K&C Science Report – Phase 1

Forest Height Estimation by means of Pol-InSAR

Limitations posed by Temporal Decorrelation

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***Abstract* — Polarimetric Synthetic Aperture Radar (SAR) Interferometry (Pol-InSAR) is a radar remote sensing technique, based on the coherent combination of radar polarimetry (Pol-SAR) and SAR interferometry (InSAR) which is substantially more sensitive to structural parameters of forest volume scatterers (e.g. forest) than conventional interferometry or polarimetry alone. However, temporal decorrelation is probably the most critical factor towards a successful implementation of Pol-InSAR parameter inversion techniques in terms of repeat-pass InSAR scenarios. This report focuses on the quantification of the effect of temporal decorrelation at L-band as a function of temporal baseline based on multi-temporal airborne experimental data acquired in the frame of dedicated air-borne experiments. Conclusions on the suitability of ALOS/PalSAR for Pol-InSAR applications are drawn and recommendations for mission characteristics of a potential follow on mission are addressed.**

***Index Terms*—ALOS PALSAR, K&C Initiative, Forest Theme, Polarimetric SAR Interferometry (Pol-InSAR), Forest Height Estimation, Temporal Decorrelation.**

I. INTRODUCTION

Towards a continuous quantitative forest monitoring, information about horizontal and vertical structure and/or about integrative forest parameters such as forest biomass is essential. In contrast to qualitative applications, quantitative approaches by means of SAR are less developed especially in tropical environments due to the limited data availability and the complexity of such environments. Most of the quantitative approaches are developed on temperate and/or boreal test sites where reference and validation data are easier to collect. The very different structure of tropical forests makes an offhand generalization not possible and requires dedicated experiments for development and validation. Pioneering work based on early airborne SAR experiments addressed tropical forest biomass classification and estimation hence demonstrating the potential of low frequency polarimetric SAR (PolSAR) measurements [3][4]. However, the complexity of radar scattering in forest environments makes the interpretation and inversion of individual SAR and PolSAR observables on the basis of empirical, semi-empirical or theoretical models difficult. The establishment of interferometric SAR (InSAR) techniques for forest monitoring in the late nineties triggered first InSAR experiments in the tropics that indicated the potential of interferometric observables at low frequencies for the estimation of vertical structure parameters [5][6][7][8][9].

Table 1: ALOS Quad-Pol Mode Parameters.

RF-centre frequency	*1.270 GHz (L-band)*
System bandwidth	*14 MHz*
Sampling Frequency	*16 MHz*
PRF	*1500-2500Hz*
Transmit Peak Power	*2 kW*
Incidence Angle	*21.5º (selective on 18.5 º)*
NE Sigma Zero	*< - 31dB*
Observation Swath	*30.6 Km (@ 21.5º)*
Range Resolution	*31.2m (ground range @ 21.5º)*
Azimuth Resolution	*20m (4 looks)*
A/D Convertion	*5bit*
Data Rate	*249 Mbps*
Repeat-Pass Time	*46 Days*

In the last years, the coherent combination of both, interferometric and polarimetric observations by means of Polarimetric SAR Interferometry (Pol-InSAR) was the key for an essential break through in quantitative forest parameter estimation [10][11]. Indeed, quantitative model based estimation of forest parameters - based on a single frequency, fully polarimetric, single baseline configuration - has been successfully demonstrated at L- and P-band and more recently even at X-band. Several experiments demonstrated the potential of Pol-InSAR techniques to estimate with high accuracy key forest parameters like forest height over a variety of natural and commercial; temperate, boreal and tropical test sites characterized by different stand and terrain conditions.

Validated results for boreal forests at X- and L-band are shown by [12] [11][13][14][15].

The launch of JAXA's ALOS in January 2006 provided - for the fist time since the SIR-C/X-SAR mission's in the 80's - the opportunity to acquire Pol-InSAR data from space. Indeed, PalSAR (i.e. the SAR instrument onboard of ALOS) is able to operate in a Quad-pol mode - declared by JAXA as an "Experimental Mode" - that allows the acquisition of Pol-InSAR data in a repeat-pass mode. The main characteristics of the PalSAR Quad-pol mode are summarized in Table 1. In this sense, ALOS-PalSAR allows the application, validation and development of Pol-InSAR inversion techniques on a much wider range of sites distributed world-wide and accessible to a much wider scientific user community than possible with airborne sensors.

A. *Importance of Forest Height*

An estimation of the 3-D forest structure allows retrieving quantitative forest parameters. One parameter providing information about the 3- D structure of forests is forest height, a key parameter for a wide range of applications in forest management and forest conservation, such as biomass estimation, illegal logging, stand delineation and disaster management.

Especially information about forest biomass and the detection of changes in forests on a global scale are highly valuable information. Forest height is correlated with biomass; this means by using allometric equations dependent on the ecosystem (boreal or tropical) biomass can be easily derived from forest height. Biomass is a parameter going directly into climatic modelling or carbon balancing and is therefore in a globally changing environment of high interest. In the frame of a changing climate, but also for the conservation of ecosystems and biodiversity a documentation of changes in forest ecosystems is essential. This includes the detection of forest clearings but also the detection of changes in the 3-D structure of forests for which height is an important parameter. Full area forest height maps resolve the horizontal forest canopy structure allowing a classification and evaluation of forest ecosystem. In contrary to this wood industry and forest management require quantitative forest information to guarantee a sustainable forest management and wood supply also here forest height is a basic parameter for the planning of logging activities.

Until now, quantitative information about forests is mainly based on the sampling of ground measurements. Their accuracy and reliability depend on the used grid and the uniformity of the forest. For remote forest types such as boreal or tropical forests, the available information becomes particularly poor due to a lack of measurements. Ground measurements are generally expensive and staff intensive. Therefore they are normally conducted only once every 10 years or more. 3-D remote sensing techniques could provide complete information in short time periods.

II. Project Description & Overview

ALOS provided, for the first time, the possibility to **demonstrate quantitative Pol-InSAR techniques from space**. This demonstration in terms of forest height estimation was the **core objective of the original project.** Based on repeat-pass fully polarimetric interferometric SAR data acquired by the ALOS/PalSAR sensor - during its early CAL-VAL phase - model based estimation of forest height was proposed. Towards higher estimation accuracy, the observation vector was planned to be extended including the two dual-pol single-baseline data sets acquired on the latter ALOS/PalSAR operation phase. There where three tasks foreseen:

Task 1: Inversion methodology development adapted / optimised to the actual ALOS/PalSAR acquisition scenario: I.e., a limited number of Quad-Polarimetric (Quad-pol), repeat-pass interferometric acquisitions with a temporal baseline of about 46 days. Assessment of the impact of temporal decorrelation on Pol-InSAR inversion techniques.

This task has been **successfully completed.** Using L-band airborne Pol-InSAR data acquired by DLR's E-SAR system in a repeat-pass mode an optimised methodology for the inversion of Pol-InSAR data affected by moderate levels of temporal decorrelation, has been developed. The performance of the developed methodology was validated in the frame of dedicated experiments/campaigns against ground-measurements, and Lidar data. **Unfortunately the 46 days temporal baseline of ALOS lead to severe temporal decorrelation that restricts dramatically the application of Pol-InSAR techniques**. The emphasis was then moved towards the assessment of temporal decorrelation levels at different temporal baselines ranging from days to weeks and the evaluation of its impact on forest height estimation techniques. The analysis, the results and the conclusions are reported in Section 3 & 4.

Task 2: ALOS/PalSAR data inversion and validation of the obtained forest height estimates over a limited number of selected test-sites. Evaluation of the performed estimation accuracy and feasibility assessment for global scale application. Evaluation of the option for the collection of a global data set for forest height mapping.

This task has been **completed.** Based on repeat-pass quad-pol interferometric SAR data acquired by the ALOS/PALSAR sensor during its early calibration/validation phase it was possible to demonstrate model based Pol-InSAR inversion over single isolated stands (see Figure 1). However, the high temporal decorrelation levels induced by the 46-day repeat-pass cycle reduce the estimation performance of forest structure parameters significantly and prevent the demonstration of Pol-InSAR inversion on a large scale.

The decorrelation levels are similar to the ones obtained in airborne experiments (see Task 1) for similar temporal baselines, a fact that can be seen as a validation of the ALOS-PalSAR sensor and data quality.

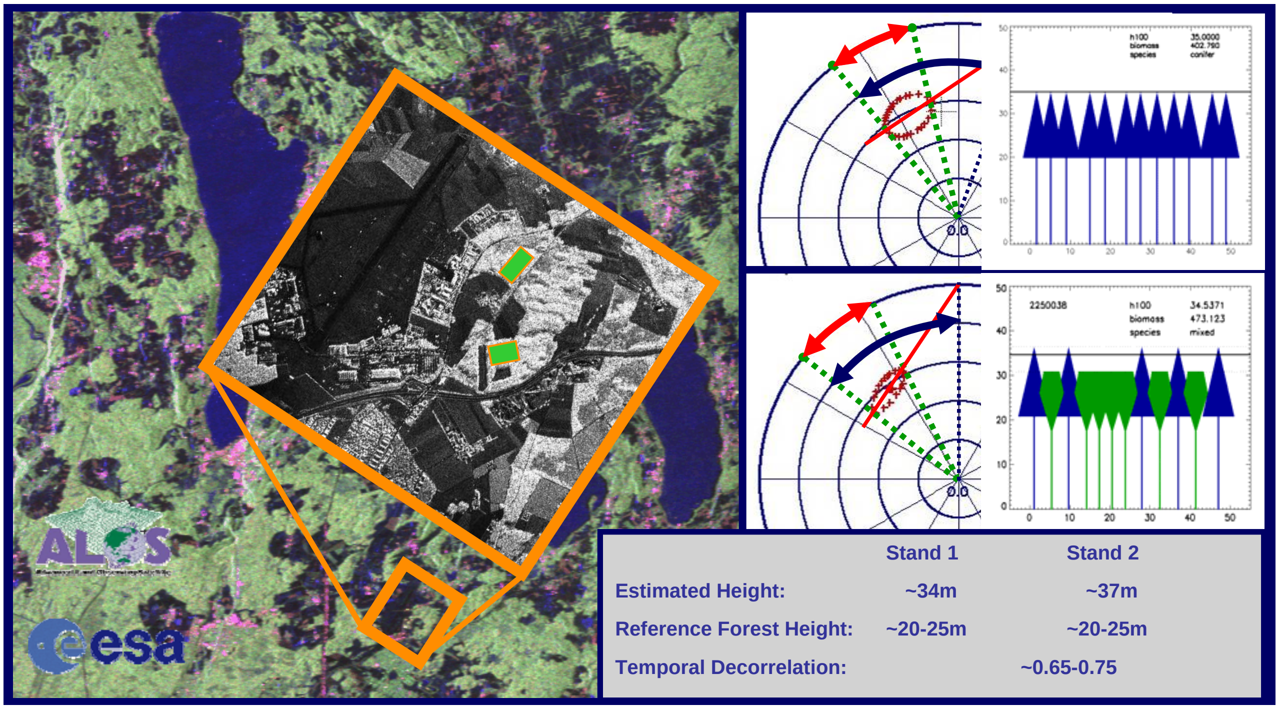

Figure 1: Forest height estimation for a mixed forest stands located within the Oberpfaffenhofen test site obtained from the inversion of dual-baseline Quad-Pol-InSAR ALOS-PalSAR data "© JAXA/METI".

Task 3: Inversion methodology development adapted to the Dual-pol ALOS/PalSAR global coverage acquisition scenario for an optimised forest height estimation performance on a global scale. The proposed methodology was proposed to be tested against ground measurements over selected test-sites worldwide in order to state about estimation accuracy and potential limitations.

This task has been **not-completed** because of the high temporal decorrelation levels that make quantitative Pol-InSAR inversion not meaningful. The very low coherence levels over forest areas degrade the value of interferometric information and make a successful performance of this task not possible.

III. Pol-InSAR Forest Height Inversion

The key observable used in Pol-InSAR applications is the complex interferometric coherence $\tilde{\gamma}$ (including both, the interferometric correlation coefficient and interferometric phase) measured/estimated at different polarizations (indicated by the unitary vector $\vec{w}$ [10][11]). $\tilde{\gamma}$ is given by the normalized cross-correlation of the two SAR images obtained from the interferometric acquisition s_1 and s_2

$$\tilde{\gamma}(\vec{w}) := \frac{< s_1(\vec{w}) s_2^*(\vec{w}) >}{\sqrt{< s_1(\vec{w}) s_1^*(\vec{w}) >< s_2(\vec{w}) s_2^*(\vec{w}) >}} \quad (1)$$

The coherence depends on instrument and acquisition parameters as well as on dielectric and structural parameters of the scatterer. A detailed discussion of system induced coherence errors can be found in [18]. After calibration of system induced decorrelation contributions and compensation of spectral decorrelation in azimuth and range the estimated interferometric coherence can be decomposed into three main decorrelation processes [19]:

$$\tilde{\gamma} := \tilde{\gamma}_{Temp}\ \gamma_{SNR}\ \tilde{\gamma}_{Vol} \quad (2)$$

-- Temporal decorrelation $\tilde{\gamma}_{Temp}$ can be real (i.e. effecting the absolute value of $\tilde{\gamma}$ only) or complex (i.e. biasing the phase of $\tilde{\gamma}$). It depends on the structure and the temporal stability of the scatterer, the temporal baseline of the interferometric acquisition and the dynamic environmental processes occurring in the time between the acquisitions.

-- Noise decorrelation γ_{SNR} introduced by the additive white noise contribution on the received signal [20][21]. It affects primarily scatterers with low (back-) scattering and is in general of secondary importance when looking on forest at conventional frequencies.

-- Volume decorrelation $\tilde{\gamma}_{Vol}$ is the decorrelation caused by the different projection of the vertical component of the scatterer into the two images $s_1(\vec{w})$ and $s_2(\vec{w})$. $\tilde{\gamma}_{Vol}$ is directly linked to the vertical distribution of scatterers $F(z)$ through a (normalized) Fourier transformation relationship

$$\tilde{\gamma}_{Vol} = \exp(i\kappa_z z_0)\frac{\int_0^{h_V} F(z')\exp(i\kappa_z z')dz'}{\int_0^{h_V} F(z')dz'} \tag{3}$$

where h_v is the height of the volume and κ_z the effective vertical (interferometric) wavenumber that depends on the imaging geometry and the radar wavelength λ

$$\kappa_z = \frac{\kappa \Delta\theta}{\sin(\theta_0)} \quad \text{and} \quad \kappa = m\frac{2\pi}{\lambda} \tag{4}$$

and $\Delta\theta$ is the incidence angle difference between the two interferometric images induced by the baseline. z_0 is a reference height and $\varphi_0 = \kappa_z z_0$ the corresponding interferometric phase. For monostatic acquisitions, as flown in the case of ALOS PalSAR, $m{:}=2$, while for bistatic acquisitions $m{:}=1$. Accordingly, $\tilde{\gamma}_{Vol}$ contains the information about the vertical structure of the scatterer and is therefore the key observable for quantitative forest parameter estimation [10][11].

The estimation of vertical forest structure parameters from interferometric measurements can be addressed as a two step process: In the first step (*modelling*) $F(z)$ is parameterized in terms of a limited set of physical forest parameters that are related through (3) to the interferometric coherence. In the second step (*inversion*), the volume contribution of the measured interferometric coherence is then used to estimate $F(z)$ and to derive the corresponding parameters. A widely and successfully used model for $F(z)$ is the so called Random Volume over Ground (RVoG), a two layer model consisting of a volume and a ground layer [22], which can be described as

$$F(z) = \tilde{m}_V\, e^{\left(\frac{2\sigma}{\cos(\theta_0)}z\right)} + m_G\, e^{\left(\frac{2\sigma}{\cos(\theta_0)}h_V\right)}\delta(z - z_0) \tag{5}$$

where m_V and m_G are the ground and volume scattering amplitudes and σ a mean extinction coefficient. Equation (5) leads to

$$\tilde{\gamma}_{Vol} = \exp(i\kappa_z z_0)\frac{\tilde{\gamma}_{V0} + m}{1 + m} \tag{6}$$

The phase $\varphi_0 = \kappa_z z_0$ is related to the ground topography z_0 and m the effective ground-to-volume amplitude ratio accounting for the attenuation through the volume $m = m_G/(m_V I_0)$. $\tilde{\gamma}_{V0}$ is the volume decorrelation caused by the vegetation layer only, given by

$$\tilde{\gamma}_{V0} = exp(i\kappa_z z_0)\frac{\int_0^{h_V} exp(i\kappa_z z')\,exp\left(\frac{2\ \sigma\ z'}{cos\theta_0}\right)dz'}{\int_0^{h_V} exp\left(\frac{2\ \sigma\ z'}{cos\theta_0}\right)dz'}\,. \tag{7}$$

Neglecting temporal decorrelation and assuming a sufficient calibration/compensation of system (e.g. SNR) and geometry (range/azimuth spectral shift) induced decorrelation contributions (6) can be inverted in terms of a Quad-pol single baseline acquisition [11],[13],[23],[24]. Assuming no response from the ground in one polarization channel (i.e. $m_3 = 0$) the inversion problem has a unique solution and is balanced with five real unknowns ($h_V, \sigma, m_{1-2}, \varphi_0$) and three measured complex coherences [$\tilde{\gamma}(\vec{w}_1)$ $\tilde{\gamma}(\vec{w}_2)$ $\tilde{\gamma}(\vec{w}_3)$] each for any independent polarization channel [23]

$$\min_{h_V,\sigma,m_i,\varphi_0} \left\| \left[\tilde{\gamma}(\vec{w}_1)\ \ \tilde{\gamma}(\vec{w}_2)\ \ \tilde{\gamma}(\vec{w}_3)\right]^T - \left[\tilde{\gamma}_V(h_V,\sigma,m_1)\ \ \tilde{\gamma}_V(h_V,\sigma,m_2)\ \ \tilde{\gamma}_{Vo}\,exp(i\varphi_0)\right]^T \right\| \tag{8}$$

Equation (8) is used to invert data sets at L-band using m_3=0 for regularisation. Note that the assumption for no ground response is not necessarily linked to the HV channel.

IV. The Effect of Temporal Decorrelation

Equation (6) accounts only for the volume decorrelation contribution of the interferometric coherence while other decorrelation effects are ignored. Such decorrelation contributions reduce the interferometric coherence, and increase the variation of the interferometric phase. The impact of such non-volumetric decorrelation effects is evaluated in the following. One has to distinguish between real and complex decorrelation contributions: Both of them bias (reduce) the absolute value of the interferometric coherence and increase variance of the interferometric phase. But, while complex decorrelation biases the expectation value of the (interferometric) phase, the expectation value remains the same in the case of real decorrelation.

A. Temporal Decorrelation

One of the most prominent decorrelation contributions in the case of non-simultaneous acquisition is temporal decorrelation caused by dynamic changes within the scene occurring in the time between the two acquisitions. Such changes can effect the location and/or the (scattering) properties of the scatterers within the scene inducing in the most general case a complex decorrelation.

Temporal changes within the scene occur, in general, in a stochastic manner and cannot be modeled accurately even when detailed information about the environmental conditions in the time between the two observations are available. The fact that everything within the scene may change and affect all or some of the polarimetric and/or interferometric observables in different ways make a general model-based consideration of temporal effects, if not impossible, very difficult.

Hence, temporal decorrelation effects - in the absence of detailed knowledge about the occurring dynamic process - can be incorporated in scattering models in a rather abstract way. Regarding Equation (6) model, temporal decorrelation may affect both, the volume component that represents the vegetation layer and the underlying ground layer

$$\tilde{\gamma}(\vec{w}) = \exp(i\varphi_0)\frac{\gamma_{TV}(\vec{w})\ \tilde{\gamma}_V + \gamma_{TG}(\vec{w})\ m(\vec{w})}{1+m(\vec{w})} \qquad (9)$$

γ_{TV} denotes the correlation coefficient describing the temporal decorrelation of the volume scatterer and γ_{TG} the correlation coefficient describing the temporal decorrelation of the underlying surface scatterer. As indicated, both coefficients may be polarisation dependent and complex: For example, changes in the dielectric properties of the canopy layer (due to changes in moisture content) or even more changes in its structural characteristics (caused by the annual phenological cycle or fire events) lead to different amount of change at different polarisations in the volume scatterer. Furthermore, a change in the dielectric properties of the ground scatterer - as for example due to a change in soil moisture - effects the scattering properties in each polarisation in a different way and leads to a polarisation dependent temporal decorrelation of the ground scatterer.

An important, and missing today, information is the behavior of γ_{TV} and γ_{TG} as a function of time. The decorrelation processes within the volume layer occur at different - in general much smaller - time scales than the decorrelation process on the ground (that includes both surface and dihedral scattering). While the vegetation layer starts already to decorrelate at temporal baselines on the order of seconds to minutes and is completely decorrelated for temporal baselines on the order of 1-2 months, the ground scattering remains partially coherent for even for baselines on the order of a half year. Especially dihedral scattering mechanisms - related in forest environments to the ground-trunk interaction - appears to be very stable in time and remain coherent even over the period of several months. However, the individual values and temporal characteristics of γ_{TV} and γ_{TG} are, of course, frequency dependent but depend also on the tree/stand canopy and architecture characteristics. The overall temporal decorrelation is then depending – according to Equation (9) – on the ground to volume ration *m* that defines the ratio of more to less temporal stable components. In other words, stands with a higher ground contribution are obviously expected to have a higher temporal coherence than stands characterized by a weak 'visible' ground scattering component.

From the parameter inversion point of view now, the RVoG model with general temporal decorrelation – as addressed in Equation (9) - cannot be solved under any (repeat-pass) observation configuration, as any additional measurement – at a different polarisation and/or baseline – introduces always two new unknowns, γ_{TV} and γ_{TG}. However, even if the general temporal decorrelation scenario leads to an under-determined problem, special temporal decorrelation cases may be accounted under certain assumptions, as it will be discussed in the next section.

B. Wind Induced Temporal Decorrelation

The most common temporal decorrelation effect over forested terrain is wind-induced movement of scatterers within the canopy layer as for example leaves and/or branches etc. In terms of the RVoG model, this corresponds to a change of the position of the scattering particles within the volume. However, in this case the scattering amplitudes as well as the propagation properties of the volume remain the same. Assuming further that the scattering properties of the ground do not change the RVoG model with temporal decorrelation in the volume component becomes [37][23]

$$\tilde{\gamma}_{Vol}(\vec{w}) = exp(i\kappa_z z_0)\frac{\gamma_{Temp}\tilde{\gamma}_{V0} + m(\vec{w})}{1+m(\vec{w})} \qquad (10)$$

The inversion of Pol-InSAR coherences contaminated by temporal decorrelation using Equation (6) by means of Equation (10) leads to overestimated forest height estimates: The lower coherence values (due to the temporal decorrelation) are interpreted by Equation (6) as to be caused by higher forest heights. Figure 2 shows the height error obtained by inverting Equation (10) for different levels of temporal decorrelation (γ_{Temp}=0.90 to 0.75) using Equation (6) as a function of forest height.

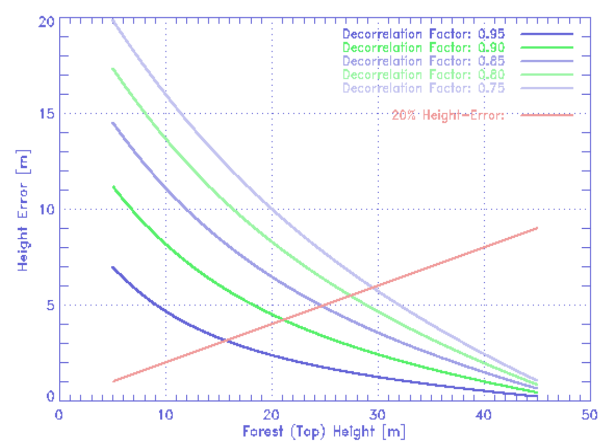

Figure 2: Height error induced by different levels of temporal decorrelation as a function of forest heights assuming as a vertical wavenumber of κ_z=0.1 rad/m.

A vertical wavenumber of κ_z=0.1rad/m has been assumed that corresponds to an 1100m horizontal spatial baseline for the ALOS Quad-pol mode. Clearly, one can see that the estimation errors induced by a constant level of temporal decorrelation are significantly higher for short than for high heights and that the errors increase with increasing temporal decorrelation. Note that even for low temporal decorrelation levels (on the order of 0.9) the height error is critical for low forest heights.

Figure 2 makes clear that for achieving acceptable height estimates temporal decorrelation has to be suppressed or compensated. Unfortunately, as already discussed, temporal decorrelation occurs in a stochastic manner within the scene [39] and can be only difficult accounted/modeled on the basis of detailed information about the environmental conditions over the time between the two observations. The first best option to reduce the impact of non-volumetric decorrelation contributions on the forest height estimation is to increase the volume decorrelation contribution with respect to the non-volumetric decorrelation by increasing the spatial baseline of the acquisitions. Figure 3 shows the height error obtained by inverting Equation (11) for different levels of temporal decorrelation (γ_{Temp}=0.90 to 0.75) using Equation (6) as a function of vertical wavenumber (and horizontal spatial baseline referred to the ALOS Quad-pol mode), assuming a constant forest height of 20m. Even for low temporal decorrelation levels (on the order of 0.9) the height error is critical at small baselines (60% for κ_z=0.05) but degreases with increasing baseline: for the same level of temporal decorrelation the height error degreases to 20% for a vertical wavenumber of 0.1. This makes clear that larger spatial baselines are advantageous in the presence of weak to moderate temporal decorrelation as they minimise the introduced bias by increasing the temporal baseline. The price to be paid is a lower overall coherence level - due to the increased volume decorrelation contribution - that caused an increased phase variance. This can be compensated by multilooking on the expense of spatial resolution. For small bandwidth systems additionally the low of common bandwidth due to the increased baseline may be an issue. However, the realisation of large baselines is, in the case of ALOS PalSAR, limited by the acquisition scenario that foresees small spatial baselines optimized for deformation applications. On the other side, the 46 days repeat-pass time of ALOS PalSAR lead to temporal coherence levels that are by far to low to be compensated by spatial baseline optimisation.

In the next sections the quantification of temporal decorrelation and its impact on forest height inversion for different repeat-pass intervals is discussed.

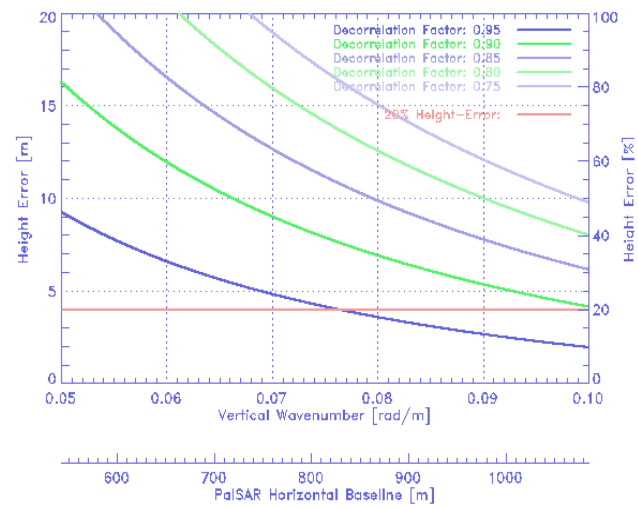

Figure 3: Height error induced by different levels of temporal decorrelation as a function of vertical wavenumber (and horizontal spatial baseline referred to the ALOS Quad-pol mode), assuming a constant forest height of 20m.

V. Airborne Experiments & Test Sites

In order to asses the effect of temporal decorrelation at L-band, temporal baselines smaller than the ones obtained by ALOS-PalSAR, i.e. 46 days, two main airborne experiments have been conducted and data from an experiment in 2003 have been evaluated.

The BioSAR-I campaign was performed over the Remningstrop test site located in Sweden in 2007. DLR's experimental airborne SAR system (E-SAR) flew over the Remningstrop forest at three different times: 09 March, 31 March, 02 May 2007. During the three data acquisitions, L-band Quad-polarimetric data have been acquired in a repeat-pass interferometric mode. The configurations flown and the available L-band data sets are summarized in Table 2 The experiment allows to investigate temporal baselines on the order of 32 days and 54 days.

The TreeSAR campaign was conducted in October 2003 over the Traunstein test site. This was an early experiment to investigate the temporal behavior of forests for a temporal baseline in the order of weeks. L-band data have been acquired by DLR's E-SAR system in a fully polarimetric mode. Data base for this campaign is summarized in Table 2.

The TempoSAR campaign was performed in June 2008 DLR's E-SAR system collected fully polarimetric and interferometric SAR data at L-band over the Traunstein test site located in Germany six times within 13 days. The experiment was designed to investigate temporal baselines on the order of days up to two weeks. The configurations flown within the frame of TempoSAR and the available L-band data sets are summarized in Table 2.

Table 2 Campaigns and Data base

Campaign	Acquisition Date	Temporal baseline	Spatial baselines
TempoSAR	2008/06/07 2008/06/08 2008/06/10 2008/06/12 2008/06/19 2008/06/20	1 – 13 days	15, 10, 5, & 0m
TreeSAR	2003/10/11 2003/10/26	15 days	0, 5, & 10m
BioSAR-I	2007/03/09 2007/03/31 2007/05/02	32 & 54 days	0, 8, 16, & 24m

A. The Remningstrop test site

Remningstrop test site (see Figure 4 left) is located in southern Sweden (58°28' north, 13°38'east). The forest is part of the southern ridge of the boreal forest zone in transition to the temperate forest zone. Topography is fairly flat with some small hills and ranges between 120m and 145m amsl. It is a managed forest, divided into several stands with similar forest structure. Prevailing tree species are Norway spruce (*Piceaabies*), Scots pine (*Pinus sylvestris*) and birch (*Betula spp.*). Forest height ranges from 5m to 35m, with biomass levels from 50t/ha to 300t/ha. For this test site a large area lidar data set is available for validation. Lidar systems are an established technique to measure forest height. In this case the lidar data are used to validate the radar measurements.

B. The Traunstein test site

The Test Site Traunstein (see Figure 4 right) is situated in the southeast of Germany (47°52' north, 12°39' east), next to the city Traunstein to the east. Geologically, the test site is placed in the pre- alpine- moraine landscape of southern Germany. Topography varies from 530 – 650m amsl, with only few steep slopes. The climatic conditions with a mean annual temperature of 7.8°C and precipitation of more than 1600 mm/a favor mixed mountainous forests, dominated by Norway spruce (*Picea abies*), beech (*Fagus sylvatica*) and fir (*Abies alba*). On a global scale this forest type is part of the temperate forest zone. It is a managed forest composed of even-aged stands which cover forest heights from 10m to 40m. Mean biomass level is on the order of 210t/ha while some old forest stands can reach Biomass levels up to 500t/ha. Compared to other managed forests in this ecological zone (mean biomass of 121 t/ha) the biomass values at Traunstein test site are significantly higher. Validation is based on forest inventory, which was done by means of a plot system on a 100m by 100m grid.

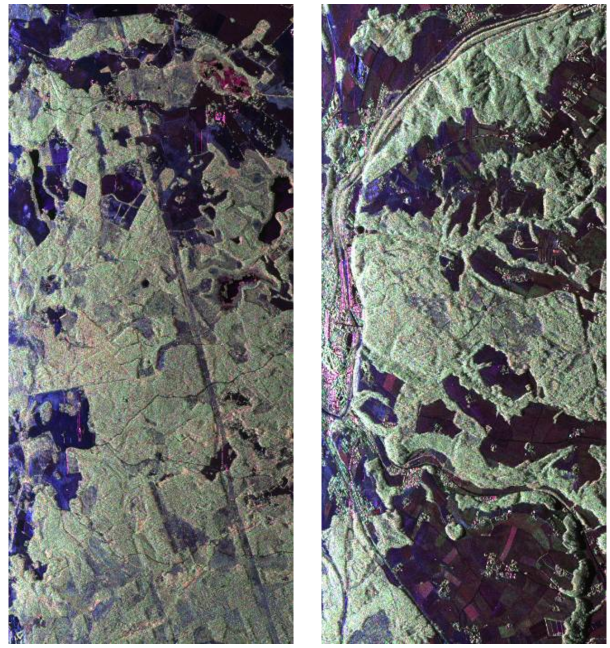

Figure 4: Remningstrop test site: left, Traunstein test site: right. Radar image Pauli decomposition, red: double bounce scattering, blue: surface scattering, green: volume scattering.

VI. ASSESSMENT OF TEMPORAL DECORRELATION

A. Pol-InSAR Inversion Height and Validation

Forest height was estimated and validated against ground measurements for Traunstein test site as well as for Pol-InSAR inversion results (left side figure 5) and forest height estimates from lidar measurements (right side figure 5) for Remningstrop test site (April flights) are shown. Figure 7 right shows the Pol-InSAR forest height map for Traunstein test site (left side) and an amplitude image containing all ground plots for validation. All height images are scaled from 0m to 50m.

The Traunstein test site was validated against forest inventory data. A forest stand map was provided and forest heights origin from ground measurements based on a 100m x 100m grid (see Figure 7 right, colors represent H100). All together, 224 inventory points are located within the test site. However, in heterogeneous forests even a small misregistration between inventory coordinates and radar image may deteriorate the results. Also, the certainty of the estimated parameters increases for larger sampling areas. For these reasons it was tried to select large forest areas which were as homogeneous as possible in terms of species, height, biomass and stadium. In total, 20 validation stands covering 123 ha and including 133 inventory points were selected. A comparison of Pol-InSAR forest height against H100 of inventory data is shown in Figure 8: with an R^2 of 0.90 and RMSE of 3.16 m, over a height range from 10 to 35m.

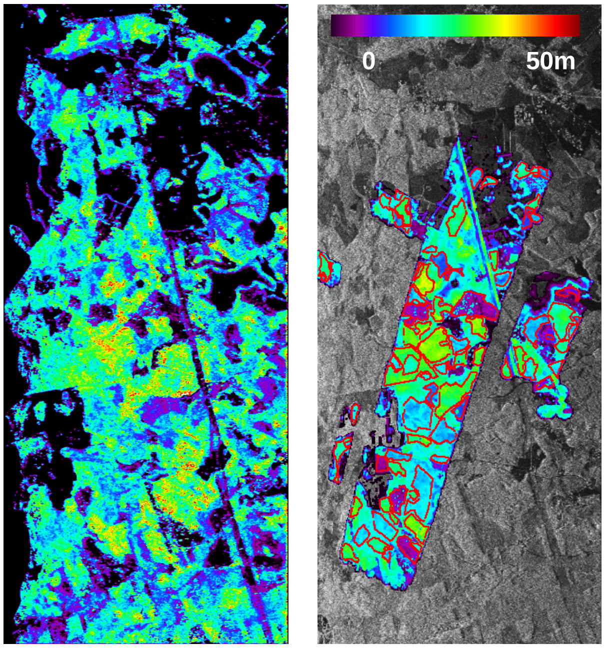

Figure 5 Forest height map Remningstrop forest; scaled from 0m to 50 m; Left: Pol-InSAR inversion height, Right: L-band amplitude image overlaid with lidar height (H100).

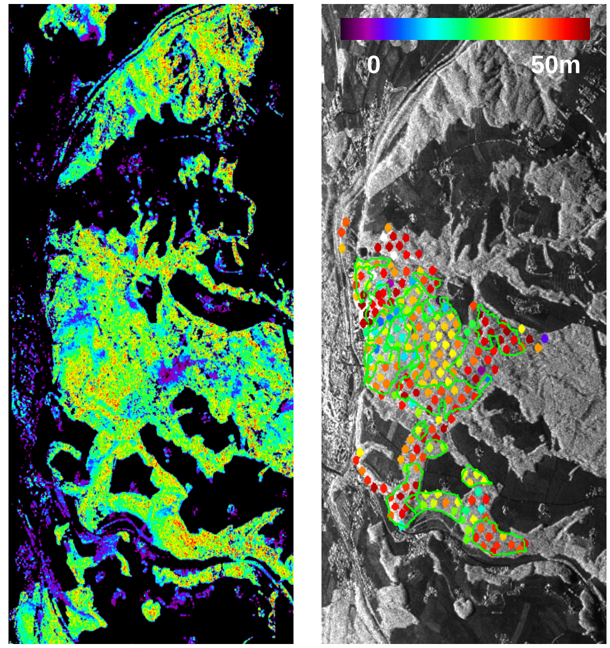

Figure 7: Forest height map Traunstein; scaled from 0m to 50 m; Left: Pol-InSAR inversion height, Right: L-band amplitude image overlaid with inventory points.

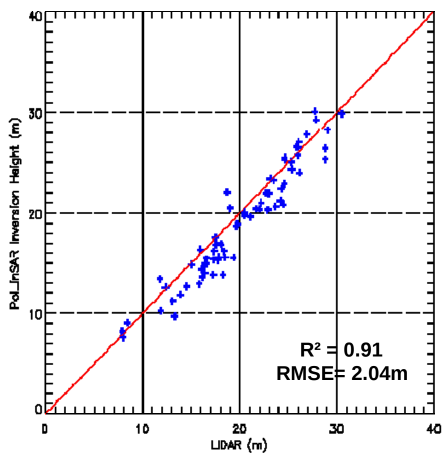

Figure 6: Validation Plot Remningstrop test site: LIDAR H100 versus Pol-InSAR height estimates.

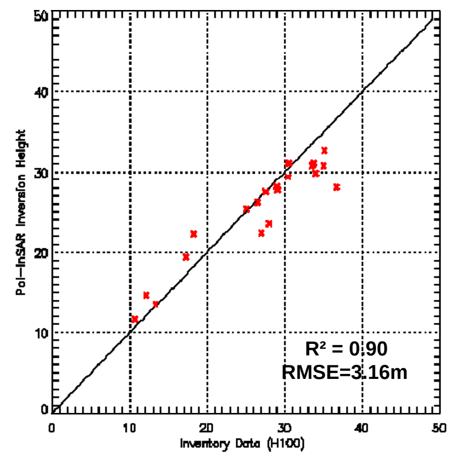

Figure 8: Validation Plot Traunstein test site: Inventory H100 versus Pol-InSAR height estimates.

The results of both campaigns demonstrate in an impressive way that Pol-InSAR forest height inversion provides consistent forest height maps at different type of forests if there is low temporal decorrelation.

B. The Impact of Temporal Decorrelation

After demonstrating the potential of Pol-InSAR inversion with data not affected by temporal effects, in this part data quality and inversion results for repeat pass acquisitions with temporal baselines from 0 day to 54 days are presented.

During the BioSAR-I campaign data with temporal baselines of 0 days, 32 days and 54 days have been acquired. Effects of temporal decorrelation are shown in Figure 9. Coherence histograms in HH, VV, and HV polarizations over the whole scene for three temporal baselines (all acquired with 0m nominal spatial baseline) are plotted.

As expected, temporal decorrelation decreases with time independent from polarizations. Even in the 0 day scenario some decorrelation effects can be observed. Also here the data are acquired in a repeat pass mode with temporal baselines in the order of one hour. As seen in Figure 9 temporal decorrelation reduces coherence level to 0.65 (32 days) and 0.30 (54 days). Coherence with 54 days temporal baseline is too low to apply valuable Pol-InSAR application. Pol-InSAR height estimates were calculated for a 32 days temporal baseline, results are shown in Figure 10. In this case Inversion forest height all over the image is fairly overestimated originated by temporal decorrelation effects.

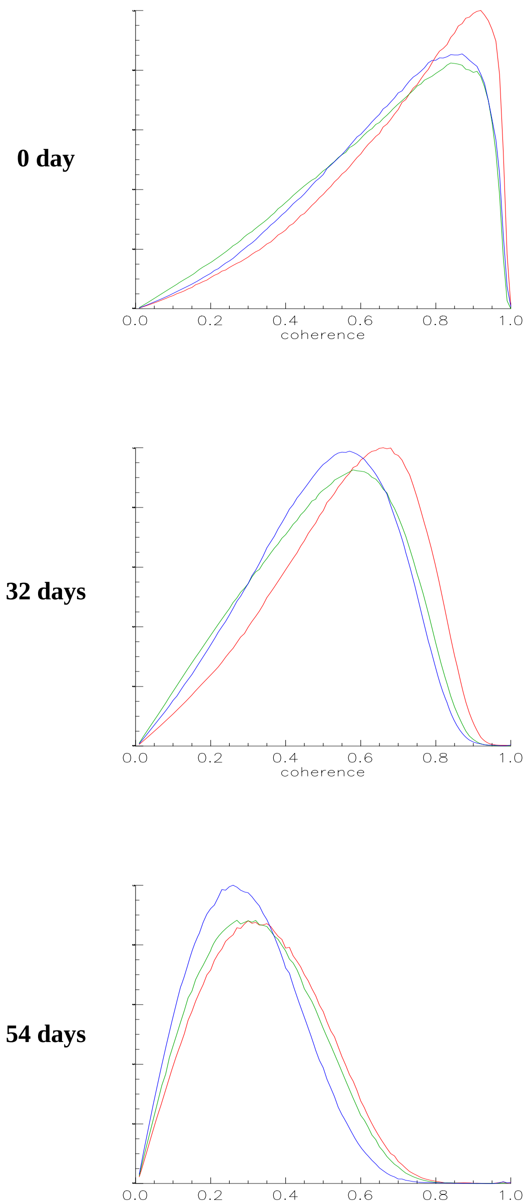

Figure 9: Coherence histograms for 0days (top), 30days (middle) and 54 days (bottom) temporal baseline; HH= red, HV= green, VV= blue.

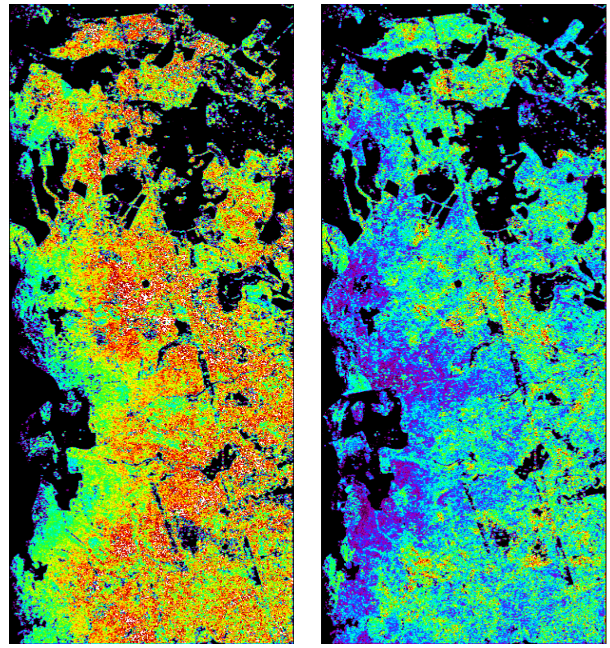

Figure 10 Forest height maps for Remningstorp forest, scaled 0 to 50m. Left: Inversion height map with one month temporal baseline, Right: Different height map between left image and the left image of Figure 5.

The level of temporal decorrelation with one month repeat-pass cycle of L-band makes a height inversion still feasible, but introduces a large height bias.

During the TempoSAR campaign data have been acquired on six days within a 13 days period. This enables to generate several temporal baselines ranging from 1 day to 13 days. Pol-InSAR forest heights for 6 temporal baselines are shown in Figure 13. As expected, overestimation tends to increase in time (comparing the results with Figure 7 left). Height errors induced by temporal decorrelation were estimated and plotted in Figure 11. There is a tendency that height errors increase with decreasing forest height, caused by the Pol-InSAR model. Low forests are more affected by uncompensated decorrelation contributions than high forests (see Figure 2). Even 1 day of temporal decorrelation can lead, dependent on forest height, to 20-100% overestimation of forest height. Usually L-band height estimates are affected by rather stochastic temporal effects due to the variable wind induced motions see also [39].

Temporal decorrelation yields always in an overestimation of forest height as indicated by Equation (10). Using the behavior of the height error in time (see Figure 11), enables us to correct forest height and volume coherence can be estimated by corrected forest height and Equation (7) under the assumption that extinction is constant in time. Under this assumption temporal decorrelation can be decomposed from volume decorrelation see Equation (2).

Estimated temporal decorrelation coefficients for different temporal baselines are shown in Figure 14. From this two main points become obvious. First: γ_{TV} decreases with increasing temporal baseline. Second: γ_{TV} is not constant in time, it depends on forest height and additionally on the random behavior of wind induced motion of forests [39]. Figure 12 shows the estimated γ_{TV} against temporal baselines. If there is no temporal decorrelation, as we can find in single pass systems, γ_{TV} should be 1. γ_{TV} tends to decrease with increasing temporal baseline. Looking on temporal baselines in the order of days a rapid drop of coherence can be observed (see Figure 12), but coherence values are still greater than 0.3 which allows a Pol-InSAR inversion. Temporal effects for temporal baselines on day level are caused by wind-induced movements of unstable scatterers within the canopy layer like leaves, branches or birds.

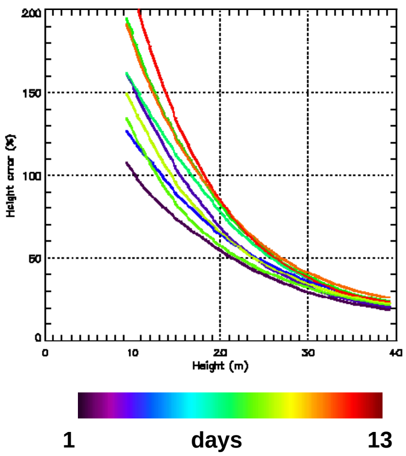

Figure 11: Height error (%) with temporal baselines (1 - 13 days).

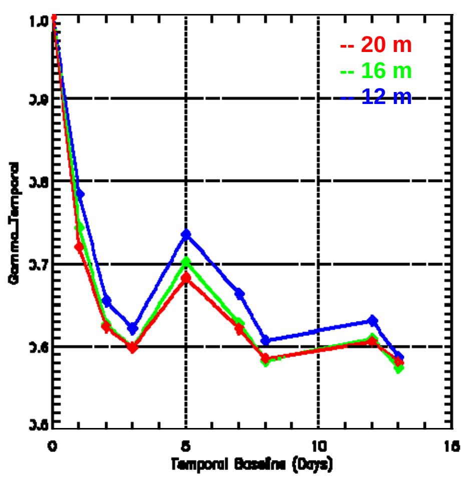

Figure 12: Temporal decorrelation (γ_{TV}) against temporal baselines. Color mean forest height (red: 20m, green: 16m, blue: 12m).

Going to temporal baselines in the order of weeks or month (as it is the case for ALOS –PalSAR) coherence is more decorrelated, there are not only the wind induced motions but also other events, for example precipitations (rainfall, snow), changes in soil moisture, breaking branches, fall of leaves, etc. Taking everything into consideration coherence level becomes too low (<0.3) to perform any kind of quantitative evaluation and/or analysis of the data.

VII. Results and Summary

With respect to quantitative Pol-InSAR applications there are several "sub-optimum" aspects on the ALOS system, mission and operation design that constrain - more or less - a large scale demonstration:

- *Coverage:* The Quad-pol mode does not provide global coverage for the defined ALOS orbit. The 30Km wide swath has on the equator - and therefore on the sensible tropical region - gaps on the order of 30Km and covers therefore only approx. 50%.

- *Repeat-Pass Time:* The repeat-pass interval of 46 days - required in order to ensure global coverage of the optical PRISM and AVNIR2 instruments - is to large to limit the impact of temporal decorrelation on the interferometric coherence.

- *Observation scenario:* The fact that the Quad-pol mode is declared as an experimental mode reflects on the observation scenario for ALOS-PalSAR: Only two consecutive Quad-pol observations (cycles) every year are foreseen allowing the formation of a single Quad-pol baseline. This, combined with the fact that the Dual-pol modes are operated at a different incidence angle - limits drastically the formation of an adequate Pol-InSAR observation space.

- Orbit Control: The ALOS orbit control allows the realisation of orbital tubes of about 500m leading to a zero mean distribution of baselines up to 1Km. Having in mind that for compensating temporal decorrelation effects large baselines are of advantage, the expected small baselines are sub-optimal.

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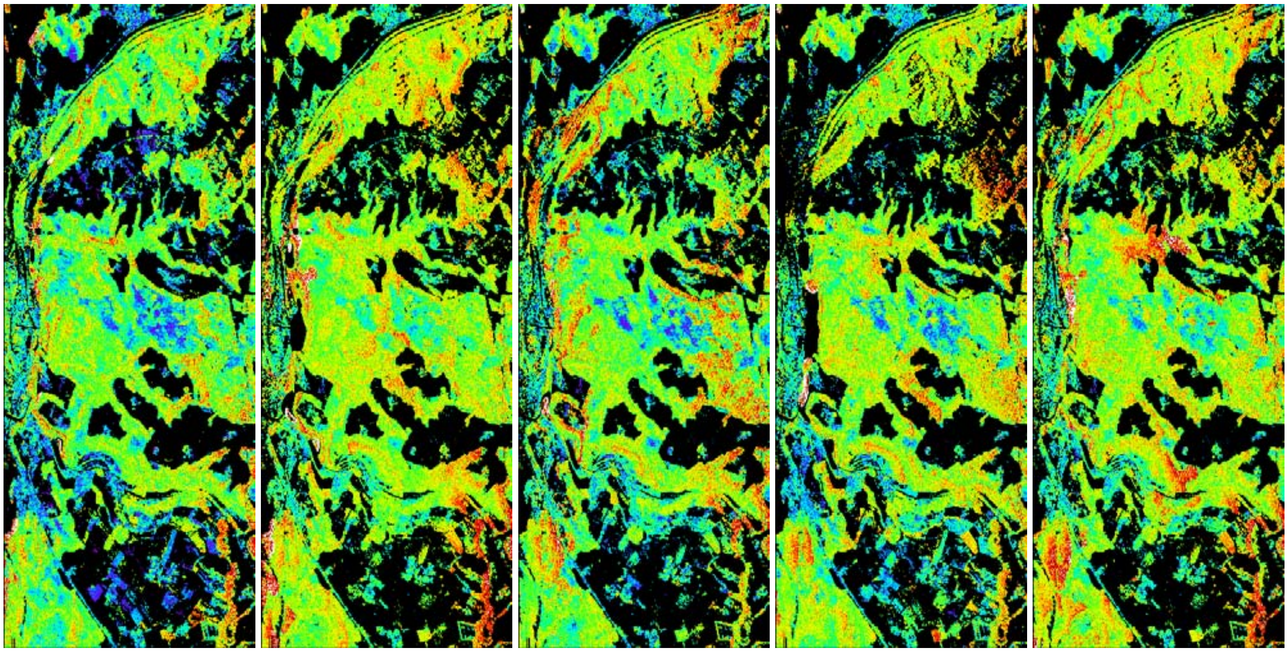
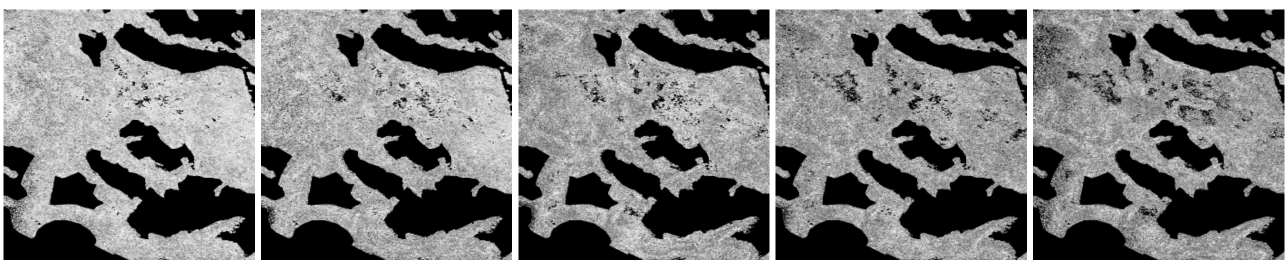


1 day **5 days** **7 days** **12 days** **13 days**

Figure 13 Forest height maps Temposar campaign with temporal baselines, from 1 to 13 days; scaled from 0m to 50m; color table in Figure 7.



1 day **5 days** **7 days** **12 days** **13 days**

Figure 14 Temporal decorrelation TempoSAR campaign from 1 to 13 days, scaled from 0 (black) to 1 (white).

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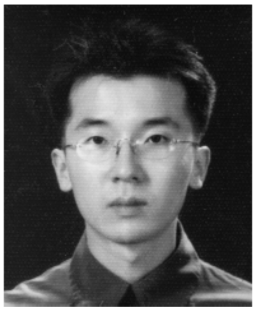

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