ANALYSIS OF AN ERS-1 SAR TIME SERIES AND OPTICAL SATELLITE DATA FOR FORESTRY APPLICATIONS IN TEMPERATE ZONES

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ABSTRACT:

Due to their weather independent operation there is a growing interest in utilising imagery collected by imaging synthetic aperture radars on satellites like ERS-1, JERS-1 and RADARSAT. Their data, acquired on a regular basis, at short intervals, over the entire planet, will allow a variety of forest ecosystem characteristics to be monitored for the years to come. To take full benefit of these advantages it is now necessary to investigate the information content of these data under a variety of scene related and environmental conditions. The objectives of this study are to exploit multidate ERS-1 observations of the Freiburg-Black Forest test-site in Germany and a rich available ground truth data set by developing techniques for change detection and monitoring in order to assess the information content of ERS-1 SAR data for forestry and other land applications, and especially to evaluate the potential for improved information extraction from multitemporal SAR data. Furthermore the combined use of optical and microwave spaceborne data should give insight into possible synergetic effects for qualitative and quantitative analysis of forest stands. Changes in backscatter observed by the ERS-1 SAR have been related to the variation of meteorological parameters for different landuse. It confirms that the temporal sequence of the C-band reflectivity of vegetated areas measured by ERS-1 appear to be sensitive to changes in moisture conditions and effects of temperature on dielectric properties. Long term variations due to phenological and seasonal effects can then be used to discriminate land use classes. Temporal backscatter profiles show that a good discrimination of vegetated areas (grassland, agriculture, forest) is achieved from October to May. Further results from this investigation demonstrate that the C-VV band of ERS-1 is sensitive to age (and therefore closely related parameters such as tree height, woody biomass) in young deciduous and coniferous forest stands. A synergetic relationship between optical and microwave data has been established. The combined data set allowed better differentiation of forest age classes, as compared to results obtained with the individual sensors. The results of this study add to the growing evidence of the valuable capabilities imaging radars have for the studying and monitoring of forests due to the demonstrated sensitivity to a variety of processes in vegetation ecosystems and the proven synergy to optical satellite data.

1. INTRODUCTION

Due to their weather independent operation there is a growing interest in utilizing imagery collected by imaging synthetic aperture radars (SAR), with the launch of the first European Space Agency (ESA) Earth Remote Sensing Satellite (ERS-1) in July 1991, the first Japanese Earth Resources Satellite (JERS-1) in February 1992, and the Canadian RADARSAT in 1995. Their data, acquired and archived on a regular basis, at short intervals, over the entire planet, will allow a variety of forest ecosystem characteristics to be monitored for the years to come. Compared to the multispectral capabilities of optical spaceborne sensors the information content of a single frequency SAR, such as the ERS-1 AMI may be limited for land and forestry applications. However, continuous spaceborne SAR coverage may provide more information than can be obtained with single or limited optical spaceborne observations. ERS-1 SAR data will actually allow eventual temporal gaps of optical coverage to be filled, as well as to ensure radar cost-efficient coverage of the site over the year. To take full benefit of these advantages it is now necessary to investigate the information content in ERS-1 SAR data under a variety of scene related and environmental conditions.

In the particular case of forests, the seasonal growing cycle resulting in leaf-on/leaf-off conditions, budding, cone emergence, leaf growth, branch growth, change of forest floor in composition, and understory cover, is expected to influence SAR backscatter. Especially important for the use of SAR for forest analysis is the sensitivity of radar backscatter to the water status of trees and understory, which can be affected by seasonal growth or senescence, and by external conditions such as insolation, water stress, temperature, floods, snow, rain, freeze, thaw, etc., as is clearly stated by theoretical models, ground measurements and previous remote sensing campaigns. The ability of microwaves to penetrate the outer part of forest canopies and be scattered by branches and trunks leads to the assumption that SAR sensors might be able to provide estimates of forest biomass or other stand attributes for both ecological investigations of carbon storage and as an economical source of forest management information. However, the success of any monitoring approach in observing longer term changes in forest attributes such as biomass level or successional stage depends on a sound understanding of the masking effects of meteorological, phenological and seasonal changes.

From that, The objectives of this study are to exploit multidate ERS-1 observations and a rich available ground truth data set in order to assess the information content of ERS-1 SAR data for forestry and other land applications, and especially to evaluate the potential for improved information extraction from multitemporal SAR data. Furthermore the combined use of optical and microwave spaceborne data should give insight into possible synergetic effects for qualitative and quantitative analysis of forest stands.

2. DESCRIPTION OF THE TEST-SITE, REMOTE SENSING DATA, AND GROUND TRUTH

Within a relatively small area, the Freiburg-Black Forest test-site in Southwest Germany represents in a unique manner landforms as well as geographical and climate units, typical for temperate Central European landscapes. The study area (about 30x30 km) stretches from France over the fertile Rhine valley with its submediterranean climate and its variety of agricultural crops, vineyards and forests, to the city of Freiburg in the centre of the area. From there it passes the western slope of the Black Forest, mostly covered with forest.

ERS-1 acquisitions (14 Single Look Complex (SLC) data sets delivered by the D-PAF, or by ESA/ESRIN) from the commissioning phase in 1991 and from the multidisciplinary phase in 1992/93 were selected to cover a variety of seasonal and therefore phenological stages and different meteorological conditions. All data were acquired at 10h20 GMT during ascending passes of the ERS-1 satellite. SPOT/XS from September 12, 1991 were also available, and have been used for the present study.

Meteorological data (e.g. precipitation, temperature, relative humidity) were compiled continuously from July 1991 onwards, by three meteorological stations of the German Meteorological Service. A digital elevation model (DEM) from the German Geodetic Survey was also available for the whole area.

Data analysis was made by selecting a wide range of well documented ground samples:

The analysis of multitemporal ERS-1 slant range SAR data was conducted using 40 test areas (forest, agriculture, grassland, built-up areas, water bodies). All test areas, each greater than 2.5 ha, were selected on flat terrain within the test site.

After geocoding, the multisensor (ERS-1, SPOT) analysis was performed using a forestry GIS from the inventory used for regular forest taxation in 1990 for a forest district in the Rhine valley and on the western slopes of the Black Forest. This data base covers about 6000 ha of forest including stand descriptions, species composition and age class. 960 forest stands (polygons) located on flat terrain were considered for data analysis.

3. PROCESSING CHAIN FOR ERS-1 DATA AND MULTISENSOR DATA FUSION.

The overall processing chain for ERS-1 (SLC) SAR data detailed below is especially designed to monitor the changes occurring to the scene at a high spatial resolution (Kattenborn et al., 1993). In developing this processing chain, emphasis was put on efficiency in terms of preservation of radiometric quality and spatial resolution, computation time, and data storage.

ERS-1 SAR data coregistration: For the first step of analysis, coregistration of the ERS-1 data was performed by shifting the frames in range and azimuth.

Data calibration: Changes in calibration constants introduced in the ESA/ESRIN and D-PAF ERS-1 SAR processors, on April 6th, and November 15th, 1992 were taken into account. Recent work shows that uncertainties in ERS-1 calibration are within ±0.8 dB (Lavalle, 1993). Antenna pattern and range spreading loss corrections (Laur et al., 1993) were also performed.

Spatial multilooking: The multilooking operation is done spatially by averaging the intensities of 5 consecutive pixels in the azimuth direction, then converting the resulting pixel value to amplitude by taking its square root. An overlapping of 1 pixel in azimuth is introduced, in order to preserve thin features present in the 1-look SLC data. The final equivalent number of looks (ENL) after this operation is L=4.8 looks in the resulting image. The pixel sampling is then approximately 16x16 meters, with a spatial resolution comparable to that of ERS-1 PRI data, but with a much better signal to noise ratio.

Data compression: Data compression is made by storing the multilooked image on linearly rescaled 8-bit amplitude data. The scaling factor, which is kept for further treatment in order to conserve data calibration, is determined using global statistics on strong scatterers. This way, saturation occurs only for very strong scatterers, mainly located within the urban areas which are not of interest for our study. Given the low values of these scaling factors (of the order of 1.5), the loss of radiometric accuracy during this operation is negligible within natural areas.

Restoration of the radar reflectivity: The next processing step consists of adaptive speckle filtering by means of the feature retaining Gamma-Gamma Maximum A Posteriori adaptive speckle filter, using an 11x11 processing window size for structures detection and an 9x9 processing window size for speckle filtering (Lopes et al., 1993). This operation allows a drastic speckle reduction from L=4.8 looks to an ENL of about L=300 looks. It restores the radiometric information with an error not exceeding, with 90% confidence level, ±0.35 dB in homogeneous (textureless) areas of the scene.

Geocoding and coregistration of ERS-1 SLC and SPOT-XS data: Geocoding of the ERS-1 SLC data was performed using orbit parameters provided with the ERS-1 data and the DEM with a resampling to SPOT pixel size of 20x20 m. Using a set of ground control points, the accuracy of geocoding was estimated to be 21.8 m in range and 9.8 m in azimuth direction, i.e. about one pixel in the map projected images. The SPOT data had been delivered in map projection (ortho-image) by ISTAR Ltd.

4. CHANGES IN RADAR BACKSCATTER WITH ENVIRONMENTAL PARAMETERS

Since some observational data suggest that the variability of SAR backscatter is related to changing environmental conditions (Dobson et al., 1991, Moghaddam et al., 1993, Way et al., 1993, Pulliainen et al., 1993), a statistical analysis was undertaken by calculating correlations between mean backscatter of test areas and meteorological parameters. In table 1, the linear correlation coefficients between precipitation measurements and mean backscatter values of three vegetated areas (grassland, agriculture and forest) and an urban area are presented. Precipitation measurements for time frames of 2, 4, 6, 8, 10 and 20 days before each ERS-1 acquisition were averaged, in order to characterise wet and dry periods before the acquisitions. This should allow to study the influence of varying moisture conditions on backscatter behaviour of different kinds of landuse classes.

These correlations show that the vegetated areas seem to react generally with an increase of backscatter (coefficients of correlations around 0.8 for precipitation averaged for 20 days) whereas the non-vegetated urban area shows no significant correlation with precipitation. There is possibly also a difference in the time response of backscatter to increasing available moisture, as can be seen from the higher correlation of agriculture for average precipitation of 2 or 4 days compared to the grassland and the forested areas.

Mean of	2 Days	4 Days	10 Days	20 Days
Forest	0.20	0.39	0.64	0.70
Grassland	-0.05	0.46	0.62	0.69
Agriculture	0.36	0.58	0.69	0.83
Urban	-0.18	0.00	0.38	0.32

Table 1: Correlation Coefficients Between Backscatter and Precipitation Averaged on Various Time Frames Before Each ERS-1 Acquisition.

Table 2 summarises the results from linear correlations between temperature at various times of the day and mean backscatter values of deciduous and coniferous forest stands. The ERS-1 backscatter of the three coniferous stands exhibit strong correlations to temperature, with maximum correlation coefficients to the last temperature measurement (09h00 GMT) before the ERS-1 acquisition (10h20 GMT). On the other hand, the mixed deciduous forest stand shows no significant correlation of ERS-1 backscatter to temperatures.

A theoretical study (Wegmüller et al., 1994) shows that C-band backscatter in ERS-1 configuration of coniferous trees decreases with decreasing temperature, leading to the high positive correlations in Table 2. This study also allows the backscatter behaviour of deciduous trees to be explained as the result of two opposite mechanisms. In late autumn and winter an increase of backscatter due to leaffall might be balanced by the decrease of backscatter due to change in trees' dielectric properties with decreasing temperatures. As a result of these opposite effects, no significant correlations are found in Table 2 for deciduous trees.

Temperature	06 h	09 h	12 h	15 h
Mixed Deciduous	0.39	0.28	0.24	0.20
Scot Pine	0.86	0.87	0.85	0.82
Scot Pine	0.81	0.82	0.80	0.77
Douglas Fir	0.73	0.77	0.75	0.71

Table 2: Correlation Coefficients Between Backscatter of a Mixed Deciduous, two Scot Pine and a Douglas Fir Stand and Temperatures at 6 h, 9 h, 12 h and 15 h GMT.

5. VEGETATION AND FOREST DYNAMICS USING ERS-1

Grassland, agriculture and forest, vegetated areas characterising a landscape, were used to study phenological and seasonal influences on ERS-1 backscatter evolution from which typical examples are presented. As can be seen from the temporal ERS-1 signatures in Fig. 1, discrimination of grassland (in this case natural vegetation) and agriculture is possible from October onwards. From the knowledge of local agricultural practice, the increase of backscatter for the agriculture area can be attributed to harvesting and soil treatment, which result in bare soil conditions during the winter period.

The same is also valid for the differentiation of forest and agriculture (Fig. 2), even if test areas are considered with a mixing of signatures during the summer period.

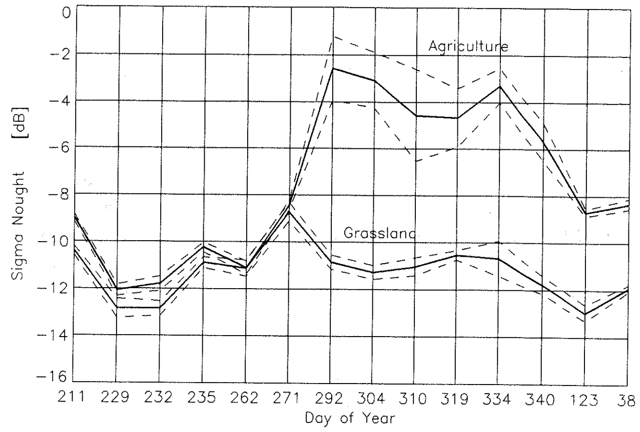

Fig. 1: Temporal Sequence of ERS-1 Backscatter for Agriculture and Grassland Test Areas.

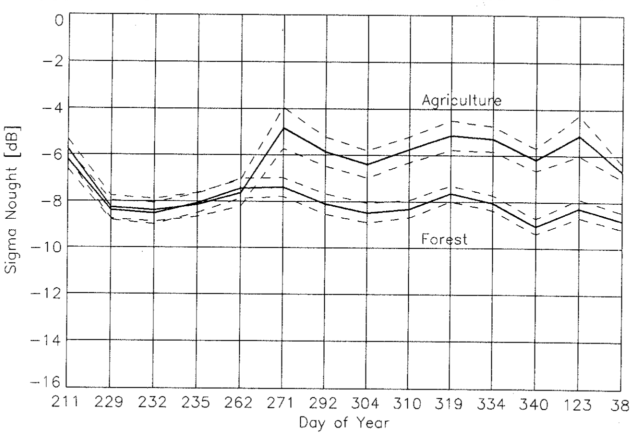

Fig. 2: Temporal Sequence of ERS-1 Backscatter for Forest and Agriculture Test Areas.

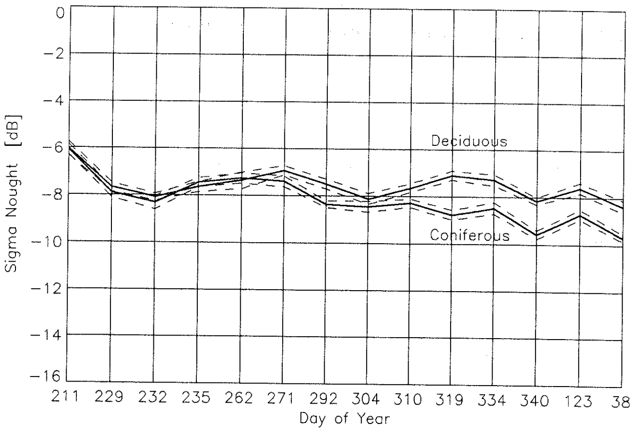

Fig. 3: Temporal Sequence of ERS-1 Backscatter for Deciduous and Coniferous Forest Test Areas.

Fig. 3 shows the comparison of the temporal ERS-1 signature of a mixed deciduous and a coniferous (spruce) stand. There is no clear indication of any effect of leaf fall on backscatter of deciduous trees in autumn and winter, whereas the coniferous stand exhibits a decrease of backscatter in these seasons. As stated above, the theoretical study of Wegmüller et al. (1994) provides an explanation of these phenomena. Similar experimental results have also been found by other authors concerning leaffall influences to backscatter (Pulliainen et al., 1991, Ahern et al., 1993), and decrease of the backscatter of conifers relative to deciduous during the winter period (Ahern et al., 1993).

To summarise the observations for all the vegetated test areas, Fig. 4 shows a plot of the ERS-1 backscatter range, defined as the difference between maximum and minimum measured backscatter of all acquisitions, versus the average ERS-1 backscatter value of all measurements. Generally, different target groups i.e. different combinations of high or low average backscatter and high or low dynamic range can be distinguished. Woody plants/forests form a group with high backscatter and a low dynamic range of backscatter over the seasons. In this group conifers show the highest dynamic range while young stands show the lowest average backscatter. Herbaceous vegetation (grassland) has a low average backscatter and medium dynamic range. Agriculture has the highest dynamic range of backscatter due to the influence of cultivation practices. A separation of woody and herbaceous vegetation and also of different accumulations of biomass seems to be possible using this representation.

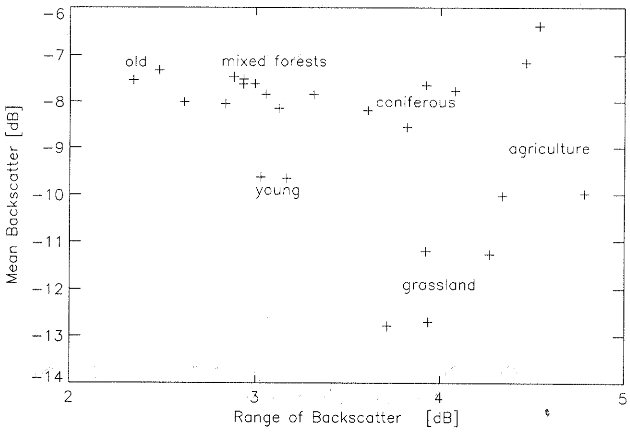

Fig. 4: Average ERS-1 Backscatter Versus Range of ERS-1 Backscatter of All ERS-1 Acquisitions for Different Vegetated Test Areas.

In order to confirm the conclusions drawn from Fig. 4, two statistical tests have been performed. The first test consists of the computation of an index of separability (Dobson et al., 1992). This test makes the assumption of Gaussian distributed classes. The second test consists of the computation of the probabilities of misclassification between classes, assuming that they are Gamma distributed (Nezry et al., 1993). Results of both tests showed up to be consistent.

As example table 3 summarises results of the probabilities of misclassification between the major classes of vegetated areas used until this stage of the study. It clearly appears that good discrimination of all the classes considered can not be achieved using only one ERS-1 acquisition. In general, better conditions for the separability of classes occur between October and May, due to combined seasonal, phenological, and cultivation practices influences on ERS-1 backscatter.

ERS-1 Date of Acquisition	Forest - Agriculture	Forest - Grassland	Agriculture - Grassland	Coniferous - Deciduous	Young - Old Forest
30/07/91	50.0	11.8	27.9	50.0	19.2
17/08/91	50.0	10.7	50.0	50.0	13.3
20/08/91	50.0	14.0	36.7	50.0	11.2
23/08/91	50.0	21.4	40.0	50.0	17.6
19/09/91	50.0	22.4	50.0	50.0	21.4
28/09/91	30.1	35.4	50.0	50.0	31.4
19/10/91	30.7	20.3	7.3	36.5	21.9
31/10/91	31.5	21.3	5.9	50.0	25.4
06/11/91	26.8	19.4	17.7	40.1	28.7
15/11/91	27.8	18.2	13.3	26.7	23.9
30/11/91	24.6	14.9	7.5	34.2	17.6
06/12/91	23.2	13.3	11.5	27.7	12.1
03/05/92	26.2	10.4	6.4	34.6	18.3
07/02/93	27.2	16.4	7.1	30.9	26.1

Table 3: Results (in Percentage) of the Test of Probability of Misclassification for Pairs of Major Land Use Classes (50.0 Means No Separability).

6. RETRIEVAL OF FOREST STAND ATTRIBUTES WITH ERS-1 AND SPOT/XS DATA

After multisensor/multitemporal data fusion, , the possibility of retrieval of forest stands attributes was investigated using GIS information and combined SPOT and ERS-1 data. Since, according to the German forest taxation practice, biomass is not generally estimated for young forest stands, age information provided for all forest stands by the GIS was considered for this study. Stand age is known to be, in general, correlated to important physical forest stand attributes.

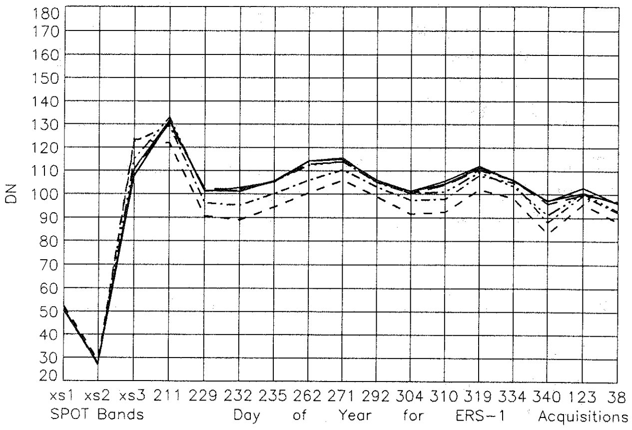

Fig. 5: SPOT Reflectivity and Temporal Sequence of ERS-1 Backscatter Averaged for Forest Age Classes 1-10, 11-20, 21-30, 81-90, 91-100, 101-110 Years (Bottom to Top). For Better Comparison SPOT and ERS-1 Signatures are Represented in Digital Numbers.

The response of forest age classes to SPOT spectral bands and to the ERS-1 time series are depicted in Fig. 5. SPOT XS1 and XS2 bands show no apparent sensitivity to age of forest stands. The SPOT/XS3 band shows decreasing reflectance for increasing forest age. On the contrary, ERS-1 radar reflectivity increases with forest age, until saturation is reached after about 30-40 years. A very interesting fact, and also potentially useful for applications, is that this behaviour remains stable. Seasonal and environmental influences affect only, and almost in the same amount, the absolute mean level of radar reflectivity of forest age classes.

Capabilities of SPOT/XS3 and ERS-1 data for discriminating stands of different ages were examined by calculating the linear correlation coefficients between forest backscatter and age for four cases (Table 4):

* correlation between age (all age classes, from 1 to 160 years) and mean backscatter of forest stands, not differentiating species composition,

* correlation between age (all age classes, from 1 to 160 years) and filtered pixel values on forest stands, not differentiating species composition,

* correlation between age (only age classes from 1 to 30 years) and filtered pixel values on forest stands, not differentiating species composition,

* correlation between age (only age classes from 1 to 30 years) and filtered pixel values on the same stand type (i.e. same species or species composition).

As expected from Fig. 5, the low correlation coefficients obtained (Table 4) in the first two cases prove that neither SPOT nor ERS-1 allow complete discrimination of age classes from 1 to 100 years. In the last two cases, if only the first three age classes (from 1 to 30 years) are considered, then a very high correlation is observed between age and ERS-1 (all acquisitions) or SPOT/XS3 signals, for either not differentiating species composition or the example of a special stand type such as red oak.

	Polygon Based	Pixel Based		
	All Stand Types			Red Oak
	1 - 100 Years	1 - 100 Years	1 - 30 Years	1 - 30 Years
SPOT/XS3 12/09/91	- 0.09	- 0.43	- 0.91	- 0.98
ERS-1				
30/07/91	0.15	- 0.20	0.98	0.89
17/08/91	0.20	0.22	0.99	0.96
20/08/91	0.25	0.28	0.99	0.97
23/08/91	0.19	0.16	0.99	0.99
19/09/91	0.21	0.09	0.99	0.95
28/09/91	0.16	0.04	0.99	0.95
19/10/91	0.16	- 0.07	0.99	0.98
31/10/91	0.18	- 0.03	0.97	0.99
06/11/91	0.17	0.52	0.98	0.93
15/11/91	0.15	0.08	0.94	0.93
30/11/91	0.13	0.19	0.73	0.92
06/12/91	0.23	0.28	0.99	0.98
03/05/92	0.12	- 0.11	0.94	0.93
07/02/93	0.18	0.20	0.91	0.93

Table 4: Correlation Coefficients Between Backscatter of Forest Age Classes (1-100 Years) and Age in one SPOT and 14 ERS-1 Scenes on per Polygon Base, on per Pixel Base, on per Pixel Base for Only the First Three Age Classes (1-30) and on per Pixel Base for the First Three Age Classes of a Red Oak Stand.

The opposite signs of the correlation coefficients between forest backscatter and age class exhibited by SPOT/XS3 and ERS-1 indicate a possible synergy of both sensors for retrieval of forest stand age. Thus, a fusion of the data has been tried by simply using a ratio of the SPOT/XS3 image radiometry and the rescaled filtered ERS-1 amplitude. These ratios of SPOT/XS3 to every ERS-1 acquisition were statistically evaluated by computing the linear correlation coefficients to age classes. Results are given in Table 5 for non-differentiating species composition and for a special stand type (ash). By showing fairly good correlations for forest age ranging from 1 to 100 years, the results in Table 5 indicate a superior sensitivity of this SPOT/X3 to ERS-1 ratio index to age classes compared to each single sensor.

	Ratio SPOT XS3/ERS-1	
ERS-1 Date of Acquisition	For All Stand Types 1 - 100 Years	For Ash 1 - 100 Years
30/07/91	- 0.75	- 0.67
17/08/91	- 0.77	- 0.75
20/08/91	- 0.76	- 0.75
23/08/91	- 0.75	- 0.77
19/09/91	- 0.80	- 0.77
28/09/91	- 0.78	- 0.78
19/10/91	- 0.75	- 0.66
31/10/91	- 0.76	- 0.74
06/11/91	- 0.82	- 0.86
15/11/91	- 0.79	- 0.87
30/11/91	- 0.78	- 0.75
06/12/91	- 0.87	- 0.82
03/05/92	- 0.77	- 0.83
07/02/93	- 0.79	- 0.89

Table 5: Correlation coefficients between ratio of SPOT/XS3 and ERS-1 for 14 ERS-1 acquisitions of forest age classes 1-12 and age without differentiation of stand type and of forest age classes 1-10 and age of an ash stand on per pixel base.

7. SUMMARY AND CONCLUSIONS

The results of this study add to the growing evidence of the valuable capabilities imaging radars have for the studying and monitoring of forests due to the sensitivity of radar to a variety of processes in vegetation ecosystems and the proven synergy to optical satellite data.

The changes in backscatter observed by the ERS-1 SAR have been confirmed to be related to the variation of meteorological parameters (i.e. precipitation, temperature) for different landuse. It confirms that the temporal sequence of the C-band reflectivity of vegetated areas measured by ERS-1 appear to be sensitive to changes in moisture conditions as already stated by Hsu et al. (1993), and effects of temperature on dielectric properties (Wegmüller et al., 1994). Long term variations due to phenological and seasonal effects can then be used to discriminate land use classes. Temporal backscatter profiles show that a discrimination of vegetated areas (grassland, agriculture, forest) is achieved from October to May. In conclusion, high spatial resolution monitoring of vegetated surfaces, forest conversion into cultivated or bare soils, or agriculture management is possible using multitemporal ERS-1 data.

The results from this investigation demonstrate that the C-VV band of ERS-1 is sensitive to age (and therefore closely related parameters such as tree height, woody biomass) in young deciduous and coniferous forest stands of temperate zones. This capability can be important for forest ecology studies. First, information about the population and growth dynamics of successional sequences on burned areas, clearings etc. can be important for prognosis about future growth and population development (patterns). Second, boreal forests are often characterised by low biomass levels, comparable to that of the young stands used in this investigation. Therefore, ERS-1 SAR could be sensitive to changes in these ecosystems.

Since this study also indicated a high sensitivity of C-band backscatter to effects of temporally varying environmental conditions, these effects may mask backscatter variations due to differences of forest stand parameters. This is an indication that complex methods of model inversion including both the complex scattering mechanisms of forest stands and the effects of variations in environmental conditions must be developed.

A synergistic relationship between optical and microwave data has been established. The combined data set provided a combination that allowed better differentiation of forest age classes, as compared to results obtained with the individual sensors. A ratio of optical SPOT/XS3 reflectance and ERS-1 backscatter showed higher sensitivity to stand age due to the opposite optical reflectance/radar reflectivity behaviour of forest canopies in IR and C-band frequencies. Age differences, however, are not directly detected. Rather, it is the different tree and stand characteristics (e.g. foliar vigor, quantity and distribution, tree height, stem and branch size, standing biomass and canopy structure) of differently aged stands which will result in different optical and microwave signatures.

In the future, additional efforts should be undertaken in order to establish efficient strategies for monitoring forest conditions and for retrieval of forest biophysical attributes using combinations of a variety of spaceborne sensors. These include:

- in improving understanding of both radar and optical data (e.g. the influence of topography on measured signals),
- in relating changes occurring in spaceborne SAR time series to spaceborne optical monitoring data.

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