Paper
Int'l J. of Aeronautical & Space Sci. 18(3), 545–554 (2017)
DOI: http://dx.doi.org/10.5139/IJASS.2017.18.3.545

IJASS
International Journal of Aeronautical and Space Sciences

Navigation Augmentation in Urban Area by HALE UAV with Onboard Pseudolite during Multi-Purpose Missions

O-Jong Kim*, Sunkyoung Yu*, Heekwon No, Changdon Kee*****

Mechanical and Aerospace Engineering and SNU-IAMD, Seoul National University, Seoul 08826, Republic of Korea

Minwoo Choi****

Republic of Korea Air Force, Gyeryong 32800, Republic of Korea

Hyojeong Seok*****

Unmmaned Vehicle Advanced Research Center, Korea Aerospace Research Institute, Daejeon 34133, Republic of Korea

Donghwan Yoon*****

Telecommunications Technology Association, Seongnam 13591, Republic of Korea

Byungwoon Park******

Mechanical and Aerospace Engineering, Sejong University, Seoul 05006, Republic of Korea

Cheolkyu Jee*******

Agency for Defense Development, Daejeon 34060, Republic of Korea

Abstract

Among various applications of the High Altitude Long Endurance (HALE) Unmanned Aerial Vehicle (UAV), this paper has a focus on the Global Positioning System (GPS) utilizing pseudolite and its improved performance, particularly during the multi-purpose missions. In a multi-purpose mission, the HALE UAV follows a specified flight trajectory for both navigation applications and missions. Some of the representative HALE missions are remote exploration, surveillance, reconnaissance, and communication relay. During these operations, the HALE UAV can also be an additional positioning signal source as it broadcast signals using pseudolite. The pseudolite signal can improve the availability, accuracy, and reliability of the GPS particularly in areas with poor signal reception, such as shadowed regions between tall buildings. The improvement in performance of navigation is validated through simulations of multi-purpose missions of the solar-powered HALE UAV in an urban canyon. The simulation includes UAV trajectory generation at stratosphere and uses actual geographical building data. The results indicate that the pseudolite-equipped HALE UAV has the potential to enhance the performance of the satellite navigation system in navigationally degraded regions even during multi-purpose operations.

Key words: HALE UAV, navigation augmentation, pseudolite

1. Introduction

There has been increased interest in utilizing the Unmanned Aerial Vehicle (UAV) for High Altitude Long Endurance (HALE) missions. The general operation environment of the HALE UAV is in the stratosphere, which is

* Ph. D Candidate
** Postdoctoral Researcher
*** Professor, Corresponding author: kee@snu.ac.kr
**** Major
***** Researcher
****** Assistant Professor
******* Principal Researcher

Received: March 30, 2015 Revised: September 9, 2017 Accepted: September 26, 2017

http://ijass.org pISSN: 2093-274x eISSN: 2093-2480

approximately 12-50km in altitude and thermodynamically stable compared to the troposphere. The advantages of the HALE UAV over satellite observations include its capability of long-term operations over a concerned area, operational adaptability, lower probability of communication loss, and easier maintenance. In contrast, when it is compared to conventional manned aircrafts, it provides wider coverage and longer endurance. Therefore, it is expected that the HALE UAV can be utilized as a new platform that may operate individually or in coordinated fleets with other platforms in various civil and military applications.

The high expectations of the HALE UAV as a new platform have led development of various aircraft to evaluate the extent of its practical use. The best-known solar-powered HALE UAVs are Helios [1] and Zephyr [2]. In contrast, Global Observer [4] and Phantom Eye [5] are HALE UAVs using the liquid hydrogen-powered system. For military applications, Global hawk, which is already in service for surveillance, is also classified as HALE UAV [6]. Some development efforts have been conducted in Republic of Korea as well. The destination of the initial phase of Korean HALE UAV development is a 50m-class unmanned airship with a target altitude of 20km [7]. Up to this point, the solar-powered gliders, such as Helios and Zephyr, have been the main stream of the studies. The achievement of the studies include the preliminary design optimization for the wing of the solar-HALE aircraft [8] and computational and empirical analyses of the HALE UAV's aerodynamic performance [9].

The HALE UAV has a vast extent of application. It can be utilized for surveillance, reconnaissance, remote exploration, communication relay, recovery support for a disaster, navigation augmentation, and many other missions. Among these applications, this paper focuses on the navigation using the HALE UAV with pseudolite.

From a navigational point of view, the pseudolite can be used to broadcast signals, which are similar to that of the Global Positioning System (GPS) satellite, to enhance navigation performance by providing increased accuracy, integrity, and availability [10, 11]. Various studies have shown that an onboard pseudolite of the HALE UAV improves the level of navigation performance. In Europe, preliminary studies utilizing stratospheric platforms as aerial transponders for the Aerial-Based Augmentation System (ABAS) and providing the differential services of GPS and Galileo were performed [12]. The HALE platform with onboard pseudolite reduced the spatial limitations of the local area differential GPS. The stratolite (stratospheric pseudo-satellite) concept for the Galileo navigation system was considered as the local differential system [13]. Pseudolite in a UAV with an altitude of 20km was considered, and the feasibility and expected advantages of this platform were discussed in terms of Dilution of Precision (DOP) and integrity.

Japan Aerospace Exploitation Agency (JAXA) proposed a pseudolite-equipped HALE platform that employs unmanned airships or airplanes to improve the availability, accuracy, and integrity of the GPS-based positioning system [14]. JAXA's studies included both the simulations and experiments. For the simulations, it was assumed that the HALE airship was equipped with the pseudolite and maintained a position over the Tokyo metropolitan area. The Geometrical DOP, which uses the pseudolite in the airship platform, was compared with the GPS case and GPS/GLONASS case. For the feasibility study of this system, the experiments using the helicopter with onboard pseudolite were performed, and the results confirmed a significant improvement in navigation performance. Another study in Japan presented the carrier phase-based inverted-pseudolite concept, which could accurately calculate the position of the pseudolite. This study validated this idea with down-scaled experiments [15].

In the United States, the HALE pseudolite concept was proposed for military applications, such as the interference mitigation of GPS [16]. Some HALE UAVs carry space-time adaptive processor of beam-formers using a GPS antenna array for robust self-navigation. In this concept, the pseudolite transmits strong encoded navigation signals to users, and receivers can reduce the GPS signal interference, ultimately resulting in robust navigation.

The previous studies of the pseudolite-equipped HALE UAV platform have been under the premise that the HALE UAV's sole purpose is navigation. However, to improve the cost-effectiveness of the HALE UAV platform operations, the HALE UAV needs to perform multiple missions simultaneously. In light of this fact, this paper investigates the improved navigation performance during multi-purpose missions. In this study, the multi-purpose mission is defined as a mission where the HALE UAV has a trajectory that is optimized for some purposes other than navigational application. The environmental observations and forest fire alarm detection can be the example of these purposes. Throughout any combination of the flight path, the HALE UAV continuously transmits the pseudolite signal.

The investigation of this study mainly stands on simulation-based analyses that give results close to the actual performance based on real data, such as surveyed building information in the concerned urban area, wind data over the Korean peninsula, and constellation of GPS satellites. The urban canyon area of the simulations is Teheran Street, Seoul, one of the thickest forests of skyscrapers in Korea.

DOI: http://dx.doi.org/10.5139/IJASS.2017.18.3.545

Another important feature for the simulations is the flight characteristics of the HALE UAV. The conventional HALE UAV experiences altitude variation due to climbing and gliding in diel cycle. In addition, the HALE UAV flies at a relatively low speed, which is approximately the same order as the wind speed. Therefore, the impact of the wind is substantial.

The primary analysis of this study is on the simulations for four cases: three scenarios and a GPS-only case. The first and second scenarios employ one and two HALE UAVs, respectively. The trajectory of these cases is around Seoul, Korea, via mountains and rivers. In contrast, the third scenario is composed to maximize pseudolite visibility as the HALE UAV flies over the urban area of interest. In each case, the enhanced positioning availability and DOPs in the urban canyon are surveyed and compared.

This study begins with an introduction to the HALE UAV and details its unique features. Next, the simulation environments and flight scenarios are described. Lastly, the simulation results and discussions conclude this paper.

The preliminary elements of the multi-purpose operation of the HALE UAV has been briefly introduced by the authors at the international conference [17]. This paper enhances the previous research with a more in-depth analysis using more plausible simulation scenarios under various environments.

2. HALE UAV

2.1 HALE UAV Configuration

The HALE UAV can be classified into two groups according to the power source: the liquid-hydrogen type such as Global Observer and Phantom Eye, and solar-powered type such as Zephyr and Helios. This study employs the Zephyr-type solar-powered HALE UAV. The Zephyr-type HALE UAV is a glider type aircraft, which carries lighter payloads but yields much longer endurance compared to the other types. The aircraft configuration used in this paper is the design result of Ref. 18: the wing span of 30m, aspect ratio of 25, and the weight of 160kg. The trajectories of this study are generated as presented in Ref. 19, which describes the flight strategy to optimize energy balance, and Ref. 18. Some values, including velocity, stall speed, and altitude change of the HALE UAV, are set according to the given values of these references.

2.2 Altitude Cycle of HALE UAV

In order to achieve a long endurance, the power of the HALE UAV is supplied using solar cells. Therefore, the altitude cycle of this kind of aircraft has a period of a day. Once a full-charge of the battery during the daytime, it is recommended that the extra energy is stored in the form of potential energy by climbing. This is because the payload of the glider type HALE UAV is limited, resulting in a limited capacity of the battery. The stored potential energy is consumed when gliding [19]. The altitude of the simulations varies between 18 km and 20 km. The recommended time schedule is described in Table 1 [19]. In addition, the altitude change according to the cycle is shown in Fig. 1.

2.3 Velocity of HALE UAV

It is expected for the HALE UAV to maintain flight as long as possible. Therefore, the proper strategy is minimizing energy consumption by flying the aircraft at its minimum allowable speed, which is slightly greater than the stall speed. The minimum speed is set to be 1.2 times the stall speed, and the stall speed is calculated as a function of the aircraft configuration and the operating altitude [18]. Therefore, the simulations employ the specified minimum speed depending on the altitude as described in Fig. 2, where speed is calculated in terms of altitude following the result of Ref. 18. The primary attention of the simulation is on the speed at altitude between 18 and 20 km.

2.4 Pseudolite in HALE UAV

This study assumes that one of the payloads of the HALE UAV is the pseudolite. The pseudolite provides additional positioning and message data as it broadcasts the GPS-like signal. The quality of the signal and the contents of messages have no direct impact on the results of the simulations because this study primarily investigates positioning availability and DOP values. However, it is assumed here that

Table 1. Altitude cycle time [19]

Operation	Local Time (hr)
Climbing Start	14.38
Cruising Start (at 20km altitude)	16.74
Gliding Start	17.64
Cruising Start (at 18km altitude)	20.76

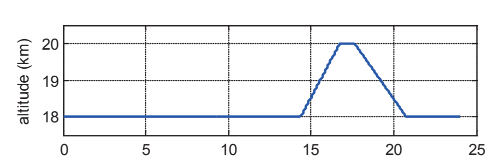

Fig. 1. Altitude cycle with the period of a day (24hrs)

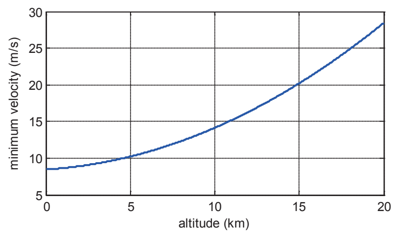

Fig. 2. Minimum speed by altitude

the GPS and pseudolite are sufficiently time-synchronized and have similar signal qualities. The message contents will act as future guidelines for the implementation. In the meantime, it is reasonable to operate similarly with that of the Satellite Based Augmentation System (SBAS), such as Wide Area Augmentation System, using the GPS frequencies.

As the SBAS is generally a geostationary satellite-based system, it has a relatively low elevation angle in middle latitude regions, where Seoul, Korea resides. In Seoul, the elevation angle of the geostationary satellite along the same longitude is calculated to be approximately 45 degrees. This elevation angle can be easily blocked by buildings in an urban area. Therefore, in this environment, the HALE UAV-based augmentation system can be one of the most promising alternatives that enhance the availability, accuracy and reliability for GPS users in an urban area.

3. Simulation Environments

3.1 Simulation Area

Figure 3 shows the Google Map of the geometrical boundary for the simulation to evaluate navigation performance. The area is the vicinity of Teheran Street, which is the southeast of Seoul. This boundary provides an excellent example of urban canyon as it consists of a thick forest of skyscrapers. It is often used as a GNSS receiver testbed in Korea because it is notoriously bad for satellite visibility. For the simulations, the grid points are set on the Teheran Street in 15-meter intervals: a total of 713 grid points are used.

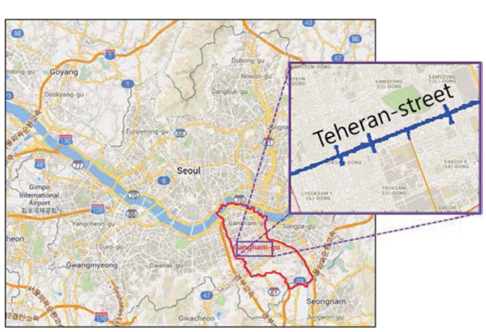

Fig. 3. The simulation boundary, the vicinity of Teheran Street in Seoul

The simulation utilizes all the available building information in the boundary to check if GPS satellites and the HALE UAVs are visible. The building data, which includes the positions and shapes of all buildings, are provided by the V-world of the Ministry of Land, Infrastructure and Transport of South Korea. As of 2014, there are 41,498 buildings in the simulation boundary.

The building data from the V-world contains detailed shapes of the buildings. However, the raw data is less useful because the shapes are exceedingly complex for the purpose of the simulation. Therefore, this study simplifies the building shapes as shown in Fig 4, and the simplified shapes are used in visibility check at each grid point. In the Line of Sight (LOS) visibility analysis, the elevation and azimuth angles of the four upper corners of each building are compared to the angles of the satellites and UAVs.

3.2 Wind Speed over Korea

Another important aspect that must be considered for the flight trajectory of the HALE UAV is the impact of wind in the troposphere [18, 20]. The glider-type HALE UAV flies at a relatively low speed in order to minimize energy consumption, because its power available is very limited. As a result, the effects of wind cannot be simply neglected. Although the wind is weak in the stratosphere of roughly 20km in altitude, it can affect the flight significantly, as the speed of the HALE UAV is the same order as the wind speed.

The trajectory of the UAV in simulation reflects the wind speed data. The wind speed is formulated using the data that has been accumulated from 2000 to 2012 over the Korean peninsula by the National Institute of Meteorological Research of Korea Meteorological Administration. The data includes the minimum, maximum, and average wind speeds by altitude during four different seasons. The simulation employs the wind speed data in forms of Gaussian distribution model with random effects within its standard deviations.

The overall averaged wind speeds of the year within one-sigma boundary are shown in Fig. 5. It indicates that the west

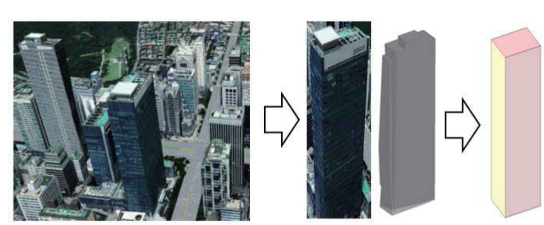

Fig. 4. Simplification process of building data

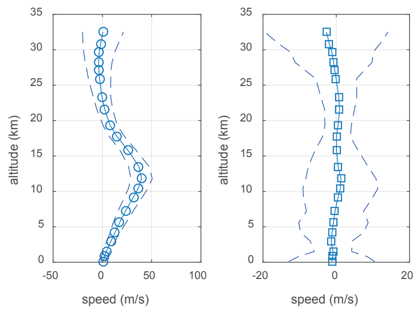

Fig. 5. Average wind speed with one-sigma boundary (Left: west wind, Right: south wind)

wind primarily affects the average speed, and the wind in the stratosphere is more stable than that of the troposphere.

3.3 GPS and HALE UAV Trajectories for Simulations

In this study, 24 hours of simulations are mainly concerned. For the GPS constellation, almanac data are considered to generate the GPS orbit in UTC 00:00 - 24:00 (20-July-2014) with an interval of 15 minutes. The trajectory of the HALE UAV is calculated using the simplified altitude, velocity, and kinematic models. The vertical component of the trajectory is set according to the change in altitude as shown in Fig. 1, and the horizontal movement of the HALE UAV is calculated using Eq. (1) from Ref. 20. The simplified models are sufficient for the purpose of this study, which is to investigate the navigation performance not to design a precise trajectory using accurate flight.

$$\bar{X} = \begin{bmatrix} x \\ y \\ \psi \end{bmatrix}, \quad \dot{\bar{X}} = \begin{bmatrix} V_{UAV} \cdot \cos\psi + V_{w,x} \\ V_{UAV} \cdot \sin\psi + V_{w,y} \\ (g / V_{UAV}) \cdot \tan\phi \end{bmatrix}. \tag{1}$$

Where, V_{UAV} is the speed of the UAV, and $V_{w,x}$ and $V_{w,y}$ are the wind speeds in the x and y axis, respectively. ψ is the heading of the UAV, ϕ is the bank angle of the UAV, and g is the gravity acceleration. Eq. (1) is defined in the Cartesian coordinates where the x-axis delineates the east direction, and y-axis indicates the north direction. In Eq. (1), as a common practice in a simple trajectory analysis [20], the inertial roll rate is ignored. This means that the aircraft can instantly reach a new bank angle.

The simulation uses the guidance and control of the HALE UAV and generates trajectories to follow the multiple waypoints. The only control input of the UAV is the bank angle as the other degrees of freedom is predefined: altitude follows Fig. 1 and speed is are set as shown in Fig. 2. The bank angle is controlled to face the target waypoints within limits because the HALE UAV is not capable of rapid maneuver. The maximum allowable bank angle is conservatively set to $|\phi|<10$ *deg* for simulations.

3.4 Flight Scenarios

As described previously, this study considers the HALE UAV not only in navigation applications, but also in multi-purpose operations. As the expected missions of the HALE UAV include disaster relief and environmental observations, the trajectory may follow mountains and rivers for forest fire detection and water pollution analysis. During the mission, the aircraft broadcasts pseudolite signals as well, and the navigation performance is investigated in terms of the positioning availability and DOP for the user in the concerned area, Teheran Street. The main scenario for simulations is generated as shown in Fig. 6, where the southern region of Seoul is enclosed by the trajectory.

This study considers three scenarios as described in following sections. In each scenario, the history of flight path of the HALE UAV is generated using Fig. 1 and Eq. (1).

3.4.1 Scenario 1: Operation around the South of Seoul (One HALE UAV)

The first scenario employs a single HALE UAV that follows the trajectory shown in Fig 6. Fig. 7 shows the history of flight path in 24 hours. The gap between the simulation path and the target trajectory reflects the altitude as the viewpoint of Google Earth is tilted in 3-D. The HALE UAV completes this loop roughly 12 times in the 24-hour simulation. In

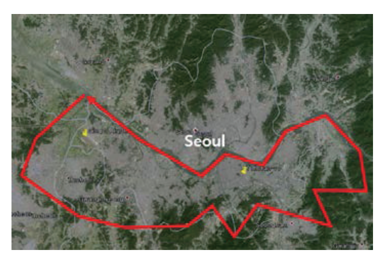

Fig. 6. The trajectory of the main scenario for multi-purpose missions

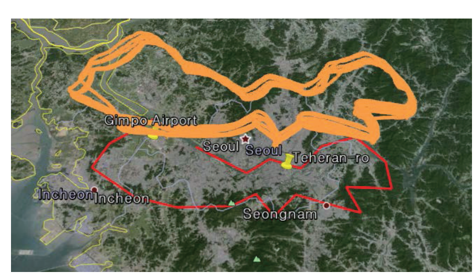

Fig. 7. Simulated flight path for Scenario 1; the gap between the target trajectory (thin red line) and flight path (thick orange line) indicates the altitude difference

this scenario, the payload consists of the equipment for fire detection, water analysis, and the pseudolite.

3.4.2 Scenario 2: Operation around the South of Seoul (Two HALE UAVs)

As the payload capacity of the HALE UAV is limited, it is plausible to employ one aircraft for each mission and divide the flight trajectory into as many sections as the number of aircraft. The second scenario utilizes the two HALE UAVs that share the operational trajectory as shown in Fig. 8. One is equipped with the payload for water analysis and pseudolite and follows a round trip trajectory along the river. The other is equipped with the payload for fire detection and pseudolite and follows a round trip path via the mountains. Both the aircraft broadcast pseudolite signals during the operations. The history of flight path in 24 hours is shown in Fig. 9.

Fig. 8. Separated trajectories of Scenario 2

Fig. 9. Simulated flight path of two HALE UAVs in Scenario 2

Fig. 10. Simulated flight trajectory for Scenario 3

3.4.3 Scenario 3: Operation over Concerned Urban Area (One HALE UAV)

The third scenario is designed to maximize the visibility of the HALE UAV for users on Teheran Street and provides a benchmark for comparison of the first and second scenarios. A single aircraft flies in a circular loop right above the concerned area for 24 hours. The history of simulated flight path at an altitude range of 18-20 km is shown in Fig. 10.

4. Simulation Results

The simulations are performed at the grid points of Teheran Street using the generated flight paths of the HALE UAVs, GPS constellation, and building information. The results of the simulation are described in two sections. The first describes the overall result for all the grid points. It compares the three scenarios in terms of the visibility of the HALE UAVs, positioning availability, and the DOP values. The second pays attention to a single grid point at the Posco-intersection and analyzes the results as a function of time. Fig. 11 shows the 713 grid points on Teheran Street and the location of the Posco-intersection on Google Map.

4.1 Simulation Results of Teheran Street

4.1.1 HALE UAV Visibility

Figure 12 compares the percentage of the LOS visible grid points of the HALE UAV by time. The visibility of 100% indicates that all of the grid points have the LOS to the HALE UAV at the given time. The visibilities of the two HALE UAVs in Scenario 2 are displayed separately: the mountain and river trajectories.

As expected, the HALE UAV in Scenario 3 yields visibility of approximately 100%. This is because the HALE UAV maintains a path directly over the grid points, and almost no signals are blocked by the buildings. Scenario 1 and Scenario 2 yields visibility of the three HALE UAVs that varies from 30

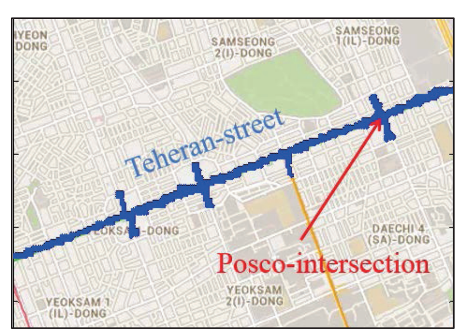

Fig. 11. Grid points for simulations

to 100%. The tendencies of the results of the two scenarios are similar because the three HALE UAVs share the same main trajectory.

4.1.2 Positioning Availability Analysis

In satellite navigation, 3-dimensional positioning is available when four or more satellites are visible. Fig. 13 presents the percentages of grid points that have a total visibility, which includes the GPS satellite and HALE UAVs, of greater than four. It is clearly seen from the figure that all the scenarios yield better positioning availability than that of the GPS-only case. The GPS-only case yields particularly low positioning availability at 2, 17.5 and 23 UTC times. However, presence of the HALE UAV improves the availability at those times to some extent.

The time-averaged values from Fig. 13 are shown in Table 2. The positioning availability of Scenario 1 is approximately 10% better than that of the GPS-only case. Furthermore, the results from Scenario 2 and Scenario 3 exhibit a similar level of performance. As for the navigational application, Scenario 3 provides the most efficient means because it uses only one HALE UAV, while Scenario 2 employs two HALE UAVs. However, when the efficiency of the whole HALE UAV platform is concerned, Scenario 2 has strong points that allow the HALE UAVs to operate multiple missions,

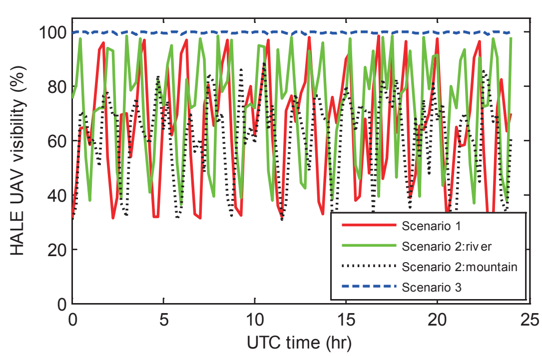

Fig. 12. Percentage of the HALE UAV visibility at grid points

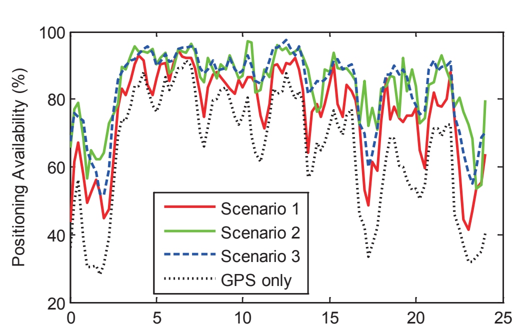

Fig. 13. Percentage of positioning availability (total visibility>=4) at grid points

including forest fire detection and water pollution analysis, simultaneously. Moreover, it can cover a wider area.

4.1.3 DOP Analysis

DOP is the one of the performance indices that represents the geometrical relationship between the signal sources and users [21]. As DOP values cannot represent the errors of the signal sources, it is assumed here that the signal from the pseudolite of the HALE UAV and the GPS satellite have similar qualities. Although the Position DOP (PDOP) values were calculated during the positioning available time of the GPS-only case, they are applied for all scenarios for comparison. Figs. 14-17 display the time-averaged PDOP values for a span of 24 hours at each grid point on Teheran Street in each scenario.

The results of Figs. 14 to 17 describe that the GPS-only

Table 2. Time-averaged percentages of the positioning availability

GPS only	Scenario 1	Scenario 2	Scenario 3
64.7%	75.8%	84.2%	83.6%

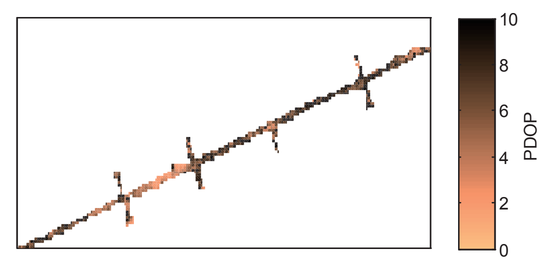

Fig. 14. Time-averaged PDOP at each grid point (GPS-only case)

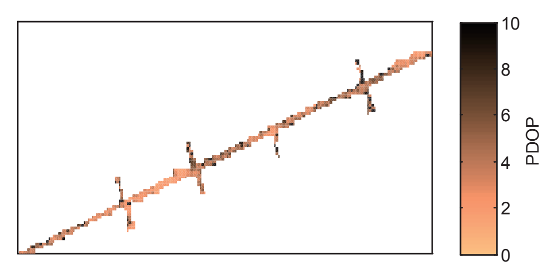

Fig. 15. Time-averaged PDOP at each grid point (Scenario 1)

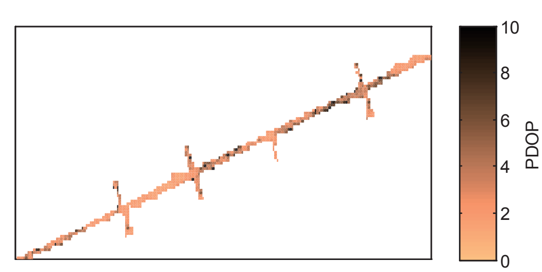

Fig. 16. Time-averaged PDOP at each grid point (Scenario 2)

case exhibits the worst PDOP values as expected. Scenario 3 yields a better PDOP than that of Scenario 2, and Scenario 2 is better than Scenario 1. The time and grid-point averages of the PDOP values are shown in Table 3.

Scenario 3 yields the best PDOP value. As the HALE UAV in Scenario 3 maintains a position directly above the grid points, it is clearly visible and gives a positive effect to the increment of vertical performance. Furthermore, the amount of the improvement is greater than that of Scenario 2, which employs two HALE UAVs. Although Scenario 1 and Scenario 2 are multi-purpose operations, they produce 57.0% and 44.1% better values compared to the GPS-only case, respectively.

4.2 Simulation Results in Posco-intersection

The previous sections discussed the results from the whole grid points of Teheran Street. In contrast, this section presents the results obtained at one grid point of the Posco-intersection on Teheran Street to investigate the characteristics over time.

4.2.1 Visibility Analysis

Figure 18 shows the total visibilities, which include the GPS and HALE UAVs, for 24 hours at Posco-intersection. The result indicates that Scenario 2 produces the best visibility. This is because the two HALE UAVs contribute at the same time in this scenario, while only one HALE UAV is available for the other scenarios.

The percentages of positioning available time when the total visibility is greater than four are presented in Table 4.

Generally, an intersection in an urban area has relatively good visibility because the open sky is available in all four directions. However, the GPS-only case in this simulation yields a positioning availability of only 66%. Therefore, it is evident that use of the HALE UAV can improve availability considerably.

4.2.2 DOP Analysis

PDOP values at the Posco-intersection over time are shown in Fig. 19. The results are synchronized with the positioning available time of the GPS-only case for proper comparison. The value of 0 in the figure indicates that the total visibility of the GPS-only case is less than four. Therefore, the calculation of the PDOP is unavailable in this case.

As expected, the GPS-only case produces the worst PDOP results. The time-averaged PDOPs are calculated as shown in Table 5.

As Scenario 3 is designed for continuous visibility of

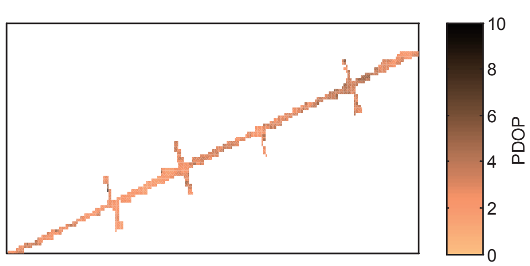

Fig. 17. Time-averaged PDOP at each grid point (Scenario 3)

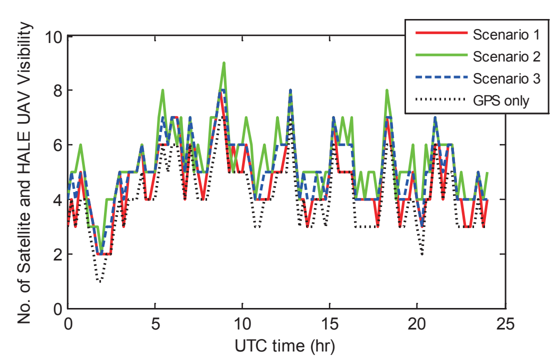

Fig. 18. Number of total visibility (GPS + HALE UAVs)

Table 3. Overall average of PDOP values

GPS only	Scenario 1	Scenario 2	Scenario 3
9.3	5.3	4.1	2.9

Table 4. Percentage of positioning availability

GPS only	Scenario 1	Scenario 2	Scenario 3
66.0%	84.5%	95.9%	93.8%

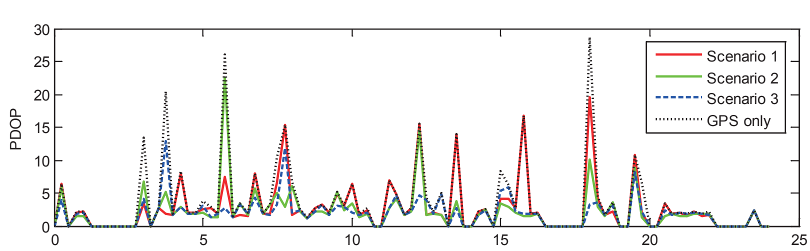

Fig. 19. PDOP values over time

Table 5. Time-averaged PDOP values

GPS only	Scenario 1	Scenario 2	Scenario 3
5.1	4.1	3.2	2.9

the HALE UAV, the PDOP of Scenario 3 yields the smallest value. The PDOP of Scenario 1 has approximately 80.4% of the value of the GPS-only case. For Scenarios 2 and 3, the PDOPs are 62.7% and 56.9% of the value of the GPS-only case, respectively.

5. Conclusion

The HALE UAV is suitable for roles between conventional aircrafts and satellites and has strong advantages compared to both systems. Therefore, the HALE UAV can be used for various missions as a new platform that operates individually or cooperatively with other platforms. Among the various applications of the HALE UAV, this study focused on the use of the HALE UAV for the navigation augmentation utilizing pseudolite during multi-purpose missions.

For multi-purpose missions, a trajectory that traced the mountains and rivers around Seoul was generated. Three scenarios and the GPS-only case were considered in investigation of the navigation performance in terms of the visibility, positioning availability, and DOP values. The investigation utilized the measured real geographical building data, flight characteristics of the HALE UAV and constellation of GPS satellites.

Simulation results were described in two sections. The first showed the overall result for all grid points in the concerned area, Teheran Street. The second showed the result at one grid point of Posco-intersection. All simulation results yielded similar tendencies. The three scenarios produced improved results in both availability and DOPs compared to those of the GPS-only case. For positioning availability, Scenario 2 always produced the best results because two HALE UAVs are employed. The improvement of Scenario 2 reached 20% and 30% at Teheran Street and Posco-intersection, respectively, compared to the GPS-only case. In contrast, Scenario 3 yielded good DOP values despite the fact that one HALE UAV was considered. It produced 44.1% and 56.9% compared to the GPS-only case around the Teheran Street and at the Posco-intersection, respectively. This was because the HALE UAV in Scenario 3 was positioned directly above the concerned area.

If only the effectiveness of navigation application is considered, Scenario 3 is probably the best solution. However, if the cost-effectiveness of the whole HALE UAV platforms is in consideration, the answer may be different. In the multi-purpose operation simulations, Scenario 1 with a single HALE UAV produced considerable improvement in terms of positioning availability and DOP. Scenario 2 with two HALE UAVs yielded better results for the navigation application. In addition, both Scenarios 1 and 2 had a wide coverage to increase the efficiency of the operations: the trajectory used in the simulations can cover the southern and central parts of Seoul, including the metropolitan area.

As this study considered only the GPS from satellite navigation systems, the result may be inappropriate to apply to the future multi-constellation environments. However, for any case that considers multi-purpose operations for the HALE UAV, it is possible to construct efficient operations even in multi-constellations. One of the possible solutions is using the HALE UAV platform as the augmentation system, such as the SBAS, in the urban area.

In conclusion, because of its long endurance and wide coverage at high altitudes, the HALE UAV platform has the potential for navigation augmentation using the pseudolite even during multi-purpose operations. And this study calculates the quantitative results of the enhanced navigation performance, which can contribute to make decisions on the system development and service start-up.

Acknowledgement

This research was supported by a grant from "An operations concept study of HALE (High Altitude Long Endurance) UAVs powered by alternative energy" funded by the Agency for Defense Development in South Korea, contracted through the Institute of Advanced Aerospace Technology at Seoul National University.

References

[1] “NASA Armstrong Fact Sheet: Helios Prototype [Internet]”, 2014 [cited 2014 Feb 28], Available from: http://www.nasa.gov/centers/dryden/news/FactSheets/FS-068-DFRC.html

[2] “QinetiQ's Zephyr Solar Aircraft Double Award by IET [Internet]”, 2011 [cited 2011 Nov 10], Available from: http://www.qinetiq.com/media/news/releases/Pages/Zephyr-wins-two-awards.aspx

[3] “Another First for Airbus Zephyr 7: Successful SatCom-Controlled High Altitude Pseudo-Satellite Test Flight in Winter Weather Conditions [Internet]”, 2014 [cited 2014 Aug 29], Available from: http://airbusdefenceandspace.com/

another-first-for-airbus-zephyr-7/

[4] "About Global Observer: Maximum Endurance, Maximum Coverage, Affordable cost (Official Webpage) [Internet]", 2015, Available from: https://www.avinc.com/globalobserver/about/

[5] "Phantom Eye (Official Webpage) [Internet]", 2015, Available from: http://www.boeing.com/boeing/bds/phantom_works/phantom_eye.page

[6] "Global Hawk (Official Webpage) [Internet]", 2015, Available from: http://www.northropgrumman.com/Capabilities/GlobalHawk/Pages/default.aspx

[7] Lee, Y., Kim, D. and Yeom, C., "Development of Korean High Altitude Platform Systems", *International Journal of Wireless Information Networks,* Vol. 13, No. 1, 2006, pp. 31-42. DOI: 10.1007/s10776-005-0018-6

[8] Lim, J., Choi, S., Shin, S. and Lee, D., "Wing Design Optimization of a Solar-HALE Aircraft", *International Journal of Aeronautical and Space Science*, Vol. 15, No. 3, 2014, pp. 219-231. DOI:10.5139/IJASS.2014.15.3.219

[9] Jin, W. and Lee, Y., "Computational Analysis of the Aerodynamic Performance of a Long-Endurance UAV", *International Journal of Aeronautical and Space Science*, Vol. 15, No. 4, 2014, pp. 374-382. DOI:10.5139/IJASS.2014.15.4 374

[10] Elrod, B. D. andVan Dierendonck, A. J., "Pseudolites", *Global Positioning System: Theory and Applications (Volume II)*, edited by B. W. Parkinson and J. J. Spilker Jr., Progress in Astronautics and Aeronautics, AIAA Washington, DC, 1996, pp. 51-79.

[11] Cobb, H. S., *GPS Pseudolites: Theory, Design, and Applications*, Ph.D. Dissertation, Stanford University, Stanford, CA, USA, Sep. 1997.

[12] Boiero, G., Dovis, F., Mulassano, P. and Mondin, M., "Increasing the Spatial Limits of LADGPS Using Stratospheric Platform", *The Journal of Navigation*, Vol. 54, Issue 2, 2001, pp. 255-267.

[13] Dovis, F., Mulassano, P. and Dumville, M., "The Stratolite Concept: Design of a Stratospheric Pseudo-Satellite for Galileo", *Proceedings of ION GPS 2002*, Portland, OR, USA, 2002.

[14] Tsujii, T., Harigae, M. andOkano, K., "A New Positioning/Navigation System Based on Pseudolites Installed on High Altitude Platforms Systems (HAPS)", *Proceedings of 24th International Congress of the Aeronautical Sciences*, Yokohama, Japan, 2004.

[15] Tsujii, T., Harigae, M., Barnes, J., Wang, J. and Rizos, C., "Experiments of Inverted Pseudolite Positioning for Airship-Based GPS Augmentation System", *Proceedings of ION GPS 2002*, Portland, OR, 2002.

[16] Sklar, J. R., "Interference Mitigation Approaches for the Global Positioning System", *Lincoln Laboratory Journal*, Vol. 14, No. 2, 2003, pp. 167-180.

[17] Kim, O., Choi, M., Yu, S., No, H., Seok, H., Yoon, D., Park, B., Kee, C. and Jee, C., "Navigation Augmentation in Urban Area with Pseudolite Equipped High Altitude Long Endurance UAV", *Proceedings of 2015 International Technical Meeting of ION*, Dana Point, CA, 2015.

[18] Shin, K., Hwang, H. and Ahn, J., "Initial Climb Mission Analysis of a Solar HALE UAV", *Journal of the Korean Society for Aeronautical and Space Sciences (Korean Language)*, Vol. 42, No. 4, 2014, pp. 468-477. DOI:10.5139/JKSAS.2014.42.6.468

[19] Park, K., Min, S., Ahn, J. and Lee, D., "Multidisciplinary Design Optimization (MDO) of a Medium-Sized Solar Powered HALE UAV Considering Energy Balancing", *Journal of the Korean Society for Aeronautical and Space Sciences (Korean Language)*, Vol. 40, No. 2, 2012, pp. 129-138. DOI:10.5139/JKSAS.2012.40.2.129

[20] Whitfield, C. A., *An Adaptive Dual-Optimal Path-Planning Technique for Unmanned Air Vehicles with Application to Solar-Regenerative High Altitude Long Endurance Flight*, Ph.D. Dissertation, The Ohio State University, 2009.

[21] Spilker Jr., J. J. and Parkinson, B. W., "Overview of GPS Operation and Design", *Global Positioning System: Theory and Applications (Volume I)*, edited by B. W. Parkinson and J. J. Spilker Jr., Progress in Astronautics and Aeronautics, AIAA Washington, DC, 1996, pp. 29-55.

DOI: http://dx.doi.org/10.5139/IJASS.2017.18.3.545