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Properties of X-, C- and L-band repeat-pass interferometric SAR coherence in Mediterranean pine forests affected by fires

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ABSTRACT

Synthetic Aperture Radar (SAR) data has been investigated to determine the relationship between burn severity and interferometric coherence at three sites affected by forest fires in a hilly Mediterranean environment. Repeat-pass SAR images were available from the TerraSAR-X, ERS-1/2, Envisat ASAR and ALOS PALSAR sensors. Coherence was related to measurements of burn severity (Composite Burn Index) and remote sensing estimates expressed by the differenced normalized burn ratio (dNBR) index. In addition, the effects of topography and weather on coherence estimates were assessed. The analysis for a given range of local incidence angle showed that the co-polarized coherence increases with the increase of burn severity at X- and C-band whereas cross-polarized coherence was practically insensitive to burn severity. Higher sensitivity to burn severity was found at L-band for both co- and cross-polarized channels. The association strength between coherence and burn severity was strongest for images acquired under stable, dry environmental conditions. When the local incidence angle is accounted for the determination coefficients increased from 0.6 to 0.9 for X- and C-band. At L-band the local incidence angle had less influence on the association strength to burn severity.

1. Introduction

Changes in traditional land use patterns have modified the incidence of fires in the Mediterranean area. Rural abandonment led to unusual accumulation of forest fuels, which notably augmented fire risk. The increased use of forests as recreational resource incurred higher incidence of man-induced fires (Chuvieco, 1999), the average number of fires per year rising by 60% from 1980 to 2007 (Schmuck et al., 2008). Increased fire activity over the last decades also reflects regional responses to changes in climate, fire intensity and duration being, at least partially, influenced by higher temperatures (warmer springs) and reduced moisture availability (dryer summer seasons). A fourfold increase in the fire frequency was observed for the last two decades when compared to the previous period in the western United States. The length of the active fire season increased with more than two months and the average burn duration of large fires increased from one week to more than a month (Westerling et al., 2006). Deforestation-related fires contribute substantially to the global green-house gas emissions and the associated global warming they cause, which in turn causes increase of extreme-weather related fires leading to further spikes of carbon emissions (Werf et al., 2004). Fire severity is an important indicator of the way fire impacts ecosystems. Since the carbon content of fuels varies in a limited range the combustion conditions have a decisive role in burned area emissions (Andreae & Merlet, 2001).

Burn severity is generally estimated using a field assessed indicator called composite burn index (CBI) and is defined as the degree of the environmental change caused by fire (Key & Benson, 2004). The index describes post-fire conditions at a site by scoring different factors (e.g. litter consumption, percentage of altered foliage etc.) for individual vegetation layers (i.e. substrate, shrubs, trees). The results are aggregated to obtain a numerical value between 0 (unburned) and 3 (highly burned) representing the average burn severity at a specific site. The poor spatial representation and the considerable effort to gather field estimates of burn severity over large areas make the use of remotely sensed data not only advisable but crucial. The estimation of burn severity from satellite data is currently accomplished using vegetation indices derived from optical sensors, data being routinely processed using the normalized burn ratio (NBR) (Key & Benson, 2006) in a bi-temporal approach (dNBR) with pre- and post-fire images (Eq. (1)).

$$dNBR = (R4-R7)/(R4+R7)_{pre-fire} - (R4-R7)/(R4+R7)_{post-fire} \quad (1)$$

where R is per pixel reflectance for Landsat TM bands.

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NBR combines information from near- and mid-infrared wavelengths whereas dNBR expresses the magnitude of the environmental change caused by fire, unburned areas retaining values close to zero (i.e. little or no change). Generally, dNBR coupled with CBI provided accurate detection of burn severity (R^2>0.75) (Allen and Sorbel, 2008; Cocke et al., 2005; Epting et al., 2005; Wagtendonk et al., 2004). However, some authors (Hoy et al., 2008; Landmann, 2003; Murphy et al., 2008) reported weaker relationships between dNBR and CBI in savannas, tropical or boreal forests. This was attributed to dNBR's inability to discern between high severity sites, to variations in topography and solar elevation angle (Verbyla et al., 2008) or the specific fuel conditions (Kasischke et al., 2008).

The use of synthetic aperture radar (SAR) data could overcome the often encountered problem of optical-based spectral indices, i.e. the discrimination of the intermediate burn severities (Chuvieco et al., 2006). Since the backscattered signal contains information on forest structure, removal of leaves and branches by fire directly influences the signal from forests. Previous work confirmed the utility of SAR data for burnt area mapping (Bourgeau-Chavez et al., 2002; Gimeno et al., 2002), the estimation of burn severity (Bourgeau-Chavez et al., 1994) or of parameters related to variations in burn severity (Kasischke et al., 1994). Statistically significant relations have been found between radar backscatter and burn severity expressed by means of dNBR (Tanase et al., 2010). The backscattering coefficient expresses the total intensity received by the radar after scattering, thus not giving information about the structural arrangement of the individual scatterers within the forest volume. SAR interferometry provides instead a direct measure of the distribution of the scatterers in a forest structure through the phase information. Furthermore, the degree of interferometric coherence or simpler the coherence measures the correlation between the backscattered signal from a given target seen under two slightly different look angles, thus being related to temporal and geometric decorrelation effects (Askne et al., 1997; Zebker and Villasenor, 1992). Coherence takes values between 0 (total decorrelation) and 1 (no decorrelation).

Coherence and interferometric phase are affected by a number of factors related to SAR frequency, image acquisition geometry, spatial separation in space between antennas and temporal interval between the two image acquisitions (Bamler and Hartl, 1998). In a repeat-pass scenario, i.e. when the two images forming an interferometric pair are acquired with a certain separation in time, coherence is primarily influenced by the latter factor, which causes temporal decorrelation. Temporal decorrelation is determined by changes in the arrangement of the scatterers within the resolution cell, thus meaning that the sensitivity to temporal decorrelation is frequency-dependent. In forested areas wind is considered the main source of temporal decorrelation (Askne et al., 2003; Castel et al., 2000; Gaveau et al., 2000). Rapid decorrelation takes place even for low wind speeds (Askne et al., 2003) in particular for high-frequency SAR systems (X- and C-band) for which a large proportion of scattering originates within the first few meters of the canopy where temporally unstable scatterers are located (twigs, needles, small branches). Other sources of temporal decorrelation are related to variations of the environmental conditions such as precipitation and freeze/thaw events (Askne & Santoro, 2009; Koskinen et al., 2001; Santoro et al., 2002) or the soil moisture distribution within a resolution cell (Luo et al., 2001).

The slight separation in space between the antennas, referred to as interferometric baseline, implies that the spectra of the two images being interfered are slightly shifted with respect to each other. If not accounted for, the spectral shift causes spatial decorrelation (Gatelli et al., 1994). While this can be compensated for if information about the orientation of the resolution cell is available in case of surface scattering, a residual part remains in case of layered media (Hagberg et al., 1995). The residual decorrelation goes under the name of volume decorrelation. Residual spatial decorrelation, in case of uncompensated topography within the resolution cell, and volume decorrelation, in case of layered media, increase with increasing perpendicular component of the interferometric baseline (Askne et al., 1997; Hagberg et al., 1995). Volume decorrelation is also directly related to the thickness of the volume. As a result of the effect of temporal and volume decorrelation, the interferometric coherence in case of repeat-pass acquisitions is significantly lower over dense mature forest than in case of small vegetation and bare soils (Wegmuller and Werner, 1995). The dynamic range of coherence between young forest and dense mature forest is related to the stability of the weather conditions throughout the interval between the acquisition of the two images forming the interferometric pair.

The potential of repeat-pass coherence in forest-related applications has been shown in a number of thematic applications including forest mapping (Castel et al., 2000; Wegmuller & Werner, 1997), change detection (Smith & Askne, 2001) and retrieval of bio- and geophysical properties (Askne et al., 2003; Eriksson et al., 2003; Santoro et al., 2002). In forests affected by fires coherence increased significantly with respect to unburned forests for European Remote Sensing Satellite (ERS) VV polarized and Japanese Earth Remote Sensing 1 (JERS-1) HH polarized data (Liew et al., 1999; Takeuchi & Yamada, 2002). Most investigations were carried out using ERS-1/2 tandem coherence because of the short repeat-pass interval and the nearly global availability of archived data. Few investigations were carried out at L-band with HH-polarized JERS-1 data. The long repeat-pass and the temporally variable interferometric baseline did not favor forest applications. X-band interferometric data from space has been previously acquired during the SIR-C mission but only in single-pass mode. Polarization effects on the interferometric signatures have not been investigated yet, according to our knowledge.

For X- and C-band the repeat-pass coherence of burned forests is primarily affected by temporal decorrelation due to the movement of the forest elements within the canopy. The removal of the needles and small twigs reduces the strongest decorrelation source of forest since the remaining branches are less susceptible to movement by wind. This reduces the decorrelation of the low- and moderately-burned forest contributing to the increased coherence of the burned areas. The level observed for bare soils is in theory reached for areas with complete combustion of the vegetation since scattering would originate from the large branches and stem, which are less affected by temporal and volume decorrelation. The frequent occurrence of forest fires at several locations in Spain and the recent availability of SAR data acquired at different frequencies, polarization states and suitable for interferometry suggested investigating to what extent the interferometric coherence can be used for burn severity assessment. The moderate topography of typical Mediterranean pine forests and the different environmental conditions at the time of image acquisition allowed studying the relative contribution of geometric and temporal decorrelation to the total forest coherence.

The objectives of the study were to:

1. investigate the signatures of interferometric repeat-pass coherence response in relation to burn severity at X-, C- and L-band;
2. infer the prediction power of interferometric coherence for burn severity estimation for each frequency;
3. assess the role of the local incidence angle and weather conditions on coherence and on the prediction power of coherence for burn severity evaluation.

This study complements a parallel investigation on burn severity assessment using SAR intensity data from the same sensors considered here (Tanase et al., in press). Since the factors determining the SAR backscatter and the interferometric coherence are different and the interferometric dataset could be formed only at a later stage, it was decided to report the results on the signatures of the two radar observables separately. Nonetheless, for a complete overview of the usefulness of SAR data in burn severity estimation, reference to the