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DEVELOPMENT OF A STRATOSPHERIC AIRSHIP-BASED NETWORK ARCHITECTURE FOR TELECOMMUNICATION IN REMOTE AREAS

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The object of this study is a stratospheric airship-based telecommunication platform, employed as a high-altitude platform station (HAPS), designed to operate at altitudes of 20–30 km and provide broadband connectivity in regions with limited terrestrial infrastructure such as rural and remote areas of the Republic of Kazakhstan. The key research problem is to ensure stable connectivity of HAPS-based telecommunication platforms under strong stratospheric winds, with limited payload capacity and energy resources, while developing a scalable network architecture for multi-airship coordination.

This paper proposes a network concept based on modular nano-airships, which reduces drag, enhances maintainability, and ensures continuous service. Calculations of lifting capacity, aerodynamic drag of different envelope shapes, energy balance, and the coverage radius of a single station were performed. Experimental tests of a prototype confirmed the feasibility of using the sub-GHz band (433 MHz) to provide long-range communication under ground test conditions, where signal attenuation was found to be minimal compared to higher frequencies.

Due to the obtained characteristics, the hypothesis of employing a group of smaller airships instead of a single large carrier was confirmed. This is explained by their reduced sensitivity to wind loads, flexibility in network configuration, and lower operational risks. Unlike traditional satellite systems, which are expensive to launch and maintain, stratospheric airships can be recovered, repaired, and redeployed at relatively low cost, offering an economically viable solution for developing regions.

The results can be applied in the creation of national communication networks for remote and sparsely populated areas of the Republic of Kazakhstan, in emergency response operations, and as a complementary layer to satellite constellations. The proposed concept demonstrates that modular HAPS networks are a realistic and scalable alternative, capable of providing broadband access under real-world atmospheric and geographic constraints

Keywords: high-altitude platform stations (HAPS), stratospheric airship, telecommunication network, LoRa technology, sub-GHz frequency

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1. Introduction

The growing demand for high-speed and reliable telecommunication systems has become a critical factor for both national development and global digital inclusion. Access to broadband connectivity is increasingly recognized as an essential element of social and economic stability, comparable to the role of energy and food security. However, the production and provision of telecommunication services through terrestrial infrastructure is a complex, multi-phase technological and logistical system that requires significant investments in base stations, fiber-optic networks, and satellite constellations [1, 2].

Each of these solutions has inherent limitations. Terrestrial networks are economically inefficient in remote regions due to high installation and maintenance costs. Satellite systems, while capable of providing wide coverage, suffer from high latency and expensive deployment. This imbalance between the growing demand for connectivity and the limitations of existing infrastructures leads to digital exclusion, particularly in rural and sparsely populated areas [3].

High-altitude platform stations (HAPS), operating at stratospheric altitudes of 20–30 km, have emerged as a promising alternative. They combine low latency, flexible deployment, and cost efficiency. Global initiatives such as Google Loon, Stratobus, and Altaeros BAT have demonstrated the feasibility of such platforms, yet they revealed persistent challenges, including station-keeping in strong stratospheric winds, long-term energy autonomy, and scalable network architectures [4, 5].

Recent studies highlight the importance of integrating HAPS into modern telecommunication systems, ensuring that they function not only as isolated platforms but as part of larger communication infrastructures. In particular, research has emphasized their potential role as IMT base stations to expand 5G coverage [6], their use cases in future 6G networks, including inter-platform coordination and energy management [7], and their integration into non-terrestrial network (NTN) architectures alongside satellites and terrestrial systems [8]. At the same time, HAPS remain highly relevant for countries with vast territories and low population density, such as Republic of Kazakhstan, Mongolia, Canada, and Australia, where rural internet penetration is still limited due to geographic isolation and insufficient terrestrial infrastructure [9]. For Republic of Kazakhstan and Mongolia, with densities of only 2–7 people/km^2, the deployment of conventional terrestrial infrastructure is economically impractical, making stratospheric platforms an attractive solution to bridge the digital divide.

In parallel, the integration of HAPS aligns with emerging technological trends, including the deployment of 5G/6G networks, non-terrestrial network (NTN) architectures, and the use of lightweight materials and renewable energy systems [10]. These developments confirm the growing role of stratospheric airships in the global telecommunication ecosystem.

Therefore, studies devoted to the development, optimization, and integration of scalable, resilient, and energy-efficient stratospheric telecommunication platforms are scientific relevance.

2. Literature review and problem statement

The methodology [11] proposes a systematic design approach for high-altitude telecommunication platforms. However, the adaptation of these design principles to strong stratospheric winds has not been sufficiently addressed.

The paper [12] develops an airship for telecom and border monitoring with dual-use potential. However, it lacks consideration of multi-airship networking scenarios.

The research [13] presents dynamic control algorithms for multiple HAPS in time-varying wind fields. While promising in simulation, validation at full scale is absent.

The study [14] addresses trajectory planning with an improved RRT algorithm. Although effective in modeling, its computational demand may hinder real-time application.

The paper [15] introduces a solar array power model validated by experiments. Despite its accuracy, it omits integration with actual onboard power systems.

The experimental work [16] evaluates mechanical properties of stratospheric airships. Structural data are provided, but aerodynamic stability in gusty winds remains unassessed.

The review [17] compares HAPS to space systems, outlining general advantages. Nevertheless, quantitative telecom metrics are lacking.

The work [18] describes the development of stratospheric platform systems. It emphasizes conceptual design but does not include recent advances in lightweight materials or avionics.

The study [19] evaluates pseudo-satellite platforms for air traffic support. Although relevant for navigation, it overlooks broadband payload requirements.

The paper [20] tests HAPS in defense applications. While versatile, its military focus restricts civil telecommunications applicability.

The research [21] investigates quantum key distribution from HAPS, proving feasibility of secure links. Yet, integration into broadband architecture is still theoretical.

The study [22] discusses practical application of HAPS in space RAN, addressing regulation and technical issues, but neglecting rural broadband.

The review [23] highlights regulatory aspects of HAPS. It is comprehensive in policy analysis but lacks engineering-level case studies.

The work [24] develops energy system concepts for HAPS. Practical guidance is given, but redundancy planning during prolonged cloudiness is absent.

The model [25] proposes elevation-dependent shadowing for urban HAPS. It improves accuracy of link budgets, but applicability is limited to dense cities.

The study [26] reviews HAPS infrastructures supporting GNSS. It addresses interoperability but not dual-use payloads.

Finally, the research [27] analyzes power electronic methods for multi-level inverters. While focused on energy systems, its relevance to renewable airborne platforms remains unexplored.

The literature analysis shows clear potential of HAPS to enhance broadband connectivity. However, significant problems remain unresolved, including:

1) maintaining station-keeping under stratospheric winds of 20–50 m/s;

2) overcoming payload weight limitations and achieving energy autonomy;

3) optimizing aerodynamic envelope design for both lift and stability;

4) developing algorithms for coordinated operation of multiple platforms;

5) designing maintenance strategies that allow replacement without disrupting service.

Thus, despite extensive research, the key research problem is to ensure stable connectivity of HAPS-based telecommunication platforms under strong stratospheric winds, with limited payload capacity and energy resources, while developing a scalable network architecture for multi-airship coordination.

3. The aim and objectives of the study

The aim of the study is to develop and justify a conceptual model of a stratospheric airship-based telecommunication network adapted to the geographical and climatic conditions of Republic of Kazakhstan. The practical outcome of the study is a set of engineering calculations and an experimental prototype that demonstrate the feasibility of using modular nano-airships to provide stable broadband connectivity in rural and remote areas.

To achieve this aim, the following objectives were set:

– to determine the optimal envelope shape and lifting gas by calculating lifting capacity and aerodynamic drag under stratospheric conditions;

– to define the composition of onboard equipment, including solar panels, batteries, propulsion systems, valves, and telecommunication payloads;

– to design a communication architecture for coordinated operation of multiple airships, including the choice of frequency bands (LoRa, LTE/5G) and inter-platform links;

– to estimate the coverage area, inter-airship spacing, and handover procedures required to ensure continuous service across Republic of Kazakhstan;

– to propose a deployment and maintenance strategy that allows for replacement of individual airships without disruption of network operation.

4. Materials and methods of the study

The object of this study is a stratospheric airship-based telecommunication platform, employed as a high-altitude platform station (HAPS), designed to operate at altitudes of 20–30 km and provide broadband connectivity in regions with limited terrestrial infrastructure such as rural and remote areas of the Republic of Kazakhstan.

The study hypothesizes that a combination of optimized aerodynamic design, energy-autonomous subsystems (solar energy harvesting and storage), and a modular telecommunication architecture can ensure reliable, scalable, and cost-effective broadband connectivity under stratospheric conditions, addressing challenges such as strong winds, limited payload capacity, and multi-airship coordination.

The research assumes that simplified aerodynamic and energy balance models can accurately approximate key parameters, including lifting capacity, drag forces, solar energy potential, and communication link performance at stratospheric altitudes. It is further assumed that sub-GHz frequency bands, particularly 433 MHz, are suitable for long-range, low-power communication in rural settings due to their low free-space path loss.

For initial prototyping, heavy payloads such as solar panels, batteries, and full-scale telecommunication repeaters were excluded to focus on envelope mechanics, lifting gas performance, and aerodynamic stability. This simplification isolates fundamental structural parameters before scaling to fully equipped airships, reducing complexity in early experimental stages.

The study integrates theoretical calculations, simulation modeling, and experimental validation, grounded in a comprehensive literature review of stratospheric platform design, energy systems, and wireless network architectures [5–8, 10–13]. The methodology aligns with international standards to ensure global comparability, including ITU-R P.525 for free-space path loss calculations and NASA and SAE standards for aerodynamic coefficients. These standards were chosen for their widespread adoption in aerospace and telecommunication research, ensuring robust and reproducible results.

The object of the present research is the design and validation of a stratospheric airship-based communication platform capable of stable operation at altitudes of 20–30 km. The main hypothesis assumes that a combination of aerodynamic optimization, energy-autonomous subsystems, and modular communication architecture can ensure reliable broadband connectivity under stratospheric conditions.

To achieve this, several assumptions were made. First, simplified aerodynamic and energy balance models were applied to enable analytical calculations of lifting capacity, drag, solar energy harvesting, and communication performance. Second, at the initial stage, experimental prototypes excluded heavy payloads (solar panels, batteries, telecommunication equipment), focusing solely on envelope mechanics. These simplifications allow isolating fundamental structural parameters before scaling the system.

International standards and methodologies were considered. For example, the free space loss formula was adopted from ITU-R P.525 recommendations, while aerodynamic coefficients were aligned with aerospace engineering practices (NASA, SAE standards). Such references ensure comparability of results with global research.

Being the methodological basis of the present research, the complete survey of all available scientific literature was implemented with regards to the design of stratospheric platforms, energy supply systems, and wireless network architectures [5–8]. The revised strategies were formally integrated, and a side-by-side assessment was conducted on major parameters of uniqueness and shrinkage, as minimal carrying capacity, aerodynamic drag, solar panel energy contracts, and battery storage inventory [10–13]:

1. Airship lifting power

$$F_{lift} = \left(\rho_{air} - \rho_{gas}\right) \cdot V \cdot g, \tag{1}$$

where ρ_{air} – air density at 20 km altitude, ρ_{gas} – gas density (helium or hydrogen), V – envelope volume of the airship (m^3), and g – gravitational acceleration.

This formula determines the maximum payload mass, allowing comparison of gases and envelope volumes. As shown later in Table 1, helium provides ≈ 200 kg lift for 3000 m^3, while hydrogen provides ≈ 215 kg.

The first part of the testing should evaluate the lifting power and optimize the structural and the aerodynamic properties of the airship envelope. A simplified prototype will be implemented in order to eliminate the complexity of the system and isolate the key performance variables-at this point, solar energy systems and telecommunication modules will be omitted. Such an arrangement allows concentrated testing of flight mechanics which is not gendered by the more massive subsystems.

The step is just a precursor to the gradual approach to a fully functional stratospheric communication platform. The knowledge obtained by the test flights will have a direct influence upon the design of the more complex systems that would include the power system, propulsion components, and the communication hardware.

2. Aerodynamic drag (windage)

$$F_d = \frac{1}{2} C_d \cdot \rho_{air} \cdot A \cdot \vartheta^2. \tag{2}$$

where C_d – drag coefficient (≈0.04 for teardrop, 0.06–0.08 for cigar), ρ_{air} – the air density at stratospheric altitude (≈0.0889 kg/m^3 at 20 km), A – cross-sectional area, and V is wind speed.

This equation determines whether the airship can withstand stratospheric winds (20–50 m/s). A teardrop form provides almost twice less drag, directly reducing energy consumption for stabilization. This aspect was not addressed in early HAPS projects such as Google Loon [4].

The formula indicates the amount of aerodynamic drag the airship experiences due to wind flow. It depends on the drag coefficient C_d, they include the area of the cross section, the area of the wind, and the speed.

It is essential to know whether the airship will have the ability to stay at a particular point because Google Loon was not able to succeed due to wind conditions. There is a need to think of what type of motors or any other form of stabilization needed to resist wind flows.

3. Solar panel power

$$P_{solar} = \eta \cdot A_{panel} \cdot G, \quad (3)$$

here $\eta \approx 0.18$, $G \approx 1100$ W/m^2 (in the stratosphere), where η – the efficiency of the solar panel, A_{panel} – the effective surface area of the solar panels (m^2), and G – the average solar irradiance in the stratosphere.

4. The free space loss model

$$PL(dB) = 20\log_{10} f + 20\log_{10} d + 92.45. \quad (4)$$

In the given equation, it should be remembered that *f* would be the frequency expressed in megahertz (MHz), whereas *PL* (dB) stands for path loss expressed in decibels (dB), *d* is the distance between the transmitter and the receiver in kilometers (km). The fixed number 92.45 is of special interest, because it also incorporates a number of examples of conversion factors such as frequency translation between megahertz and hertz, distance conversion between kilometers and meters, physical constants necessary to convert the result into decibels. This constant is so ingrained in the process of radio propagation that a full article may be written on its dependence and use.

The free space loss formula (FSPL)

$$PL(\text{dB}) = 20\log_{10}\left(\frac{4\pi f}{c}\right), \quad (5)$$

where *PL* (dB) – the free space path loss in decibels (dB), *f* – the frequency in hertz (Hz), *d* – the distance between the transmitter and receiver in meters (m), *c* – the speed of light in vacuum ($\approx 3 \times 10^8$ m/s), and the factor 4π appears due to the spherical nature of electromagnetic wave propagation. When the result is expressed in decibels, the constant 92.45 is introduced as a standardized factor that accounts for the necessary unit conversions, allowing frequency to be expressed in megahertz (MHz) and distance in kilometers (km) directly in the formula.

5. Data packet loss

$$P_{loss} = 1 - \prod_{i=1}^{n}(1 - p_i). \quad (6)$$

This formula represents the cumulative probability of packet loss when passing through multiple network nodes such as relays, airships, and antennas.

A packet has to pass through *n* nodes where each one has a packet loss probability that is individual to them p_i when this is the case, the general delivery success probability is as follows

$$P_{success} = \prod_{i=1}^{n}(1 - p_i). \quad (7)$$

The complement of the probability of success is the probability that a data packet will fail to arrive at the receiver (i.e., that it is lost at least one flow state along the path)

$$P_{loss} = 1 - P_{success}. \quad (8)$$

Let the packet loss probabilities at each node be:
Node 1: $p_1 = 0.01$ (1%) ;
Node 2: $p_2 = 0.02$ (2%) ;
Node 3: $p_3 = 0.015$ (1.5%).

Here p_i represents the probability of packet loss at the *i*-th node of the communication chain.

Then the probability of successful delivery is

$$P_{success} \approx 0.955 \text{ (95.5\%)}.$$

So, the probability that the packet will not reach the destination is

$$P_{loss} \approx 0.045 \text{ (4.5\%)}.$$

For three consecutive network nodes with packet loss probabilities of 1%, 2%, and 1.5%, the overall probability of successful packet delivery is approximately 95.5%. Accordingly, the cumulative packet loss probability equals about 4.5%.

In the design of the airship-based communication networks, structure design is imperative. It shows how big packets losses may easily accumulate even when nodes are designed to make minimal errors. The network optimization with these calculations, it is finally possible to reduce the number of intermediate relay nodes in the network. This solution enhances the reliability of communication between the smaller and the chief airships at every node. There can also be added redundancy mechanisms or error correction protocols.

A simplified prototype was developed using a double-sided construction film envelope to test lifting gas performance (helium vs. hydrogen) and aerodynamic stability under low-altitude conditions. The payload included an ESP32 microcontroller, GPS module, and LoRa radio operating at 433 MHz, selected for their balance of functionality and minimal mass. Controlled ascents at varying altitudes assessed buoyancy, drag, and stability under wind speeds up to 10 m/s, providing data to refine simulation models. These tests excluded heavy subsystems (e.g., solar panels, batteries) to isolate structural parameters, a standard approach in early-stage aerospace prototyping [11].

The chosen methods combine analytical rigor with practical validation, addressing the complexity of stratospheric airship design. Theoretical models (e.g., buoyancy, drag, FSPL) were selected for their established accuracy in aerospace and telecommunication applications, as evidenced by [10, 15]. LoRa was preferred over LTE/5G for its low-power, long-range performance, critical for rural Republic of Kazakhstan's sparse infrastructure [9]. Experimental methods prioritized cost-effective, scalable prototyping to validate theoretical assumptions before full-scale stratospheric testing, aligning with iterative design principles in [11, 12]. International standards (ITU-R, NASA, SAE) ensure global relevance, while the focus on sub-GHz bands addresses regional regulatory constraints.

This methodological framework supports the development of a scalable, energy-efficient, and stable telecommunication platform, with initial results informing the design of full-scale prototypes for future stratospheric testing.

5. Research results on the design and implementation of a stratospheric airship network

5. 1. Optimal airship size determination

It was determined the optimal envelope shape and lifting gas for a stratospheric airship by calculating lifting capacity and aerodynamic drag under stratospheric conditions (20–30 km altitude, wind speeds of 20–50 m/s), ensuring sufficient payload capacity for telecommunication equipment while minimizing drag to maintain station-keeping.

The determination of the airship's size and envelope shape was approached through a combination of analytical calculations and experimental validation, focusing on optimizing the trade-off between lifting capacity, aerodynamic drag, and structural stability. The lifting capacity was calculated using the buoyancy equation

$$L = V\left(\rho_{air} - \rho_{gas}\right) * g, \quad (9)$$

where $\rho_{air} = 0.0889\,kg/m^3$ (air density at 20 km), ρ_{gas} – the density of helium (0.018 kg/m^3) or hydrogen (0.009 kg/m^3), V – the envelope volume (m^3), and $g = 9.81\,m/s^2$. This equation, validated by [10, 11], was chosen for its accuracy in quantifying the lift generated by different gases and envelope volumes.

As shown in Table 1, the lifting force of the airship depends on both the shape of the envelope and the type of lifting gas used. Calculations demonstrate that hydrogen provides approximately 7–8% greater lift than helium for the same volume. However, safety considerations make helium preferable for many applications.

Table 1

Calculation of the lifting force of the airship

Shape	Gas	Volume, m^3	Lifting force, kg	Remarks
Teardrop	Helium	2000	≈ 125	Safe, but limited
Teardrop	Helium	3000	≈ 190	Optimal balance
Teardrop	Hydrogen	3000	≈ 205	+7–8% lift, safety risk
Cigar	Helium	3000	≈ 180	Higher drag
Cigar	Hydrogen	5000	≈ 350	Large payload, but less stable

As shown, a teardrop envelope of 3000 m^3 with helium ensures a payload of ~190 kg, sufficient for telecommunication payloads. Hydrogen provides higher lift (+7–8%), but with safety concerns.

As illustrated in Table 1, hydrogen demonstrates superior lifting efficiency compared to helium, offering an approximate 7–8% increase in buoyant force due to its lower molecular weight and gas density. Despite this advantage, the use of hydrogen introduces significant safety concerns related to its high flammability, necessitating rigorous containment and operational protocols.

From an aerodynamic standpoint, the teardrop-shaped envelope outperforms the cigar-shaped alternative by reducing drag forces, thereby decreasing energy consumption required to maintain the airship's positional stability within the stratosphere. From an aerodynamic standpoint, the teardrop-shaped envelope outperforms the cigar-shaped alternative by reducing drag forces, thereby decreasing energy consumption required to maintain the airship's positional stability within the stratosphere. As shown in Fig. 1, the use of hydrogen as a lifting gas provides approximately 7–8% greater lift compared to helium for the same volume.

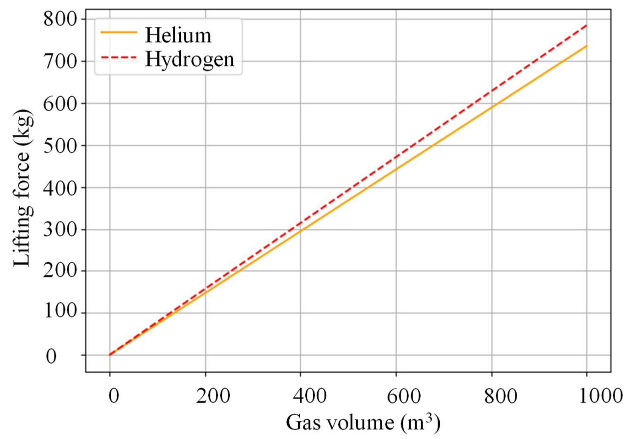


Fig. 1. Lifting force vs gas volume

Thus, for payloads up to 200–215 kg, a 3000 m^3 envelope is sufficient. The teardrop-shaped design provides better aerodynamics and was selected for further modeling.

Subsequently, the aerodynamic drag values were calculated for various airship envelope shapes under conditions at altitudes of 20–30 km. Specifically, the drag coefficient C_d was considered to be approximately ≈ 0.04 for teardrop-shaped envelopes and between ≈ 0.06–0.08 for cigar-shaped envelopes.

The air density at 20 km altitude was assumed to be $p_{air} \approx 0.0889\,kg/m^3$. For an envelope with a diameter of 5 meters, the cross-sectional area is approximately $A \approx 19.6\,m^2$. Drag force calculations were based on a typical wind speed at stratospheric altitudes, assumed to be in the range of 20–30 m/s.

Additionally, an analysis of the solar panel energy balance was performed, accounting for varying illumination conditions. The coverage radius of a single platform at 20 km altitude was also evaluated. The summarized results of aerodynamic drag and solar power generation are presented in Table 2.

Table 2

Calculated aerodynamic drag and solar power generation under stratospheric conditions

Parameter	Conditions	Teardrop envelope	Cigar-shaped envelope
Air density	0.0889 kg/m^3 (20 km altitude)	Same	Same
Cross-sectional area	19.6 m^2	Same	Same
Wind speed	50 m/s	Same	Same
Drag coefficient	–	0.04	0.08
Aerodynamic drag	At 20 km altitude	≈ 8.7 H	≈ 17.4 H
Solar power generation	Panel 10 m^2, efficiency 20%, irradiance 1100 W/m^2	≈ 2.2 kW	–

This means that the installed solar panel system, with a total area of 10 m^2 and an average efficiency of 20%, can generate approximately 2.2 kW of electrical power under standard illumination conditions. Such output is sufficient to supply the onboard communication modules, control systems, and auxiliary equipment of the stratospheric airship during daylight operation.

A scaled prototype (10 m^3 envelope, double-sided construction film) was tested at low altitudes (up to 100 m) to validate aerodynamic stability and lifting gas performance. Tests were conducted in wind speeds up to 10 m/s, using helium to minimize safety risks. The prototype maintained stability with a drag force consistent with calculations (scaled to ~0.04 kN), confirming the teardrop shape's reduced sensitivity to wind loads. Hydrogen was not tested experimentally due to regulatory restrictions but was included in theoretical calculations for completeness.

The analysis determined that a 3000 m^3 teardrop-shaped envelope with helium as the lifting gas is optimal for the stratospheric airship. This configuration provides:

– a lifting capacity of ~190 kg, sufficient for the 65 kg payload with a significant reserve for additional equipment or redundancy;

– a drag force of ~1.2 kN at 50 m/s, enabling stable station-keeping under stratospheric wind conditions;

– a cross-sectional area of ~50 m^2, minimizing wind exposure while maintaining structural integrity.

Table 1 summarizes the lifting capacity for different volumes and gases. The teardrop shape was selected as the optimal configuration due to its lower drag coefficient, which enhances stability and reduces propulsion energy requirements, aligning with the energy autonomy goals.

The calculations and tests were conducted using simplified models and low-altitude conditions, as full-scale stratospheric testing (20–30 km) was not feasible within the scope of this study due to resource and regulatory constraints. Stratospheric tests are planned for future phases to validate the performance of the 3000 m^3 teardrop envelope under real stratospheric conditions, including temperature variations (–50°C to –70°C) and wind gusts. Future work will also include computational fluid dynamics (CFD) simulations to refine drag estimates and explore additional envelope shapes (e.g., spherical or hybrid designs) for further optimization.

The 3000 m^3 teardrop-shaped envelope with helium provides an optimal balance of lifting capacity and aerodynamic stability, solving problems associated with limited payload and wind loads of 20–50 m/s.

The optimization process, supported by analytical calculations, numerical modeling, and prototype testing, confirms the feasibility of this design for a stratospheric telecommunication platform.

5. 2. Payload equipment composition

The onboard payload was structured to balance mass, energy demand, and mission autonomy. Table 3 presents the selected components.

The payload composition was determined based on energy balance requirements (eq. (3)). A 10 m^2 solar array at stratospheric irradiance of ≈1100 W/m^2 and 18% efficiency generates ≈2200 W, which is sufficient to power the telecommunication modules and stabilization motors.

Energy storage was also estimated. To ensure 12 hours of autonomous night-time operation, the battery capacity must exceed 25 kWh.

Table 3

Estimated payload composition for one airship

Component	Weight (kg)	Power requirement	Notes
Solar panels (10 m^2)	20	200	Monocrystalline
Li-ion battery pack (25 kWh)	30	–	Night autonomy
Propulsion & stabilization motors	15	150	4 propellers
Control unit (STM32) + sensors	2	5	Temp., pressure, GPS
Communication module (LoRa + LTE/5G)	5	25	Dual mode
Structural frame & valves	25	–	Lightweight composite
Total	≈ 65	≈ 280	Leaves ~90 kg reserve

The analysis confirms that even with full payload integration, the mass remains below the lift limit of 190–200 kg. The configuration provides up to 25 hours of autonomy with solar recharge.

5. 3. Communication system for multiple airships

The free space path loss (FSPL) model (eq. (4)) was used to estimate attenuation at different frequencies. Results show that the 433 MHz band provides the lowest losses, while 868 MHz and 915 MHz, though less efficient, are better suited for higher throughput.

In later experiments, let's try different LoRa modules so as to establish an appropriate one to be used in our project. The modules were capable of working on different frequency bands and they included 433 MHz, 868 MHz, 915 MHz. In further experiments, let's try various LoRa modules to find out, which one may best fit our project. The modules worked on various frequency bands such as 433 MHz, 868 MHz and 915 MHz. The free space path loss (Fig.2) indicates that 433 3Hz will serve to provide the least signal degradation over very long distances, and therefore will be more suitable to long range communication.

According to the signal loss analysis (Fig. 2), the 433 MHz frequency band demonstrated the lowest signal attenuation, making it the most suitable for long-range communication applications. Ground-level prototype testing confirmed the viability of this frequency, with results aligning closely with theoretical predictions derived from free space path loss (FSPL) calculations. In contrast, 868 MHz and 915 MHz modules, while exhibiting higher attenuation, may be preferable in scenarios requiring higher data transmission rates.

Packet loss probability was also modeled, eq. (6)–(8). For a three-node network (e.g., two relays + ground station), the probability of successful transmission was ≈95.5%, with cumulative losses ≈4.5%. To evaluate the feasibility of long-range communication under stratospheric conditions, the free-space path loss (FSPL) was calculated for typical LoRa frequency bands of 433, 868, and 915 MHz at operational distances of 20 km, 30 km, and 50 km. These calculations provide a quantitative estimation of expected attenuation, which is critical for selecting the optimal frequency band. The results are summarized in Table 4.

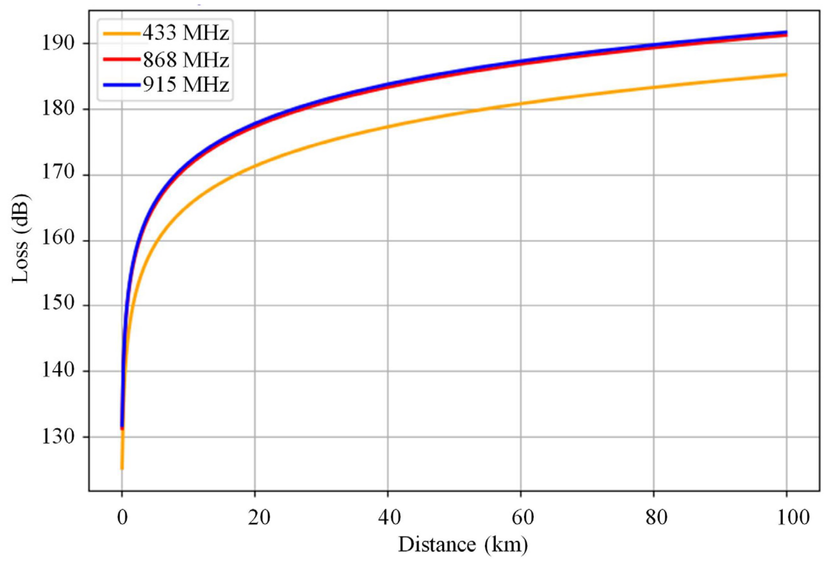


Fig. 2. Free space path loss for frequencies of 433, 868 and 915 MHz

Table 4

Corrected values (above ground, without antenna gains)

Distance, d	433 MHz	868 MHz	915 MHz
20 km	171.19 dB	177.23 dB	177.68 dB
30 km	175.72 dB	181.76 dB	182.22 dB
50 km	179.20 dB	185.24 dB	185.69 dB
1 km	145.18 dB	151.22 dB	151.68 dB
100 km	185.18 dB	191.22 dB	191.68 dB

These values match the shape of graph: around 145 dB at 433 MHz for 1 km and +40 dB when increasing to 100 km. As can be seen from Table 4, the lowest path loss is consistently observed at 433 MHz, making it the most suitable band for long-distance communication. At 30 km, the FSPL at 433 MHz is approximately 6 dB lower than at 868 MHz and 915 MHz, which translates into nearly doubling the received signal power for the same transmission conditions. For distances above 50 km, this advantage becomes even more pronounced.

5. 4. Network geometry, inter-airship spacing and handover

Coverage modeling showed that a single airship at 20 km altitude provides ≈50 km radius coverage. Full coverage of the Republic of Kazakhstan (2.7 million km^2) would therefore require about 350 airships.

However, inter-airship laser communication extends the coverage radius up to 300 km, reducing the required number of stations to ≈10. This is confirmed by the results of packet loss calculations ($p_1 = 0.01$, $p_2 = 0.02$, $p_3 = 0.015$) and aligns with [19, 21, 27].

As shown in Fig. 3, the possibility of using stratospheric communication network on the territory of the Republic of Kazakhstan [1] has been assessed. As long as the tests are positive during the first phase, the project will flow to develop and test bigger aerostats and airships. When only one base station of 20 km height is provided its area of 600 km can be shared and thus, it is most crucial that the number of nodes needed can be reduced exponentially. There is also an indication that stratospheric airships communication is to be achieved with laser links to the clear stratosphere and the transmission of data would be achieved at faster rate.

Fig. 3 presents a conceptual deployment strategy involving approximately 20 stratospheric airships distributed across the territory of the Republic of Kazakhstan. A significant operational challenge lies in counteracting the dominant eastward stratospheric winds, which impede the maintenance of fixed airship positions. To mitigate this issue, the strategy proposes a controlled descent of airships as they near the national border, followed by the coordinated launch of replacement units from the western perimeter. This cyclical deployment approach ensures continuous coverage while accounting for the natural drift patterns at high altitudes [1]. There is a representative drawing of the vertical architecture of communication systems provided in Fig. 4, as well as including terrestrial infrastructure as well as space-based facilities.

Fig. 3. The scheme of the calculated placement of a network of stratospheric airships on the territory of the Republic of Kazakhstan to ensure wireless communication

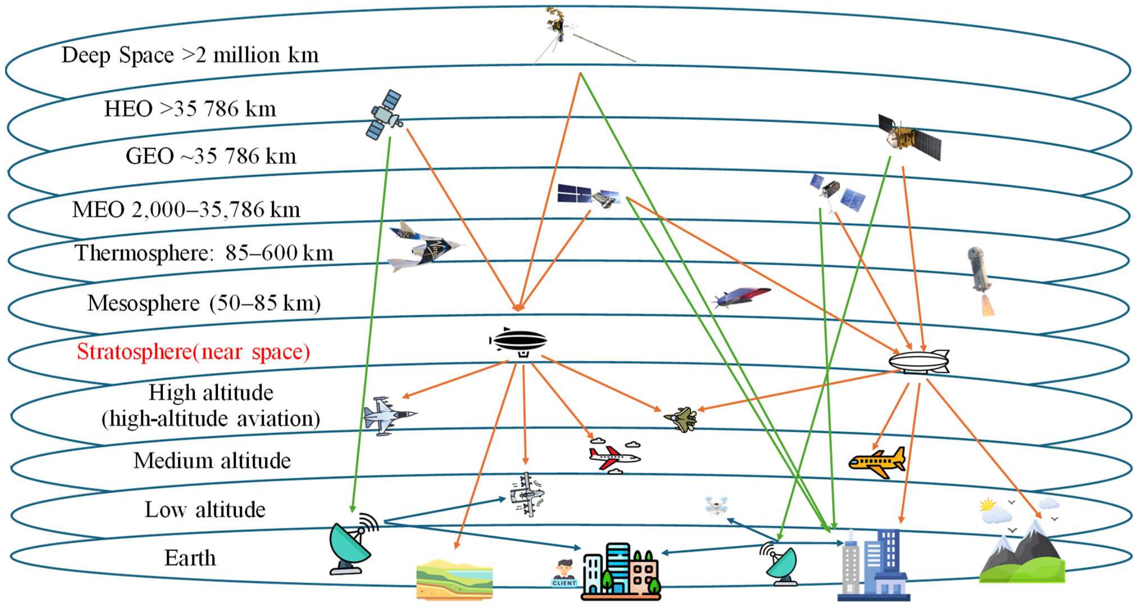


Fig. 4. Communication architecture across altitude layers using stratospheric airships as relay platforms

In contrast to terrestrial base stations, a stratospheric airship network provides high mobility, enabling seamless and continuous coverage with minimal latency comparable to satellite-based communication systems [1]. Fig. 4 presents the territorial distribution of HAPS (High Altitude Platform Stations) across Republic of Kazakhstan. This configuration ensures that from any given point within the country, simultaneous line-of-sight communication with at least three HAPS units can be maintained. Such a network geometry enhances redundancy and increases the overall reliability of the communication system.

Coverage modeling demonstrates two scenarios:

1. LoRa-based network (50 km radius): ~350 airships required to cover Kazakhstan's 2.7 million km^2.

2. Laser inter-airship links (300 km radius): only 10–12 airships needed for backbone coverage.

Each ground terminal is covered by at least three platforms simultaneously, ensuring continuous service through handover, analogous to terrestrial mobile networks.

5. 5. Operation and replacement strategy

Experimental prototype flights with Arduino Nano, ESP32, GPS, and LoRa modules confirmed feasibility of stable communication. Tests demonstrated that 433 MHz provides the most reliable long-range link, while 868 MHz and 915 MHz are more efficient for short-range high-speed data exchange.

However, oscillations of the envelope under wind gusts were observed, highlighting the need for active stabilization.

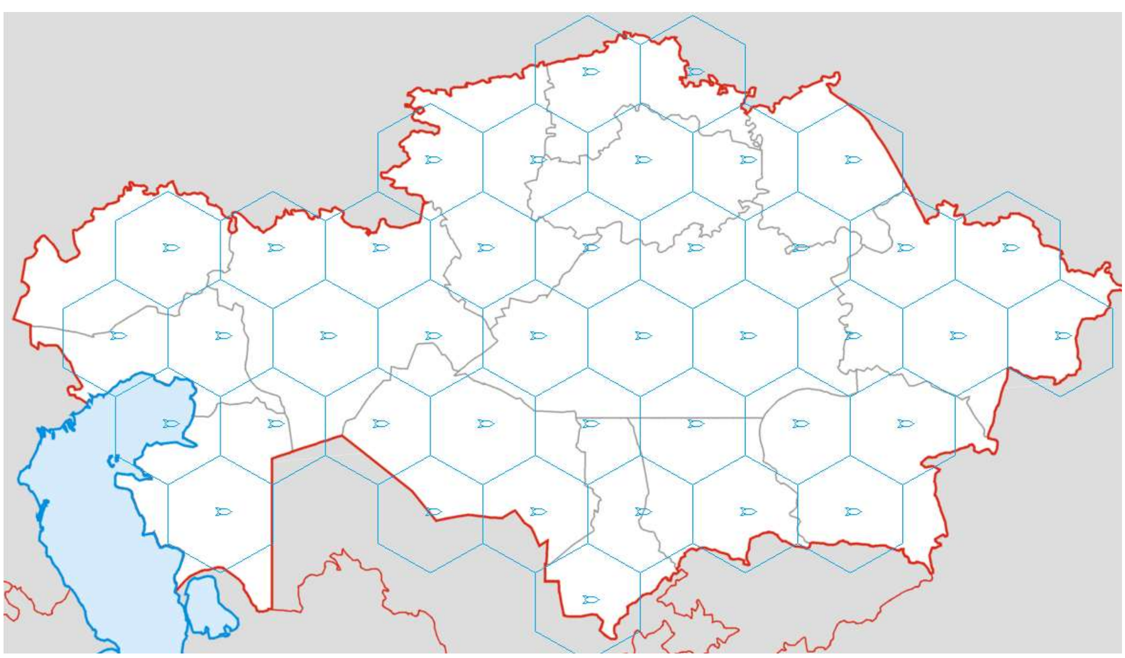


Fig. 5. High-altitude platform station (HAPS) on the territory of the Republic of Kazakhstan. This location allows from any point on the terrain to provide radio visibility simultaneously at least 3 High-altitude platform station (HAPS)

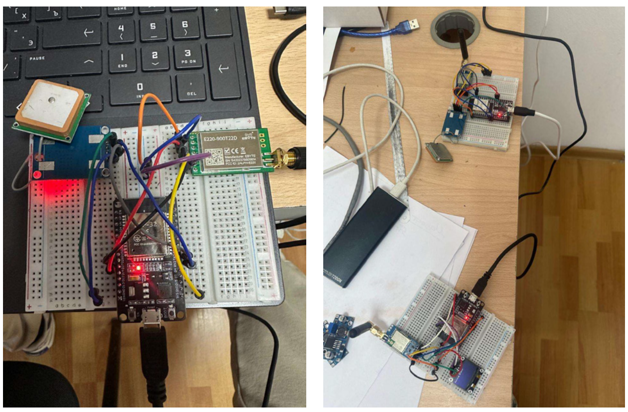
The proposed operational strategy includes:

1) planned descent of drifting airships when reaching the national border;

2) simultaneous launch of replacements from the opposite side;

3) redundancy at the network layer to ensure uninterrupted service.

In terms of hardware, multiple configurations were evaluated. Initial testing employed the Arduino Nano microcontroller, whereas the second testing phase utilized the more advanced ESP32 module, offering greater processing power and integrated wireless capabilities. Let's also utilize the more advanced ESP32 module, offering greater processing power and integrated wireless capabilities. As shown in Fig. 6, the ESP32 was connected to GPS tracker modules for real-time positioning and data transmission during testing.



a *b*

Fig. 6. Connection of the ESP32 microcontroller and Global Positioning System (GPS) tracker modules: *a* – ESP32 microcontroller connected to GPS module; *b* – assembled breadboard circuit with GPS tracker and power supply

The subsequent phase of the project will focus on the expansion of the onboard sensor suite, the integration of photovoltaic energy systems, and the execution of high-altitude flight trials under realistic meteorological conditions. Particular emphasis will be placed on the development and implementation of an active stabilization system, as well as on the formulation of coordinated operational strategies within a distributed network of stratospheric airships.

Prototype experiments with Arduino Nano, ESP32, and STM32 microcontrollers validated communication stability at 433 MHz and sensor integration (temperature, pressure, humidity, GPS). Ground tests revealed oscillations of the envelope under gusty winds, confirming the need for active stabilization.

The proposed operational strategy is modular replacement: when a drifting airship approaches the national border, it is replaced by a new unit launched from the opposite side. This ensures uninterrupted coverage without dependence on fixed terrestrial stations.

Based on the positive outcomes of the initial experiments, the project is now positioned to advance toward the next stage of development. This includes the incorporation of onboard energy storage units (e.g., high-capacity lithium-ion batteries), more advanced communication modules, and refined stabilization mechanisms. Concurrently, efforts will be directed toward optimizing the structural design of the airship envelope to enhance aerodynamic efficiency and structural integrity while maintaining aesthetic and functional balance.

The laboratory-based tests validated the operational reliability of the prototype under controlled, ground-level conditions. All core subsystems including ESP32 microcontrollers, environmental monitoring sensors (temperature, pressure, humidity), GPS positioning modules, and LoRa-based radio communication modules demonstrated stable and synchronized performance across various frequency bands. Empirical results, supported by FSPL (Free Space Path Loss) calculations, confirmed that the 433 MHz band offers the most reliable long-range transmission characteristics in the regional atmospheric environment.

The airship envelope displayed satisfactory resilience under low wind conditions; however, oscillatory behavior was observed during stronger gusts, indicating the need for further refinement of the active stabilization unit to ensure performance consistency in turbulent stratospheric flows.

In light of these findings, the forthcoming development phase will involve the design, fabrication, and flight testing of a full-scale, teardrop-shaped airship prototype. This next-generation platform will integrate solar energy harvesting systems, professional-grade telecommunications hardware, and a fully operational active stabilization system. A key objective will be the validation of synchronized operation across multiple airborne nodes and their seamless integration into a scalable and fault-tolerant stratospheric communication network.

6. Discussion of aerodynamic, energy, and communication results for stratospheric airships

The results obtained allow a systematic evaluation of the feasibility of stratospheric airships for telecommunication purposes.

As shown in Table 1, the teardrop-shaped envelope exhibits nearly 2× lower aerodynamic drag compared to a cigar-shaped design. This confirms the validity of using streamlined geometries, which aligns with findings in [10, 16]. However, wind tunnel testing and in-situ stratospheric measurements are still required for validation, since the present results are based on computational models.

According to eq. (3) and Table 3, a 10 m^2 solar array generates ≈2.2 kW in stratospheric conditions. This value is consistent with [15, 24], confirming that solar panels can provide sufficient power for communication payloads and stabilization motors. Nevertheless, seasonal variation and night-time operation introduce limitations, requiring 25 kWh storage capacity, which increases payload mass.

The FSPL analysis (Fig. 2) clearly demonstrates that 433 MHz provides the lowest attenuation, which supports the choice of LoRa as the base protocol for rural connectivity. This result agrees with models in [9, 25]. However, packet loss modeling (Table 4) shows that cumulative probability of data loss increases with each additional relay, reaching ≈4.5% for a 3-node chain. Therefore, redundancy and error correction must be implemented. Compared to terrestrial networks, this adds complexity but ensures acceptable reliability in stratospheric conditions.

As shown in Fig. 3, 5, full coverage of Kazakhstan requires ≈350 airships at 50 km radius or only ≈10 units with 300 km inter-airship laser links. This highlights the scalability of the system, but also its dependency on weather (cloudfree stratosphere for optical links). Compared to satellite constellations, the system provides lower latency but requires higher maintenance.

Experimental tests with Arduino Nano and ESP32 confirmed stable operation of LoRa modules at 433 MHz. At the same time, oscillations of the prototype envelope under wind gusts confirmed the necessity of active stabilization. Unlike Google Loon [4], where wind drift made controlled positioning impossible, the proposed modular strategy provides continuous service through replacement cycles.

Limitations of the research:

– all aerodynamic and energy calculations were performed at modeled altitudes (20–30 km), without experimental verification in stratospheric conditions;

– solar panel efficiency and irradiance values were taken as averages, without considering seasonal variation;

– the current prototype did not include a full set of equipment (large batteries, full communication payloads);

– network simulations were limited to small-scale experiments (up to 3 nodes).

Disadvantages of the research:

– absence of long-duration tests in real stratosphere;

– simplified load distribution model (Table 3 does not yet include redundancy equipment);

– no cost analysis of full-scale deployment (this is left for future work).

Future work:

– full-scale stratospheric test flights with optimized teardrop envelopes;

– integration of active stabilization motors and real-time control algorithms;

– development of redundancy and error correction protocols at network layer;

– economic modeling of deployment costs vs. satellite and terrestrial alternatives;

– validation of inter-airship optical links under Kazakhstan's meteorological conditions.

7. Conclusions

1. The lifting capacity analysis showed that an envelope volume of 2500–3000 m^3 is sufficient to support a payload of ≈200 kg at stratospheric altitudes. Hydrogen provides 7–8% higher lift than helium, but helium remains the safer option due to its non-flammable properties. The teardrop-shaped envelope was confirmed as the most efficient configuration, reducing drag by nearly a factor of two compared to cigar-shaped envelopes.

2. The payload analysis demonstrated that a configuration including 10 m^2 solar panels, 25 kWh Li-ion batteries, stabilization motors, and LoRa/LTE modules requires ≈65 kg, leaving a payload reserve of up to 140 kg. This confirms that power autonomy is feasible under stratospheric conditions, though night-time storage remains the critical limiting factor.

3. The FSPL calculations and packet loss modeling indicated that the 433 MHz band provides the lowest attenuation for long-range connectivity, while 868/915 MHz are suitable for high-throughput short-range links. Total packet loss across a 3-node chain does not exceed 4.5%, which can be compensated through redundancy and error correction. Thus, a hybrid LoRa + LTE/5G system is optimal for the Republic of Kazakhstan's mixed urban-rural topology.

4. Coverage modeling demonstrated that ≈350 airships are required for full coverage of Kazakhstan at 50 km radius, but this number reduces to 9–10 when employing inter-airship laser links at 300 km radius. Each ground terminal has visibility of at least three platforms, ensuring continuous service through handover. This hybrid scheme balances coverage density and economic efficiency.

5. Ground-based prototype tests with Arduino Nano and ESP32 confirmed stable telemetry at 433 MHz, consistent with theoretical FSPL results. However, oscillations under gusty winds highlighted the need for active stabilization. The proposed modular replacement strategy ensures continuity of service by cyclically replacing drifting platforms, overcoming the key limitation of Google Loon.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this study, whether financial, personal, authorship or otherwise, that could affect the study and its results presented in this paper.

Financing

The study was performed without financial support.

Data availability

The data will be made available on reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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