Design of SmallSat SAR for Dedicated New Zealand Applications

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Abstract

Spaceborne Synthetic Aperture Radar (SAR) is a proven technology for remote sensing of the surface of the Earth and is used for a variety of applications. However, conventional SAR satellites are large, heavy, and expensive, preventing the formation of large constellations, which are desirable to reduce the time between acquisitions of a particular area on the ground. To reduce the costs typically associated with spaceborne SAR platforms, it is proposed to design a SAR system for use on a small satellite platform. This small-satellite SAR system is designed around two specific scenarios: detection of fishing vessels in the New Zealand Exclusive Economic Zone (EEZ), and interferometric measurements of deformations of New Zealand's land surface. It is shown that the performance limitations of small-satellite SAR systems—mainly high ambiguity levels and low radiometric sensitivity—can still be tolerated for the targeted applications. The sparse nature of ships on the ocean and of point-like scatterers in Persistent Scatterer Interferometry (PSI) can be exploited to resolve ambiguities, and to distinguish targets from the noisy background. The proposed SmallSat SAR system is developed within the framework of a recently initiated collaboration between the German Aerospace Center (DLR), the New Zealand Space Agency (NZSA), and the University of Auckland.

1 Introduction

New Zealand (NZ) is an island nation in the southern Pacific Ocean, and is surrounded by a large Exclusive Economic Zone (EEZ) of approximately 4 Million km^2 [1]. Its extent relative to the New Zealand mainland is shown in **Figure 1**. Illegal, Unreported and Unregulated (IUU) fishing in New Zealand's EEZ is causing considerable damage to New Zealand's marine ecosystem and the fishing industry [2] Currently, IUU fishing vessels in the NZ EEZ are monitored by patrol ships and sporadic flights by the New Zealand Defense Forces. However, the coverage achieved by these means is not satisfactory, which opens the case for spaceborne remote sensing. Another geographic feature of New Zealand is its location on the *Pacific Ring of Fire*. This belt around the Pacific Ocean is known for its high tectonic and volcanic activity, causing earthquakes and volcanic eruptions. It is also desirable to monitor by spaceborne means deformations to the land surface of New Zealand caused by tectonic shifts and earthquakes.

Synthetic Aperture Radar (SAR) is an attractive solution to both of these applications, as it is capable of achieving regular coverage independent of weather conditions. Regular revisit times of less than 24 hours are desirable for monitoring IUU vessels In order to achieve that, the number of satellites could be increased to form a constellation. It is proposed to use small satellite (SmallSat) platforms to make up the satellite constellation in order to keep the total costs acceptable. Each satellite shall contain a fully functional SAR system optimized for the given applications.

The goal of this research project is to determine whether such a dedicated SmallSat system is feasible in principle.

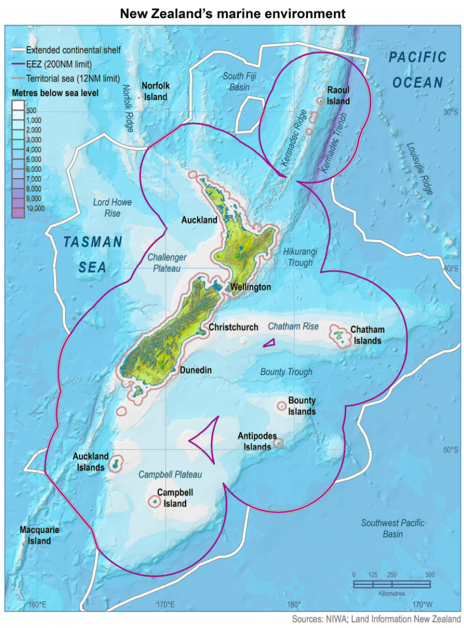

Figure 1 New Zealand EEZ outlined in red, from [1].

To that end, the minimum requirements on image quality that a SmallSat-SAR system has to fulfill in order for ship targets to still be detectable are investigated. Specifically, SAR images of the sea were simulated with varying Signal-to-Noise Ratio (SNR) and resolution to investigate what image quality is required to achieve suitable values for the probability of detection and Probability of False Alarm (PFA). Using SmallSat SAR for the purpose of measuring tectonic deformations has not been explored in detail yet, but some preliminary concepts will be presented.

This novel SmallSat SAR system is being developed within the framework of a collaboration between the German Aerospace Center (DLR) and the New Zealand Space Agency (NZSA). A letter of intent was signed at the International Astronautical Congress (IAC) in October 2018 in Bremen to initiate the partnership between the two institutions. The first author of this paper is currently undertaking PhD research with the University of Auckland, which is one of several research institutions throughout New Zealand sharing the technical-scientific responsibilities of the NZSA. The work presented here is the result of a six-month research visit at the DLR Microwaves and Radar Institute.

The outline of the paper is as follows. The two intended imaging scenarios and the resulting requirements are described in Section 2, before Section 3 reviews the reasons for why building a SmallSat SAR presents a challenge. Section 4 explains the analysis undertaken to assess a SmallSat's suitability for ship detection. Subsequently, Section 5 gives an overview of how SmallSat's could be used to measure surface deformations, before Section 6 presents conclusions and provides an outlook on further work in this project.

2 Applications

This section will briefly explain the intended imaging scenarios, and the expected operating conditions for the proposed SAR system.

2.1 Detecting Ships at Sea

Modern fishing vessels have a maximum length of 140 m, with typical dimensions being 70 m × 13 m in length and width [3]. The minimum length of the ships of interest is assumed as 30 m. The principle concept is to correlate ships detected in SAR images with data obtained by the Automatic Identification System (AIS), similar to previous large-scale SAR platforms [4]. If ships are detected by SAR but do not appear in AIS, they will be suspected of being engaged in illegal activities, and a patrol ship or aircraft is deployed to investigate further.

Due to the ships' motion and the possible irregularity of illegal activities, it is desirable to acquire images of any given area within the EEZ at regular intervals, ideally less than 24 hours. However, given that current monitoring of IUU activities around New Zealand is almost non-existent, detecting only one in every two ships (meaning a probability of detection of 0.5) would already be satisfactory. The PFA should be low in order to minimize the risk of resources (e.g., deploying navy vessels) being wasted. A PFA of 1×10^{-10} would lead to two false per whole coverage of the NZ EEZ, which is deemed acceptable.

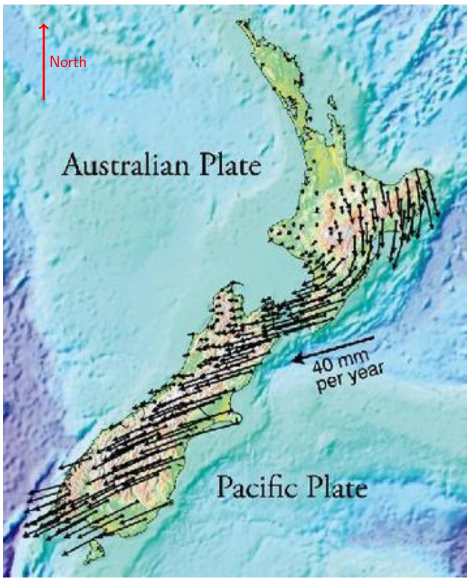

Figure 2 Tectonic motion of New Zealand's land surface; from [5].

2.2 Measuring Deformations of Land Surfaces

The tectonic movements of New Zealand's land surface are indicated in **Figure 2**. It can be seen that the surface of the South Island and the southern North Island are slowly drifting in a south-western direction. Other parts of the surface move slower or not at all. The maximum velocity of surface motion is approximately 40 mm per year [5]. Due to the high strains caused by these movements, earthquakes are a common occurrence in New Zealand.

Ideally the proposed SmallSat SAR system should also be capable of measuring the deformations caused by these surface motions.

3 Limitations of SmallSat-SAR

The design of SAR systems for small satellite platforms is complicated by the fact that small antennas are typically associated with a non-satisfactory SAR performance. Specifically, the performance of small SAR antennas in terms of

1. radiometric sensitivity;
2. ambiguity levels;

is worse than larger, conventional antennas [6]. These limitations are connected directly to the smaller antenna size, and partially to the limited onboard resources of SmallSat platforms.

The radiometric sensitivity is reduced due to the lower gain associated with reduced antenna aperture [6]. Additionally, the transmit power available on SmallSat platforms is limited, reducing the SNR and lowering the radiometric sensitivity [7]. The Azimuth Ambiguity-to-Signal Ratio (AASR), Range Ambiguity-to-Signal Ratio (RASR), azimuth resolution Δx and swath width W_s are interrelated

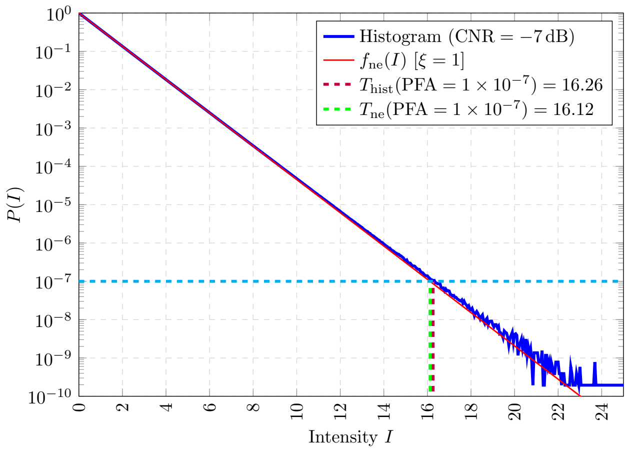

Figure 3 Monte-Carlo simulation for CNR $= -7$ dB using 1×10^{11} simulated pixels. The normalized histogram of the pixel values obtained in the simulation is shown along with the Probability Density Function of the exponential distribution $f_{ne}(I)$ for $\xi = 1$, where ξ is the rate parameter. The clutter is modelled as a Γ-distributed Random Variable with a texture parameter equal to 1.

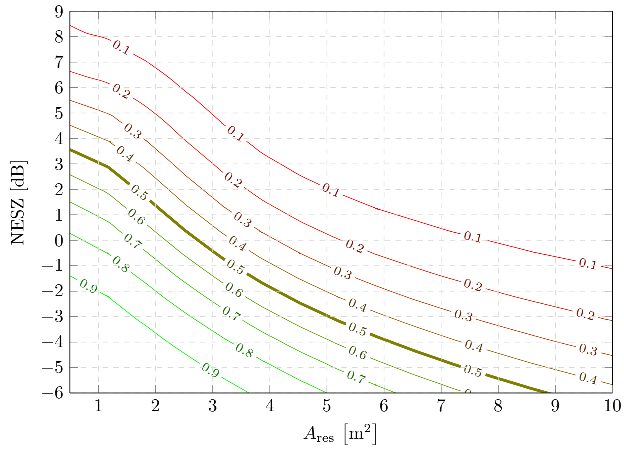

Figure 4 Contours for probability of detection P_d as a function of the area of the resolution cell A_{res} and the NESZ. A system is considered to comply with design requirements if it achieves $P_d \geq 0.5$; this contour is shown in bold.

through the fundamental SAR constraint

$$\frac{W_s}{\Delta x} < \frac{c}{2v} \quad , \tag{1}$$

where c is the speed of light, and v is the platform velocity [6].

The following sections explore under what circumstances the performance limitations of SmallSat SAR can meet the requirements of ship detection and surface deformation measurements.

4 Ship Detection

SAR images of ship targets on the ocean surface were simulated in order to derive requirements on the image quality necessary to detect ship targets. To that end, the simplifying assumption that the image background is completely dominated by noise was made. Thus, the influence of the sea clutter can be neglected. The assumption is justified by the fact that for realistic system designs the Clutter-to-Noise Ratio (CNR) is expected to be on the order of -7 dB and below. Figure 3 shows that when the CNR is -7 dB and the texture parameter of the Γ-distributed is equal to one (corresponding to a spiky clutter distribution), the simulated clutter distribution is equal to the negative exponential distribution, which is the distribution of pure Gaussian noise in the intensity domain.

Under this assumption, Monte-Carlo (MC) simulations of ship targets measuring 30 m × 7 m in noisy SAR images were implemented, and the probability of detection was determined for varying resolution and Noise-Equivalent Sigma Zero (NESZ). The Constant False Alarm Rate (CFAR)-threshold was selected to yield a PFA of 1×10^{-10} on object level[1]. A contour plot of the probability of detection over the size of the resolution cell is shown in Fig. 4.

Table 1 System Design Parameters

Parameter	Symbol	Value	Units
Average transmit power	P_{avg}	15	W
Wavelength	λ	0.03	m
Antenna length	L_a	4	m
Antenna width	W_a	0.83	m
Antenna gain	G	46.66	dB
Look angle	γ	40	°
Orbit height	H	500	km
Satellite velocity	v	7100	m s^{-1}
Noise temperature	T_s	300	K
Noise figure	F	5	dB
System losses	L	5	dB
Rx bandwidth	B_r	100 & 140	MHz

Fig. 4 shows that to achieve a probability of detection of at least 0.5, a NESZ of more than -5.5 dB is sufficient if the resolution cell is 10 m^2 or less.

The relationship between maximum NESZ and resolution cell area can be translated into an initial SAR system design. Consider the system parameters shown in Tab. 1 A system with such a configuration could reasonably be implemented on a typical SmallSat platform. Figure 5 shows the NESZ corresponding to these system parameters plotted over the ground range. It can be seen that the image requirements are fulfilled for both bandwidths over a swath width of almost 30 km.

5 Deformation Monitoring

The low SNR of SmallSat SAR limits the applications of such systems for Earth observation, e.g. deformation monitoring. However, Persistent Scatterer Interferometry (PSI) could be used to address the issue of limited radiometric

[1]The detection algorithm used for these simulations uses regular CFAR-thresholding followed by a simple clustering algorithm in order to detect entire targets rather than individual pixels

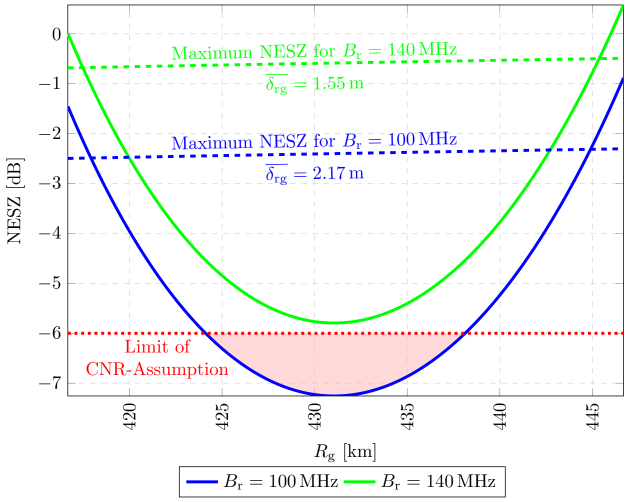

Figure 5 NESZ versus ground range for system parameters shown in Tab. 1 and two different bandwidths ($B_r = 100$ MHz and 140 MHz; the corresponding mean range resolutions are $\overline{\delta_{rg}} = 2.17$ m and 1.55 m). The required NESZ (dashed lines) for each bandwidth correspond to $P_d = 0.5$ and $P_{FA,\,goal} = 1 \times 10^{-10}$. The plot shows the NESZ within the 3 dB beamwidth of the antenna beam on the ground. The shaded area indicates NESZ values which do not comply with the assumption that noise is dominating over sea clutter.

sensitivity of SmallSat SAR systems for the application in surface deformation measurements. PSI uses highly persistent point-like scatterers in the imaged scene for interferometric measurements [8], and was proposed to circumvent the issue of reduced coherence between subsequent images for interferometric deformation measurements. It is particularly relevant for a SmallSat SAR with low radiometric sensitivity that the naturally occurring point-like scatterers are potentially much brighter than the noise-floor. The coverage and spatial resolution of the deformation measurements depend on the amount of available point-like scatterers used for PSI, and their locations. Artificial scatterers with high Radar Cross-Section (RCS), such as corner reflectors, could be used to enhance the coverage resolution of the measurements [9].

To address ambiguities, the Pulse Repetition Frequency (PRF) can be varied between subsequent acquisitions. In this way, the bright returns caused by the persistent scatterers will remain at the same locations in each acquisition, whereas ambiguities shift locations and can thus be filtered out. An additional way of mitigating the impact of ambiguities for both the ship detection application and the surface deformation measurements is to defocus and smear ambiguities by employing waveform diversity as presented in [10].

6 Conclusions

This paper presents ideas for how a SmallSat SAR system could be enabled by exploiting the peculiarities of specific application scenarios. The two scenarios presented are detecting illegal fishing vessels in the New Zealand EEZ, and measuring deformations of New Zealand's land surface using PSI. Both applications make use of a sparse scatterer distribution.

The proposed SmallSat SAR mission presented in this paper will serve the public interest of New Zealand by protecting economic and environmental resources through the detection of vessels fishing illegally in the New Zealand EEZ. Additionally, the mission will facilitate geophysical surveying of New Zealand by measuring deformations of its land surface.

Future work will focus on a more detailed system design, and on investigating whether the assumptions made for the ship detection scenario are also valid for the surface deformation measurements. Various methods of improving the system performance will be considered. For example, given that short revisit times are crucial for maritime surveillance, a concept of operations for a constellation of small satellites will be explored.

Due to the limited experience with the development of satellite (and especially SAR) systems in New Zealand, the NZSA and the University of Auckland collaborate with the DLR in Oberpfaffenhofen, Germany. The DLR holds a leading position in the development of SAR systems, thanks to the highly successful TanDEM-X mission and the innovative Tandem-L proposal [11]. New Zealand will benefit from the cooperation by drawing from DLR's extended knowledge and experience on SAR technology, whereas DLR will gain by being able to implement new ideas (developed in cooperation with the University of Auckland) with the support of another research organization.

7 Literature

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