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Operational Feasibility Study of High Altitude Balloon Platform based on the Wind Environment in South Korea

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ABSTRACT

Naval helicopters flying at extremely low altitudes often face communication problems when the helicopter is located in the distance from the mother ship. Accordingly, new attention is being cast on the high altitude balloon (HAB) to solve this problem due to its cost-effectiveness and ability of rapid deployment to the battlefield. The balloon is one of a lighter-than-air vehicle that the blowing wind determines its speed, direction, and travel distance. Therefore, it is likely that seasonal changes in wind conditions will restrict the operation of the balloon. In this paper, the feasibility study of the balloon, which is regarded as a future communication relay platform, on the theater of operation of the Republic of Korea Navy the First Fleet was performed. The trends of the balloon trajectory for five years (2014 ~ 2018) with respect to seasonal wind variations were investigated employing the numerical trajectory prediction program. Simulated balloon trajectories of summer and winter showed considerable differences due to seasonal wind. Summer season was found that it has the most favorite flight environment for the balloon campaign. Upon reflecting on the simulation results, the HAB operating procedure, which capitalised on the Ulleungdo, was also suggested.

Keywords: Stratospheric balloon; Navy communication relay platform; High altitude balloon; Lighter-than-air vehicle

1. INTRODUCTION

Naval helicopters carrying out anti-ship and anti-submarine warfare generally fly at or below 100 m altitudes. This low altitude operation rises frequent communication problems when the helicopter is located in the distance from the mother ship. This not only limits the maximum operational radius of the helicopter from the mother ship or base, but also hinders the pilot's accurate and timely situational awareness on the battlefield. To solve this problem, securing a line-of-sight (LOS) is imperative. Accordingly, a high altitude balloon (HAB) which flies at stratosphere can be a reasonable solution as a communication relay system[1]. HABs have been used to fulfill various scientific and engineering research goals by leading countries in aerospace technology such as India, the United States, and Japan[2,3,4].

The HAB is an lighter-than-air (LTA) vehicle that the blowing wind determines its speed, direction, and travel distance. Therefore, the operation of the balloons could be restricted by seasonal changes in wind conditions. In this context, the feasibility of the HAB operation for the communication relay platform was investigated with regard to seasonal wind variations in present work. To investigate seasonal trends of the ZPB trajectories, the daily flight simulation for 5 year from 2014 to 2018 was performed by employing the numerical simulation program on the zero-pressure balloon (ZPB). Based on the results of simulations, the viable operating procedures at the operational jurisdiction of the Republic of Korea Navy (ROKN) First Fleet was suggested.

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2. BALLOON FLIGHT MODEL FOR TRAJECTORY PREDICTION

A high altitude balloon is a LTA vehicle. Thus, its motion is determined by both the buoyant force of lifting gas and aerodynamic drag of the balloon. To precisely calculate these force acting on the balloon, the surface area and volume which was designed by its mission requirements also should be taken into account. Lifting capacity is also influenced by the density of the buoyant gas. The density of the buoyant gas is a function of the temperature of the gas. Therefore, it is imperative to calculate the radiative and convective heat transfers between the balloon and its surrounding environment for achieving reasonable accuracy. For a preliminary study to analyse the operational feasibility of balloon operation, the simulation program presented in Lee and Yee's work[5] was used. In the following section, the dynamic and thermal model was briefly introduced.

2.1 The Dynamic Model for Balloon

The Eqn. (1) define the force of the balloon buoyancy :

$$F_{Buoyant} = (\rho_{air} - \rho_{He}) \cdot g \cdot Volume_{Balloon} \tag{1}$$

As we define u_{wind} and V_{bal} as the absolute velocity elements of the wind and the balloon, respectively. Then, the relative velocity value of the balloon, V_{rel}, can be obtained by the following Eqn. (2) :

$$V_{rel} = u_{wind} - V_{bal} \tag{2}$$

To find the value of the drag force, the Eqn. (2) is substituted in the following Eqn. (3):

$$Drag = \frac{1}{2} \cdot \rho_{air} \cdot V^2_{rel} \cdot C_d \cdot A_{top} \tag{3}$$

where $A_{top} = \pi r^2_{max}$ denotes the value of the top projected area of the balloon

The gross system mass of the balloon is m_G, the mass of the buoyant gas is m_g, therein, the mass of the total balloon system M_{total} is defined by

$$M_{total} = m_G + m_g \tag{4}$$

The mass of air, which is generated by the acceleration of the balloon immersed in the air during the ascent, should be taken into consideration. Accordingly, $M_{virtual}$ can be calculated as the following Eqn. (5):

$$M_{virtual} = M_{total} + C_{virtual} \cdot \rho_{air} \cdot volume_{bal} \tag{5}$$

The $C_{virtual}$ is virtual mass coefficient.

Consequently, the Eqns. of the motion for a balloon can be written as follows Eqn. (6):

$$\ddot{x} = \frac{Drag_x}{M_{virtual}}$$

$$\ddot{y} = \frac{Drag_y}{M_{virtual}}$$

$$\ddot{z} = \frac{F_{buoyant} - M_{total} \cdot g + Drag_z}{M_{virtual}} \tag{6}$$

2.2 Thermal Model for Balloon

In the present study, the assumption that the buoyant gas is transparent, and the radiant heat transfer effects are negligible are used. Therefore, the temperature of the gas is only influenced by the internal free convection, Q_{conInt}, which occur inside of the balloon film. Therein, the value of the buoyant gas temperature can be obtained in the following Eqn. (7):

$$\frac{dT_{gas}}{dt} = \frac{Q_{conInt}}{C_v \cdot m_{gas}} + (\gamma - 1) \cdot \frac{T_{gas}}{\rho_{gas}} \cdot \frac{d\rho_{gas}}{dt} \tag{7}$$

where T_{gas}, ρ_{gas}, and m_{gas} depict the temperature, density, and mass of the buoyant gas, respectively. C_v denotes the specific heat at constant volume of the buoyant gas. γ is the specific heat ratio. If the interaction between the buoyant gas and the film are negligible, the adiabatic temperature change of the gas can be obtained by Eqn. (7).

To find the value of the envelope film temperature, the simple transient energy-balance Eqn. (8) was introduced:

$$\frac{dT_{film}}{dt} = \frac{Q_{sun} + Q_{albedo} + Q_{IRplanet} + Q_{IRfilm} + Q_{conExt} - Q_{conInt} - Q_{I}}{C_f \cdot m_{film}} \tag{8}$$

In the above Eqn. (8), the absorbed direct solar heat is Q_{sun}, the absorbed albedo heat is Q_{albedo}, the absorbed planetary IR heat is $Q_{IRplanet}$, the absorbed IR self-glow from the interior is Q_{IRfilm}, the convectional heat flux between the atmosphere and the film is $Q_{convExt}$, the convectional heat between the buoyant gas and the film is denoted as $Q_{convInt}$, and the emitted IR energy from the balloon film is depicted as Q_{IRout}. The specific heat of the film material is represented by C_f. Further details also can be noted in Farley's, & Palumbo, *et al.*'s works[6,7].

2.3 Flight Simulation Information

The balloon flight simulation information with the specification are as listed in Table 1. The target altitude of this ZPB for the communication relay mission was selected 25km MSL due to the lowest wind speeds all the year round. According to the radiosonde data for five year (2014~2018), it was recorded at or below 12 m/s.

The launch site is assumed to be Donghae-si where the ROKN First Fleet is stationed. This littoral place seems the reasonable selection for the balloon campaign since it can not only mitigates the safety concerns but also enhance the accessibility to the jettisoned payload after flight termination.

The flight window of the balloon for the communication relay mission was chosen 6 h after taking into considerations of followings: airspace infringement to neighboring countries, a typical navy helicopter operation time per mission, the time required to reach the target altitude, and additional flight time for a contingency which requires the extension of the communication relay mission.

Table 1. Balloon flight simulation information and specification

Variables	Value
Information of the flight simulation	
Target altitude	25 km
Flight termination	6 h after the launch
Launch site	Donghae-si
Launch time	KST 09:00 and 21:00, (UTC+9)
Balloon specification	
Payload	10 kg
Percentage of free lift	10 %
Buoyant gas mass	2.69 kg
Total mass	18.06 kg
Maximum volume	443m^3

To investigate seasonal trends of the ZPB trajectories, the daily flight simulation for five year from 2014 to 2018 was performed. To examine how the trajectories are varied between day and nighttime, the launch times of the simulations were determined as KST 09:00, 21:00 hrs, which are representative operation time of the ship-based helicopters.

The weather data, given by the National Centers for Environmental Prediction (NCEP) in the form of the Global Forecast System (GFS) model, were employed for the trajectory simulation. The simulation program employed the GFS analysis file which provides a grid resolution of 0.5° at longitude and latitude. These elements in both the longitude and latitude can be obtained in the corresponding value of a 26-layer vertical resolution.

3. RESULTS AND DISCUSSION

In this paper, although daily flight simulations for five years (2014-2018) were conducted, only the simulation results of the winter and summer of 2018 were presented as an example. The reason for this is that those season's simulation results showed significant differences in balloon trajectories concerning seasonal wind variations.

The simulation results of the balloon launched from the Donghae-si in January and July of 2018 with different launch time (KST 09:00, 21:00) are as shown in Figs. 1 and 2, respectively. The red line, which represents the daily flight paths of the balloons, showed the tendency of the balloon's movement. The yellow circles denote the position of the balloon when the 6 hrs elapsed after the launch.

The simulation results of the winter and summer depict remarkably different trends. The balloon moves notably eastward in winter regardless of day and night time, as shown in Fig. 1(a) and (b). Thus, several balloon flights crossed over the borderline of the Incheon FIR. These airspace violations were caused by the jet stream, which becomes stronger in winter due to an increment of the temperature difference between the polar region and the equatorial region.

The differences in longitude and latitude distributions with altitude are as presented in Figs. 1(c) - 1(f). On these figures, one can identify that the movement of the balloon significantly depends on the altitude range from 5 km to 15 km. It is natural consequences since the balloons flying at this altitude range face strong wind environment. In particular, in Figs. 1(c) and (d), the gradient of the altitude over longitude at an altitude of 10 ~15 km is the lowest. This implies that the balloons move farther in the longitude-wise than the vertical direction due to the strong jet stream. The predicted trajectories of the balloons in the longitude-wise showed no significant differences between day and night time. One reason for this would be that the longitudinal wind velocity components with altitudes less varied during these flight windows.

On the other hand, the predicted balloon trajectories in the latitude direction with the altitude changes showed more broad distributions at nighttime than the daytime, as indicated in Figs. 1(e) and 1(f). This phenomenon could be explained by the ideal gas Eqn. Volume = ($m_{gas} R_{gas} T_{gas}$ / P). The volume of the balloon envelope, which determines the buoyant force of the balloon, is affected by the temperature of the buoyant gas. Owing to the absence of the thermal energy from sunlight at night, the temperature of the buoyant gas inside the balloon is lower than that of the daytime. Accordingly, the volume of the balloon is relatively smaller than that of the daytime during the ascent phase, resulting in less buoyant force. This connotes that the balloon could be exposed longer time in the troposphere where the strong wind blows; hence, it seems that the flight trajectories in the latitudinal direction are distributed more broadly than that of the daytime.

In this simulation results in winter showed the tendency of the flight trajectories that travelled distance of the longitudinal direction is greater than that of the latitudinal. These particular results were led by the longitudinal velocity component of the jet stream which is far stronger than that of latitudinal in winter. In this respect, it is conceivable that the required mission flight without crossing the eastern border of the Incheon FIR is achieved by shortening the exposed flight time in the troposphere with a high rate of climb. To this end, following methods such as injecting more buoyant gas into the balloon envelope, or dropping ballasts could be implemented to increase the ascending speed in realistic balloon campaign.

Unlike the trajectories in winter, in summer, the balloons change its direction westward at or above 15 km MSL altitude while moving eastward in the early stage of flight, as depicted in Figs. 2(a) and 2(b). This behavior of the balloon is referred to as boomerang flight. Therefore, there is no risk of crossing the approved airspace in summer.

The differences in longitude and latitude distributions with altitude are presented in Figs. 2(c) - 2(f). The predicted balloon trajectories in the longitudinal direction in summer also showed no significant differences between day and night time like that of winter.

Unlike the more broadly distributed trajectory trends of the winter nighttime for the latitude-wise

(Launching from the ROKN 1st Fleet in Donghae-si, January 2018 KST 09:00 (left), 21:00 (right), UTC+9)

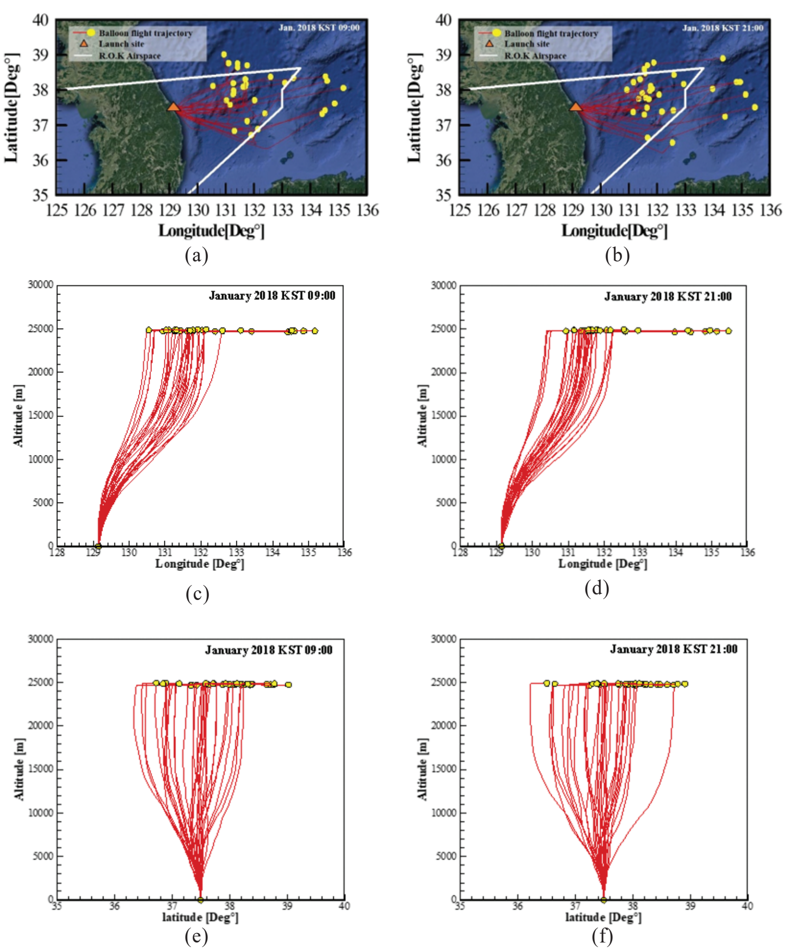

Figure 1. Flight simulation results in winter: (a) and (b) Predicted trajectories, (c) and (d) Longitude variation with altitude, and (e) and (f) Latitude variation with altitude.

(Launching from the ROKN 1st Fleet in Donghae-si, July 2018 KST 09:00 (left), 21:00 (right), UTC+9)

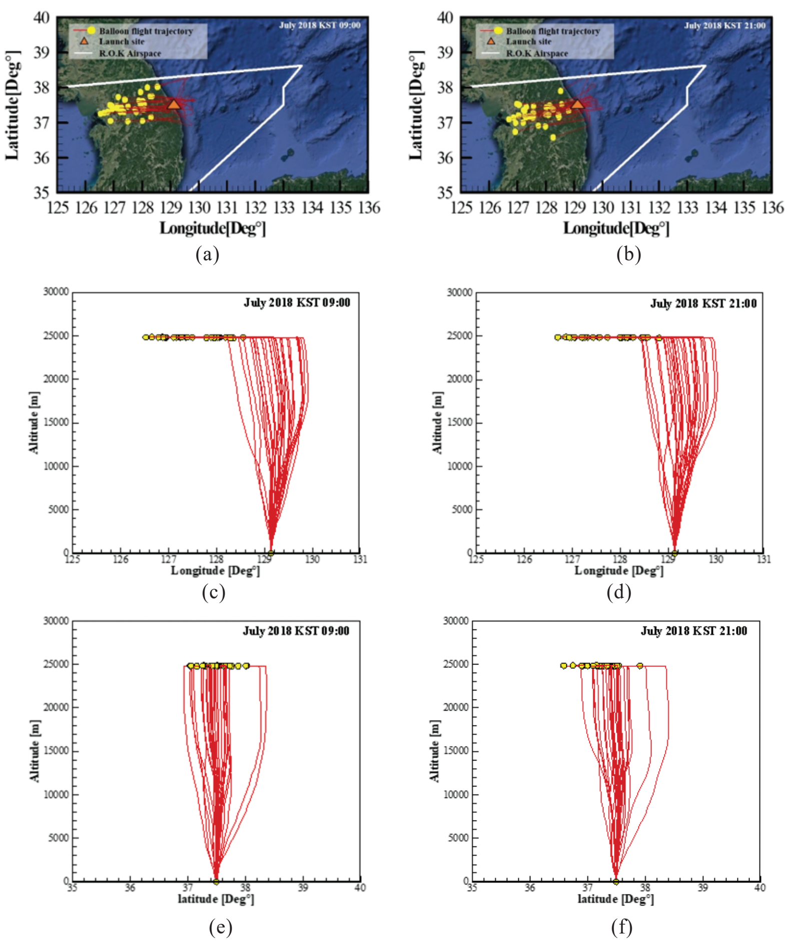

Figure 2. Flight simulation results in summer: (a) and (b) Predicted trajectories, (c) and (d) Longitude variation with altitude, (e) and (f) Latitude variation with altitude.

balloon trajectories over altitude, summer nighttime trends revealed no notable difference with the daytime trends. It is conceivable that the reason for the narrow distribution in the latitudinal direction at both day and night is the slow wind speed. The lowest wind speed spectrum appears in summer throughout the year. Since travel distance is proportional to wind speed and the time the balloon faces the wind, it is a logical consequence that the shortest travel distance is recorded in summer.

As previously mentioned, several balloon trajectories crossed the boundary line of the Incheon FIR in winter. Strong winds such as the winter's jet stream will impact on the operational feasibility of the balloon campaign negatively. To tackle these concerns, the results of the daily flight simulation for 5 years from 2014 to 2018 were thoroughly investigated with respect to airspace violation.

The mean value of the monthly flight simulation results for five year is presented in Fig. 3. It is consisted of the feasibility analysis and elapsed time at the moment of airspace violation after balloon launch. The operation feasibility of December recorded the lowest value, approximately 50 per cent. Afterward, the values increased from 71 to 78 per cent as the spring season is coming. It recorded operational feasibility over 97 per cent without airspace violation within the required mission time (6 h) from May to October (from late spring to mid-autumn season), after that it decreased again in winter.

Even though the value of operational feasibility in winter was the lowest the whole year, it seems acceptable values upon considering both the limited operation days of a ship-based navy helicopter due to adverse sea state in winter and average elapsed flying time at the moment of airspace violation. The average elapsed flying time of the balloon in those periods after launch was 4:40, which was shorter than the expected 6 h for the communication relay mission. Although a typical navy helicopter operation time per mission can be covered in that flight window, additional flight time allowing the extension of the communication relay mission in case of operational contingency might be required. Therefore, if necessary, subsequent balloon launch procedure could be an alternative method to augment the communication relay mission as listed in Fig. 4. The subsequent balloon flight operation will begin 2 h 50 min after the first balloon launch upon taking into account the average required time for the ascent, 1 h 50 min.

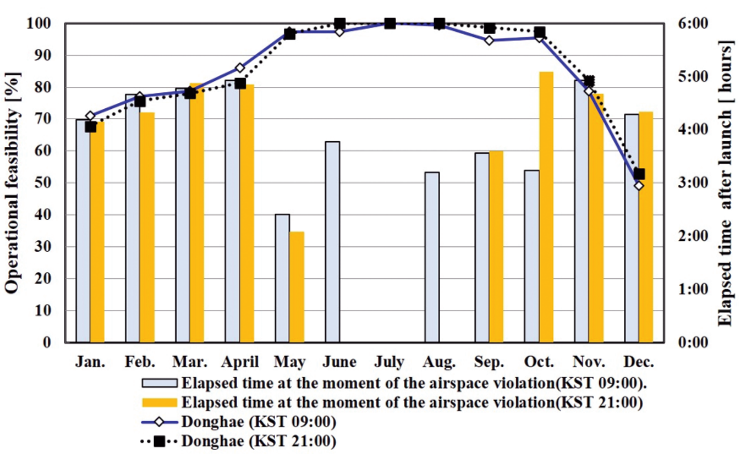

Figure 3. Monthly flight simulation results based on the wind data for 2014~2018 years.

Given that above operation procedures, it could be inferred that seamless wireless communication could be possible all year-round. However, future work should include the follow-up balloon operation for the verification of the suggested subsequent launch method in the actual operational environment.

In case of the airspace infringement between May and October, the elapsed time after the launch was recorded as taking three hours on average. This result was generally attributed to the fact that the wind blowing from the south make the balloons penetrate the north border of the Incheon FIR, which is approximately 38° north. Such cases are negligible concerning the value of operational feasibility.

The nature of boomerang flights returning to the launch site can realize a great savings of time and effort for

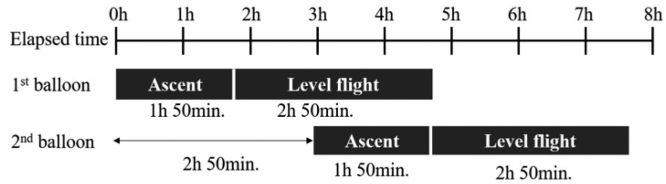

Figure 4. Subsequent balloon flight operation timeline.

retrieving payload in summer, and solves airspace violation problems. However, as demonstrated in Fig. 2(a) and 2(b), if the boomerang flight trajectory moves too much towards the shore, it is not compatible with the purpose of sea-based operation in terms of safety and recovery efficiency.

Taking these into consideration, launching a balloon at the Ulleungdo was devised for balloon operations in summer. This method could benefit from the geographical advantage of the Ulleungdo, which is located in the center of the Incheon FIR eastern sector. Fig. 5 show the trajectory simulation results of the Ulleungdo in July. It can be observed that balloons move westward without violating the boundary line of the Incheon FIR by virtue of the boomerang flight. Furthermore, the distance travelled in the direction of the shore was considerably reduced compared to that of launching in the Donghae-si. In realistic balloon campaign in summer, several balloon trajectories flying above the land could be minimised by controlling the rate of climb speed via employing dropping ballasts and exhausting lift gas, along with conducting the flight termination.

(Launching from the Republic of Korea Navy base in Ulleungdo, July 2018 KST 21:00)

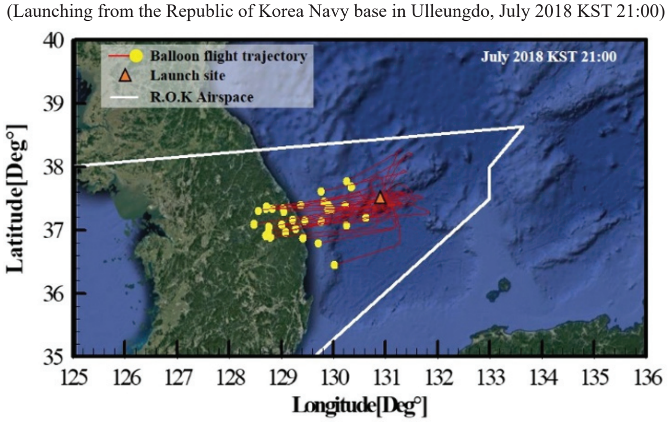

Figure 5. Flight simulation results.

4. CONCLUSIONS

In this study, the operational feasibility of the HAB as a communication relay platform at the ROKN First Fleet was investigated with respect to the seasonal wind variations. To this end, balloon trajectories of the five year (2014~2018) were analysed by the numerical trajectory prediction program. The conclusions can be summarised in three part.

First, the simulation results of the winter and summer depict remarkably different trends. The balloon moves notably eastward in winter regardless of day and night time. Unlike the trajectories in winter, the balloons fly westward at high altitude, except eastward movement in the early stage of flight. It is confirmed that the differences of the balloon trajectories are affected by the rate of climb differences caused by the sunlight, as well as the wind velocity.

Second, the simulation results in winter there were some cases which balloons deviated from the approved airspace due to strong winds, but the average operating rate was estimated to be over 70 per cent except for December. In light of the restriction of a ship-based helicopter operation due to unfavourable sea conditions in winter, it is acceptable values for the communication relay mission.

Lastly, it is confirmed that the summer season can provide the best flight environment for the balloon campaign, albeit it has several excessive shoreward movements. To tackle those shoreward movements of the balloons in summer, launching the balloons at the Ulleungdo was devised along with a successive balloon launching operation procedure. Given that above operation procedures, it could be inferred that seamless wireless communication in the operational region of the Republic of Korea Navy's first fleet could be possible all year-round.

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