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Armando Marino

A New Target Detector Based on Geometrical Perturbation Filters for Polarimetric Synthetic Aperture Radar (POL-SAR)

Doctoral Thesis accepted by
The University of Edinburgh, UK

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I would like to dedicate this thesis to my grandfather, Armando Marino, with whom I share not only his name, but also very nice moments of our lifes

Supervisor's Foreword

To both detect and identify objects remotely has always been a key driver in remote sensing research, ever since the first airborne photographs. In the twentieth century, radar technology made available a whole new domain of target identification, namely the active sensing of objects with polarimetric radio waves. And when such systems made their way into Earth orbit in the 1970s, the world was then open to new possibilities of mapping and surveillance. This thesis is concerned with microwave observations using polarimetric SAR (Synthetic Aperture Radar) imaging techniques. The oft cited advantages of microwave imaging are its capability to supply useful images in almost any weather conditions and at night time, but if long enough wavelengths are used it also has the capacity to penetrate foliage.

The focus of the methods described in this thesis is on polarimetry, since a target illuminated by polarized waves generally scatters the incoming electromagnetic radiation with a different (and sometimes unique) polarization. This property makes polarimetry an invaluable tool to perform target detection/classification. In the last decade, the community has become increasingly aware of the importance of SAR polarimetry and this has led to even more satellite systems able to acquire this type of data, including ALOS-PALSAR, RADARSAT-2 and TerraSAR-X. The availability of polarimetric modes (at least dual polarisation) in now standard on most of the future radar satellite missions.

This thesis presents a groundbreaking methodology for radar target detection. The detection approach introduced, "Perturbation Analysis", was completely novel and demonstrated a step change in the approach to interpreting polarimetric data. Perturbation Analysis was able to push the performance limits of current algorithms, allowing for the detection of targets smaller than the resolution cell and embedded in high levels of clutter. The methodology itself is extraordinarily flexible resulting in the employment of another two applications: (1) ship detection for maritime surveillance, and (2) change detection for land change analysis and classification of dynamic ecosystems. The manuscript itself is a thoroughly well-organised piece of work, covering every detail and perspective in order to provide a comprehensive vision of the various problems and solutions where PA can be employed. At the time Dr. Marino's viva, the methodology has already led to the publication of two journal papers and more than 20 conference papers. Moreover, this thesis was awarded "Best PhD Thesis 2011" by the RSPSoc (Remote Sensing and Photogrammetry Society) during their annual conference in Bournemouth, 14th of September 2011.

Prof. Iain H. Woodhouse

Preface

When I found out my thesis was going to be published I began to wonder what would make the best incipit. I started asking around for suggestions from friends with a higher experience in the publishing world. I received plenty of advice (thanks to all), however the one that caught most of my attention was: “Armando, you should start your preface by telling, in a humorous way, an experience you had during your PhD and remains impressed in your memory… in this way, surely you will capture the attention of your readers throughout all the rest [of the preface]”. I have to admit that I actually evaluated the possibility that the suggestion was coming from a witty friend that just wanted to have a laugh at my preface expenses. But then, I realised that for most of life’s mistakes you have to make them in order to learn from them. So, I started to ponder for something witty that would be worth the preface of this thesis. As an actual fact, I could not think of anything! Well, perhaps it is better I rephrase this last sentence. I could not think of one unique funny event because there were many episodes that got stuck in my mind, like a bottle neck.

I could tell you about the time I felt like Indiana Jones in the neither lost nor doomed German forests (hopefully, I am not breaking any copyright right now) looking for possible real targets that were giving positive detections to the algorithm. Or, I could try to describe the expressions of my roommate colleagues when they found me in one of my trances induced by the progressive rock music I would listen to whilst working. Or perhaps, I could tell about my first conference, when my friends described me as a “mental road-police waving around” to illustrate the directions of polarisations, but in actual fact I was just fighting against the feeling of running away screaming. The truth is that I find all the processes of investigation to be an incredibly fascinating game. Sometimes you win and feel like you deserve the Nobel prize for a silly calculation that a fresher could have done, and sometimes you lose and you cannot stop thinking about the return match and a new strategy that will bring you to victory. With the impossibility of finding a single episode, I cannot do more than just say that all the words, maths and simulations the reader will find in the following are the result of a game that I enjoyed a lot to play in both the good and bad moments. My ultimate hope is that the reader will enjoy the content as well. But now I am already too impatient to start telling more about the content of this thesis!

Synthetic Aperture Radar (SAR) is an active microwave remote sensing system able to acquire high resolution images of the scattering behaviour of an observed scene. In this thesis, the contribution of SAR polarimetry (POLSAR) in detection and classification of objects is described and found to add valuable information compared to previous approaches. The first two chapters will be dedicated to introducing the concepts of SAR and polarimetry that forms the basis of the following developments.

The core of this thesis is a new target detection/classification methodology that makes novel use of the polarimetric information of the backscattered field from a target and will be presented in two chapters. The first of them, Chap. 4 contains all the mathematical demonstrations aimed to bring the reader from a physical/algebraic concept to a final formula ready to apply. On the other hand, Chap. 5 is concerned with the statistical description of the detector, in order to acquire more information regarding its theoretical performances (in particular its ROC, Receiver Operating Characteristic, curve).

One unavoidable step in proposing a new algorithm to the World is its validation and in this thesis this part is taken strongly into account in two chapters. Chapter 6 proposes a validation based on data collected with an airborne system: E-SAR L-band (DLR, German Aerospace Centre) in a campaign narrowly aimed to target detection (included camouflaged conditions). Chapter 7 is concerned with satellite data, since they represents a particularly interesting scenario for target detection. The datasets includes ALOS-PALSAR L-band (JAXA, Japanese Aerospace Exploration Agency), RADARSAT-2 C-band (Canadian Space Agency) and TerraSAR-X X-band (DLR).

I hope you will enjoy this thesis as much as I did!

Acknowledgments

Surely a PhD is not the kind of task that one can accomplish without the help of a myriad of people. I am afraid that a detailed description would end up as a chronicle of the past 4 years of my life being as long as the entire thesis. It could start from my supervisor and end at the Cameo ticket boy. Therefore, considering I do not have enough time to write it nor the reader is interested in my diary, I believe there are two ways out to this problem: (1) to make the list as short as possible missing out many names; (2) to not write at all! Considering ingratitude is not amongst my favourite sins, I will attempt the first solution and try to keep the list as short as possible.

First of all I would like to thank my supervisor Dr. Iain Woodhouse for the never-ending encouragement and support he provided when pursuing my ideas, it did not matter how bizarre they appeared at first glance. Then there are my friends within the University of Edinburgh who assisted me in fitting into my new office environment and orienteering around many pubs: Iain Cameron, Karen Viergever, Bronwen Whiteney, Mahmet Karatay, Rachel Gaulton. Without them I would still be fighting with IT or secretarial nuisances and would probably ignore the real value of a good pint.

Many people contributed to the actual advance of my PhD and thesis. Amongst all I would like to give my special thanks to Shane Cloude from AEL consultants. Without his continuous suggestions and advice the entire work would not be as it appears in this thesis. I would like to thank all the people with whom I had brainstorming discussions about my work: Marco Lavalle, Andreas Reigber, Eric Pottier, Maxim Neumann and Laurent Ferro-Famil. I am also infinitely grateful for the help of Juan Manuel Sanchez Lopez and Rafael Schneider who gave up their time to help with the proof-reading of my thesis.

I am immensely grateful for the sponsorships provided to me for my PhD, which includes many people, however, in brief the list most certainly has to include Nick Walker from eOsphere Ltd, Dr. Iain Anderson from Defence Science and Technology Laboratory of the Ministry of Defence UK, Tony Kinghorn and Neil Whitehall from the Electro Magnetic Remote Sensing Defence Technology Centre and Ralf Horn and Matteo Nannini from the German Aerospace Agency (DLR).

Without their continuous adjustments on the directions of my research I would never have attained the results presented in this thesis.

I would also like to thank the people within DLR who first planted the seed for research within me (or perhaps first watered it). Without them I surely would not have started my PhD in Edinburgh or developed such passion for research. To name but a few of these people, I have picked a small sample: Irena Hajnsek, Florian Kugler, Luca Marotti, Kostas Papathanassiou and Rafael Schneider.

I leave the last paragraph for a special thank to everybody who has been close to me during my PhD, especially in the beginning when home looked so far away. Amongst these people are my parents, Franco and Anna who accepted the idea to live afar from their son and provide me with an opportunity of attempting my aspirations. My friends amongst others, Pasquale Bellotti, Giampaolo Cesareo, Vincenzo Costa and Giuliano Raimondo. Last but not least I would like to thank my girlfriend, Greer Gardner, who supported me in all my decisions putting my aspirations before everything.

Contents

Acronyms

EM	Electro magnetic field
SAR	Synthetic aperture radar
PF	Polarisation fork
FOLPEN	Foliage penetration
POLSAR	Polarimetric SAR
POLinSAR	Polarimetric SAR interferometry
X-pol	Cross-polarisation
Co-pol	Co-polarisation
CR	Corner reflector
RedR	Reduction Ratio
SCR	Signal to clutter ratio
SNR	Signal to noise ratio
CNR	Clutter to noise ratio
pdf	Probability density function
CDF	Cumulative distribution function
DF	Discrete probability function
ROC	Receiver operating characteristic
H	Horizontal
V	Vertical
SLC	Single look comples image
DEM	Digital elevation model
LOS	Line of sight
RVoG	Random volume over ground
OVoG	Oriented volume over ground
RCS	Radar cross section
STD	Single target detector
PTD	Partial target detector
hfs	Historical fire scar

Symbols

$X_{1,}\ X_2$	X-Pol Nulls
$C_{1,}\ C_2$	Co-Pol Nulls
$S_{1,}\ S_2$	X-Pol Max
γ	Complex polarimetric coherence
γ_d	Detector
$\underline{k}$	Scattering vector
$k_{1,}\ k_2$ and k_3	Components of the scattering vector $\underline{k}$
$\underline{\omega}$	Scattering mechanism
$\underline{\omega}_T$	Target of interest (scattering mechanism)
$\underline{\omega}_P$	Perturbed-target (scattering mechanism)
$i(.)$	Complex image
$[S]$	Scattering (Sinclair) matrix
$[C]$	Covariance matrix
$[T]$	Coherency matrix
$[U]$	Unitary rotation matrix
$\langle . \rangle$	Finite averaging
$E[.]$	Expected value (infinite averaging)
$\underline{k}^T$	Transpose of $\underline{k}$
$\underline{k}^*$	complex conjugate of $\underline{k}$
$\lVert \underline{k} \rVert$	Modulus of $\underline{k}$
$\lvert \underline{k}_i \rvert$	Amplitude of the component $\underline{k}_i$
$\left(\frac{\lvert b\rvert}{\lvert a\rvert}\right)^2, \left(\frac{\lvert c\rvert}{\lvert a\rvert}\right)^2$	Reduction ratios *RedR*
T	Detector threshold
P_T	Power of target component
P_C	Power of clutter component
$[I]$	Identity matrix
$[A]$	Weighting matrix
$N(.)$	Gaussian (Normal) distribution

$\Gamma(.)$	Gamma distribution
δ (.)	Dirac function
X_i	Random variable
x_i	Realisation of the random variable X_i
P_D	Probability of detection
P_F	Probability of false alarm
P_M	Probability of missed detection