Usefulness of ERS coherence time series for monitoring the vegetation cycle of a mixed deciduous forest

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ABSTRACT
The usefulness of ERS Tandem coherence time series for monitoring the seasonal dynamics of a mixed temperate forest is analyzed. Firstly, we present the experimental approach conducted on the Fontainebleau forest. Thanks to a theoretical work, a first explanation of the temporal variations of the interferometric coherence over deciduous trees is then given.

INTRODUCTION
Recent studies, based on measurements of atmospheric CO2 concentrations and on the use of atmospheric transport model, have suggested that temperate ecosystems, particularly forests, might presently act as major carbon sinks. This would mainly result from a human-induced effect of CO2 fertilization on forest growth [1]. However, large uncertainties still exist for determining whether carbon sink or source occurs in temperate deciduous forests [2]. In this context, the potentialities of space-borne Synthetic Aperture Radars (SARs) for monitoring forest ecosystems must be investigated. Today, few studies are concerned with temperate deciduous forests. In addition, they all suffer from a lack of experimental data both in radar time series and in the associated relevant ground data [3]. In the present study, we have conducted experiments to complete the assessment of the potentialities of ERS C-band system for the analysis of temperate forest dynamics. As we have shown before [4], the usefulness of ERS C-band backscattering coefficients was not demonstrated for this purpose. However, using interferometric coherence information, some studies have recently shown interesting results for retrieving structural parameters of boreal forests [5]-[7], but they have also pointed out the need for a better understanding of interferometric signatures of forests [8].

The present paper aims to evaluate the relevance of ERS-1/2 SAR instruments for monitoring temporal and structural changes in a mixed temperate forest ecosystem. Emphasis is put on the capability of InSAR time series for detecting the leafy cycle of a deciduous forest. Firstly, we present our experimental approach consisting of the processing of 9 interferograms and the analysis of coherence images versus forest parameters. Secondly, after describing the coherent model we have used in this work, a first explanation of the seasonal coherence signatures is proposed.
SITE DESCRIPTION AND DATABASES

The Fontainebleau forest

The Fontainebleau forest, located 70 kilometers southeast of Paris (48°25' N, 2°40' E) has been intensively used for remote sensing studies [4;9-11]. On a relatively flat topography with large stands of about 10 ha, the site captures the main characteristics of a mixed temperate deciduous-coniferous ecosystem. Particularly, the deciduous stands exhibit a large dynamics of wood biomass with values ranging from 10 to 500 tons of dry matter per hectare as well as a high seasonal variation of leaf biomass between winter and summer.

Besides the inventory measurements aimed at determining the structural parameters of about 55 test stands, intensive measurements were performed during each overpass of ERS-1/2 satellites [4]. The field campaigns consisted of measurements of ephemeral biological parameters like the PAI (Plant Area Index) or the leaf water content for three representative test stands (oaks: C08, beeches: H13; pine trees: P08). As an illustration, Fig.1 shows the seasonal variation of the Plant Area Index (sum of Leaf Area Index and Wood Area Index) measured during the 96-growing season for oak, beech and pine trees, respectively. Throughout the year, deciduous trees exhibit a well-pronounced seasonality, characterized by the leaf-on in April and the leaf-off in November. On the whole, maximum Leaf Area Index (LAI) is reached 4-6 weeks after leaf-on and ranges from about 1 to 8, depending on stand development. For coniferous trees, LAI shows minimum values in winter and maximum values in July, ranging from 1 to 7. A detailed description of the forest and the associated ground data can be found elsewhere in [4] and [9].

This forest was used as a test site during several airborne and space-borne campaigns such as EMAC-94 (http://www.estec.esa.nl/vrwww/emac/). Within the frame of these campaigns, we have developed a large remote sensing database dedicated to experimental studies and model validation. Among the data available, 45 ERS-1/2 SAR intensity images were acquired from April 1994 to January 1997 (figure 2). The results obtained from the temporal analysis of the ERS-1/2 backscattering coefficients can be found in [4]. Particularly, the modeling work gives us a better understanding of the seasonal signatures of the C-band backscattering coefficient. Based on this previous result, we now try to interpret the interferometric coherence signatures of the Fontainebleau forest.
Tandem ERS-1/2 database

The interferometric data acquired over the Fontainebleau forest include 9 Tandem pairs provided under the Single Look Complex format. We have focused on 1-day time interval acquisitions provided by all the ERS Tandem pairs available on the Fontainebleau forest during a year-period from August 1995 to July 1996 (Table 1). The perpendicular components of all tandem baselines range from 27 m to 256 m.

<table>
<thead>
<tr>
<th>Pair</th>
<th>Phenological State</th>
<th>ERS-1 date</th>
<th>Incidence angle (°)</th>
<th>Baseline (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Max. LAI</td>
<td>06 Aug. 95</td>
<td>22.75</td>
<td>83</td>
</tr>
<tr>
<td>2</td>
<td>LAI max.</td>
<td>15 Oct. 95</td>
<td>22.75</td>
<td>256</td>
</tr>
<tr>
<td>3</td>
<td>LAI max.</td>
<td>19 Nov. 95</td>
<td>22.75</td>
<td>168</td>
</tr>
<tr>
<td>4</td>
<td>LAI max.</td>
<td>24 Dec. 95</td>
<td>22.75</td>
<td>185</td>
</tr>
<tr>
<td>5</td>
<td>Max. LAI</td>
<td>03 Mar. 96</td>
<td>22.75</td>
<td>35</td>
</tr>
<tr>
<td>6</td>
<td>LAI max.</td>
<td>19 Mar. 96</td>
<td>26.5</td>
<td>27</td>
</tr>
<tr>
<td>7</td>
<td>Bud burst</td>
<td>23 Apr. 96</td>
<td>26.5</td>
<td>82</td>
</tr>
<tr>
<td>8</td>
<td>LAI max.</td>
<td>28 May 96</td>
<td>26.5</td>
<td>103</td>
</tr>
<tr>
<td>9</td>
<td>Max. LAI</td>
<td>02 Jul. 96</td>
<td>26.5</td>
<td>70</td>
</tr>
</tbody>
</table>

Table 1: Acquisition parameters for the 9 Tandem pairs.

Thanks to the DIAPASON software developed at the Radar Department of CNES, we processed the 9 coherence images. The coherence $\gamma$ is calculated as:

$$\gamma = \frac{\left| g_{ERS-1} \cdot g^*_{ERS-2} \right|}{\sqrt{\left(g_{ERS-1} \cdot g^*_{ERS-1}\right) \left(g_{ERS-2} \cdot g^*_{ERS-2}\right)}}$$

(1)

where $g_{ERS-1}$ et $g_{ERS-2}$ indicate complex pixel values of the referenced ERS system. A spatial expectation over a 25 (azimuth) by 5 pixels window has been performed, insuring unbiased expectation of coherence values [7] and [12]. To compare the coherence estimates on forested areas within a time-series, a normalization process has to be carried out [13]-[15]. The different factors of spatial and temporal decorrelation are analyzed and, particularly, the effect of baseline is compensated [16].

EXPERIMENTAL APPROACH

Influence of forest structure

Fig. 3 shows the variation of the coherence $\gamma$ versus total aboveground biomass (expressed in tons of dry matter per hectare) of deciduous and coniferous stands. Overall, there is a negative relationship between the coherence $\gamma$ and total biomass. The statistical correlation coefficients of the different logarithmic relationships between $\gamma$ and total biomass are smaller than 0.5 and 0.8 for deciduous and coniferous stands, respectively.

Furthermore, it is observed a seasonal dependence of the relationships between coherence and biomass. For deciduous species, $\gamma$ is a decreasing function of biomass in winter and autumn whereas it is almost independent of biomass in spring and summer. The leaf number, increasing volume scattering, is certainly one of the main driving factors of decorrelation. The absence of leaf therefore explains the highest coherence values observed during the winter season and the presence of leaves explains the lowest and stable coherence profile during summertime (where the number of leaves is maximal). Today, these results are not fully understood and need to be interpreted by a sensitivity analysis using a coherent model [17].

For coniferous species, the trends are all decreasing but compared to deciduous trees, the slopes are higher, especially in autumn. The increase of volume scattering as a function of biomass might certainly explain the $\gamma$ decreasing profiles. Because the seasonality of LAI for conifers is not as marked as that of deciduous trees (needles are present at any season) (Fig. 1), the observed seasonal variations need to be understood by taking into account other temporal changes occurring in the forests (e.g. in soil moisture).
Fig. 3: Decorrelation versus total biomass for deciduous trees and conifers. The mean trends are given for the 4 seasons. Only experimental data of wintertime are plotted.

Influence of seasonal changes in forests

Deciduous species

Fig. 4 shows the seasonal variation of coherence for 4 different forest structural types (thickets, pole, mature, seed trees stands) corresponding to different total biomass of 30 t.DM ha$^{-1}$, 120 and 95 t.DM ha$^{-1}$, 310 and 150 t.DM ha$^{-1}$, 200 and 85 t.DM ha$^{-1}$ for deciduous and coniferous trees, respectively. On the whole, seasonal variation of coherence is well pronounced. The highest coherence values are observed in winter when leaves are absent whereas low and constant values of about 0.2-0.25 are found in spring and summer after leaf emergence. The decrease of coherence occurs during the period of leaf-on in March-April and an increase in coherence values is found again in autumn during leaf-fall.

Fig. 4: Seasonal decorrelation observed over 4 different stand development. The tendency lines are also indicated. A seed trees stand is characterized by a sparse distribution of big trees.
Furthermore, the seasonal variation of coherence strongly depends on stand development. The $\gamma$ dynamic range is high for the youngest stands with low biomass whereas mature stands with high biomass exhibit a smaller dynamic range. This mainly results from the winter coherence values, which decrease as biomass increases. Besides, the summer values are almost identical at about 0.2, indicating no correlation at all. Indeed, this value corresponds to minimal ERS system signal to noise ratio.

Coniferous species

The seasonal variation of coherence for conifers is compared to that of deciduous trees (Fig. 4). Surprisingly, the seasonal variation is quite the same for both tree types. However, the same interpretation does not hold since pine trees as evergreen trees do not exhibit large phenological variation throughout the year (see Fig. 1). Other factors of decorrelation including dielectric changes in canopy and soil must therefore be analyzed.

Influence of soil contribution

As for backscattering coefficients, the importance of soil contribution to the scene coherence is a function of both the moisture status of the soil surface and the attenuation by the vegetation layer. This was demonstrated for $\sigma^o$ on the Fontainebleau test site using multitemporal ERS data combined with a backscattering model [4]. For a beech stand, the analysis of the different contributions shows that the decrease in backscattering from January to March is mainly due to the drying of the soil surface (Fig. 5).

In contrast, leaf emergence leads to an increase of about 2 dB during a short period when leaves contain a high percentage of water. Meanwhile, the contribution of the soil drops down due to the high attenuation by the foliage. As well, the seasonal profile of coherence results from the contribution of each forest component at a given season. In winter, high values of coherence can be related to the high moisture content of the soil surface and low coherence values can be related to both the presence of leaves and the small contribution of the dry soil surface.

For conifers, the seasonal variation of backscattering was not yet simulated. However, one can observe similar temporal profiles between coherence and soil water content. The higher the soil humidity is, the higher the coherence value. The soil contribution is expected to be more important than for deciduous because the pine tree stand is more open than the beech stand.

Fig. 5: Comparison between simulated $\sigma^o$ and ERS-1/2 data for the H13 beech reference stand (from [4]).

Influence of foliage

The variation of mean summer coherence values as a function of maximum of Leaf Area Index measured during summertime is plotted on Fig. 6. As expected, $\gamma$ is a decreasing function of the foliage biomass. However, the sensitivity of coherence is weak, of the order of 0.025 per LAI unity.

![Fig. 6: Variation of coherence versus maximum of Leaf Area Index measured during summertime.](image)

THEORETICAL APPROACH

Model description

The basic idea is to simulate a forest scattering scene by giving the positions, sizes, density and orientations of each element category to be included within one resolution cell [17]. The forest is divided in 3 horizontal layers above a rough dielectric interface representing the soil surface. Each layer contains discrete scatterers in a free space. The radar response is calculated with a Monte Carlo technique by adding together the complex individual scattered fields from all of the scatterers positioned within a given resolution cell. This single scattering model treats all the scatterers independently. As such, the incident wave is not the same for all the scatterers but differs in phase depending on the propagation distance to each one. The incident field takes also into account attenuation due to the different layers encountered during the propagation path before the interaction. The same treatment is applied to the scattered wave returning back to the radar. Coherency loss can be introduced as well, but here it is found to be insignificant. These inputs of the model are derived from in-situ forest measurements [4].

Deciduous and coniferous leaves are modelled respectively by elliptic shaped discs and needles. Scattering matrices function for leaves are calculated using the generalised Rayleigh-Gans approximation which assumes that one scatterer’s dimension is very small compared to the incident wavelength. Branches and trunks are modeled by a finite dielectric circular cylinder with the exact scattering matrix. The relative permittivity $\varepsilon_r$ of the scatterers is estimated with the dual-dispersion model given by Ulaby and El-Rayes [18]. The branches and the leaves may be separated into different groups according to their sizes. Each branch and leaf group has its own orientation distribution.

The Integral Equation Method (IEM) is used for modelling the rough soil surface interaction to calculate the amplitude of the scattered field [19]. Correlation length, standard deviation height and the permittivity of the soil are the only parameters required.

A realistic measurement configuration and processing of the different cells has been considered. As such, each ground range resolution cell is viewed with a little different angle and contains a realisation of the forest scene according to the statistical forest characteristics. Since the repeat pass mode of ERS-1/2 Tandem acquisitions imposes different viewing geometry, the ability of our model to simulate different baselines and window sizes configurations is of prime interest.

The total scattered field at both receivers can be decomposed into ground, branches and leaves contributions:
\[ E_{s1,2} = E_{g1,2} + E_{b1,2} + E_{t1,2} \]  \hspace{1cm} (2)

The correlation coefficient \( \gamma \) is then calculated as:

\[ \gamma = \frac{\sum_{i=1}^{N} (E_{g1} + E_{g2} + E_{g3} + E_{g4}) \cdot (E_{g1} + E_{g2} + E_{g3} + E_{g4})^*}{\sqrt{\sum_{i=1}^{N} |E_{g1}(i)|^2 \cdot \sum_{i=1}^{N} |E_{g2}(i)|^2}} \]  \hspace{1cm} (3)

\[ \gamma = \frac{\sum_{i=1}^{N} (E_{g1} \cdot E_{g2}^* + E_{g3} \cdot E_{g4}^* + E_{g1} \cdot E_{g2}^* + E_{g3} \cdot E_{g4}^* + \ldots)}{\sqrt{\sum_{i=1}^{N} |E_{g1}(i)|^2 \cdot \sum_{i=1}^{N} |E_{g2}(i)|^2}} \]  \hspace{1cm} (4)

Since ensemble averaging of the crossed terms \( E_{g1}^* \cdot E_{g2} \) should make them cancel out, we finally obtain the equation:

\[ \gamma = \lambda_g + \lambda_b + \lambda_f \]  \hspace{1cm} (5)

where \( \lambda_g = \frac{\langle E_{g1}E_{g2}^* \rangle}{\langle |E_{g1}| \cdot |E_{g2}| \rangle} \cdot \lambda_b = \frac{\langle E_{g3}E_{g4}^* \rangle}{\langle |E_{g3}| \cdot |E_{g4}| \rangle} \cdot \lambda_f = \frac{\langle E_{g1}E_{g2}^* \rangle}{\langle |E_{g1}| \cdot |E_{g2}| \rangle} \cdot \lambda_t = \frac{\langle E_{g3}E_{g4}^* \rangle}{\langle |E_{g3}| \cdot |E_{g4}| \rangle} \cdot \lambda_t = \frac{\langle E_{g1}E_{g2}^* \rangle}{\langle |E_{g1}| \cdot |E_{g2}| \rangle} .

The module of these quantities are plotted in Figure 7. The decreasing of coherence in spring can be attributed to the decreasing of soil moisture content and increasing of foliage attenuation. However, the soil contribution remains the most important component and therefore limits the effective detection of budburst. For low biomass stands, the soil moisture should impose its influence on the seasonal profile of coherence. For high biomass stands, the soil contribution is reduced and the decreasing of coherence in spring is not enough large for monitoring the foliage development. The 1996-year was characterized by a very dry period beginning early in spring. In normal conditions, soil moisture remains high until June and we expect the effect of leaf development to be discriminated from that of decreasing soil moisture.

Fig. 7: Comparison between simulated \( \gamma \) and Tandem ERS-1/2 coherence measurements for the H13 beech reference stand. Foliage, wood and soil contributions to the total simulated coherence are also indicated.

CONCLUSION

The objective of the present paper was to analyze the potentialities of coherence time-series for monitoring the temporal changes of a mixed temperate forest. Firstly, the experimental approach has shown decreasing relationships between the coherence values and the forest biomasses. However, these relationships are seasonally dependent. For youngest stands, the seasonal variation is very marked whereas for mature stands, the trend remains stable. Besides, the lowest values of coherence are observed in summertime for all the forest stands. Surprisingly, the trends observed are quite the same for both deciduous and pine trees.

The interpretation of such signatures requires an experimental-theoretical approach. Particularly, we have to investigate the importance of the contributions of the different forest components on the coherence signature, e.g., forest structure, soil moisture and foliage development. In this way, the Fontainebleau forest is a test site of prime interest.

AKNOWLEDGMENTS

This work was financially supported by the Radar Department of the French Space Agency (CNES). We would like to thank Jean Claude Souyris, for his permanent interest and support for our research works within the frame of the Fontainebleau project.

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