Near-Space SAR: A Revolutionary Microwave Remote Sensing Mission

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Abstract

Inspired by the recent advances in near-space defined as the region between 20km and 100km, this paper proposed the concept of near-space SAR. To the author's knowledge, this is the first time that the near-space SAR is being proposed for microwave remote sensing missions. By placing the SAR's transmitter /receiver in the near-space platforms, many functions that are currently performed with the satellites or airplanes could be performed much more cheaply and with much greater operational unity. These advantages make near-space SAR attractive for a variety of remote sensing missions. In this paper, the potential and challenges of the near-space SAR, compared to current spaceborne SAR and airborne SAR, were detailed. Various near-space SAR configurations are introduced, and their potential for different applications such as passive imaging, high-resolution and wide-swath imaging, and inverse SAR imaging were investigated. It is shown that, the use of near-space SAR can lead to the solutions that are previously thought to be out of reach for remote sensing scientists and customers.

Keyword: *Near-Space, SAR, Remote Sensing.*

1. Introduction

Near-space [1] defined as the region between 20km and 100km was a cultural blind spot—too high up for aircraft, but too low for satellites. But once we step back from platform based thinking and look at the effects, near-space becomes intriguing —opening doors for completely new air and space opportu-nities, which can offer many new capabilities that are not accessible to the orbiting satellites or maneuvering aircrafts. On the other hand, synthetic aperture radar (SAR) has been an invaluable remote sensing tool for the past few decades [2]. However, the long lead times and high costs of placing satellites in orbit has led both the commercial industry and researchers to look for alternative platforms for their payloads. Moreover, the requirements of stealth and robust survivability in military applications also call for new radar platforms other than the satellite and the airplane. Fortunately, these requirements can be filled by using near-space platforms at a fraction of the cost of the traditional platforms. As such, we have proposed to use the near-space passive radar for homeland security in [3].

Inspired by the recent advances in near-space because it offers a crucial perch for the defense of the spacecraft as well as greater leverage for our net-centricity, this paper proposed the concept of near-space SAR. To the author's knowledge, this is the first time that the near-space SAR is being proposed for microwave remote sensing missions. By placing the SAR's transmitter/receiver in the near-space platforms, many functions that are currently performed with satellites or airplanes could be performed much more cheaply and with much greater operational unity. In this paper, the potential and challenges of the near-space SAR, compared to current spaceborne SAR and airborne SAR, were detailed. Various near-space SAR config-uretions and their potential for different applications were investigated.

The remaining sections of this paper are organized as follows: The superiority of near-space SAR compared to current spaceborne SAR and airborne SAR are investigated in Section II, followed by the strengths and weakness of various configurations of near-space SAR in Section III. Finally, Section IV concludes the whole paper.

2. Superiority of Near-Space SAR

Space effects have revolutionized the remote sensing missions greatly [4]. However, we still have a long way to go to truly operate the space. The space effects that we desperately wanted but in many cases did not always receive, are the persistent, intelligence, surveillance, and reconnaissance (ISR). The current spaceborne SAR does an exceptionally good job of providing strategic space effect. However, even as good as they are, they cannot provide a constant, staring presence on a timescale of days, weeks, or months over a selected target or area of interest. Most low earth orbit satellites have a specific target in view for less than 15 minutes at a time and revisit the same sites infrequently. Costing billions or at least millions each with multiple satellites to provide staring persistence is almost prohibitively expensive. Satellites traditionally operate in the orbits above 200km, where the effects of the tenuous atmospheric dragging on orbital lifetime begin to decrease markedly. Orbiting much lower than 200km will significantly reduce the lifetime of the satellites. In contrary, airplane cannot fly very high because there is insufficient oxygen to allow conventional fuels to burn, to allow engines to operate. Moreover, at high altitudes, aerodynamic effects also become much harder to achieve, causing the wings to be very insufficient. Generally speaking, air-breathing aerodynamically lifted platforms cannot routinely operate much above 18.3km. As a result, physical limitations due to orbital mechanics and fuel consumption prevent a persistent region coverage for both spaceborne and airborne SARs. We thus have two gaps,

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one is the capability and the other is the altitude between satellite and airplane. Fortunately, these two gaps can be simultaneously filled through the use of near-space platforms flying in the region where the prevailing winds are relatively because it is above storms and jet stream.

Another superiority is the robust survivability. Since there is a rapidly growing number of emerging technologies for jamming various radars [5], [6], the survivability of the current radars must be further improved or some novel platforms such as near-space platform need to be developed. Near-space platforms have extremely small radar cross section (RCS), making them relatively invulnerable to most traditional tracking and locating methods. Estimates of their RCS are as small as that of a bird [1], thus currently documented military radars are unable to find them. Moreover, at this altitude, the acquisition and tracking will be technical challenges even without considering what sort of weapon could reach them because few weapons are designed to engage a target with very low RCS including non-maneuvering ones. Even if the acquisition and location problems are overcome, near-space platforms are still difficult to destroy. The way they are manufactured has a lot to do with their relative invulnerability. Near-space balloons can be manufactured in two basic types: zero-pressure and super-pressure. Zeros-pressure ball-oon has a venting system that ensures the pressure inside the balloon is same as the surrounding atmos-phere. Super-pressure balloons are inflated and sealed, much like a child's toy helium balloon. Zero--pressure balloons are less vulnerable to puncture. Imaging an inflated, lightweight plastic garment bag used by dry-cleaners floating on the wind; even if there are many small holes in such balloon, it still can float in the air.

The last but not the least superiority is low cost. The near-space platforms can offer inherent cost advantages compared to the satellites, because they require only helium for lift and require no expensive space launch to reach its operating altitude. If there is malfunction in the payloads, they can be brought back and repaired. Not being exposed to the high levels of radiation common to the space environment, payloads flown in near-space require no costly space-hardening manufacture. Opera-ting in near-space obviously eliminates a great deal of expense involved in space sensor construction. Addition-ally, the infrastructure cost savings involved with near-space are huge. Near-space platforms require extremely minimal launch infrastructure. Only a simple tie-down and an empty field are required.

In summary, whilst the large imaging platforms such as the Spot and LandSat series provide an excellent source of imaging data that is widely used around the globe, such large costly spacecraft is not able to provide a cost-effective solution to the problem of temporal resolution. The low cost of small near-space platforms, however, allows the cost-effective use of multiple near-space platforms to provide a more rapid imaging revisit.

3. Configuration of Near-Space SAR

Near-space has several operational advantages, which can increase the capability, reliability and flexibility of future remote sensing missions. It shows much promise for different applications such as inverse SAR imaging, high-resolution and wide-swath imaging, and passive imaging. Each of these topics is considered in this section.

3.1 Near-Space ISAR Imaging

Most users require instant access to up-to-date SAR data. The revisit times of current spaceborne SAR sensors, ranging from several days to several weeks, will not suffice for important applications such as sea-ice monitoring and maritime services, risk and disaster management, traffic observation and security [7]. Inverse SAR (ISAR) has the potential for persistent regional coverage. ISAR is a version of SAR that can be used operationally to image the targets such as ships, aircrafts and space objects. The principles of ISAR imaging of the targets flying along a straight path with a constant velocity are basically the same as those of the general SAR. If one is interested in persistent regional coverage, the current ISAR platforms such as satellite, airplane, and ground are not able to provide a cost-effective solution to this problem. The low cost of near-space platforms, e.g., near-space balloons, can provide a persistent regional coverage.

Due to the unavoidable consequences of orbital mechanics, a satellite at other than GEO altitudes cannot remain within a specific region indefinitely. Even if one were able to launch a satellite on demand for a particular mission, it would only be in view of that commander for very short bursts of time a few times a day. Table I shows just how short these times would be for selected LEO orbits.

Table I: Pass times of LEO satellites.

orbital altitude(km)	maximum pass time (minutes: seconds)				
	angle above horizon (degrees)				
	0	5	10	30	45
200	7:49	5:37	4:08	1:40	1:00
300	9:35	7:16	5:34	2:24	1:27
400	11:10	8:44	6:54	3:08	1:54

In the case of near-space ISAR, the obvious excellence besides robust survivability, high sensitivity and low cost is the persistent regional coverage. Many of the near-space platforms in use by industry today as well as most envisioned systems are essentially variations on the lighter-than-air balloon theme. However, the majority of them are much more high-tech than the simple balloons people imagine. More importantly, the near-space platforms are above the storms and in a region where the prevailing winds are relatively benign. Therefore, not constrained by the orbital mechanics like satellites or the high fuel consumption rates like airplanes, many envisioned near-space systems could stay on the stations above a specified site almost indefinitely, providing persistent coverage of up to an 85-mile-diameter field of view on the ground. For these reasons, near-space ISAR can be seen as an ideal way to improve the capability and flexibility of persistent regional remote sensing at a reasonable cost.

3.2 High-Resolution and Wide-Swath Imaging

Future SAR will be required to produce high-resolution imagery over a wide area of surveillance. However, the minimum antenna area constraint makes it a contradiction to simultaneously obtain both unambiguous wide-area and high azimuth resolution. It is well known that, the SAR achieves its high spatial resolution in the range direction by utilizing wide-bandwidth transmitted pulses. With appropriate processing of the received pulse, the range resolution obtainable is

$$\rho_r = c/(2B_r \sin\eta) \quad (1)$$

where c, B_r and denote the speed of light, the frequency bandwidth of the transmitted pulse, and the incidence angle, respectively.

In the azimuth direction, high resolution is obtained by exploiting the relative motion between the target and the radar, which leads to target returns having a Doppler bandwidth. Azimuth resolution is related to the antenna length L_a by

$$\rho_a = L_a / 2 \quad (2)$$

The ground swath width W_s is decided by the antenna height W_a, which determines the vertical beamwidth, $\theta_v = \lambda / W_a$. If R is the slant range from radar to midswath, then there is [8]

$$W_s \approx \frac{\lambda R}{W_a \cos\eta} \quad (3)$$

As well as considerations of antenna beamwidth, the actual achievable resolution and swath for a SAR is subject to a number of restrictions imposed by various operating factors. The details can be found in [9]. A basic limitation is the minimum antenna area constraint, which can be represented by [8]

$$A_a = W_a L_a > 4 v_s \lambda R \tan(\eta) / c \quad (4)$$

where v_s is the velocity of SAR platforms. This requirement arises because the illuminated area of the ground must be restricted so that the radar does not receive ambiguous returns in range or/and Doppler. In this respect, a high operating pulse repetition frequency (PRF) is desirable to suppress azimuth ambiguity. But the magnitude of the operating PRF is limited by range ambiguity. This consideration can be combined into one inequality which expresses the range of slant range values that are appropriate to each of the unambiguous swath intervals

$$\left(\frac{n}{PRF} + \tau\right)\frac{c}{2} \le R \le \left(\frac{n+1}{PRF} - \tau\right)\frac{c}{2} \quad (5)$$

where n is an integer that effectively labels each swath interval, and τ is the pulse duration.

As noted previously, near-space SAR can operate in the region between 20km and 100km which is higher than that of a airplane but lower than that of a satellite, and can fly with a velocity of 1500m/s [1]. We can conclude from Eqs. (3) to (5) that, simultaneous high-resolution and wide-swath is more easier to achieve for near-space SAR than both spaceborne SAR and airborne SAR. Even so, the unambiguous swath width and the achievable azimuth resolution are still tough requirements on near-space SAR system design.

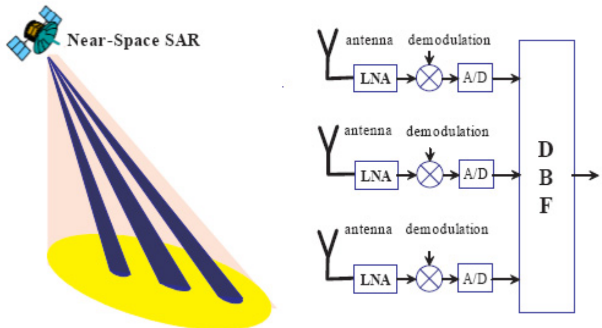

Fig. 1: High-resolution and wide-swath near-space SAR system

This limitation can be overcome by splitting the receiving antenna into multiple sub-apertures. A promising technique is the digital beamforming [10]. As shown in Fig. 1, each sub-aperture signal is separately amplified, down-converted and digitized. The digital signals are then combined in a dedicated processor to form multiple antenna beams with arbitrary shapes. This technique uses a dedicated small antenna to illuminate a large footprint on the ground. The scattered signal is then received by a large antenna array which allows for a combination of the displaced phase centre technique in azimuth with a variant beamsteering in elevation. The displaced phase centre technique can be used to gain additional samples along the synthetic aperture which enables an efficient suppression of azimuth ambiguities. Multiple beams in elevation allows for the simultaneous mapping of several distinct subswaths with high antenna gain. Each subswath can be mapped with a high PRF, which enables the use of short antennas to achieve high azimuth resolution. Residual range ambiguity could be suppressed by appropriate null-steering in elevation. Similarly, multiple beams in azimuth allows for the division of a broad Doppler spectrum into multiple narrowband subspectra with different Doppler centroids. A coherent combin-ation of the subspectra will then yield a broad Doppler spectrum for high azimuth resolution. In summary, the combination of near-space with digital beamforming enables a new generation of SAR systems with simultaneous high-resolution and wide-swath.

3.3 Near-Space Passive Imaging

For reasons of stealth and other operational advantages, more attention has been focused on bistatic SAR (BiSAR). As such, we proposed the concept of near-space passive BiSAR. The passive receiver is placed on near-space platform is teamed with a higher cost transmitter placed on satellite. This configuration is of interest as they oer two significant advantages over current spaceborne/airborne SARs. Firstly, the passive receiver is

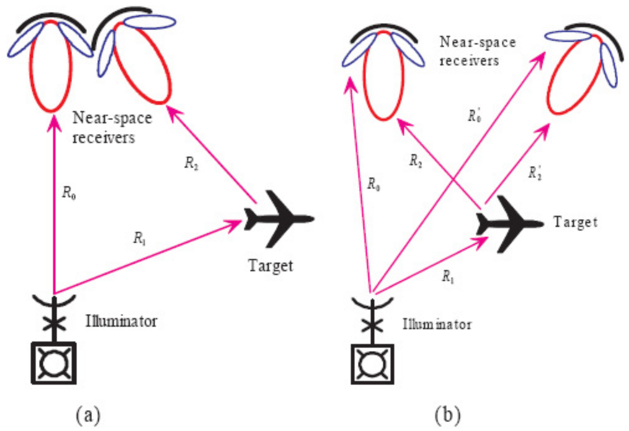

Fig. 2: Configurations of near-space passive imaging system

stealthy. Even where the illuminator (transmitter) is known, this operation can add to the stealth of aircraft. The second advantage is the counterstealth and survivability potential of bistatic radar. Thus near-space, particularly those with large bistatic angles, are likely to see an enhanced signature. Notice that, this configuration can use transmissions from multiple nearby signals of opportunity such as existing radars, communications, navigation and broadcast transmissions which are readily available, resulting in a multi-static SAR.

Another attractive configuration is a two-channel receiver configuration, as shown in Fig. 2(a). One channel is fixed to collect the signal arriving at the radar traveling directly from the illuminator. This signal can be used as the reference signal of matched filter. The second channel is configured to gather the scattered signal from the bearing along which the detection of targets is being attempted. Typically the signal scattered from a target is much weak than that in the direct-path signal, so unless the antenna linked to this receiver attenuates sufficiently in the direction towards the illuminator, the reflected channel will contain more energy from the direct-path signal than from the scattered signal. To get around this disadvantage, the use of array antennas is investigated in [11]. The second attracted configure-tion involves two or more receivers located far apart, as shown in Fig. 2(b), each using its independent antennas. In this configuration, each receiver performs its own matched filter using its received signal, the results of which can then be combined in some manner to provide a single estimate of the number of targets present, locations and velocities. It is important to note that, the configuration using only a single receiver is also feasible. In this case, the received signal would contain energy both from the direct-path signal and from the scattered signal. Once they are separated, successful matched filter can achieve.

However, these configurations will be subject to the problems and special requirements that are either not encountered or encountered in less serious form for current SARs. The biggest technological challenge lies in the synchronization of the receiver with non-cooperative illuminator: time synchronization, the receiver must precisely know when the illuminator fires; spatial synchronization, the receiving and transmitting antennas must simultaneously illuminate the same spot on the ground; phase synchronization, the receiver and illuminator must be coherent over extremely long periods of time. To obtain focused images, the phase information of the transmitted pulse has to be preserved. Consequently, oscillator phase noise deserves special attention in BiSAR systems [12], [13]. Some possible synchronization technique [14] have recently bee proposed for BiSAR. But it should be extended to near-space passive BiSAR with further work.

4. Conclusion

Inspired by the promise of near-space, this paper proposes the near-space SAR concept. Various near-space SAR configurations and their potential for different applications are investigated. It is shown that the use of cost effective, near-space platforms leads to the solutions previously thought to be out of reach for remote sensing scientists and customers. Issues have been highlighted, however there are clear paths of future work such as synchronization, motion compensation, signal detection, and flying formation available to overcome them. Although exploring the potential of near-space microwave remote sensing missions will take significant work on many fronts, we are indeed convinced the effort will be worth it.

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