Near-Space Vehicles:
Supply a Gap between Satellites and Airplanes for Remote Sensing

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ABSTRACT

Near-space is defined as the atmospheric region from about 20 kilometer (km) to 100 km above the Earth's surface; near-space vehicles offer several advantages to Low Earth Orbit (LEO) satellites and airplanes because near-space vehicles are not constrained by orbital mechanics and fuel consumption. Some of the near-space vehicle advantages include their potential for some specific radar applications that require persistently monitoring or fast-revisiting frequency which are explained herein. The role of near-space vehicles is reviewed in supplying a gap between satellites and airplanes for microwave remote sensing applications. Several potential applications such as passive surveillance, reconnaissance, and high resolution wide swath imaging are described. The novel multiple-input and multiple-output (MIMO)-based multi-aperture in elevation and space-time coding (STC) synthetic aperture radar (SAR) are presented for high resolution wide swath imaging. Therefore, given their operational flexibility, near-space vehicle-borne radars may supply the gap between space-borne and airborne radars which is the reason we appeal to the systems engineering community for more publications and more support on the research and development of near-space vehicle-borne radars.

INTRODUCTION

Near-space is defined as the atmospheric region from about 20 kilometer (km) altitude to 100 km altitude above the Earth's surface [1] as shown in Figure 1 [2]. Note that the lower limit is not determined from operational considerations, but from the international controlled airspace altitude because it is too high for airplanes but too low for satellites. Very few sensors are currently operating in near-space, because the atmosphere is too thin to support flying for most aircraft, and yet too thick to sustain orbit for satellites [3]. Nevertheless, potential benefits for vehicles operating in near-space may include possible persistent monitoring and high revisiting frequency (revisit the same site in a short time interval) that are critical to some specific radar and navigation applications, but not accessible for current satellites and airplanes because there is no orbit constraint for near-space vehicles [1]. Near-space is a sub-space of the suburban geo-location of RF signals (GRFS) systems discussed in Dr. Progri's book ***Geolocation of RF Signals: Principles and Simulations*** [4]. The effective range of suburban GRFS systems is from 10 km to 100 km in ground, air, space, and water. Interested readers should definitely consider this book for further considerations and consultations.

There is a region in near-space where the average wind is less than 10 m/s; hence, persistent coverage and high flying speed can be obtained for the vehicles operating in this region. Moreover, near-space vehicles are relatively low cost when compared to satellites and airplanes [3]. Additionally,

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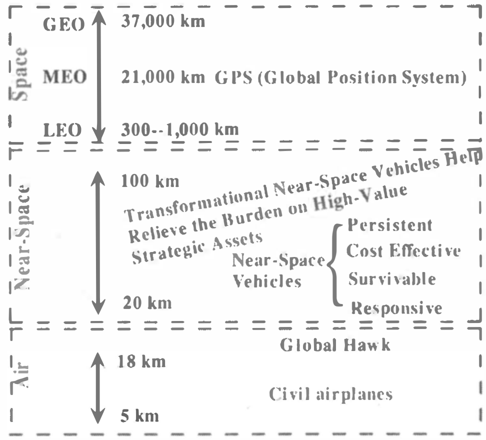

Fig. 1. Near-space definition and its advantages while compared to space including: geosynchronous orbit (GEO); middle earth orbit (MEO); and low earth orbit (LEO), and airplane

as near-space is below the ionosphere, therefore, there are no ionospheric scintillations that will significantly degrade the RF communications and navigation performance which explains why near-space has received much attention in recent years and why several types of near-space vehicles are being studied, developed, or employed [3-5].

However, it appears that there is still a need for more published work related to near-space concentrated primarily on the design of different near-space vehicles including free-floaters and maneuvering vehicles [5, 6]. Some works on the use of near-space vehicle-borne sensors for communication applications have been reported [7]. Other works have been reported on near-space vehicles in radar and navigation applications [2, 4, 8-10]. In fact, by placing radar transmitters and/or receivers inside near-space vehicles, many functionalities currently performed with satellites or airplanes could be performed more efficiently than conventional airborne and space-borne radars.

As current space-borne SAR and airborne SAR have limited applications in persistently monitoring and high resolution wide swath imaging, we have investigated the potential and challenges of near-space vehicle-borne passive bi-static SAR and displaced phase centered antenna (DPCA) SAR in [2]. Herein, we review mainly the role of near-space vehicles in supplying a gap between satellites and airplanes for microwave remote sensing applications from a top-level system description, with an aim for further research. Several potential applications such as passive surveillance, reconnaissance, and high resolution wide swath (HRWS) imaging are described. The remaining sections are organized as follows. In the *Near-Space Vehicles Classification* section, several typical types of near-space vehicles are described. Next, the role of near-space vehicle-borne bistatic radars for surveillance and reconnaissance and the role of monostatic multi-antenna SAR for HRWS imaging are described in the *Near-Space Vehicle-Borne Bistatic Radars for Surveillance and Reconnaissance* section and the *Near-Space Vehicle-Borne Monostatic SAR for High Resolution and Wide Swath (HRWS) Imaging* section, respectively. Finally, this is concluded in the *Conclusion* section.

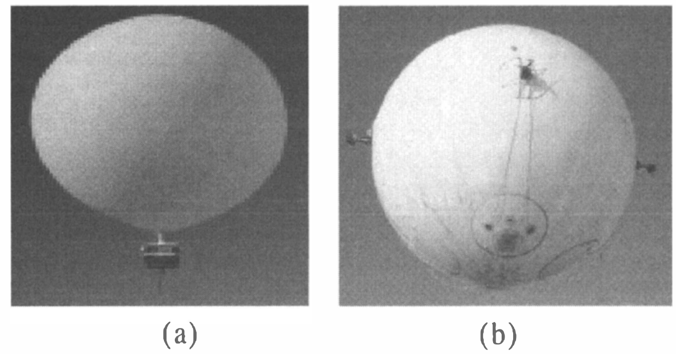

Fig. 2. Example of Near-Space Vehicle Prototypes: Fig. 2A. Free-floater of the US Air Force Space Battle Lab – *Courtesy of the US Air Force Space Battle Lab;* Fig 2B. Maneuvering vehicle of the US Naval Research Lab – *Courtesy of the US Naval Research Lab*

NEAR-SPACE VEHICLES CLASSIFICATION

Near-space vehicles can be classified into two major categories:

1) **Free-floaters,** and

2) **Maneuvering vehicles** [1, 3].

Figure 2 gives an example of near-space vehicles for each category. Each near-space vehicle category is further explained in great detail.

FREE-FLOATERS

Near-space free-floaters can be further classified into *Free-Floating Balloons* and *Steered Free-Floaters.* The flying speed and direction of free-floating balloons depend primarily on existing winds. Limited steering is also possible by variable ballasting, causing the balloon to float at different altitudes to take advantage of different wind directions and speed. These balloons can transport tens to thousands of pounds to over 30 km. *Steered free-floaters* also drift on the wind, but they are able to exploit the wind to maneuver at will. These free-floaters can provide a persistent coverage which has a particular value for remote sensing monitoring. This is currently impossible for satellites and airplanes by means of today's state-of-the-art technology. Moreover, free-floaters have already demonstrated commercial viability as communications platforms [3, 5, 7].

MANEUVERING VEHICLES

Near-space maneuvering vehicles can use a variety of propulsion mechanisms to fly or keep station over a specific area of interest from days to months [11]. They can provide a large footprint and a long mission that are commonly associated with satellites and the responsiveness of an unmanned aerial vehicle (UAV). Persistent coverage is also possible for maneuvering vehicles. Moreover, not constrained by orbital mechanics like satellites, maneuvering vehicles can move at a speed as fast as 1000 - 1500 m/s with a maximum payload of 4000 pounds [3]. Thus, maneuvering vehicles are potentially the most useful type for remote sensing that requires a high revisiting frequency.

NEAR-SPACE VEHICLE-BORNE BISTATIC RADARS FOR SURVEILLANCE AND RECONNAISSANCE

Space-borne and airborne radars have played an important role in surveillance and reconnaissance; however, even as good as they were envisioned and employed [12], it is impossible for the limited space-borne radars to provide persistent coverage for an area of interest because, generally speaking, most of LEO satellites have a specific target in view for less than ten minutes at a time and revisit the same site infrequently. Similarly, persistent coverage is also impossible for airborne radars. In contrast, persistent coverage is possible for near-space vehicles.

On the other hand, near-space vehicles, especially free-floaters, are inherently survivable. Free-floaters move very slowly when compared to usual airborne targets, almost drifting on the wind similar to the chaff cloud that is often ignored by many types of Doppler radars. This is particularly valuable for surveillance and reconnaissance. Surface-to-air missiles may be a threat to near-space vehicles, but they are most likely not designed to engage a non-maneuvering target at near-space altitude [13]. Economics also discourage such an exchange. Additionally, near-space vehicles are 10 to 20 times closer to their targets than a typical 400 km LEO satellite. This differential distance implies that near-space vehicles could detect much weaker signals.

The simplest and most mature application of near-space vehicles for surveillance and reconnaissance is the passive bi-static radar which was investigated in [2]. This system involves placing a passive receiver inside near-space vehicles and utilizing opportunistic illuminators such as global navigation satellite systems (GNSS) receivers and space-borne or airborne imaging radars. A typical near-space vehicle-borne receiver should contain at least two channels:

1) **One channel is used to receive the scattered signals with which the detection of targets is being attempted;** and

2) **The other channel is employed for receiving the direct-path signals, which are used as reference signals for matched filtering.**

This system offers two other significant advantages: the first advantage is the potential of bi-static observation; and the second is the regional persistence. This system has a technical challenge of synchronization (including spatial, time and phase synchronization) processing [14]. One potential solution is the direct-path signal-based approach detailed in [15].

NEAR-SPACE VEHICLE-BORNE MONOSTATIC SAR FOR HIGH RESOLUTION AND WIDE SWATH (HRWS) IMAGING

Future remote sensing applications such as disaster evaluations and ocean observations, will be required to produce high resolution imagery over a wide area of surveillance. However, there is a contradiction between the high resolution imagery over a wide area of surveillance and the minimum antenna elements required to perform the high resolution density, imaginary processing known as minimum antenna area constraint. This constraint can be analytically modeled by means of the following inequality:

$$W_s / \rho a \leq c / 2v_s$$

where W_s is the swath width, ρ_a is the azimuth resolution, c is the speed of light in a vacuum, and v_s is the platform velocity. Generally, c / v_s is nearly constant at 20,000 for LEO satellites and typically in the range of 300,000-750,000 for airplanes. As near-space vehicles can fly at a speed ranging from stationary to 1500 m / s, the c / v_s will be greater than 100,000. Thus, while compared to space-borne and airborne SARs, near-space vehicle-borne SAR can provide a more flexible choice for satisfactory HRWS imaging.

Moreover, some multi-antenna or multi-aperture techniques, such as azimuth multi-channel (see Figure 3, h_s is the platform altitude) and multi-channel in elevation (see Figure 4), can be further employed to alleviate the requirements on the minimum antenna area. For an azimuth multi-channel system the relationship between the vehicle speed and the along-track sub-channel offset have to be adjusted in order to obtain a signal that is equivalently sampled as a single-channel signal of the same effective sampling rate. For a monostatic elevation multi-channel system, the swath may become no longer continuous since blind ranges will be introduced when the receiver is switched off during transmission. Such a restriction could be overcome by bi-static configurations allowing for simultaneous transmission and reception.

Another potential configuration is the MIMO-based multi-aperture in elevation, as shown in Figure 5. Transmit-receive signal waveforms, used in any two sub-apertures, are orthogonal, but the same transmit-receive signal waveforms are used in each sub-aperture. The basic idea is to form multiple transmit and receive beams which are steered toward different sub-swathes. This is different from a phased array radar because orthogonal transmit waveforms are employed in a phased array radar system. Multiple beams can then be formed by grouping the antenna elements into

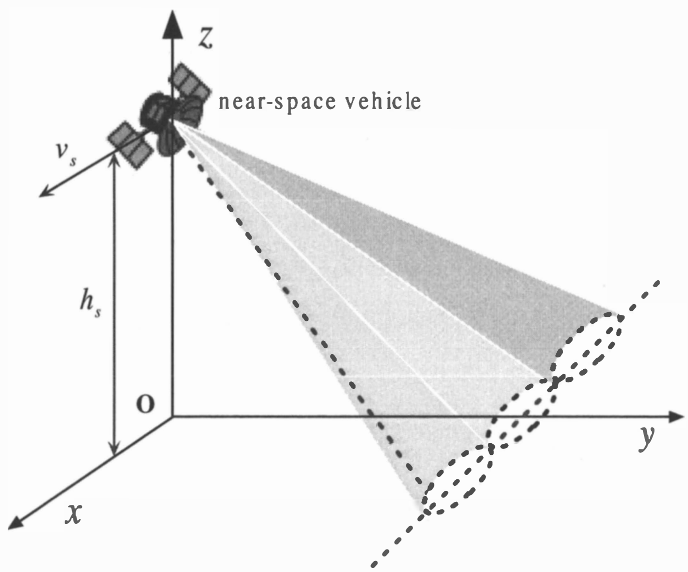

Fig. 3. Geometry configuration of multi-channel in azimuth

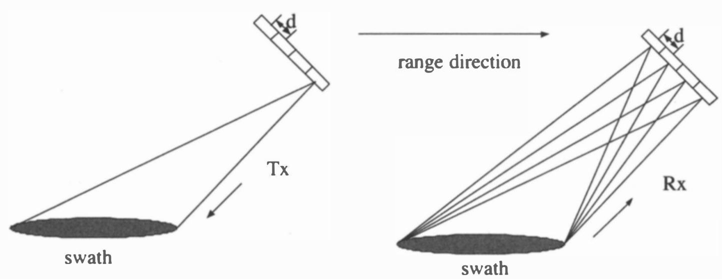

Fig. 4. Geometry configuration of multi-channel in elevation

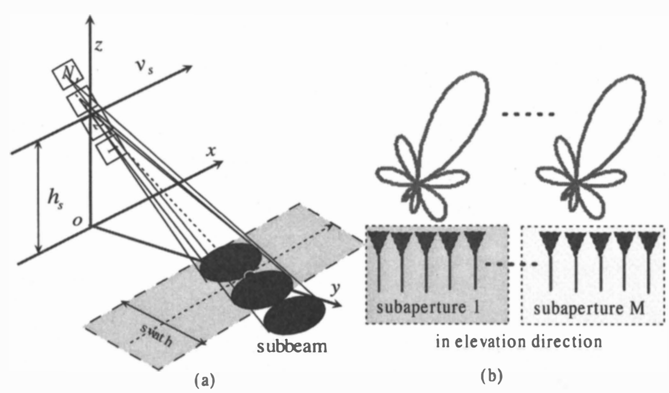

Fig. 5. Geometry configuration of MIMO-based multi-aperture in elevation

multiple groups, each forming a virtual transmit or receive sub-aperture. These sub-apertures can be disjoint or overlapping in space.

Another potential configuration is the near-space vehicle-borne space-time coding (STC) MIMO SAR for HRWS remote sensing shown in Figure 6 [16 - 18]. In elevation, orthogonal waveforms are transmitted from different sub-antennas which illuminate a wide swath. Each receiving sub-antenna receives signals from all reflected paths. Next, a digital beam-forming on the receiver is carried out by a jointly spatiotemporal processing. In azimuth, the space-time coding scheme results in equivalent phase centers when the radar moves from one position to another. This enables a coherent combination of the sub-sampled signals with the DPCA technique. It implies that we can broaden the azimuth beam from the diffraction-limited width, giving rise to improved resolution without increasing the system operating pulse repetition frequency.

CONCLUSION

Near-space vehicles offer an opportunity for developing new radar remote sensing techniques for several reasons. First, they can support uniquely effective and economical operations. Second, they enable new remote sensing tools. Third, they provide a crucial corridor for prompt regional strikes. This investigates the role of near-space vehicles in supplying a gap between satellites and airplanes for microwave remote sensing applications. Several potential applications such as passive surveillance, reconnaissance, and HRWS imaging are described. The novel MIMO-based multi-aperture in elevation and STC MIMO SAR are presented. We show that near-space vehicles indeed are good radar platforms in some specific remote sensing applications. Note that the near-space vehicle-borne GNSS receivers for radio occultation (or the act of blocking or hiding from view) measurements, discussed in [19], are also quite useful in monitoring regional environments.

Near-space vehicle-borne radars cannot replace space-borne and airborne radars, but they could provide more efficient remote sensing functionality than space-borne radars. Although near-space vehicles have a much smaller coverage area than satellites due to their lower altitude, they can still offer regional coverage of hundreds of kilometers and provide cost-effective remote sensing services. Near-space vehicle-borne radars could also extend remote sensing services into areas with limited or no access to space-borne and airborne radars, such as ocean remote sensing [4]. Therefore, given their operational flexibility, near-space vehicle-borne radars may supply a gap between space-borne and air-borne radars which is the reason we appeal to the systems engineering community for more publications and more support on the research and development of near-space vehicle-borne radars.

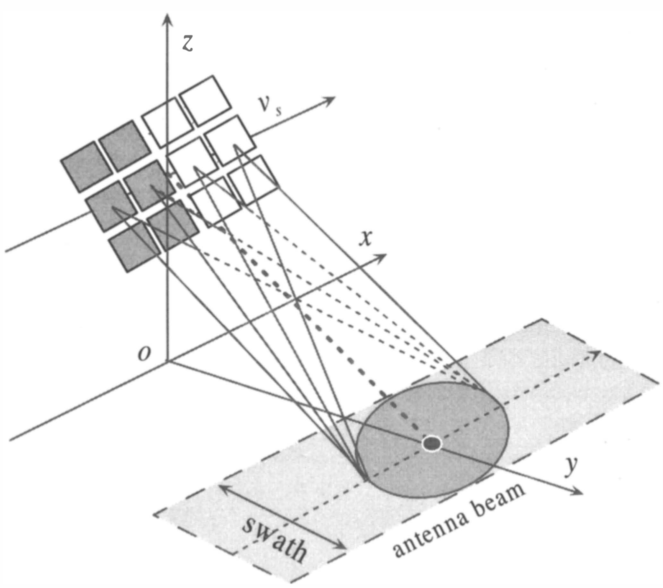

Fig. 6. Geometry configuration of space-time coding MIMO SAR

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