Concepts and Main Applications of High-Altitude-Platform Radio Relays

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Abstract

Novel radio systems using high-altitude platforms (HAPs) at altitudes around 20 km above the ground are proposed as a way of overcoming the drawbacks of conventional satellite and terrestrial radio systems. This paper provides an introduction to the field, acting as a precursor to several extended papers on HAPs that will be featured in a future *Radio Science Bulletin* special issue. The concept, genesis, development, and recent status are detailed, and the proposed applications and advantages of different categories of HAPs are discussed. The possibilities of microwave-energy transmission from ground stations to receiving rectifier antennas (*rectennas*) on HAPs are described as a way of overcoming the long periods of darkness, when solar cells are not usable. Finally, the paper describes the new HAPS projects being realized, followed by a short forecast of future trends in the area. A thorough comparison of radio communication and remote sensing using GEO and LEO satellites, terrestrial radio systems, and HAPS is presented in tabular form.

1. Introduction

Radio communication systems are one of the main promoters of the modern economy and social growth. Their importance is also predominant for defense and security issues. Nowadays, the global numbers of mobile phones and of mobile PC subscribers alone have exceeded two billion and four hundred million, respectively. Their numbers are still increasing, as shown in Figure 1 [1, 2]. Most mobile radio communication equipment and systems are terrestrial. However, for long distances, reliable communication, and for scarcely populated rural regions and oceans, geostationary (GEO) and low-Earth-orbit (LEO) satellites are used as base-station relays in the sky [3, 4].

GEO satellites are located 36,500 km above the ground in an equatorial orbit, and are geostationary related to the Earth. Their main applications are for good-quality long-range mobile radio communication, and for broadcasting

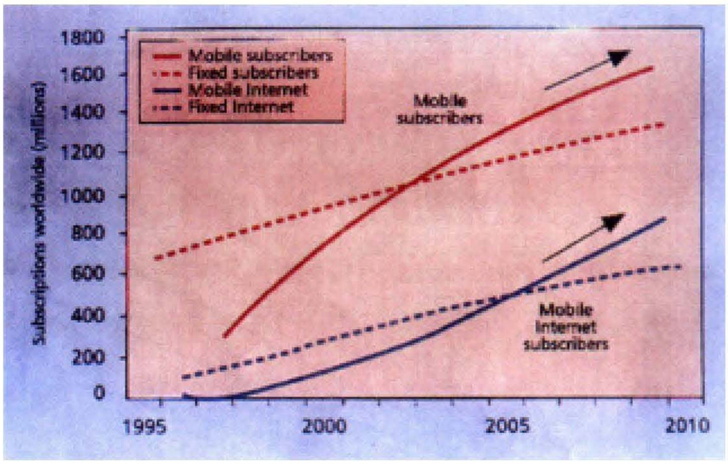

Figure 1. The global growth of mobile and fixed radio-communication subscribers [1].

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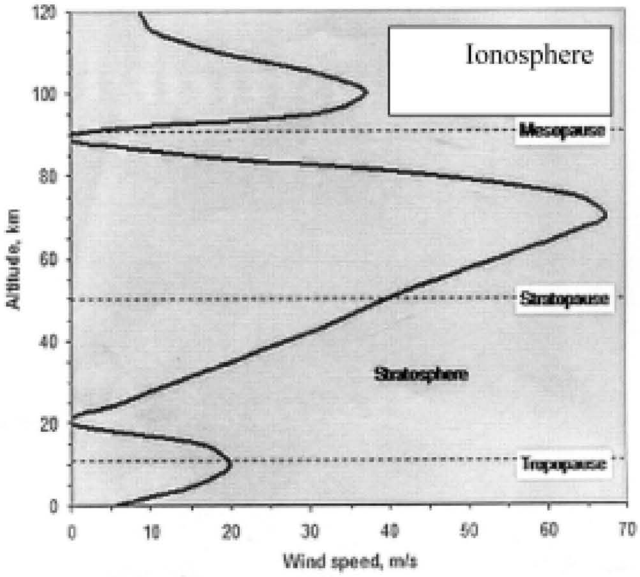


Figure 2. The annual average wind speed as a function of altitude: values vary with season and locations [8] (http://nssdc.gsfc.nasa.gov/space/model/atmos/cospar1.html).

[5, 6]. Nowadays, more than 400 GEO satellites are active, despite their high price and high launching and insurance costs. GEO satellites are characterized by high dispersion losses in the range of 200 dB, and time delays in the range of 0.3 s, due to their long distance from the ground stations [7]. The long delay causes synchronization problems, and limits high-speed Internet transmission.

Due to the tremendous growth in radio communications and the danger of the GEO satellite orbit saturation, LEO satellites were designed. These are located around 1000 km above ground. The launch of a single LEO satellite is significantly simpler and cheaper than for a GEO satellite, and the dispersion losses and delay times are smaller. However, the LEO satellite radio systems require handover, and the whole system operation needs 12 to 66 satellites [3]. The big LEO Iridium and Globalstar systems were technological successes but economic failures. The main reasons were the high cost of the LEO system, and the rapid development and improvement of terrestrial mobile-radio communication systems. Nowadays, these LEO systems are still operational, due to the important requirements for secure mobile-radio communication.

Today third-generation terrestrial mobile communication systems are expanding quickly. However, they have several limitations, mainly linked to designs intended as a way of overcoming the main limitations due to the lack of line-of-sight (LOS) propagation conditions. In most cases, even with high base-station antennas, mobiles are shadowed and affected by multipath and fading, which limit the quality and the operational range of terrestrial radio-communication systems [7, 8]. Future terrestrial mobile-radio design improvements will require a significant increase in the number of base stations. This will negatively impact the environment in dense urban zones, and more in scarcely rural zones, where the level of transmitted radiation is usually higher. The operational range is limited. Even for a high-altitude terrestrial base station, it is in the order of only 30 km [8, 9].

A new technique for efficient mobile-radio communication systems and other applications is the development of high-altitude platforms (HAPs), located in the stratosphere at an altitude of the order of 20 km for relay radio stations [3]. These HAPs stations will be stabilized relative to the ground as stratospheric quasi-stationary platforms (SQ-SP), due to significant progress in the technology [3, 10]. The performance and advantages of HAPs are, in several aspects, better than for GEO and LEO satellites and conventional terrestrial stations, as will be explained in this paper. This paper is intended as an introduction to the challenge of HAPS. It will be followed by a special *Radio Science Bulletin* issue, which will include several extended papers on the subject.

2. HAPs Concepts

HAPs are high-flying aircraft or airships, which will operate from altitudes of 17 to 24 km. The main reason for this operating altitude is that numerous wind-speed measurements show that the slowest wind speeds occur at these heights, extending above the tropospheric jet-stream wind altitudes, as shown in Figure 2 [11]. Less power is therefore required for the platform's stabilization. A second minimum wind zone occurs at around 90 km altitude, but this is less advantageous for HAP operation [3, 11].

Numerous temperature measurements show that the temperature decreases with altitude, and reaches a local minimum near the tropopause layer, around an altitude of 18 km. The average temperature is quite constant, around −56° C, at this lower stratospheric layer where HAPs will

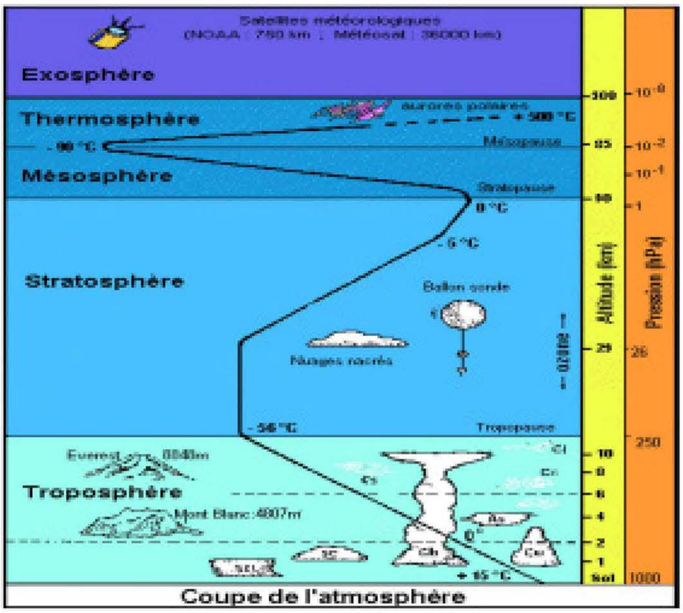


Figure 3. The average temperature as a function of altitude [11] (NASA/COSPAR).

operate, as shown in Figure 3. Therefore, the noise temperature and insertion losses of the antennas and the front-end circuits of the receivers (RX) for HAPS are reduced to a minimum [7, 10], and the receiver sensitivity is maximized at altitudes of 17 to 24 km.

The radiation effects – especially due to the sun's activities – are significantly reduced at an altitude around 21 km. This is due to the long-distance separation from the intense radiation of the Van Allen belts at altitudes ranging from 1500 to 5000 km, and from 13000 to 20000 km, which affect satellites [7, 9]. The extensive shielding seen on satellites for enhancing operational lifetimes is therefore not necessary for HAPs.

However, the ultraviolet (UV) radiation and ozone concentrations are higher at 21 km than at lower altitudes. It is therefore recommended that light composite materials, made of carbon fibers, be used in the construction of the HAPs. The exposed electronic devices must also be hardened against UV radiation [5, 11].

A general concept of the HAP is shown in Figure 4 [3]. The operation of the HAP requires electrical energy for the motors used to stabilize the platform in a quasi-stationary position related to the ground. Electrical energy is also required for the payload, which especially includes the transmitters (TX), receivers, power supply, and sensors to relay information to ground [3].

For GEO satellites, the maximum sun eclipse time is 1.2 hours and occurs only twice each year. LEO satellites suffer only from very short eclipses. In contrast, HAPs will suffer from very long eclipses. The HAPs Earth shadow results in eclipses near to 12 hours per day for locations in proximity of the equator, and up to 24 hours per day in the winter for locations in proximity of the Earth's poles [7, 10]. HAPs therefore need significantly larger and heavier energy storage systems than do satellites. The electrical power required by HAPs is in the range of 10 to 150 KW [8, 11]. This power can be obtained by efficient solar cells [12]. During eclipse periods, batteries, such as NiH2 or LiIon can be use. Another alternative is fuel cells, which are very heavy and are still not sufficient for long eclipse periods [8]. A possible solution may be the transmission of microwave (MW) energy from the ground. This would be converted at the platform to direct current using rectifier antennas (rectennas), characterized by very high efficiency in energy conversion [13, 14]. The rectenna function is shown in Figure 4, and will be explained briefly in Section 3.

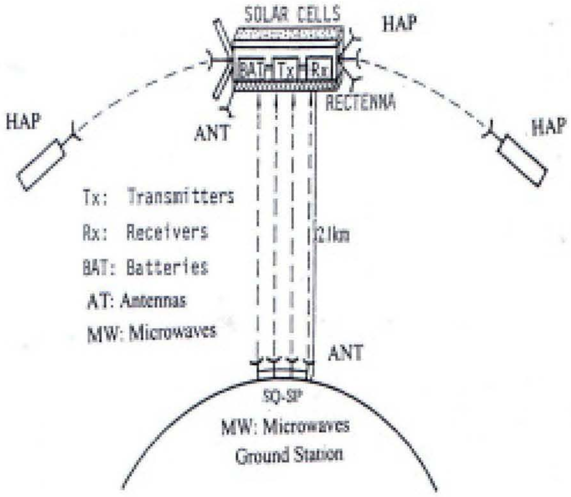


Figure 4. The concept of the HAPs [3].

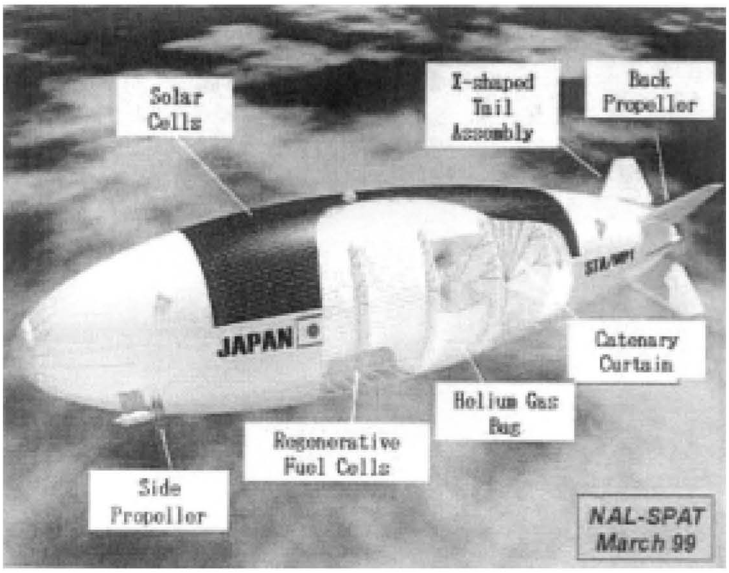


Figure 5. Japan's future HAP airship for a mission duration of three years. It is intended to operate at an altitude of 20 km, it has a length of 245 m, and a diameter of 60 m [26] (ASTAP02/FR06/EG.HAPS.04; http://www.aptsec.org/astap).

From geometric principles, the maximum HAP radio-operation radius under line-of-sight conditions for a zero elevation angle and an altitude of about 20 km, is around 600 km. To cover larger areas as do satellites, information can therefore by relayed between HAPs, as shown in Figure 4 [3]. Inter-HAP communication can use high-capacity, millimeter-wave or infrared-beam carriers, which are not affected by moisture, clouds, and precipitation losses in the stratosphere [7, 9].

An important advantage of HAPs over terrestrial radio systems is the mostly favorable line-of-sight propagation conditions, similar to satellites. However, the dispersion losses of HAPs – which are proportional to the square of the separation distances – and the delay times are significantly lower than for satellites [9]. HAPs can therefore provide much higher rates of information and faster Internet transmission using significantly lower transmitter power, and smaller and less-costly terrestrial mobile handsets, than for satellites. These handsets can operate even inside buildings without external antennas, which cannot be achieved for satellites [7, 8]. The full comparison between GEO satellites, HAPs, LEO satellites, and terrestrial radio systems is given in Table 1.

At the HAPs altitude, the atmospheric pressure is low, but the air density is still sufficient for activating aircraft propellers operated by electrical motors from solar energy or fuel. The relatively smooth-flowing air stream, combined with state-of-the-art propulsion, aerodynamic, thermodynamic, and material designs, will provide a stable and controlled flight. This will result in accurate position maintenance and minimal axial (pitch, roll, yaw) rotation. The rate of change of the velocity of stratospheric winds is well within the capability of the propulsion and control systems of HAPs for maintaining the desired position and heading [11].

There are two categories of HAPs:

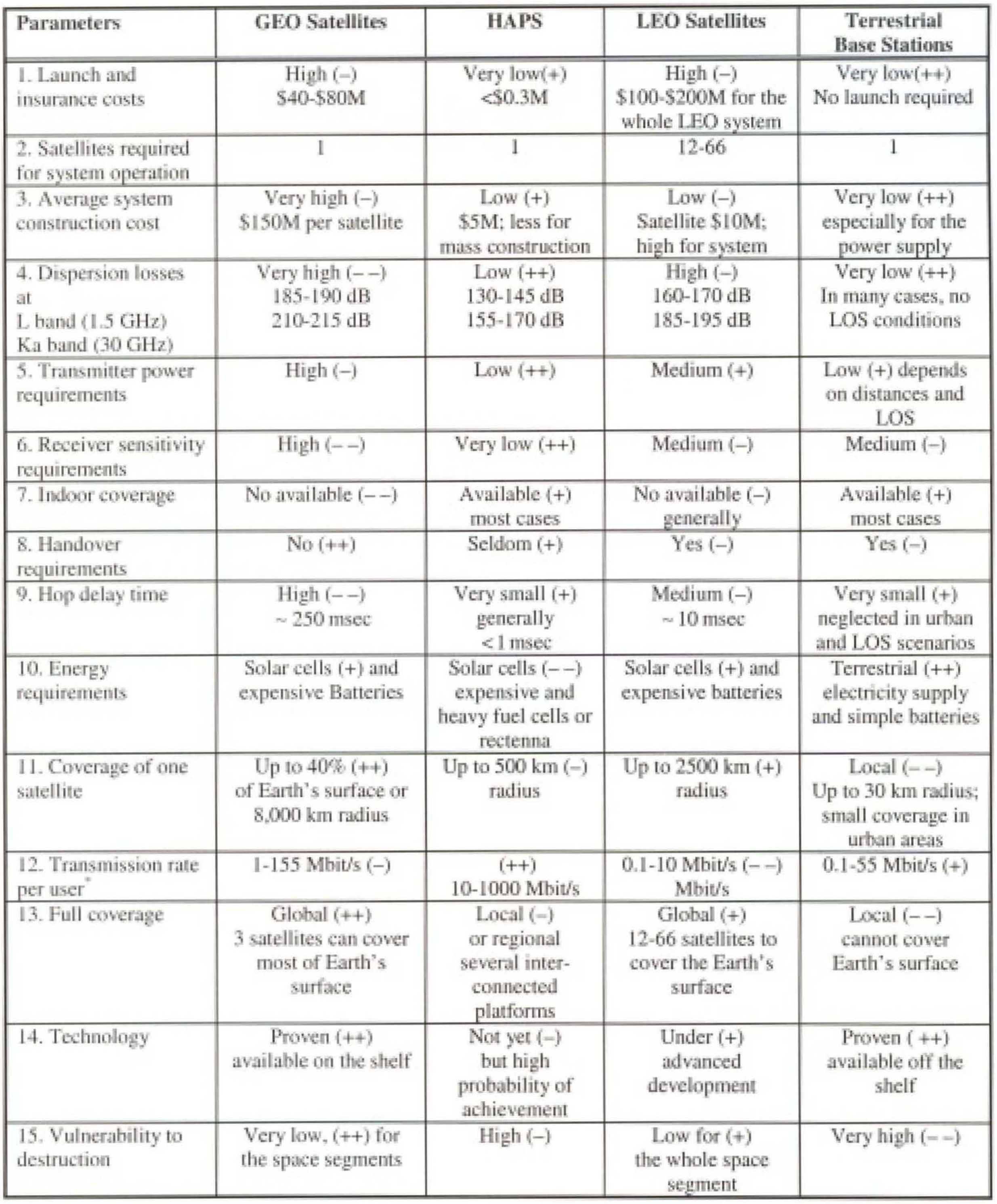
Lighter-than-air (LTA) HAPS are usually balloon aerostats, or airships filled with helium gas, as shown in Figure 5. The lighter-than-air HAPS need less energy for launching and stabilization over a fixed spot [7, 10].

Heavier-than-air (HTA) HAPS are manned airplanes or UAVs (unmanned aerial vehicles). According to Bernoulli, a lift force keeps the heavier-than-air airplane in the air. An adequate forward thrust is provided by propellers activated by electric motors, jet engines, or other thrusters. The heavier-than-air vehicle has to move in order to float. Most HAPs will fly in a circle of up to 2 km radius, controlled from the ground [11, 14].

The International Telecommunication Union (ITU) has recognized the HAP as a separate category of radio station, the High Altitude Platform Station (HAPS), and has assigned the 2, 31/28, and 47/48 GHz frequency ranges for its operation [8].

The majority of the experimental and operational commercial HAPs are unmanned, solar-powered UAVs, e.g., those built by NASA, as shown in Figure 6 [10]. The Russian M55 GN stratospheric single-seat aircraft, which was designed and built as a piloted, manned HAP, is an alternative. To maintain continuous operation, pilots may operate in eight-hour shifts, with replacement aircraft taking over to provide continuous operations over 24 hours [10, 15].

Table 1. A comparisons of GEO and LEO satellites, HAPS, and terrestrial radio communications systems



Parameters	GEO Satellites	HAPS	LEO Satellites	Terrestrial Base Stations
1. Launch and insurance costs	High (–) $40-$80M	Very low(+) <$0.3M	High (–) $100-$200M for the whole LEO system	Very low(++) No launch required
2. Satellites required for system operation	1	1	12-66	1
3. Average system construction cost	Very high (–) $150M per satellite	Low (+) $5M; less for mass construction	Low (–) Satellite $10M; high for system	Very low (++) especially for the power supply
4. Dispersion losses at L band (1.5 GHz) Ka band (30 GHz)	Very high (– –) 185-190 dB 210-215 dB	Low (++) 130-145 dB 155-170 dB	High (–) 160-170 dB 185-195 dB	Very low (++) In many cases, no LOS conditions
5. Transmitter power requirements	High (–)	Low (++)	Medium (+)	Low (+) depends on distances and LOS
6. Receiver sensitivity requirements	High (– –)	Very low (++)	Medium (–)	Medium (–)
7. Indoor coverage	No available (– –)	Available (+) most cases	No available (–) generally	Available (+) most cases
8. Handover requirements	No (++)	Seldom (+)	Yes (–)	Yes (–)
9. Hop delay time	High (– –) ~ 250 msec	Very small (+) generally < 1 msec	Medium (–) ~ 10 msec	Very small (+) neglected in urban and LOS scenarios
10. Energy requirements	Solar cells (+) and expensive Batteries	Solar cells (– –) expensive and heavy fuel cells or rectenna	Solar cells (+) and expensive batteries	Terrestrial (++) electricity supply and simple batteries
11. Coverage of one satellite	Up to 40% (++) of Earth's surface or 8,000 km radius	Up to 500 km (–) radius	Up to 2500 km (+) radius	Local (– –) Up to 30 km radius; small coverage in urban areas
12. Transmission rate per user*	1-155 Mbit/s (–)	(++) 10-1000 Mbit/s	0.1-10 Mbit/s (– –) Mbit/s	0.1-55 Mbit/s (+)
13. Full coverage	Global (++) 3 satellites can cover most of Earth's surface	Local (–) or regional several inter-connected platforms	Global (+) 12-66 satellites to cover the Earth's surface	Local (– –) cannot cover Earth's surface
14. Technology	Proven (++) available on the shelf	Not yet (–) but high probability of achievement	Under (+) advanced development	Proven (++) available off the shelf
15. Vulnerability to destruction	Very low, (++) for the space segments	High (–)	Low for (+) the whole space segment	Very high (– –)

* Data rates depend upon application and hardware complexity.

For GEO satellites, $h = 36000$ km, $d = 38000$ km; for HAPS, $h = 21$ km, $d = 70$ km;
for LEO satellites, $h = 700$ km, $d = 1000$ km; for terrestrial base stations, $2 < h < 30$ m, $0.1 < d < 20$ km.

3. Genesis and Development of HAPS

3.1 The Preliminary Stage: Up to 1990

The first steps for the realization of HAPs were carried out in the USA, with the development of high-altitude airplanes, manned and unmanned, such as the U-2 plane, shot down by the Soviet Union in 1960. This was followed by the SR71 Blackbird plane, which flew at an altitude above 25 km in 1976 [15]. In the beginning of the 1960s, a few high-altitude echo balloons were also launched to reflect broadcasting for Bell Labs, but the results were disappointing [5].

The possibility of HAP realization was studied by NASA, first for military and meteorological purposes, and later for radio-communication and remote-sensing applications. The US also developed lighter-than-air tethered balloons for military and homeland security supervision, used at altitudes up to 3 km, for operational times of a few days [8, 16].

The long-term operation of unmanned UAV HAPs may require a microwave energy source and large antennas from a ground station below the platform. It may also require a rectenna on the HAP to convert the *microwave energy to direct current (dc) for charging the batteries, and activating the payload and propellers to stabilize the platform, especially in case of stratospheric winds. This is in addition to efficient solar photovoltaic cells, exposed on the top of the platforms, as shown in Figure 4 [7, 14].

The pioneers in the development of rectennas were R. H. George and W. C Brown from Raytheon. They developed very power-efficient microwave rectennas, with efficiencies exceeding 85% at the ISM frequency of 2.45 GHz [13, 14]. Rectennas will also be used for future solar power satellites (SPS) [17].

At the beginning of the 1990s, NASA also invested in the development of several preliminary HAP projects, especially for military remote sensing, intelligence, metrology, and radio communication [15, 16]. The US department of defense and NASA developed a manned heavier-than-air HAP with a crew of two pilots. The first gasoline model was the Rutan Voyager, which made a flight of 216 hours without interruption in 1986 [11, 16].

The first commercially oriented project for radio-communication HAPs, the Stratospheric High Altitude Relay Platform (SHARP), was initiated by the Communication Research Center (CRC) group in Ottawa, Canada, in collaboration with the University of Toronto, and several local firms. They succeeded in the operation of a one-eighth-scale model unmanned heavier-than-air HAP in 1987. It was a radio-controlled aircraft with a 4.5 m wingspan, powered from a ground-based microwave transmitter operating at 2.45 GHz. The carrier beam energized a disc-shaped rectenna located on the aircraft, providing 25 kW of dc power to a 100 kg payload, and to motor-driven propellers [8, 14]. However, no final 21-km altitude HAP was developed, because of funding problems [3, 15].

3.2 The Development Stage: From 1990 to Present

The successor of the U-2 and the Blackbird, the U-2R "Dragon Lady," is still operational today. Designed for high-altitude intelligence and reconnaissance missions, this aircraft can fly above 20 km altitude. It can carry some of the most advanced long-range reconnaissance gear available today. Its mission payloads include the highest-resolution synthetic-aperture radar (SAR), as well as sophisticated signals intelligence (SIGINT) systems. The U-2R provides near-real-time imagery to war fighters and national authorities. The "Dragon Lady" was used extensively during operation Iraqi Freedom in 2003, and provided important damage-assessment information after Hurricane Katrina struck the Gulf of Mexico in 2005 [15].

Figure 6. The Helios NASA experimental heavier-than-air solar-powered HAP flight over Hawaii, at an altitude of around 21 km in 2001 [15].

The later US manned canard aircraft HAP model was the Proteus. It was capable of lifting a 1000 kg payload to an altitude of 20 km, and could circulate there for many hours [7, 18]. This manned High Altitude Long Operation (HALO) option, shown in Figure 7, was proposed by Angel Technologies for broadband communication in 1998. With this option, full-time operation of 24 hours, seven days per week may be possible, using a time shift of three Proteus aircraft [16, 18]. Currently, the Proteus is owned by Northrop Grumman, and can also be operated as an UAV.

Several UAV heavier-than-air HAPS models were have been developed in the US:

- The NASA Pathfinder project Helios solar-powered UAV model HAP, shown in Figure 6 [8, 11], used motors and propellers fed by solar cells located on large transparent wings of over 35 m span. It reached an altitude of 30 km in 2001, and was expected to stay in operation without landing for more than six months. However, the Helios model crashed over Hawaii in 2003, and the project was discontinued [15].

- Smaller versions, but not less effective than the Helios and especially for radio-communication applications, are the Sky Tower HAPs, The Sky Tower development was a joint project between NASA and the Japan Ministry of Communications with the cooperation of the Aerovironment Corp. [19].

- The NASA/Northrop Grumman project Global Hawk UAV uses gasoline engines, operates at an altitude of 20 km, and remains on station for more than 24 hours [10, 13]. The Global Hawk UAV supports the USAF, NATO members, and Australia in the global war against terrorism; monitors wild fires and hurricanes; and other applications. These HALE (high-altitude, long-endurance) UAVs, combined with satellite and line-of-sight communication links to ground forces, permit worldwide operation. The Global Hawks have flown more than 24,000 hours on operational missions. Improved versions – the RQ-4B and RQ-4N – are under contract. They can carry payloads of nearly 1000 kg payload [20].

- Lockheed-Martin, Boeing, Raytheon, and General Atomics Aeronautical Systems Inc. are companies that are also involved in HAP design and development, especially for military applications [11, 15, 21].

In 2006, the QinetiQ company in the UK built the Zephyr, an ultra-light high-altitude long-endurance UAV for the US and UK ministries of defense. The Zephyr is a carbon-fiber UAV, launched by hand, as shown in Figure 8 [22]. This low-cost, light UAV recently achieved an 82 hour flight at an altitude up to 20 km. It is useful for reconnaissance and relaying radio communications for homeland security, and in the worldwide fight against terrorists [15].

The first enterprise to make commercial use of near-space HAPs using lighter-than-air balloons for radio communication was Space Data, in Chandler, Arizona [23, 24]. The Space Data balloons are extremely low cost, and can be launched within minutes by just one person from almost anywhere. The balloon has a diameter of about 8 m, a total weight of about 6 kg, and a payload weight of about 3 kg. The radius of operation is in the range of 8 to 320 km. The balloons operate at altitudes from 20 to 30 km. The 2008 Space Data commercial operating US network comprises 11 launch sites, three remote ground stations, a network operation center, and numerous balloons. It has logged more than 250,000 flight hours over the US. Space Data has also developed a worldwide military combat version of their lighter-than-air HAP system, called Skysat [24].

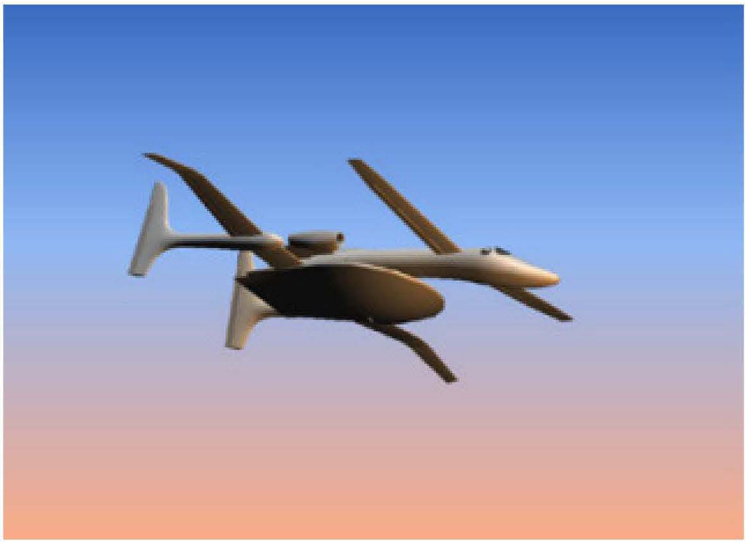


Figure 7. The Proteus Manned Canard aircraft HAP, owned by Northrop-Grumman [18]. The Proteus program is supported by the NASA Dryden Flight Research Center.

Figure 8. The launch of the Qinetiq ultra-light low-cost Zephyr high-altitude long-endurance UAV [22] (copyright QinetiQ).

The Sanswire Corp. specializes in the design and development of big lighter-than-air HAPs airships, which they call Stratellites. A prototype was tested in 2005, with a length of 75 m, a width of 44 m, and a height of 26.5 m. The Stratellite is powered by electric motors, and energized by solar energy and batteries. The expected payload weight is up to 1400 kg. It holds its position using six onboard GPS units for a duration of up to 18 months [15, 25]. In 2005, Sanswire joined the German TAO company, and they operate from the USA [25].

The Japanese have cooperated with Canada and the US in the design and development of HAPs [16]. Japan invested in lighter-than-air airship HAPs, and developed the airship shown in Figure 5 [26, 27].

Russia is also involved in lighter-than-air and heavier-than-air HAP developments. The Russian ROS Aero Systems Corp. developed several models of lighter-than-air airship HAPs named Berkut. These can carry up to 1200 kg payload, especially for communication and surveillance applications. These solar-powered HAPs are expected to supply up to 15 kW for payloads and 100 kW for position stability, with a flight endurance of up to four months [28]. The Russians also developed the M55 GN stratospheric manned single-seat aircraft in 1993. In 2007, QUCOMHAPS, an Irish company, intended to order 50 M55 GN aircraft to supply Malaysia, Indonesia, Saudi Arabia, and the AER with 24 hour by seven day full-time coverage for surveillance and radio-communication applications [29].

The European Union has recently invested in the study and realization of HAP systems. The European HELINET project, which ran from 2000 to 2003, aimed at developing a fast Internet network served by HAPs [10]. This was followed by CAPANINA, which ran from 2003 until January 2007. This tested the feasibility of delivering broadband communications from different types of HAPs. Practical trials were held in the UK (tethered balloon), Sweden (free-floating balloon), and the USA (unmanned UAV). The project also developed detailed design and analysis for equipment, especially antennas, and system architectures. This work is continuing through the COST 297 project, which is a research discussion forum for “High Altitude Platforms for Communications and Other Services” (HAPCOS) [30]. The membership mainly comprises European academic organizations and companies, and is led by the University of York. The activities are supported by three working groups: Radio Communications, Optical Communications, and Aeronautics and Other Applications [10]. Several HAP prototype models are in the realization process [30, 31].

Several countries such as South Korea, Israel, and China are also involved in HAP development, especially for military applications [32-34].

3.3 The Realization and Commercialization Stages: From 2010 to the Future

The realization and commercialization of HAPs seem to be very near. Several organizations and countries are planning to use HAPs for commercial purposes, especially for military radio-communication and remote-sensing purposes.

QinetiQ’s Zephyr project in the UK, discussed earlier, is expected to continue through to the commercialization stage. It will be used for civilian Earth observation, small-scale communications relay, and military missions [22].

The StratXX organization in Switzerland is aiming to deliver a range of lighter-than-air HAPs and lower-altitude aerial platforms. The purpose is to deliver a combined remote-sensing and radio-communications system [36].

Figure 9 : An artist's impression of the Lockheed-Martin future high-altitude long-endurance HAP using a thin-film solar-cell array [21]

A small Italian company, ERS-SRL, is planning to deliver communications and environmental monitoring services, using the German GROB future high-altitude, long-endurance manned or UAV aircraft [37]. The QUCOMHAP project for communication relays and reconnaissance in Asian countries, using Russian manned M-55 aircraft HAPs, is still at the paper stage [29].

The Sanswire company claims to be able to commercialize its products by 2010, and to become a leader in civilian and military HAPS applications [25] The US Space Data and UK QinetiQ companies have a strong potential for becoming leaders in commercial HAPs operational systems [23, 24].

The Japanese are also involved with the NASA in the development of a long-term space solar-power (SSPs) program. This will require huge rectennas [13, 14], microwave power transmission up to 5 GW from geostationary satellites to the ground, and huge solar-cells arrays. Japan also initiated the Skynet project [26]. This intends to develop a network of from five up to 15 HAPS, to cover almost the total Japanese territory, with radio communication, fast Internet, and broadcasting [26, 27]. However, no activities have been recently published on the Skynet project.

Most of the development and investment in HAPs systems remains in the military and homeland-security domains. The US Department of Defense Rapid Eye program is an exploratory development program. It has the overall goal of developing and demonstrating the ability to deliver persistent remote-sensing and radio-relay capabilities anywhere on the globe within one hour, and to remain on-station until relieved or until the mission is completed [38, 39].

Boeing has recently commenced studies of solar-cell power generation, produced by its subsidiary, Spectrolab. By 2010, the company plans to offer space solar cells with efficiencies as high as 33%. These cells are five times more efficient than the solar arrays used to propel the Helios UAV [11]. This could provide primary power sustaining an airborne platform for nearly unlimited times. It could contribute to the future development of commercial and military HAP systems [39]. Boeing and Aurora Flight Sciences, in the joint Orion program, are developing a heavier-than-air UAV aircraft powered by hydrogen fuel. It may operate up to 100 hours at an altitude of around 21 km [15, 38].

Lockheed Martin is continuing to make progress with lighter-than-air HAP technology. This is being funded by the US Army, for the delivery of remote sensing and communications for tactical scenarios. Their newly designed HAP, shown in Figure 9, will have a very long endurance using thin-film solar cells [40, 41].

Aurora Flight Sciences plans to build the Odysseus unmanned HAP based on a radical idea. Instead of one single plane, three separate planes will take off individually.

Figure 10. The Aurora Flight Sciences Corp. Odysseus future high-altitude long-endurance HAP concept. This is based on launching three separate planes and joining them together in the stratosphere [40].

Once aloft, they will join together at the wing tips to create one giant aircraft design of 150 m wingspan. Odysseus will allegedly be powered by a large array of solar panels, positioned on the aircraft's wings. These will have the ability to pivot, so that the sunlight collection area is maximized. The Odysseus UAV, shown in Figure 10, will have two flight configurations. In the "Z-mode," the wing is partially folded, so the solar cells are canted to catch as much sunlight as possible during the day. In the flat configuration, the wing span is maximized to reduce drag and power consumption during the night, as shown in Figure 10 [39, 40].

Recently, the US Defense Advanced Research Projects Agency initiated an ambitious Vulture UAV high-altitude, long-endurance project. The Vulture is intended to keep a 450 kg payload powered by a constant 5 kW supply from solar and fuel cells for up to five years of operation, at an altitude of 27 km. It is intended to operate like a pseudo-satellite. This UAV has to be kept precisely on station at least 95% of the time [41]. The three main competitors for this project are the Aurora Flight Sciences Corp.'s Odysseus, concept shown in Figure 10; a larger modification of the QinetiQ Zephyr UAV, shown in Figure 8, is being proposed by Boeing; and Lockheed Martin plans a modified version of their lighter-than-air UAV shown in Figure 9 [21, 42].

4. Important HAP Applications

HAPs will have numerous applications. The most important are the following:

1. National or limited regional coverage of commercial and military radio-communication systems. In particular, cellular, voice, Internet, and video could be provided for extended rural coverage up to 1000 km in diameter, in comparison with 20 to 40 km for a common terrestrial rural mobile or cellular system. In addition, very high speed Internet could be supplied for limited urban areas, operating using the $3G^{+}$ or 4G mobile-radio communications. This could also provide emergency communication in case of natural disasters and conflicts [8, 10]. Radio communication is thus the main HAPs application [7, 15].
2. Permanent military, intelligence, surveillance, and reconnaissance (ISR) missions, with very high resolution, in cooperation with national or international homeland-security missions [11, 39]. Examples include coastal or border-guard observation, and missile-launch detection [16, 40].
3. Extended local or national television broadcasting coverage, including high-definition TV (HDTV), voice, and digital audio, for operational distances up to 1000 km [10].
4. Local or regional radio-communication services, such as personal computers, data communications, distance learning, and financial transactions. These services can be extended to global coverage using multiple HAPs cooperating with global GEO or LEO satellite systems [3].
5. Persistent surveillance for illegal activities such as drug traffic, signal gathering, and spectrum monitoring, which are important for homeland security [15, 16].
6. Monitoring ground vehicles, aircraft, and ships for traffic control, security surveillance, and position information, including special missions such as detection and localization of stolen cars for the police or defense authorities [7, 15].
7. Remote sensing of regional weather conditions for forecasting and atmospheric data gathering, including hurricane detection and monitoring [3].
8. Automatic control and telemetry data collection for electrical utilities.
9. Surveillance of pollution for environmental-conservation purposes, including monitoring concentrations of carbon dioxide, ozone, and radiation levels, even at high altitudes [8, 16].
10. Space observations and radio-signal monitoring from space and from the ground [3, 8].
11. Providing significant enhancement in reliability and accuracy to the Global Positioning System (GPS) by adding Differential GPS sources to the HAPs payload [3].
12. Scientific exploration of the moon, Mars, and other planets [43].

The feasibility of HAPs systems and the fulfillment of the applications described, depend on significant research achievements, funding, and technological improvement. Improvements are needed in aeronautical science, control, electromagnetic compatibility (EMC), wireless power transmission, payload efficiency, and radio-frequency interference (RFI) reduction techniques [3, 8, 9].

5. Conclusions

A description of the use of HAPs for radio-system operations has been presented in this paper, with reference to GEO and LEO satellites and terrestrial mobile radio-communication systems. The wireless microwave-power-transmission concept, using rectifier antenna (rectenna) elements, has been presented. Significant efforts for the realization of HAP systems have been made, starting from the 1950s, beginning in the US and Canada [13, 14]. Actual progress on HAP system realization has been achieved, especially in the USA, Japan, Russia, and also in Europe [8, 40]. The important applications of HAPs have been described.

HAP systems can be used efficiently in multiple radio applications with dependent service areas of diameters from 60 to 1000 km, which represent the maximum limit for line-of-sight reception. However, these can form part of an enhanced global communication network, by coordinating the operation of multiple HAPS, GEO satellites, and terrestrial systems. The HAP systems are thus not competing with the operation of GEO or LEO satellites or terrestrial systems, but instead complement them. This is due to the several unique advantages of HAPs, specifically the local and regional services, as presented in this paper and in Table 1.

Today, numerous organizations, companies, and research and academic institutes are involved in the design, development, and construction of HAPs. Several prototypes have been developed, and have operated successfully for a limited time. The actual status of HAPs is similar to the status of the GEO satellites following the Early Bird launch, and before the establishment of the INTELSAT organization. Forecasters predict that in spite of the deep current economic crisis, in a few years, the early growing pains of HAP systems will be resolved. This will be followed by commercial success, and the achievement of numerous civilian and military HAPs applications, especially in radio communication, remote sensing, and homeland security [39, 40].

6. Acknowledgment

This work has been carried as a result of collaboration facilitated by COST 297 - HAPCOS.

7. References

1. Y. Kim, et al., "Beyond 3G: Vision, Requirements and Enabling Technologies," *IEEE Communications Magazine*, **41**, 3, March 2003, p. 120-124.

2. A. Joel, "Telecommunications and the IEEE Communications Society," *IEEE Communications Magazine*, **40**, 5, May 2002, pp. 6-14, 162.

3. J. Gavan and S. Tapuchi, "Low Interference Wideband Wireless Systems Using High Altitude Platforms," XXIX URSI General Assembly, Chicago, IL, August 9-16, 2008.

4. W. W. Wu and J. N., Pelton, "The Challenge of 21st Century Satellite Communications: INTELSAT Enters the Second Millennium," *IEEE Journal on Selected Areas in Communication*, **5**, 4, May 1987, pp. 571-591.

5. C. Pritchard, "Geostationary Versus Non- Geostationary Orbits," *Elsevier Space Communications*, **11**, 3, 1993, pp. 205-215.

6. J. Gavan, "Satellites the Link of Telecommunication," *Mada (Science) Review*, **28**, 4, July 1984, pp. 182-188.

7. J. Gavan and M. Haridim, "Stratospheric Quasi-Stationary Platforms (SQSP): Can They Replace Communication Satellite Systems," *Telecommunications and Space Journal*, April 1997, pp. 275-288.
8. R. Stuzak, "Mobile Telecommunications Via Stratosphere," *InterComms, The International Communication Project*, **1**, August 2003; available at http://www.intercomms.net.

9. J. Gavan and R. Perez (eds.), *Handbook of Electromagnetic Compatibility*, New York, Academic Press, 1995, Chapters 1, 19, 20, and Appendix 4.

10. T. C. Tozer and D. Grace, "High Altitude Platforms for Wireless Communication," *Electronics and Communication Engineering Journal*, June 2001, pp. 127-137.

11. A. Colozza and J. L. Dolce, "High-Altitude, Long-Endurance Airships for Coastal Surveillance," NASA TM-2005-213427, Cleveland, Ohio, 2005, pp. 1-15.

12. F. Geyer, D. Caswell, and C. Signorini, "Powering the Future," ESA Bulletin No. 131, August 2007, pp. 46-49.

13. W. C. Brown and E. E. Eves, "Beamed Microwave Power Transmission and its Application to Space," *IEEE Transactions on Microwave Theory and Techniques*, **40**, 6, June 1992, pp. 1239-1249.

14. J. O. Mc Spadden, T. Yoo, and K. Chang, "Theoretical and Experimental Investigation of a Rectenna Element for Microwave Power Transmission," *IEEE Transactions on Microwave Theory and Techniques*, **40**, 12, December 1992, pp. 2359-2366.

15. A. K. Widiawan and R. Tafazolli, "High Altitude Platform Station (HAPS): A Review of New Infrastructure Development for Future Wireless Communications," *Wireless Personal Communications*, **42**, 3, August 2007, pp. 387-404.

16. T. C. Tozer, D. Grace, J. Thompson and P. Baynham, "UAVs and HAPs – Potential Convergence for Military Communications," IEE Colloquium on Military Satellite Communications, 2000, pp. 10/1-10/6.

17. URSI, "Executive Summary: URSI White Paper on Solar Power Satellite (SPS) Systems," *Radio Science Bulletin*, No. 321, June 2007, pp. 13-27.

18. P. Lert, "Proteus: Rutans Low Orbit Chameleon," *Flight Journal*, February 1998, pp. 2-5.

19. http://www.aerovironment.com.

20. "Northrop Grumman and its Global Hawks Awarded NASA Research Contract," *Satnews Daily*, August 18, 2008.

21. http://www.lockheedmartin.com/akron/protech/ aeroweb/aerostat/haa.

22. "Endurance Record Attained by Solar Powered Zephyr UAV," *Satnews Daily*, August 26, 2008.

23. http://www.spacedata.net.
24. J. Quenneville, "Space Data; Near Space Communication System for Emergency Response," *Space Data*, 2008, pp. 1-8.

25. http://www.sanswire.com.

26. http://www.nal.go.jp/eng/research/spf, www.Jaxa.j8\index.

27. Stratospheric Wireless Communications 7th ASTAP HAPS – EG/Japan.

28. http://www. rosaerosystems.pbo.ru.

29.http://www.qucomhaps.com.

30.http://www.hapcos.org.

31.D. Grace, M. Mohorcic, M. H. Capstick, M. Pallavicini and M. Fitch, “Integrating Users into the Wider Broadband Network via High Altitude Platforms,” *IEEE Wireless Communications*, **12**, 5, October 2005, pp. 98-105.

32.Y. G. Lee, D. M. Kim, C. H. Yeam, “Development of Korean High Altitude Platform Systems,” *International Journal of Wireless Information Networks*, **13**, 1, January 2006.

33.“Eitan: A High Altitude Long Endurance UAV,” *The Israel High-Tech & Investment Report*, September 2007.

34.A. Mohammed, S. Arnon, D. Grace, M. Mondin and R. Miura, “Advanced Communication Techniques and Applications for High Altitude Platforms,” *Eurasip Journal of Wireless Communication and Networking*, 2008, pp. 1-3, article ID 934837.

35.WRC-1997 Resolutions 52,122. WRC-2000 Resolution.

36.http://www.stratxx.com.

37.http://www.ers-srl.com.

38.Scientific American.com, “Pentagon Developing New Unmanned Spy Planes,” September 17, 2007, http://www.sciam.com.

39.M. A. Stewart, K. Frishie and G. Trinkle, “High Altitude Surveillance,” *Geo. Intelligence*, July 2004, pp. 1-4.

40.E. Herlik, “Persistent UAS in the Stratosphere will Revolutionize Commercial and Defense Markets,” Homeland Security Research Corp., 2008, pp. 1-217.

41.P. Richfield, “DARPA Vulture Project Aims for Ultra long UAV Missions,” *The Integrator USAF*, July 30, 2007.

42.A. D. Simpson, et al. “ Big Blue High Altitude UAV Demonstrator of Mars Airplane Technology,” IEEE Aerospace Conference 2007, pp. 4461-4471.