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# Simulation of interferometric SAR raw signals relevant to actual ground sites(*)

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**Summary.** — An efficient and reliable simulation scheme is of great relevance for the interpretation of the real campaign data analysis and the testing of the different interferometric procedures. In a previous work, an interferometric SAR (INSAR) raw signal simulator has been presented and tested *versus* canonical scenes. In this paper, a simulation over an actual ground site is presented and discussed in order to fully validate the simulator and to show how it can be employed to get some insight into the physical mechanisms governing the interferogram formation. Use of the simulator is finally suggested in order to support a classification scheme based on INSAR coherency maps.

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## 1. – Introduction

Across-track SAR interferometry (INSAR) is a remote-sensing tool able to generate a high-resolution Digital Elevation Model (DEM) of the area under survey by combining two complex SAR images of the same scene acquired from two slightly different look angles [1]. The DEM generation, however, requires some rather delicate processing steps. First of all, a phase-preserving focusing of the raw signals in order to get the two single look complex images must be accomplished [2]; then registration of these two images

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must be done in order to perfectly (within 1/8 pixel error) align them [3]. Followingly, the interferogram can be generated by multiplying the first complex image by the complex conjugate of the other. Finally, a phase unwrapping procedure permits to generate a DEM into the radar reference coordinates [4-6], and a geocoding algorithm performs the transformation into the usual cartographic system [7].

In order to test such processing procedures, and also to better understand physical phenomena involved in the interferogram formation, an interferometric raw signal pair simulator was developed and presented in refs. [8-10]. This simulator is based on an electromagnetic scattering model relying on the Physical Optics (PO) approximation, and on an asymptotic analytical evaluation of the SAR system transfer function. The proper correlation between the returns to the two antennas is also accounted for, so that, as shown in ref. [10], the image pairs obtained from the simulated raw signals exhibit the correct baseline decorrelation.

In refs. [8-10] the effectiveness of the simulator is demonstrated by using some reference scene, *i.e.* planes, cones and pyramids. However, the application of the simulator to actual ground scenarios is highly desirable, especially for future INSAR mission planning and for the processing algorithm testing. In fact, use of the simulator over the scene under study can help to choose the optimal flight height, trajectory and look angle in the mission planning phase. Furthermore, we note that the effectiveness of any INSAR processing algorithm is usually assessed by comparing the output DEM to a reference one (obtained by other techniques, for instance, aerophotogrammetry). Resulting differences are thus interpreted as processing errors; however, such discrepancies can be sometimes caused by errors within the reference DEM [11], or by other effects, such as fluctuations of the atmospheric index of refraction [12]. In order to avoid these drawbacks, the algorithm to be tested can be applied to simulated data: the output DEM can therefore be compared to the input DEM of the simulator.

All this motivates the effort to design and implement an efficient and reliable INSAR simulation tool.

Within such a framework, in order to fully validate and explore the potentiality of our simulator, in this paper we present and discuss a study relevant to a meaningful actual ground site. In particular, we present some simulation results relevant to the Mount Etna, Sicily, Italy. We consider the ERS-1/2 SAR system. Simulation results are then compared to real data. However, because of uncertainties on the system and ground geometry, and due to the occurrence of unmodelled and/or unpredictable electromagnetic effects, we cannot expect that real and simulated fringes are identical in all respects. Therefore, a preliminary theoretical analysis of the causes of discrepancies is accomplished. An interpretation of the results of the comparison between real and simulated data, based on the previous theoretical considerations, is then provided.

The paper is organised as follows: in sect. **2** a brief description of the employed simulator is provided; in sect. **3** we theoretically evaluate the differences between simulated and real fringes; in sect. **4** simulation results are presented and compared to actual data; finally, in sect **5** some conclusions are drawn.

## 2. – The simulator

In this section we provide a brief description of the INSAR raw signal pair simulator presented in ref. [10], which was used to perform the simulation examples shown in sect. **4**.

The simulator input data are: the environmental data, *i.e.* the DEM of the scene under survey and its permittivity and conductivity maps, and the INSAR system electronical and geometrical data. The DEM is used to generate a facet model of the surface, *i.e.* the surface is approximated with planar facets, much larger than the incident wavelength but smaller than the SAR resolution, over which a microscopic roughness is superimposed. The power backscattered by each rough facet to the two SAR antennas is then evaluated by using the PO approximation. PO is also used to evaluate the correlation coefficient between the fields backscattered to the two SAR antennas. The latter can be evaluated by following an approach similar to that of ref. [13], thus getting

$$\rho = \exp[j2k(R_1 - R_2)] \exp\left[ -\frac{1}{2}\left(\frac{4\pi\sigma \sin\vartheta B_\perp}{\lambda R}\right)^2\right] \times \\ \times \operatorname{sinc}\left\{\pi\Delta y\left[\frac{2\cos(\vartheta-\alpha_y)B_\perp}{\lambda R\cos\beta}\right]\right\} \operatorname{sinc}\left\{\pi\Delta x\left[\frac{2\tan\alpha_x \sin\vartheta B_\perp}{\lambda R}\right]\right\}, \tag{1}$$

where $\sigma$ is the facet height profile standard deviation, $R$ the average antenna-facet centre range, $\vartheta$ the average look angle, $B_\perp$ the baseline component perpendicular to the look direction, $\Delta x$ and $\Delta y$ are the facet dimensions, and $\alpha_x, \alpha_y$ the tilt angles of the mean plane along azimuth and ground range directions, respectively. The two backscattering coefficients of each facet relevant to the two SAR antennas are then generated as complex random variables with given power and correlation coefficient (evaluated as explained above) and with prescribed self and joint probability density functions (pdf) [10, 14, 15].

Once the two backscattering coefficient maps have been generated, the two raw signals are evaluated using the following expression [16]:

$$s_{1,2}(x', r'_{1,2}) = \iint \gamma_{1,2}(x, r_{1,2}) g(x'-x, r'_{1,2} - r_{1,2}; r_{1,2}) \mathrm{d}x\, \mathrm{d}r_{1,2}, \tag{2}$$

wherein subscripts 1 and 2 refer to the signal received by the antenna $A_1$ and $A_2$, respectively, $\gamma(\cdot)$ is the backscattering coefficient of the scene, and the SAR impulse response function $g(\cdot)$ is evaluated as in ref. [16].

The evaluation of the integral (2) is performed in the Fourier-transformed domain; a grid deformation method [16] or a modified kernel Fourier-transform method [17] can be employed, so that range migration, range curvature, and variation of focus depth are automatically taken into account. For further details, the reader is referred to ref. [10].

In ref. [10], simulation of raw signals relevant to canonical scenes (planes and pyramids) and subsequent INSAR processing is performed. Results show the effectiveness of the simulator; in particular, it is shown that the baseline decorrelation effect [18-21] is correctly simulated.

## 3. – Comparison between actual and simulated data: Theoretical considerations

The simulator described in the previous section can be used to generate the interferometric raw signal pair relevant to an actual ground scenario; then, this pair can be processed in order to obtain an interferogram. If we employ the system and orbit data of a real mission, and if a reference DEM of the imaged scene is available, we can think to perform a validation of our simulator by simply comparing the fringes obtained from the real raw data with the fringes obtained from the simulated raw data. However, because of uncertainties on the system and ground geometry, and due to the occurrence of unmodelled and/or unpredictable electromagnetic effects, we cannot expect that real and simulated fringes are identical in all respects. In fact, the interferometric phase is much more sensitive to such effects than SAR amplitude images. As a consequence, it is convenient to perform a comparison which ensures on one side that structural features over the interferogram, *i.e.* fringe spacing and pattern, are preserved, and on the other side that statistical consistency is achieved, *i.e.* that the phase decorrelation noise and the unwrapped phase statistics are also preserved.

Among the geometrical causes of discrepancies between real and simulated fringes we mention: DEM uncertainties and interpolation, and, above all, uncertainty on the baseline length and orientation [22], due to the finite accuracy of the orbit data (for spaceborne SAR systems) or of the knowledge of the airplane attitude (for airborne SAR systems). The main unmodelled (in our simulator) electromagnetic effects are, at present, the atmospheric effects on propagation delay, the volumetric scattering, and scene temporal changes (for repeat pass interferometry only). Consequently, preliminarly to any comparison between actual and simulated data, it is crucial to theoretically investigate the relevance of such causes of error over the interferometric phase. To this end, in this section we recall (when available in literature) or derive the relationships which measure the phase errors in terms of the DEM uncertainties, of the baseline errors, and of the atmosphere refractive index fluctuations. The relevance of this issue is not limited to the simulation field, since some of the considered error sources (*i.e.*, uncertainties on the baseline length and orientation, and atmospheric effects) can also dramatically hamper the accuracy of the DEMs obtained from real SAR interferometers.

Let us first consider the role of the accuracy of the input (to the simulator) DEM. The resolution of usually available DEMs is lower than the one required by the simulator (*i.e.* at least the SAR system resolution) and therefore an interpolation is needed. However, even in the favourable case of a high-resolution input DEM, a proper interpolation scheme need to be devised. In fact, these maps are generally referenced to a ground coordinate system by no means related to the SAR ground coordinate system (*i.e.* azimuth and ground range). The solution of this problem is provided by taking into account the guidelines given in ref. [23]. In any case, the DEM and phase accuracies are related by the following expression [22]:

$$\sigma_\varphi = \frac{4\pi B \cos(\vartheta - \alpha)}{r\lambda \sin\vartheta} \sigma_z, \tag{3}$$

wherein $\vartheta$ is the look angle, $B$ and $\alpha$ are the baseline length and orientation angle, $r$ is the range, $z$ is the height of the ground point, and $\phi$ is the interferometric phase, see also fig. 1.

For instance, by inserting in eq. (3) the system parameters of ERS-1, see table I, and using a 100 m baseline length and a $0^\circ$ baseline orientation angle, we get that a 5 m height error corresponds to about $15^\circ$ phase error. Therefore, this kind of error does not seem to severely affect the simulated interferogram, unless very large errors are present in the DEM.

Let us now consider the uncertainty in the knowledge of the baseline. It can be shown [22] that an error $\Delta B$ on the baseline length and an error $\Delta\alpha$ on the baseline orientation cause a systematic phase error $\Delta\varphi$ equal to

$$\Delta\varphi \cong \frac{4\pi}{\lambda} \sin(\vartheta - \alpha)\Delta B - \frac{4\pi}{\lambda} B \cos(\vartheta - \alpha)\Delta\alpha. \tag{4}$$

Fig. 1. – INSAR geometry.

This phase error can be interpreted as the resulting interferogram of the scene obtained with a reduced baseline equal to the baseline error. In order to better understand and remove the effect described in eq. (4) it is useful to approximate its expression. We let $\vartheta = \vartheta_0 + \Delta\vartheta$ where $\vartheta_0$ is the look angle corresponding to a flat earth ($z = 0$) and $\Delta\vartheta = z/(r \sin\vartheta)$ accounts for the elevation of the considered point. Then, $\Delta\varphi \approx \Delta\varphi_0 + \Delta\varphi_{\mathrm{top}}$, wherein $\Delta\varphi_0 = \Delta\varphi\ (\vartheta = \vartheta_0)$ is the phase uncertainty in the case of flat earth, and

$$\Delta\varphi_{\mathrm{top}} \cong \frac{4\pi \cos(\vartheta_0 - \alpha) \cdot \Delta B \cdot z}{\lambda r \sin\vartheta_0} + \frac{4\pi B \sin(\vartheta_0 - \alpha) \cdot \Delta\alpha \cdot z}{\lambda r \sin\vartheta_0} \tag{5}$$

is a residual term which accounts for the topography. For instance, in the ERS-1 case (with baseline length and orientation previously considered), if the error on the baseline length is equal to 1 m and the error on the baseline orientation is zero, then the phase error $\Delta\varphi_0$ is about $30\pi$ rads (15 fringes) at the center of the scene. However, this basic term corresponds to an "artificial" tilted mean plane over the unwrapped interferogram, and can be empirically identified and removed: in the processing case, this can be accomplished by using the knowledge of the elevation of a few tie-points in the scene [20]; in the simulation case, the mean plane can be easily identified on the difference between simulated and real interferogram. From its knowledge, it is possible to adjust the input orbital data of the simulator in order to obtain a better simulation. In any case,

TABLE I. – *Main ERS-1 system data used in the simulation runs.*

| | |
|---|---|
| Carrier frequency | 5.3 GHz |
| Platform height | 775.8 km |
| Look angle | 23° |
| Azimuth antenna dimension | 10 m |
| Range antenna dimension | 1.0 m |
| Pulse duration | 37.1 $\mu$s |
| Chirp bandwidth | 15.55 MHz |
| Sampling frequency | 18.97 MHz |
| Pulse repetition frequency | 1678 Hz |

the residual topographic term may be appreciable if large ground elevation variations are contained in the scene. For instance, in the ERS-1 case, if the error on the baseline length is equal to 1 m, the error on the baseline orientation is zero, and the ground elevation is 1000 m, then the phase error due to the topographic term is about 30°. Therefore, after the mean plane removal, the phase errors due to baseline errors are small (fraction of a cycle), unless very large ground elevation variations are contained in the scene.

With reference to the effect of the atmosphere on the interferometric phase, in Appendix A we show that, in the repeat pass case, the relation between the interferometric phase and the change of the atmosphere refraction index profile that occur between the two passes is given by the following expression:

$$\varphi = \frac{4\pi}{\lambda_0}\left[(r_1 - r_2) + \frac{1}{\cos\vartheta}(l_1 - l_2)\right], \tag{6}$$

wherein

$$l_1 = \int_z^{H_{\mathrm{atm}}} [n_1(\zeta) - 1]\mathrm{d}\zeta, \qquad l_2 = \int_z^{H_{\mathrm{atm}}} [n_2(\zeta) - 1]\mathrm{d}\zeta, \tag{7}$$

$H_{\mathrm{atm}}$ is a conventional atmosphere height, $n_1(\zeta)$ and $n_2(\zeta)$ are the refractive index profiles at the two passes, $l_1$ and $l_2$ are the corresponding excess electrical path lengths, and $z$ is the height of the considered point (see Appendix A). Since the excess electrical path length is dependent on weather conditions, it is variable with space and time. From eq. (6) it is evident that a few centimetres variations on the electrical excess path length can heavily affect the interferometric phase. Atmospheric effect could be simulated, or compensated for, if a detailed knowledge of the meteorological conditions at each SAR passage were available: in fact, the refractive index is related to air pressure, temperature and water vapour content [25]. In the case of single pass interferometry, however, atmospheric effects are usually negligible (see Appendix A).

Volumetric scattering can arise in correspondence of vegetated areas or for inhomogeneous soils whose electromagnetic penetration depth is significant. The presence of volumetric scattering affects the scene backscattering coefficient and decreases the correlation of INSAR image pairs [20, 21]. Several volumetric scattering models are available [24, 25], and their efficient inclusion in the simulation code is currently under development.

With reference to temporal changes, it is clear that they cause a decorrelation (temporal decorrelation, [19]). However, they are completely unpredictable and their simulation is not meaningful.

As a conclusion, above considerations suggest that the main differences between simulated and real fringe patterns are usually due to baseline errors and, above all (for repeat pass INSAR systems) to atmospheric effects. Besides, we expect that, for repeat pass INSAR systems, simulated interferometric pairs show a higher coherence than the real ones, since temporal decorrelation is not accounted for by the simulator.

## 4. – Comparison between actual and stimulated data: An example

In this section we illustrate results of a simulation experiment corresponding to a real scene. We used system parameters of ERS-1/ERS-2 mission and orbit data of the tandem raw signal pair acquired on 5 and 6 September 1995 over Mount Etna, Sicily, Italy. The considered scene is about 10 km (azimuth) × 15 km (ground range) large. A 25 m × 25 m

Fig. 2. – Images obtained from simulated (a) and real (b) raw data.

aerophotogrammetric DEM of this area, realised in 1989, was interpolated to obtain a range-azimuth oriented input grid whose spacing is half the ERS pixel spacing (see [10] for motivations of this choice).

The simulated raw signal pair was processed, and resulting image and interferogram are shown in figs. 2(a) and 3(a). Then, the real raw signal pair was also processed in the same way, and resulting image and interferogram are shown in figs. 2(b) and 3(b). All images and (complex) interferograms were averaged by using a $8 \times 2$ pixel window. In all images, near range is on the left.

As a first qualitative comment, it can be stated that real and simulated images are very similar, whereas, as expected, real and simulated fringes are similar, but not identical in all respects. As a quantitative test of geometrical consistency, we counted the number

Fig. 3. – Interferograms obtained from simulated (a) and real (b) raw data pairs.

Fig. 4. – Phase difference between interferograms obtained from simulated and real raw data pairs.

of fringes from the top of the volcano to a reference point on the right edge of the scene, and verified that it is the same on real and simulated interferograms. Furthermore, by subtracting simulated from real fringes, we get the phase difference pattern reported in fig. 4. Some phase differences between the two interferograms, localised in small areas (see the left part of the image), are due to atmospheric effects (see previous section), in fact we have verified that they are always different if other data, acquired at different times, are used. Such differences are of the order of magnitude predicted in the previous section. However, in the upper-right corner of fig. 4 a very clear phase difference corresponding

Fig. 5. – Coherence maps of image pairs obtained from simulated (a) and real (b) raw data.

to more than one fringe appears. This difference appears even if we use other data acquired at different times. Actually, it has been verified [26] that, after the construction of the aerophotogrammetric DEM used as input of the simulator, a lava flow caused by the 1991-1993 eruption changed the topography of the considered zone by a maximum amount of more than 100 m. This justifies the observed discrepancy between real and simulated interferograms.

With regards to phase statistics, some interesting remarks can be made by a simple visual comparison of the two interferograms. It can be noted that phase noise due to decorrelation in the layover area (left part of the images) is present on both real and simulated fringes. This is a further confirmation that baseline decorrelation effect is correctly simulated. However, in the right part of the real interferogram two decorrelation areas appear, which are not present in the simulated interferogram. These areas correspond to vegetated zones, so that decorrelation is most likely due to temporal changes, which are not modelled in our simulator. This suggests that simulation can be used to separate baseline decorrelation from decorrelation due to others sources, as a preliminary step for a coherence-based classification scheme. Quantitative coherence measurements over real and simulated images fully support previous qualitative considerations, as can be verified by analysing the coherence maps reported in fig. 5.

## 5. – Concluding remarks

Use of a SAR interferometric raw signal pair simulator over a real scene is illustrated both theoretically and by an example. The interferograms obtained from simulated data are compared with the ones obtained from real data. Qualitative and quantitative comparison results are discussed. Real and simulated fringes turn out to be very similar. A localised geometrical difference has been explained in terms of DEM errors. Differences in phase statistics encountered in another particular zone are explained in terms of unmodelled temporal changes over a vegetated area, and suggest that simulation can be used to separate baseline decorrelation from decorrelation due to others sources, as a preliminary step for a coherence-based classification scheme.

## Appendix A.

### Atmospheric effects on the SAR interferometric phase difference

By taking into account the atmospheric refractive index profile, the INSAR phase difference can be written as

$$\varphi = \frac{4\pi}{\lambda_0}(r_{1\mathrm{el}} - r_{2\mathrm{el}}), \tag{A.1}$$

wherein $\lambda_0$ is the wavelength in vacuum, and $r_{1\mathrm{el}}$ and $r_{2\mathrm{el}}$ are the electrical path lengths, given by (see fig. 6)

$$r_{1\mathrm{el}} = \frac{1}{\cos\vartheta_1}\int_z^{H_{\mathrm{atm}}} n_1(\zeta)\mathrm{d}\zeta + r_1 - \frac{H_{\mathrm{atm}}}{\cos\vartheta_1} = r_1 + \frac{1}{\cos\vartheta_1}\int_z^{H_{\mathrm{atm}}}[n_1(\zeta) - 1]\mathrm{d}\zeta, \tag{A.2}$$

$$r_{2\mathrm{el}} = \frac{1}{\cos\vartheta_2}\int_z^{H_{\mathrm{atm}}} n_2(\zeta)\mathrm{d}\zeta + r_2 - \frac{H_{\mathrm{atm}}}{\cos\vartheta_2} = r_2 + \frac{1}{\cos\vartheta_2}\int_z^{H_{\mathrm{atm}}}[n_2(\zeta) - 1]\mathrm{d}\zeta. \tag{A.3}$$

Fig. 6. – Effect of the atmosphere on interferometric phase.

In eqs. (A.2), (A.3), $z$ is the height of the considered point, $H_{\mathrm{atm}}$ is the height of the atmosphere upper limit; $n_1(\zeta)$ and $n_2(\zeta)$ are the refractive index profiles at the two passes, if a repeat pass INSAR system is considered. In the single pass case, $n_1(\zeta)$ and $n_2(\zeta)$ are equal. The integrals

$$l_1 = \int_z^{H_{\mathrm{atm}}} [n_1(\zeta) - 1]\mathrm{d}\zeta, \qquad l_2 = \int_z^{H_{\mathrm{atm}}} [n_2(\zeta) - 1]\mathrm{d}\zeta \tag{A.4}$$

are called excess electrical path length [25]. Substituting eqs. (A.2), (A.3) in eq. (A.1), and using eq. (A.4), we get

$$\varphi \cong \frac{4\pi}{\lambda_0}\left[(r_1 - r_2) - \frac{B_\perp \tan\vartheta}{r\cos\vartheta}\bar{l} + \frac{1}{\cos\vartheta}(l_1 - l_2)\right], \tag{A.5}$$

where $B_\perp$ is the baseline component perpendicular to the look direction, $\bar{l}$ is $(l_1 + l_2)/2$ and the relation

$$\frac{l_1}{\cos\vartheta_1} - \frac{l_2}{\cos\vartheta_2} \cong -\frac{\sin\vartheta\,\delta\vartheta}{\cos^2\vartheta}\bar{l} + \frac{1}{\cos\vartheta}(l_1 - l_2) = -\frac{B_\perp \tan\vartheta}{r\cos\vartheta}\bar{l} + \frac{1}{\cos\vartheta}(l_1 - l_2) \tag{A.6}$$

is used. Equation (A.5) shows that two "atmospheric noise" terms are present in the interferometric phase, the second arising only for repeat pass systems. In order to evaluate the relevance of these terms, we recall that the excess electrical path length for the standard neutral atmosphere is about 2.3 metres [25]. To this length, a further term due to ionospheric refraction should be added. Actual measurements show that the overall excess electrical path length varies from 2.2 to 2.7 metres [25]. Considering that the baseline to range ratio is of the order of $10^{-3}$–$10^{-4}$, and that the wavelength is of the order of centimetres, we can conclude that the first error term is negligible, or anyway a fraction of a cycle: for example, in the ERS-1 case, with $B_\perp = 80\,\mathrm{m}$, we have that the first phase error term is about $\pi/170$ rads. On the contrary, examination of the second noise term shows that even a variation of a few centimetres on the excess electrical path length can cause a large phase error.

## REFERENCES


[1] Graham L. C., *IEEE Proc.*, **62** (1974) 763.
[2] Raney R. K. and Vachon P. W., *Proceedings of IGARSS '89, Vancouver 1989*, pp. 2588–2591.
[3] Fornaro G. and Franceschetti G., *IEE Proc.*, **142** (1995) 313.
[4] Goldstein R. M., Zebker H. A. and Werner C. L., *Radio Sci.*, **23** (1988) 713.
[5] Fornaro G., Franceschetti G. and Lanari R., *IEEE Trans. Geosci. Remote Sensing*, **GE-34** (1996) 720.
[6] Fornaro G., Franceschetti G., Lanari R., Rossi D. and Tesauro M., *IEE Proc., Radar Sonar and Navigation*, **144** (1997) 266.
[7] Schreier G., *SAR Geocoding: Data and Systems* (Karlsruhe, D: Wichmann), 1993.
[8] Franceschetti G., Iodice A., Migliaccio M. and Riccio D., *Proceedings EUROPTO '96*, **2968**, Taormina, 1996, pp. 273–284.
[9] Franceschetti G., Iodice A., Migliaccio M. and Riccio D., *Proceedings of IGARSS '97, Singapore 1997* (IEEE-GRSS, 1997) pp. 1701–1703.
[10] Franceschetti G., Iodice A., Migliaccio M. and Riccio D., *IEEE Trans. Geosci. Remote Sensing*, **36** (1998) 950.
[11] Coltelli M., Fornaro G., Franceschetti G., Lanari R., Migliaccio M., Moreira J. R., Papathanassiou K. P., Puglisi G., Riccio D. and Schwäbisch M., *J. Geophys. Res.*, **101-E10** (1996) 23127.
[12] Tarayre H. and Massonet D., *Proc. IGARSS '94, Pasadena, 1994* (IEEE, 94CH3378-7, 1994), pp. 717–719.
[13] Franceschetti G., Iodice A., Migliaccio M. and Riccio D., *J. Electro. Waves Applic.*, **11** (1997) 353.
[14] Just D. and Bamler R., *Appl. Opt.*, **33** (1994) 4361.
[15] Davenport W. B. and Root W. L., *An Introduction to the Theory of Random Signals and Noise* (IEEE Press, New York) 1987.
[16] Franceschetti G., Migliaccio M., Riccio D. and Schirinzi G., *IEEE Trans. Geosci. Remote Sensing*, **GE-30** (1992) 110.
[17] Franceschetti G., Lanari R. and Marzouk E. S., *IEEE Trans. Aerospace Electron. Syst.*, **AES-31** (1995) 227.
[18] Li F. K. and Goldstein R. M., *IEEE Trans. Geosci. Remote Sensing*, **GE-28** (1990) 88.
[19] Zebker H. A. and Villasenor J., *IEEE Trans. Geosci. Remote Sensing*, **GE-30** (1992) 950.
[20] Gatelli F., Monti Guarnieri A., Parizzi F., Pasquali P., Prati C. and Rocca F., *IEEE Trans. Geosci. Remote Sensing*, **GE-32** (1994) 855.
[21] Rodriguez E. and Martin J. M., *IEE Proc.-F*, **139** (1992) 147.
[22] Zebker H. A., Werner C. L., Rosen P. A. and Hensley S., *IEEE Trans. Geosci. Remote Sensing*, **GE-32** (1994) 823.
[23] Franceschetti G., Migliaccio M. and Riccio D., *IEEE Trans. Geosci. Remote Sensing*, **GE-32** (1994) 1160.
[24] Ulaby F. T., Moore R. K. and Fung A. K., *Microwave Remote Sensing*, Vol. **II** (Addison-Wesley, Reading, MA) 1982.
[25] Ulaby F. T., Moore R. K. and Fung A. K., *Microwave Remote Sensing*, Vol. **III** (Dedham, MA: Arthec House) 1986.
[26] Sansosti E., Tesauro M., Lanari R., Fornaro G., Puglisi G., Franceschetti G. and Coltelli M., *Int. J. Remote Sensing*, **20** (1999) 1527.