A NEW APPROACH TO ESTIMATE FOREST PARAMETERS USING DUAL-BASELINE POL-INSAR DATA

Lu Bai [1] [2] [3], Wen Hong [1] [2], Fang Cao [1] [2], Yongsheng Zhou [1] [2] [3]

[1] *National Key Laboratory of Microwave Image Technology*
[2] *Institute of Electronics, Chinese Academy of Sciences, No. 19 BeiSiHuanXiLu, Beijing, China*
[3] *The Graduate University of Chinese Academy of Sciences, Email:bilu81@gmail.com*

ABSTRACT

In POL-InSAR applications using ESPRIT technique, it is assumed that there exist stable scattering centres in the forest. However, the observations in forest severely suffer from volume and temporal decorrelation. The forest scatters are not stable as assumed. The obtained interferometric information is not accurate as expected. Besides, ESPRIT techniques could not identify the interferometric phases corresponding to the ground and the canopy. It provides multiple estimations for the height between two scattering centers due to phase unwrapping. Therefore, estimation errors are introduced to the forest height results. To suppress the two types of errors, we use the dual-baseline POL-InSAR data to estimate forest height. Dual-baseline coherence optimization is applied to obtain interferometric information of stable scattering centers in the forest. From the interferometric phases for different baselines, estimation errors caused by phase unwrapping is solved. Other estimation errors can be suppressed, too. Experiments are done to the ESAR L band POL-InSAR data. Experimental results show the proposed methods provide more accurate forest height than ESPRIT technique.

1. INTRODUCTION

Polarimetric interferometric SAR (POL-InSAR) combines polarimetric SAR and interferometric SAR techniques [1]. The coherent use of polarimetric and interferometric information makes POL-InSAR possible to extract the vertical distribution of scatterers within the resolution cell [2]. Hence, it is widely applied to the forest, which exhibits volume scattering [3]. From the POL-InSAR data, much forest information can be obtained. For instance, forest height [4], the underlying topography [5] even the forest structure [6-7] can be inversed from single baseline or multiple baseline data.

Since there are several independent scattering mechanisms in forest, the observations can be simplified to a sum of the returns from several effective scattering centers [1]. The scattering centers are stable so that their returns in different observations are highly coherent. The POL-InSAR data model is similar to the model used in antenna array. Therefore, ESPRIT techniques, used to be applied in DoA applications, are introduced to obtain the interferometric phases of these scattering centers and to estimate forest height [8-9].

ESPRIT techniques are based on the assumption that the returns of scattering centers are highly coherent. Correspondingly, accurate interferometric information can be obtained from the POL-InSAR observations [10]. However, it is not the case for the forest scatters. Forest observations suffer from severe volume decorrelation and temporal decorrelation. The scattering behaviours of forest scatters change with the imaging geometry and their spatial locations may change due to the wind or other reasons. The coherences of the observations are low and the quality of interferometric information is reduced. Therefore, estimation errors occur in the forest parameters obtained by ESPRIT techniques. Besides, ESPRIT techniques could not identify the scattering center corresponding to the ground. Multiple estimations for the height between centers are yielded due to the phase unwrapping. Therefore, estimation errors appear in the forest height results.

To improve the estimation for forest height, we propose a new approach based on dual-baseline POL-InSAR data. It uses the dual-baseline coherence optimization to identify the stable scattering centers and their accurate interferometric phases [11]. Using the interferometric phases for different baselines, it avoids the estimation errors caused by phase unwrapping and suppresses other phase errors. Finally, forest height is inversed from the maximum height between stable scattering centers. Experiments are applied on the ESAR L band data to examine the performances of new approach.

The remainder of this paper is composed of four sections. Firstly, the ESPRIT data model for forest is described and analyzed briefly. Next, the new approach to estimate forest parameter is proposed. Then, experimental results of the ESAR L band dual baseline data are present and analyzed. Finally, the advantages of the new approach are summarized.

2. ESPRIT DATA MODEL

Forest observation contains the volume scattering in the forest canopy, the double bounce scattering between tree stem and the ground and the direst scattering from

Proc. of '4th Int. Workshop on Science and Applications of SAR Polarimetry and Polarimetric Interferometry – PolInSAR 2009', 26–30 January 2009, Frascati, Italy (ESA SP-668, April 2009)

the ground. Since these scattering mechanisms in forest are independent, each contribution can be regarded as the return from an effective "point-like" scattering center [8]. Correspondingly, the fully polarized observation $\vec{k}_1$ can be written as [3]:

$$\vec{k}_1 \equiv \begin{bmatrix} E_{hh}^1 \\ \sqrt{2}E_{hv}^1 \\ E_{vv}^1 \end{bmatrix} = \begin{bmatrix} s_{HH}^1 & \cdots & s_{HH}^d \\ \sqrt{2}s_{HV}^1 & \cdots & \sqrt{2}s_{HV}^d \\ s_{VV}^1 & \cdots & s_{VV}^d \end{bmatrix} \begin{bmatrix} \sigma^1 e^{-j\frac{4\pi}{\lambda}R^1} \\ \cdots \\ \sigma^d e^{-j\frac{4\pi}{\lambda}R^d} \end{bmatrix} + \begin{bmatrix} n_{hh}^1 \\ n_{hv}^1 \\ n_{vv}^1 \end{bmatrix}$$
$$= \mathbf{S\sigma} + \vec{n}_1 \quad . (1)$$

E_{hh}^1, E_{hv}^1 and E_{vv}^1 represent the acquisitions in HH, HV and VV polarizations. d denotes the number of scattering centers. Limited by the dimension of polarization space, d is no more than three. σ^i and R^i stand for the total power and the slant range of i th scattering center. s_{hh}^i, s_{hv}^i and s_{vv}^i ($i=1,\ldots,d$) are the normalized complex scattering coefficients in different polarization. Symbols n_{hh}^1, n_{hv}^1 and n_{vv}^1 mean the addictive white Gaussian noises.

Similarly, the fully polarized observations $\vec{k}_2$ in the salve flight tracks can be expressed as [3]:

$$\vec{k}_2 = \begin{bmatrix} s_{HH}^1{}' & \cdots & s_{HH}^d{}' \\ \sqrt{2}s_{HV}^1{}' & \cdots & \sqrt{2}s_{HV}^d{}' \\ s_{VV}^1{}' & \cdots & s_{VV}^d{}' \end{bmatrix} \begin{bmatrix} \sigma^1{}' e^{-j\frac{4\pi}{\lambda}R^1{}'} \\ \cdots \\ \sigma^d{}' e^{-j\frac{4\pi}{\lambda}R^d{}'} \end{bmatrix} + \begin{bmatrix} n_{hh}^2 \\ n_{hv}^2 \\ n_{vv}^2 \end{bmatrix} . (2)$$

Considering the severe volume and temporal decorrelation, effective scattering centers in different observations change. Thus, new parameters are used.

Assuming that volume decorrelation and temporal decorrelation are small, the effective scattering centers stay the same. The returns from each effective scattering center are highly coherent and provide accurate interferometric information Therefore, the observation $\vec{k}_2$ is simplified to [3]:

$$\vec{k}_2 = \mathbf{S} \begin{bmatrix} e^{-j\frac{4\pi}{\lambda}\Delta R^1} & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & e^{-j\frac{4\pi}{\lambda}\Delta R^d} \end{bmatrix} \boldsymbol{\sigma} + \vec{n}_2 = \mathbf{S\Phi\sigma} + \vec{n}_2 \quad (3)$$

where ΔR^i denotes the slant range difference to the i th scattering center. Eq. 3 is good to describe the stable scattering centers, whose results are highly coherent. Since the returns of forest scatters are lowly coherent, the direct usage of the model in forest may lead to estimation errors.

Based on Eq. 1 and Eq. 3, ESPRIT techniques provide the interferometric phases ϕ^i for each scattering centers. However, it cannot identify the interferometric phases corresponding to the ground and the canopy. The locations of these scattering centers are unknown. Therefore, ESPRIT algorithm would provide multiple estimations for the height between scattering centers:

$$\left|\Delta h^{mk}\right| = \begin{cases} \dfrac{\left|\phi^m - \phi^k\right|}{\kappa_z} \\ \dfrac{2\pi - \left|\phi^m - \phi^k\right|}{\kappa_z} \end{cases} \quad m,k = 1,\ldots,d \quad and \quad m \neq k \quad (4)$$

where κ_z is the vertical wave number. Since it is hard to discern the right estimation, all of them are used to estimate height difference. Therefore, the estimation errors would be passed to forest height results.

3. DUAL-BASELINE SOLUTIONS

Dual-baseline data are composed of three fully polarized acquisitions. Compared with single baseline data, they not only increase another spatial baseline but also add another temporal baseline. Therefore, the dual-baseline data are more sensitive to the changes of forest scatters with the imaging geometry and the time. In other words, they are potential to obtain the stable scattering centers, which suffer less from volume and temporal decorrelation, and to estimate accurate interferometric information. Besides, they provide a set of interferometric phases for the same scattering center. Using the set of interferometric phases, a unique estimation for the height between scattering centers is calculated. The estimation errors caused by phase unwrapping can be suppressed. Therefore, we propose a new approach based on dual-baseline POL-InSAR data.

The proposed approach uses dual-baseline coherence optimization to extract the stable scattering center, whose returns in different acquisitions are highly coherent. According to the highly coherent assumption, the number and the interferometric phases of the stable scattering centers can be estimated. Since height between the stable scattering centers would not changes, the corresponding interferometric phase difference vary with the vertical wave numbers of respective baselines.

According to the fact, a unique set of interferometric phases are identified to estimate height between stable scattering centers. Forest height is inversed from the largest height between all the possible stable scattering centers.

3.1. Coherence Optimization

As a good indicator for the quality of the interferometric phase, coherence describes the similarities of the two observations. The coherences γ_{pq} between p and q observations ($p,q=1,2,3$ and $p \neq q$) are defined as [11]:

$$\gamma_{pq}(\vec{\omega}) = \frac{\left|\vec{\omega}^H \left\langle \vec{k}_p \vec{k}_q^{\,H} \right\rangle \vec{\omega}\right|}{\sqrt{\left(\vec{\omega}^H \left\langle \vec{k}_p \vec{k}_p^{\,H} \right\rangle \vec{\omega}\right)\left(\vec{\omega}^H \left\langle \vec{k}_q \vec{k}_q^{\,H} \right\rangle \vec{\omega}\right)}} = \frac{\left|\vec{\omega}^H \mathbf{C}_{pq} \vec{\omega}\right|}{\sqrt{\left(\vec{\omega}^H \mathbf{C}_{pp} \vec{\omega}\right)\left(\vec{\omega}^H \mathbf{C}_{qq} \vec{\omega}\right)}} \quad (5)$$

where $\vec{\omega}$ is the projection vector related to the polarization state.

Coherence optimization detects the stable scattering centers that keep high coherences for all the baselines. Mathematically, coherence optimization is to find the optimal projection vectors that maximize the total coherence $\sum_{p\neq q}\gamma_{pq}(\vec{\omega})$. The optimization problems can be simplified to [11]:

$$\sum_{p=1}^{3}\sum_{q=1,q\neq p}^{3} \frac{\left|\vec{\omega}^H \mathbf{C}_{pq} \vec{\omega}\right|}{\vec{\omega}^H \mathbf{C}_e \vec{\omega}} \quad where \quad T_e = \frac{1}{3}\sum_{p=1}^{3}\left|T_{pp}\right|. \quad (6)$$

Estimation for the optimal projection vector is obtained from the eigenvector corresponding to the maximum eigen value:

$$\left(\frac{3}{2}\sum_{p=1}^{3}\sum_{q=1,q\neq p}^{3} \mathbf{C}_{pq} e^{-i\phi_{pq}}\right)\vec{\omega} = \lambda \mathbf{C}_e \vec{\omega} \quad (7)$$

where ϕ_{pq} is the interferometric phase for the baseline pq . Using the estimation for projection vector, improved estimations for interferometric phases are obtained from

$$\phi_{pq} = \arg\left(\vec{\omega}^H \mathbf{C}_{pq} \vec{\omega}\right) \quad (8)$$

The optimization process Eqs. 7-8 is iteratively applied until its coherence converges. The first optimal projection vector $\vec{\omega}_{opt}^1$ is obtained. The other two optimal projection vectors are orthogonal to $\vec{\omega}_{opt}^1$. The second optimal projection vector $\vec{\omega}_{opt}^2$ can be found in the subspaces orthogonal to $\vec{\omega}_{opt}^1$ using Eqs. 7-8 interactively. The third optimal projection vector is orthogonal $\vec{\omega}_{opt}^1$ and $\vec{\omega}_{opt}^3$.

3.2. Stable Scattering Centers' Estimation

Coherence optimization only provides the candidates for the stable scattering centers. Since the stable scattering center keeps high coherence for all the baselines, it can be identified from:

$$\gamma_{12}\left(\vec{\omega}_{opt}^i\right) > 0.5, \gamma_{13}\left(\vec{\omega}_{opt}^i\right) > 0.5, and \quad \gamma_{23}\left(\vec{\omega}_{opt}^i\right) > 0.5 \quad (9)$$

If $\gamma_{12}\left(\vec{\omega}_{opt}^i\right)$, $\gamma_{13}\left(\vec{\omega}_{opt}^i\right)$ and $\gamma_{23}\left(\vec{\omega}_{opt}^i\right)$ are higher than 0.5, the scattering center corresponding to $\vec{\omega}_{opt}^i$ is recognized as a stable scattering center. When all the optimal projection vectors are checked, the number of stable scattering centers d is obtained. Since stable scattering center provides accurate interferometric information, its interferometric phases:

$$\begin{aligned} \phi_{12}^i &= \vec{\omega}_{opt}^{i\,H} \mathbf{C}_{12} \vec{\omega}_{opt}^i \\ \phi_{13}^i &= \vec{\omega}_{opt}^{i\,H} \mathbf{C}_{13} \vec{\omega}_{opt}^i \end{aligned} \quad (10)$$

are used to estimate forest height.

3.3. Forest Height Estimation

Inteferometric phase difference $\Delta\phi^{mk}$ counteract the common phase component related to the slant range, it is directly related to the height between the scattering center m and k. Therefore, the absolute height between scattering center m and k can be estimated from their absolute interferometric phase difference $\left|\Delta\phi^{mk}\right|$. Considering the interferometric phases for the dual baselines, there are four possible set of phase difference to estimate the height:

$$\left\{\left|\Delta\phi_{12}^{\ mk}\right|, \left|\Delta\phi_{13}^{\ mk}\right|\right\} = \begin{cases} \left\{\left|\phi_{12}^m - \phi_{12}^k\right|, \left|\phi_{13}^m - \phi_{13}^k\right|\right\} \\ \left\{2\pi - \left|\phi_{12}^m - \phi_{12}^k\right|, \left|\phi_{13}^m - \phi_{13}^k\right|\right\} \\ \left\{\left|\phi_{12}^m - \phi_{12}^k\right|, 2\pi - \left|\phi_{13}^m - \phi_{13}^k\right|\right\} \\ \left\{2\pi - \left|\phi_{12}^m - \phi_{12}^k\right|, 2\pi - \left|\phi_{13}^m - \phi_{13}^k\right|\right\} \end{cases} \quad (11)$$

$$m,k = 1,...,d \quad and \quad m \neq k$$

Since the height between the two stable scattering centers Δh^{mk} do not change, the absolute phase difference $\left|\Delta\phi_{pq}^{\ mk}\right|$ for baseline pq can be expressed as:

$$\left|\Delta\phi_{pq}^{\ mk}\right| = \Delta h^{mk} \cdot \kappa_{z,pq} \quad (12)$$

where $\kappa_{z,pq}$ is the vertical wave number for baseline pq. According to Eq. 12, the right estimation $\{|\Delta\phi_{12est}^{mk}|,|\Delta\phi_{13est}^{mk}|\}$ can be identified from Eq. 11 using

$$\begin{gathered}\left(|\kappa_{z,12}|-|\kappa_{z,13}|\right)\left(|\Delta\phi_{12est}^{mk}|-|\Delta\phi_{13est}^{mk}|\right)\geq 0\\ \left|\frac{|\Delta\phi_{12est}^{mk}|}{|\kappa_{z,12}|}-\frac{|\Delta\phi_{13est}^{mk}|}{|\kappa_{z,13}|}\right|^2\leq\left|\frac{|\Delta\phi_{12}^{mk}|}{|\kappa_{z,12}|}-\frac{|\Delta\phi_{13}^{mk}|}{|\kappa_{z,13}|}\right|^2\end{gathered} \quad (13)$$

Since the influences of other phase errors, the phase difference $|\Delta\phi_{12}{}^{mk}{}_{est}|$ and $|\Delta\phi_{13}{}^{mk}{}_{est}|$ cannot provide the same height estimation Δh^{mk}. We proposes to take the height $\Delta h^{mk}{}_{est}$ that gives the smallest estimation error as the final estimation for the height between scattering center m and k. It can be calculated from:

$$\Delta h_{est}^{mk}=Min\left(\left(\Delta h^{mk}-\frac{|\Delta\phi_{12est}^{mk}|}{|\kappa_{z,12}|}\right)^2+\left(\Delta h^{mk}-\frac{|\Delta\phi_{13est}^{mk}|}{|\kappa_{z,13}|}\right)^2\right).(14)$$

Because all the stable scattering centers locate between the ground and the canopy, the largest height between stable scattering centers would not exceed the forest height. Therefore, the forest height can be estimated from the maximum height as:

$$h_V=Max\left(\Delta h_{est}^{mk}\right) \quad . \quad (15)$$

The proposed approach uses the dual-baseline data to obtain the accurate interferometric phases and to solve the phase errors so as to improve the forest height estimations.

4. EXPERIMENTS AND DISCUSSION

Experiments are applied on E-SAR L band data of Traunsterin, Germany. They are single look complex data acquired on Oct 16th, 2003. Their sizes are 4650 pixels (azimuth) × 1414 pixels (rang). The average baseline was 5m and 10m respectively. The time interval between the two flights was 20 minutes and 10 minute. As Fig. 1 shown, the experimental data covers 8 homogeneous forest areas. Their average forest heights are indicated by the grey colors.

The experimental data are firstly processed using 7×7 Boxcar POL-InSAR filter. According to the dual-baseline coherence optimization, the three optimal projection vectors are obtained. Using Eq. 9, the number and interferometric phases of stable scattering centers are obtained. From the interferometric phases of stable scattering centers, the proposed approach estimates the forest height as Eqs. 13-15. To compare with the proposed approach, ESPRIT technique is applied on the POL-InSAR data with 10m baseline. ESPRIT technique uses the same number of scattering centers as the proposed method. But ESPRIT technique uses covariance matrix of single baseline data to estimate the interferometric phase. Contrasting the forest height estimations with the reference height, the performance of proposed approach is analyzed.

Fig. 2 shows the forest height estimated from the proposed approach and the ESPRIT algorithm. Only the estimations in the 8 forest areas are presents, other results are masked. ESPRIT results are overestimations for forest height. It is because ESPRIT technique cannot discern the right estimations from the multiple phase differences and estimation errors appear in the forest height. The proposed approach provides the closer estimations for forest height.

To examine the performance, the average forest height given by the ESPRIT technique and the proposed approach are presented in Tab. 1. Seen from the statistics, the results of propose approach are closer to the reference heights. Most of the average results are lower than reference forest heights. On the contrary, the average results of ESPRIT technique are far from the reference forest height.

To detect the differences in forest estimations, the results on the profile marked in Fig. 2 are presents in Fig. 3. There are obvious overestimations in ESPRIT results. The proposed approach yield accurate and stable estimations for the forest height.

To sum up, the proposed approach uses the dual-baseline data improve the accuracy of forest height. It not only obtains the accurate interferometric phases of stable scattering centers, but also suppresses the estimation errors effectively.

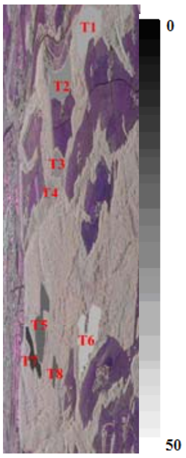
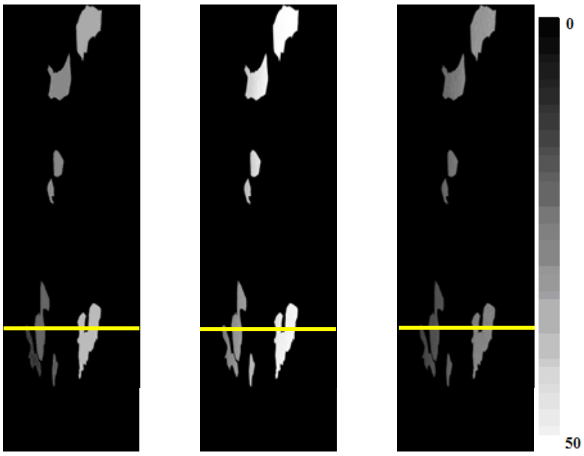


Figure 1. Total Power Image of Experimental data.

(Red, blue and green reprent the amplitudes $|E^1_{vv}|$, $|E^1_{hv}|$ and $|E^1_{hh}|$ respectively. Grey color indicates the reference heights.)



(a) Reference Height (b) ESPRIT (c) Proposed Approach

Figure 2. Forest Height Results.

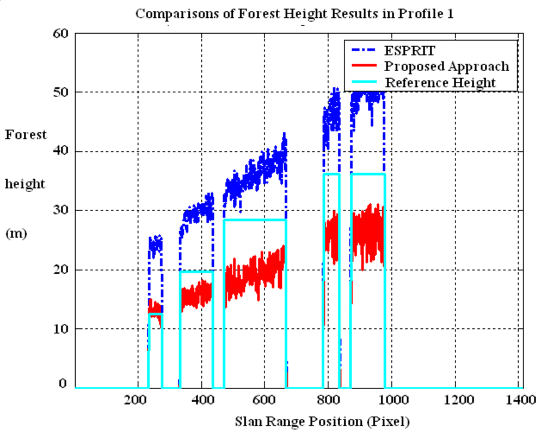


Figure 3. Comparisons of Forest Height Results.

Table 1. Comparisons of Average Forest Height Results

Forest Area	Reference Height(m)	ESPRIT Results (m)	Proposed Approach(m)
T1	32.49	56.54	29.43
T2	27.20	44.79	23.73
T3	26.30	42.31	22.43
T4	27.32	38.02	20.39
T5	19.68	29.47	15.79
T6	36.10	48.43	25.68
T7	12.46	26.95	14.31
T8	18.66	35.87	19.16

5. CONCLUSIONS

This paper proposes a new forest parameter estimation approach using dual-baseline POL-InSAR data. The approach introduces the coherence optimization to extract the highly coherent scattering components so as to guarantee the quality of interferometric information. Besides, it coherently uses the interferometric phases of different baselines to suppress the estimations errors. The experimental results validate the proposed method yields more accurate estimations for forest height than ESPRIT technique

6. ACKNOWLEDGEMENT

The experimental data are provided under the contract of the Dragon 2 program between the ESA and MOST of China. The authors would like to thank Prof. Eric Pottier, Prof. Erxue Chen for providing the detailed information of the data.

7. REFERENCES

1. Cloude, S.R., Papathanassiou, K.P. Polarimetric SAR interferometry. (1998). IEEE Trans. Geosci. Remote Sens., 36(5), 1551 - 1565.
2. Papathanassiou, K. P., Cloude, S. R. Single baseline polarimetric SAR interferometry. (2001). IEEE Trans. Geosci. Remote Sensing, 39, 2352-2363.
3. Guillaso, S., Ferro-Famil, L., Reigber, A., Pottier, E. (2003). Urban area analysis based on ESPRIT / MUSIC methods using polarimetric interferometric SAR. In Proc. 2nd GRSS/ISPRS Joint Workshop on Remote Sensing and Data Fusion over Ubran Areas, 77-81.
4. Kasilingam, D., Nomula, M., Cloude, S. (2002). A technique for removing vegetation bias from polarimetric SAR interferometry. In Proc. IGARSS. 2, 1017 - 1019.
5. Cloude, S.R. Robust parameter estimation using dual baseline polarimetric SAR interferometry. (2002). In Proc. IGARSS. 2, 838 - 840.
6. Cloude, S.R. (2007). Dual Baseline Coherence

Tomography. IEEE Geoscience and Remote Sensing Letters, 4(1), 127-131.
7. Cloude, S.R. Polarization Coherence Tomography. (2006). In Proc. 6th European SAR Conference.
8. Yamada, H., Yanaguchi, Y., Rodriguez, E., et al. (2001). Polarimetric SAR Interferometry for Forest canopy analysis by using the super-resolution method. In Proc. IGARSS, 3, 1101-1103.
9. Yamada, H., Yamaguchi, Y., Boerner, W. M. (2003). Forest Height Feature Extraction in Polarimetric SAR Interferometry by using Rotational Invariance Property. In Proc. IGARSS. 3, 1426-1428.
10. Stefano Tebaldini, Fabio Rocca. (2008).Polarimetric SAR Tomography of Forested Areas: a Covariance Matching Approach. In Proc. 7th European SAR Conference.
11. Maxim N., Ferro-Famil L., Reigber A. (2008). Multibaseline Polarimetric SAR Interferometry Coherence Optimization. Geosci. Remote Sensing Letter, 5(1), 93-97.