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Article

Rapid Mapping of Forest Fires in the European Mediterranean Region – a Change Detection Approach Using X-Band SAR-Data

Eva-Maria Bernhard, André Twele & Monika Gähler, Oberpfaffenhofen

Keywords: Change detection, TerraSAR-X, burned area detection, forest fire

Summary: Usually, optical data are used for detecting burned areas in a rush mode, but the analysis of these data is often limited due to persistent cloud cover or haze. This paper focuses on the potential of X-band SAR data for mapping forest fires in the European Mediterranean region. The goal of the study was the development of an object-based, semi-automatic, robust and fast but at the same time accurate and transferable algorithm for the detection of burned areas in case of rapid mapping. For this reason change detection techniques based on image differencing, rationing and index calculation were applied. Prior to the SAR data analysis, a number of pre-processing procedures were carried out, including the elimination of speckle noise by Gamma-DE-MAP filtering, radiometric and geometric calibration as well as computation of sigma nought, a scattering coefficient. In the course of devastating fires in Greece and La Palma in 2009, a multi-temporal backscatter coefficient analysis of fire affected and unburned areas were performed. Within this comparison, the detected signal of VV and HH polarisations showed significantly higher values in images acquired after the fires than before the fires. However, VV polarised data showed a higher amplitude between pre- and post-disaster backscatter levels than HH polarised data. The classification result has been validated by SPOT 5 data and achieved an overall accuracy of 77.9%. Thus, burned area detection with SAR data could potentially play a significant role in forest fire detection in Europe.

Zusammenfassung: *Brandflächendetektion auf Basis von X-Band Radarsatellitendaten im europäischen Mittelmeerraum*. Eine schnelle Brandflächendetektion mittels Satellitendaten wird zurzeit hauptsächlich auf Basis von optischen Daten vorgenommen, wobei hier Wolkenbedeckung und Rauch zu starken Beschränkungen bei der Erfassung führen können. Der Fokus dieser Arbeit lag auf der Ermittlung des Potenzials von X-Band Radarsatellitendaten zur Brandflächendetektion im europäischen Mittelmeerraum. Hauptaugenmerk lag dabei auf der Entwicklung eines objekt-basierten, semi-automatischen, robusten und schnellen, jedoch auch räumlich genauen und übertragbaren Algorithmus zur Brandflächendetektion im Rahmen katastrophenbedingter Notfallkartierung. Das Verfahren stützt sich auf eine multitemporale Veränderungsanalyse, die auf der Basis von Differenzbildern, Ratiobildern und einer Index-Berechnung beruht. Hierfür wird zunächst eine Datenvorprozessierung durchgeführt, welche eine Reduktion des störenden Speckle-Effektes durch den Gamma-DE-MAP Filter, sowie eine radiometrische und geometrische Kalibrierung umfasst. Am Beispiel der verheerenden Waldbrände in Griechenland und La Palma im Jahr 2009 wurde das Rückstreuverhalten von verbrannten und unverbrannten Flächen auf multitemporaler Datenbasis untersucht. Dabei ergab sich, dass sowohl die VV- als auch die HH-Polarisation signifikant höhere Werte in Satellitendaten aufweisen, die nach dem Brand aufgenommen wurden, als in Satellitendaten, die vor dem Brand aufgezeichnet wurden. Es war jedoch festzustellen, dass durch die Nutzung von VV Polarisation ein höherer Unterschied in Rückstreuwerten zwischen der Pre- und Postdesaster Satellitenbildszene festzustellen war als bei Nutzung von HH Polarisation. Die erreichte Klassifikationsgenauigkeit des Verfahrens belief sich auf 77,9% und wurde anhand von SPOT 5 Satellitenbildern validiert. Somit könnten Radar-Sensoren in Ergänzung zu optischen Satelliten eine entscheidende Rolle für die Feuerbeobachtung und Kartierung im europäischen Mittelmeerraum spielen.

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1 Introduction

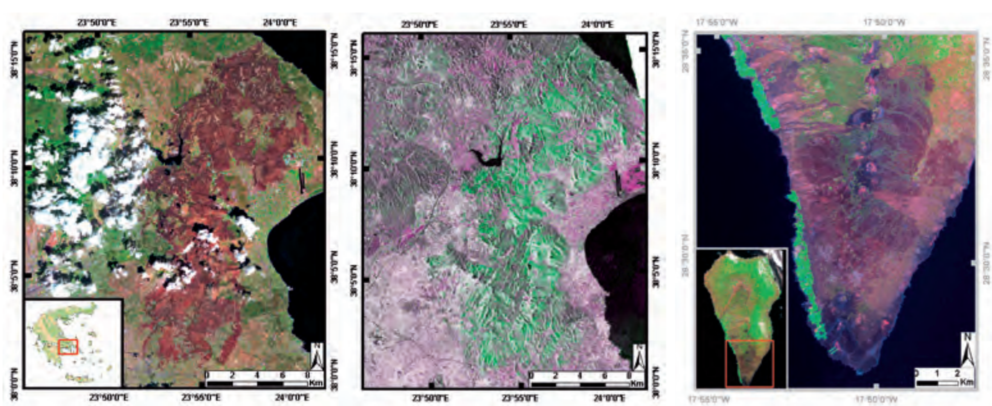
Forest fires do not only pose a severe threat to land and life, but also cause long-term damage to vegetation and soil moisture. Furthermore, fires contribute to an increase in soil erosion and land degradation and affect global warming due to rising CO2-emissions (Chuvieco 2009). Since the 1970s, the number of forest fires doubled in the Mediterranean region and in 2009, fires destroyed more than 323.000 hectares of land (Jrc 2009, Justice & Koronzti 2001). This increased fire activity reflects regional changes in reduced moisture availability and higher temperatures due to climate change. Thus, the number of fires will most likely aggravate in the future, and an allover fire monitoring is mandatory. In the course of devastating forest fires in Spain and Greece in July/August 2009, the International Charter *Space and Major Disasters* was activated in order to supply and analyse satellite data for rapid mapping purposes. The fires destroyed thousands of hectares of forest land as well as farmland, and numerous residents had to be evacuated. The *Center for Satellite Based Crisis Information* (ZKI) of the *German Aerospace Center* (DLR) was assigned to detect the burned areas based on the following optical data sets: SPOT 5, IKONOS and ALOS AVNIR-2. In some parts of the image, cloud cover precluded the detection of fires, and spectrally similar regions (cloud shadows, rimland and open space) furthermore led to misclassifications. However, a fast and exact detection of the fire-affected areas is indispensable both for on-site help and for an assessment of the aftermath. Therefore, the potential of TerraSAR-X to detect burned areas in a rush mode was investigated. A more detailed description concerning the TerraSAR-X satellite can be found in (Buckreuss & Schättler 2010, Pitz & Miller 2010).

Multi-temporal spaceborne Synthetic Aperture Radar (SAR) data have been used for many and diverse mapping purposes. Land cover changes which occur in bad weather conditions or active fires can be detected by the use of microwaves due to its ability to penetrate clouds and haze (Attema et al. 1998). They are independent of sun illumination and thus offer a high frequency in data acquisitions. Previous work confirmed the utility of SAR data for the estimation of burned areas in different parts of the world. Most studies focusing on burned area detection by means of microwaves were carried out in the boreal forest (Ranson et al. 2001, French et al. 1999, Bourgeau-Chavez et al. 1995, Kasischke et al. 1992), with a few exceptions such as Tanase et al. (2010), Gimeno et al. (2004), Gimeno & Ayanz (2004), Menges et al. 2004, and Siegert & Rücker (2000), who focused on forest fires in the Mediterranean region, in the tropical rain forest and Australia. Many researchers employed P-, L- and C-band data for burned area mapping (Gimeno et al. 2004, Menges et al. 2004, Karszenbaum et al. 2003, Ranson et al. 2001), except Tanase et al. (2010), whose study showed promising results in using TerraSAR-X data for fire severity assessment, observed on created plots in a burned area in the European Mediterranean region. Due a lack of studies utilizing X-band SAR data for detailed burned area mapping, the present study further investigated this topic. The radar backscattering coefficient expresses the total intensity received by the SAR system. The measured signal is a complex combination of different sources and is influenced by viewing geometry, soil and vegetation moisture, vegetation type and orientation, surface roughness and topography. The removal of leaves and branches due to fire directly influences the radar backscatter, depending on wavelength and study area. Therefore a backscatter increase over burned areas as well as a decrease could be detected (Nakayama & Siegert 2001, Tanase et al. 2010). X-band SAR is more sensitive to canopy surface scattering and can not penetrate deeply into the vegetation like L- or P-bands (Lillesand et al. 2004). For this reason, the suitability of X-band SAR for detecting burned areas in a Mediterranean region needs to be investigated.

2 Study Areas and Satellite Data

The study areas were located in the Canary Island of La Palma and in Grammatico, 30 kilometers northeast of Athens, Greece. Both study areas are influenced by the Mediterranean climate with wet and mild winters and dry and hot summers. These conditions make the Mediterranean region prone to forest fires, primarily in the late summer months, when vegetation suffers from water stress. Both study areas are characterized by a strong relief with steep slopes. The elevations are ranging from sea level up to 500 meters (Greece) and 1900 meters (La Palma) above sea level. The distinctive topography strongly influences the radar backscatter. The forest fire in Grammatico was located near the Gulf of Petalion in the east and the Gulf of Notois Evoikos in the north. The area was mostly covered by sclerophyllous vegetation, pastures and transitional woodland-shrub vegetation (CORINE land cover classification). The total burned area comprises approximately 3.100 hectares. The fires in La Palma were located in the south of the island, and affected an area covered by coniferous forest, pastures, sclerophyllous vegetation, sparsely vegetated areas, and agricultural areas which consisted of permanently irrigated land, fruit trees and berry plantations (CORINE land cover classification). In La Palma the forest fires destroyed an area of approximately 2.800 hectares. Fig. 1 shows SPOT 5 images of the study sites in Greece (a) and La Palma (c). The images are displayed as false colour composites with the band combination middle infrared, infrared and green. The burned area can clearly be visually discriminated (brown) from the remaining parts of the image. Also shown in Fig. 1 is a TerraSAR-X false colour composite (b) of the forest fires in Greece. For the RGB image, a pair of satellite data before (08.03.2009, green) and after (31.08.2009, red and blue) the fire is used. The fire-affected area is clearly silhouetted (green) against the mainland in purple and the sea in black.

The SAR data set consists of three pairs of TerraSAR-X StripMap images, always acquired before and after the forest fires. More detailed information on the satellite data is given in Tab. 1. All images were ordered in



(a) (b) (c)

Fig. 1: The study areas in Greece (a, b) and La Palma (c) shown by SPOT 5 (a, c) and TerraSAR-X images (b).

Tab. 1: Available satellite data.

Study Area	Date	Fire Condition	Modus	Polarisation	Orbit	Incidence Angle
La Palma **La Palma**	13.12.2007 09.08.2009	before after	StripMap StripMap	HH HH	ascending ascending	33.4° 33.4°
Greece **Greece**	13.05.2008 29.08.2009	before after	StripMap StripMap	VV VV	descending descending	26.5° 26.5°
Greece **Greece**	08.03.2009 31.08.2009	before after	StripMap StripMap	HH HH	ascending ascending	31.1° 31.1°

single-look slant-range complex (SSC) format. The TerraSAR-X sensor is able to record data in X-band with four different polarisation modes: horizontal transmit and horizontal receive (HH), horizontal transmit and vertical receive (HV), vertical transmit and vertical receive (VV) or vertical transmit and horizontal receive (VH).

Due to a lack of ground truth data, SPOT 5 images were used for the evaluation of the TerraSAR-X detected burned area. Pre-processing steps applied to the SPOT 5 data include orthorectification, topographic normalization, co-registration to the TerraSAR-X images and atmospheric correction. The burned area used for validation was derived through a visual classification based on different band combinations and indices (e.g., MSAVI, NDSWIR and BAI).

3 Methodology

The goal of the study was the detection of forest fires in X-band SAR data at HH and VV polarisation in topographically varied landscape in the Mediterranean. For this scope, adequate pre-processing was mandatory, and different change detection approaches were used.

3.1 *Pre-Processing*

The TerraSAR-X pre-processing was performed in three steps using the SARscape software (by Sarmap). All images were acquired in SSC format and the corresponding data pairs had the same orbit and frame. First, the radar data were multi-looked to the standard StripMap resolution of 3 meters x 3 meters per pixel. Second, a speckle filter was applied. For highly textured, hilly and high-resolution satellite images, the Gamma-DE-MAP filter provides good results and was accordingly applied to all images. Subsequently, the images were geocoded and orthorectified to Universal Transverse Mercator (UTM) projection using a digital elevation model (DEM) with 30 meters pixel spacing. To avoid radiometric distortions due to the strong relief, a topographic normalization was applied. Since a radiometric calibration of the backscatter values is mandatory for intercomparison of radar images acquired in different modes or different points in time, it was accordingly applied to the data set. All resulting images were converted to sigma nought. Sigma nought is a conventional measure of the strength of radar signals reflected by a distributed scatterer, and is usually expressed in dB values. Plots with 20 meters x 20 meters were generated and randomly distributed over the image to analyse radar backscatter changes between burned and unburned areas. Since different classes (like sparsely vegetated areas or coniferous forest) are difficult to identify in single-polarised TerraSAR-X data, they were chosen on the basis of SPOT 5 images. By the use of the CORINE land cover classification, the classes coniferous forest, sparsely vegetated areas, bare rock, continuous urban fabric and sea and ocean were identified and assigned to the TerraSAR-X images. Six plots for each class were selected. Considering the microwave characteristics, half of the plots were arranged in slopes facing the SAR antenna and half in slopes facing away from the sensor. Previous to this work, the burned area was mapped using SPOT 5 images. The area detected was used to define eight plots in the TerraSAR-X images, also half oriented toward the sensor and half oriented away.

3.2 *Change Detection*

The pre-processed images were further analysed in the eCognition Developer software (by Trimble). On pixel basis, three different change detection techniques were applied: Image differencing, rationing and the calculation of the normalized change index (NCI) based on images acquired before and after the disaster. Image differencing, image rationing and NCI calculation are well known techniques for land cover change detection (Lu et al. 2004). Image differencing means measuring changes in radar backscatter by subtracting the dB values, pixel by pixel, between the two dates before and after the fire, whereas image rationing describes the measurement of changes by dividing the dB values, likewise pixel per pixel. The NCI is calculated by

$$NCI = \frac{(post - pre)}{(post + pre)} \quad (1)$$

where "post" is the post-disaster data set and "pre" is the pre-disaster data set. Thus, three new layers were generated. Fig. 2 shows the difference layer of the HH polarised TerraSAR-X images from August 31, 2009 and March 03, 2009 on the left compared to the SPOT 5 data on the right. The higher the difference between the two TerraSAR-X images, the brighter the image. The difference value is much higher over the burned area than in the remaining parts of the image and thus clearly visible. Just some parts of the sea surface are, similar to the burned area, also visible in greyish tones, possibly due to a different state of waves. For a direct comparison of the burned areas derived from SAR and optical data, the TerraSAR-X difference image was overlayed by the burned area (red) extracted of the SPOT 5 images. It becomes obvious that there is a high correlation between the grey areas of the difference image and the extent of the burned areas detected from SPOT 5 data. Furthermore, the orange and blue circles in Fig. 2 highlight probably the biggest advance of the TerraSAR-X satellite in case of burned area mapping. Regions which can not be interpreted in optical images due to cloud cover can be analysed in microwave data. In this example, the orange circle shows greyish tones in the TerraSAR-X image as an indication of fire affected areas, whereas the blue circle does not show high difference values in the TerraSAR-X image which indicates unburned vegetation.

An image segmentation was performed using the three change detection layers. In order to avoid misclassifications due to high difference values of the sea surface, the first classification step was to extract areas covered by water. The water classification was performed on the post-disaster satellite image. Due to the fact that water usually acts like a specular reflector, the water areas were detected by means of their low backscatter values. Subsequently, the burned area was detected via a threshold based on the change detection difference layer. Small, misleadingly detected unburned areas were eliminated by defining a minimum mapping unit.

4 Results and Discussion

The radar backscatter value is dependent on the roughness of the ground layer, the shape, the orientation of scatterers and the sensor geometry. The rougher the surface, the higher the backscatter value (LILLESAND et al. 2004). X-band SAR is more sensitive to canopy surface scattering than L- or P- bands. Thus, the same surface seems rough for X-band microwaves causing high backscatter values, but intermediate or smooth for L-band micro-

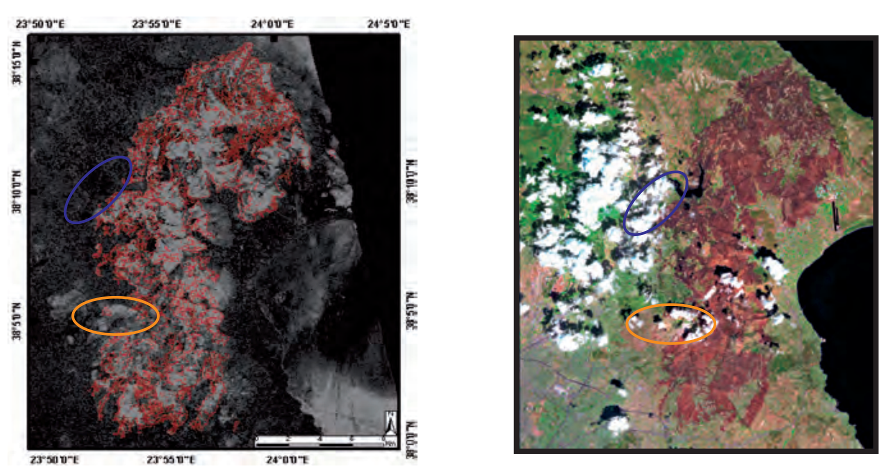


Fig. 2: TerraSAR-X difference image in comparison to the SPOT 5 image.

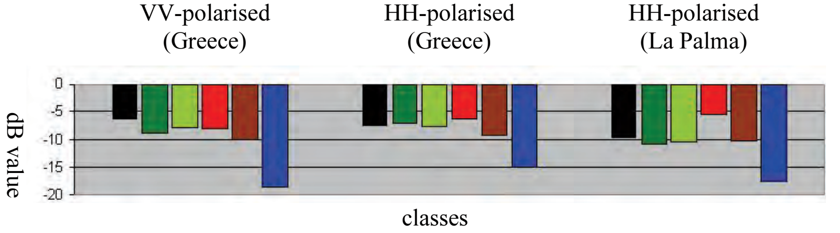
waves resulting in lower backscatter values (Lillesand et al. 2004). Hence, in unburned forests, X-band radar waves show a high tree crown scattering behaviour. Forest fires cause the removal of foliage, branches and even trees. Thus, other elements, like the ground layer, become transparent to the radar wave. According to this, the backscatter is primarily the result of the scattering mechanism occurring in trees that remained during the fire, the proportion of exposed ground and tree and soil moisture. The radar signal of burned areas is dependent on many factors such as fire severity (e.g., percentage of removed foliage, size and number of remaining branches and height of stems), wind velocity and direction, relief, vegetation and human influences like fire breaks or streets. Therefore, a general answer concerning the radar backscattering behaviour for burned areas can hardly be given.

Single-Temporal Analysis

The VV polarised image of Greece showed higher post-disaster backscatter values over burned areas than the HH polarised image. The backscatter results of Greece (VV and HH) and La Palma (HH) are exemplified in Fig. 3. Although the VV polarisation, compared to the HH polarisation, showed differences in post-disaster backscatter values over fire affected and the remaining parts of the image, a burned area detection on a single-temporal data basis turned out to be too inaccurate. The higher VV polarised backscatter values could be explained by the fact that vertical polarisation is more sensitive to vertically oriented objects than horizontal polarisation. The percentage of branches and foliage removed as well as the size and height of remaining branches and stems are important factors for variations in radar backscatter. In case the vegetation, primarily stems, is not completely destroyed through fire, the backscatter of vertical polarised waves interacts stronger with the remaining objects than HH polarised waves. This process is strengthened through the double bounce effect arising between stems and the ground.

Multi-Temporal Analysis

The image information given by the calculated difference, ratio and normalized change index was more or less equivalent. Thus, considering the rapid mapping workflow, just one technique was used for burned area mapping. The multi-temporal backscatter analysis was based on the image differencing change detection method. Therefore, the mean backscatter value of plots located in pre- and post-disaster images were compared (see Fig. 4). All post-disaster values were significantly higher than the pre-disaster values. This can be explained by a removal of tree crowns and foliage due to fire, and consequently an increase in backscatter levels due to missing ground vegetation resulting in an exposal of a rough ground sur-



burned area	-6.131	-7.362	-9.745
coniferous forest	-8.952	-7.035	-10.984
sparsely vegetated areas	-7.761	-7.560	-10.528
continous urban fabric	-8.077	-6.110	-5.625
bare rock	-10.140	-9.274	-10.408
sea and ocean	-18.507	-15.079	-17.667

Fig. 3: Mean Backscatter values in TerraSAR-X post-disaster images.

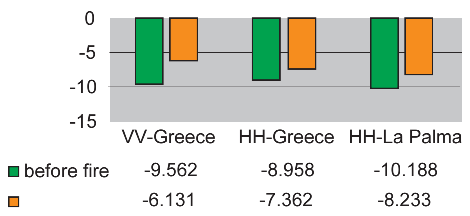


Fig. 4: Mean backscatter values in pre- and post-disaster images.

face. This means that the lack of canopy surface scattering in fire affected areas is more than outbalanced by a backscatter increase of the exposed ground surface. Hence, on the basis of a change detection approach, the burned area could be clearly distinguished in the TerraSAR-X images of Greece and La Palma. At both polarisations, the backscatter showed a clear increase over the burned area. However, the amplitude of backscatter changes due to the forest fire was higher in VV polarisation data than in HH polarisation data. The difference value of the VV polarised images showed a change of + 3.431 dB whereas the HH polarised image showed a change of just + 1.596 dB in Greece and + 1.955 dB in La Palma. It should be considered that just one pair of VV polarised images was available. Different study areas and a more comprehensive SAR data set could bring further results regarding this topic. The relative radiometric accurcy for TerraSAR-X products includes errors from calibration devices and from processing, and is expected to be 0.68 dB or 0.78 dB in worst case, and is thus much smaler than our detected change values (Eineder et al. 2006).

The object-based change detection approach achieved promising results for burned area mapping. A comparison to the previously classified burned area using SPOT 5 data showed that most parts of the burned area were well detected. Fig. 5 shows the SPOT 5 image of Greece, overlayed by the TerraSAR-X detected burned area (red). The burned area was clearly detected, with just some small unburned areas inside the burned area, and some small burned areas outside the main burned area which could not be identified. In order to determine the usefulness of SAR data as an alternative to traditional methods for forest fire mapping, the results of the change detection based classification were compared to the results obtained from the SPOT 5 classification in Greece. In order to minimise differing topographic effects, the burned area in the ascending and descending data pair was classi-

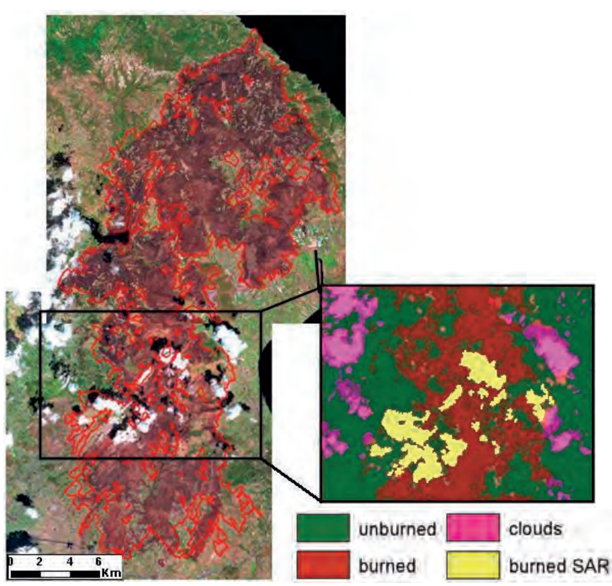


Fig. 5: Mapped burned area with TerraSAR-X (red); background shows a SPOT 5 image.

fied separately, and finally combined. The classification result achieved an overall accuracy of 77.9%. The combination of optical and radar data was used to take advance of both sensor types. Fig. 5 shows a detailed map of the final classification result consisting of a synergy of both remote sensing techniques. The green areas are classified as unburned, the objects in magenta are clouds, the red area is the burned area detected on the basis of the SPOT 5 image and the pink objects are areas which were classified as clouds or cloud shadows in the SPOT 5 image, but as burned areas in the TerraSAR-X image. Hence, the joint analysis of optical (high spatial accuracy) and microwave (penetration of clouds) data shows a great advance.

Another interesting aspect for the SAR-based burned area detection came up when further investigating the forest fire in La Palma. The fire affected areas showed a high difference in pre- disaster vegetation cover. Upper regions of the burned area were mostly covered with dense vegetation, primarily coniferous forest, whereas in lower regions, mainly sclerophyllous and sparse vegetation was prevalent before the fire. The pre-disaster vegetation type was determined using the CORINE land cover classification and intersected with the burned area detected using SPOT 5 and TerraSAR-X data (see Fig. 6). The results show that TerraSAR-X could mainly detect coniferous forests,whereas burned sclerophyllous vegetation could only be detected using SPOT 5 data. This leads to the assumption that the pre-disaster vegetation density could act as limitating factor in forest fire mapping with X-band SAR data. In case fires occur in sparsely vegetated areas, the detection of the burned area extent could become difficult since only minor changes in radar backscatter occur.

5 Conclusion and Future Work

Within this work, a TerraSAR-X image processing methodology was developed to investigate the utility of X-band SAR data for burned area mapping in the European Mediterranean. A multi-temporal change detection approach based on image differencing was successfully used for mapping forest fires. The temporal variation in dual-polarised (HH and VV) backscatter coefficients was assessed. For both polarisations, the backscatter value increased significantly, whereas using VV polarisation, the absolute backscatter level was consistently higher for fire affected areas in comparison to HH polarised data. Burned area detection with X-band SAR data achieved remarkable results in a multi-temporal change detection approach, but delivered poor accuracies when using single-temporal data. Another aspect arised respective to the vegetation type existing before the fire. Sparse and lower growing vegetation types could probably limit the burned area mapping with X-band SAR data.

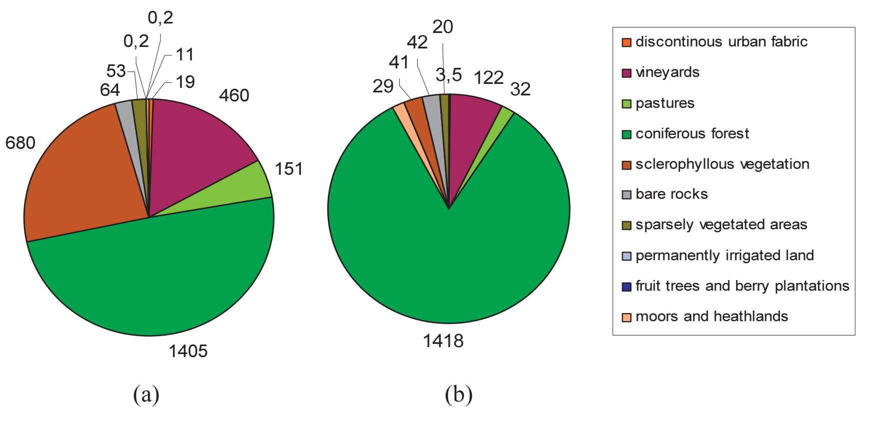


Fig. 6: Fire-affected vegetation in La Palma, mapped on the basis of SPOT 5 (a) and TerraSAR-X (b) data and CORINE, all numbers in hectares.

Remote sensing images required to detect forest fires must be both, temporally close and rich in details. These two conditions can only be satisfied if optical and radar data are used simultaneously. This work investigated a combination of optical and radar data. Further work should focus on a better data fusion of these two different remote sensing techniques and should include combined data from multiple satellites in order to improve the timeliness and accuracy of burned area mapping. Thus, future research will involve a further operationalisation of the TerraSAR-X based methodology, also in combination with other optical sensors.

Due to the fact that forest fires cause similar effects to vegetation like loss of crown foliage and branches, and the removal of understory layers, it is likely that similar results can be achieved in other Mediterranean regions. However, different trends may be observed in other environments such as boreal or tropical forests. Thus, a future research topic is the testing of the proposed methodology in other study areas.

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Address of the Authors:

Eva-Maria Bernhard, André Twele, Monika Gähler, German Aerospace Center (DLR), German Remote Sensing Data Center (DFD), D-82234 Oberpfaffenhofen, Tel.: +49-8153-28-2481, -3510, -3309, Fax: -1445, e-mail: Eva-Maria.Bernhard@dlr.de, Andre.Twele@dlr.de, Monika.Gaehler@dlr.de

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