Local-Area Differential GNSS Architectures Optimized to Support Unmanned Aerial Vehicles (UAVs)

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ABSTRACT

As the applications of Unmanned Aerial Vehicles (UAVs) expand, UAVs will be combined into networks that cooperate to perform various missions within 10 to 200 km of a centralized controller. GNSS is the primary source of navigation for UAVs operating over large areas, and UAVs combined into local networks can easily make use of local-area differential corrections integrated into their guidance commands to improve their navigation accuracy and integrity. This paper develops a Local-Area Differential GNSS (LADGNSS) architecture around a concept of local-area UAV network operations that emphasizes low cost for commercial applications and high integrity to allow UAVs to operate in close proximity to each other and potential "targets" while minimizing collision risk. Using the well-established Ground-based Augmentation System (GBAS) as a starting point, a simplified LADGNSS architecture is identified that retains most of the performance of GBAS at a far lower cost. Because LADGNSS performance will be limited by the characteristics of UAV receivers and flight dynamics, future work will be focused on identifying and understanding UAV receiver performance through a series of flight tests at the Korea Advanced Institute of Science and Technology (KAIST).

1.0 Introduction: UAV Network Concept

While the best-known applications of Unmanned Aerial Vehicles (UAVs) are remotely-piloted military reconnaissance and strikes using relatively large aircraft, commercial applications of much smaller UAVs have grown dramatically over the past few years and are now of major interest to the media (see [1]). A large number of applications have been proposed, and many of these have already been put into practice in certain places due to the capability and inexpensiveness of today's UAV and controller hardware [2]. This emerging reality should also make *networks* of UAVs guided by a single intelligence (either human or artificial) practical, if not now, within the next few years.

The applications proposed for UAV networks can be divided into two categories. The first is *observation and data collection*, where the objective is to measure or monitor something that changes relatively slowly but is difficult or costly to observe by other methods. Aerial photography is one example that is already popular, as UAVs can perform this function much more cheaply than manned aircraft. Near-real-time observations of Arctic ice are another potential application, as the growth of shipping in the Arctic will likely require more detailed and more frequent observations of ice than can be made by satellites. A more unusual application proposed by Prof. Grace Gao of the University of Illinois is monitoring the ejecta of volcanoes to assess the resulting environmental hazards. The eruption of the volcano Eyjafjallajökull in Iceland in 2010 showed the usefulness of such monitoring, as the resulting clouds of ash posed a potential hazard to aviation and caused passenger flights in and around Western Europe to be suspended intermittently over several weeks [3]. This was very disruptive to people and business but was necessary due to the high level of uncertainty regarding the level of danger posed by the ash cloud in various locations.

The second category of UAV network applications is *reconnaissance and surveillance*. It shares with the first category the general motivation of collecting information, but the key difference is the need to detect and react to anomalies quickly. Military needs for reconnaissance and surveillance are widespread and, to some degree, are being carried out by the existing array of military UAVs. However, a networked approach that is mostly (if not completely) automated would take much of the burden off soldiers who have to operate and coordinate today's UAVs. Many facilities in the civil world share the need for all-the-time monitoring and could benefit from this

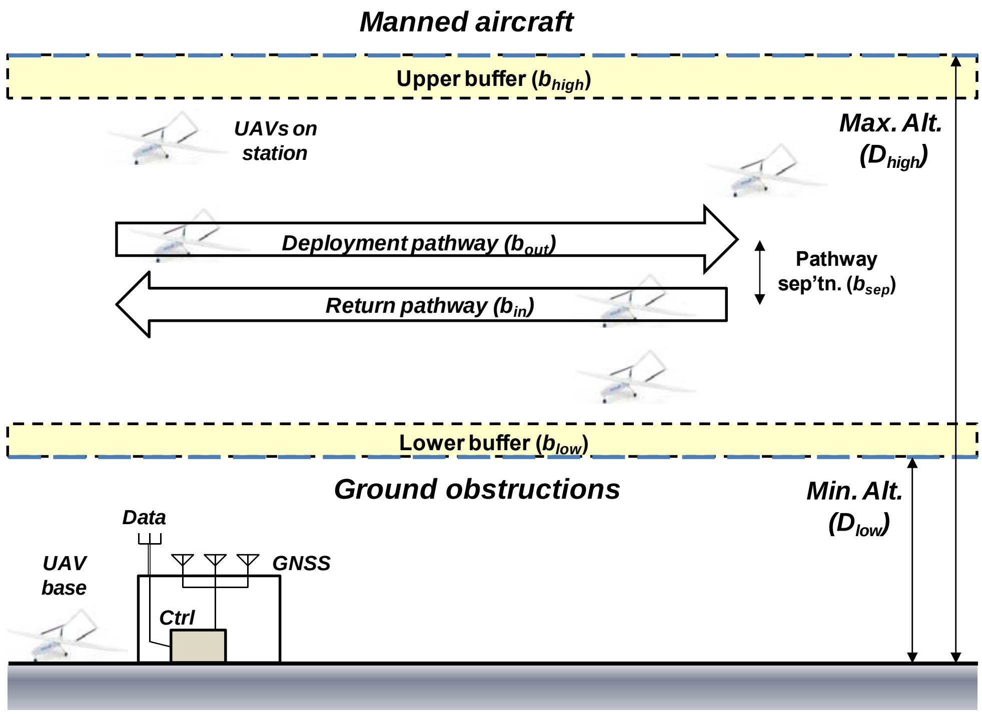

Figure 1: Local-Area UAV Network Concept

technology. If it is sufficiently inexpensive, the market could grow from obvious candidates like airports, prisons, shopping malls, and company/university campuses to residential complexes and neighborhoods.

Figure 1 illustrates one concept of local-area UAV network operations [4,5]. The control station shown at the lower left is the source of LADGNSS corrections and integrity information as well as real-time guidance for each UAV in the network. The LADGNSS and guidance information are separate data messages combined in the same outbound transmission. Because the guidance function requires feedback from each UAV, the datalink is two-way and can be used to relay GNSS information as well from UAVs to the control station, although signals from UAVs are at a lower update rate. Most of the time, individual UAVs are "on station," meaning that they are stationary or nearly so and are observing the ground, taking measurements or photographs, etc.

Because the endurance of each UAV is limited, the control station must recover, refuel, and re-launch UAVs periodically at a site near the control station. Specific pathways in space are defined to separate deploying and returning UAVs from those on station. All UAVs must maintain safe separation from each other, from other (non-participating) UAVs, from the ground and obstructions on the ground, and from manned aircraft. The primary responsibility of each UAV is to stabilize itself and to control its motion from one location to another as guided by the central controller.

Section 2.0 of this paper describes simple, commercial-off-the-shelf (COTS) LADGNSS systems as well as the very complex and robust GBAS architecture as starting points for the design of an LADGNSS approach most suited for the operation concept shown in Figure 1. Section 3.0 uses GBAS as the starting point and explains how the GBAS ground system can be simplified for this application to remove the most complex and expensive components of GBAS while retaining the performance of GBAS that is feasible in the context of UAV navigation. Section 4.0 describes how the information in the ground-to-airborne datalink can be simplified. Section 5.0 explains the modifications on the airborne (UAV receiver) side and how selected information is relayed back from each UAV to the ground system. Section 6.0 describes the future work needed to fully develop this concept, in particular, the need for UAV flight tests to better quantify the performance of UAV receivers as part of LADGNSS. Section 7.0 briefly summarizes the paper.

2.0 Local-Area DGNSS Architecture Alternatives

2.1 Commercial DGPS Used in Testing

Figure 2 shows both the ground (reference receiver) and mobile (UAV) hardware for the dual-frequency NovAtel LADGPS system used by the Unmanned System Research Group at KAIST for UAV flight testing UAVs [6]. This system provides L1/L2 code and carrier differential corrections to support RTK as well as code-

Figure 2: COTS DGPS Equipment Used by KAIST USRG for UAV Flight Tests

-based DGPS. The reference receiver is an NovAtel OEM-V-1DF with an attached patch antenna and radio-modem transmitter in a portable enclosure. The Microhard Systems radiomodem transmits corrections to users in the 902 - 928 MHz band. It supports a user-selectable data rate of either 345 kbps or 1.1 Mbps and a maximum line-of-sight range exceeding 100 km at the lower data rate. The mobile unit shown in Figure 2 includes the flight-control computer and the modem receiver hardware in addition to a NovAtel OEM 615 GPS receiver (the small patch antenna is mounted separately). Because the mobile unit is relatively large and is not designed to fit a particular UAV, it is best suited for relatively large vehicles that have space, payload capacity, and power for the unit and its antennas.

In support of UAV flight testing, this equipment works reasonably well, as it is more reliable than the experimental UAVs that are the focus of the experiments. In practice, obstruction of the line of sight needed by the datalink is the most significant constraint. However, a system that supports a network of UAVs operating continually without interruption needs both redundancy and means of detecting anomalous behavior in individual components. In particular, the need to guarantee to very high probability that UAVs in the network do not collide with the ground or other vehicles potentially requires levels of integrity and continuity similar to what is achieved by GBAS for precision approach of manned aircraft. For that reason, it makes sense to begin with the GBAS architecture and remove components where possible before trying to build the required integrity and continuity into existing commercial LADGNSS systems.

2.2 Ground-based Augmentation System (GBAS)

Figure 3 shows an overview of the components of GBAS as fielded at an airport to support precision approach to at

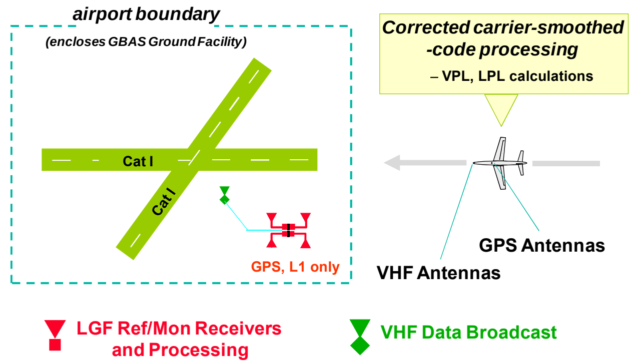

Figure 3: GBAS Architecture for Category I Precision Approach

least Category I minima [7,8]. The ground system (also known as the "Ground Facility") includes four or more reference receivers connected to multipath-limiting antennas (MLAs) that generate differential corrections and integrity information for L1 C/A code (only). This information is sent to users via a VHF Data Broadcast (VDB) using a Time-Division Multiple-Access (TDMA) structure in the 108 - 118 MHz Instrument Landing System (ILS) Localizer band. The aircraft also has multiple GPS receivers and antennas and combines the information received by the ground with its local measurements to derive 3-D position and velocity estimates, ILS-lookalike glideslope and localizer outputs to support either piloted or autopiloted approaches with existing ILS equipment, and vertical and lateral protection levels that bound the navigation error to the very high probabilities required for precision approach integrity. Note that GBAS is also known as the Local Area Augmentation System, or LAAS, in the United States.

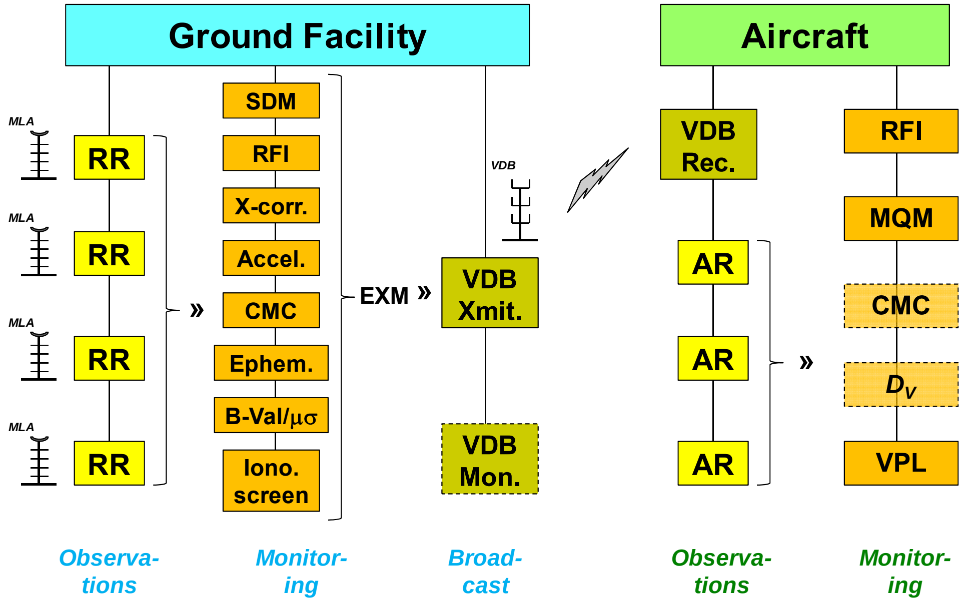

Figure 4: GBAS Ground and Aircraft Components and Software Functions

Figure 4 shows the components and functions of GBAS in more detail. Each ground reference receiver is connected to an MLA, which is a unique multi-element ground antenna specially designed to attenuate multipath signals reflected from the ground [9]. These antennas are typically separated from each other by 100 meters or more to maximize the statistical independence of multipath errors at each antenna, which further reduces the impact of multipath on correction accuracy and monitor detectability. Because the ground facility is responsible for assuring the quality of the GNSS signal in space, many different monitor algorithms act upon the receiver observables in order to detect anomalies of different types. Executive Monitoring, or "EXM," combines the outputs of these monitors and determines which corrections (for which satellites tracked by the ground facility) are safe to broadcast to users. Only satellites for which corrections and integrity information are broadcast can be applied in user positioning, and the aircraft also performs limited monitoring of its own measurements (note that two airborne monitor blocks, CMC and D_V, are dashed to indicate that they are only required for the GAST-D variation of GBAS now being developed to satisfy CAT II/III precision approach criteria [10]. Protection levels, indicated by the "VPL" box at the lower right of Figure 4, are computed based on the ground and airborne integrity parameters for the satellites that pass all of these monitors and are used in the airborne navigation solution.

While GBAS does an excellent job of meeting existing civil aviation requirements for precision approach and other phases of flight, it is highly tailored to these requirements and to the airport environment where it is designed to operate. Therefore, it is not necessarily optimal for applications in different environments or governed by different requirements. While today's large military UAVs share many characteristics of manned aircraft, commercial UAVs optimized for low-cost observation or reconnaissance will be much smaller and less lavishly-equipped. In addition to having inexpensive, low-power receiver chipsets and antennas (generally significantly smaller than shown for the mobile station in Figure 2), small UAVs will experience greater dynamics and wind disturbances relative to larger aircraft. In many cases, they will operate close enough to the ground (within 50 meters or so) that multipath from ground obstructions significantly exceeds multipath coming from the UAV itself.

This suggests that, for small UAVs operating close to the ground, UAV errors will tend to dominate the overall error budget, which suggests that the focus in GBAS on minimizing ground-system errors is not necessarily optimal. On the other hand, larger UAVs flying at higher altitudes would have errors similar to those of manned aircraft, and the approach taken by GBAS is more suitable. The remainder of this paper will focus on cost-sensitive applications mandating small UAVs operating close to the ground, as these applications likely have the largest commercial market, and they motivate the most changes from the approach taken by GBAS.

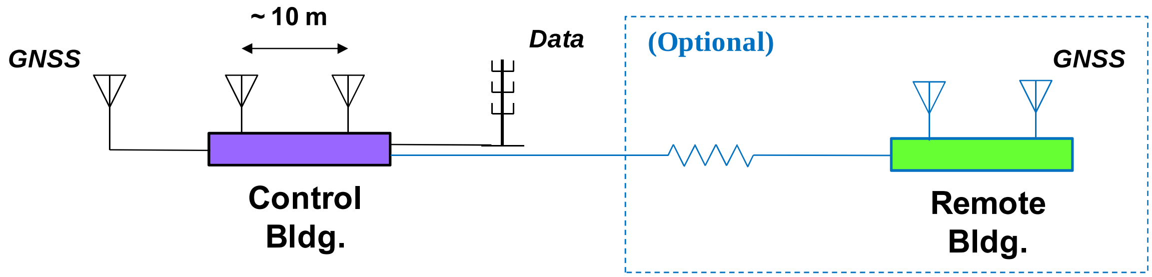

Figure 5: Example of Simplified LADGNSS Ground System Hardware for UAV Networks

3.0 GBAS Ground Station Modifications

3.1 Ground System Hardware Changes

As noted earlier, a key feature of GBAS is the use of MLAs in the ground station and their separation by relatively large distances to make their multipath errors as statistically independent as possible. For several reasons, these antennas are not suitable for low-cost commercial applications. First, they are very expensive and require careful siting to achieve their full performance. Second, unlike GBAS at airports, siting constraints for most commercial applications will not have room to spread ground antennas over hundreds of meters. Third, the multipath rejection achieved by MLAs and the further reduction of errors due to multipath independence become much less significant when UAV multipath errors (which enjoy no such protection) are large. Therefore, it makes sense to replace MLAs with more-common commercial "multipath-resistant" antennas (such as patch antennas surrounded by metallic "choke rings") and site them much closer together depending on the amount of room available near the central controller shown in Figure 1.

Figure 5 shows an example of an LADGNSS ground-system layout to support a low-cost UAV network. The primary ground system is on the left hand side of the figure and includes three non-MLA GNSS reference receiver antennas separated by short baselines (on the order of 10 meters) so that they can fit within a small area close to the building housing the processors for the navigation and guidance functions as well as the datalink equipment. Because multipath errors on antennas this close together are likely highly (although not completely) correlated, the presence of multiple receivers is mostly needed for redundancy as opposed to error reduction. Three reference receivers is the minimum to allow operations to continue if one of the three is detected and excluded (properly or improperly) as faulted. If budget and space permit, a fourth receiver and antenna near the control station might be worthwhile.

The remote building (with additional reference receivers and antennas) shown on the right-hand side of Figure 5 is optional but might have value in support of networks operating over more than 5 - 10 km. In addition to providing additional redundancy, measurements from a remote site would be useful for "pseudo-user" integrity monitoring of the corrections broadcast from the primary system. This would include position-domain monitoring (PDM) that continually compares the LADGNSS-corrected position to its known, surveyed position for many possible subsets of the GNSS satellites approved by the primary system. This serves as a complement to the range-domain monitoring conducted within the primary reference system (see [11,12]), and it would help detect spatially-decorrelating errors such as atmospheric and satellite ephemeris errors that are not easy to observe at the primary site.

The intent of the architecture proposed here is to rely on monitoring at the primary site plus simple monitors aboard each UAV to sufficiently mitigate spatially-decorrelating errors. This avoids the need for one or more remote sites, but in some cases for large coverage regions, the redundancy and monitoring improvements provided by remote sites may be worthwhile. This is especially the case if additional datalink transmitters are needed at remote sites to adequately cover the UAV service area.

3.2 Ground System Software (Monitor) Changes

Several related factors motivate the simplification of ground system monitoring from what is required for GBAS. The complexity of the combined monitors for each threat or anomaly of concern and the executive monitoring needed to sort out the results of these monitors goes well beyond what is desirable for a low-cost commercial system. Commercial UAV networks will not have the measurement quality provided by MLAs with very strict siting criteria, making them more vulnerable to false alerts. GBAS was developed to not only meet very demanding integrity requirements for aviation precision approach, but very conservative interpretations of the impacts of potential faults and anomalies. This must be done while simultaneously limiting the unexpected loss of service (continuity) to a very small probability under the very conservative assumption that the sudden loss of any single measurement leads to loss of service. It would be very difficult to design cost-effective commercial UAV networks under the same assumptions, and it should not be necessary to do so [4]. Therefore, simplifications to existing GBAS monitoring may affect integrity under the most conservative assumptions but are likely to have little to no effect under the set of assumptions more typically used to assess safety risk in most industries (see [13] for more details, including a comparison of "specific risk" vs. "ensemble risk").

With this in mind, the following changes to GBAS are proposed for an LADGNSS ground station used with low-cost, commercial UAV networks. To simplify the terminology, the LADGNSS system proposed for UAV networks will be denoted as "LD-UAV."

3.2.1 Signal Deformation Monitoring (SDM): This monitoring is designed to detect anomalous code waveforms that may affect reference and user receivers differently and potentially cause hazardous levels of error. It requires accurate measurements of the code correlation peak (or the code chips themselves) at several different spacings and careful combinations of these measurements into one or more test statistics [14,15]. Even with good equipment and accurate measurements, it is difficult to detect all potential code deformations that might cause significant errors while not alerting nominal code deformations that are typically present (these vary with time and by satellite [16]).

Without the measurement accuracy provided by MLAs and very strict siting, SDM as practiced by GBAS would become that much more difficult. It makes more sense to eliminate SDM from LD-UAV and mitigate its absence by selecting ground and airborne GNSS receivers that are either the same (in terms of RF front end bandwidth and filtering and code tracking) or very similar. This would make the response to both nominal and anomalous signal deformations the same (or nearly the same) at both ground and user, causing the resulting error to cancel out when users apply their differential corrections.

In practice, it is unlikely that a perfect match can be achieved between ground and airborne receiver characteristics. Because UAVs are more demanding environments for GNSS receivers, the choice of receiver for UAVs will be more restricted, meaning that ground receivers will be selected to match the design parameters of airborne devices designed for very low size, weight, and power. While a perfect match is not be necessary, the lack of dedicated SDM in LD-UAV should motivate the design of families of GNSS chipsets that can serve both roles (reference and mobile) while retaining common RF chains and code-tracking strategies.

3.2.2 Ephemeris Monitoring: Because it is very difficult to independently detect satellite ephemeris anomalies solely from measurements taken at a single airport, the ephemeris monitoring included in existing GBAS ground system consists of comparisons between the ephemeris parameters currently broadcast by each satellite and parameters broadcast up to 48 hours earlier and projected forward to the current time by simple orbit models (see [17]). This is sufficient for Category I precision approach service, but it has a disadvantage that failed comparisons or observed satellite outages (i.e., the satellite is flagged "unhealthy" in its navigation data) require a lengthy reset period before a clean comparison of trusted ephemeris parameters can be conducted again. This is the case because satellites observed to be unhealthy may be undergoing orbit changes; thus there is no basis to trust the first set of ephemerides broadcast after the maneuver as a standard to validate the ones that follow.

The comparison algorithms used by GBAS are not difficult to implement in LD-UAV and should be retained. A key question is what to do during the reset period. Ideally, all satellites flagged “healthy” in their navigation data should be usable unless they show substandard behavior that is observable to real-time monitors. Satellites that appear perfectly healthy but might have the small class of very rare anomalies undetectable to the ground station might still be usable if they are deweighted properly in the navigation solution. Another option, and the one preferred for LD-UAV, is to supplement ground monitoring with simple monitoring on each UAV and utilize the airborne-to-ground component of the two-way datalink needed for guidance as a means to alert the ground system of any UAV detections. This will be discussed further in Section 5.0.

The minimum anomalous error detectable by GBAS ephemeris monitoring with the required integrity probability (and under worst-case assumptions) is expressed as a “P-value” and is broadcast to users to allow them to compute ephemeris-fault-based protection levels, which increase with the distance from ground system to aircraft [23]. This feature can be eliminated from LD-UAV for simplicity, as unlike GBAS, the UAV ground controller will know the location of each UAV and can adjust the nominal protection levels received from each UAV accordingly.

3.2.3 Ionospheric Geometry Screening: The introduction of GPS receivers at many locations in the U.S. and worldwide has revealed that, under extreme conditions, ionospheric delays can change dramatically over relatively small distances and create errors that are potentially hazardous to LADGNSS. Typical spatial gradients of ionospheric delay at L1 are 0.5 – 2 mm/km, while the very largest gradient observed and validated over the U.S. (on November 20, 2003) was approximately 410 mm/km. When extreme gradients are combined with worst-case GNSS satellite geometry and timing, they may go undetected by the GBAS monitors that normally notice large rates-of-change in code and carrier measurements (including the excess-acceleration and code-minus-carrier, or "CMC," monitors) [18].

Under general flight conditions, it is very difficult to guarantee that the worst-case undetected ionospheric spatial gradient is bounded by the protection levels computed by aircraft [19]. The solution for GBAS under the constraints of a particular operation, Category I precision approach, is to compute the worst-case undetected position error in the ground system and increase one or more broadcast parameters that affect the airborne protection levels so that satellite geometries potentially giving hazardous errors (not just unbounded errors) are made unavailable [20]. This is both very cumbersome and very limiting of airborne availability and would not be acceptable in the networked-UAV environment. Therefore, it will not be used in LD-UAV. As with ephemeris anomalies, the resulting potential vulnerability to worst-case ionospheric gradients will instead be at least partially mitigated by airborne monitoring, to be discussed in Section 5.0. Any remaining hazard will be reassessed in terms of its probability with respect to a 10^{-7} ensemble integrity probability (the tightest expected to apply to networked-UAV separation standards) [4,13,21].

3.2.4 "B-Value" and Mean/Sigma Monitoring: "B-Value" monitoring, also known as the Multiple Reference Consistency Check (MRCC), looks for individual reference receiver faults by comparing the pseudorange corrections derived from each reference receiver with the average over all reference receivers [22]. While the EXM associated with this check can be complex if one or more measurements appear faulted, this monitor is fundamental to multi-reference LADGNSS and must be retained. The absence of MLAs with strict siting means that the thresholds on MRCC will be significantly higher for LD-UAV than for GBAS, but this penalty corresponds to the loss of accuracy in the differential corrections, which is accounted for in the sigmas broadcast to UAVs and the eventual protection levels computed by UAVs.

In GBAS, the actual B-values computed within MRCC are broadcast to users to allow them to compute "H1" protection levels, which are protection levels that assume that one of the reference receivers has failed (thus its B-value expresses the error due to the failure). As with ephemeris protection levels, the broadcast of B-values should be removed from LD-UAV, leaving UAVs to only compute "nominal" or "H0," protection levels, which are those that assume no undetected failures in the measurements used by the UAVs [23]. As with the ephemeris case, because the ground station knows its B-values and the (nominal) protection levels computed by each UAV, it can adjust its separation guidance to handle the uncommon situation where B-values are large enough to be significant but not large enough to cause MRCC alerts in the ground station.

Another use of B-values within the GBAS is for longer-term (over minutes to days) monitoring of trends in uncorrelated ground station errors (see [24]). This is less-effective without ground antennas separated far enough to make multipath errors (mostly) independent between antennas, but the simpler versions of it should be retained for LD-UAV. In particular, estimation of the sample mean and variance should be maintained along with a record of B-values crossing one or two "thresholds of concern" that are below the threshold for MRCC detection and exclusion. For example, if the MRCC threshold is about 6 times the bounding nominal B-value sigma, cases where 2.5 × sigma and 4.5 × sigma are exceeded should be noted and compared to their expected frequency under normal conditions (note that exceeding 4.5 × sigma is an example of a situation where the ground station may need to adjust for the possibility of H1 protection levels being significant, as described above).

3.2.5 Other Monitors and Executive Monitoring (EXM): The other ground-system monitors shown in Figure 4, including checking for RFI (which includes monitoring the received signal power), excess acceleration, CMC, and code cross-correlation, should generally be retained for LD-UAV. Since these monitors operate on the same code and carrier measurements output, it should be possible to simplify their execution by combining them into a single algorithm. This would also simplify EXM, which in GBAS has to sort out separate alerts from multiple monitors that might be caused by the same phenomenon in the received measurements, such as a sudden jump in the carrier phase.

3.3 Use of SBAS Corrections (Where Available)

While not available everywhere, the use of corrections and integrity information from Space-based Augmentation Systems (SBAS), including the U.S. Wide Area Augmentation System (WAAS) in the ground system is a straightforward means of eliminating most, if not all, of the risk that might be encountered by the ground-system modifications proposed for LD-UAV. One method for doing this is described in [25] based on an analysis of WAAS monitoring relative to GBAS integrity risks.

Figure 6 shows two tables from [25] that summarize how SBAS integrity information would be used. The left-hand

Ionosphere

GIVE Value	GIVE Integer	GBAS Class.	*Notes*
≤ 6.0 m	0 – 12	Good	*WAAS verifies that no threat is present here.*
15.0 m	13	Not Observed	*WAAS observations are too limited to confirm that no threat exists.*
45.0 m	14	Bad	*WAAS detects a nearby ionosphere storm – possible threat.*
Not Monitored	15	Not Observed	*WAAS observations are too limited to provide any iono. assurance.*

Ephemeris and SDM

UDRE Value	UDRE Integer	GBAS Class.	Ephemeris MDE
≤ 50.0 m	0 – 12	Good	500 m
150.0 m	13	OK	1500 m
Not Monitored	14	Neutral	GBAS value (≈ 2700 m)
Do Not Use	15	Do Not Use	Exclude from Use

Figure 6: Use of SBAS Integrity Bounds in LD-UAV Ground System [25]

table shows how bounds on SBAS Grid Ionospheric Vertical Errors (GIVEs) translate into information regarding nominal or potentially anomalous ionospheric conditions, while the right-hand table does the same for the SBAS User Differential Range Errors (UDREs) that bound satellite errors. In the ionospheric case, each satellite tracked by an LD-UAV ground station has a theoretical ionospheric pierce point (IPP) that is surrounded by as many as four SBAS grid points from which SBAS corrections and integrity bounds are interpolated [26]. While the close proximity of LD-UAV reference and user receivers means that the SBAS ionospheric corrections are not needed, the GIVE values represent the results of continent-wide monitoring of the ionosphere and will reveal any anomalies that could threaten LD-UAV (or GBAS). The same is true of the UDRE values generated for each satellite.

The use of SBAS correction data in an LD-UAV ground system requires reference receivers that can receive and decode data from SBAS satellites, but this is not needed for UAVs. The primary limitations of using SBAS are (1) being unable to reliably receive corrections from SBAS Geosynchronous satellites; (2) being able to receive corrections but being outside the primary coverage area of SBAS, which makes it less likely that the GIVE and UDRE values for the satellites tracked by LD-UAV will help eliminate potential threats; and (3) needing extreme levels of integrity currently beyond that provided by SBAS, such as the 10^{-9} level required by Category II/III precision approach. Since (3) should not apply to UAV networks, location relative to SBAS coverage is the primary constraint. The current coverage of SBAS in North America, Europe, and Asia is sufficient to justify equipping LD-UAV ground stations with the ability to receive and decode SBAS corrections, but LD-UAV needs to be workable (perhaps with higher protection levels and thus larger separation standards) without relying on SBAS.

4.0 Ground-to-Airborne Datalink Modifications

The amount of data required to be transmitted by GBAS [8,27] is extensive and can be greatly reduced for this application. First, the precision-approach path-definition data broadcast by GBAS is no longer needed. Second, as described in Section 3.0, several integrity parameters broadcast by GBAS, such as B-values and ephemeris P-values, are no longer needed. Third, transmission elements needed by GBAS to confirm ground-to-airborne consistency, such as the ephemeris CRC data, can be removed or greatly simplified to take advantage of the UAVs ability to relay information back to the ground station. Fourth, parameters that still need to be sent, such as differential corrections, correction rates, and sigma values that bound errors in the differential corrections, can be re-coded to save data bits and better suit this application.

One example where re-coding helps add data with minimal impact is in the transmission of pseudorange corrections for both short and long smoothing time constants. This is a key aspect of the GAST-D modification to GBAS, as it provides a means for airborne receivers to detect ionospheric anomalies potentially invisible to the ground station [10,28]. In GAST-D, a new message (Message Type 11) is added to broadcast independent corrections and correction rates for the shorter time constant (30 seconds for GBAS, as opposed to 100 seconds for the longer time constant also used in Category I) along with separate error sigmas for these corrections [27]. While GAST-D GBAS needs to be backward-compatible with older equipment, LD-UAV can provide corrections, rates, and sigmas for the shorter time constant as delta values from the full values already provided for the longer time constant. This saves bits and is simpler to implement.

Since the LD-UAV navigation datalink is part of the two-way datalink used for guidance and tracking of each UAV in the network, the choice of transmission frequency and data format will depend on the needs of guidance as well as the needs of LADGNSS. The key for both functions is very high reliability of communications to the edge of network coverage with an update rate on the order of 1 Hz. GBAS differential corrections are updated at 2 Hz to meet the time-to-alert for aviation precision approach, but 1 Hz should be adequate for LD-UAV corrections. Guidance commands will rarely need to be updated at anything close to 1 Hz, but the capability to rapidly send out "emergency" commands when failures occur or safe separation is otherwise threatened is likely to be the driving requirement.

5.0 Airborne (UAV) Modifications

As explained above, much of the simplification of LD-UAV relative to GBAS reflects the use of small, low-cost UAVs and UAV receiver hardware. However, this does not mean that significant integrity monitoring cannot be implemented on UAVs. The airborne receiver algorithms required by Category I GBAS, and the expanded processing and monitoring required by the GAST-D upgrade of GBAS, can easily be implemented by today's UAV receivers and processors as long as the receiver chipset on the UAV outputs raw measurements (e.g., pseudorange, carrier phase, C/N_0) in addition to position fixes.

As shown in Figure 4, GBAS airborne receivers include rudimentary monitors to detect sudden measurement changes (MQM) and RF interference that might not be observable at the ground station. GAST-D adds to this several monitors designed to detect ionospheric spatial decorrelation that might be invisible or undetectable at the ground station. One is an airborne CMC test similar to that implemented in the ground station. The other uses the difference between 30-second and 100-second smoothed pseudoranges to compute differential vertical and lateral position values (D_V and D_L, respectively) that are monitored and included in the protection levels for GAST-D [10,28]. These monitors are helpful and are not complicated; so they should be included in LD-UAV, although the definitions of the shorter and longer time constants may change. In addition, there is no need to include D_V and D_L in the nominal protection levels calculated by the UAV (under nominal conditions, the impact of ionospheric decorrelation is negligible; thus D_V and D_L are dominated by ground-system errors already accounted for in the broadcast sigmas). Note that the additional satellite geometry screening performed in GAST-D (see Section 2.3.9.4 of [28]) is also not needed in LD-UAV, as it has a unique purpose in supporting Category II/III precision approaches that does not apply to UAV operations.

GAST-D GBAS also implements an airborne variation of Receiver Autonomous Integrity Monitoring (RAIM) based on the corrected pseudoranges with the shorter smoothing time constant. This check is not continuous – it is nominally updated once per minute, at least once during the final approach interval, and when a new satellite is added to the position solution after its smoothing filter has converged (see Section 2.3.9.6 of [28]). This test is designed as additional protection against ionospheric spatial decorrelation. An expanded version of this RAIM test can also be used to detect ephemeris faults, as these also generate spatially-decorrelating errors that may be more detectable by UAVs than at the ground system, which has limited monitoring capability in any case [29,30]. This form of RAIM with infrequent updates should be included on each UAV as a mitigation for both residual ionospheric and ephemeris risk.

Since GBAS only has a one-way datalink from ground to aircraft, airborne monitor detections cannot be directly relayed back to the ground system. This is not the case for LD-UAV; thus the ground system and guidance controller can make use of UAV monitor detections soon after they occur. The return datalink from UAVs to the ground system will mostly be used for tracking – to report UAV locations to the central controller – but it should also be used to report UAV protection levels on an infrequent basis (perhaps once per minute) as well as unexpected changes in UAV navigation integrity. For example, a sudden and unexpected (meaning not caused solely by predictable satellite loss) in protection level should result in a notification, as should an alert from any of the airborne monitors mentioned in this section. Both the LD-UAV ground system and guidance controller can adapt as needed depending on the number of UAVs that report unexpected problems (details of this will be described in [5]).

Ideally, as with GBAS-equipped aircraft, each UAV would have two or more independent GNSS receivers, antennas, and processors, but this is likely impractical for small UAVs. UAVs with "single-string" GNSS equipment will have lower reliability and availability in service, but this may well be acceptable given that each UAV has limited endurance and may only be able to operate on station for a few hours. The impact of "single-string" equipage on integrity is more complicated and depends on the ability of the airborne monitors to detect airborne receiver or navigation processor failures without an independent receiver/processor chain to compare to. The level of integrity achievable from a single GNSS receiver/processor chain on a low-cost UAV is an area for further research and depends heavily on the quality of the measurements output by UAV receivers.

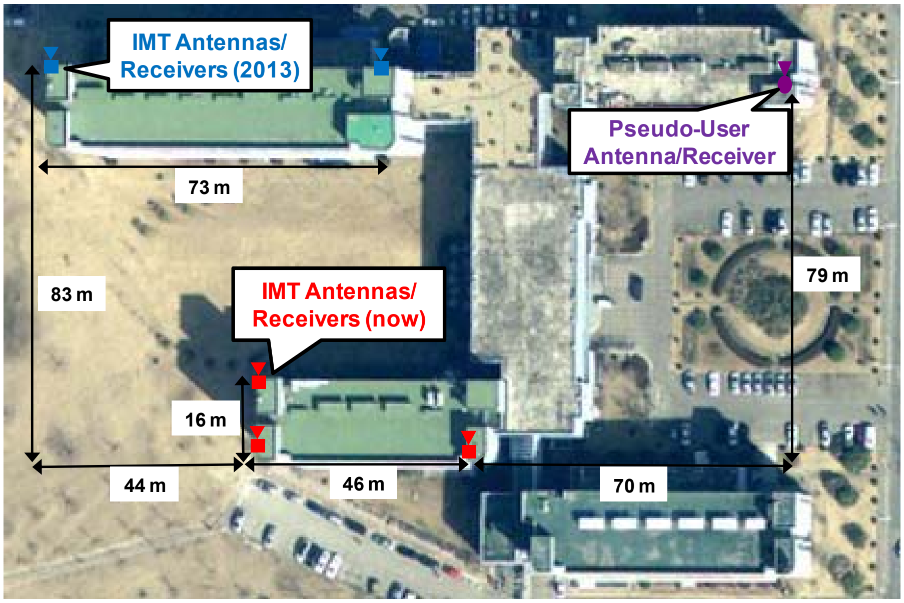

Figure 7: GBAS Integrity Monitor Testbed (IMT) at KAIST

6.0 Future Plans: KAIST Flight Tests

As explained above, the most important technical factor in the design of LADGNSS for UAV networks is the fact that the performance of UAV receivers and antennas is likely to dominate the overall system. Understanding the limitations of current UAV equipment under different operating environments (e.g., near the ground vs. at relatively high altitude) is thus critical to making detailed trade-off decisions in both the ground and airborne subsystems.

To acquire this information and refine the LD-UAV architecture proposed here, a series of UAV flight tests in cooperation with the Unmanned Systems Research Group at KAIST will begin later this year. These flight tests will be supported by both the existing commercial LDGPS equipment shown in Figure 2 and the GBAS prototype known as the KAIST Integrity Monitor Testbed (IMT), which is an upgraded and modernized dual-frequency (L1/L2) version of the original IMT developed at Stanford University from 1998 – 2005. Figure 7 shows the location of the KAIST IMT reference receivers within the KAIST campus. The three existing reference receiver antennas (shown in red) are relatively close together and represent a configuration that will be typical of LD-UAV. The two reference receiver antennas shown in blue (which have been fielded and are awaiting network connections to the existing system) are on a separate building and have larger separations more representative of GBAS. A pseudo-user receiver, to be used like the remote receivers in Figure 5, is also included (antenna location shown in purple) on a third building.

The KAIST IMT is located near the center of campus and has many areas with different terrain that suitable for UAV test flights within 1 km of the buildings shown in Figure 7. In addition, the KAIST Unmanned Systems Research Group has a variety of UAVs of different sizes that can be evaluated. As noted earlier, the size of the current mobile unit shown in Figure 2 prevents it from being mounted on the smallest UAVs. However, the UAVs that can carry the mobile unit include a mid-size RC model helicopter (an Align TRex 600) as well as a single-engine aircraft (a Cessna 172). Again, a key focus is to understand the error growth and changes in dynamic behavior from the manned aircraft that use GBAS and the smaller UAVs likely to be used in autonomous UAV networks.

7.0 Summary

This paper has described several applications for autonomous UAV networks guided by central controller and a concept of operations for UAV networks that combine guidance and navigation. Networks that operate within 100 km of the central controller will benefit from the increased accuracy, safety, and reliability provided by LADGNSS corrections rather than using GNSS in “standalone” mode. In these terms, GBAS currently provides the highest level of LADGNSS performance to meet the requirements of aviation precision approach, but it is both expensive (relative to commercial applications) and is tightly designed around the airport and civil aviation requirement, including very conservative interpretations of the potential hazards caused by various subsystem failures and anomalies.

This paper has proposed a simplification of GBAS called "LD-UAV" to provide high-reliability and high-integrity differential corrections to commercial UAV networks with far less cost and significantly lower complexity. One key change is the expectation that small, low-cost UAVs will suffer higher GNSS errors that will dominate the overall LADGNSS error budget and limit the benefit of reducing errors within the ground system. Therefore, the ground-system hardware and siting are greatly simplified and designed to be similar to the restricted hardware that can be mounted on UAVs. Ground-system monitoring is also reduced and simplified. The potential loss of integrity is recovered by the use of SBAS where SBAS coverage is good and by additional (but simple) monitoring on each UAV. The use of a two-way datalink to relay UAV monitor information back to the ground station provides a significant advantage over GBAS.

The LD-UAV architecture presented in this paper is not meant to be optimal for all classes of UAVs and networks. Networks operated from spacious facilities using large UAVs with planforms similar to those of existing manned aircraft, such as those operated from military bases, violate some of the assumptions used to generate LD-UAV and may thus be better off with GBAS or a hybrid between GBAS and LD-UAV. In addition, LD-UAV needs further development based upon a better knowledge of the performance of GNSS receivers on small, low-cost UAVs. To support this, flight tests of several types of UAVs in different flight environments will begin at KAIST later this year.

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