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Azimuth Signal Processing for Near-Space High-Resolution and Wide-Swath SAR Imaging

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Abstract

Near-space defined as the space region between 20km and 100km can offer many capabilities that are not accessible for satellites and airplanes. By placing transmitter/receiver inside near-space platforms, many functions that are currently performed with satellites or airplanes could be performed much more cheaply and with greater operational unity. It appears that near-space can provide a satisfied solution to high-resolution and wide-swath (HRWS) SAR imaging. Inspired by these promising advantages, this paper describes the concept of near-space HRWS SAR for remote sensing applications. A multiple-beam based azimuth ambiguity suppression technique is presented. The system concepts, signal models, and correspond-ding azimuth signal processing algorithms are provided. An example near-space HRWS SAR system is conceptually designed.

1. Introduction

Near-space, defined as the space region between 20km and 100km [1] was too high for conventional aircrafts, but too low for low earth orbit (LEO) satellites. Once we step back from platform-based thinking and look at its effect, near-space will open a door to new air and space opportunities, which offers many new capabilities that are not accessible for current satellites and airplanes [2] for the following reasons [3]: Firstly, near-space is above the troposphere and atmosphere region where most weather occurs, so a high velocity can be achieved. Secondly, near-space sensors are inherently survivable, even if the acquisition and location problems are overcome, nears-pace assets are still difficult to be destroyed. The last but not the least is low cost. Near-space inherent simplicity and without space-hardening requirements all contribute to this strong advantage. Moreover, if they carried payloads have malfunction, they can be brought back and repaired. Thus, by placing radar sensors into near-space, many functions that are currently performed with satellites or airplanes could be performed much more cheaply.

Spaceborne SAR has an imaging capability of wide-swath but with a limited azimuth resolution. In contrast, airborne SAR has an imaging capability of high-resolution but with a limited swath coverage. There is therefore a clear incentive consideration to increase swath coverage and azimuth resolution simultaneously. Inspired by recent advances in near-space technology, this paper proposes the concept of near-space SAR to overcome the inherent limitations of conventional SAR to perform high-resolution and wide-swath (HRWS) imaging. To the author's knowledge, we are the first author that proposes the concept of near-space SAR for HRWS remote sensing applications. An azimuth ambiguity suppression technique is presented in this paper. The emphasis is placed on presentation of system concepts, signal models, and signal processing algorithms.

The remaining sections are organized as follows. Section 2 outlines the principle of near-space HRWS SAR with multi-beam in azimuth to further suppress azimuth ambiguities. Next, corresponding azimuth signal processing algorithm is detailed in Section 3, followed by an example design of near-space HRWS SAR in Section 5. Section 5 is the conclusion.

2. Near-Space HRWS SAR

Future SAR will be required to produce high-resolution imagery over a wide area of surveillance.

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However, minimum antenna area constraint makes it a contradiction to simultaneously obtain both un-ambiguous high azimuth resolution and wide-swath. This requirement arises because the illuminated ground area must be restricted so that the radar does not receive ambiguous echoes in range or/and azimuth. In this respect, a high operating pulse repeated frequency (PRF) is desired to suppress azimuth ambiguities. But the operating PRF is limited by range ambiguity.

To overcome inherent limitations of conventional SAR to perform HRWS imaging, several techniques using multiple receive apertures have been suggested in [4], [5]. However, the use of a quad-element array will become difficulty for high-resolution applications because of the need for synthesizing a number of apertures to cover a given swath coverage. As such, multi-beam in azimuth, as shown in Fig. 1, is used here. This arrangement enables correct sampling of azimuth spectrum with an PRF fitting the total antenna azimuth length, which is N times smaller than the PRF necessary for the antenna azimuth length. This configuration allows for division of a broad Doppler spectrum into multiple narrow subspectra with different centroids. Thereafter, a coherent combination of the subspectra will then yield a broad Doppler spectrum for high azimuth resolution. This technique is hence especially attractive for high-resolution near-space SAR that uses a long antenna for unambiguous wide-swath coverage.

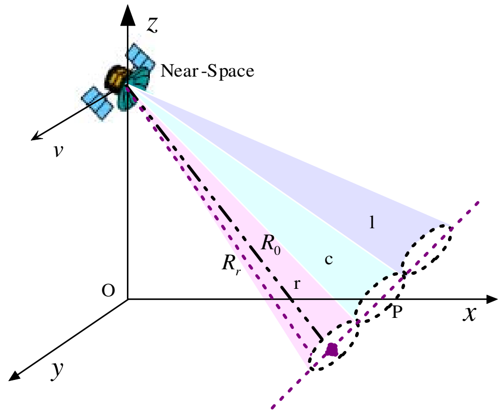

Fig. 1: Spatial model of near-space HRWS SAR

3. Azimuth Signal Processing

We can view the SAR shown in Fig. 1 as a conventional SAR (the central beam) operating with a PRF one third of that required to adequately sample its beam-width, together with additional two beams, on either side of the central one. For the left beam, its instantaneous slant range is term of the slow time μ is given by [6]

$$R_l(\mu) = \sqrt{R_0^2 + v_s^2\mu^2 - 2R_0 v_s \mu \sin(\theta_s)} \ , \qquad (1)$$

where R_0 , v_s and θ_s are the closest slant range, platform velocity and squint angle, respectively. The Doppler centroid frequency and azimuth bandwidth can be derived from Eq. (1), respectively, by

$$f_{dl} = \frac{2}{\lambda} v_s \sin(\theta_s), B_{dl} = \frac{2v_s \cos(\theta_s)}{L_{as}} \ , \qquad (2)$$

where L_{as} denotes the length of each beam antenna.

Similarly, for the central beam and right beam, we have

$$f_{dc} = 0, B_{dc} = \frac{2v_s}{L_{as}} \ , \qquad (3)$$

$$f_{dr} = -\frac{2}{\lambda} v_s \sin(\theta_s), B_{dr} = \frac{2v_s \cos(\theta_s)}{L_{as}} \ , \qquad (4)$$

Generally we have the following approximation

$$B_{dl} \approx B_{dc} \approx B_{dr} = B_{ds}, f_{dl} - f_{dc} = f_{dc} - f_{dr} = B_{ds} \ , \qquad (5)$$

The ambiguous Doppler spectrum can be recovered unambiguously by applying reconstruction filters. Some algorithms have been proposed by other authors [7]. Here, another algorithm is used. From the sampling theory we know that the sampled signal spectrum $X_s(f)$ is the sum of the unsampled signal spectrum, $X_0(f)$, that is repeated every sampling frequency f_s

$$X_s(f) = f_s \sum_{n=-\infty}^{\infty} X_0(f - nf_s) . \qquad (6)$$

If $f_s \geq 2B_{ds}$, the replicated spectra do not overlap, and original spectrum can be regenerated by chopping $X_s(f)$ off above $f_s/2$. Thus, $X_0(f)$ can be reproduced from $X_s(f)$ through an ideal low-pass filter that has a cutoff frequency of $f_s/2$. Subsequent data processing involves interpolating the data from each channel. We then have

$$y_s(n) = \begin{cases} x_s\left(\frac{n}{N_0}\right), n = 0, \pm N_0, \pm N, ... \\ 0, otherwise \end{cases} \qquad (7)$$

where N_0 is an interpolation scale.

Accordingly, the spectrum is represented by

$$Y_s(f) = \sum_{n=-\infty}^{\infty} y_s(n) e^{-j2\pi fn} = X_s(N_0 f) \qquad (8)$$

Then, the linear filters can be derived as

$$H_k(f) = \begin{cases} N_0, \left| f - \frac{f_{ck}}{N_0} \right| \le \frac{B_{ds}}{N_0}, i \in [-1,0,1] \\ 0, otherwise \end{cases} \quad (9)$$

where f_{ck} is the corresponding Doppler centroid.

Finally, the filtered signals can be combined coherently, as shown in Fig. 2. By this, the capability of ambiguity suppression allowing for improved resolution and an enlarged swath. Notice that, for optimum performance the relation between sensor velocity and the along-track offsets of the three sub-channels has to result in equally spaced effective phase centres. This results in a uniform sampling of the received signal. If a non-optimum PRF is chosen, the gathered samples will be spaced non-uniformly. This problem can be solved using the reconstruction algorithms detailed in [8].

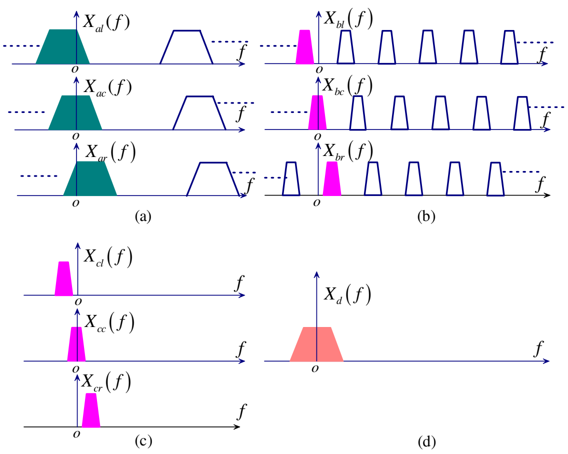

Fig. 2: Azimuth spectra synthesis for three channels.

3. Azimuth Signal Processing

A quantity directly related to the SAR processing is the noise equivalent sigma zero (NESZ) defined as the radar cross section for which the SNR is equal to 1 ($SNR = 0dB$). The NESZ can also be interpreted as the smallest target cross section which is detectable by the SAR system against thermal noise. From the radar equation we can get [9]

$$NESZ = \frac{8\pi R_s^3 v_s \lambda K T_{sys} F_n L_f}{P_{avg} N A_{as}^2 \rho_r} \quad (10)$$

where R_s is the slant range which can be assumed constant, $K = 1.38 \cdot 10^{-23}$ is the Boltzmann constant, T_{sys} is the system noise temperature, L_f is the loss factor, F_n is the receiver noise figure, P_{avg} is the average transmit power and ρ_r *is* the size of the range resolution cell for one look.

To further evaluate the quantitative performance of near-space HRWS SAR an example system is considered. The SAR operates in X-band with a center frequency of 10GHz. The geometric ground-range and azimuth resolution are set to $\rho_r = 0.2m$ and $\rho_a = 0.2m$, respectively. To calculate the system performance we assume that an overall loss factor $L_f = 3dB$, a fixed flying height of 60*km*, and a receiver noise figure of $F_n = 3dB$ are assumed. It is further assumed that the signal bandwidth is adjusted for varying angle of incidence such that the ground-range resolution is constant across the swath. The system performance is represented by the radiometric resolution of the SAR image given by the NESZ in Eq. (10). One possible system design is provided in Table I.

Table I: Performance of an example system

parameters	variables	values
transmit power	P_{avg}	10W
sub-array number	N	3
antenna length	L_{as}	1.2m
platform velocity	v_s	1000m/s
incidence angle	θ_s	70^o
antenna width	H_a	0.2m
swath width	W_s	$76.94km$
radiometric resolution	NESZ	$-37.11dB$
incidence angle	θ_s	75^o
antenna width	H_a	0.33m
swath width	W_s	$81.43km$
radiometric resolution	NESZ	$-37.83dB$
incidence angle	θ_s	80^o
antenna width	H_a	0.7m
swath width	W_s	$85.28km$
radiometric resolution	NESZ	$-39.16dB$

We can notice that, for the incidence angle given in Table I the swath ranges from $75-85km$ and the NESZ is approximately $-37dB$. These results show that a comparable performance improvement to current SAR systems, however with only a small number of antenna beams, and a total antenna size not larger than that of current systems. An important conclusion is the unambiguous range and swath width can be increased using a near-space SAR with multiple beams in azimuth. But, some additional means of inter-beam suppression should be provided. One possible technique is the use of waveform diversity to provide some cross-cancellation of data in different channels [10]. Another disadvantage of near-space maneuvering vehicles as sensor platforms is the limited payload weight.

3. Conclusion

Near-space offers a significant new remote sensing opportunity and is a key remote sensing resource. Inspired by recent advances in near-space, this paper proposes firstly the concept of near-space SAR for HRWS imaging. The novelty of this concept resides in the sensor platform. It is shown that, the use of cost effective near-space platforms can provide the solutions that previously thought to be out of reach for remote sensing and government customers. A promising issue is that the cost-efficient near-space platforms allow for many novel configurations of bi- or multi-static SAR systems for future cooperative imaging. Practically near-space can provide many novel applications such as passive imaging, sparse arrays imaging, and even MIMO SAR imaging [11]. However, there are several technical challenges available to be overcome. The first technological challenge is motion compensation. As a matter of fact, problems arise due to the presence of atmospheric turbulence, which introduce trajectory deviations from nominal position, as well as altitude (roll, pitch, and yaw angles) [12]. For current SAR systems, the motion compensation is usually achieved with GPS (Global Position Systems) and INU (Inertial Navigation Units). However, for near-space SAR the motion measurement facilities may be not reachable, so some new efficient motion compensation techniques should be developed. We think that raw data-based autofocus algorithms may be the best choice. Another technical challenge lies in required synchronization between transmitters and receivers, which includes spatial, time and phase synchroni-zation. Although achieving the potential of near-space for remote sensing applications requires significant work and progress on many fronts, we are indeed convinced the effort will be worth it.

Acknowledgements

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