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Local Differential GNSS Augmentation for Integration into Urban Air Mobility †

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Abstract: This paper describes a concept for local GNSS (Global Navigation Satellite System) augmentation derived from the established Ground Based Augmentation System (GBAS) in civil aviation. The aim of this concept is to provide reliable and accurate GNSS measurements for integration into a redundant, safe and reliable integrated navigation architecture tailored to serve Urban Air Mobility (UAM). The proposed concept for local GNSS augmentation addresses the specific challenges of UAM, in particular for take-off and landing operations, and ensures safe separation between UAM vehicles en route between vertiports. By using less expensive hardware compared to the traditional GBAS, the concept aims to make the integration into future urban airspace easier and more cost-effective, both in terms of ground infrastructure demands and on-board navigation hardware. In addition to the high-level system concept and considerations, we present an initial nominal performance assessment of local augmentation using lower-cost airborne and ground hardware. This assessment is based on actual UAV (Unmanned Aerial Vehicle) flight trials conducted in different urban scenarios, as well as long-term rooftop measurements.

Keywords: urban air mobility; GNSS; navigation; local augmentation; GBAS

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1. Introduction

Urban Air Mobility (UAM) has emerged as a promising solution to the growing demand for efficient and sustainable transport in densely populated urban areas. Especially using electric vertical take-off and landing (eVTOL) vehicles, UAM offers the potential to reduce traffic congestion and commute times while minimising the environmental impact associated with traditional ground transport. Despite the many benefits, the implementation of UAM presents several challenges that must be overcome to ensure safe and effective operations. These challenges include ensuring safe, reliable and accurate navigation in complex urban environments, seamless integration with existing air traffic management systems and the development of necessary infrastructure, such as vertiports [1].

In recent years, significant developments have been made to address these challenges. Advances in GNSS (Global Navigation Satellite System) augmentation, sensor fusion and other navigation technologies have contributed to enhancing the accuracy and reliability of UAM navigation systems. In the ongoing DLR (German Aerospace Center) projects, safe and reliable navigation, also considering cyber–physical threats, is one of the researched aspects [2].

Even though it is not considered a stand-alone solution for the challenge of reliable navigation in UAM, especially for the critical phases of flight, such as during take-off and landing within densely populated areas, the GNSS is still one of the cornerstones of future solutions. While not providing the required accuracy for safety-critical operations in urban centres on its own, the idea of using local differential augmentation inspired by the Ground Based Augmentation System (GBAS) used in classical aviation for precision approach guidance has been around for at least a decade [3]. Over the years, a variety of studies researched the implications of the new environment, hardware, operational aspects and constraints, and developed accordingly, adapting its means to ensure system integrity [4,5].

In this research, we build upon this foundation and present an approach to local augmentation aimed at integration into urban air mobility. We discuss the integration of ground infrastructure and ground-based monitoring systems to improve the accuracy and reliability of the GNSS in densely populated regions. This work also explores the airborne integration of the developed solution into a multi-sensor approach, exploiting sensor redundancy and enhancing navigational accuracy and integrity. We conclude with the results of initial flight tests using a simplified version of the Urban GBAS (U-GBAS) hardware which has shown promising results, providing nominal performance in urban environments and successfully integrating noise and multipath propagation models.

2. System Concept

2.1. Overall Concept

The core idea of the suggested urban augmentation system (U-GBAS) is a network of local reference receivers located mainly at vertiports within an urban area. It is logical for the main driver of such a system to ensure safe and reliable operations, especially for passenger flights (air taxis), placing references at the locations where the strictest requirements are placed upon the operation (take-off/landing).

Equipping each of the vertiports within an urban area with a U-GBAS reference would create a network spanning over an urban or metropolitan area, typically up to the size of tens of kilometres. The core service volume of the system would be defined by a polygon spanned by the reference locations, and thus by the vertiports. Within this service volume, many integrity aspects would be covered/supported by the ground network. Only when leaving this volume, additional onboard monitoring would be required and either availability or provided accuracy would be reduced. Figure 1 shows an exemplary scenario how such a network could look like and evolve over time for the city of Hamburg, Germany. These scenario simulations were performed in the work of Niklaß et al. [6].

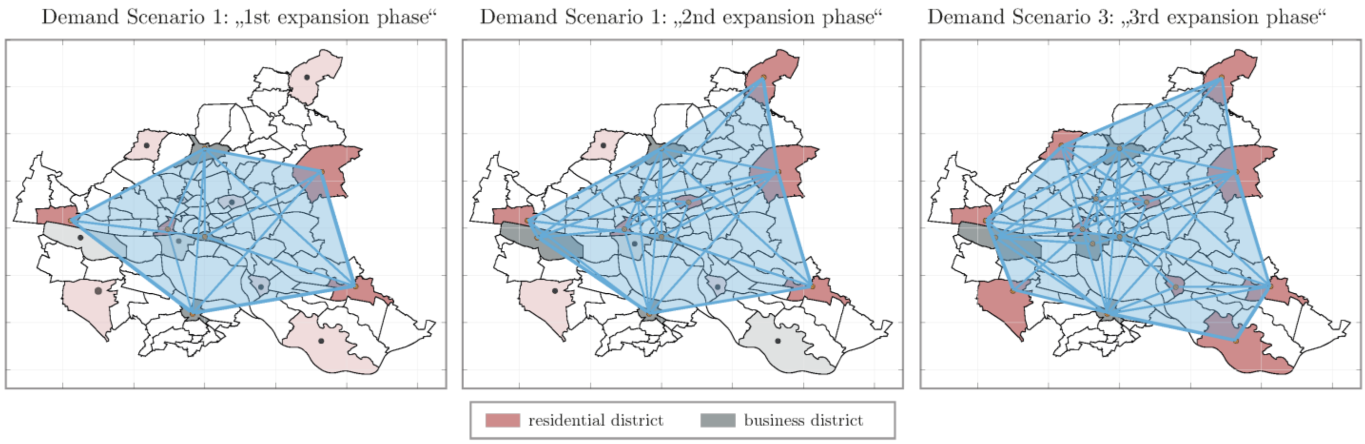


Figure 1. Assumed initial vertiport locations (black dots) for city of Hamburg based on a demand simulation. Figure adapted from [6]. The core service volume covered by the system is shaded in blue for each of the scenarios.

At the same time, it can be assumed that most passenger traffic that would occur between vertiports in the same metropolitan area would automatically happen within the core service volume. Outside, traffic can be assumed to be less dense, potentially in higher altitudes and, therefore, less demanding in terms of accuracy and separation between vehicles. Thus, operational demand would match very well with the system's performance.

2.2. Ground Infrastructure

In terms of ground infrastructure, the proposed system differs significantly from what we know from classical GBAS [7]. GBAS, as a stand-alone system that has to cover all potential threats and faults with a single, self-sufficient installation at an airport, relies on particular, very expensive antennas installed in open-sky environments as well as on receivers.

Both from a siting and a financial perspective, such hardware, in the range of several hundred thousand Euros, is unfavourable for the deployment of larger numbers within a U-GBAS network. Thus, we envision the use of smaller and cheaper hardware, especially in terms of antennas, while still covering all relevant civil frequency bands and multiple constellations to make full use of geometry diversity, especially in areas where parts of the sky are obstructed.

While this comes, of course, at the cost of nominal performance, we envision the primary mode of operation to be an integral part of an onboard multi-sensor navigation and integrity system (see also Figure 2 in Section 2.5). While technically being able to provide stand-alone integrity, the U-GBAS would typically augment the GNSS measurements used in a sensor fusion system. Depending on the instantaneous demands, the user could decide what systems to use to meet the current requirements in terms of accuracy while maintaining a continuous operation.

2.3. Integrity Monitoring

For brevity in the scope of this paper, in this section, we focus on integrity monitoring aspects that are particularly different from the classical GBAS in the envisioned urban system. The different conditions under which the proposed U-GBAS must operate, compared to the classical GBAS, pose new challenges but also provide freedom for new solutions. On one side, certain monitoring cannot be implemented with the foreseen lower-cost hardware in less optimal siting conditions. On the other hand, the aspect of a regional network of connected receivers covering an area of several kilometres opens up new possibilities to compensate for the typically lower-quality observations provided by the individual reference receivers.

2.3.1. Ionosphere

Monitoring for ionospheric threats in currently operational classical GBASs is limited to the use of L1 signals. Thus, either extensive computations to exclude potentially dangerous geometries [8] or precise carrier-phase-based monitoring within the ground station are required to mitigate ionospheric errors [9]. Both approaches are hardly applicable to the envisioned urban augmentation.

Recently we proposed a new airborne monitoring approach for the traditional GBAS that leverages the use of a second frequency to assess the ionospheric threat at the user side [10], deriving ionospheric protection levels based on the used satellite geometry. This approach is currently under consideration for future dual-frequency GBAS in classical aviation [11,12] but also for use within augmentation systems in the context of urban air mobility [13].

When applied to urban air mobility, and especially in a scenario with a network of ground reference stations at vertiports, additional benefits can be leveraged. With a variety of baselines between stations, ionospheric disturbances and gradients observable within the service volume can be identified by monitoring in the ground stations and potentially harmful satellites can be excluded from use.

2.3.2. Ephemeris

In a similar manner to ionospheric monitoring, mitigating the threat of ephemeris errors becomes significantly easier when measurements from multiple receivers spread over an area can be utilized. Thus, a proposed network of receivers spread over tens of kilometres in an urban area allows for the monitoring of according threats within the serviced area based on differential code measurements. An according methodology has recently been presented, also deriving an associated user-specific ephemeris protection level [13].

2.3.3. Interference

With a network of receivers within the service area, the option to monitor for intentional and unintentional interference with the GNSS signals can also be leveraged. Especially in dense urban areas, it is much more likely to experience interference events for a variety of reasons, be it hardware malfunctions, intentional disturbance of operations or side-effects of the use of personal privacy devices. With receivers close to vertiports, and thus within the city at least to some extent, monitoring can be implemented to warn UAM users and locate an interference source within a few kilometres.

While the use of array receivers would allow us to go even one step further and identify the origin of an interference to potentially counteract [14]. Even with conventional single-element antennas, whenever an interference is detected on the ground a warning can be issued to vehicles in the surrounding airspace or planning to land at the affected vertiport. Thereby, air traffic management can react to such disturbances earlier and re-route traffic to avoid critical situations.

2.3.4. Other Threats

Aside from the previously described threat-monitoring approaches that require a totally new approach compared to classical GBAS when transferring the system into the urban environment, further signal-in-space threats require monitoring. Among those are, for example, cycle slips during tracking, which are especially likely to happen on the airborne side when operating under severe multipath conditions. Additionally, code-carrier divergence, excessive acceleration and ground station multipath have to be monitored. Given the space limitations, we will not go into detail here but a good overview can be found in the literature, for example by Pullen et al. [3].

2.4. Data Link

In the classical GBAS, a one-directional VHF-Uplink with very limited capacity (max ~1.7 kB per second) is used to uplink local corrections and integrity parameters to airborne users. In the context of urban air mobility, providing a higher data-rate, as well as sufficient security, is a crucial aspect. To partially compensate for the degraded performance of received signals, as well as potentially blocked signals due to urban obstacles, the uplink should provide corrections for all major GNSS constellations, maximizing the diversity of usable satellite geometries. Thus, the uplink needs to support up to 50 satellites provided with corrections for at least two frequencies. Additionally, to further improve performance in urban scenarios, the provision of corrections for multiple code-carrier smoothing time constants is foreseen. Especially for low-elevation satellites, shorter-filter time constants, and therefore shorter waiting periods before a satellite can be used, are favorable. For high-elevation satellites on the other hand, long time constants minimize residual noise and multipath. With currently three foreseen time constants between 20 s and 200 s to be provided with corrections, the total data rate increases by a factor of two to three.

The currently planned solution within our developments is a C-Band data link [15]. Broadcast messages are utilized to provide all necessary information to operating UAVs in fixed and rotating fields. To ensure system integrity on all levels, these broadcast messages are authenticated using the Timed Efficient Stream Loss-tolerant Authentication (TESLA) protocol. The suitability of this method, especially with regard to latency and throughput, has already been demonstrated in real-time during flight tests [16,17]. An additional downlink channel is considered to allow further integrity monitoring.

2.5. Airborne Integration

As previously outlined, the core concept revolves around integrating a multi-sensor onboard system, which may include an Inertial Navigation System (INS), barometric sensors, cameras (especially for take-off and landing) and other sensors tailored to the vehicle's specific needs and operational requirements, such as Lidar for night operations. The primary mode of operation would be a tight integration with an INS, providing corrected ranges together with integrity information. This aims towards a sensor fusion approach, an integrated integrity concept [18] and a risk-sharing methodology across different subsystems. Additionally, the design would also allow for loose coupling, which facilitates the provision of a U-GBAS position with integrity information to the sensor fusion.

Furthermore, when the instantaneous accuracy is sufficient, a standalone U-GBAS position can provide vertical and horizontal protection levels comparable to the (anticipated) positioning services within the classical GBAS [19]. A high-level overview of the interaction between ground and airborne subsystems, as well as the onboard integration, is given in Figure 2.

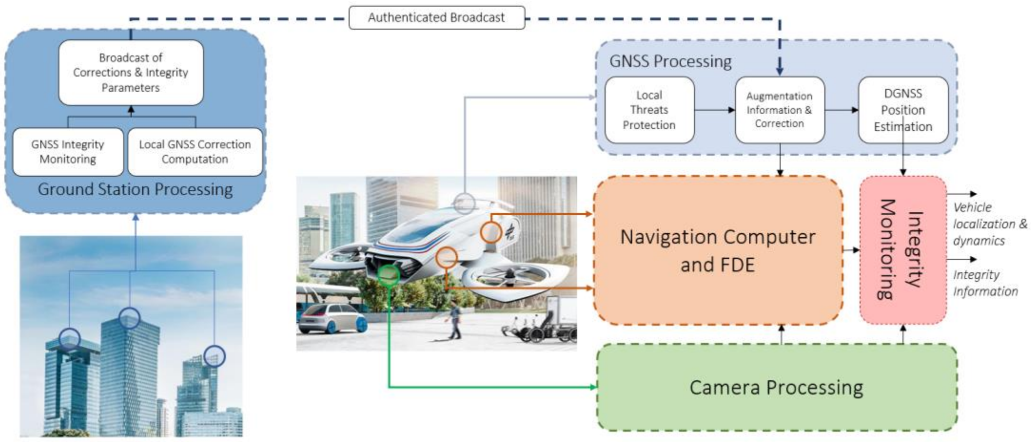
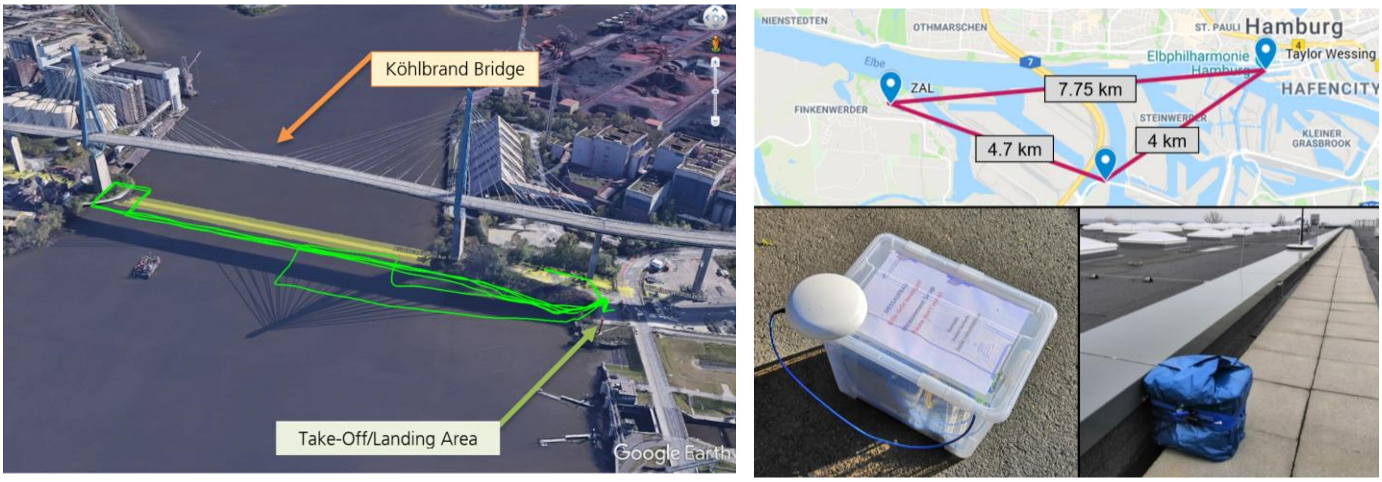


Figure 2. High-level system overview of the integration of the U-GBAS on ground within a multi-sensory onboard unit providing positioning as well as integrity information to the flight control system as well as air traffic management.

3. Experimental Results and Discussion

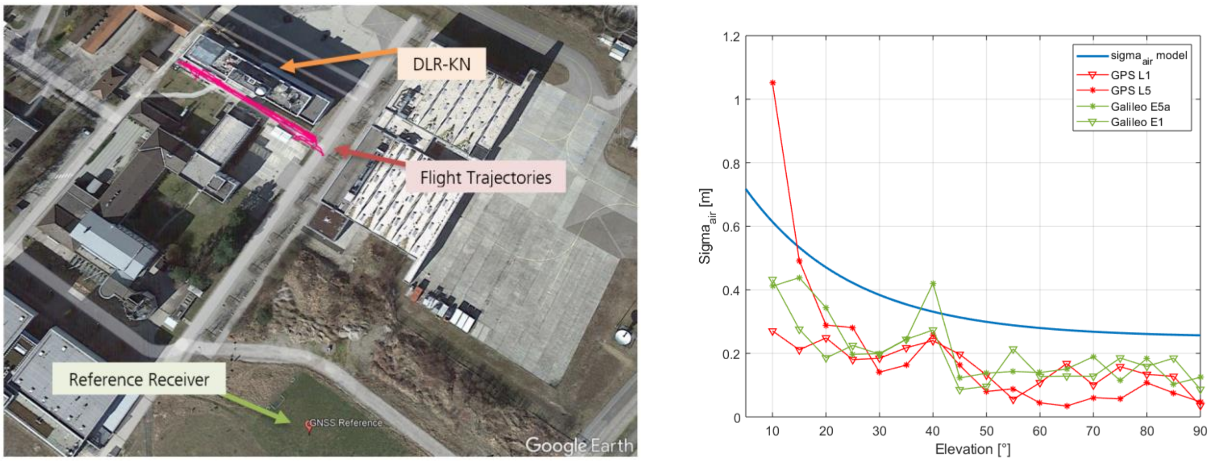
In this section, we give a brief overview of flight experiments conducted for initial, post-processing validations of the described concept. From multiple tests and experiments carried out in the course of two DLR internal projects, we focus on two scenarios. In 2019, flights were conducted in the city of Hamburg, in northern Germany. A detailed description of the flights can be found in [20]. Herein, we focus on the aspects of U-GBAS navigation. The trajectories flown by our drone during the tests are depicted in Figure 3a. All flights were below the street level of the bridge, some of them partially under the bridge as well as very close to the western bridge pier. During the campaign, three mobile GNSS reference stations were distributed across the city of Hamburg, two of them on rooftops and a third close to the take-off/landing area next to the bridge. Figure 3b shows one of the receivers installed on rooftops, about 4–5 km away from the area where the flights were conducted. In this campaign, no real-time processing took place, but all the data were collected and used afterwards in post-processing.

In the second scenario, flights were conducted on the DLR campus in Oberpfaffenhofen, near Munich. The flight paths for these flights are shown in Figure 4a. At different heights, several flights were carried out along the façade of an office building, which represents a particularly challenging scenario in terms of signal blockage and multipath errors. In this case, a single portable local reference receiver of a similar type was placed nearby (~100 m) in a grass field, thus representing a best-case scenario in terms of local corrections.



(a) (b)

Figure 3. Flight trials in the city of Hamburg: (**a**) trajectory of the four flights conducted next to and below the bridge; (**b**) one of the three portable reference stations distributed across the city as shown in the map.

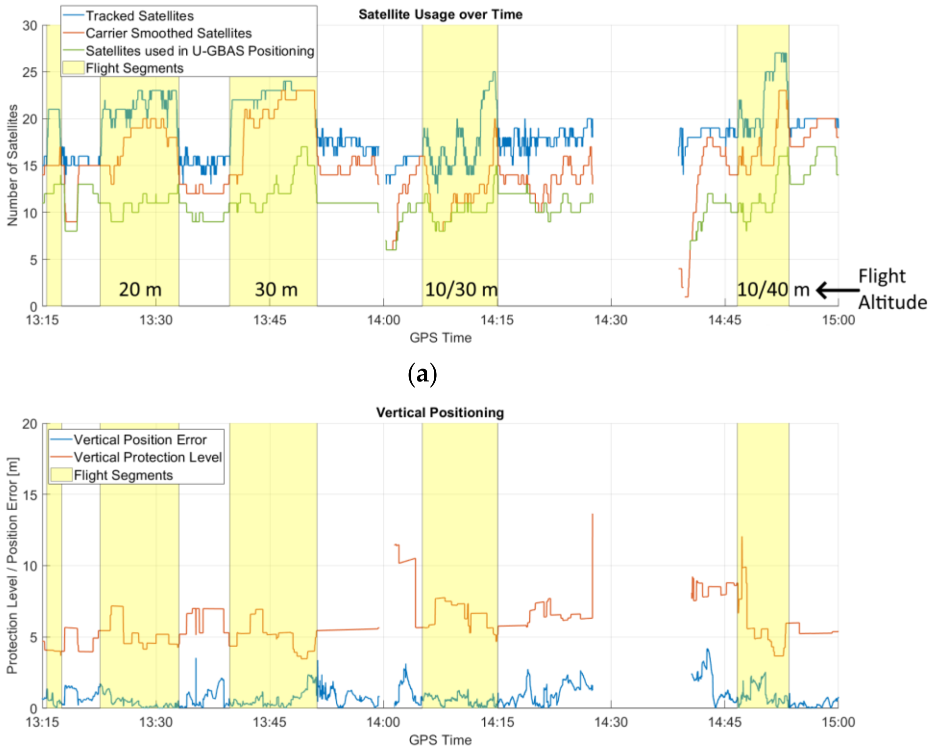


(a) (b)

Figure 4. (**a**) Flight trajectories conducted in different heights (10–40 m) between two office buildings at the DLR campus Oberpfaffenhofen; (**b**) derived preliminary model for residual airborne noise and multipath (σ_{air}) for 100 s code-carrier smoothing derived from around 4 h of GNSS measurements from the drone (blue) as well as measured residual errors over elevation for GPS and Galileo.

Based on the flights (conducted with a DJI Spreading Wings S900 frame, DJI Ltd., Shenzhen, China as well as a Tallysman TW3972 antenna, Tallysman Wireless Inc., Ottawa, Canada) described here, we derived initial airborne noise and multipath models, as illustrated in Figure 4b. The measured residual noise and multipath errors considering 100 s code-carrier smoothing are shown in red and green for GPS and Galileo in the plot. Due to the limited number of samples, the differences between the constellations and the frequencies can be seen to be rather insignificant. Especially the expected lower multipath on L5/E5a, due to the different signal modulation/higher bandwidth, is only visible over parts of the satellite elevation. Thus, for initial evaluations, a uniform, in most cases conservative model was therefore fitted to the data.

Even though our final goal is an integrated solution in which augmented GNSS is on piece to enable a robust, accurate and reliable means of navigation during all phases of flight in UAM, we also want to present preliminary results of the stand-alone U-GBAS for the scenario conducted in the urban canyon between office buildings. Figure 5a shows the number of tracked and used satellites during the different flights. Typically, 15–25 satellites were tracked, of which 8 to 17 could be used during the flights. In Figure 5b, the achieved position errors (based on RTK-post-processing), as well as nominal (H0) protection levels in the vertical domain, are presented.



(**a**)

(**b**)

Figure 5. Results of flights between office buildings. (**a**) Satellite tracking and usage statistics during flights and on the ground; (**b**) achieved nominal (H0) protection level using a close-by reference station. Protection levels are derived for an L1/E1 100 s smoothing processing mode using GPS, Galileo and the nominal airborne noise model shown in Figure 4b.

During flights, even in deep urban scenarios with rather limited satellite visibilities, errors typically stayed below 2.5 m, and for most of the higher flights even below 1 m. As expected, the largest errors were seen when the drone was static on the ground. Nominal protection levels typically ranged from 4 to 8 m, bounding the errors during flight.

Finally, for the flights along the bridge in Hamburg, we want to give a first idea regarding the suitability of the corrected ranges for integration with, e.g., an INS within a navigation filter. In Figure 6, we show the root mean squared error over approximately 90 min of flights and separated for individual tracked satellites during that time period. As expected, the errors for stand-alone GNSS measurements reach up to several meters, largely depending especially on the satellite elevation. After applying local corrections, those errors typically drop to less than half a meter. Worth noting is that this also applies to shorter code-carrier smoothing times, where only the residual noise is larger. While for the provision of a stand-alone U-GBAS position smoothing is necessary, potentially shrinking the number of usable satellites due to obstructions and cycle slips, in case of an integrated solution with subsequent filtering in an integrated GNSS/INS filter, this allows for potentially more usable satellite and ultimately even better performance under such challenging conditions.

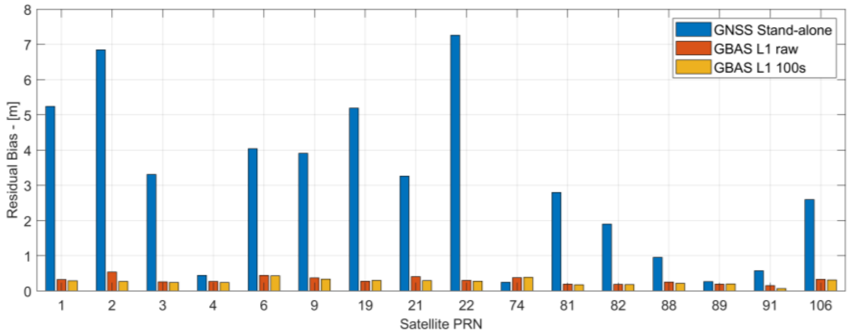


Figure 6. RMS error (bias) on ranges after application of corrections for the flight conducted in Hamburg.

4. Conclusions and Outlook

Based on the concept of classical Ground Based Augmentation Systems and incorporating recent advancements, we developed and presented a U-GBAS concept for local GNSS augmentation tailored to Urban Air Mobility. The cornerstone of this concept lies in its integration with other navigation methods, yielding a multisensory solution that includes integrity information, thereby enhancing reliability and precision. In preliminary flight trials, we assessed the nominal performance of this concept using representative hardware and obtained promising initial results. Notably, these trials were conducted in realistic urban scenarios involving flights near and between office buildings and near a major bridge in the city of Hamburg.

This research lays the foundation for further developments and enhancements of UAM navigation systems with applications beyond the urban domain. Initial real-time demonstrations are underway using an internally developed TESLA-authenticated transmission of local corrections and integrity parameters to the drones. Theoretical developments towards the ultimate goal of integration with INS, camera, barometer and possibly other sensors in a comprehensive integrity concept are underway.

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