objectives for this project assignment are:

- Provide a summary of the GBAS system and its signals for aircraft landing as developed by Indra Navia

- Examine to what extent a UAV platform could be made compatible with such a system in collaboration with Andøya Space Centre

- Evaluate potential ways of integrating the GBAS signals in the UAVs avionics to allow for the benefits of GBAS to be used while performing autonomous UAV landing.

- Finally, based on the above points, propose a system design by which this can be achieved.

The results of this assignment will be used to define a master thesis topic.

2   Background

The GBAS avionics module and its interfaces are the main focus, with the aim to define the tasks and calculations it is to perform. Finally a proposal as to how the entire system can be realised should be developed, taking into account the existing UAV avionics. An overview of the elements that make up such a system is shown in figure 1. In this figure, the GBAS module is shown in 2 parts, "GBAS Receiver" and "Signal Processing". In practice, the functionality of the 2 blocks will more than likely be combined into one physical unit.
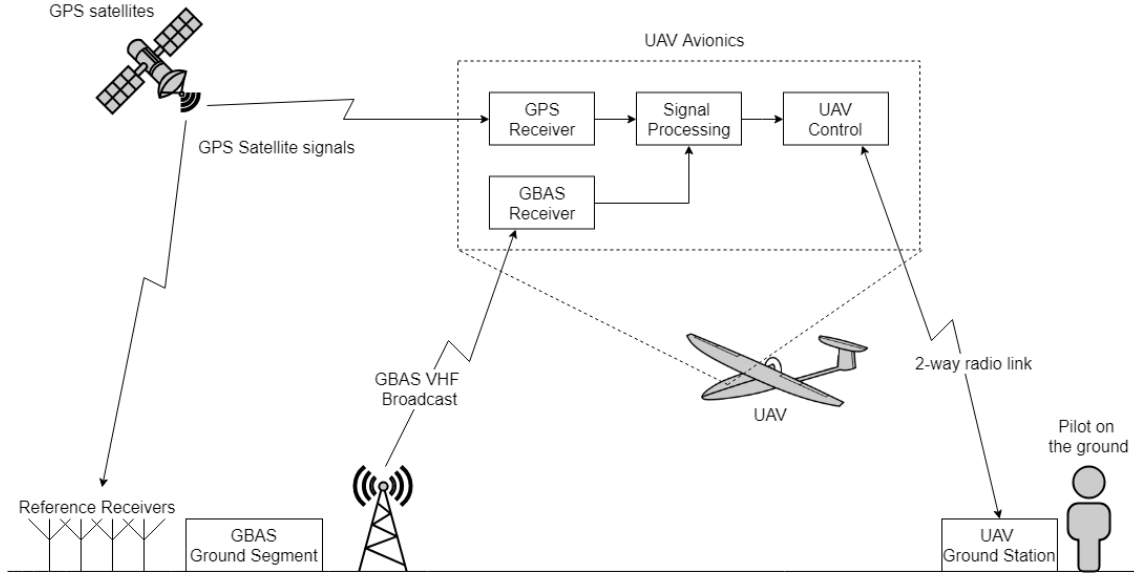

Figure 1: Modular system overview of a GBAS equipped UAV in the vicinity of a GBAS ground station

The GPS satellites, their signals and reception, as well as the functionality and internal performance of the GBAS ground segment are considered outside the main scope of this project, and will not be covered in-depth and are only summarised here as part of the background.

The "GBAS Receiver" block deals with the reception and decoding of the GBAS VHF broadcast from the ground station. This signal has a carrier frequency ranging from 108.025MHz to 117.975MHz, and will require the installation of a VHF receiver antenna on board the UAV. The messages received in this module are described in section 4.

The "Signal Processing" block will communicate with the UAVs GPS receiver and the autopilot. It will need to acquire raw pseudo-range measurements from the GPS receiver and combine those with the correction data from the GBAS receiver. The result will then be communicated to the UAVs autopilot so that it can be used for navigation. As the design of an autopilot falls outside the scope of this project, we will instead carefully study the existing autopilot for integration options. This will be discussed when looking at the UAV in section 5 and 6.

We will also require communication with a pilot on the ground. The 2 way radio link between the pilot and the UAV autopilot is an existing interface, so we will have to decide what information should be sent and investigate what options exist for adding this to the existing dataflow (see section 5 and 6).

Finally section 7 gives a proposal for how the system can be designed, taking into account the identified challenges and pitfalls.

2.1 GPS

The Global Positioning System (GPS) is one of several Global Navigation Satellite Systems (GNSS). It is based on a constellation of 24 satellites with an additional 3 spares for full global coverage (figure 2). The satellites broadcast their ephemeris (orbital elements that can be used to calculate the satellites position) and current time. By measuring the transmission time, a receiver can calculate the distance (pseudo range) to each satellite in view. Using 4 or more satellites, an accurate position in 3D space can be determined using trilateration.
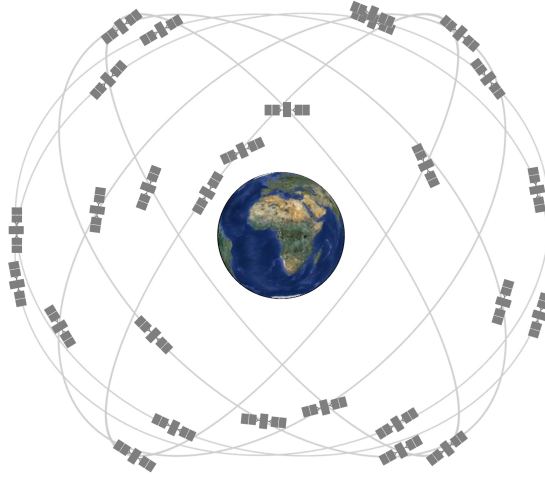

Figure 2: Illustration of the GPS satellite orbits [1].

There are sevral error sources that interfere with the pseudo-range measurement, as indicated in equation 1.

$$p = \rho + d_\rho + c(dt - dT) + d_{ion} + d_{trop} + \epsilon_{mp} + \epsilon_p \tag{1}$$

The pseudorange measurement (p) is a result of the true range (ρ) the addition of satellite orbital errors (d_ρ) the product of the speed of light (c) and the difference between the satellite clock offset from GPS time (dt) and receiver clock offset from GPS time (dT). In addition error sources from ionospheric delay (d_{ion}), tropospheric delay (d_{trop}), multipath delay (ϵmp) and receiver noise (ϵ_p) are added.

As the calculation of the pseudo range p is based on the speed of light c, even small inaccuracies in the measured time t will result in large errors according to $\Delta p = c * \Delta t$. The main error source is atmospheric disturbance, in addition position inaccuracy and clock deviations in the satellite and the receiver are contributing factors [2].

2.2 GBAS

The Ground Based Augmentation System (GBAS) is an airport based service for providing aircraft with high precision GNSS positioning during approach and landing operations. It can do so under the assumption that the main sources for GNSS inaccuracy change slowly and are spatially correlated over short baselines [3]. Atmospheric disturbance is the dominating source of error with limited spatial and temporal variation on the scale of the flight operation. This makes the system very valuable for safe landing of aircraft under bad weather and low visibility conditions. The system provides GNSS measurement corrections and integrity information required for precision operations in the covered area.

The system consists of 2 parts; the ground station and the aircraft receiver, as can be seen in figure 1.

The ground station is a stationary structure at the airport. Using multiple (typically 4) GNSS receivers, the station tracks all satellite ranging sources in view. As the receiver antennas positions and each satellites supposed position are known, a comparison can be made between the measured pseudo-range and the calculated geometric range. The difference between the two form the basis for the so-called "pseudo range correction" for each satellite. The exact steps for the pseudo range correction calculation are more complex than simple difference and can be found in [4]. These range corrections together with system integrity information, as well as general information about satellites health and the airport configuration are broadcast over VHF for any GBAS equipped aircraft in the area to receive. This means one ground station can service an entire airport and all aircraft in the vicinity, making it a cost effective solution.

From a distance of approximately 43km (23NM), the aircraft can receive the GBAS broadcast and apply the range corrections to its position calculation procedure. This gives the "augmented" GPS position that the aircraft uses for navigational purposes during precision operations. Due to the reduced uncertainty in position and high system integrity, the aircraft can continue its flight trajectory even under very low visibility conditions. In the absence of this position correction, the aircraft has to fall back to a different system.

What sets the GBAS system apart from other systems that give similar or maybe even better positional accuracy is the way it deals with uncertainty and integrity.
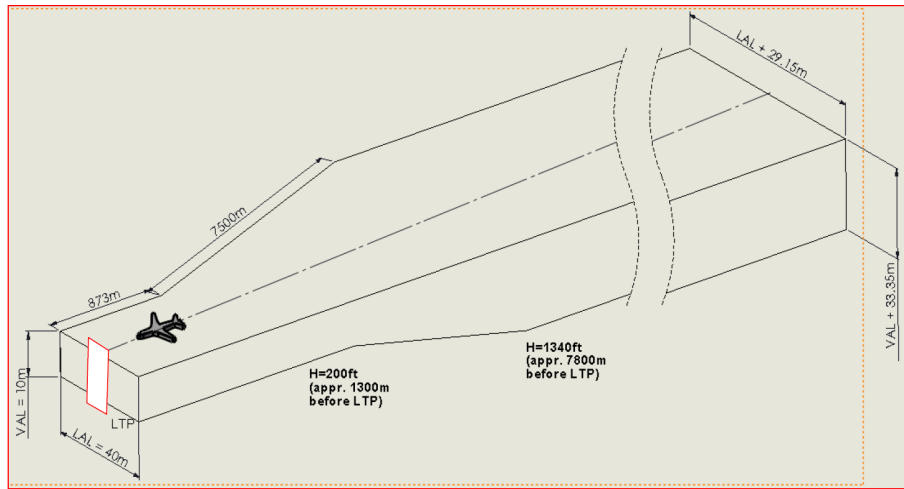

Figure 3: Illustration showing the vertical and lateral alarm limits, and an aircraft that is exceeding the vertical protection level as indicated by the white rectangle.

As figure 3 shows, the avionics calculate the Vertical and Lateral Protection Levels (VPL/LPL), based on the GBAS ground stations estimate of the current errors, and integrity parameters based on its own satellite signals.

2.3 UAV

Unmanned Aerial Vehicles (UAV) are increasingly becoming a part of airspace activities. Both on a small scale hobby level as well as on a professional scale, data are more and more collected using UAVs. Applications range from simple photography to research, surveillance and monitoring both for civil and defence purposes. Much of this information was previously too laborious or costly to collect on a regular basis.

The extended use of UAVs has required the introduction of regulations to prevent conflict and accidents in the airspace. UAV operations are presently divided into 3 categories, based on risk and damage potential in the case of accidents [5].

The contact between operator and UAV can be classified on the degree of visual communication as follows:

- VLOS (Visual Line of Sight): Pilot can observe the UAV with the naked eye.

- EVLOS (Extended Visual Line of Sight): Pilot is in touch with external observers that VLOS VLOS to the UAV.

- BLOS (Beyond Line of Sight): Neither pilot nor observers have VLOS on the UAV.

  - BVLOS (Beyond Visual Line of Sight): Subcategory of BLOS with the same definition.

  - BRLOS (Beyond Radio Line of Sight): Subcategory of BLOS. No direct radio link between pilot and UAV. (Satellite communication, cellular network, radio relays, etc.)

If there is no direct radio link between pilot and UAV, the operation is considered BRLOS even if the UAV is physically located in VLOS. Each category has specified requirements and regulations which have to be fulfilled for legal UAV operation [5].

3 Current UAV landing solutions

3.1 Real Time Kinematic GPS

Presently the most widely used UAV landing solution for commercial UAVs is based on Real Time Kinematic (RTK) GPS. RTK GPS is based on the difference in carrier phase between the measurement from the GPS satellites received by the UAV and similar measurements done at a given ground station. This allows the UAV to know its position accurately relative to the ground station. Often, but not necessarily always, this ground station is located near the pilot on the ground, as the correction data is sent over the same communication link as the pilots control signals.
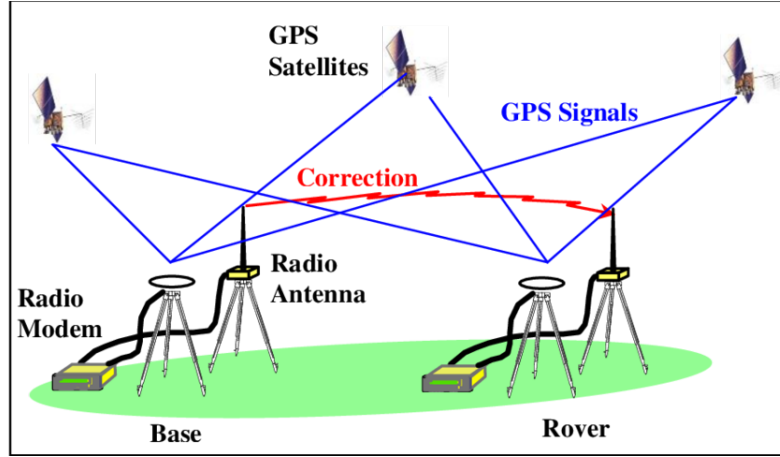

Figure 4: Overview of a typical RTK setup [6].

The combination of GPS code position with phase difference information can result in centimetre-level accuracy, more than sufficient for autonomous landing in the vicinity of the RTK base station.

3.2 Application at ASC

Andøya Space Center (ASC) has the required technology to perform automatic landing of UAVs using a GPS-based RTK solution, and this is the preferred method by which they land. ASCs pilots have extensive experience with manual landing of their UAVs, should that be needed, but RTK based autonomous landing is preferred as it limits the risk of pilot error.

3.3 Limiting factors

RTK solutions are primarily designed to facilitate operations in the vicinity of the reference base station. For any practical use, this means landing in the same general area where the UAV took off. The accuracy generally only holds for a range of about 20km from the reference station, where after the accuracy dramatically drops. This limits the use of the system in its present configuration. UAVs that depart from one base station will not easily be able to use the RTK information of a different station to land there.

GBAS is also a form of differential GPS. In addition to increased accuracy in position estimates, GBAS also supplies detailed error and integrity information. This allows the calculation of the Vertical and Lateral protection levels required for safe landing in civil aviation.

Autonomous landing of large UAVs will be able to benefit in a similar way from the reliability and integrity of the GBAS system.

4   GBAS signals

In order to provide the intended service, the GBAS ground station collects data on all GNSS satellites in view, and monitors their health and errors. Together with information on the airports runways and landing approaches as well as its own system integrity measurements, this forms the basis for the data that is broadcast to aircraft in the area.

This section will describe the signals that the GBAS station transmits in great enough detail as to be able to decode them in the UAV. Furthermore, how the information contained in the broadcast can be used by a UAV after reception and decoding will be discussed.

4.1   Data Broadcast

The GBAS data is transmitted as a VHF radio broadcast on a channel in the aeronautical radio navigation frequency band, corresponding to a carrier frequency between 108.025MHz and 117.975MHz. The channels are spaced 25kHz apart, and different airports will use different channels, such that a pilot will have to select which channel to receive on.

Every second, the GBAS station will broadcast 2 GBAS frames. Each of these frames are divided into 8 time slots in which a GBAS data burst occurs. This means the transmission of a GBAS data burst is contained in a 62.5 millisecond time slot, that is 1/16th of a second. Figure 5 shows this relation. The application data contains the messages that we are interested in receiving and decoding. This data is scrambled, thereby using the full spectrum width and reducing transmission errors.
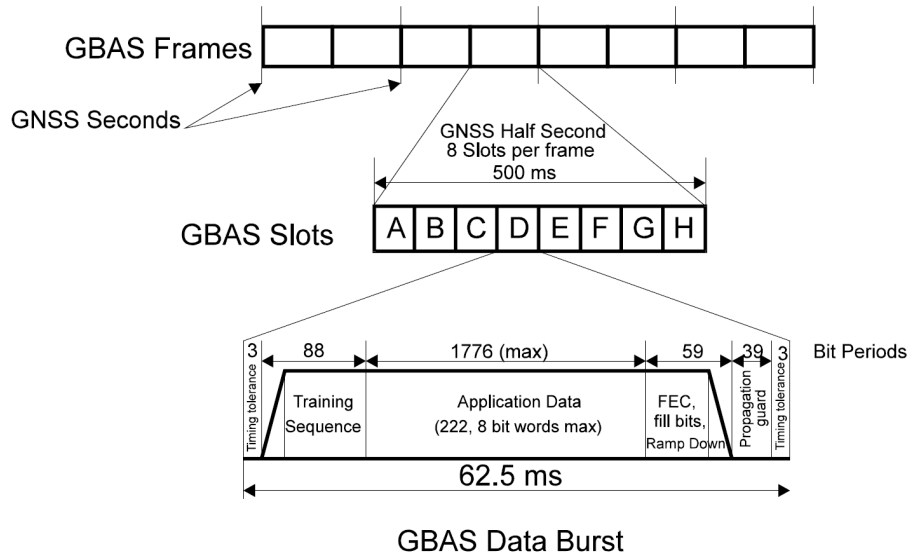
Figure 5: Structure of the way GBAS frames, slots and data bursts are built up and relate to each other in time [4].

4.2   Message types

Each data burst contains application data in the form of one or more "messages". These messages are divided into types based on what aspect of the GBAS system the information pertains. While more than 4 message types exist, the following are the types that are the most extensively used:

- Message Type 1: Data on GPS pseudo-range corrections, transmitted at least once per frame and at most once per slot.

- Message Type 2: Information on the GBAS station and position, transmitted at least once every 20 frames and at most once per frame.

- Message Type 4: The airport configuration data and landing approaches

- Message Type 11: Data on pseudo-range corrections smoothed over a shorter time span than MT1

Of these 4 message types, MT1 and MT11 are broadcast at least once per frame and at most once per slot. MT2 and MT4 are being broadcast at least once every 20 consecutive frames and at most once every frame. The content of these messages and what they can be used for are discussed in more detail below. More extensive details on how the GBAS ground station calculates the values for each message type that is discussed here, as well as other message types can be found in EUROCAE [4].

4.2.1 Message type 1

This message provides 100 second smoothed pseudo range corrections as well as 100 second smoothed pseudo rate corrections for each ranging source in view of the GBAS ground segment. Furthermore, it contains low-frequency ephemeris data for one (the first) of the sources. By varying which source this applies to, low frequency data for all ranging sources can be collected over at most 10 seconds. The content of MT1 is shown in table 1, where:

- Modified Z-count denotes the time that the MT1 data is applicable for. This value is reset every 20 minutes (1200 seconds) and follows GPS time, such that the value loops around at xx:00, xx:20 and xx:40. Except from the point of reset, this value should thus be continuously increasing.

- Additional messages are not provided for GPS-only GBAS systems, so we can ignore this field.

- Number of measurements indicates the number of ranging sources currently tracked, and thus how many measurement blocks are included in the message.

- Measurement type will indicate C/A code L1. As this is again a fixed value, a receiver might choose to ignore it.

- The Ephemeris Decorrelation Parameter represents the impact of undetected errors in the ephemeris on the user range. We can use this to assess the quality of the pseudo-range, i.e. if we want to use it as basis for position calculation.

- The Ephemeris CRC (Cyclic Redundancy Check) can be used to verify that we are using the same ephemeris data as the GBAS ground station.

- Source availability duration, if provided, is relative to modified Z count and allows us to plan ahead when to use a source for our position calculation. If this is not provided the default value is 0xFF.

- For each of the N ranging sources:
    - Range source ID, is the ID of the satellite. Only values in the range 1-32 are valid satellite IDs. Used to map the correction to the right satellite in the receiver.
    - Issue of data, identifies which ephemeris data was used to calculate the corrections provided.
    - Pseudo-range correction, 100 second smoothed. This is the correction we want to apply to the measured pseudo-range to this satellite before using it in position calculation
    - range rate correction indicates the rate of change of the 100 second smoothed pseudo-range correction between the current message and the correction in the broadcast immediately prior.

– σ_{pr_gnd} is the standard deviation of a normal distribution associated with the signal-in-space contribution of the pseudo-range error at the GBAS reference point.

– B values are integrity parameters associated with the pseudo rate correction calculated. Each of their values represent the difference between the correction found with all receivers and the correction found when excluding 1 of the 4 receivers. Large values thus indicate bad integrity.

Table 1: Format of Message Type 1 data

Data Content	Bits	Range of Values	Resolution
Modified Z-count	14	0 to 1199.9 sec	0.1 sec
Additional Message Flag	2	0 to 3	1
Number of measurements (N)	5	0 to 18	1
Measurement Type	3	0 to 7	1
Ephemeris Decorrelation Parameter	8	0 to $1.275 * 10^{-3}$m/m	$5 * 10^{-6}$ m/m
Ephemeris CRC	16		
Source Availability duration	8	0 to 2540s	10s
For N Measurement Blocks:			
Range Source ID	8	1 to 255	1
Issue of Data	8	0 to 255	1
Pseudo-range Correction	16	±327.67m	0.01m
Range Rate Correction	16	±32.767m/s	0.001m/s
σ_{pr_gnd}	8	0 to 5.08m	0.02m
B_1	8	±6.35m	0.05m
B_2	8	±6.35m	0.05m
B_3	8	±6.35m	0.05m
B_4	8	±6.35m	0.05m

4.2.2 Message type 2

This message type contains information on the GBAS station itself, including the station's location, its configuration and general local conditions. The entire content of MT2 is shown in table 2, where:

- The GBAS Reference Receivers, field denotes the number of reference receivers that are configured for normal operation of the GBAS station.

- Ground Accuracy Designator letter, indicates the minimum signal in space accuracy performance provided by the GBAS station

- Spare bits are not currently in use.

- GBAS continuity/integrity designator, indicate what approach services the GBAS station supports.

- Local magnetic Variation, is the published magnetic variation in the GBAS reference point. This value is updated each magnetic epoch and could be used to calibrate a UAVs magnetic compass.

- $\sigma_{vert\_iono\_gradient}$, Refractivity and scale height are parameters used in the calibration of the tropospheric corrections and residual tropospheric uncertainty parameters.

- The GBAS Reference point fields indicate the coordinates of the point at which the pseudo-range corrections apply. This is usually either one of the reference receivers or the centroid of all reference receivers.

Table 2: Format of Message Type 2 data

Data Content	Bits	Range of Values	Resolution
GBAS Reference Receivers	2	2 to 4	1
Ground Accuracy Designator letter	2		
Spare	1		
GBAS Continuity/Integrity Designator	3	0 to 7	1
Local Magnetic Variation	11	$\pm180°$	$0.25°$
Spare	5		
$\sigma_{vert\_iono\_gradient}$	8		
Refractivity Index	8	16 to 781	3
Scale Height	8	0 to 25500m	100m
Refractivity Uncertainty	8	0 to 255	1
GBAS Reference point Latitude	32	$\pm90°$	0.0005 arcsec
GBAS Reference point Longitude	32	$\pm180°$	0.0005 arcsec
GBAS Reference point Height	24	±83886.07m	0.01m

4.2.3 Message type 4

The entire content of MT4 is shown in table 3. If the GBAS station supports GBAS approach services, this message contains information on N possible final approaches at the airport. A final approach segment (FAS) data block containing the airport name, the runway identifier and approach path is given for each supported approach. This message also contains the vertical and lateral alert limits for this approach, that are critical for landing operations. Full details on the content of the FAS data block can be found in [4].

Table 3: Format of Message Type 4 data

Data Content	Bits	Range of Values	Resolution
For N data sets:			
Data set length	8	2 to 212	1 byte
FAS data block	304		
FAS vertical alert limit	8	0 to 25.4m	0.1m
FAS lateral alert limit	8	0 to 0 to 50.8	0.2m

4.2.4 Message type 11

The entire content of MT11 is shown in table 4. This message type is very similar to MT1, however the pseudo-range corrections are smoothed over 30 seconds instead of 100 seconds for MT1. This gives quicker changing, but noisier correction measures.

4.3 Signal in space

The GBAS messages are split into 3 bit symbols, which motivates the need for additional fill bits should the total message length not be a multiple of 3.

These 3 bit symbols are coded into phase changes according to table 5 so that they can be broadcast as Differential 8-Phase Shift Keying (D8-PSK), at 10500 symbols/s over VHF (carrier frequency between 108-117.975 MHz and 25kHz channel spacing as discussed in section 4.1). This equates to the phase of the carrier wave shifting by $\Delta\phi_k$ 10500 times a second, and measuring these shifts allows us to determine the 3 bit symbols that were encoded on the signal.

Table 4: Format of Message Type 11 data

Data Content	Bits	Range of Values	Resolution
Modified Z-count	14	0 to 1199.9 sec	0.1 sec
Additional Message Flag	2	0 to 3	1
Number of measurements (N)	5	0 to 18	1
Measurement Type	3	0 to 7	1
Ephemeris Decorrelation Parameter	8	0 to $1.275 * 10^{-3}$m/m	$5 * 10^{-6}$ m/m
For N Measurement Blocks:			
Range Source ID	8	1 to 255	1
Pseudo-range Correction	16	±327.67m	0.01m
Range Rate Correction	16	±32.767m/s	0.001m/s
$\sigma_{pr\_gnd\_D}$	8	0 to 5.08m	0.02m
$\sigma_{pr\_gnd\_30}$	8	0 to 5.08m	0.02m

Table 5: GBAS D8-PSK Data encoding from 3 bit messages to phase shift

Message Bits			Phase Shift $\Delta\phi_k$
0	0	0	$0\pi/4$
0	0	1	$1\pi/4$
0	1	1	$2\pi/4$
0	1	0	$3\pi/4$
1	1	0	$4\pi/4$
1	1	1	$5\pi/4$
1	0	1	$6\pi/4$
1	0	0	$7\pi/4$

4.4   Receiving GBAS using Software Defined Radio

Figure 6 shows a block diagram of a typical D8PSK demodulator. A Software Defined Radio (SDR) module will contain all the elements up to the output of the Q and I values. Decoding the Q and I values into the 3 bit symbols will then be done by software.
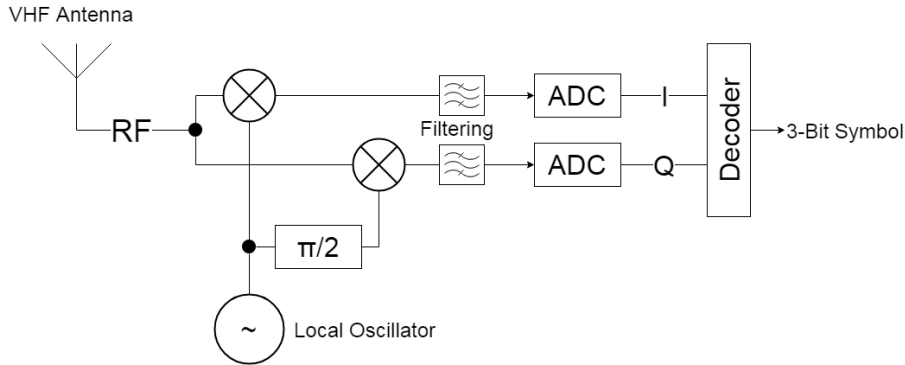

Figure 6: Block diagram showing the structure of a typical D8PSK demodulator. The 3 bit symbols can then be passed on to a decoder in order to extract the messages and their content.

The GBAS signal is very similar to the VHF Digital Link Mode 2 (VDL-M2) signal. VDL-M2 is an aeronautical VHF data link used to communicate between aircraft and airports [7]. It is very similar to the GBAS signal in that is uses D8PSK at the same data rate, however the encoded phase shift are somewhat different, with an offset of $1\pi/8$, see table 6, and different scrambling of the signal. There exist multiple open source Software Defined Radio (SDR) applications for receiving VDL-M2, and with minor modifications these should work just as well on the GBAS signals

Table 6: GBAS D8-PSK Data encoding from 3 bit messages to phase shift

Message Bits			Phase Shift $\Delta\phi_k$
0	0	0	$1\pi/8$
0	0	1	$3\pi/8$
0	1	1	$5\pi/8$
0	1	0	$7\pi/8$
1	1	0	$9\pi/8$
1	1	1	$11\pi/8$
1	0	1	$13\pi/8$
1	0	0	$15\pi/8$

5 Application of GBAS in a UAV

5.1 UAV description

To explore the possibilities of using GBAS in landing operations of UAVs, Indra Navia is collaborating with ASC. As a test platform for this technology, ASC has suggested using a Magline Cruiser 2 UAV. With a max takeoff weight of 75kg and a windspan of 5.2 meters [8], this is a UAV of significant size. See figure 7 for a photo of the UAV in question.

The aircraft has a gasoline powered propulsion motor, whereas radio and avionics are powered from a battery. Typically reaching a speed of 60-70 knots and with 8 hours of flight time, most parts of Norway and Svalbard can be reached from Andøya.

Figure 7: Andøya Space Center's Cruiser 2 UAV in flight. (Photo by ASC)

The Cruiser 2 is controlled by a CloudCap Piccolo 2 autopilot, that communicates with its ground station over a 2.4GHz radio link. This autopilot is able to perform fully autonomous or pilot-in-the-loop missions [9] over long distances. In order to be able to maintain a data link even during operations beyond radio range, both the aircraft and its ground station are equipped with Iridium satellite communication transceivers.

For payload integration and communication with avionics and the aircraft itself, the autopilot has 3 main ways of interfacing with external hardware [10]:

- Multiple serial connections each supporting full duplex RS232 or RS422 communication between the autopilot and a device.

- A Control Area Network (CAN) bus, where any node can broadcast to any other node.

- Digital and analogue General Purpose Input/Output (GPIO) pins that can be read from and written to, by software on the UAV ground station.

For positioning, the aircraft is equipped with a Novatel FlexPak-G2 RTK/GPS receiver, connected to the autopilot by means of a serial connection port. It is this receiver that enables ASCs current RTK landing operations. The autopilot itself also has a built in GPS receiver with basic code based positioning support. It is currently not in use, but can conceivably be used as a backup GPS receiver in the event of, say, a GBAS test module failing in flight. ASC has not tried whether such on-the-fly switching of GPS receivers is possible on this UAV.

5.2 GBAS receiver requirements

In order to use the GBAS positioning corrections, a GBAS receiver module has to be installed on board the UAV. This module will handle the reception and decoding of the messages, sort out the data fields of interest and route them to the desired location, be that the autopilot or the UAV ground station for the pilot to observe.

Such a module must at least consist of:

- An antenna in the VHF range

- A radio receiver

- A radio demodulator

- A decoder for the GBAS messages

- A controller for routing the data to the appropriate location

- Input/output capabilities in order to interface with other avionics

As discussed in 4.4, a software defined radio module is a good choice as a radio receiver, as it allows us to do most of the processing in software. There are any number of units available that are suitable in the VHF range. These modules are generally the size of a large flash drive, featuring an SMA connector for an antenna and a USB plug for connecting to a host device.

Using a linux-based Single Board Computer (SBC) would be a versatile choice as USB host. Many of the VDL-M2 decoders already run on these devices, and they are generally powerful enough to allow for additional software for demodulation, decoding and control algorithms. Furthermore, many of these SBCs have hardware interfaces available directly on the board, usually featuring a variety of GPIO pins and serial communication ports. This means that all points on the list with the exception of the antenna and radio receiver can be covered by one SBC. Exact selection of SDR and SBC is left as part of further work.

5.3 Information to autopilot

After the GBAS signals have been decoded, the next step lies in supplying the autopilot with the signals so that it can navigate using the corrected GPS solution.

The pseudo range corrections from the GBAS system have to be applied to the measured pseudo ranges from the GPS receiver. Analysis of the installed hardware in the UAV shows 3 main locations where this can be feasible:

(a) GPS and GBAS combined in autopilot

(b) GPS and GBAS combined in GPS receiver

(c) GPS and GBAS combined in GBAS module

Figure 8 shows the information flow between the modules in each of the 3 cases.

These options show several critical differences.

Option (a) is the least intrusive to the existing GPS-Autopilot interaction, as the autopilot should still be able to get the same data it currently does in the case of GBAS failure. However, this is also the most intrusive to the autopilot software as additional calculations need to be performed here.

Option (b) allows the position solution to be calculated entirely by the dedicated GPS hardware. It leaves the direct link between the autopilot and GPS in place, and puts the least strain on the GBAS and autopilot modules. This is the easiest solution, but requires that the GPS module is able to take external pseudo-range corrections into account when calculating the position solution, which is not a given fact.
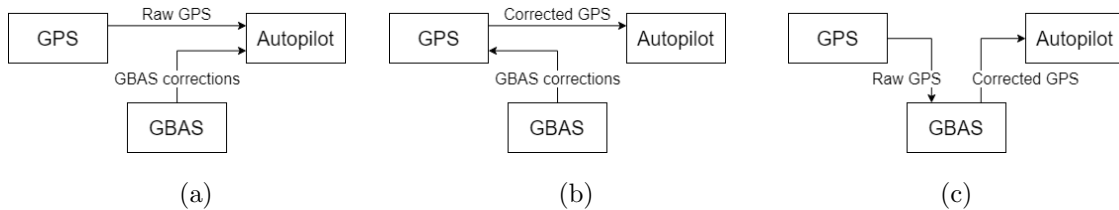
Figure 8: Information flow on board the UAV in each of 3 possible cases. Each represents one way in which the GBAS corrections can be applied to the GPS signals, such that the autopilot ends up with corrected data: a) correction in autopilot, b) correction in GPS module, c) correction in GBAS module.

Option (c) shifts the calculation of corrected pseudo range and position solution over to the GBAS module. This solution requires more work to be done by the GBAS module, but does give great flexibility in terms of how the calculations are performed. Since it is also useful for testing and comparing algorithms, this is the preferred approach. A significant downside is that the autopilots position information is dependent on the GBAS module. Should the GBAS module fail, the UAV might loose all positioning information, which would be detrimental for missions beyond VLOS. Here, using the GPS receiver built into the autopilot as a backup could be explored.

We have here made the assumption that all 3 ways are actually possible, and that any of the modules is able to combine the 2 signals and calculate a corrected GPS solution. In section 6 we shall see that is not entirely the case.

5.4 Downlink to pilot

During the approach to an airport, it should be possible for a pilot on the ground to be kept informed of the GBAS status and integrity. This is especially critical during remote landing, where safety and accuracy are more difficult to control. When first entering the GBAS area, the pilot should be presented with the contents of Message type 4, so that they may choose the runway and approach to use. Potentially, a piece of software on the ground station computer can take the pilots approach selection and generate new waypoints for the UAV based on the contents of MT4.

The most obvious and straightforward approach for communication with the pilot is using the built in pass through serial connection that is already present in the autopilot and is intended for payload data.

Care should be taken that this might be limiting for other payloads, since the GBAS receiver is not intended to be the actual payload. During testing and development using the payload serial is suitable, however an alternative is preferable in the long run. Here CANbus communication with the autopilot for direct inclusion of GBAS status messages can be attempted.

6 Challenges for using GBAS in a UAV

The critical processes to use GBAS in a UAV are related to receiving the GBAS signal, supplying it to the autopilot through one of the options in figure 8 and transmitting the necesary information to the pilot on the ground.

6.1 GBAS receiver

The receivers main challenge will be to correctly lock on and decode the GBAS transmission in such a robust way that the pilot can rely on good correction throughout the entire landing operation. This is important, as integrity is one of the major aspect of GBAS that make it so favourable. In the event that is does fail, it should preferably fail in a safe manner. Typically, this involves letting the autopilot and the pilot on the ground know that GBAS positioning isn't available, and supply the autopilot with data straight from the GPS receiver module.

The GBAS receiver will be a physical module that has to be integrated in the UAV, in addition to a dedicated antenna. The UAV however has physical limitations with regards to the size, weight and shape of the payload to which the module must conform. Furthermore, in its final form the receiver is not intended to be the main payload of the UAV. The space, weight and power consumption could potentially be considered as downsides to having a GBAS equipped UAV.

Ideally, the inclusion of a GBAS receiver should be non-intrusive to other payloads. This might be too strict of a demand during an initial testing phase.

6.2 Information to autopilot

Examination of the Piccolo 2 autopilot documentation, shows that it is not built to support pseudo-range corrections. It appears that the position is transmitted to the autopilot using a CAN message containing long-, lat- and altitude [11], and that the autopilot never sees the raw pseudo-range measurements. In addition, the software of the autopilot is not easily accessible for modification or openly available. The question arises whether this functionality can be included in the autopilot at all.

Inspecting the FlexPak-G2 GPS receiver, it does support a pseudo range correction mode. Looking deeper into it however, it turns out this is in relation to a Satellite Based Augmentation System (SBAS) (Covering SBAS falls outside the scope of this project), and this functions as an entirely closed system without any apparent exposed way of providing corrections through data lines from outside the module [12]. More critically still, this GPS receiver is not able to provide raw pseudo-range measurements, only a GPS or RTK position solution. This motivates the need to replace this module for a different one as discussed in section 7.

6.3 Downlink

There are multiple ways by which information from the GBAS receiver can be added to the existing down link from the UAV. Each method does include their own limitations that have to be considered.

The main challenge is dealing with the varying change of supported throughput depending on how well the communication link is.

The downlink bandwidth is limited and the throughout will change during the flight. This can result in competition between the different applications and requires a critical evaluation of the information that needs to be exchanged. Furthermore, the internal CAN bus bandwidth is considerably larger than what the radio link for external communication allows. This is especially critical when iridium communication is used, since this limits the amount of information transferred considerably.

7 System Design Proposal

Based on the points brought up in section 5 and 6, this section proposes how a system for integrating GBAS signals with ASCs UAV hardware can be designed.

Of the 3 architectures in figure 8, we choose to base the system design proposal on option (c). The main motivation for this is the limited access to the autopilot software for option (a), and the great flexibility in implementation that option (c) allows.

Figure 9 shows a block diagram of the modules and how they communicate, as well as information flow between functional blocks inside the GBAS module.
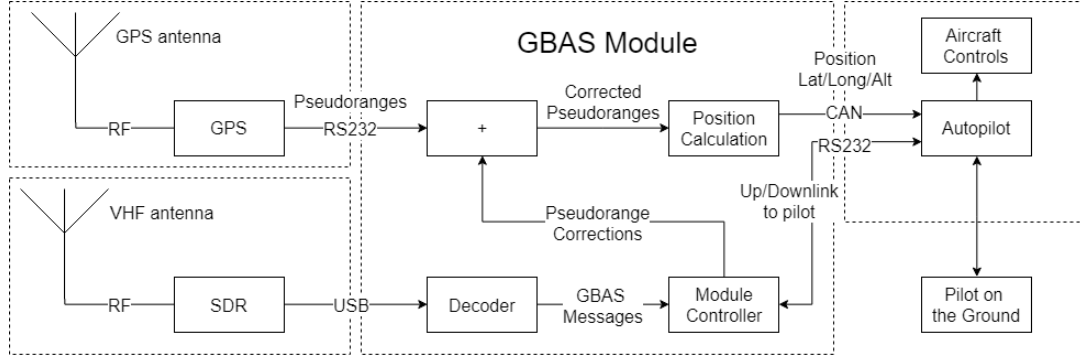

Figure 9: Overview of the proposed solution. The GBAS module block will have to be designed and constructed, while suitable GPS and SDR modules exist as off the shelf components. The aircraft and autopilot are preexisting parts. Software to visualise the GBAS data for the pilot would also need to be written.

As was mentioned in section 6.2, the current GPS receiver does not allow output of any raw GPS data, including pseudo-ranges. It therefore has to be replaced with one that is able to do this. The GPS antenna mounted in the UAV can be re-used for the new GPS receiver, but an additional antenna should be mounted and connected to the autopilot's built-in GPS receiver. This will serve as a back-up, should the GBAS module stop functioning.

The computations done by the GBAS module are performed on a single board computer. The computer receives input from the SDR over a USB connection as well as GPS data over RS232 (figure 9). The blocks within the GBAS module roughly represent independent software operations. The result is communicated with the autopilot and the pilot on the ground over the CAN bus and an RS232 connection.

8   Conclusion

In this project assignment, we have looked at the GBAS system, its signals, and given a brief overview of what they could be used for in the scope of UAV operations. An SDR can be used to recieve these signals, and 3 different ways were examined to integrate these with the existing hardware of a UAV at ASC:

(a) GPS and GBAS combined in autopilot

(b) GPS and GBAS combined in GPS receiver

(c) GPS and GBAS combined in GBAS module

By comparing these options with documentation for the UAV and existing avionics hardware, it was concluded that the GPS receiver has to be exchanged with a new unit that can output the required raw pseudo-ranges. Furthermore, one of the 3 proposed methods, GPS and GBAS combined in the autopilot, is not feasible due to limitations in the autopilot.

To allow a greater freedom in terms of implantation and testing, it is suggested to base further work on combining GPS and GBAS in the GBAS module. A system design has been proposed based on this.

Implementation of the proposed concept design introduced here will be part of further work during a master thesis. At this stage the following tasks are envisioned:

- SDR software development for demodulating the GBAS VHF broadcast. This can to a large extent be based on existing open-source VDL-M2 demodulation software available.

- Designing software functions for descrambling and message decoding of the demodulated signal.

- Decide on the needed hardware to run these functions, that is suitable for inclusion in a UAV.

- Integrate this with the UAV autopilot for bench testing.

- Simulations during flight tests to collect data on system responds. This requires that proper safety measures can be put in place and the potential uncertainties are deemed acceptable by ASC.

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