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Preserving natural ecosystems: atolls observed by partially polarimetric SAR satellite imagery

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***Abstract* – In this study, the potential of dual-polarimetric (DP) Synthetic Aperture Radar (SAR) data to observe atolls is addressed. The partial polarimetric information is exploited to both define the coastal profile and to classify the observed area. Experiments are undertaken on a fine resolution DP L-band ALOS PALSAR-2 SAR scene collected under horizontal linear polarization transmission over the Goidhoo Atoll belonging to the Maldivian Baa Atoll, that was selected as test site due its importance for the local ecosystem and the extraordinary value of its biodiversity.**

Preliminary results show that partial polarimetric information can be exploited for atoll observation purposes, including the coastline extraction and the classification of the observed scene.

I. INTRODUCTION

Climate change is an important topic to be addressed but two main issues must be considered. First, is there a simple way to predict climate change ? Second, are economic growth and climate change irredeemably in contrast ? We hereafter focus on the first key question.

In fact, while climatologists agree that the meteorological effects of climate change cannot be adequately predicted for many areas, there is a general consensus that any further global warming will bring with it a further sea-level rise. Since, atolls are among islands with the lowest elevation monitoring and, therefore, atolls are effective proxy of climate change.

An atoll is generally a ring-shaped coral reef, island or series of islets that surrounds a body of water called lagoon. Since reef building corals thrive only in warm waters, atolls are only found at tropical and sub-tropical latitudes, i. e., most of the atolls are located in the Pacific and Indian Oceans. Among the most relevant atolls archipelagos there is the Republic of Maldives, which is made by 26 atolls. It stretches from Ihavandhippolhu Atoll in the north to Addu Atoll in the south. The average ground-level elevation is 1.5 m and the highest natural peak is one of the lowest in the world being 5.1 m. Every Maldivian atoll is formed by a marginal rim surrounding a lagoon commonly 40-60 m deep and interrupted by deep channels, which lead to strong water circulation inside the lagoon, encouraging the development of many patch reefs [1]. Atolls and their associated rim reefs, lagoons and lagoon reefs vary tremendously in their formation, size and physical setting. The atoll rim can be continuous (ribbon reefs) without gaps for tens of kilometers or discontinuous with reefs of different shapes (cuspate, prong, circular, elongated). The Maldivian government has recognized the value of coral reefs and has established 35 marine protected areas since 1995. However, most of the Maldivian atolls are more than 1000 km^2 large, making their in-situ monitoring quite costly. Hence, remote sensing plays a key role for a systematic monitoring. In particular, the Synthetic Aperture Radar (SAR) is a very suitable sensor to observe atolls since it provides routinely images independently of the solar illumination and in almost any weather condition with fine spatial resolution and dense temporal resolution. However, to the best of our knowledge, very few studies focused on the exploitation of SAR data to observe atolls [2, 3].

Hence, in this study, a preliminary investigation on the capability of fine resolution polarimetric SAR imagery to monitor atolls is undertaken, considering the Baa atoll (Republic of Maldives) as a test site. In detail, two issues are addressed in this study: i) the extraction of the atoll's coastline and ii) the atoll classification, with the aim of showing the added-value of partial polarimetric SAR measurements in fulfilling both the tasks.

II. TEST SITE

The Indian Ocean Baa Atoll system (Republic of Maldives) consists of three different natural atolls: Maalhosmadulu Atoll, Fasduthere Atoll and Goidhoo Atoll that, altogether, counts up to 75 islands (see Figure 1). The Baa Atoll, declared as UNESCO heritage and world biosphere reserve due to its biodiversity richness, is 38 km wide and 46 km long, covering an area of approximately 1127 km^2. It includes 105 coral reef ecosystems for a total reef area of 263 km^2 [4]. Most of the atoll is composed by vegetated and sandy inhabited islands whose bathymetry is characterized by atoll rim passages which are usually 35 m - 56 m deep and an average lagoon depth that spans from 30 m up to 50 m [4]. A micro-tidal regime applies with a spring tide range of about 1.2 m [4]. The Baa atoll calls for wind conditions characterized by moderate winds (5.0 m/s, on average) blowing from south- to north-west during summer/autumn and east northeast during winter/spring.

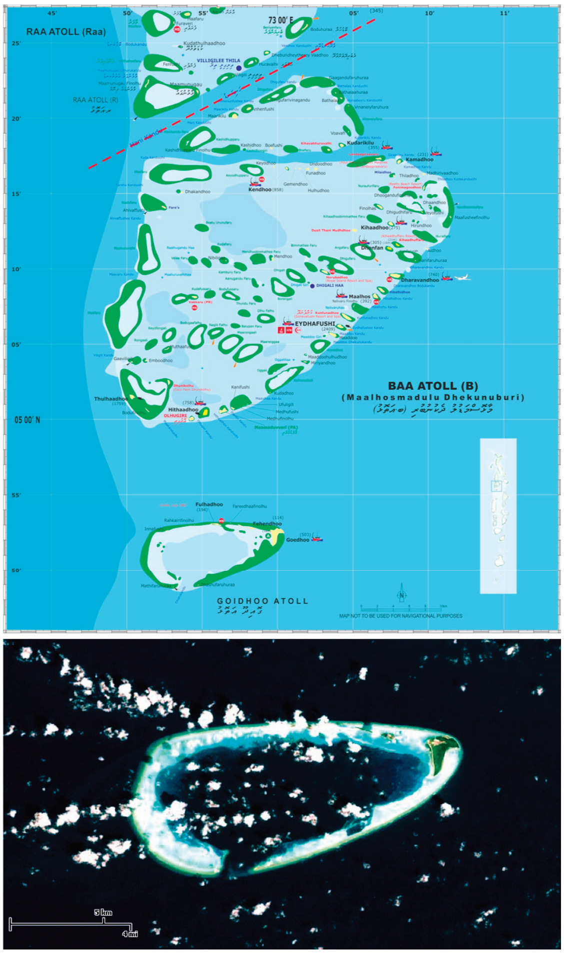

Fig. 1. Maldivian Baa Atoll archipelago. Top: the Baa Atoll system (Photo Credit: Baa Atoll). Down: Landsat 8 satellite optical image of the Goidhoo Atoll.

Due to its location with respect to other atolls, the Baa Atoll is exposed to ocean swell along its western and south-western boundaries [4, 5].

In this study, the Goidhoo Atoll, that consists of Goidhoo, Fehendhoo and Fulhadhoo islands, is observed that belongs to the administrative atoll of Baa [5]. Although on the Goidhoo Atoll there is intensive agriculture activity mainly growing water melon, pumpkin and bilimbi along with a mangrove system [5], the anthropogenic activities have generated no disturbance [6]. Of course, the marine biodiversity is outstanding all over the Maldives although the reef corals were severely impacted by the El Nino southern oscillator event [5]. Associated to the environmental protection the Baa Atoll is also a good example of green/blue economy since the ruled economic activities appear to be sustainable with the ecosystem.

III. METHODOLOGY

In this section, the methodology considered to monitor atolls by means of dual-polarimetric (DP) SAR satellite measurements is briefly revised. It must be underlined how the partial polarimetric information was already successfully exploited for several environmental applications including sea surface observation, inland water body monitoring, and shoreline rotation analysis [7]-[9]

The approach consists of two steps: i) coastline extraction and ii) scene classification.The coastline is extracted according to a two-step approach where the land/sea contrast is first enhanced using a DP parameter that relies on the joint use of co- and cross-polarized channels [7]:

$$r = \langle |S_{xx}||S_{xy}| \rangle \tag{1}$$

where x, y can assume the meaning of horizontal (H) or vertical (V) polarization, while $|\cdot|$ and $\langle\cdot\rangle$ stand for modulus and ensemble average, respectively. In [7] it was already shown that the r parameter is effective and robust to separate land from sea areas, better than single-polarization intensity backscattering signals that, in complex atoll environment (sandy beaches, mangroves, lagoons, etc.) may result in unsatisfactory land/sea discrimination capability. Then, a global-threshold constant false alarm rate (CFAR) approach in combination with an edge detector based on a Sobel kernel is applied to provide a binary image from which the land/sea boundary is detected. The parameter r is assumed to follow a Rayleigh distribution over the sea surface [7].

The scene classification is based on the extra-information provided by DP SAR information from which, at least partly, [10] rough information of the scattering process can be inferred. Among the different polarimetric SAR-based classifiers, the coherent polarimetric decomposition theory is here considered that was shown to be effective even in complex scenarios [11, 12]. In detail, the DP entropy/mean scattering angle classification scheme is adopted which is based on the eigen-decomposition of the 2×2 covariance matrix [10]. Although DP SAR provides partial polarimetric information with respect to full-polarimetric SAR, this DP decomposition can be still exploited to perform a rough classification of the observed scene based on the analysis of the dominant scattering mechanisms, especially when the scattering scene does not call for a large degree of randomness. The classification process is basically based on the pixels partitioning in the 9-zones $H/\bar{\alpha}$ plane according to their mean entropy and mean scattering angle values and in the subsequent clustering performed according to the minimization of the Wishart distance between the classes [10], see Figure 2 where the conventional scattering-based partitioning of the $H/\bar{\alpha}$ plane proposed for quad-polarimetric SAR data is shown [13].

Entropy H can be interpreted as a measure of the random-

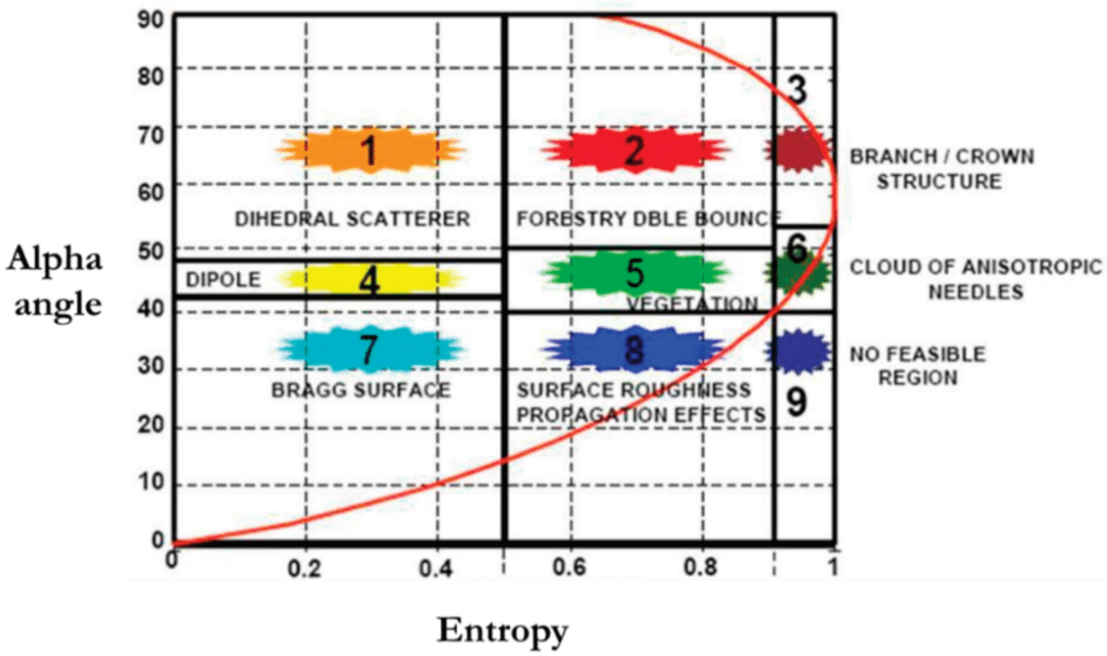

Fig. 2. H-$\bar{\alpha}$ plane for scattering-based classification purposes.

ness of the scattering process:

$$H = -\sum_{i=1}^{2} p_i \log_2 p_i \quad , \quad p_i = \frac{\lambda_i}{\sum_{j=1}^{2} \lambda_j} \tag{2}$$

where λ_i is the i-th eigenvalue of the 2×2 covariance matrix.
The mean scattering angle $\bar{\alpha}$ provides information on the average angle from which the signal is backscattered off the target:

$$\bar{\alpha} = p_1\alpha_1 + p_2\alpha_2 \tag{3}$$

where the α_i is the angle corresponding to the i-th eigenvector of covariance matrix. The joint analysis of H-$\bar{\alpha}$ allows extracting rough information on the scattering mechanisms that rules the observed scene and that can be used for classification purposes.

IV. EXPERIMENTS

In this section, experiments undertaken over the Goidhoo Atoll using a DP HH+HV ALOS PALSAR-2 SAR scene are presented to investigate the potential role played by partial polarimetric information in supporting the monitor of atolls from space. The SAR acquisition was collected at L-band on 14 January 2018, in ascending pass, with an incidence angle of about 35° and a very fine spatial resolution of approximately 4 m in both range and azimuth directions.
The HH- and HV polarized intensity images are shown, in dB scale, in Figure 3. It can be noted that the 3 islands of the Goidhoo Atoll call for a larger backscattering in both channels with respect to the surrounding sea. The backscattering intensity over land is very similar in both polarization witnessing the complexity of the scattering scenario, while ocean backscattering, being dominated by Bragg/tilted Bragg mechanisms, calls for co-pol backscattering intensity larger than the cross-pol one. In addition, it can be noted a ring-shaped ocean feature which is likely due to surface waves refraction and shoaling in shallow water near the atoll related to coral reef bathymetry [2]. Results relevant to the coastal profile detection was also shown in Figure 3, where the extracted coastline (a false alarm probability of 10^{-6} was set) is depicted in red and overlaid on the r parameter image. Zoom-in images for Fehendhoo and Goidhoo islands demonstrate the soundness of the proposed methodology, i. e., the extracted coastline well-fits the actual coastal profile very well and it is not severely influenced by false coastlines induced by the presence of the coral reef except for the north-eastern part of the Goidhoo island where a finer tuning of the algorithm should be needed to improve the performance.
Then, the second issue is addressed that consists of classifying the atoll according to the scattering information. Focus is made on the Goidhoo island since it is characterized by a more heterogeneous environments made by buildings, mangroves, sparse vegetation, crops and coral reefs. The classification output is shown in Figure 4, where, according to the conventional $H/\bar{\alpha}$ plane scheme, the following color-code is adopted: dark purple, purple and vio-

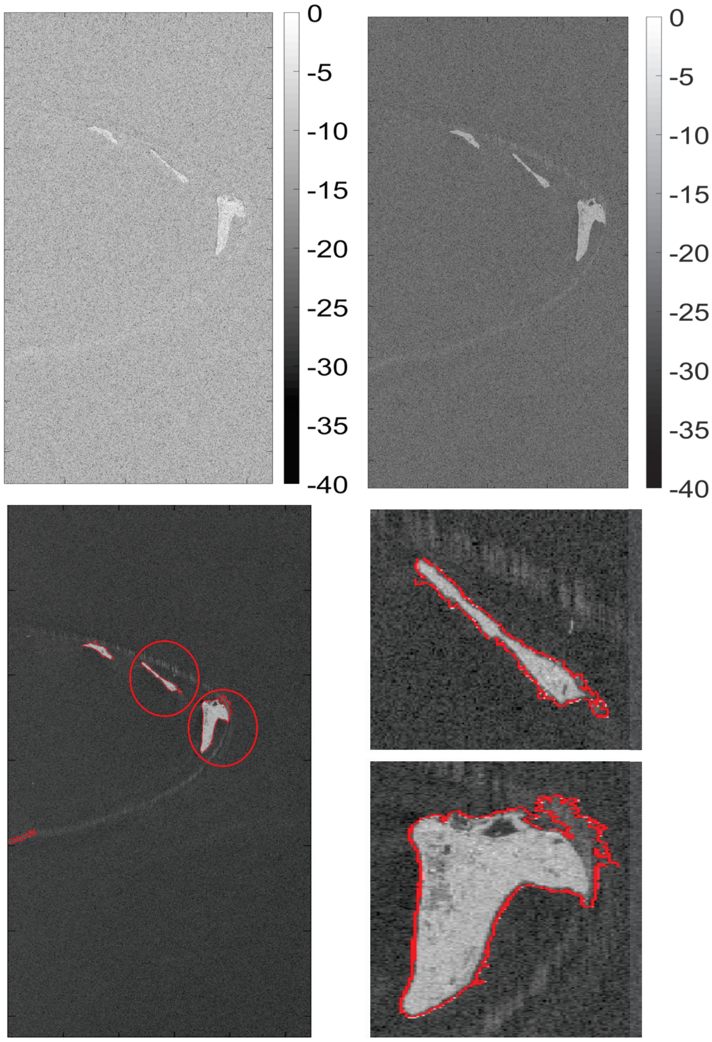

Fig. 3. Coastline extraction results. Top: DP (HH and HV) intensity SAR images (dB) of the Goidhoo Atoll. Down: Extracted coastline, in red, overlaid on the r image, with zoom-in images relevant to the Fehendhoo and Goidhoo islands.

let mean a dominant complex structure, dihedral reflector and random surface, respectively; blue, green and light green mean a dominant Bragg surface, anisotropic particles and double reflection, respectively; while gray and yellow mean a dominant dipole and random anisotropic scattering, respectively. Hence, it can be noted that the main scattering classes obtained from the H-$\bar{\alpha}$ decomposition are Bragg and random surfaces over the ocean and double-bounce, complex structures and anisotropic particles over land. By visually inspecting Figure 4, even with the support of optical imagery, it can be noted that the proposed approach is able to at least roughly identify: 1) the ocean/lagoon scattering signature including the coral reef/sea boundary; 2) the presence of sparse vegetation; 3) sandy beaches and small urban settlements.

V. CONCLUSIONS

In this study, partial (HH+HV) polarimetric SAR information is exploited to observe the Goidhoo Atoll within the Baa Atoll archipelago (Republic of Maldives). Two different algorithms have been applied on an L-band ALOS PALSAR-2 SAR scene to: i) extract the coastal profile according to the r parameter and ii) classify the atoll area according to the $H/\bar{\alpha}$ decomposition.

Preliminary results demonstrate the soundness of the proposed approach, witnessing the potential role played by DP SAR satellites in monitoring atolls. Future work will include the exploitation of available ancillary information and ground truth measurements to support the interpretation of the preliminary results.

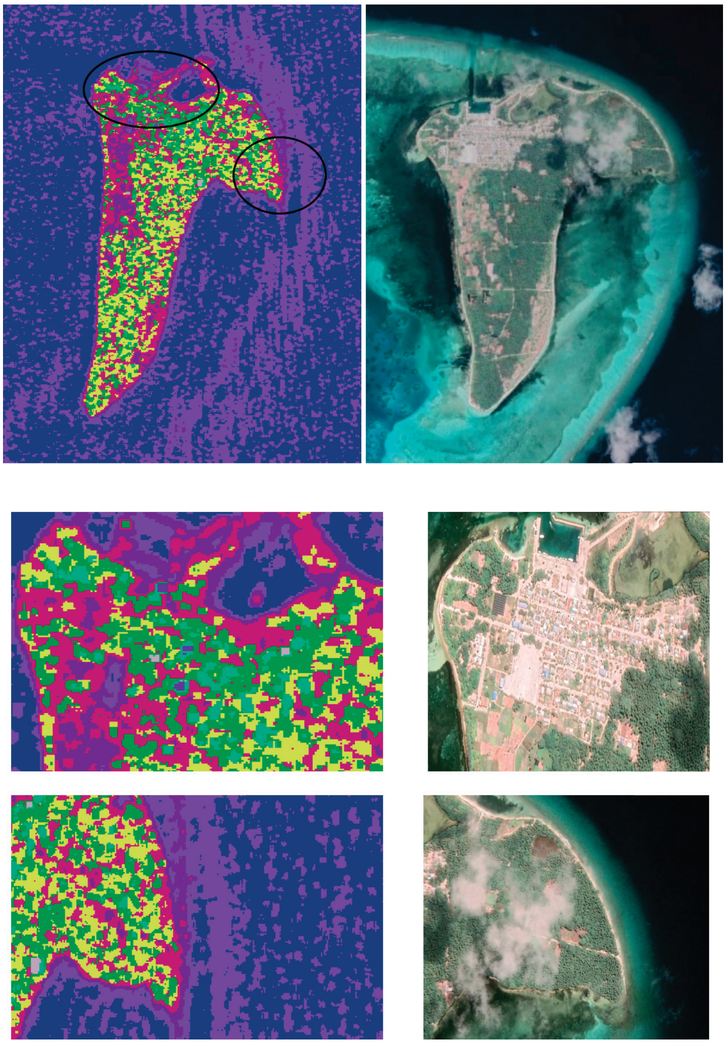

Fig. 4. Classification results. DP H-$\bar{\alpha}$ output over the Goidhoo island with corresponding Google Earth© optical images shown for reference purposes.

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