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Original Research

HAPS BETWEEN KESSLER SYNDROME, BENEFITS FOR HUMANITY, AND TECHNOLOGICAL CHALLENGES

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Abstract: Kessler syndrome represents a significant threat to satellites in orbit and human endeavors in space exploration. The Earth's orbital environment hosts important infrastructures like the International Space Station and a high volume of satellites for communications, navigation, and Earth observation. The research aims to mitigate the dangers and potential impacts of Kessler syndrome by employing the latest technological innovations, specifically High-Altitude Platform Systems (HAPS), with carefully developed strategies for the survival and advancement of mankind. The study employs a hybrid SWOT-AHP method in designing the viable strategies for HAPS implementation in the context of Kessler syndrome. The key contribution of the research lies in demonstrating that, despite existing technological limitations, HAPS platforms can serve as viable alternatives to satellites made inoperable by Kessler syndrome. More significantly, by implementing the strategies suggested in this research, HAPS platforms can be transformed into multi-purpose systems with immense potential for a wide variety of applications in the event of cataclysmic events disabling orbital communications and navigation systems. Such platforms would be capable of functioning together with operational satellites or in a fully autonomous mode, thereby resolving key issues of Kessler syndrome.

Keywords: HAPS, Kessler syndrome, Satellites, SWOT-AHP, Strategies

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1. INTRODUCTION

HAPS are the aircrafts or balloons that have the ability to fly or hover in the stratosphere at altitudes of about 20 km. Their operations are carried out without a crew, completely autonomously, with the possibility of a constant presence above a specific area where the mission is carried out. One of the characteristics is the ability to take off and land, which allows the ground crew to periodically maintain and change the systems with which the system is equipped (GSMA, 2021). The functioning characteristics of the HAPS platform are officially defined in the ITU Radio Regulations (No. 1.66A) as “a station located on an object at an altitude of 20 to 50 km and at a specified, nominal, fixed point relative to the Earth” (ITU, 2016, p 13.). There are a large number of satellites in Earth's orbit. These satellites can be grouped into three main categories: payloads, rocket engines, and debris associated with the launch or disintegration of a particular payload or carrier rocket. This last, most numerous grouping consists of objects that are in orbits that intersect with each other, thus increasing the probability of a collision between them. As satellites collide, additional fragments are created, the formation of which increases the probability of collisions with other satellites, which would further increase the number of debris exponentially. This chain reaction could lead to the creation of a large debris belt around the Earth (Kessler & Cour-Palais, 1978).). This phenomenon is called The Kessler syndrome, after NASA scientist Donald J. Kessler who studied this scenario. Considering that the low-intensity Kessler syndrome boundary has already been passed, a second massive ingestion of a large amount of orbital debris would further enhance its development, rendering the conduct of a space mission impossible (Doboš & Pražák, 2022).

2. LITERATURE REVIEW

2.1. High Altitude Platform Stations

Based on design, there are two basic categories of HAPS aircraft: lighter-than-air HAPS called aerodynes and heavier-than-air HAPS – also called aerostats (balloons, airships, dirigibles) (HAPS Alliance, 2024; Bagarić et al., 2025). Balloons in the form of HAPS have promising potential for efficient data collection and transmission compared to traditional methods such as satellites, towers or drones. They have the ability to provide critical connectivity to underserved or remote areas, improving modern communications. The advantage of balloon platforms over other high-altitude aircraft or stationary transmission bases lies in the breadth of their potential applications. They are characterized by a longer flight duration compared to other systems as well as independence from runways. Compared to UAS, balloons have a lower need for technical maintenance, and therefore landing. In addition, unlike ground telecommunications base stations, they can be easily relocated to adapt to a specific mission. When talking about the challenges of their application, there is the problem of maintaining their position and navigation within international airspace (van Wynsberghe & Turak, 2016; GSMA, 2021).

Airships are the largest platforms, and, as such, they are characterized by greater capabilities in terms of payload weight (several hundred kg), power (over 10kW) and flight autonomy (up to a year). What they have in common with HAPS platforms with fixed wings is precise control over platform positioning. On the negative side, the sheer size of these systems causes additional operational complexity (GSMA, 2021). Although most missions require airships to maintain a fixed position at high altitudes, cruising in a specific direction is the primary mode of operation, especially for conducting target tracking and signal transmission tasks within a given area. It should be noted that the method of generation and the amount of energy consumption significantly affect the cruise coverage area and endurance of airships, which greatly affects their performance (Zhu et al., 2021).

HAPS platforms with fixed wings have the ability to precisely position and also have greater weight, available power and flight capabilities compared to balloons. On average, they can carry a load weighing several tens of kg and have a power of more than several hundred watts. They have the ability to perform missions for a longer period of time compared to balloons. With limitations in terms of payload weight and power requirements, they can remain in the air for several months. Hybrid approaches that represent a combination of aerostatic and aerodynamic configurations (GSMA, 2021). Tethered UAS HAPS Compared to balloons and classic aircraft, they have a number of advantages, primarily reflected in lower cost, shorter commissioning time, easier maintenance, increased mobility and a whole range of other parameters. It should be noted that a completely new generation of tethered UAS HAPS is being developed, and well-known companies are leading the way, including Elistair (France and the USA), Ziian (China), Drone Evolution (Great Britain) and Logos Technologies (USA) (Mittal et al., 2024).

Latency is a measure of time that refers to delays in communication systems. It is the time interval between the moment a signal or data leaves its source and the moment it reaches its final destination. HAPS (High-Altitude Platform Systems) have lower latency during signal transmission due to their lower altitude compared to satellites. Satellite communications include satellites in geostationary Earth orbit, satellites in medium Earth orbit, and low Earth orbit satellites, which include altitudes of 36,000 km, then 2000–36,000 km, and finally altitudes below 2000 km. The round-trip time (RTT) from the user to these satellites is approximately 240–280 ms, 54–86 ms, and 6–30 ms, respectively. In comparison, the RTT for HAPS is 360 ms and 680 ms to points within 50 km and 100 km radius, respectively (Takabatake et al., 2024).

The advantages of using HAPS include free deployment, low operating costs, the ability to perform maintenance during use, payload, and better performance for certain purposes due to lower altitude deployment, low propagation delay, wide angle, wide range of activated altitudes that can be used for broadband broadcasting, even in the event of a disaster. However, HAPS has disadvantages in terms of vehicle tracking, balloon technology that still requires further development, and stabilization of the antenna on board, which is still a challenging task (Mahardika Putro et al., 2023; Delgado et al., 2024). HAPS has the ability to provide extremely high data rates and wide coverage. The problem is the high probability of interference with various other terrestrial services (fixed, mobile, etc.). Therefore, HAPS transmitters are required to reduce their transmit power to meet the interference-to-noise ratio (INR) requirement to protect receivers of existing services. The problem is that if the transmit power from the HAPS aircraft is excessively reduced (the signal–to–interference–plus–noise ratio SINR of the HAPS downlink), this can lead to a complete loss of communication (Jo et al., 2022). Interference of communications in HAPS platforms is another major parameter that affects and limits system performance together with channel fading. Interference would cause problems such as crosstalk, call drops, or degradation of communication quality during communication, thus reducing user satisfaction with the service (Guan et al., 2019).

HAPS are considered by academic and industrial circles as future key enablers of the heterogeneous network vertical, which involves the integration of terrestrial networks with networks that are not located on the ground. When the mobile communications dimension is carefully considered, HAPS are capable of directly delivering services to terrestrial users distributed within a radius of about 100 km (Maki et al., 2025). When considering terrestrial base stations (BS), they are certainly lower in altitude than HAPS with a much narrower coverage area, requiring a much larger number of base stations to achieve wide coverage. In other words, HAPS offer lower latency than satellites and wider coverage than terrestrial base stations (Guan et al., 2019). The design problems of HAPS are reflected in the fact that the aerodynamic frame of the aircraft needs to have a very long endurance in conditions where there is low air density in order to achieve a positive lift-to-drag ratio. For this reason, large wing spans are required, for which advanced composite materials are used (satisfactory resistance with low weight). In addition, large aerodynamic surfaces simultaneously provide a large surface area on which solar cells can be placed (e.g. Zephir-S has a wing area of 28 m^2). However, due to undesirable physical properties such as very dynamic aero elasticity, it causes abnormal oscillations, which affect stability (Bagarić et al., 2025).

The most common solutions for powering airships are photovoltaic (PV) cells and rechargeable batteries. The low efficiency of photovoltaic cells poses a major problem for airship missions at high altitudes. In addition, the problem of developing high-energy-density rechargeable batteries and advanced power management systems to improve endurance has arisen (Xu et al., 2020). HALE spacecraft can replace or supplement the role of satellites for a number of missions, but at a lower cost. In addition, because the atmospheres of Mars and Venus are similar to those at high altitudes on Earth, solar-powered HALE spacecraft can be used to explore Mars and Venus (Gao et al., 2013). HALE aircraft in the HAPS role have the problem of how to meet the power requirements due to the weight of the rechargeable batteries. It should be noted that the weight of the batteries takes up about 50% of the total mass of the solar-powered HALE aircraft, therefore, for renewable energy, regenerative energy technologies such as solar cells, rechargeable batteries and energy management systems are key areas to achieve the desired long-term endurance (Gao et al., 2013). In order to improve telecommunication services, especially 5G Evolution and the upcoming 6G era, it is expected that HAPS will be actively used to transmit radio waves or broadcast radio waves as a base station (Hokazono et al., 2022).

The following Table 1. shows a comparison of the most important characteristics of satellite and HAPS systems:

Table 1. Comparison table of different systems (GSMA, 2021)

Coverage	System	Satellite for global coverage	Time per orbit (hours)	Time in site per gateway	Latency RTT (ms)	Mass (kg)	Life time (years)
Global coverage	GEO	3	24	Always	600/700	3500	15
	MEO	10-30	5-12	2-4 hours	<150	700	12
	LEO	100+	1.5	15 minutes	<50	5-1000	<5-7
Regional coverage	HAPS	1 aircraft ~ 12.731 km^2		Always	<10	<320 (Ballon) <100 (Aircraft)	>5 (Ballon) >8 (Aircraft)

Application areas where HAPS has great potential for application are mobile telephony in the mobile service (MS), high-speed internet in the fixed service (FS), digital TV and news gathering in the broadcast service (BS) and other services such as remote sensing, radio broadcasting, traffic monitoring and weather monitoring (Park et al., 2008). The stratosphere is a very inhospitable environment. It is characterized by low pressure and low temperatures (down to -65 C), jet stream winds blowing at speeds of 100 km/h, average wind speeds of 40 km/h, and the effects of gravitational waves and solar radiation. Key technological and regulatory drivers in this area include artificial intelligence and machine learning, the emergence of new materials, regulatory advances, advances in battery design and power management, new weather forecasting models, and finally public UAS acceptance (HAPS Alliance, 2023). HAPS have a number of advantages over satellites. HAPS can very well serve as a second type of range source. Since GNSS positioning performance degrades significantly in urban areas, deploying several HAPS as additional range would improve GNSS positioning performance. HAPS can indeed improve HDOP, VDOP and 3D positioning accuracy of legacy GNSS (Zheng et al., 2023).

2.2. The Kessler syndrome

NASA makes a clear distinction between the terms space debris and orbital debris. Space debris includes both natural meteoroids and artificially created orbital debris. Orbital debris refers to any object that has been man-made and placed into orbit around the Earth and no longer serves a useful purpose. This includes defunct spacecraft, abandoned launch stages, mission-related debris, and fragmentation debris (Adamišinová, 2022). Orbital debris represents one of the most serious security threats to the sustainability of orbital systems. The reasons for this are reflected in the laws of orbital physics and as a result of the massive use of Earth's orbit by humanity for positioning various satellites (Doboš & Pražák, 2022). Earth's orbits are an extremely crowded space. As of January 2021, there were 3,372 operational satellites in orbit. When analyzed by orbit, 2,612 were in low Earth orbit (LEO), 136 in medium Earth orbit (MEO), 562 in geostationary orbit (GEO), and 59 in elliptical orbits (Doboš & Pražák, 2022). The company, SpaceX's Starlink, now accounts for nearly half of all satellite traffic. In February 2024, SpaceX announced that it would prematurely deorbit about 100 of its 5,500 satellites after discovering a design flaw that could make them a collision hazard, fueling fears of the Kessler syndrome, a catastrophic wave of satellite collisions (Clarke, 2024). The number of satellites is increasing steadily and by 2029, there could be at least 107,000 active satellites. In addition to functional systems, there is a significant amount of space debris in orbit. As of January 2021, the US Space Surveillance Network has tracked over 28,000 objects in orbit. It is estimated that there are already approximately 900,000 objects larger than 1 cm orbiting the Earth, of which approximately 34,000 are larger than 10 cm (Doboš & Pražák, 2022).

According to NASA experts, those pieces of debris that are at an altitude of 600 kilometers will fall back to Earth in a few years, pieces of debris that are at an altitude of 800 km will fall to Earth over the next few centuries, while those orbiting above 1,000 kilometers will circle the Earth for a thousand years or more (Clarke, 2024). In terms of solving orbital debris, the first step would be to stop generating new ones, while the second step would involve removing large pieces of debris that have the potential to create a cascading effect that Kessler's scenario implies (Kelvey, 2024). The National Academy of Sciences believes that the current state of orbital debris has already reached the so-called tipping point. "i.e., the total mass of debris currently in orbit has reached a threshold where it will continually collide with itself, with a further progressive increase in the amount of orbital debris. This increase will lead to an inevitable increase in spacecraft failures, further increasing the rate of growth of orbital debris (Adilov et al., 2018). A lot needs to go wrong for the Kessler syndrome to manifest, but things get considerably more complicated if nations continue to destroy satellites with missiles on purpose (Kelvey, 2024). The U.S. Air Force intercepts more than 25,000 pieces of space debris larger than 10 centimeters each day, weighing in at about 9,000 metric tons. This dangerous debris orbits Earth at speeds of approximately 10 kilometers per second, or more than 22,000 miles per hour. Orbital debris collisions cost satellite operators an estimated $86 million to $103 million annually, and that number is sure to grow as each operator and each collision generates more debris (Scientific American, 2024).

Today, satellite losses due to collisions are quite rare, but it is worth noting that if the behavior in LEO changes, they will become a common occurrence every year. The long-term effect of the accumulation of debris is particularly alarming (Drmola & Hubik, 2018). The increase in LEO debris poses an extremely high threat to space operations, compromising the ability to launch new and maintain existing spacecraft in medium Earth orbit (MEO) where GNSS satellites primarily operate. Currently, MEO hosts a constellation of 31 active global positioning satellites (GPS), 35 active BeiDou satellites, 24+ Galileo satellites, 24+ GLONASS, 7 Indian Regional Navigation Satellite System and 7 Quasi-Zenith Satellite Systems (KZSS). The loss of satellite communications would cause far-reaching and incalculable consequences for various industries, including transportation, banking, energy, and military operations. (Mariappan & Crassidis, 2023).

Mariappan & Crassidis (2023) propose two categories of potential solutions emerge: short-term and long-term. In the short term, the focus is on deorbiting and burning debris that poses an immediate threat. The long-term approach focuses on recycling. Researchers have proposed innovative methods for recycling debris into powders that can be used as fuel, artificial soil, and other resources for space missions. The problem of orbital debris is reflected in the following:

1. Space agencies and private companies are sending more objects into space than ever before, creating a protected environment.
2. The aforementioned objects are a generator of debris, which can return to Earth or remain in orbit.
3. When the aforementioned debris falls to Earth, it can affect safety issues and cause contamination.
4. When the aforementioned debris remains in orbit, the aforementioned space debris increases further.
5. Since the debris moves at high speeds, debris impacts on existing objects (satellites) represent a source of new artificial space debris.
6. At the aforementioned high speeds developed by the aforementioned pieces and with current resources, artificial space debris is very harmful and/or potentially deadly in the event of an impact.

If nothing is done to change behavior in accordance with points 1-6, the consequences will be very negative for space exploration (Pla, 2023).

NASA believes that even small objects can cause some degree of damage:

- Most satellites can survive impacts from objects as small as ~1 mm, but individual components of the satellite system can be disabled or completely destroyed;
- Most satellites can sustain damage from objects as small as 1 cm;
- For every object that NASA is able to track (via radar or optical telescopes), there are incomparably more small objects that it is unable to track, which can cause significant damage to a spacecraft (Matney, 2023).

3. DATA AND METHODOLOGY

For the purposes of the research, relevant literature was consulted, including high-quality academic articles in the field of HAPS implementation as well as material dealing with the Kessler syndrome. Based on this literature, a SWOT analysis was conducted to identify key factors affecting the subject of the analysis, and then a TOWS matrix was formed to develop specific strategies based on the findings obtained from the SWOT analysis. Furthermore, by applying the hybrid SWOT-AHP method, a detailed prioritization of strategies was performed, allowing for an objective evaluation and ranking of HAPS implementation strategies in light of the Kessler syndrome according to their importance and potential impact on decision-making.

4. RESULTS AND DISCUSSION

Table 2. TOWS matrix of HAPS potential application in light of the Kessler syndrome

	S	W
	S1 HAPS missions are carried out below orbital zones that would be affected by the Kessler syndrome; S2 HAPS are relatively cheaper to position and maintain compared to satellites, with the ability to perform a variety of missions; S3 Continuous signal coverage of a narrow area where the mission is to be carried out; S4 Low signal latency; S5 Reconfigurable to handle different tasks.	W1 Limited coverage area compared to satellites; W2 Dependence on weather conditions in the stratosphere (wind, turbulence, solar radiation, cold…); W3 Vulnerable structure to various types of stresses; W4 Shorter service life compared to satellites; W5 Need for further improvement of energy sources.
O	SO1 Integration of production capacities of different HAPS manufacturers in order to develop more efficient systems	WO1 Development of hybrid systems that rely less on satellites and creation of regional networks that form a single global network
O1 Further process of improving battery technology; O2 Development of alternative forms of energy supply (hydrogen); O3 Possibility of taking over the role of satellites whose functioning is endangered by the Kessler syndrome for the realization of certain missions; O4 Further 5G and 6G integration enabling high-speed and low-latency connections; O5 Development of innovative materials used for the construction of HAPS.		
T	ST1 Development of HAPS regional Global Positioning Systems	WT1 Legislation enabling the active implementation of HAPS platforms
T1 Legislation obstacles for HAPS application T2 Further development of orbital debris removal technology; T3 The risk of the Kessler syndrome is acceptable compared to the effort invested in further development of HAPS technology; T4 Challenges in terms of frequency spectrum allocation may pose obstacles to the deployment of HAPS; T5 High costs of developing a system with a satisfactory level of technology.		

Table 3. Local and global importance of SWOT factors

Factor	Importance of SWOT factors	SWOT subfactors	Local importance of SWOT subfactors	Global importance of SWOT subfactors
	0.195	S1 HAPS missions are carried out below orbital zones that would be affected by the Kessler syndrome	**0.333**	0.065
		S2 HAPS are relatively cheaper to position and maintain compared to satellites, with the ability to perform a variety of missions;	0.079	0.015
		S3 Continuous signal coverage of a narrow area where the mission is to be carried out;	0.174	0.034
		S4 Low signal latency;	0.275	0.054
		S5 Reconfigurable to handle different tasks.	0.138	0.027
	0.138	W1 Limited coverage area compared to satellites;	**0.412**	0.057
		W2 Dependence on weather conditions in the stratosphere (wind, turbulence, solar radiation, cold…);	0.090	0.012
		W3 Vulnerable structure to various types of stresses;	0.209	0.029
		W4 Shorter service life compared to satellites;	0.177	0.024
		W5 Need for further improvement of energy sources.	0.112	0.015
	0.391	O1 Further process of improving battery technology;	0.117	0.046
		O2 Development of alternative forms of energy supply (hydrogen);	0.251	0.098
		O3 Possibility of taking over the role of satellites whose functioning is endangered by the Kessler syndrome for the realization of certain missions;	**0.364**	0.142
		O4 Further 5G and 6G integration enabling high-speed and low-latency connections;	0.105	0.041
		O5 Development of innovative materials used for the construction of HAPS.	0.162	0.063
	0.276	T1 Legislation obstacles for HAPS application	**0.369**	0.102
		T2 Further development of orbital debris removal technology;	0.156	0.043
		T3 The risk of the Kessler syndrome is acceptable compared to the effort invested in further development of HAPS technology;	0.322	0.089
		T4 Challenges in terms of frequency spectrum allocation may pose obstacles to the deployment of HAPS;	0.064	0.018
		T5 High costs of developing a system with a satisfactory level of technology.	0.090	0.025

Based on the size of the obtained normalized weights, the order of strategy application can be defined as follows:

$$SO1\,(0.310) \rightarrow WT1\,(0{,}282) \rightarrow WO1\,(0.255) \rightarrow ST1\,(0.153). \qquad (1)$$

The first strategy that would be implemented in order to fully exploit the HAPS potential in light of the Kessler syndrome is SO1Integration of production capacities of different HAPS manufacturers in order to develop more efficient systems (0.310). The implementation of this strategy would lead to successful projects in the field of HAPS, which would influence the public and decision-makers to change the legal regulations in order to actively implement HAPS platforms, either independently or in cooperation with satellites. This would be followed by the following strategy WT1 Legislation enabling the active implementation of HAPS platforms (0.282), which would create conditions to support their deployment and integration into existing systems. Third strategy WO1 The development of hybrid systems that rely less on satellites and the creation of regional networks that form a single global network (0.255) would enable greater resilience and redundancy, as well as improved connectivity. The last successive strategy ST1 Development of HAPS regional Global Positioning Systems (0.153) will enable more precise positioning, more reliable navigation, and improved communication in areas where satellite signals are not available due to the Kessler syndrome. Successive implementation of the four aforementioned strategies regarding HAPS potential application in light of the Kessler syndrome will reduce the damage associated with the phenomenon itself and enable alternative infrastructure for communication, navigation and observation, without relying on disabled satellites.

5. CONCLUSION

This study suggests that the implementation of appropriate strategies could significantly mitigate or even completely prevent the adverse effects of Kessler syndrome in certain contexts. The primary contribution of this research lies in highlighting the potential of high-altitude platform systems (HAPS) and advocating for increased investment in the development of technologies that would improve their effectiveness in addressing the challenges posed by Kessler syndrome. The shortcoming of this study is that there is a large gap between human technological capabilities and the desire to take urgent steps in this regard. It should be noted that the question is not whether Kessler syndrome will occur, but when it will occur and whether humanity will be prepared for such a scenario, especially in light of the launch of mega constellations of satellites. The potential consequences for human life and the future of space exploration require significant attention and justified concern.

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