Integrated Wireless Sensor Systems via Near-Space and Satellite Platforms: A Review

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Abstract— **Due to extreme conditions, the near-space region is vastly underused and can be utilized for various scientific uses. The unconstrained orbital mechanism and low fuel consumption advantages for using synthetic aperture radar over the satellites and airplanes navigation systems make these conditions superior for a wide range of services, monitoring, earth observation, and sensing applications. The augmented integration within the existing global navigation system can help in measuring the direction-of-arrival, as well as collecting and distributing accurate location information. For wireless sensing applications, it can enable a new range of opportunities, a wide range of smart sensor applications as experimental platforms for deployment of new technologies. Here, we also examine the implementation of near-space platform (NSP) coverage and associated technologies. Then, a brief integration of communication and navigation services using NSP from a top-level system description of how to relay, associated complementary systems, including radar sensor systems, satellite systems, and terrestrial networks can be used.**

Index Terms— **Near-space platform (NSP), high-altitude platform (HAP), airborne sensor, spaceborne sensor, integrated communication and navigation, wireless sensor systems, smart sensor, radar and navigation.**

I. Introduction

AIRBORNE networks have received much attention in recent years. Driven by the advances in wireless sensor technologies, airborne networks have promise in providing effective, wide-applicable, low-cost, and secure information exchange among airborne vehicles. For example, if the in-flight sensors among commercial airlines can allow adverse weather conditions and emergency situations to be shared especially when the flights are in the areas outside the reach of ground control stations, aviation accidents will be significantly reduced. Unmanned airborne vehicles can rely on sensor networks for safe maneuvering. It is anticipated in [1] that airborne networks can provide information exchange among airborne vehicles and connect with space and ground networks to complete future multiple-domain communication networks. The developments of reliable routing protocols that minimize the number of packets lost due to link and path failures have been reported in [2]–[4].

TABLE I
Typical LEO Satellites Pass Time (Minutes: Seconds) for Different Angles Above Horizon (Degrees)

	angle above horizon				
satellite orbital altitude	0°	5°	10°	30°	45°
200 km	7:49	5:37	4:08	1:40	1:00
300 km	9:35	7:16	5:34	2:24	1:27
400 km	11:10	8:44	6:54	3:08	1:54

On the other hand, although satellites and airplanes represent two well established platforms for wireless sensors, they cannot provide a starting presence on a timescale of days, weeks, and even months over a selected area of interest. Even if we can launch a satellite on demand for a particular mission, it would only be in view for very short bursts of time. Table I gives the pass time (minutes: seconds) of typical low earth orbit (LEO) satellites for different angles above the horizon (degrees) [5]. It shows just how short these times would be for selected LEO orbits. Satellites usually operate in orbits higher than 200 km and air-breathing airplanes routinely operate at altitudes lower than 18 km. On the contrary, an alternative platform, named near-space platform (NSP) operating at an altitude between 20-100 km [6] or high-altitude platform (HAP) operating at an altitude between 17-22 km [7] (see Figure 1), could play a role similar to an artificial satellite with advantages over its counterparts of being less expensive, more adaptable and closer to the ground.

Table II shows the relative advantages of satellites, NSPs and airplanes. Satellites have superiority in footprint and overflight. Airplanes, both manned and unmanned, are extremely responsive. They can be launched in minutes to hours, and once on station they can be redirected at will. NSPs are also extremely responsive compared to satellites and almost as responsive as airplanes to launch and redirect. The cost for the development of satellites is much greater, and thus it is more efficient to cover a large area with several NSPs rather than with many terrestrial base stations or with a satellite. In addition, due to their long development period, but satellites always have the risk of becoming obsolete once they are

Manuscript received June 6, 2014; revised August 15, 2014 and September 4, 2014; accepted September 4, 2014. Date of publication September 16, 2014; date of current version September 24, 2014. This work was supported in part by the National Natural Science Foundation of China under Grant 41101317, in part by the Program for New Century Excellent Talents in University under Grant NCET-12-0095, in part by the Sichuan Province Science Fund for Distinguished Young Scholars under Grant 2013JQ0003, and in part by the Fundamental Research Fund for the Central Universities under Grant ZYGX2013J008. The associate editor coordinating the review of this paper and approving it for publication was Prof. Habib F. Rashvand.

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Digital Object Identifier 10.1109/JSEN.2014.2356580

Fig. 1. Near-space definition and its advantages while compared to space including geosynchronous orbit (GEO), middle earth orbit (MEO) and low earth orbit (LEO), and airplane.

TABLE II
RELATIVE ADVANTAGES OF SATELLITES, NSPS AND AIRPLANES

	satellites	NSPs	airplanes
cost		√	
persistence		√	
responsiveness		√	√
footprint	√	√	
resolution		√	√
overflight	√		
power	√		√

in orbit. NSPs also enjoy favourable path-loss characteristics while compared with both terrestrial and satellite sensors. They can frequently take off and land for maintenance and upgrading. It is thus necessary to construct a mixed infrastructure comprising NSP, terrestrial, and satellite systems. In doing so, a powerful, integrated network infrastructure can be constructed by making up for the weakness of the others.

Traditionally very few vehicles can operate in near-space because the atmosphere is too thin to support flying for airplanes and too thick to sustain the orbit for satellites. Advances in airship super pressure ultraviolet-resistent hull material and designs [8], computer aided design models, high-altitude aircraft technologies and better buoyancy/ballonet management technologies, and more knowledge of the stratosphere environment have made long-term persistent NSPs more possible. Currently, aircraft and airship on-station loitering times in the stratosphere are limited to a few days determined by the amount of fuel that can be carried aboard, and their payload power supply capabilities are limited to a few kW. But there is increasing interest in delivering multi-kilowatts or even megawatts of power by wireless to provide for continuous operation in stratosphere with higher-power payload capabilities [9].

In near-space, there are no ionospheric scintillations that degrade wireless signal propagation performance. Moreover, not constrained by orbital mechanics and the possibility of having control over the flight path make them almost stationary over the service region [10], [11]. They can be moved on demand in order to serve different regions, and are able to take off and land for payload maintenance and upgrading. Therefore, NSPs provide large footprint and long missions that are commonly associated with satellites and responsiveness that is associated with unmanned aerial vehicles. These features make NSPs attractive for a large class of applications, among which telecommunication is one of the most promising commercial revenues that they can provide. Other interesting applications worth mentioning are remote sensing [12], environment monitoring, and agriculture support [13].

The applications of NSPs in broadband communications are surveyed in [7]. The survey begins with an introduction of NSPs, followed by discussions about suitable platforms, possible architectures, and some points on channel modeling, antennas, transmission and coding techniques. In [14], HAP is suggested for a joint provision of cellular communication services and support services for navigation satellite systems. It is shown that NSP is suitable to implement the macrocells with large radius. The role of NSPs in providing global connectivity for future communication services is discussed in [15]. Additional work about the role of NSPs in various communications and networks can be found in [16]–[20].

This paper makes an overview of integrated wireless sensor systems via near-space and satellite platforms from a top-level system description, with an objective to call for more investigations. The application focus is placed on relaying communications and passive radar for regional remote sensing. Although NSP has a much smaller coverage area than satellites due to their lower altitude, they can offer a regional coverage (effective observation area) of hundreds of kilometers in radius and provide cost-effective communication, navigation and localization services, particularly for the areas with limited or no access to spaceborne and terrestrial sensors.

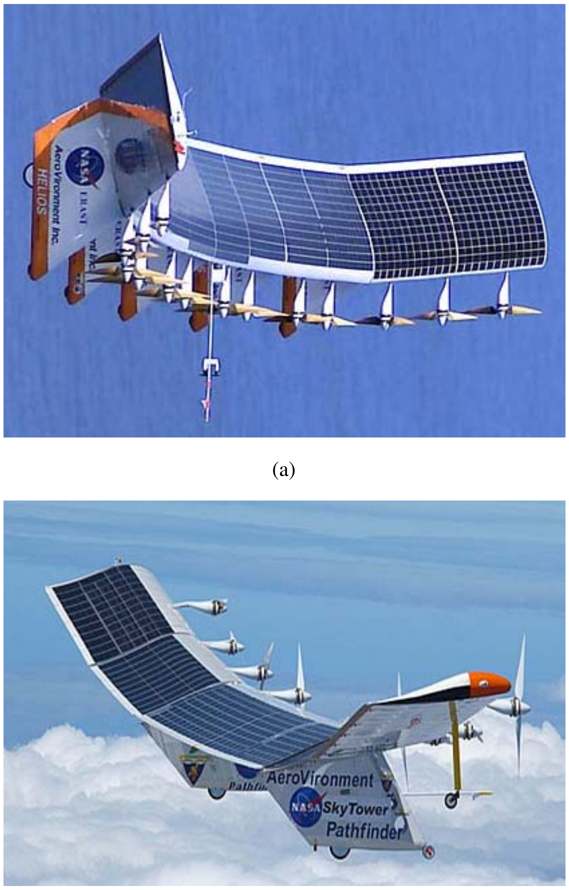
The remaining sections are organized as follows. Section II explains what NSP is and why it should be exploited for wireless sensor systems, several typical NSPs are introduced. Section III makes an overview of NSPs in wireless sensor systems such as communication, radar and smart sensor systems. Section IV presents the integrated wireless sensor systems for providing regional services. Section V analyzes the coverage problem. Section VI discusses several realistic issues. Finally, this paper is concluded in Section VII.

II. NEAR-SPACE PLATFORMS IN WIRELESS SENSOR SYSTEMS

A. Near-Space and Near-Space Platform

Near-space is defined as the altitude between 20 km and 100 km, where the wind is normally predictable. It is suggested in [7] that the most preferable altitudes fall from 19 km to 22 km where there are no clouds, thunderstorms, or precipitation. Near-space is thus a good place for lighter-than-air vehicles to operate. NSPs are the vehicles that can operate in near-space.

Some NSPs already exist and more NSPs are currently in prototype [7], [21], [22]. Figure 2 gives two typical NSPs (HELIOS and Pathfinder) designed by NASA, USA. HAPs



(a)

(b)

Fig. 2. Typical two NSPs designed by NASA, USA. (a) Helios. (b) Pathfinder.

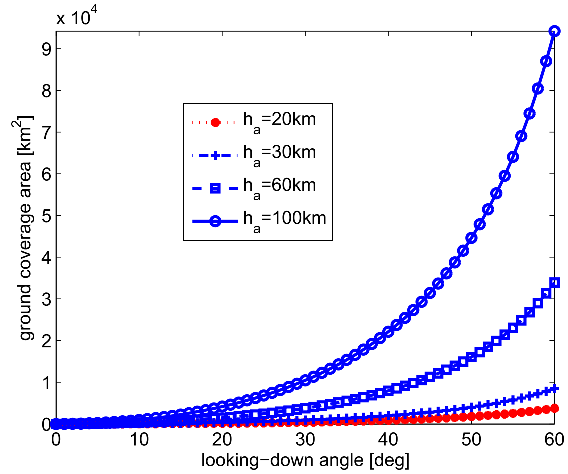


Fig. 3. Ground coverage area as a function of looking-down angle for different flying altitude.

can be classified into three major categories: (1) free-floater, (2) steered free-floater, and (3) maneuvering vehicle.

A free-floater is essentially a large balloon floating with the wind. It is normally manufactured in two types: zero-pressure and super-pressure. Limited steering is possible by using variable ballast, enabling it to float at different altitudes to take advantage of different wind directions and speeds. However, free-floater has no station-keeping ability because no active steering or propulsion techniques are employed in this platform. Free-floaters have already been demonstrated commercial viability for communication platforms. They can lift payloads with tens to thousands of kilograms to the altitudes higher than 30 km, depending on its volume.

Steered free-floaters also drift in the winds, but they can exploit the winds as a sailing ship and can be navigated with high precision. With limited steering, a steered free-floater can stay at a position for a short time. Its sensors could be more complex than those flown on a free-floater. Steered free-floaters have been commercially mature and military deployment is imminent.

Maneuvering vehicles have propulsion and control capabilities. They can maneuver and thus fly to and stay at an area for a long time. Maneuvering vehicles provide large footprint and long mission duration that are associated with satellite and responsiveness that is commonly associated with unmanned aerial vehicle. Maneuvering vehicles are the most useful type of NSPs for the applications that require a fast revisiting frequency. They are possible substitutes for the satellites supporting wireless sensor systems [17].

B. Why Near-Space Platforms Should be Used in Wireless Sensor Systems

Current spaceborne and airborne communication and navigation techniques have two disadvantages [23]. The first one is that they cannot provide persistent regional monitoring. The second one is there are little sensors in the altitude between satellite and airplane. Moreover, the requirements of stealth and robust survivability in military applications also call for new platforms other than satellite and airplane. These objectives can be simultaneously implemented by using NSPs.

NSP is 10-20 times closer to the targets than a typical 400 km LEO satellite. This distance difference implies that it can detect much weaker signals. Figure 3 shows the ground coverage area as a function of the looking-down angle at different flying altitudes. Although an orbiting satellite has a much larger footprint than NSP, the latter has an impressive footprint with possibility of persistent coverage and good signal strength. NSP is more flexible than satellite because the former can be repositioned and repaired on the ground in case of failure. NSP also provides a platform for the "last mile" broadband problem due to its large coverage without deploying too many terrestrial base stations [24].

Another reason for which NSP-based wireless sensor systems are highly favored is their line of sight path loss characteristics. NSP can be directly linked to a satellite communication system to provide fixed wireless access services. Multiple NSPs can also be linked together. Due to lower latency and more favorable link budget, NSP is a more cost-effective platform than satellite for the provision of services to mobile users. Furthermore, frequency reuse can be achieved by spot beam antennas without installing huge antennas, thus high spectral efficiency can be achieved [25].

Additionally, since smart sensors [26] that are capable of manipulation and computation of the sensor-derived data can be installed in NSPs, smart sensor systems are also possible for NSP-based systems. Much work has been undertaken to develop common communication protocols for smart sensor communications, such as inter IC bus (I^2C), serial peripheral interface (SPI), and internet-based communication. Some authors have investigated frameworks for smart sensor and intelligent systems. For example, Schmalzel et al. [27] developed a new architecture for intelligent systems based on smart sensors. We think smart sensors can enable the NSP systems to support implementation of highly autonomous methodologies and develop appropriate communication protocols for timely and high-quality interactions with the system elements.

In summary, NSPs possess all the potentialities to propose themselves as a novel stratospheric segment in wireless sensor market. They are able to overcome the main drawbacks of satellite technology, due to their reduced distance from the ground with respect to satellites, and their quasi-stationary characteristics in the sky. Additionally, their costs for construction, deployment, launch and maintenance are much lower than those of satellites. Certainly, it is evident that NSPs can replace neither satellites, nor terrestrial radio links, for reasons of coverage, reliability, safety, and cost. In fact, satellites, NSPs, and terrestrial systems have different but complementary characteristics. While satellites are more suited for covering very large areas and providing broadcast applications, NSPs are able to cover remote or sparsely populated areas at reduced cost and offer broadband services to mobile users when fixed directive antennas cannot be used [28].

III. Overview of NSPs in Wireless Sensor Systems

In recent years, the applications of NSPs in wireless sensors have received much attention. In the following, we make an overview of such developments.

A. NSPs in Communication Sensors

Establishing NSP wireless communication services is first presented by Djuknic *et al.* in 1997 [13]. The suggested platforms include high altitude aeronautical vehicles (HAAVs) such as airships, planes and helicopters, which could operate at stratospheric altitude for a long time and carry multipurpose communications payloads. The authors concluded that HAAVs would have many advantages over their terrestrial and satellite counterparts because the former offers considerable opportunities for providing wireless communication services and developing innovative communication concepts such as cell scanning and stratospheric radio relaying. Through communications established between the platforms with user terminal on the ground, NSPs have capability to serve more users with lower infrastructure than terrestrial networks. Therefore, NSPs can provide broadband high-speed wireless service a complement to terrestrial and satellite systems.

Many research projects have been dedicated to NSP-based communication services. Comprehensive overviews are available in [21], [22], and [29]. The first NSP program is the Stationary High Altitude Relay Platform initiative in Canada but the first commercial video telephony and internet services via NSPs is initiated by the Sky Station Inc. in United States [30]. The SkyTower aims to market NSP to deliver various communication services such as fixed broadband communications, narrowband and broadcast communications [31]. The advanced concept technology demonstration (ACTD) was initiated to design, build, and test a high-altitude aerostat prototype that is able to maintain a geostationary position over 21 km for up to six months, generate its own power and carry multiple payloads. It is designed for military and civilian activities including: (1) weather and environment monitoring, (2) short and long range missile warning, (3) surveillance, and (4) target acquisition.

In Europe, two organizations have funded research activities, European Space Agency (ESA) and European Commission (EC). The representative research projects include HeliNet (network of stratospheric platforms for traffic monitoring, environmental surveillance and broadband services), CAPANINA (broadband communications technology), UAVNET (unmanned air vehicles network), CAPECON (civil UAV applications and economic affectivity of potential configuration solutions), and USICO (UAV safety issues for civil operations) [32], [33]. Specially, the CAPANINA project is to investigate possible broadband applications and services, and the most appropriate integration options for the aerial platforms, including deploying multiple platforms to serve the same coverage area, along with the most appropriate backhaul and network infrastructure. Such multi-platform configurations can be used for both fixed and mobile users [34]. Skynet was a Japanese project for the development of a balloon based on a stratospheric platform that can operate at an altitude of over 20 km for communications, broadcasting and environmental observation [35]. In Korea, research activities on NSPs conducted by Electronics and Telecommunications Research Institute (ETRI) [36]. The main objective is to develop a full-scale 200 m airship that could carry telecommunication and remote sensing payloads weight up to 1000 kg. Additionally, Chinese National Natural Science Foundation and 863 Programs have funded several research projects on NSPs [37]–[40].

As the demand of high-capacity wireless communication services has brought increasing challenges, especially for the "last mile" delivery, the use of NSPs for delivering broadband wireless communications is suggested in [41]. The role of NSP in beyond 3G networks is extensively investigated in [42]. The authors discussed different hybrid system architectures with an emphasis on the merits of NSPs and suggested a terrestrial-NSP-satellite integrated system. Furthermore, a method of significantly improving the capacity of NSP communication networks operating in a millimeter-wave band is presented in [43]. It is shown how NSP constellation can share a common frequency allocation by exploiting the antenna directionality. Several good reviewing papers are published to investigate the role of NSPs in broadband communications and global wireless connectivity, respectively [7], [15], [28]. The potentialities and challenges are presented from the perspective of integrated terrestrial/NSP/satellite communication infrastructure.

Several sensor systems for global connectivity are presented in [15]. The problem of deploying NSP sensor networks to provide wireless communications for terrestrial users is investigated in [44]. The aim is to provide communication services to ground users with quality of service (QoS) guaranteed. The channel estimation for a long term evolution (LTE) down link that uses orthogonal frequency division multiplexing (OFDM) for NSP systems is investigated in [45]. The performance of propagation models for efficient handoff in NSP systems to sustain QoS is analyzed in [46] and [47]. Radio resource allocation for multicast transmissions over NSPs is investigated in [48]. The authors formulated an optimization problem for a scenario in which different sessions are multicast to user terminals (UTs) across NSP service area, and then solve it to find the best allocation of NSP resources such as radio power, subchannel, and time slots. The optimization problem comes out to be a mixed integer non-linear program, which is further solved by the Lagrangian relaxation algorithm [49]. Additionally, data communications and optical communications from NSPs are proposed in [50]–[53].

B. NSPs in Radar and Navigation Sensors

NSP is also a promising platform for radar and navigation sensors. Since NSP supplies a gap between satellite and airplane [23], the applications of NSPs in microwave remote sensing, especially synthetic aperture radar (SAR) imaging which obtains its high range resolution by utilizing the transmitted wide-band waveform and high azimuth resolution exploiting the relative motion between the target and the radar platform, are extensively investigated in [54]. In SAR remote sensing, wide-swath is of great utility; however, it cannot be efficiently achieved by current spaceborne and airborne SARs due to the minimum antenna area constraint [55]. Spaceborne SAR has an imaging capability with a wide swath but with a limited azimuth resolution. In contrast, airborne SAR has an imaging capability with a high resolution but with limited swath coverage. Moreover, neither spaceborne nor airborne SARs provide persistent imaging capability. Typical solutions are based on the displaced phase centre processing technique, but they may bring a non-uniform spatial sampling problem. Another representative approach is to use multiple orthogonal waveforms [56]. This approach significantly reduces the ambiguous signal peaks; however, the ambiguity energy is unchanged, and it is not suitable for distributed targets. Range ambiguity suppressing through azimuth modulation is also feasible [57], but a key problem is how to design practical orthogonal waveforms [58], [59]. There is therefore an incentive to increase the swath width and azimuth resolution simultaneously by using NSPs as the radar platforms [60].

In the following, we introduce two typical application potentials, while a more comprehensive overview is available in [61].

One potential application is in homeland security [62]. To protect mass transit, civil aviation, and critical infrastructure from terrorist attacks, it is necessary to protect homeland security without impacting normal day-to-day human activities. Radar has been used in various military and civilian applications. Many countries have their civil aviation radar systems, which are specifically designed to detect threats. However, attacks may be not well dealt by current radar systems. It appears that passive radar using NSP receiver and opportunistic illuminator can provide a solution to these problems [5]. Rather than emitting signals, passive radar relies on opportunistic transmitters and passive receivers to detect threats. This is particularly attractive for homeland security applications, because it is an advantage for the sensor to serve also other purposes like traffic monitoring and weather prediction.

Another potential application is in disaster monitoring. The frequency of natural disasters has shown rapid increase in recent years. Taking tsunami detection as an example, tsunamis can be originated by earthquake, submarine landslide, volcanic eruption, meteorite impact or by a combination of these factors. Tsunami wave has sufficient energy to cross an entire ocean with low detectable height in the deep ocean, but it will become more detectable near to shore [63]. It is reported that the Sumatra Tsunami has a recorded wave height of 60-80 cm in deep-ocean, but had a maximum wave height of 15 m near to the Banda Aceh [64]. It is has been proved in [65] that there is a link between Tsunami wave amplitude and radar cross section. Significant variations of a few dB in the radar cross section synchronous with sea level anomaly are found both at C and Ku bands in the geophysical data record of the altimeter satellite Jason-1. Tsunami detecting by NSP radar has been investigated in [66], which concluded that Tsunami is detected by measuring: (1) Tsunami wave height, (2) Tsunami orbital velocities, (3) induced radar cross section modulations.

C. Integrated Communication and Navigation Sensors

The increasing number of space missions has encouraged a network able to support different services such as navigation and communications [67]. Provision of telecommunication services by means of NSPs is thus becoming a relevant topic of interest for next generation systems. Mobility on demand, large coverage, and sensor re-configurability are only some examples of expected benefits for wireless sensors based on the use of such platforms [14]. High performance communication and navigation sensors for interplanetary networks is investigated in [68]. The authors proposed the transmission strategies relying upon a packet-layer coding approach to improve the overall performance. An integrated mobile satellite broadcast, paging, communications and navigation system was proposed in [69]. The designed networks support a mix of mobile satellite services optimized for wireless market applications and, in particular, for the needs of the rural populace and traveling public.

Dreher et al. [70] designed the antenna and receiver with digital beamforming for satellite navigation and communications. An integrated communication, navigation and surveillance satellite system for air traffic management was studied in [71]. Chen et al. presented a multimodal wireless networks with communications and surveillance on the same infrastructure [72]. However, as commented in [14], research regarding the use of NSPs for communications usually neglects the fact that it is also a privileged infrastructure for the provision of navigation and positioning services. The authors believe that

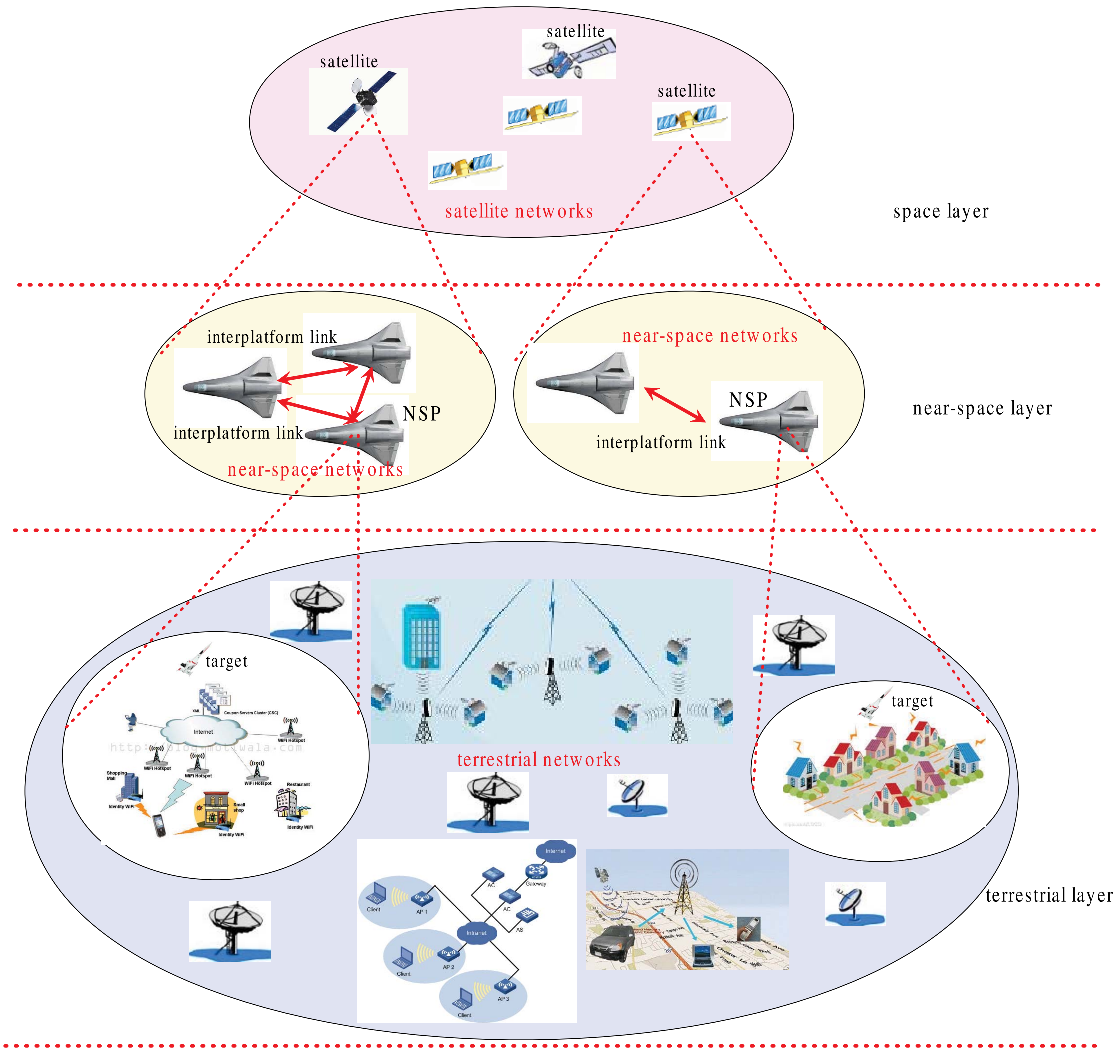


Fig. 4. Illustration of integrated wireless sensor systems with NSP and satellite platforms.

NSPs can act as an augmented infrastructure for the global navigation satellite systems (GNSS) to perform direction of arrival (DOA) estimation and broadcast position information.

IV. Integrated Wireless Sensor Systems

Both past and on-going research activities have shown that NSP-based sensors could either be integrated into current major terrestrial (e.g., WiMAX, 3G/4G) and satellite wireless networks [73]–[75], or provide services as standalone systems [76]. Certainly the trend is not to replace existing communication technologies, but instead to co-exist with them in a complementary and integrated view [77]. Although NSPs provide the flexibility to accommodate a wide spectrum of applications ranging from communications to navigation and remote sensing [78], this paper focuses on integrated wireless sensor systems for communication and navigation applications.

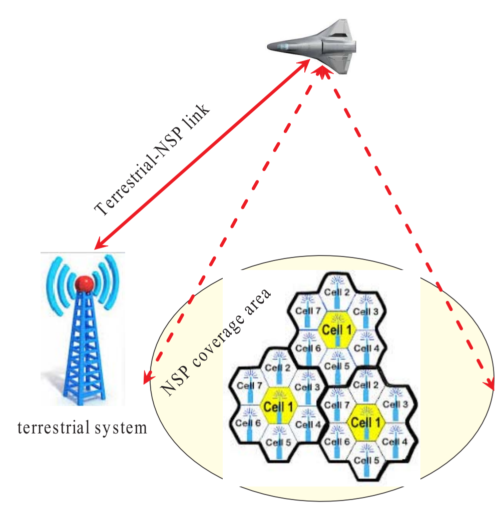


Fig. 5. Illustration of NSP-terrestrial system.

Figure 4 gives an extensive system architecture, which can be further categorized as an integrated terrestrial-NSP sensor system (see Figure 5) and an integrated terrestrial-NSP-satellite sensor system. In the terrestrial-NSP sensor system, connections to other communication networks [79] via a gateway station (GS) are allowed. It can be further divided into two topologies taking into account where the switching takes place [80]: (i) With on ground switching:

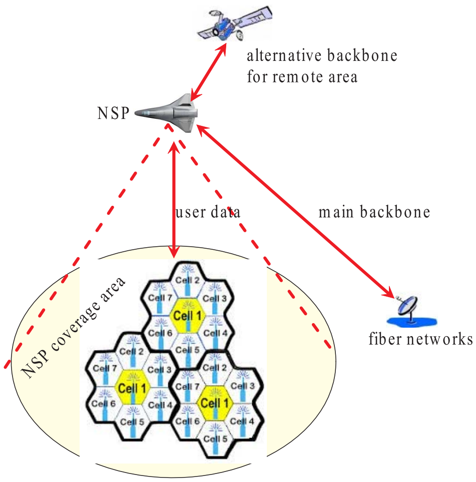


Fig. 6. Illustration of standalone NSP system.

The path between two users encompasses an uplink from user to NSP, feeder downlink to GS where the switching is performed, feeder uplink from GS to NSP and downlink to the users. (ii) With on-board switching: The path between two users takes only uplink from the user to NSP, where switching is performed; and downlink from NSP to users. The terrestrial-NSP-satellite sensor system is particularly useful when the NSPs are placed above extreme environment with deficient (rural and remote areas) or non-existent terrestrial infrastructure. In this case, the NSP sensor can be used as a relay for satellite communications [81]. Additionally, we can use only a stand-alone NSP sensor system [82], as shown in Figure 6. This NSP system may be deployed economically and efficiently in a rural or remote area where it is rather expensive and inefficient to deploy terrestrial sensor systems.

Multiple NSPs can be interconnected via ground stations or inter-platform links to extend the sensor observation area [83], [84], especially making use of a sensor network in the sky. It has been demonstrated in [85] that 16 NSPs can serve Japan with the minimum elevation angle of 10°, whereas a network of 18 NSPs is feasible to cover the whole of Greece including all the islands [86]. Instead of extending the coverage area, multiple NSPs can also be deployed in some planar or vertical arrangement so as to cover the same single coverage area. By exploiting spatial discrimination, such multiple NSP configurations provide incremental rollout and the systems can be expanded on demand for higher capability [43]. In response to increasing traffic load and type of service demands there is a possibility of deploying 3-6 NSPs to cover the same cell area [15]. If the NSPs are interconnected via ground stations, they can be enabled only above the area where the ground station is placed. In contrast, when interplatform links are employed, the NSP operation can be independent of terrestrial sensors and thus highly flexible system coverage and lower signal delays can be obtained.

Localization services can also be integrated into the sensor network because exploiting the user position information allows improvement in the system capacity. GNSS are widely employed to provide localization services, but they require at least four satellites in view, a situation seldom verified in an urban environment [14]. On the other hand, current terrestrial networks cannot provide effective localization services for mobile users, particularly in a rural environment. In contrast, the integrated NSP and satellite system can be a complementary to existing localization systems. For instance, the localization accuracy provided by the GNSS for critical applications and harsh environment can improve by the NSP networks. Long-endurance flight and several other operation features make NSP a good calibrator for GNSS localization services. Moreover, it provides an additional ranging signal that can be exploited by the users to choose the optimal set of measurements according to the specific scenario [14].

Detecting passive targets with opportunistic spaceborne illuminators can also be integrated into the sensor systems. As shown in Figure 7, the passive NSP receiver consists of two channels. One heterodyne channel pointing directly towards the satellite is used to extract the reference signal for matched filter and synchronization compensation. The signal is sampled in a delayed window that can be predicted using the knowledge of the NSP position information. The other antenna directing to the observed ground area of interest is used as the radar channel to receive the reflected signals. Taking GPS satellite as an example, Figure 8 illustrates the functional blocks of extracting the reference signal from the direct-path channel for matched filtering the reflected signals. Note that the configuration using a single-channel receiver is also feasible. In this case, decoding the navigation message is required, which needs the synchronization information.

V. Arrangement of Near-Space Platforms

To arrange multiple NSPs to monitor a given region, we consider a formation geometry shown in Figure 9, where θ_{in} is the incidence angle, θ_e is the geocentric angle, R_e is the Earth radius, and h_s is the NSP altitude.

The projection distance from the user to a NSP can be expressed as

$$D_e = R_e \theta_e \tag{1}$$

where

$$\theta_e = 90^\circ - \theta_{\text{in}} - \sin^{-1}\left[\frac{R_e \sin(90^\circ + \theta_{\text{in}})}{R_e + h_s}\right]. \tag{2}$$

Supposing the distance between two NSPs is L_h and its projection distance on the ground is L_e, we then have the following geometry relation

$$\frac{L_h}{L_e} = \frac{R_e + h_s}{R_e} \Rightarrow L_h = \frac{(R_e + h_s)L_e}{R_e}. \tag{3}$$

If the triangle geometry shown in Figure 9(b) is employed, L_e should be

$$L_e \le D_e. \tag{4}$$

Otherwise, if the quadrate geometry shown in Figure 9(c) is employed, L_e should be

$$L_e \le \frac{\sqrt{2}}{2} D_e. \tag{5}$$

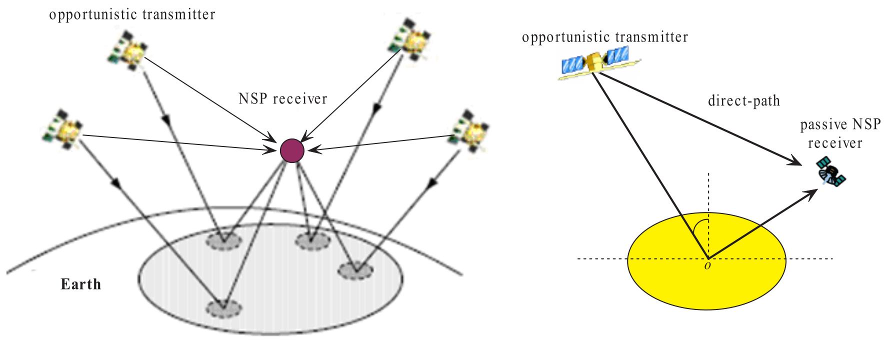


Fig. 7. Geometry of passive NSP-borne receivers and opportunistic spaceborne transmitter.

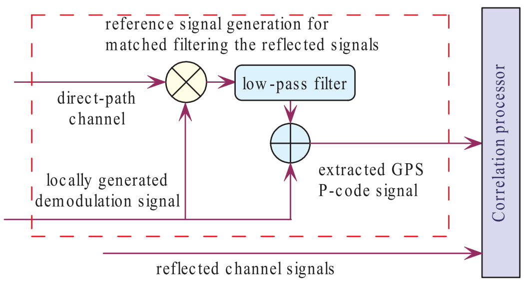


Fig. 8. Functional blocks of extracting the reference signal from the direct-path channel for matched filtering the reflected signals.

As an example, suppose the Earth radius is $R_e = 6378$ km, Figure 10 gives the required NSP arrangement parameters for different combinations of the incidence angle θ_{in} and platform altitude h_s. We can notice that the required NSP distance decreases with the increase of incidence angle θ_{in}, but it increases with the increase of the platform altitude h_s. It is necessary to note that, the received signal signal-to-noise ratio (SNR) will deteriorate with the decrease of the incidence angle [87].

To determine the required number of NSPs to monitor a given region, we consider the formation geometry illustrated in Figure 9(c). Suppose the length and width of the region required for monitoring are L_l and L_w, respectively, the corresponding geocentric angles are

$$\varepsilon_x \approx \frac{180L_l}{\pi R_e} \tag{6}$$

$$\varepsilon_y \approx \frac{180L_w}{\pi R_e} \tag{7}$$

The required number of NSPs can be derived as

$$N = [\lceil \frac{\varepsilon_x}{\frac{180d_x}{(R_e+h_s)\pi}} \rceil + 2] \times [\lceil \frac{\varepsilon_y}{\frac{180d_y}{(R_e+h_s)\pi}} \rceil + 2] \tag{8}$$

where d_x and d_y denote the distance between two NSPs in x-axis and y-axis, respectively, and $\lceil x \rceil$ denotes the nearest integer greater than or equal to x. According to the geometry relation, d_x and d_y can be derived as

$$d_x = d_y = (R_e + h_s) \cdot \frac{\sqrt{2}\varepsilon_s}{2} \tag{9}$$

where ε_s is the NSP's geocentric angle.

Suppose there is an area of 500 km $\times$ 500 km to be observed. Table III gives the required number of NSPs in different geometry configurations. Note that $R_e = 6378$ km is assumed in the table. We can notice that the required NSPs decreases with the increase of the NSP altitude and the decrease of the signal incidence angle θ_{in}.

VI. Limitations and Vulnerabilities

NSPs provide promising platforms for future integrated wireless sensor systems. The use of cost effective NSPs can lead to the solutions that were previously thought to be out of reach for wireless customers. Certainly, there are several limitations and vulnerabilities:

A. Launch Constraints

Weather will be a risk factor that could be significant if the NSPs are not furnished with reliable sensors for on-site meteorological data with which a vehicle controller can predict turbulence, icing, and violent gusts that jeopardize the craft. The experience with high-altitude tropospheric operation from around-the-world balloonist teams and weather teams should be collected and codified to aid computer predictions. Since NSPs may operate in the troposphere for over five hours, the weather condition must be within allowable parameters before a let-down can commence. Note that a satellite faces similar launch constraints but the constraints only have to be met during launch. Unmanned and manned aircrafts are also subject to similar launch and recovery constraints, although their limitations are less stringent than that for NSPs. Currently it is difficult to make NSPs to the altitudes higher than 20 km. Increasing the altitude greatly increases the NSP size, quickly making it too difficult to manage on the ground and during launch. A rule of thumb is that for every extra 30 km of altitude to reach, the NSP volume should be doubled.

B. Survivability Constraints

As NSP technology develops, it should be assumed that target detection technology will also develop. Near-space was not historically a viable region in which vehicles can operate and thus missiles were not designed to reach that altitude. But modern surface-to-air missiles can reach as high as jet aircraft fly and consequently NSPs are not beyond current

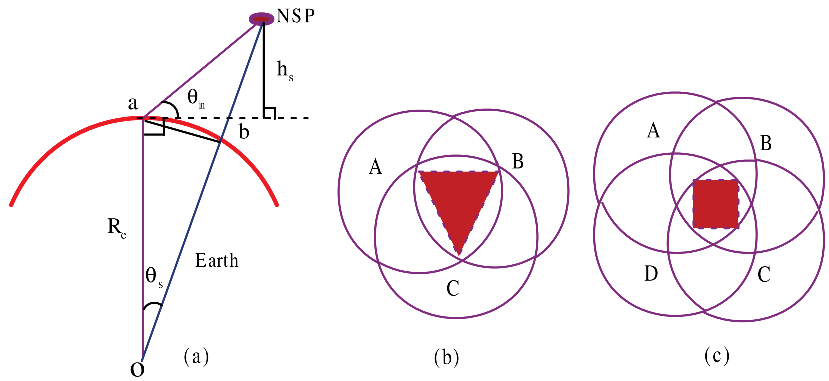


Fig. 9. Illustration of NSP observation geometry and coverage region: (a) geometry, (b) triangle coverage, and (c) quadrate coverage.

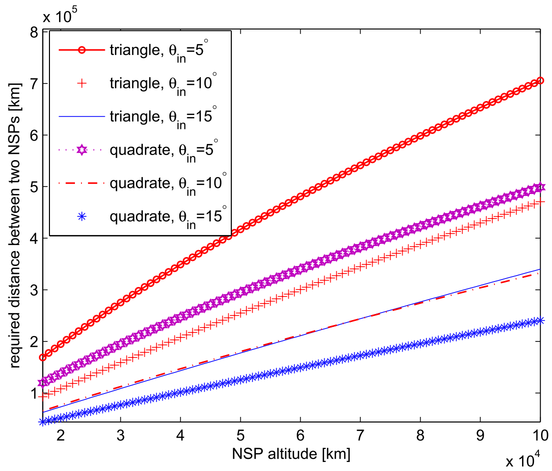


Fig. 10. Required distance between two NSPs.

TABLE III
REQUIRED NUMBER OF NSPS IN DIFFERENT GEOMETRY CONFIGURATIONS

incidence angle	NSP altitude [*km*]	required number of NSPs
5°	20	5 × 5
	30	5 × 4
	60	4 × 3
	100	3 × 3
15°	20	10 × 8
	30	8 × 6
	60	5 × 5
	100	4 × 4
20°	20	13 × 10
	30	10 × 8
	60	6 × 5
	100	5 × 4

conventional weapons. Therefore, NSPs need to be flexible, replaceable and cost-effective; otherwise, their use may be limited in military applications. On the other hand, once a NSP loses control, even high-performance radars may have difficulty in detecting and tracking the NSP due to its small radar cross section.

C. Legal Constraints

Freedom of overflight is another limitation. The legal status of the near-space regime is a grey area that is not directly addressed by treaty or policy. Near-space is not a new legal regime; the question is whether it falls under air law where nations claim sovereignty, or space law where overflight rights exist. Due to lack of clear legal precedent governing near-space regime, there are considerable disagreements over whether overflight rights exist or not [88].

D. System Implementation Issues

For the integrated wireless sensor networks via near-space and satellite platforms, synchronization compensation is a technical challenge. In the case of indirect phase synchronization using identical local oscillators in the transmitter and receiver, phase stability is required over the whole coherent integration time. Even if the toleration of low-frequency phase errors can be relaxed to 45° [89], the requirement of phase stability is only achievable with ultra-high-quality oscillators [90]. Moreover, as aggravating circumstances are often accompanied for NSPs, the phase stability will be further degraded. Several potential synchronization techniques or algorithms, such as using ultra-high-quality oscillators [89] and an appropriate bidirectional link [91] are proposed. However, in most of cases, we cannot alter the transmitter; hence, it is necessary to develop a practical synchronization technique without alteration to the transmitters. One potential solution is to follow the direct-path signal-based synchronization approach detailed in [92].

On the other hand, problems may arise due to the presence of atmospheric turbulence, which introduce NSP trajectory deviations from a normal position, as well as altitude (roll, pitch, and yaw angles). As a consequence, motion compensation is often required. In current communication and navigation systems, GPS and inertial navigation systems are usually employed for this task. However, for NSP sensors, motion compensation facilities may be not reachable because NSP has a very limited load capability. Therefore, some efficient motion compensation techniques should be developed.

Antenna design and implementation is also a key technique in NSP systems. Dielectric lens antenna is widely used in NSP systems due to its superior performance [93], [94]. A dielectric lens antenna ground plane is designed in [94]. The designed antenna has relatively high aperture efficiency and multiple scanned beams over a wide angle. But, if a lower carrier frequency is employed, the feed-waveguide volume and weight will increase greatly and consequently it is difficult to be installed on NSPs. To resolve this disadvantage, a novel multi-beam dielectric lens antenna array operating from 1.77 GHz to 2.44 GHz fed by a Yagi-Uda unit is designed in [95]. In fact, there is a trade-off on deployment of directional antennas on NSPs where the speed, the aerodynamic nature and drift caused by winds puts many challenges on establishing en effective link between NSPs [96]. A few studies on overcoming such challenges have been reported. For example in [97], Alshbatat et al. proposed an adaptive MAC protocol for unmanned aerial vehicle (UAV) communication networks where in their model, the RTS/CTS exchange is conducted omnidirectional and data transfer is conducted directionally with one of four beams. They assume four antennas on a UAV where two of them are located beneath the wing and others above. In this model, it is assumed that the UAV has capability to plan and tilt to the desired transmission direction, which actually is not a realistic assumption.

VII. Conclusion

In this review paper we have demonstrated the unique positioning NSP technological advantages for a wide range of monitoring, earth observations, and other sensing based applications over satellites and other airborne networks. The relatively large coverage area and some navigation support capabilities of NSP make this part of a promising infrastructure for the future systems as required for the co-existence of navigation and communication stations for the provision of integrated services connecting terrestrial stations with the satellites. In many persistent surveillance applications superiority of NSP stationary monitoring over periodic snapshots from moving satellite or airplane platforms enables integration of direct sensing for different applications such as infrared, electro-optical, hyper-spectral imagery, and smart sensors and other traditional and upcoming sensors. Also, we have explained how NSP can play a significant role as an additional, always present, layer between satellite networks and terrestrial networks. We urge the engineering community to support the research and development of NSPs for their potential applications to serve the humanity.

Acknowledgements

The authors would like to thank the editor (Prof. H. F. Rashvand) and anonymous reviewers for their valuable ideas, time, and suggestions to improve the quality of the manuscript.

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