공학석사 학위논문

A Regional Alternative Navigation Using the High Altitude Long Endurance UAVs

고고도 장기체공 무인기를 활용한 국지적 대체항법에 관한 연구

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ABSTRACT

A Regional Alternative Navigation Using the High Altitude Long Endurance UAVs

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Global Navigation Satellite Systems (GNSS) – GPS, QZSS, BEIDOU and GLONASS – is operating widely in civil and military area and many countries want to have their own navigation system due to its various application fields. GNSS signals, however, can be easily interfered because its signal is too weak. Thus, a sort of backup or alternative system is needed in order that the navigation performance is assured to a certain degree in case of GNSS jamming.

In order to suggest a series of backup or alternative system of regional navigation, in this paper, a high altitude long endurance unmanned aerial vehicle (HALE UAV) with pseudolites using inverted GPS and transceiver system was introduced. Inverted GPS system is a device to determine the position of the HALE UAV using the

pseudolite signals from UAVs and the known ground station's position, and transceiver system is to determine the location of the UAV using bidirectional range measurements between UAVs and UAVs or between UAVs and ground stations by canceling the clock offset via a double-differencing method.

The positioning errors of the regional navigation system using HALE UAV with inverted GPS or transceivers concepts were simulated and the position errors of HALE UAV using the measurements from the other airborne and the ground stations were estimated, and user position errors based on the position error of HALE UAV and general pseudorange error were calculated .

In our simulation, the simple flight dynamics of HALE UAV, stratosphere environment such as wind information for the reality were considered, and the performance of regional alternative navigation during 24 hours was simulated. Then a variety of case: six HALE UAVs on six ground stations, six HALE UAVs far away from six ground stations and ten HALE UAVs on six ground stations were conducted in simulations.

As a simple result, six HALE UAVs on six ground stations enable users to have the position error of approx. 10~15m on average within a radius 150km at the HALE UAV altitude of 18km. In case of ten HALE UAVs, the improvement of the alternative navigation performance was checked.

The result of this paper may contribute to the independent backup or alternative navigation system with HALE UAVs and pseudolites under the situation of unavailable GNSS.

Keywords: Regional alternative navigation, Pseudolite, Inverted GPS, Transceiver, HALE UAV

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1. Introduction

1.1 Motivation

Nowadays, as the utilization for unmanned aerial vehicle (UAV) is increased sharply, the interest of the UAVs operated in the stratosphere is increasing around the globe. Because UAV that people do not ride could make a flight for long periods of several months and 24-hour at high altitude, it can be utilized in a variety of civilian and military purposes. Among them, the UAVs using eco-friendly green energy (etc. alternative energy) has attracted the attention. Since the air of the stratosphere is stable, if it happens the event of contamination, the pollutant has a long-term residual characteristics. Additionally, instead of the fossil fuel, the various studies have been conducted on how to operate the solar high altitude long endurance (HALE) UAVs by using a solar battery and a motor for the long-term endurance [1].

Because these HALE UAVs are able to stay longer than a few months and be operated on a mission over 24-hour, it could be performed effectively on a variety of the mission; surveillance, reconnaissance and communication relay, etc. Also it could be used the navigation system if it equips with pseudolites [2].

In modern society, navigation has been already used in a civilian / military area in various ways without classification. In war time, it has been an essential element for the efficient operation performance and its effect was already proven by the Iraq War and the counter-terrorism operations in Afghanistan. In peace time, it has been a essential society infrastructure and is second to harbors facilities, railways, telecommunications because it used in a variety of fields such as air / maritime safety, intelligent transport systems, precision agriculture, precision measurement, etc [3].

Thus, in this paper, the alternative navigation system that uses the HALE UAVs using the alternative energy with pseudolites is suggested. The alternative navigation system means the navigation system that is operable independently of the positioning system without relying on satellite navigation systems such as global satellite system (GPS). In war time, when it occurs the spoofing / jamming of an existing satellite navigation systems such as the RF interference or unavailable situation of the satellite navigation systems such as the sudden stop of the system, it could provide with the method of position determination.

As our country does not have a own navigation system, if the satellite navigation systems in other countries such as GPS cannot be used, it will occur the problem of major activities in civil and military area. Thus, if pseudolites mounts on the HALE UAVs, it can be operated a own navigation system for successful operations performance in war time and prevent a vast economic damage caused by a sudden stop navigation system and minimize the economic loss in peace time.

Therefore, in this study, through a survey of national and international case studies related to HALE UAVs using alternative Energy and stratosphere environment, it proposed the way of an alternative navigation in accordance with features of the HALE UAVs. Based on the characteristics of the HALE UAVs, the alternative navigation algorithms and the navigation performance in accordance with the operational mission scenarios were proposed by taking into account the environmental and operational conditions in the Korean Peninsula.

1.2 Literature Survey

Currently cases of an independent alternative navigation system using the HALE UAVs has not seen. But as similar cases, the cases of augmentation navigation system using the UAV or airship have been researched. In this section, the existing relevant case studies will be shown as a literature survey.

- Hight Altitude Platform Systems (HAPS, Japan)

In Japan, Japan Aerospace Exploration Agency (JAXA) proposed the navigation system that could provide with the navigation using the airship or UAV with equipped the pseudolite at a high altitude such as the stratosphere [4], [5]. As the pseudolite transmits the similar navigation signal such as GPS in a high altitude, the study has been conducted on the improvement of navigation performance in an aspect of precision, availability and integrity.

The pseudolite was attached below the helicopter by Toshiaki Tsujii, the experiment was performed with preferably hovering in narrow area. The positioning solution was estimated by GPS method using the six GPS receivers and they had a already known position. In this experiment, the results of the helicopter equipped with a GPS receiver were compared with the results obtained in standalone GPS and. The results of a cm grade difference were obtained by analyzing the performance difference between them.

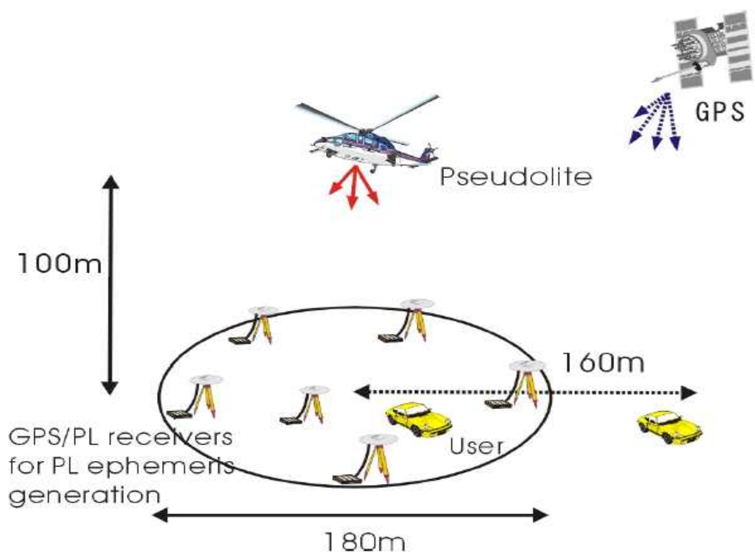

Figure 2-1 Experiment environment using helicopter

The navigation performance and solution of ground-user was evaluated by using the pseudolite mounted on a helicopter and it had the experiment using the way to obtain the location of a moving user from a fixed helicopter. The experimental results showed that the lower the mask angle guaranteed the more improved navigation performance of the ground-user.

- Battle-field Navigation System (BNS, USA)

Rockwell Collins had developed a PseudoLite (PL) based Battlefield Navigation System (BNS) in partnership with DARPA, UAV Battlelab (Eglin AFB, FL.), and SSC San Diego [6]. The system was composed of one APL (Airborne PL) on the Hunter UAV and three GPLs (Ground PLs). The APL system consists of a GPS signal generator, a Personal Computer (PC) controller, a GPS reference receiver, an Inertial Measurement Unit (IMU) to provide inertial aiding, a Rubidium frequency standard, and various power supplies and remote control data links. The role of reference receiver is to navigate from GPS satellites, providing self-location and timing information for the pseudolite signal generator.

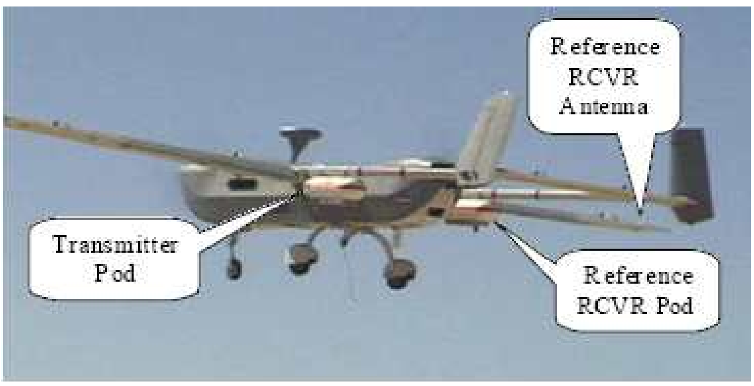

Figure 1-2 APL System Construction in Hunter UAV

After the APL self-navigation solution is determined, it is broadcasted to the user equipments, which are JDAM (Joint Direct Attack Munition) or PLGR (Precision Lightweight GPS Receiver).

Rockwell Collins has demonstrated that pseudolite-based navigation performance is consistent with satellite based navigation. The position of the mobile APL is, however, estimated by GPS, so BNS is not a fully-alternative or fully-backup for GNSS.

- Interference Mitigation of Navigation (Lincoln Laboratory, USA)

JAY R. Sklar had a study to improve the error by analyzing the factors that interfere with the GPS and also carried out the position determination. Through the robust receiver against the jamming mounted in UAV, the position of the pseudolite was calculated and the ground-user was conducted his own position determination by using the broadcasted signal including the position information of UAV from each UAV [7].

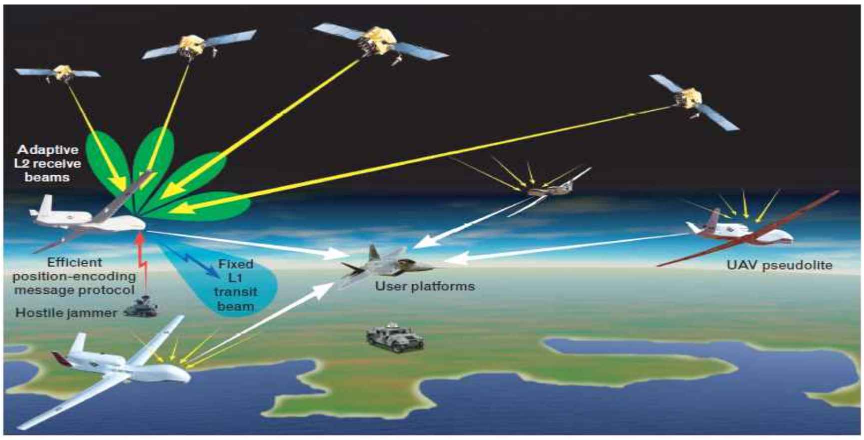

Figure 1-3 Concept of Alternative navigation in Lincoln Laboratory

1.3 Contents and Method

The purpose of this study is to construct the independent alternative navigation system that broadcasts the navigation signal by using the HALE UAVs equipped with pseudolite or transceiver, which has a advantage of a long endurance in stratosphere. In this study, it consists of the three sections; the features and trajectory generation of the HALE UAV, the deduction of alternative navigation algorithm and the estimation of alternative navigation performance in accordance with the arrangement of UAVs and reference station regarding the positioning algorithm. Structurally, it mentioned the process of the various simulations to estimate the navigation performance of each alternative navigation algorithm. The detailed description and method of each process are as follows.

Firstly, considering the design concept of the HALE UAV using the alternative energy such as the solar power and the stratosphere environment such as wind information, the flight profile and the trajectory change of the UAV for 24 hours was calculated. Based on the characteristics of the HALE UAVs using the alternative energy, the HALE UAV should be to be light-weight for maximum endurance. And it should climb and charge the energy when the solar energy is sufficient, while it should be carried out the glide or decent flight with a maximum endurance speed when the solar energy is insufficient. Thus, it is important the constitution of a flight profile of the HALE UAV and The trajectory of HALE UAV is necessary because the HALE UAV should broadcast continuously a navigation message in a certain area to the user.

Secondly, The alternative navigation algorithm was constructed for the alternative navigation simulations. In this paper, the alternative navigation algorithm is made up by the inverted GPS (IGPS) algorithm and transceiver algorithm. Inverted GPS algorithm was introduced by Raquet for the first time [8]. It can estimate the position of pseudolite under the unavailable GNSS situation. Through the known position of a ground reference station, it can estimate the pseudolite position by using the IGPS algorithm. In other words, if the pseudolite broadcasts the navigation signal to the reference station, the reference station transmits the received signal to the computing center. Then, the computing center carries out the calculation of the transmitted signal and estimates the position of pseudolite. Transceiver is a compound word of transmitter and receiver and it can transmit the navigation signal as well as receive that from other transmitter. Moreover it can receive its own signal internally. Transceiver method has a very large advantage that no reference clock, later it referred to the text. Thus, it can be considered an ideal alternative means of navigation.

Finally, the alternative navigation performance for each UAV arrangement and alternative navigation algorithm was estimated. In this study, the basic configuration of alternative navigation system for simulations consists of the six HALE UAVs and the six reference stations. The six HALE UAVs are located above the six reference stations and its altitude is between 18km to 20km and the arrangement of the six reference station. For the efficient DOP (Dilution of Precision), the HALE UAVs are arranged to have a distance of 50km among the UAVs relative to the center UAV and they has a symmetrical arrangement in the form of a hexagon. The arrangement of six reference station has two arrangement; an ideal symmetrical arrangement such as the arrangement of six HALE UAVs and a practical arrangement using the currently operated reference station's position such as Muju, Gimcheon, Changnyeong, Jinju, Namwon, and Geochang for the reality of simulation results.

For a variety of the UAV utilizations for alternative navigation, the UAVs's location, the detail construction of alternative navigation system has 4 construction; the six HALE UAVs on the six reference stations, the six HALE UAVs far-away from the six reference stations, the ten HALE UAVs on the six reference stations and one UAV failure in the six HALE UAVs on the six reference stations. Thus, the user's navigation performance according to various UAV construction will be shown in the simulation results. Based on above arrangements and construction of the HALE, the DOP in accordance with the situation was calculated. The simulation was carried out by each algorithm for the user position accuracy based on the DOP.

1.4 Contributions

The aim of this study is to configure an independent local alternative navigation system for using the HALE UAVs equipped with pseudolite or transceiver, which has a advantage of the long endurance and high altitude. The HALE UAV has a operation area between the operation area of satellite and that of manned aircraft. Thus the HALE UAV Will be utilized in various fields of civil-military because it could gather the advantages from the satellite and manned aircraft.

Considering these benefits, the simulations carried out for estimating the user navigation performance in accordance with each algorithm such as inverted GPS and transceiver algorithm for using the regional alternative navigation of the HALE UAVs under the unavailable GNSS situation.

In this paper, the regional alternative navigation system was suggested by utilizing the HALE UAVs under the unavailable GNSS situation. If the regional alternative navigation system is constructed by using the HALE UAVs equipped with pseudolite or transceiver, it is expected that an independent alternative navigation system would be made by the HALE UAVs equipped with pseudolite or transceiver for the country of a short operation radius.

II. High Altitude Long Endurance (HALE) UAV

2.1 The concept and mission of the HALE UAV

The HALE UAV, considered in this paper, operates in the stratosphere with duration of several days without landing. There have been various HALE UAVs in development to accomplish the practical levels and it has a variety of utilization fields.

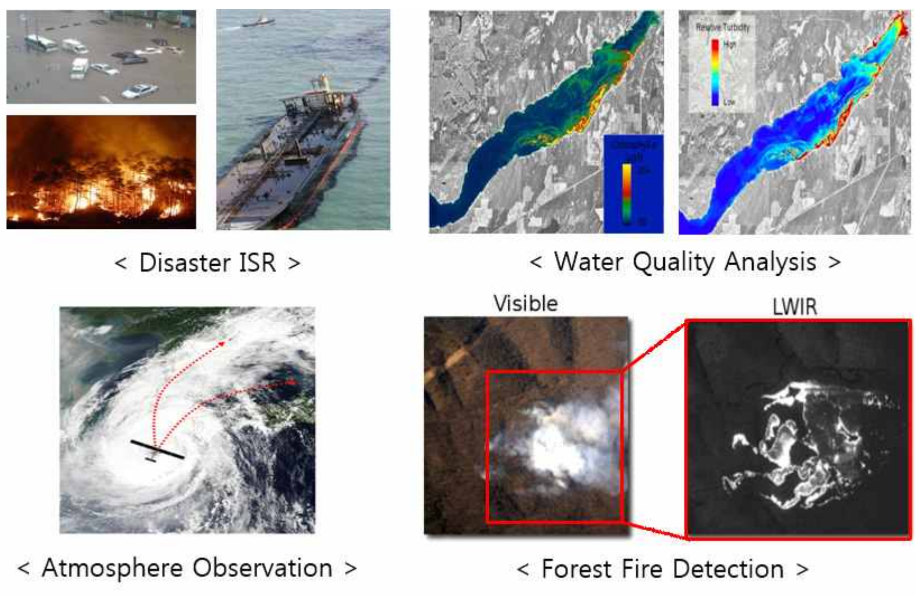

Figure 2-1 The mission of HALE UAV [1]

One of famous project was the Helios program managed by

National Aeronautics and Space Administration (NASA) [2]. NASA Helios was manufactured by AeroVironment, and it was powered using solar cells and lithium battery pack. Its wingspan is about 75.3m, and total weight is up to 929kg. The target altitude of Helios is up to 100,000ft (~30.5km), and 96,864 feet of altitude record was achieved in 2001. Its endurance could be from several days to months according to the supplemental electrical energy.

Another solar powered HALE UAV is Zephyr, developed by QinetiQ and sold to Airbus Company in 2013. In 2010, Zephyr achieved the endurance record about 2 weeks stay with soaring excess of 70,000 feet (~21.3km) [10]. And Airbus Zephyr 7 successfully finished its 11 days of non-stop flight for satellite communication controlled pseudo-satellite test even in winter weather conditions. Zephyr 7 has 50kg weight with 5kg of payload and wing span of 22.86m. Its target altitude is about 65,000ft (~19km) and maximum velocity is 66.7m/s [11].

Not all HALE UAVs use solar energy as its power source. Global Hawk is the one of HALE UAV which are already practically used. Its wingspan is 39.9m and takeoff gross weight of 14,628kg with payload of 1,360kg. Its maximum altitude is 60,000ft (~18.3km). As this UAV uses conventional turbofan engines, its maximum endurance is about 32+ hours [1].

Global Observer, manufactured by AeroVironment, has endurance time of 4 to 6 days using liquid-hydrogen powered system [9]. Its operating altitude of 45,000ft (~13.72km) to 55,000ft (~16.77km), and payload can be up to 181.5kg weight. The wingspan is 53.3m. Its mission possibilities are communication relay, disaster response and maritime operations .

Phantom Eye uses liquid hydrogen propulsion system, producing only water as a byproduct [12]. Its endurance time is 4 days at 65,000ft (~19km) with 204.1kg payload. Its wingspan is 46m and takeoff gross weight is 4,445kg. 고고도 장기체공(High Altitude Long Endurance, HALE)

Table 2-1 Main performance of the foreign HALE UAVs

구분	Global Observer	Zephyr	Phantom Eye
Duration	7 days	3 months	4 days
Gross Weight	1,805 kg	50 kg	4,44 5kg
Payload	180 kg	3 kg	204 kg
Fuel	Hydrogen encergy	Solar energy	Hydrogen encergy

And also, the development of the HALE UAV is actively conducting by Korea Aerospace Research Institute(KARI). In particular, KARI is being developed in a HALE UAV; EAV (Electrical Aerial Vehicle)-3. By embarking on development from 2010 to August 2015, there is cases of successful flight 14.12km altitude at Goheung Air Center [13].

EAV-3 is an archaeological want to use alternative energy power secondary battery (lithium ion) and solar cells, as shown in Figure 2-2 are known as long-endurance UAV. EAV-3 uses the alternative energy of solar power and secondary battery (lithium-ion) as shown in figure 2-2.

Figure 2-2 Korean HALE UAV, EAV-3 [13]

In this paper, based the research in Korea about the HALE UAV using alternative energy, the design concept and flight profile of the HALE UAV for the alternative navigation system will be mentioned next section.

2.2 The design of HALE UAV for simulations

In this paper, solar powered HALE UAV concept is considered for simulations. The HALE UAV configuration is assumed to the glider type according to the paper [14], ‘Initial Climb Mission Analysis of a Solar HALE UAV’. The HALE UAV configuration is shown in Table 2-2 and Figure 2-3 as a glider type aircraft. Also, the HALE UAV is assumed to equip with pseudolite or transceiver.

Table 2-2 HALE UAV configurations values

Classification	Values
Main wing area	35.98 m^2
Main wing span	29.98 m
Aspect ratio	25
Chord length	1.2 m
Weight	160 kg
Solar cell covered area	26.98 m^2
Fuselage length	18 m
Main wing airfoil	DAE-11

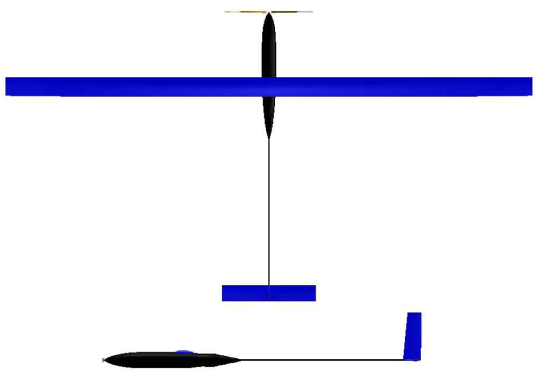

Figure 2-3 HALE UAV configuration

The DAE-11 airfoil has a good lift-drag characteristic, small pitching moment between 200,000 and 1,000,000 Reynolds number. Thus, it is proper to apply for the solar cell to the HALE UAV[].

For flight profiles, based on Table 2-2, the simplified altitude and velocity profiles, and kinematic model are considered, because the purpose is not to design the real trajectory of UAV using accurate flight models but to evaluate the alternative navigation performance using the HALE UAV equipped with pseudolite or transceiver. There are some special features in the HALE UAV different from conventional aircraft, and these features should be considered properly for simulations.

2.3 Flight Profile of HALE UAV

The HALE UAV is assumed that it uses alternative energy such as solar power. Then, the HALE UAV's flight profile is generated. For HALE UAV using the solar power, it uses the electrical energy converted from solar power and charges a sort of battery by solar power in daytime. In nighttime, it uses the charged battery power with a minimum power flight or glide flight of maximum lift-drag ratio due to capacity limitations of the battery as shown Figure 2-4.

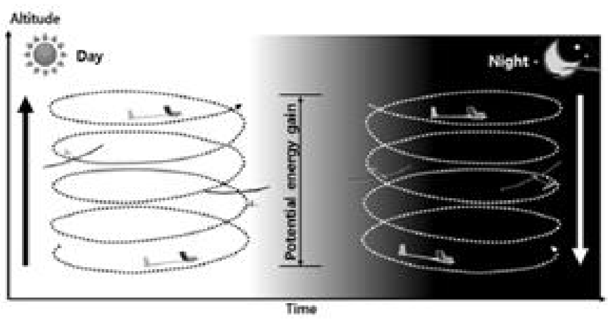

Figure 2-4 Concept of altitude change

Through such a flight procedure, the HALE UAV can fly in a long period of time. Therefore, the HALE UAV must be operated the level or climb flight in daytime, the glide flight with optimum velocity and maximum lift-drag ratio in night time [15].

The altitude change was considered between 18km to 20km as the mission altitude of HALE UAV and the recommended start time of climb, level, glider flight is as shown Table 2-3.

Taking this into consideration, the HALE UAV's flight altitude during 24 hours would be between 18km and up to 20km as the following Figure 2-5.

Table 2-3 Each flight start time (local time)

Flight	Start time (hr, local time)
Climb flight	14.38
Level flight (altitude : 20km)	16.74
Glide flight	17.64
Level flight (altitude : 18km)	20.76

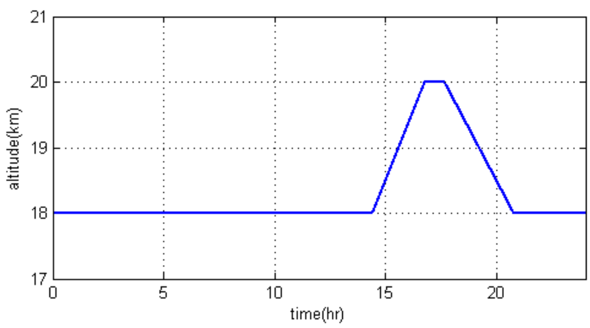

Figure 2-5 Altitude profile of HALE UAV (24 hr)

The HALE UAV is advantageous to fly during long time. Therefore, it should fly at a maximum endurance velocity of the HALE UAV. However, it is hard to calculate a maximum endurance velocity(MEV) in the current stage. So, it is assumed that a maximum endurance velocity is a 1.2 times of the HALE UAV stall velocity. The stall velocity is calculated according to the HALE UAV design as in Table 1 and operating altitude as in Figure 1 [14], [15]. Therefore, the velocity of the HALE UAV during 24 hours for simulations is selected as in Figure 2-6 [14], [15].

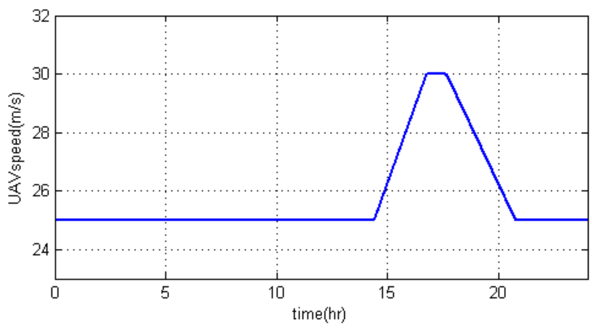

Figure 2-6 Velocity profile of HALE UAV (24 hr)

In summary about velocity profile, the HALE UAV flight velocity is 25m/s at 18km altitude and 30m/s at 20km altitude. The climb starts at approx.14 hour and the glide or descent starts at 17.5 hour. Between the climb and the descent or glide flight, the HALE UAV do a cruise flight. That means the HALE UAV starts the climb when the solar power is the strongest and then it charges the battery during the cruise flight. Next, the HALE UAV starts the glide or descent flight when the battery is full charged for the optimum flight profile.

2.4 Wind effect in the stratosphere

Another special features to be considered in the flight profile of HALE UAV is the wind effect [12] [14]. Because of the limited power of HALE UAV, the velocity of this aircraft is relatively low to minimize the consuming energy. Therefore, the wind effect cannot be neglected, even when the wind in stratosphere near 20km height is weak compared to the one in troposphere. The velocity of HALE UAV as in Figure 2-6 has a similar scale compared to the wind speed in stratosphere.

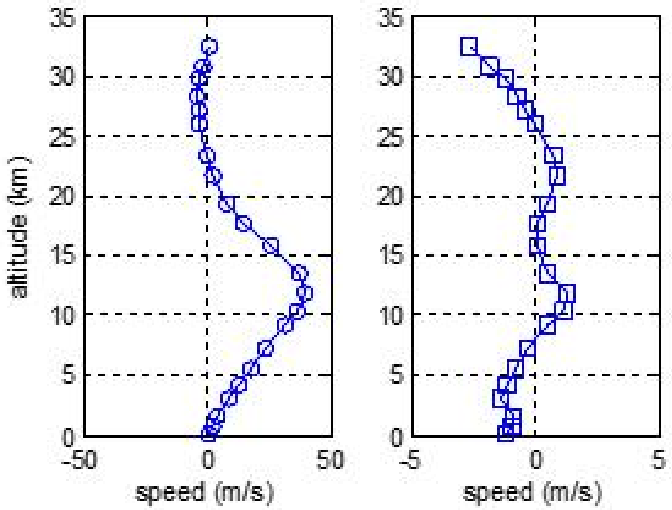

Figure 2-7 Average wind speed

(left: west wind, right: south wind)

For simulations, the wind speed profile is formed and applied to the generation of the trajectory of UAV. The profile is formed using the accumulated data from 2000 to 2012 over the Korean peninsula by National Institute of Meteorological Research of Korea Meteorological Administration. The data include the minimum, maximum and average wind speeds along the altitude in four seasons as shown in Figure 2-7.

Wind profiles are generated based on these data with the overall average of the whole year, and it has the variations between the smallest and the largest wind speed along the altitude as shown in Figure 2-8.

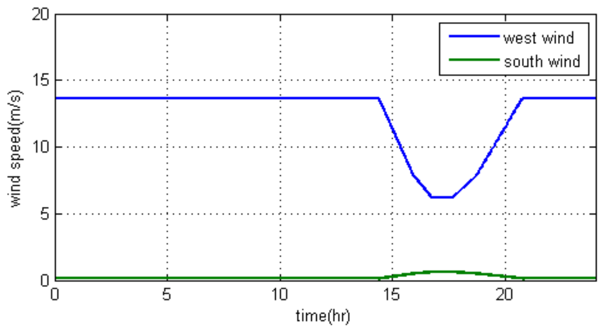

Figure 2-8 Average wind change

2.5 Trajectory of HALE UAV

Heretofore, it is mentioned about the flight profile and wind information to generate the trajectory of the HALE UAV. Thus a trajectory was generated by using the flight profile and wind information. For the trajectory of HALE UAV, a simple dynamic model was used as shown in Equation (2-1) and it was considered a steady banked turn [16].

$$\bar{X} = \begin{bmatrix} x \\ y \\ \psi \end{bmatrix}, \quad \dot{\bar{X}} = \begin{bmatrix} V_{UAV} \cdot \cos\psi + V_{w,x} \\ V_{UAV} \cdot \sin\psi + V_{w,\mathrm{y}} \\ (g / V_{UAV}) \cdot \tan\phi \end{bmatrix} \tag{2-1}$$

Where, V_{UAV} is the speed of UAV, and $V_{w,x}$ and $V_{w,y}$ are the wind speed in x and y axis respectively. ψ is the heading of the UAV, ϕ is the bank angle of UAV attitude, and g is the gravity acceleration. These values are given by Cartesian coordinates, and there is a simplification eliminating the inertial roll rate which means that the aircraft can reach a new bank angle instantly. This is common in simple trajectory analysis [16].

The HALE UAV should be flown in the type of holding flight to continuously provide navigation messages to the ground user. To hold on a certain area, the HALE UAV is inevitable to fly in the form of a continuous banked flight. Also, the HALE UAV should be flown with a small bank to minimize drag because the drag increases the thrust of HALE UAV in order to maintain a constant altitude and velocity. Thus, the bank angle of the HALE UAV was limited to 10 degrees for simulations. Considering the HALE UAV altitude cycle, velocity profile and wind information, the horizontal plane trajectory with interval of 5 minutes of HALE UAV during 24 hours was created as shown in Figure 2-9.

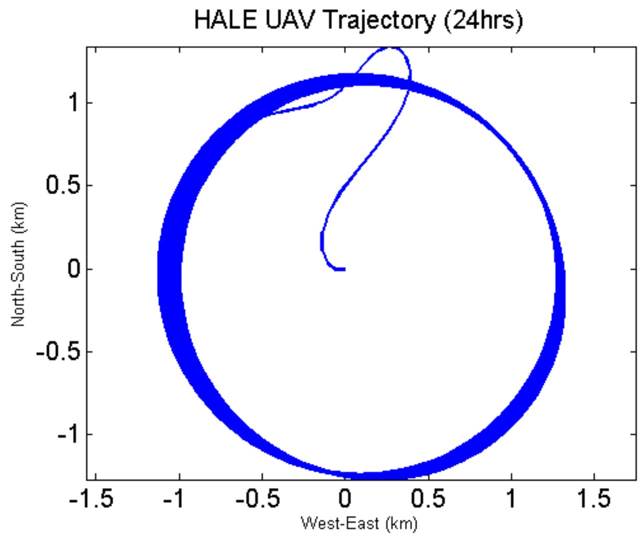

Figure 2-9 Trajectory of HALE UAV (24 hr)

Figure 2-9 shows that the HALE UAV has the trajectory of circle form with approx. 1km radius. In this paper, the above HALE UAV trajectory was used for the alternative navigation simulations.

III. Algorithm of Alternative Navigation

3.1 Pseudolite

Pseudolite is a contraction of the term 'pseudo-satellite' and it is a GNSS-like signal transmitter [17]. Thus, it can provide additional measurements and message data. Moreover Indoor navigation system are possible by only using pseudolites and it can use with GNSS out of doors which can not track the GNSS satellite signals.

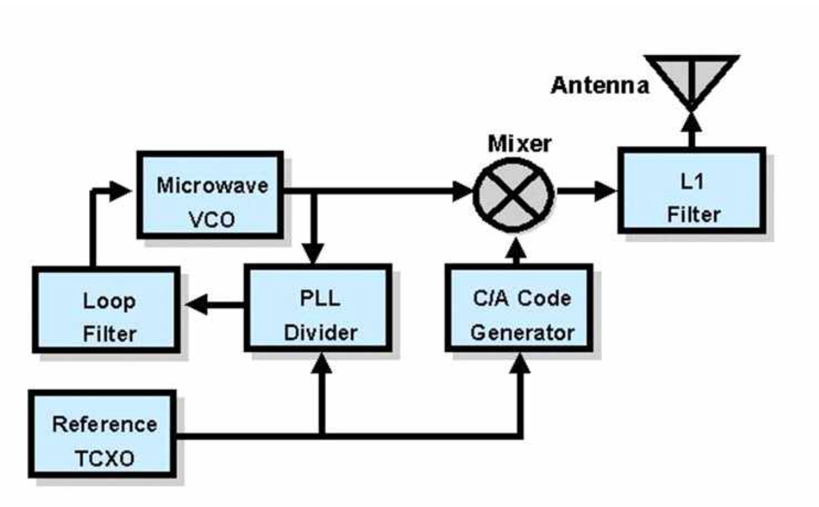

Figure 3-1 Block diagram of pseudolite [20]

Pseudolite generates the PRN (Pseudo Random Number), the carrier phase frequency and message construction like the GNSS. Also, it can generate another navigation message with different frequency comparing the GNSS. Thus user can receive the navigation signal by using the existing receiver from the pseudolite. Figure 3-1 shows the general block diagram of pseudolite and Figure 3-2 shows the example of pseudolite use.

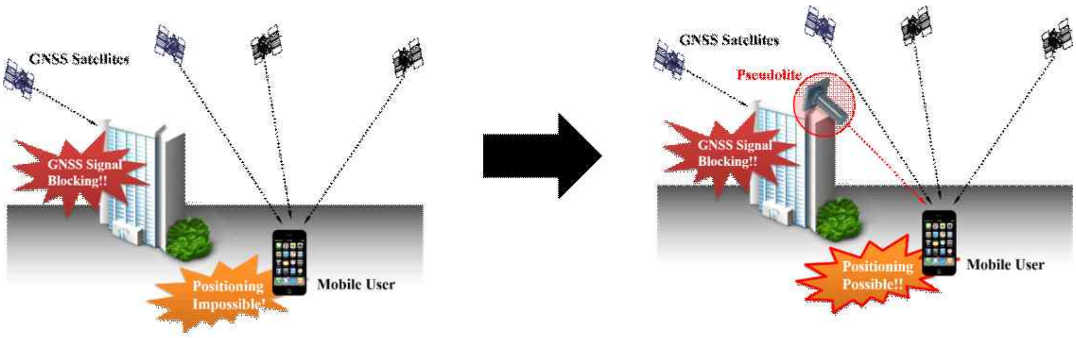

Figure 3-2 Example of pseudolite utilization

Since the pseudolite can utilize to provide a position information like navigation satellites, A alternative navigation can be researches by using the pseudolite concept. At present, our country has no choice but to rely on navigation systems in other countries in war time. Thus own satellite navigation system should be constructed. However, its cost is highly vast and the development period takes a long. Therefore, it is expected that the prior research regarding the independent alternative navigation should be necessary before constructing our satellite navigation system.

3.2 Inverted GPS Algorithm

In this paper, the alternative navigation algorithm is made up by the inverted GPS (IGPS) algorithm and transceiver algorithm. Inverted GPS algorithm was introduced by Raquet for the first time [8]. It can estimate the position of pseudolite under the unavailable GNSS situation. Through the known position of a ground reference station, it can estimate the pseudolite position by using the IGPS algorithm. In other words, if the pseudolite broadcasts the navigation signal to the reference station, the reference station transmits the received signal to the computing center. Then, the computing center carries out the calculation of the transmitted signal and estimates the position of pseudolite. Figure 3-3 shows the relationship among the pseudolite, reference station (RS) and computing center (CC).

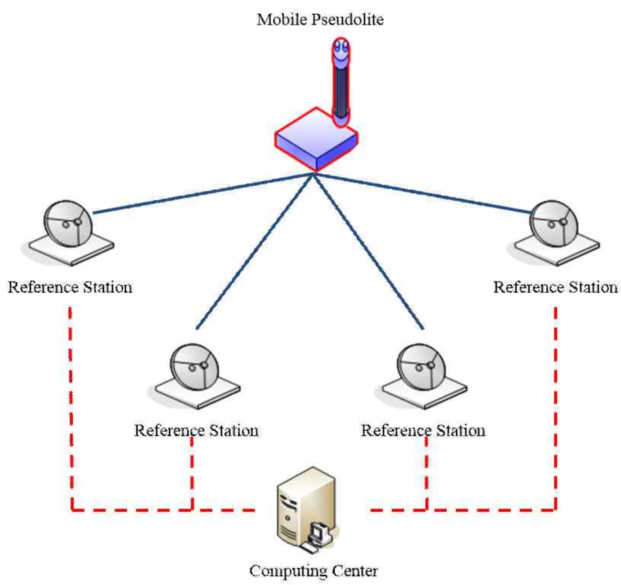

Figure 3-3 Concept of inverted GPS

Therefore, if the HALE UAV with a pseudolite is selected as the reference like GNSS satellite, inverted GPS method has advantages that ionospheric delay error related to the GNSS reference satellite can be ignored due to the HALE UAV operation altitude. That means that inverted GPS method can overcome the limitation of 'satellite-based' when GNSS satellite signals is unavailable.

The measurements of IGPS algorithm is shown in Equation (3-1), (3-2) and it assumed that there is the reference clock.

$$\begin{aligned}\rho^i_{RS_k} &= d^i_{RS_k} + B_{RS_k} - b^i \\ &= (\overline{R}^i - \overline{R}_{RS_k}) \cdot \hat{e}^i_{RS_k} - b^i\end{aligned} \tag{3-1}$$

$$\begin{aligned}\rho^i_{RS_k} - B_{RS_k} + \hat{e}^i_{RS_k} \cdot R_{RS_k} &= \overline{R}^i \cdot \hat{e}^i_{RS_k} - b^i \\ &= [\hat{e}^i_{RS_k} \quad -1]\begin{pmatrix} R^i \\ b^i \end{pmatrix}\end{aligned} \tag{3-2}$$

$\rho^i_{RS_k}$: pseudorange between i-th UAV and k-th reference station

$d^i_{RS_k}$: a real distance between i-th UAV and k-th reference station

B_{RS_k} : the clock error of k-th reference clock

b^i : i-th UAV transmitter clock error

3.3 Transceiver Algorithm [18]

Transceiver is a compound word of 'transmitter' and 'receiver'.

Literally, it transmits the navigation signal as well as receives that from others. The output of the transmitter is split, with one line going to a passive broadcast antenna and the other going to one front end on the dual front-end receiver. This allows the receiver to monitor the transmitter's output signal, so it can receive its own signal internally.

The i-th transceiver receives the signal such as equation (3-3) from another transceiver and also receives its own signal internally such as equation (3-4). It is assumed that the line bias would be estimated exactly, so that it would be included in the clock bias.

$$\rho_i^j = d_i^j + B_i - b^j + \varepsilon_{\rho ji} \tag{3-3}$$

$$\rho_i^i = B_i - b^i + \varepsilon_{\rho ii} \tag{3-4}$$

ρ_i^j : pseudorange measurement received at i-th transceiver from j-th one

ρ_i^i : pseudorange measurement internally in i-th transceiver

d_i^j : distance between i and j-th transceiver

B : clock error of the receiver part in transceiver

b : clock error of the transmitter part in transceiver

ε_ρ : pseudorange measurement noise

And the j-th transceiver receives the signal such as equation (3-5) from another transceiver and also receives its own signal internally such as equation (3-6).

$$\rho_j^i = d_j^i + B_j - b^i + \varepsilon_{\rho ij} \tag{3-5}$$

$$\rho_j^j = B_j - b^j + \varepsilon_{\rho jj} \tag{3-6}$$

The receiver clock error can be eliminated in the receiver part by taking internal self-differences between the signals received by j-th and by i-th transceiver, as shown in equation (3-7). $\tilde{\rho}_i^j$ means the internal self-differences between the signals received at i-th transceiver.

$$\tilde{\rho}_i^j = \rho_i^j - \rho_i^i = d_i^j - (b^j - b^i) + \varepsilon_{\rho ji} - \varepsilon_{\rho ii} \tag{3-7}$$

Similarly to the equation (3-7), a new measurement of j-th transceiver $\tilde{\rho}_j^i$ can be measured by the self-difference, as shown in equation (3-8).

$$\tilde{\rho}_j^i = d_j^i - (b^i - b^j) + \varepsilon_{\rho ij} - \varepsilon_{\rho jj} \tag{3-8}$$

Thus, the clock errors can be eliminated by combining equation (3-7) and (3-8). Then the range between i-th transceiver and j-th transceiver as the following equation can be determined. (3-9).

$$\frac{\tilde{\rho}_j^i + \tilde{\rho}_i^j}{2} = d_j^i + \frac{\{\varepsilon_{\rho ij} - \varepsilon_{\rho jj} + \varepsilon_{\rho ji} - \varepsilon_{\rho ii}\}}{2} \tag{3-9}$$

Considering the geometry factor of the i-th and j-th transceivers, the distance between i-th transceiver and j-th transceiver is the inner product of the pair's line-of-sight vector and its relative position vector such as equation (3-10).

$$d_i^j = e_i^j \cdot (R^j - R^i) \tag{3-10}$$

e_i^j : Line-of-sight vector from i-th to j-th transceiver

R^j : Position vector of the j-th transceiver

The all measurements among the transceivers can be described by the following matrix from. This over-determined system could provide the positions of all the transceiver in a least square solution such as equation (3-11).

$$\begin{bmatrix} \frac{\tilde{\rho}_1^2 + \tilde{\rho}_2^1}{2} \\ \frac{\tilde{\rho}_1^3 + \tilde{\rho}_3^1}{2} \\ \vdots \\ \frac{\tilde{\rho}_j^i + \tilde{\rho}_i^j}{2} \\ \vdots \\ \frac{\tilde{\rho}_{n-2}^n + \tilde{\rho}_n^{n-2}}{2} \\ \frac{\tilde{\rho}_{n-1}^n + \tilde{\rho}_n^{n-1}}{2} \end{bmatrix} = \begin{bmatrix} -e_1^2 & e_1^2 & 0 & \cdots & 0 & \cdots & 0 \\ -e_1^3 & 0 & e_1^3 & 0 & \cdots & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & \cdots 0 \cdots & -e_i^j & 0 \cdots 0 & e_i^j & \cdots 0 \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & \cdots & \cdots & 0 & -e_{n-2}^n & 0 & e_{n-2}^n \\ 0 & \cdots & \cdots & \cdots & 0 & -e_{n-1}^n & e_{n-1}^n \end{bmatrix} \begin{bmatrix} R^1 \\ R^2 \\ R^3 \\ \vdots \\ R^i \\ \vdots \\ R^j \\ \vdots \\ R^{n-2} \\ R^{n-1} \\ R^n \end{bmatrix} \tag{3-11}$$

As shown in equation (3-3) ~ (3-11), the receiver part clock bias in transceiver and the transmitter part clock error in transceiver can be eliminate. Thus the real distance between transceivers can be used. Thus, the reference clock could be not required for alternative navigation system using only transceivers in HALE UAV and reference station. In this paper, this algorithm calls the transceiver algorithm. This algorithm will be used for the HALE UAVs position estimation.

Figure 3-4 is a block diagram of the transceiver. The signals received from receiver front-end and from the transmitter are self-differenced, and then a reconstructed measurement of j-th transceiver $\tilde{\rho}_j^i$ is estimated. The transceiver algorithm can estimate the transceiver's position in real-time. A communication module is used for transferring the measurement and receiving the estimated position information. The inevitable processing time delay should be compensated by IMU.

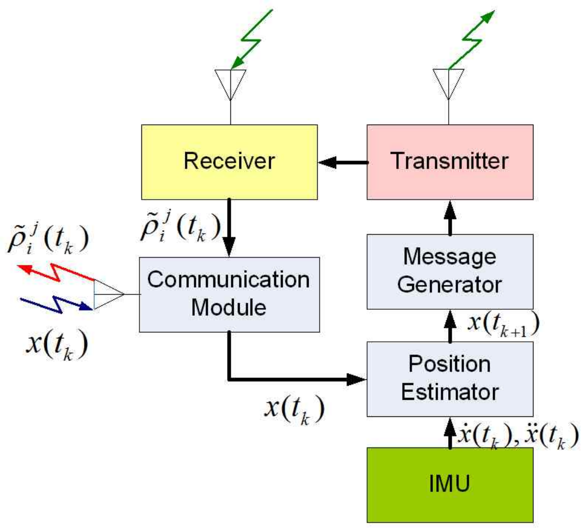

Figure 3-4 Block diagram of transceiver

IV. Alternative Navigation System

4.1 Concept of alternative navigation

The concept map of alternative navigation system is as shown in Figure 4-1. The alternative navigation system consists of three parts: ground segment, HALE UAV segment and user segment.

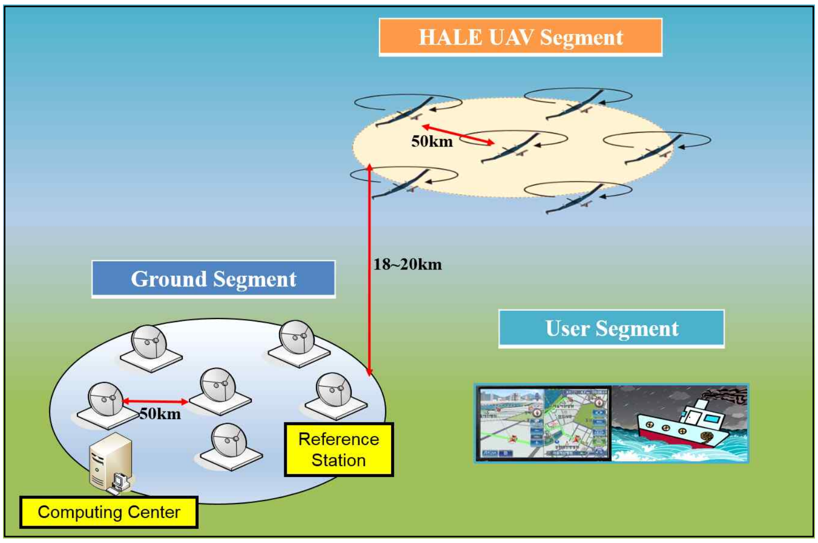

Figure 4-1 Overview of alternative navigation

Ground segment is composed of one computing center (CC) and six reference stations (RS) which are located in already known positions. RSs receive navigation signals from the HALE UAVs' pseudolites or transceivers, and then the RSs transfer the received signal to CC. The computing center estimates each the HALE UAV's position by combining the collected measurements, and then the CC transmits the result to each HALE UAVs. After receiving the transmitted information from the CC, each HALE UAVs compensates for a time delay and estimates its own position by the aid of the additional sensor such as an IMU [7]. And then the pseudolite or transceiver generates a set of navigation messages based on the estimated HALE UAV positions in real time and broadcasts the message to the user segment. The pseudolite or transceiver could generate GNSS-like signal, so the user on ground can get user own position using the GNSS receiver. If the system should be operated in unavailable GNSS situation like our simulations, the navigation signal should have a different frequency such as S-band. Also, the navigation user should have a receiver matching with the transmitted signal.

4.2 Composition of HALE UAV and reference station

4.2.1 DOP (Dilution of Precision) [19]

In the satellite navigation system such as GNSS, Users of position accuracy is determined by DOP that represents the geometry of the radio wave signal.

Typically, if four or more satellites are visible, the position solution is as shown equation (4-1) by the least-squares solution.

$$\vec{x} = (H^T H)^{-1} \cdot H^T \cdot \vec{z} \tag{4-1}$$

Equation (4-1) can be represented as equation (4-2) because of $\bar{x} = \bar{x}_{true} + \delta\bar{x},\ \bar{z} = \bar{z}_{true} + \delta\bar{z}$.

$$\delta\bar{x} = (H^T H)^{-1} H^T \delta\bar{z} \tag{4-2}$$

Based on equation (4-1), (4-2), the covariance of solution is shown in equation (4-3).

$$\text{cov}\left[\delta\bar{x}\right] = (H^T H)^{-1} H^T \text{cov}\left[\delta\bar{z}\right] H (H^T H)^{-1} \tag{4-3}$$

Also, equation (4-2) can be represented as equation (4-4) because of $\delta\bar{z} = -\delta\bar{\rho},\ \text{cov}\left[\delta\bar{z}\right] = \text{cov}\left[\delta\bar{\rho}\right]$.

$$\text{cov}\left[\delta\bar{x}\right] = (H^T H)^{-1} H^T \text{cov}\left[\delta\bar{\rho}\right] H (H^T H)^{-1} \tag{4-4}$$

If it is uncorrelated among each satellites that have noise measurements at the same level for all satellites, it can be derived in the following equation (4-5)

$$\text{cov}\left[\delta\bar{x}\right] = \text{var}\left[\delta\rho\right] (H^T H)^{-1} \tag{4-5}$$

Thus, the position error is determined by the geometric elements of satellites such as $(H^T H)^{-1}$. $(H^T H)^{-1}$ is a 4×4 matrix and an expanded representation is the following equation.

$$(H^T H)^{-1} = \begin{bmatrix} \sigma_{xx}{}^2 & \sigma_{xy}{}^2 & \sigma_{xz}{}^2 & \sigma_{xt}{}^2 \\ \sigma_{yx}{}^2 & \sigma_{yy}{}^2 & \sigma_{yz}{}^2 & \sigma_{yt}{}^2 \\ \sigma_{zx}{}^2 & \sigma_{zy}{}^2 & \sigma_{zz}{}^2 & \sigma_{zt}{}^2 \\ \sigma_{tx}{}^2 & \sigma_{ty}{}^2 & \sigma_{tz}{}^2 & \sigma_{tt}{}^2 \end{bmatrix} \tag{4-6}$$

Thus, each DOP is expressed as the following equation (4-7).

$$\begin{aligned} HDOP &= \sqrt{\sigma_{xx}{}^2 + \sigma_{yy}{}^2} \\ VDOP &= \sigma_{zz} \\ PDOP &= \sqrt{\sigma_{xx}{}^2 + \sigma_{yy}{}^2 + \sigma_{zz}{}^2} \\ TDOP &= \sigma_{tt} \\ GDOP &= \sqrt{\sigma_{xx}{}^2 + \sigma_{yy}{}^2 + \sigma_{zz}{}^2 + \sigma_{tt}{}^2} \end{aligned} \tag{4-7}$$

In other words, DOP has a significant impact on the position error. Since DOP is affected by the geometry of the satellite, the proper satellite arrangement can determine the user's location accuracy. Therefore, within the framework of the alternative navigation performance, the arrangement of the reference station and the UAV are quite important because the arrangement of the reference station and the UAV significantly impact on the alternative navigation performance.

4.2.2 Composition of HALE UAVs

As previously mentioned, the HALE UAV equipped with pseudolite or transceiver has a optimum DOP value and improved navigation performance when all UAVs is evenly distributed in all directions. One UAV should be placed on the center of UAV segment for determining the three dimensional position solution. Also, four or more HLAE UAV are necessary to determine the position.

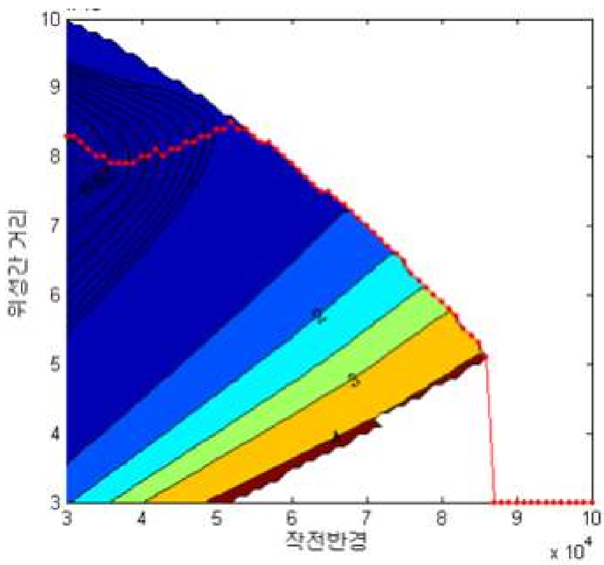

Figure 4-2 Optimum distance among UAVs [20]

In order to pursue the overlapping effects with a small number of UAV, in this study, the number of UAVs is limited six UAVs. Additionally, if available UAVs are enough, it is considered the case of ten UAVs.

In summary, for efficient geometric arrangement of the UAVs, a

UAV is located in center, the remaining five UAVs are arranged to have the same distance of 50km each other such as a pentagonal shape as shown figure 4-1.

Based on the reference [20], the distance among the UAVs is set 50km for the optimum operational radius as shown in figure 4-2.

4.2.3 Composition of reference stations

4.2.3.1 Ideal arrangement of reference station

Based on the UAV distribution above mentioned, it should be considered a reference station arrangement. Ground reference stations also arranged to have a geometrically symmetrical configuration to improve the DOP. Considering the small radius of operation in Korea, the number of reference station is limited six and distance among reference stations is 50km such as the distance among the HALE UAVs. The following figure 4-3 shows the Ideal arrangement of reference station.

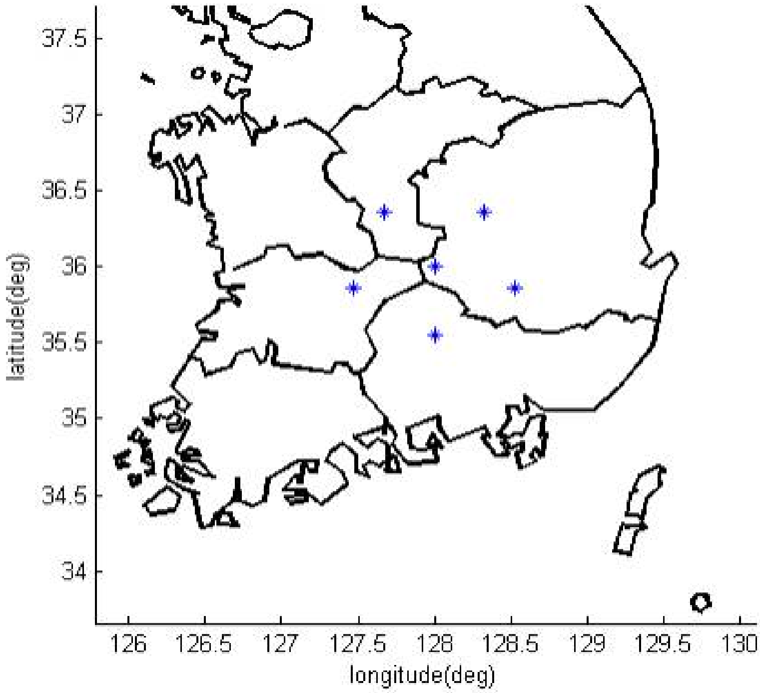

Figure 4-3 Ideal arrangement of reference station(* : RS)

4.2.3.2 Practical arrangement of reference station

Reference station arrangement referred to in section 4.2.3.1 shows the ideal arrangement that not considered a terrain and conditions of Korea. However, if the HALE UAV is used in practice, reference stations might be not an ideal arrangement. Therefore, in this section, positions of the GPS reference station in operation was used as the reference station position. In order to select the symmetrical position of reference stations as possible, positions of the GPS reference stations in Muju, Gimcheon, Changnyeong, Jinju, Namwon, and Geochang were used as the reference station position. The following figure 4-4 shows the reference station arrangement using positions of the GPS reference station in operation.

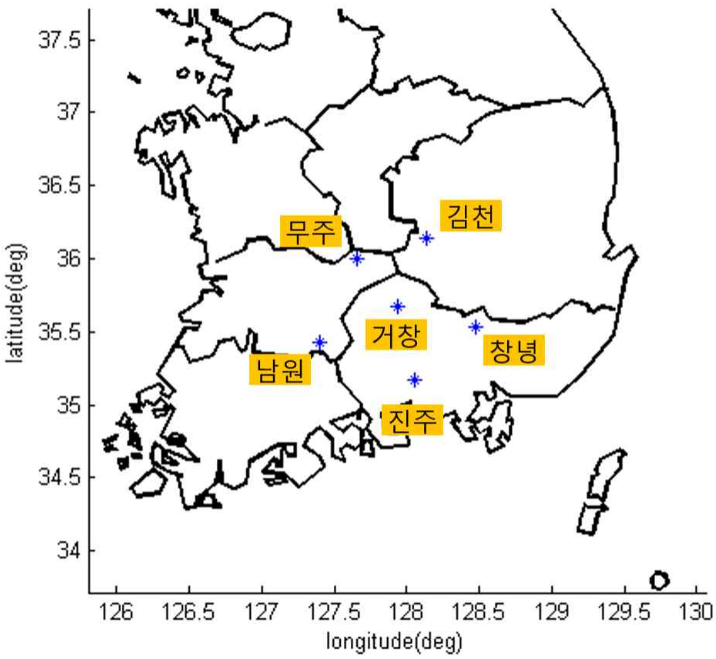

Figure 4-4 Reference station arrangement using positions of the GPS reference station

In this paper, the performance of alternative navigation was simulated in the ideal arrangement and the practical arrangement of reference station.

4.3 Simulation cases for alternative navigation system

4.3.1 Six HALE UAVs on six reference stations (case I)

In the first case, it was considered a situation that six HALE UAVs are on the six RSs as a normal case. For efficient geometric arrangement of the RS, a RS is located in center, the remaining five RSs are arranged to have the same distance of 50km each other. Six RSs are placed in a pentagonal shape. And then, a UAV is locate on the center RS and the remaining five UAVs are arranged to have the same distance of 50km each other at the 18~20km altitude.

A two-dimensional position of the central RS and UAV are the same position. However, the remaining RSs and UAVs are placed reversibly each other for the efficient and geometric arrangement. Then the service area is formed near the RSs. The RSs and UAVs arrangement in the first case is shown in Figure 4-5.

For simulations, the arrangement of reference station is made up by the ideal and practical arrangement as previously mentioned. In two reference station arrangement, the coordinates of a central HALE UAV is same as a central reference station.

In this case, the navigation service area would be formed more widely than the reference station network formation region such as figure 4-5.

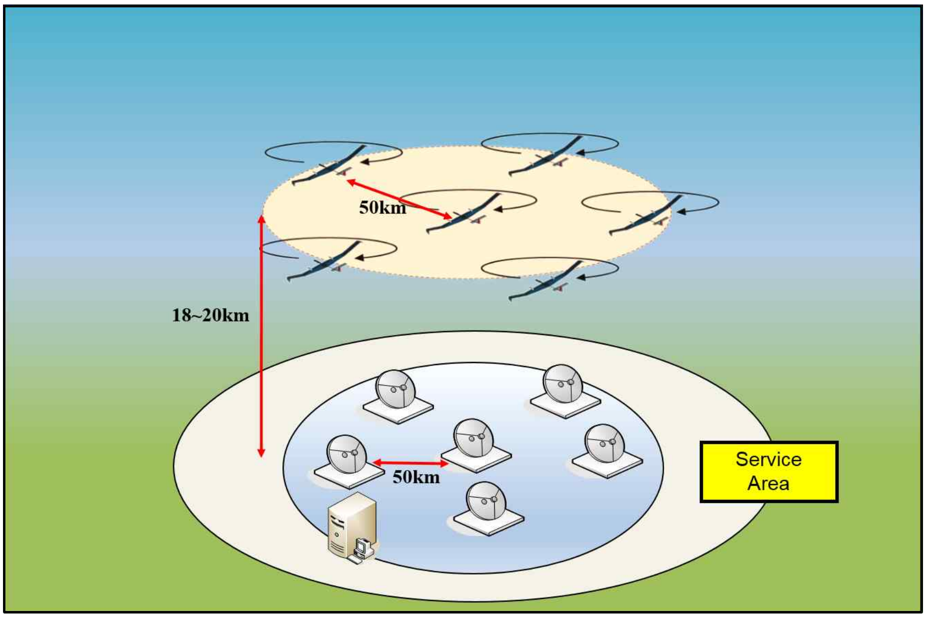

Figure 4-5 Placement of RSs and UAVs (case I)

4.3.2 Six HALE UAVs away from six reference stations (case II)

As the second case, it was considered a situation that six HALE UAVs are far away from the six RSs. The arrangement form of the RSs and UAVs is basically same. However, the HALE UAVa segment(the central UAV) is away 80km from the reference stations segment(the central RS). The reason for the distance of 80km between the central reference station and the central UAV is because it is the maximum distance for visibility between reference stations and UAVs at the 18~20km altitude of UAVs.

This arrangements are necessary when the user's navigation is required at place apart from the RS such as a local disaster away from the RSs and a flexible use of alternative navigation. The RSs and UAVs arrangement in the second case is shown in Figure 4-6.

For simulations, the arrangement of reference station is made up by the ideal and practical arrangement as previously mentioned. In this case, the navigation service area would be formed below the HALE UAVs segment the such as figure 4-6.

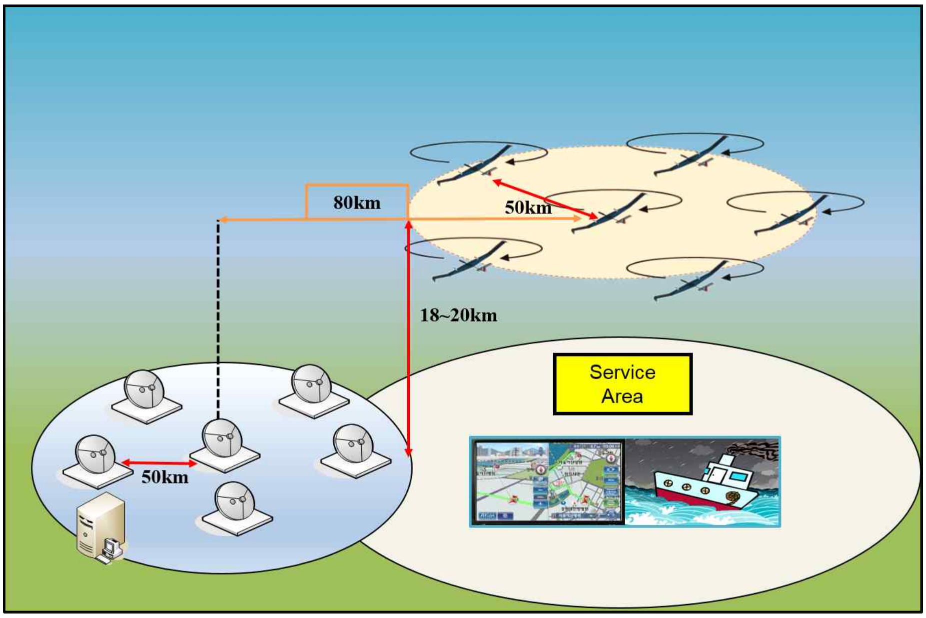

Figure 4-6 Placement of RSs and UAVs (case II)

4.3.3 Ten HALE UAVs on six reference stations (case III)

In the third case, it was considered the arrangement that case I and case II are combined. It is arrangement added four UAVs on the first case. The added four UAVs are located at position away from the RS as the second case. The distance is 80km between the central HALE UAVs for visibility between reference stations and UAVs. This case is necessary in using the alternative navigation on a large area and in improving the alternative navigation performance in case II situation if additional the UAVs are available. The RSs and UAVs arrangement in the third case is shown in Figure 4-7.

This case could be used if available UAVs are enough and have more measurements from pseudolite or transceiver. Thus, the geometric factor could be enhanced and the position accuracy of user would be better than other cases. The service area could be wider than other cases because of more measurements and enhanced geometric factor.

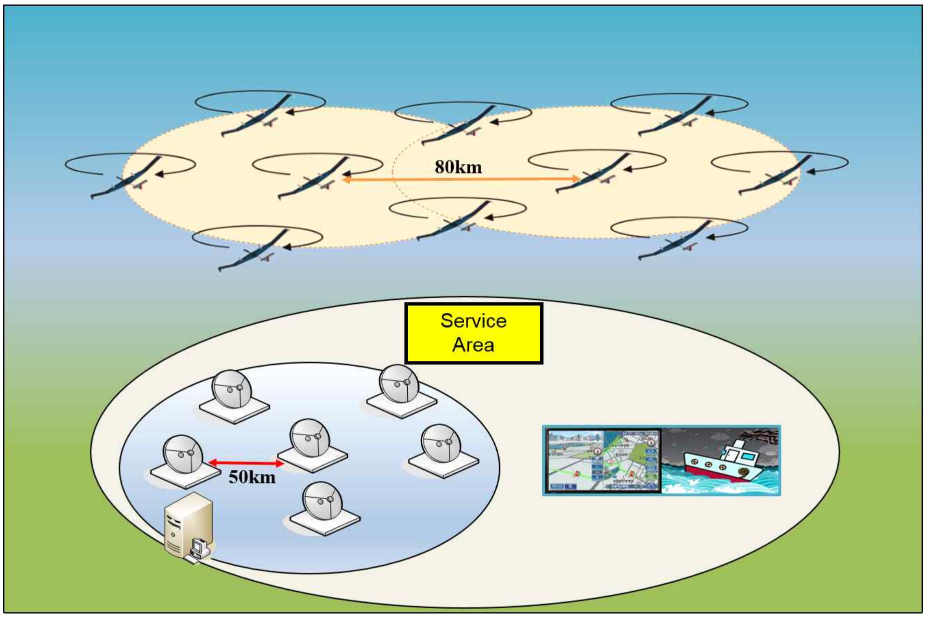

Figure 4-7 Placement of RSs and UAVs (case III)

4.3.4 One HALE UAV failure in case I (case IV)

As the last case, it was considered the situation of one HALE UAV failure in case I. In this case, the alternative navigation performance must be degraded and the service area would become narrow comparing the normal case (case I). Also, the geometric layout of the HALE UAVs breaks. Thus, the relocation of the normal HALE UAVs should be made to improve the geometry factor. In this study, the alternative navigation performance needs to be confirmed when one HALE UAV is failed and verify the navigation performance improvement after rearrangement of the available HALE UAVs. The RSs and UAVs arrangement in the third case is shown in Figure 4-8.

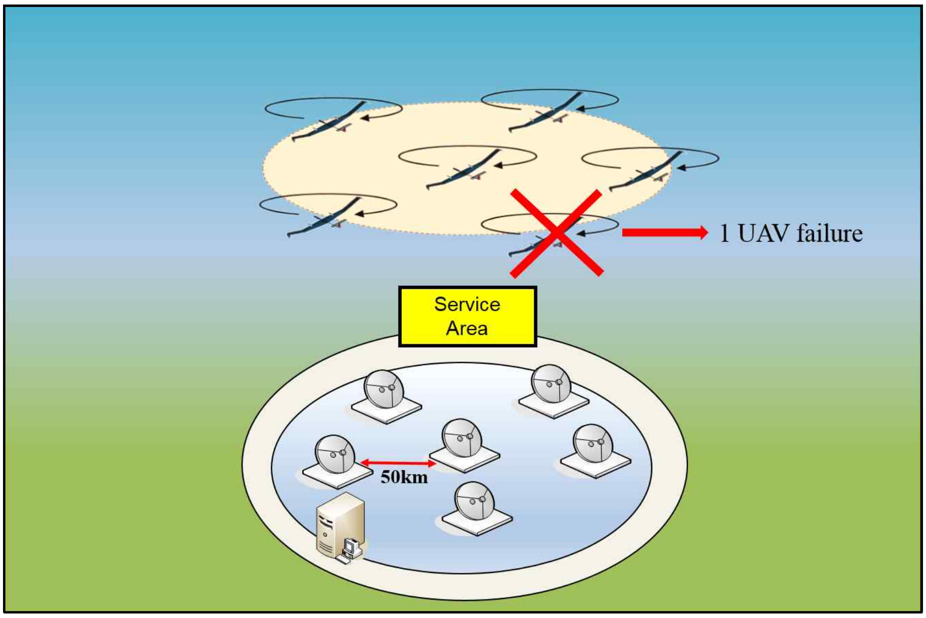

Figure 4-8 Placement of RSs and UAVs (case IV)

It is predicted that the position accuracy of user would be degraded because of the reduction of measurements and geometric factor.

4.4 Position estimation of the HALE UAVs

In this paper, two algorithm of the inverted GPS algorithm and the transceiver algorithm for the HALE UAVs position estimation were used as previously mentioned. In order to offer position information to the user segment, reference coordinates are absolutely necessary. Therefore, it is essential that the RSs are located on the known position. Based on two algorithm, the position estimation of the HALE UAVs consists of IGPS method, enhanced IGPS (EIGPS) method, transceiver I method and transceiver II method.

4.4.1 Inverted GPS method

Four algorithms to estimate the HALE UAV position are proposed. The first method is the inverted GPS method. In this case, the RSs have only receiver and the HALE UAVs have a pseudolite. It is assumed that the reference clock can be visible to all the RSs and the reference clock could eliminates the receiver clock error (B_{RS_k}) in each RS. Thus, the receiver clock bias in each of the RSs is eliminated by reference clock. And then the computing center estimates the position and clock error of the HALE UAV equipped with pseudolite as shown in equation (3-2). So, this method is called inverted GPS (IGPS) method. Referring to Equation (3-2) is shown as the following equation.

$$\rho^i_{RS_k} - B_{RS_k} + \hat{e}^i_{RS_k} \cdot R_{RS_k} = \overline{R}^i \cdot \hat{e}^i_{RS_k} - b^i$$
$$= [\hat{e}^i_{RS_k} \quad -1]\begin{pmatrix} R^i \\ b^i \end{pmatrix}$$

4.4.2 Enhanced inverted GPS (EIGPS) method

For the second method, the HALE UAV equipped with a pseudolite-receiver set is considered. In this case, the HALE UAVs can broadcasts the navigation message and receive the others signals. Also, it is assumed that the reference clock can be visible to all the RSs and the reference clock could eliminates the receiver clock error (B_{RS_k}) in each RS. Also, the CC estimates the HALE UAVs position, clock error of the HALE UAV equipped with pseudolite (b^i) and the receiver clock error using all measurements between the HALE UAVs and RSs as shown in equation (4-8), (4-9).

$$\rho^i_{RS_k} - B_{RS_k} + e^i_{RS_k} \cdot R_{RS_k} = [e^i_{RS_k} \quad -1]\begin{pmatrix} R^i \\ b^i \end{pmatrix} \tag{4-8}$$

$$\rho^i_j = [e^i_j \quad -1 \quad -e^i_j \quad 1]\begin{bmatrix} R^i \\ b^i \\ R^j \\ B^j \end{bmatrix} \tag{4-9}$$

This estimating algorithm is like the IGPS method. So, this method is called enhanced IGPS (EIGPS) method in this study.

4.4.3 Transceiver I (TRCVR I) method

For the third method, the HALE UAV equipped with transceiver is considered. Transceiver broadcasts the navigation signal as well as receives that signal from other transmitters. Transceiver is integrated with the part of transmitter and receiver. Thus it could be assumed that the part of transmitter and receiver have the same clock error. That means that the clock error of transmitter and receiver is same and is has a advantage that the estimated clock error is reduce. However, transceiver I method cannot use the transceiver algorithm because the reference station has not a transceiver but only a receiver.

Also, it is assumed that the reference clock can be visible to all the RSs and the transmitter part and receiver part of the transceiver share the same clock. Then, the reference clock could eliminates the receiver clock bias in each RS. The transmitter part and receiver part of the transceiver have the same clock error. And then the CC estimates the HALE UAVs position, the clock error of the HALE UAV equipped with transceiver using all measurements between the HALE UAVs and RSs as shown in equation (4-10), (4-11). And this method is called transceiver I method in this study.

$$\rho^i_{RS_k} - B_{RS_k} + e^i_{RS_k} \cdot R_{RS_k} = [e^i_{RS_k} \quad -1]\begin{pmatrix} R^i \\ B^i_{HALE} \end{pmatrix} \qquad (4\text{-}10)$$

$$\rho_j^i = [e_j^i \quad -1 \quad -e_j^i \quad 1]\begin{pmatrix} R^i \\ B_{HALE}^i \\ R^j \\ B_{HALE}^j \end{pmatrix} \tag{4-11}$$

4.4.4 Transceiver II (TRCVR II) method

For the last method, it is considered that all the RSs and HALE UAVs is equipped with transceiver. That means that all the RSs and HALE UAVs can broadcast the signals as well as receive them. The reference clock is not necessary according to transceiver positioning algorithm because the alternative navigation system need not to eliminate the RSs clock bias as previously mentioned in transceiver algorithm.

Using the real distance between SV and RS and between the SVs, the receiver part clock bias and the transmitter part clock error can be eliminated in transceiver as mentioned in transceiver algorithm. And the all measurements among the transceivers can be described by the following equation (4-12). The HALE UAVs position can be solved by using the equation (4-12). So, this method is called transceiver II method in this study.

$\tilde{\rho}_{RS_k}^j$ means the self-differenced measurement from j-th transceiver of HALE UAV to k-th transceiver of reference station.

$$\begin{pmatrix} \dfrac{\tilde{\rho}_{RS_1}^{1} + \tilde{\rho}_{1}^{RS_1}}{2} + e_{RS_1}^{1} \cdot R_{RS_1} \\ \vdots \\ \dfrac{\tilde{\rho}_{RS_k}^{j} + \tilde{\rho}_{j}^{RS_k}}{2} + e_{RS_k}^{j} \cdot R_{RS_k} \\ \vdots \\ \dfrac{\tilde{\rho}_{1}^{2} + \tilde{\rho}_{2}^{1}}{2} \\ \vdots \\ \dfrac{\tilde{\rho}_{j}^{i} + \tilde{\rho}_{i}^{j}}{2} \\ \vdots \\ \dfrac{\tilde{\rho}_{n-1}^{n} + \tilde{\rho}_{n}^{n-1}}{2} \end{pmatrix} = \begin{bmatrix} e_{RS_1}^{1} & 0 & \cdots & 0 & \cdots & & 0 \\ \vdots & & \vdots & & \vdots & & \vdots \\ 0 & \cdots & 0 & \cdots 0 & e_{RS_k}^{j} & 0 \cdots & 0 \\ \vdots & & \vdots & & \vdots & & \vdots \\ -e_{1}^{2} & e_{1}^{2} & 0 & \cdots & 0 & \cdots & 0 \\ \vdots & & \vdots & & \vdots & & \vdots \\ 0 & \cdots 0 \cdots & -e_{i}^{j} & 0 \cdots 0 & e_{i}^{j} & \cdots & 0 \\ \vdots & & \vdots & & \vdots & & \vdots \\ 0 & \cdots & 0 & \cdots & 0 & -e_{n-1}^{n} & e_{n-1}^{n} \end{bmatrix} \begin{pmatrix} R^{1} \\ R^{2} \\ \vdots \\ R^{i} \\ \vdots \\ R^{j} \\ \vdots \\ R^{n} \end{pmatrix} \tag{4-12}$$

4.5 Position accuracy calculation of the HALE UAV and user

In this study, DOP based on a position estimation of the HALE UAV and the concept of user equivalent range error (UERE) were used in the calculation about position accuracy calculation of the HALE UAV and user. UERE is defined as the total statistical level of pseudorange errors (i.e., accuracy) experienced by a GPS receiver in the navigation process which are uncorrelated across the satellite-derived PR measurements being used for the navigation solution [21].

Kovach suggested a new UERE in his paper [21]. Park reconstructed the error budget of the alternative navigation system [18]. In our navigation system, all the pseudorange from our alternative navigation system do not include any ionospheric delay error because the HALE UAVs operate in stratosphere area.

Additionally it is assumed that the tropospheric delay error is almost zero between the HALE UAVs as there is little water vapor and gas in stratosphere area. Therefore the error budget of the alternative navigation system was reorganized as the following in table 4-1.

Table 4-1 UERE for simulations

Error source	Between UAVs	Ground user/RS
Receiver noise	0.2 (m)	0.2 (m)
Tropospheric delay	0.0 (m)	0.5 (m)
Ionospheric delay	0.0 (m)	0.0 (m)
Multipath	0.1 (m)	0.9 (m)
Other error	0.4 (m)	0.4 (m)
UERE	0.46 (m)	1.12 (m)

In conclusion, the UERE of the measurement between the HALE UAVs is 0.46m and between the HALE UAV and surface user / RS is 1.12m. And the position accuracy of the HALE UAVs can be expressed in $\sigma_{(HALE\ UAV)}$. Thus, the DOPs of user and UAV were calculated based on the observation matrix in section 4.4. Using the DOPs and new UERE, position accuracy of the HALE UAV and user was calculated. The position accuracy of HALE UAV can be calculated as equation (4-13) and the position accuracy of user can be calculated as equation (4-14).

$$(Position\ Accuracy)_{HALE\ UAV} = (DOP)_{HALE\ UAV} \times \sigma_{UERE} \qquad (4\text{-}13)$$

$$(Position\ Accuracy)_{USER} = (DOP)_{USER} \times \sqrt{\sigma^2_{HALE\ UAV} + \sigma^2_{UERE}} \qquad (4\text{-}14)$$

It is assumed that the mask elevation angle is 5 degree in order to confirm the visibility between the RS and the HALE UAVs.

V. Simulation results and analyses

Since 24 hours simulations are mainly performed with interval of 5 minutes (289 epoch), the position accuracy of the HALE UAVs and the ground user were calculated per the time interval. And the averaged position accuracy of the ground user was computed during 289 epoch. In other words, equation (4-13), (4-14) was calculated per each epoch and the results of equation (4-14) were averaged in accordance with horizontal and vertical accuracy. Thus, the numerical values in following sections are the average positioning accuracy of ground user.

In this part, the simulation results of ideal RSs arrangement mainly mentioned because the simulation results of practical RSs arrangement has a similar tendency. Thus, the simulation results of practical RSs arrangement were sum up in the last section.

5.1 Six HALE UAVs on six reference stations (case I)

The simulations of case I was conducted as a normal case. As previously mentioned, the navigation system has 6 HALE UAVs and 6 reference stations and the HALE UAVs are on the RSs at an altitude of 18~20km. The ground user should be located near the RSs to receive a navigation message from the HALE UAVs because the service area is formed near the RSs. The position of the UAVs estimated epoch by epoch during 24 hours with interval of 5 minutes.

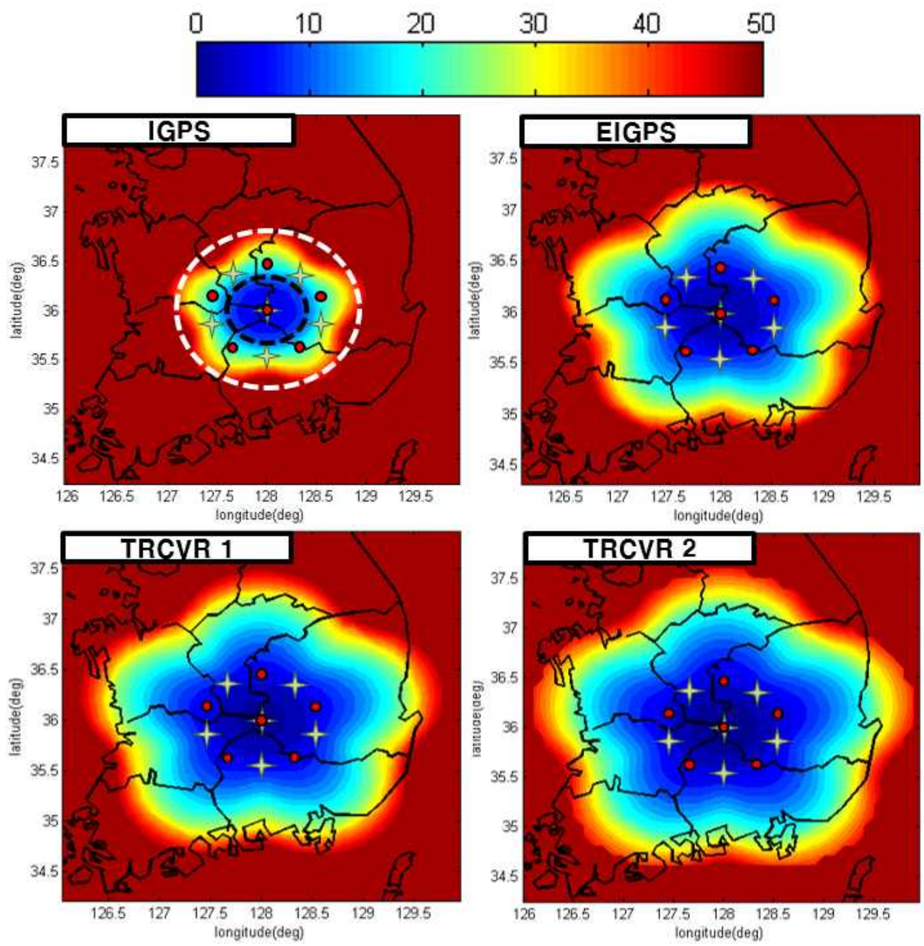

Figure 5-1 Averaged horizontal position accuracy of ground user (Case I, ideal RSs arrangement)

The position accuracy of the ground user estimated based on the HALE UAVs position error and the UERE between the user and the

HALE UAVs. The average position accuracy of the ground user from simulations is shown as the following figures 5-1, 5-2 and table 5-1 in this case.

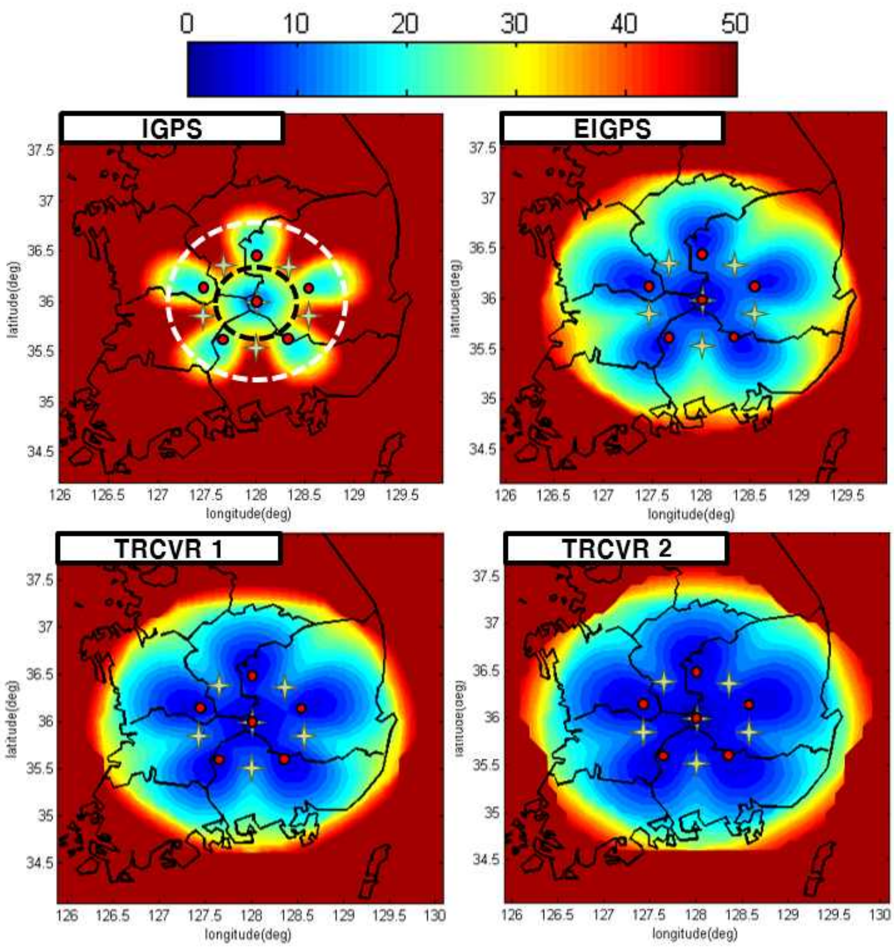

Figure 5-2 Averaged vertical position accuracy of ground user (Case I, ideal RSs arrangement)

Figure 12 and Figure 13 show the horizontal and vertical error of all the user in service area. In these figures, x axis is the longitudinal coordinate and y axis is the latitude coordinate. The color bar represents the degree of user position error. The white dash line means the area of 150km diameter and the black dash line is the area of 75km diameter as a central area to compare with the navigation performance of each positioning algorithm. The black line means territorial boundaries and administrative districts of Korea.

The area of available navigation service was broaden in order: IGPS, EIGPS, TRCVR I and TRCVR II. And the user position accuracy in 150km diameter and central area were represented to be good in order like the area of available navigation service. In particular, the user accuracy was sharply bad outside the HALE UAVs network area in IGPS method results. And TRCVR I and II methods show that the alternative navigation performance is below approx. 20m over half of Korean territory under unavailable GNSS. This means that our alternative navigation performance except IGPS may be able to provide the ground user in civil and military with considerably accurate positioning. The service area below 20m accuracy became wider in same order. And it shows below 20m accuracy in white dash line area and below 4m accuracy in black dash line area except IGPS method.

The average position accuracies of ground user are summarized in Table 3.

Table 5-1 Averaged position accuracy of user (Case I, ideal RSs arrangement)

Classification		IGPS	EIGPS	TRCVR I	TRCVR II
Horizontal accuracy	150 km diameter area	43.96 m	18.06 m	13.40 m	9.67 m
	75 km diameter area	9.02 m	3.71 m	2.75 m	1.98 m
Vertical accuracy	150 km diameter area	40.74 m	16.74 m	12.41 m	8.96 m
	75 km diameter area	24.82 m	10.20 m	7.56 m	5.46 m

5.2 Six HALE UAVs far away from six RSs (case II)

The previous section is a case of the optimal geometric arrangement with six RSs and HALE UAVs in order to guarantee the best alternative navigation performance.

However, the HALE UAVs are not always necessary to operate under circumstances of Case I. In some cases, it might be required the alternative navigation in area away from the RS such as extraordinary situation. Thus, it needs to provide the alternative navigation after moving to the area with the maneuverability of UAV because extraordinary cases are difficult to predict. Therefore, in this section, the case of the HALE UAVs located far from the RSs was simulated .

Figure 5-3 and Figure 5-4 show the horizontal and vertical error of all the user in service area in the case II. The tendency of the area of available navigation service is similar to the case I. Also that of the user position accuracy in 150km diameter area and central area is similar, too. However, the alternative navigation performance was degraded because the geometry factor is bad comparing to the case I. The position accuracy of IGPS method was terrible. Only TRCVR 1 and 2 showed the alternative navigation performance of approx. 20m in 150km diameter area.

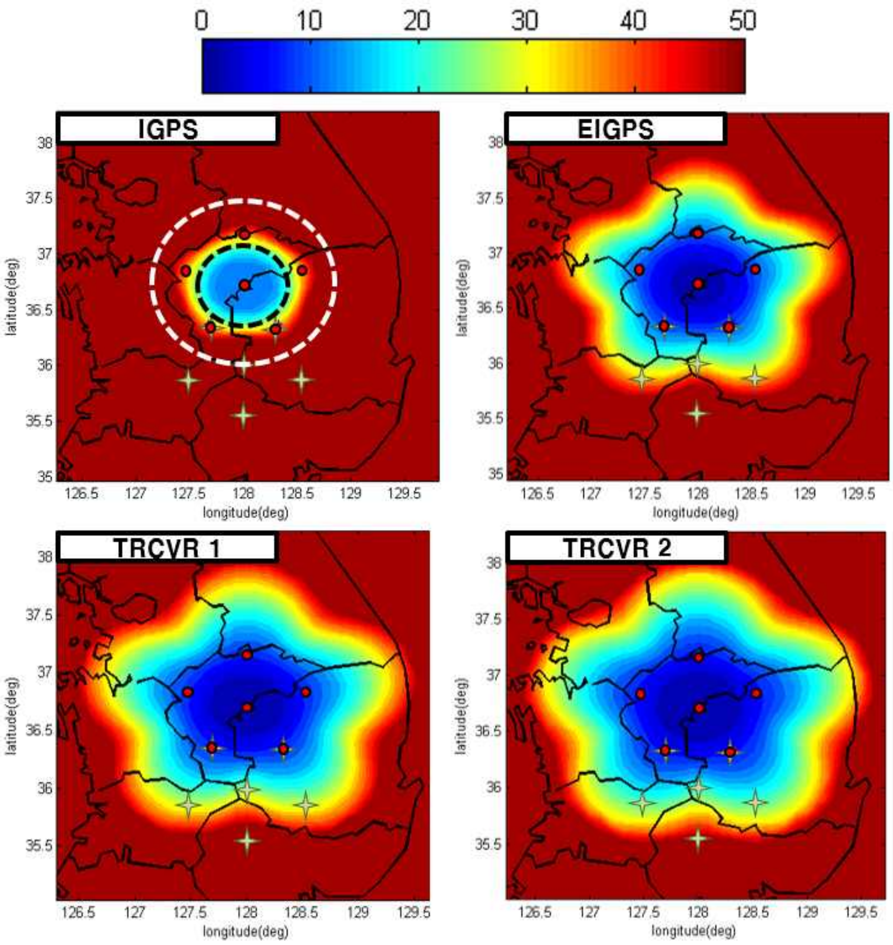

Figure 5-3 Averaged horizontal position accuracy of ground user (Case II, ideal RSs arrangement)

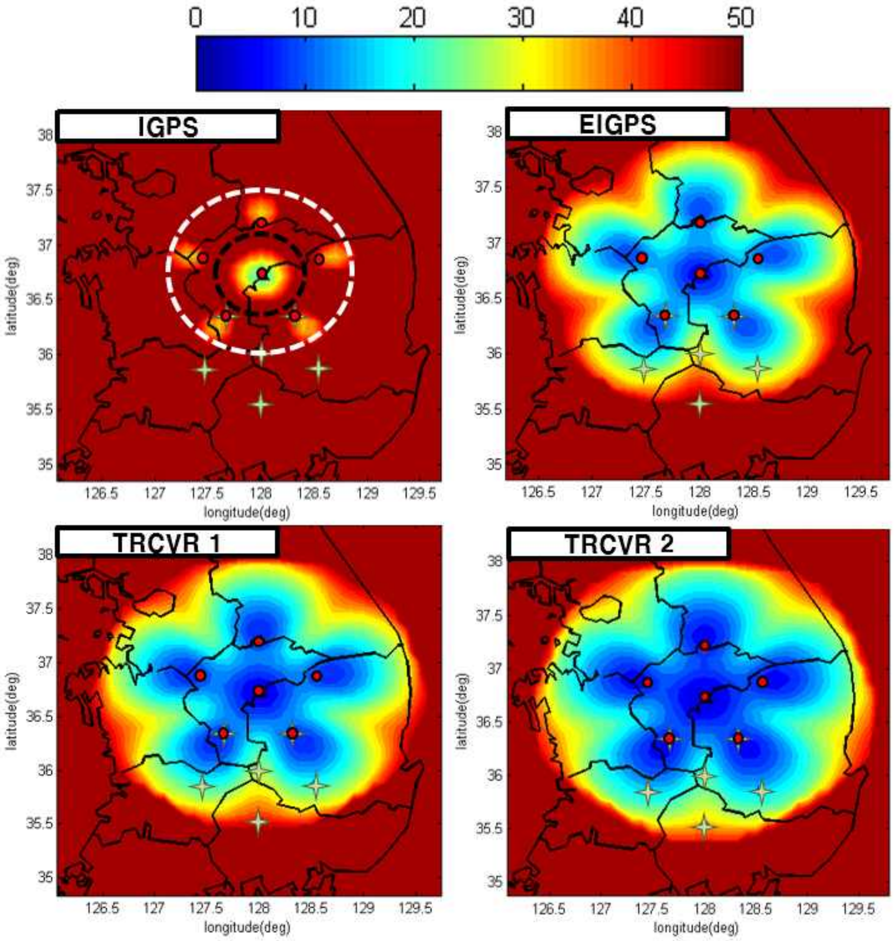

Figure 5-4 Averaged vertical position accuracy of ground user (Case II, ideal RSs arrangement)

Table 5-2 Averaged position accuracy of user (Case II, ideal RSs arrangement)

Classification		IGPS	EIGPS	TRCVR I	TRCVR II
Horizontal accuracy	150 km diameter area	82.47 m	26.48 m	21.69 m	15.94 m
	75 km diameter area	17.89 m	5.74 m	4.71 m	3.46 m
Vertical accuracy	150 km diameter area	76.44 m	24.54 m	20.10 m	14.78 m
	75 km diameter area	46.21 m	14.84 m	12.15 m	8.93 m

Inspiring aspects are that EIGPS, TRCVR 1 and TRCVR 2 have the navigation performance of less than 6m in horizontal position accuracy on the central area. That means those navigation method might be utilized the narrow disaster area with high position accuracy. The average position accuracies of ground user in the case II are summarized in Table 5-2.

5.3 Ten HALE UAVs on six RSs (case III)

The case II has the advantage of providing with the navigation in areas away from the RS, but it showed a worse position accuracy than the case I because the case II has a poor geometric arrangement between the RSs and the UAVs. To overcome this, the CASE III was considered. This case has the disadvantage that a lot of UAV needed. However if possible, it is able to improve the user position accuracy near RSs and that of the area away from the RSs through the network linkage between the HALE UAVs except IGPS method. Though it does not have the network linkage between the HALE UAVs in IGPS method, the user position accuracy is a little improved due to more measurements from the increased number of the HALE UAVs.

Figure 5-5 and 5-6 show the horizontal and vertical error of all the user in service area in the case III. Those shows a more accurate user position and wider service area for the four navigation methods.

All four methods improved the user position accuracy comparing to the case I and II by the increased measurements due to the increment of the HALE UAVs.

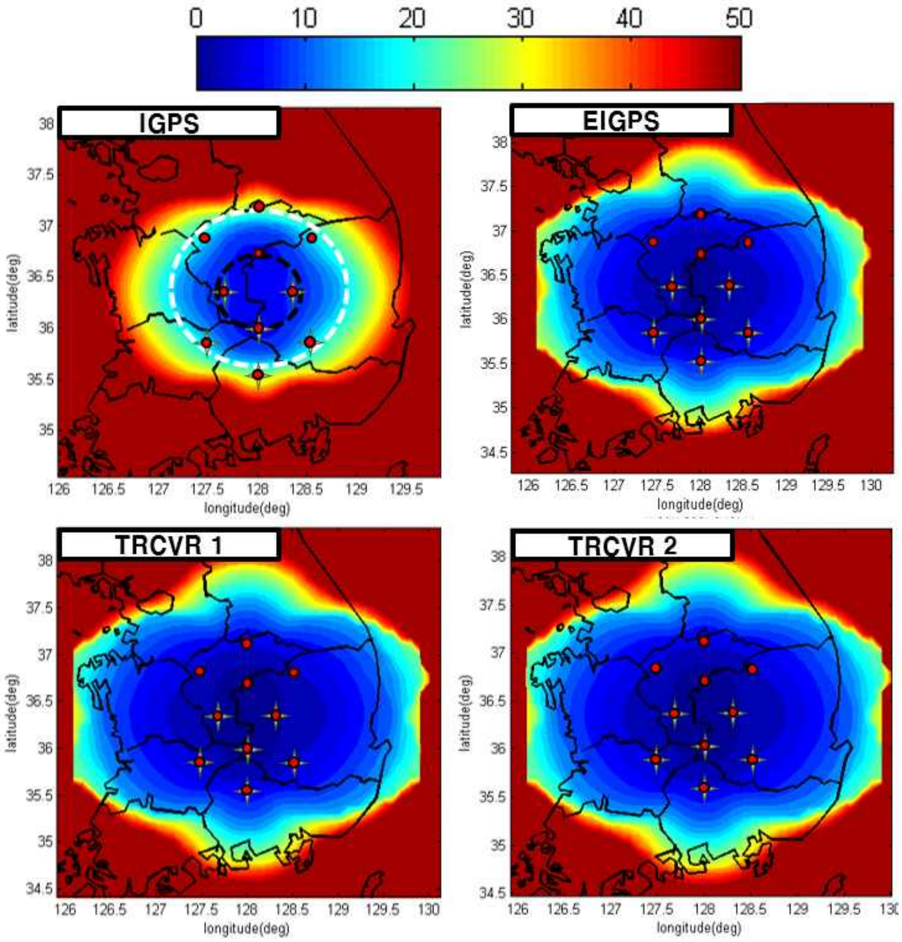

Figure 5-5 Averaged horizontal position accuracy of ground user (Case III, ideal RSs arrangement)

Also, three cases – EIGPS, TRCVR I and TRCVR II – have more improved user position accuracy by the HALE UAVs linkage. In addition, except for the IGPS, those methods show that the alternative navigation performance is below approx. 20m over almost of Korean territory. In that case, the alternative navigation system might be provide the ground user with much accurate position accuracy in almost Korean territory under the unavailable GNSS situation.

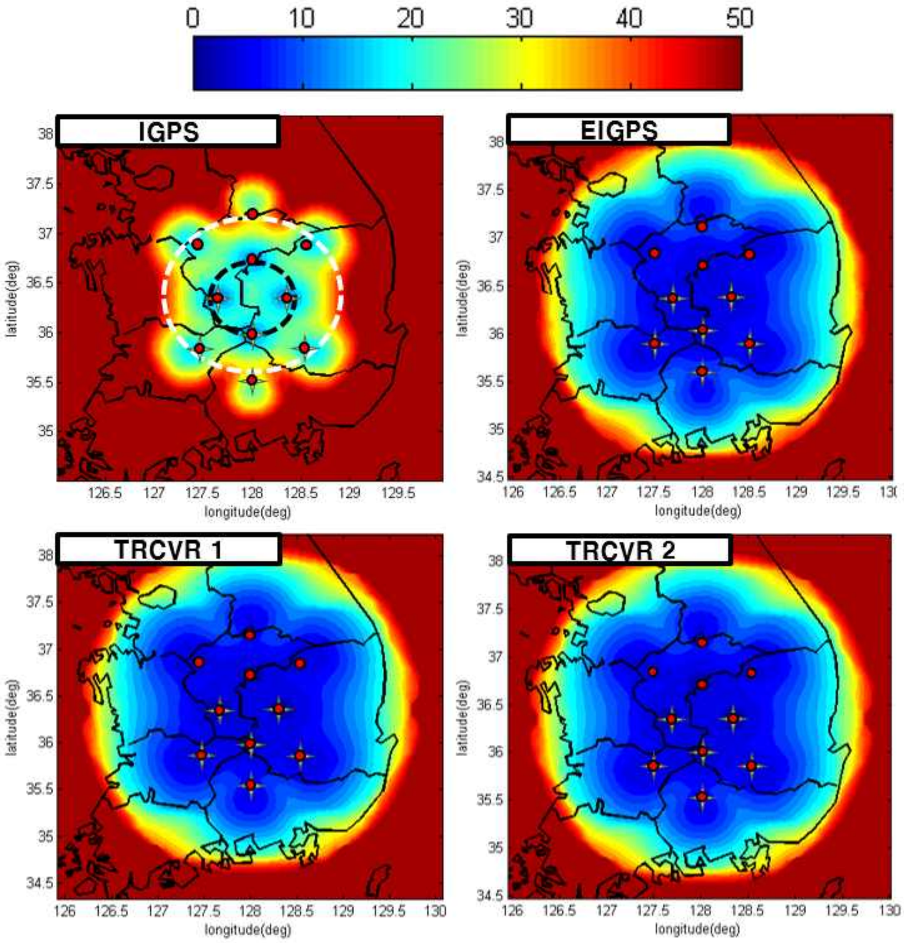

Figure 5-6 Averaged vertical position accuracy of ground user (Case III, ideal RSs arrangement)

The summarized average of position accuracies in case III is shown in Table 5-3.

Table 5-3 Averaged position accuracy of user (Case III, ideal RSs arrangement)

Classification		IGPS	EIGPS	TRCVR I	TRCVR II
Horizontal accuracy	150 km diameter area	20.43 m	5.86 m	5.12 m	4.76 m
	75 km diameter area	7.49 m	2.15 m	1.88 m	1.74 m
Vertical accuracy	150 km diameter area	29.55 m	9.80 m	8.57 m	7.96 m
	75 km diameter area	18.91 m	5.42 m	4.74 m	4.40 m

5.4 One HALE UAV failure in case I (case IV)

So far, simulations were performed for the cases that all the HALE UAVs operates normally. However, all the HALE UAVs are always hard to operate properly. Thus, all the operators and managers of the HALE UAVs would prepare for the emergency situation such as one HALE UAV failure.

In this section, simulations were conducted assuming that one UAV breaks down in the case I. And the improved alternative navigation performance was confirmed by rearrangement of remained the HALE UAVs in order to be good the geometry factor. The IGPS method was excluded because the navigation performance of IGPS was worst among the positioning methods. Only the figure of horizontal case will be shown in this paper because the vertical case have a tendency of the horizontal case. Both results are summarized numerically in the Table 5-4.

As seen in Figure 5-7 and 5-8, if one HALE UAV is failed, the distribution of the user position accuracy is changed by the variation of geometry factor. The white dash line means the area of 150km diameter.

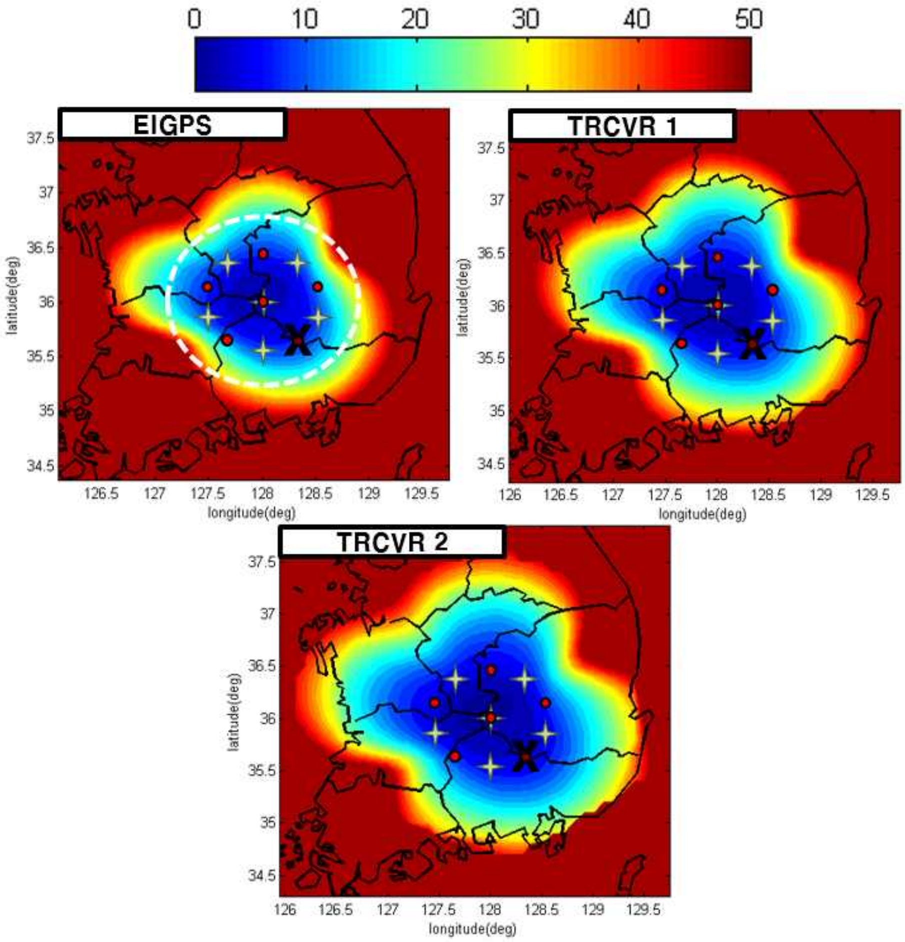

Figure 5-7 Averaged horizontal position accuracy of ground user (Case IV, ideal RSs arrangement, before the relocation)

In this case, the whole horizontal and vertical accuracy are reduced and the unavailable navigation area is appeared comparing to the case I. Therefore, the relocation of the HALE UAVs should be performed for the optimization of the navigation performance by using the maneuverability of HALE UAVs.

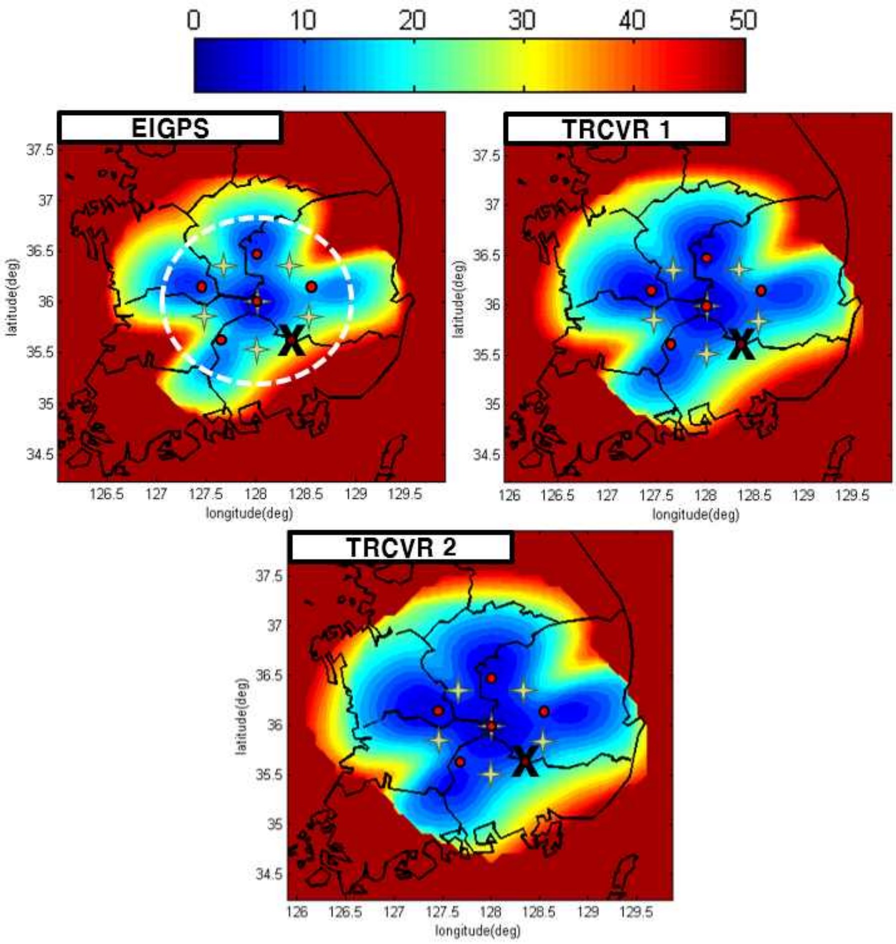

Figure 5-8 Averaged vertical position accuracy of ground user (Case IV, ideal RSs arrangement, before the relocation)

The user position errors after the rearrangement of the remaining

HALE UAVs is shown in Figure 5-9, 5-10.

Figure 5-9 and 5-10 shows that the horizontal position accuracy of ground user is improved and the service area becomes broader than Figure 5-7 and 5-8. The summarized average of position accuracies in case IV is shown in Table 5-4. It shows that the average position accuracy is improved 15% ~ 20% percent by the rearrangement of the HALE UAVs.

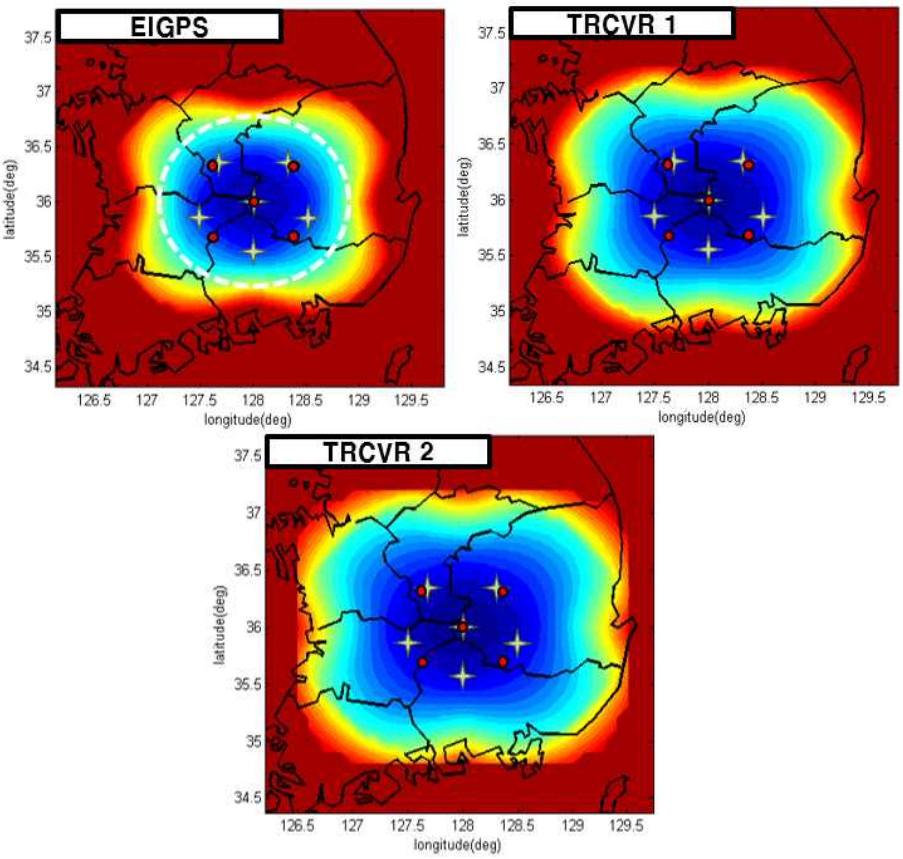

Figure 5-9 Averaged horizontal position accuracy of ground user (Case IV, ideal RSs arrangement, after the relocation)

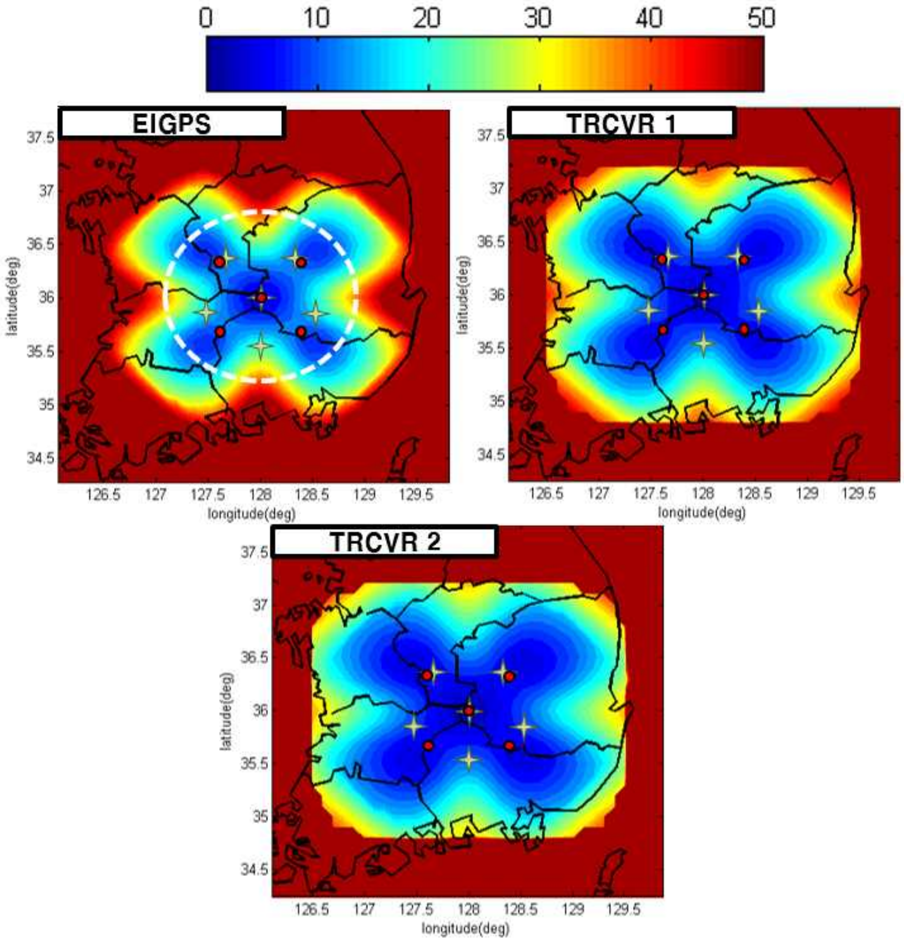

Figure 5-10 Averaged vertical position accuracy of ground user (Case IV, ideal RSs arrangement, after the relocation)

Table 5-4 Averaged position accuracy of user (Case IV, ideal RSs arrangement)

Classification		EIGPS	TRCVR I	TRCVR II
Horizontal accuracy (150 km diameter area)	Before relocation	27.54 m	18.64 m	13.65 m
	After relocation	23.55 m	14.68 m	11.33 m
Vertical accuracy (150 km diameter area)	Before relocation	26.96 m	18.25 m	13.37 m
	After relocation	23.49 m	14.62 m	11.30 m

Through the relocation of HALE UAVs, it was founded that the position accuracy of user was improved approx. 4m～2m. The results is degraded than the results of case I, but it was reasonable position accuracy considering a HALE UAV failure.

5.5 Cases using practical position of reference stations (Case I, II, III)

So far, simulations were performed for the cases that uses a ideal position of reference stations. However, the position of reference cannot be guaranteed the ideal position considering the actual environment. Thus, in this section, the practical positions of GPS reference station in Korea were set to the position of reference stations for alternative navigation system in this paper. The simulation cases is same as case I, II and III except for case IV in this section. Case IV was excluded because the case IV is under a emergency situation.

As using the practical positions of GPS reference station in Korea as he position of reference stations for alternative navigation system, the geometric factor is not optimum. In order to select the symmetrical position of the GPS reference stations as possible, positions of the GPS reference stations in Muju, Gimcheon, Changnyeong, Jinju, Namwon, and Geochang were used as the reference station position as fiugre 4-4 in section 4. As the pre-mention, the DOP of practical position of reference stations is less than the DOP of ideal position of reference stations. Thus, the alternative navigation performance using the practical position of reference stations will be degraded.

Table 5-5 and 5-6 show the result of alternative navigation using the practical position of reference stations according to 150 km and 75 km diameter area.

Table 5-5 Position accuracy of user according to reference arrangement (area of diameter 150 km)

Classification			Case I	Case II	Case III
Practical arrangement of RSs	Horizontal accuracy	IGPS	49.28 m	110.44 m	29.82 m
		EIGPS	21.69 m	34.23 m	8.25 m
		TRCVR I	16.02 m	21.26 m	7.25 m
		TRCVR II	11.70 m	19.18 m	6.66 m
	Vertical accuracy	IGPS	44.20 m	99.11 m	35.49 m
		EIGPS	19.45 m	30.71 m	9.81 m
		TRCVR I	14.37 m	26.18 m	8.62 m
		TRCVR II	10.49 m	19.08 m	7.92 m
Ideal arrangement of RSs	Horizontal accuracy	IGPS	43.96 m	82.47 m	20.43 m
		EIGPS	18.06 m	26.48 m	5.86 m
		TRCVR I	13.40 m	21.69 m	5.12 m
		TRCVR II	9.67 m	15.94 m	4.76 m
	Vertical accuracy	IGPS	40.74 m	76.44 m	29.55 m
		EIGPS	16.74 m	24.54 m	9.80 m
		TRCVR I	12.41 m	20.10 m	8.57 m
		TRCVR II	8.96 m	14.78 m	6.88 m

Table 5-5 Position accuracy of user according to reference arrangement (area of diameter 75 km)

구분			Case I	Case II	Case III
Practical arrangement of RSs	Horizontal accuracy	IGPS	16.46 m	41.79 m	9.71 m
		EIGPS	7.24 m	12.96 m	2.68 m
		TRCVR I	5.35 m	11.06 m	2.36 m
		TRCVR II	3.91 m	8.05 m	2.17 m
	Vertical accuracy	IGPS	25.76 m	55.83 m	23.50 m
		EIGPS	11.33 m	17.31 m	6.50 m
		TRCVR I	8.37 m	14.75 m	5.71 m
		TRCVR II	6.11 m	10.75 m	5.24 m
Ideal arrangement of RSs	Horizontal accuracy	IGPS	9.02 m	17.89 m	7.49 m
		EIGPS	3.71 m	5.74 m	2.15 m
		TRCVR I	2.75 m	4.71 m	1.88 m
		TRCVR II	1.98 m	3.46 m	1.74 m
	Vertical accuracy	IGPS	24.82 m	46.21 m	18.91 m
		EIGPS	10.20 m	14.84 m	5.42 m
		TRCVR I	7.56 m	12.15 m	4.74 m
		TRCVR II	10.20 m	8.93 m	4.40 m

Table 5-5 and 5-6 show that the result of alternative navigation using the practical position of reference stations was degraded than that of the practical position of reference stations because of the worse DOP. In the results of TRCVR II method, the results of the practical position of reference stations shows the decrease of 20%(2.03m), 17%(1.50m) in horizontal and vertical accuracy of user in comparison with the result of ideal position of reference stations in case I. And it shows that the decrease of 33%(5.32m), 29%(4.30m) in horizontal and vertical accuracy of user in comparison with the result of ideal position of reference stations in case II. Also it shows that the decrease of 39%(1.9m), 15%(1.40m) in horizontal and vertical accuracy of user in comparison with the result of ideal position of reference stations in case III. However, the result of he practical position of reference stations is almost comparable to the result of ideal position of reference stations. Thus, that means the alternative navigation system could be constructed by using the GPS reference station in operating without new reference stations.

VI. Conclusions

HALE UAV plays an intermediate role between the satellite operation zone and tropospheric aircraft operation zone. It could have advantages of both system: satellite and conventional aircraft. Therefore HALE UAV will be utilized in a wide variety of missions in civil and military sectors including back-up or alternative navigation. In this paper, the alternative navigation in regional area such as Korea was simulated on the assumption that GNSS is unavailable. Simulation was performed in four methods – IGPS, EIGPS, transceiver I and transceiver II – and 4 cases: HALE UAVs on RS, HALE UAVs far-away from RSs, ten HALE UAVs on RS and one HALE UAV failure.

The IGPS method showed that the navigation performance was degraded the navigation performance due to the measurements shortage. The EIGPS method could make up by the commercial equipment such as pseudolite-receiver set and it showed that the navigation performance of EIGPS method improved by approx. 60% than IGPS method. Transceiver I method required just one transceiver and it showed that the navigation performance of transceiver I method was improved by 15% than EIGPS method. It was found that position accuracy of IGPS is very susceptible to the geometry, and it could not be operated for the regional service area. Furthermore, IGPS, EIGPS and transceiver I methods are based on the IGPS algorithm, so they should have an additional reference clock to eliminate the RS clock error. In this paper, it was assumed that a reference clock is visible to all the RS. In fact, its visibility is a remaining problem when the satellite based navigation system is ruled out.

The transceiver II method provided the ground user with the best position accuracy and the widest service area below 20m position accuracy among four methods in our simulations. In addition, the transceiver II method has the advantage of not being required a reference clock as the algorithm referred to in the section 3. Thus, it may be the most ideal means of alternative navigation. And a pseudolite-receiver set may be able to be consisted of commercial devices, so EIGPS method is highly potential for utilization in this respect. Also, it was verified that our alternative navigation system could provide the ground user with the good navigation performance by the relocation of UAVs when one HALE UAV fails.

This paper may contribute to the regional alternative navigation system with HALE UAVs independent of the GNSS. In particular, the country with short radius of operations such as Korea is expected to be able to operate an independent and alternative navigation system.

In the future, additional simulation would be carried out to improve the position accuracy of user by using differential GPS (<3m), and carrier-phase differential GPS (cm level) algorithm considering the random wind components.

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초 록

범지구 위성항법 시스템(GNSS, Global Navigation Satellite System)은 인공위성에서 방송된 신호를 수신기를 사용하여 사용자에게 자신의 위치, 속도, 시간 등을 실시간으로 제공하는 시스템으로 사용자의 수와 장소, 시간에 구애받지 않고 지속적으로 서비스가 가능하다는 장점을 바탕으로 민군 분야에서 폭넓게 활용되고 있으며, 많은 국가들이 그것의 다양한 활용분야 때문에 자국의 항법시스템을 구축하기를 희망한다. 그러나 GNSS 신호는 해당 신호가 너무 약하여 쉽게 방해받을 수 있다. 따라서 GNSS jamming과 같은 상황 하에서 일정한 항법 성능을 보장하기 위한 일련의 백업 또는 대체항법 시스템이 필요한 추세이다.

본 논문에서는 국지적인 지역의 대체항법을 제안하기 위해 약 18 km ~ 20 km의 고고도에서 수일 또는 수개월에 걸쳐 장시간 체공이 가능한 무인기로 정의되는 고고도 장기체공 무인기(HALE UAV, High Altitude Long Endurance Unmanned Aerial Vehicle)와 Inverted GPS 알고리즘을 활용하는 의사위성, 트랜시버의 개념을 도입하였다.

Inverted GPS 알고리즘은 의사위성이 장착된 무인기로부터의 신호를 위치가 고정된 지상국이 수신하여 신호를 처리함으로써 무인기의 위치를 추정하고 추정된 무인기의 위치를 기반으로 사용자에게 항법메세지를 방송하는 알고리즘이며, 트랜시버 알고리즘은 트랜시버를 장착한 무인기간 또는 해당 무인기와 위치가 고정된 지상국 간의 양방향 측정치를 사용하여 시계오차 상쇄를 통해 무인기의 위치를 추정하고 사용자에게 항법메세지를 방송하는 알고리

즘이다. 따라서 본 논문에서는 위의 두 가지 알고리즘을 기반으로 의사위성 또는 트랜시버를 장착한 고고도 장기체공 무인기를 활용한 대체항법의 성능을 시뮬레이션을 위해, 두 가지 알고리즘을 활용한 고고도 장기체공 무인기의 위치정확도를 먼저 추정하였으며, 추정된 무인기의 위치정확도와 일반적인 의사거리 오차를 사용하여 최종적인 지상 사용자의 위치정확도를 산출하였다. 본 시뮬레이션에서는 무인기의 궤적을 산출하기 위해 간단한 무인기의 동역학과 바람과 같은 성층권 환경을 고려하여 약 24시간 동안의 대체항법 성능을 산출하였다. 또한 무인기와 지상국의 배치 변화를 여러 가지의 상황에 대한 시뮬레이션을 실시함으로서 최적의 배치를 도출하고자 하였다.

본 논문의 결과는 GNSS 사용 불가능한 상황 하에서 의사위성 또는 트랜시버를 장착한 고고도 장기체공 무인기를 활용하는 독립적인 대체항법 시스템 구현에 도움이 될 것으로 판단된다.

주요어 : 대체항법, 고고도 장기체공 무인기, 의사위성, 트랜시버
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