POLARIMETRIC SAR INTERFEROMETRY

WITH A PASSIVE POLARIMETRIC MICRO-SATELLITE CONCEPT

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ABSTRACT

This paper proposes a spaceborne SAR mission consisting of a bi-static SAR configuration for estimation of the global vegetation biomass. The bi-static SAR configuration is based on a master satellite (transmitter) and on two or more receiver-only SAR satellites. The master satellite consists of an existing or planed SAR satellite (preferably in L-Band) with dual or full polarimetric capabilities. The receiver-only satellites have a dual polarized antenna and are positioned behind or ahead the master satellite, allowing single-pass fully polarimetric SAR interferometry. This innovative technique is used for reliable estimation of vegetation height on a global basis, which is offering a main input for the estimation of the global terrestrial biomass. The expected accuracy of the biomass estimation is compatible with the requirements posed by the Kyoto Protocol for the monitoring of carbon sinks as well as for ecological process modeling, forest inventory, and predictive modeling in hydrology.

INTRODUCTION

SAR interferometry is a established SAR technique to estimate the terrain height by means of the phase difference estimation in two images acquired from spatially separated antennas in the across-track direction. Additionally, the sensitivity of the interferometric phase center and coherence to the spatial variability of height and density of vegetation makes the estimation of vegetation parameters from interferometric measurements a challenge [13], [15], [16]. On the other hand, radar polarimetry is sensitive to the shape, orientation and dielectric properties of scatterers. This allows the identification and separation of different scattering mechanisms occurring inside the resolution cell of natural media by measuring differences in the polarization signature. In polarimetric interferometry both techniques are coherently used to provide combined sensitivity to the vertical distribution of scattering mechanisms [2]. Hence, it becomes possible to investigate volume scatterers and to extract information about the underlying scattering processes using only a single baseline-single frequency polarimetric radar sensor. This promises a break-through in essential radar remote sensing problems as surface parameter estimation under vegetation cover, and forestry applications. However, temporal decorrelation affects significantly the performance of this new technique so that a global application requires a single-pass spaceborne interferometric system.

Recently, several passive interferometric configurations consisting of two or more receiving-only micro-satellites have been proposed as a cost-efficient option for future interferometric spaceborne SAR systems. Such a configuration has been originally proposed for single pass interferometry with the receiver satellites positioned at a distance corresponding to the across-track baseline required for interferometry. Due to security reasons for orbit maintenance, the receiver satellites are positioned several tenths of kilometers behind or ahead the master satellite, so that two receiver satellites are required for building an interferometric configuration. Several configurations have been proposed to build such a configuration of receiver satellites in a stable manner.

In this paper the potential of such a passive polarimetric and interferometric micro-satellite concept for the estimation of forest above ground biomass on a global scale using the technique of polarimetric SAR interferometry is investigated. Based on the required parameter estimation accuracy and on operational constrains, different inversion parameter scenarios are discussed. The performance analysis for different configurations is presented and recommendations concerning the design of a configuration dedicated to forest parameter estimation are addressed.

INTERFEROMETRIC SAR WITH PARASITIC SATELLITES

To achieve high-quality single-pass interferograms on a global scale, several bi- and multi-static SAR missions have been suggested which combine a conventional spaceborne radar with a set of low-cost receivers onboard a constellation of passive microsatellites (Fig. 1). Examples for such parasitic SAR configurations are the Interferometric Cartwheel [6] and the Cross-Track Pendulum [8]. In the Interferometric Cartwheel, all satellites share the same orbital plane but the receiver satellites have slightly elliptical orbits with equal eccentricities and different arguments of perigee. As a result, the altitudes of the individual receivers will slightly differ for each orbital position and this height difference is used for cross-track interferometry. An almost constant interferometric baseline will be available in case of three receiver satellites as shown in Fig. 1 on the right. The deviations from the desired nominal baseline are less than ±7% if for each orbit position the satellite pair with maximum cross-track separation is chosen. Comparable baselines result also from the Pendulum configuration where the satellites have circular orbits with different inclinations and/or ascending nodes. The major advantage of the Cross-Track Pendulum is the small and constant along-track displacement between the individual receivers, but additional fuel is required to keep the whole formation stable.

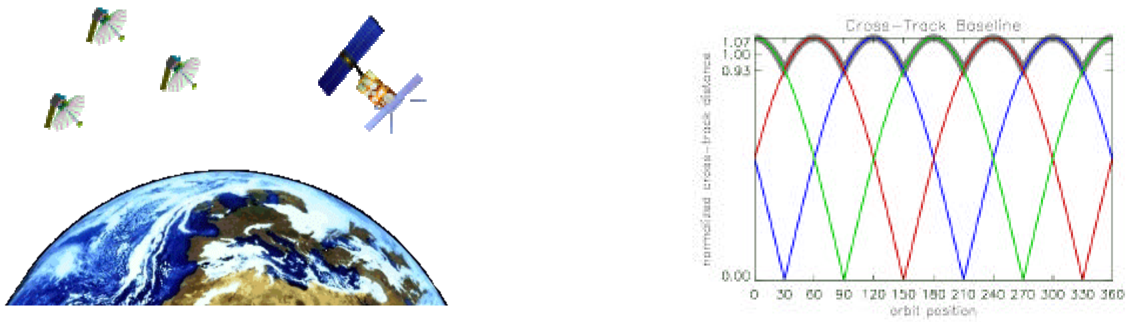

Fig. 1. Parasitic SAR with one active transmitter and three passive receivers (left) and cross-track baselines as a function of orbit position (right). By selecting the satellite pairs with maximum cross-track separation a very stable interferometric baseline is achieved.

In [5] and [7] the interferometric performance and the height accuracy for several parasitic SAR configurations in combination with spaceborne illuminators operating in different frequency bands has been addressed. It turns out that for surface scattering a relative height accuracy in the order of one up to few meters is achievable with appropriately designed systems, but also that volume decorrelation degrades substantially the interferometric performance in vegetated areas especially at longer wavelengths and/or operation using long baselines [5].

POLARIMETRIC SAR INTERFEROMETRY

As mentioned above, volume scattering constrains seriously the performance of conventional high resolution interferometric techniques. One of the most promising ways to overcome this problem is the introduction of model based parameter inversion techniques. The sensitivity of interferometric observables to structural properties of volume scatterers makes the estimation of volume scatterering parameters on a global scale one of the most challenging applications of a spaceborne single-pass interferometric system. Unfortunately, the complexity of the scattering process does not provide easy separability of the physical forest parameters in terms of the interferometric observables. This prevents straightforward parameter estimation and requires the inversion of a scattering model that relates the interferometric observables to physical parameters of the scattering process. A simple model to describe vegetation scattering at longer wavelengths - which has been proved to be widely valid *for most important forest types including temperate, boreal, and, tropical forests worldwide in both, flat and mountainous terrain conditions* [10], [1], [13], [4] - is the random volume over ground scattering model [15], [10]. Accordingly, the complex interferometric coherence γ (amplitude and phase) is described in terms of four parameters: a interferometric phase corresponding to the ground topography f_0, the ground / volume scattering amplitude ratio m, and two parameters related to the volume (vegetation) parameters: the volume height h_V and the volume extinction coefficient s. The variation of polarisation implies only a variation of the effective ground-to-volume amplitude ratios, mainly caused by the strong polarimetric behaviour of the ground. This implies the variation of the location of the effective scattering center with polarisation, and hence, the polarisation dependency of the interferometric coherence. As the only polarisation dependent parameter is m, the model can be inverted in terms of three single-baseline interferograms formed at different polarisations, i.e. using a single baseline fully polarimetric interferometric system [10]. The inversion of the random volume over ground scattering problem with single baseline polarimetric interferometry relies on the fact that the random volume contribution on the interferometric coherence is polarisation independent. Polarisation influences the interferometric coherence only through the variation of the ground/volume amplitude ratio. This allows the inversion of the random volume over ground scattering model in terms of a six-dimensional optimisation problem [10]

$$[h_V \;\; s \;\; f_0 \;\; m(Pol.1) \;\; m(Pol.2) \;\; m(Pol.3)]^T = [M]^{-1}[g(Pol.1) \;\; g(Pol.2) \;\; g(Pol.3)]^T \tag{1}$$

Up to now, the inversion performance of this technique at L-band has been validated for deciduous as well as coniferous forest stands in several European test sites with flat and mountainous terrain. In all cases the estimation accuracy lies in the order of 10%. Fig. 2 shows the estimated compared to the measured tree heights for eight coniferous (Stands 1-8) and six deciduous (Stands 9-14) homogeneous forest stands, with heights ranging from 15m up to 35m. The mean values of the measured heights, averaged over each individual stand, are indicated with squares while the crosses indicate the corresponding mean values of the estimated heights. The error bars represent the height variation of each stand [10].

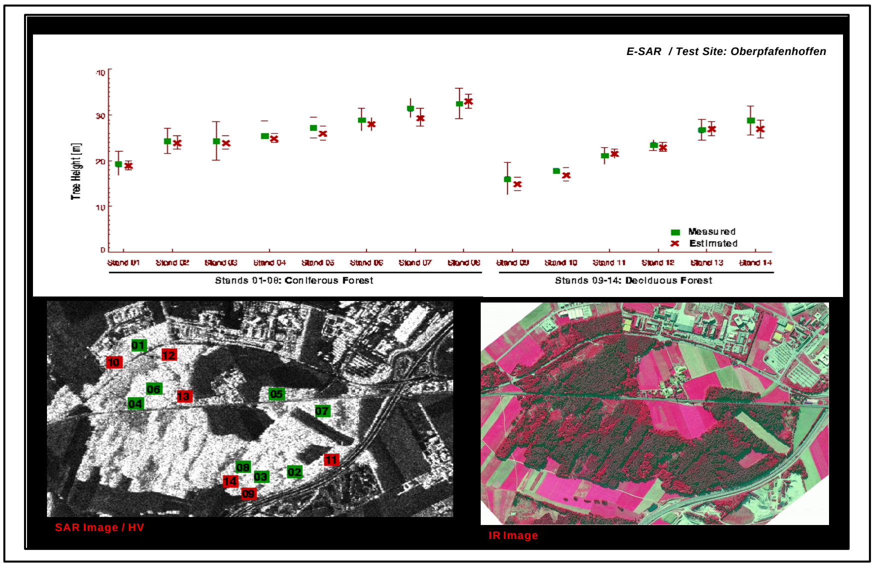

Fig. 2. Top: Estimated versus measured tree heights. Bottom: HV Amplitude image and IR image of the test site.

SPACEBORNE SAR MISSION DEDICATED TO BIOMASS ESTIMATION

In the scope of the Call for Proposals of the European Space Agency in the frame of the Earth Explorer Opportunity Missions Program, CNES and DLR have jointly submitted a proposal for an innovative spaceborne SAR mission entitled VOICE (**Vo**lumetric **I**nterferometry **C**artwheel **E**xperiment). The main scientific objective of this mission is the quantitative estimation of key forest parameters as forest height, forest and canopy density, underlying forest topography and above ground forest biomass and the estimation of seasonal changes of above ground biomass on a global basis. The expected estimation accuracy for the main parameters (forest height and biomass) is about 10-20% up to a biomass level of about 400 tons per hectare [tons /ha] with a spatial resolution of about 70 m x 70 m (i.e., 1/2 ha), which allows the inventory of all important biomes of our planet including the essential Boreal and Tropical forest ecosystems with a unprecedented accuracy (see Table 1).

Table 1. Biomass saturation values. Using the information about forest species and forest height, the biomass saturation limit increases potentially up to 400 tons/ha.

	Biomass Saturation Limit		***% of Earth's Vegetated Area***	***% of Total Above Ground Biomass***
	[tons / ha]	[kg / m^2]		
Backscatter Saturation C-band	20	2	25	4
Backscatter Saturation L-band	40	4	35	8
Backscatter Saturation P-band	120-150	12-15	60	20-30
Forest Height	250-400	25-40	~75-90	80-90

The proposed approach to estimate above ground biomass from forest height and stand and/or canopy density estimates obtained from polarimetric interferometry shows some significant advantages compared to the conventional backscatter saturation based methodology. The first one is the significantly higher biomass level which can be measured. Using forest height alone the saturation level covers the mean biomass level of boreal forests while the combination with tree species information (supported with ground topography in tropical ecosystems) allows the complete coverage of temperate and tropical forests (cf. Table 1). The second main advantage lies in the fact that instead of a direct relation of backscatter amplitude to biomass, important forest parameters as forest height, stand and/or canopy density and underlying topography are directly estimated. These parameters are requested for a wide spectrum of forest applications apart of biomass estimation.

DISCUSSION AND CONCLUSIONS

Under the rapidly growing population the stress on our natural environment is increasing. Meeting the basic needs for this population places tremendous demands on our natural resources. A few of the most important environmental problems that human society faces are deforestation, wildlife and habitat destruction (including loss of bio-diversity), air pollution, soil erosion, and desertification. All of these environmental problems are directly or indirectly linked to the carbon cycle. Understanding and quantification of the carbon cycle is therefore crucial for the sustainability of our life. In the context of carbon cycle modeling, two aspects of terrestrial biomass need to be clearly separated: carbon sinks represented mainly by the carbon stored in wood of trees and carbon fluxes caused by carbon sink modification and vegetation activity through respiration. By monitoring the changes in above ground biomass and estimation of total biomass and its temporal variability with a spatial and temporal resolution suitable for modeling ecosystem processes at regional, continental and global scales, VOICE will significantly contribute to the understanding of the carbon cycle.

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