Device performance: To obtain low-driving-voltage optical modulators for band-operation, we designed them to have large induced phases $\phi$, by varying the lengths $L_1$ and $L_2$. We considered an electrode structure with the following parameters. The gap between the electrodes of ACPWs and CPWs is 27 pm. The width and the thickness of the electrodes are, respectively, 5 and 20 $\mu$m. The characteristic coefficients of the modulating electrode (ACPW) are $\gamma_1 = 14.5 + j598.1$ and $Z_0 = 52.5 \Omega$. Those for the stub (CPW) are $\gamma_2 = 16.0 + j550.0$ and $Z_0 = 44.5 \Omega$. Using (3), we obtained a combination of $L_1$ and $L_2$ that gave a maximum $\phi$. When $L_1 = 1.41L_2 = 14.81$ mm and $L_2 = 0.12L_2 = 1.37$ mm, $\phi$ had a maximum of 1.38 at 10 GHz, where $L_1$ and $L_2$ were the wavelengths on the modulating electrode and the stub, respectively. $2L_p$ was set to be $3 \times (c/\epsilon_0)$. As shown in Fig. 2, the normalised induced phase of the fabricated reflection-type modulator for the 1.55 $\mu$m region (solid line) was larger than that of the conventional structure where the optical reflection was not used (dashed line). The $V_0$ was 2.9 V at 7 GHz and 3.4 V at 10.5 GHz, while that of the conventional structure was 5.8 V at 10.5 GHz.

![Fig. 2 Normalised induced phase of fabricated modulator](image)

**Conclusion:** We have developed a LiNbO$_3$ modulator with lightwave reflection and double-stub structure. The modulator has a reflection-type Mach-Zehnder interferometer consisting of a Y-branch and a pair of optical reflections. The halfwave voltage was 2.9 V at 7 GHz. The proposed structure provides very low driving voltage for band-operation, without using complicated three-dimensional waveguide structures.

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**References**


**Optimum redundant array configurations for Earth observation aperture synthesis microwave radiometers**

I. Corbella, A. Camps, N. Dufio and M. Vall-ionsera

Two-dimensional aperture synthesis radiometry is the technology selected for ESA's SMOS mission to provide high resolution L-band radiometric imagery. The array topology is a Y-shaped structure. The position and number of redundant elements to minimise instrument degradation in case of element failure(s) are studied.

**Introduction:** The MIRAS instrument [1, 2], single payload of the European Space Agency's SMOS mission, will be the first two-dimensional aperture synthesis radiometer for Earth Observation. It will operate at L-band, where there is a good sensitivity to the soil moisture content and the sea surface salinity, the atmosphere is almost transparent, and there is a frequency band reserved for passive observations. The imaging is performed through a Fourier synthesis process of the cross-correlations $V_{ij}$ measured between the bandpass signals $b_i(t)$ and $b_j(t)$, centered at $f_0$, $\omega_0 = 2\pi f_0$ collected by every pair of antennas. If all the antennas have the same antenna radiation pattern $|F_c(\omega, \eta)|^2$ and spatial decorrelation effects are negligible, the relationship between the brightness temperature and the observables is

$$V_{ij} = V(u_{ij}, v_{ij}) \Delta \frac{1}{k_0 B G} \int \left| \int \frac{\omega_0^2 - \omega^2 - \eta^2}{\sqrt{1 - \omega^2 - \eta^2}} \right| b_i(t) b_j(t) \exp(-j2\pi(u_{ij} \eta + v_{ij} \eta)) d\eta$$

where $k_0$ is the Boltzmann's constant, B and G are the receivers' noise bandwidth and power gain, $\Omega$ is the solid angle of the antennas, the spatial frequency sampled (baseline) depends on the antenna position difference: $(u_{ij}, v_{ij}) = (u_2 - u_1, v_2 - v_1)/f_0$, and the director cosines ($\xi, \eta$) = (sin $\phi$ cos $\theta$, sin $\phi$ sin $\theta$) are defined with respect to the X and Y axes.

![Fig. 1 Hub configurations](image)

**Hub configurations**

a. Array configuration without redundancy: each circle represents an antenna position (NEL = 21 antennas per arm spaced $d = 0.875$ wavelengths, SMOS/MIRAS configuration), the square represents a noise injection radiometer used to measure V0. Its output is not correlated with rest of the antennas
b. (Hexagonal hub) Redundant antennas marked with diamonds, arrows indicate redundant baselines

**References**


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Since \( c^2 + n^2 \leq 1 \), \( f(u, v) \) is optimally sampled over a \( (u, v) \) hexagonal grid, as provided by a Y-array, which additionally provides the largest \( (u, v) \) coverage, and therefore achieves the best angular resolution [3]. The loss of \( (u, v) \) points due to element failure(s) distorts the instrument’s spatial response named equivalent array factor (\( A_{eq} \)) [4], and degrades the radiometric sensitivity and accuracy [5]. In [5] it is shown that the failure of a single element degrades the spatial resolution by less than 10%, but the radiometric accuracy degrades very quickly: from \(-4.5 \) to \(-13 \) K for the single failure of one element in positions 8 to 1 (Fig. 1a in [5]). The most critical elements are those closest to the array centre, since they lead to the shortest baselines, for which \( f(u, v) \) has the largest amplitude. Owing to the stringent performances required to monitor the soil moisture and the ocean salinity it is clear that the instrument’s spatial response named equivalent array factor (system impulse response) corresponding to hubs 0 and 3 in terms of MBE. In all cases, the SLL slightly worsens.

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SAR interferometric phase statistics in wavelet domain

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Synthetic aperture radar (SAR) interferometry is employed to obtain topographic information. Owing to noise, interferometric information has to be filtered. The wavelet transform can be employed to filter the interferometric phase, maintaining the spatial resolution, but new signal models have to be studied in this domain for further processing.

Introduction: Synthetic aperture radar interferometry (InSAR) is an established technique to obtain information about the earth’s surface topography. The interferometric phase is calculated as the phase difference between two complex SAR images from the same area, but taken from slightly different positions. Owing to the lack of interferometric coherence between both SAR images, the interferometric phase is noisy. In addition, the interferometric phase is only known within the interval [-π, π], it being necessary to unwrap it to recover unambiguously the height information. The unwrapping process is also affected by phase noise, since it induces phase residues. Phase filtering is thus necessary to reduce noise effects.

In the last decade, the wavelet transform (WT) has shown a big potential for image processing applications. In the field of SAR data processing, the use of the WT is emerging since it allows processing of SAR imagery, keeping the spatial resolution and image details.

Since the physics behind SAR data is completely different from that of optical images, any data processing has to take this into account. Thus, it is necessary to review or even define new noise models adapted to this problem. In this Letter, we provide a study of a signal model for the interferometric phase in the wavelet domain. This model is validated with real interferometric data.

Complex interferometric phase noise model: Earth topography can be represented locally by a constant slope [1], thus the interferometric phase \( \phi \) can be assumed to be a constant phase ramp. In the spatial domain the measured interferometric phase complies with the model \( \phi = \phi_0 + \nu \) [2], where \( \nu \) is a phase noise term. The real and imaginary parts of the measured phase \( \phi \), coded in the unit circle, defined as the complex interferometric phase, can be modelled by [3, 4]:

\[
\begin{align*}
\cos(\phi) &= N_0 \cos(\phi_0) + \nu_x \\
\sin(\phi) &= N_0 \sin(\phi_0) + \nu_y
\end{align*}
\]

(1)

(2)

the wavelet transforms of which are [3]:

\[
\begin{align*}
\mu_1 &= \text{DWT}_2D(\cos(\phi_0)) = 2N_0 \cos(\phi_0^w) + \nu_x^w \\
\mu_2 &= \text{DWT}_2D(\sin(\phi_0)) = 2N_0 \sin(\phi_0^w) + \nu_y^w
\end{align*}
\]

(3)

(4)

where \( \nu_x^w \) and \( \nu_y^w \) are noise terms independent from the wavelet scale. The phase term \( \phi_0^w \) represents the interferometric phase in the wavelet domain, which contains the same information as \( \phi_0 \). The WT is able to localise \( \phi_0 \) in the space-frequency plane. \( N_0 \) has a one-to-one relation with the coherence \( |\gamma| \) providing, thus, the same information [3, 4].

For a constant interferometric phase and homogeneous noise (i.e. constant \( |\gamma| \)), the parameter \( N_0 \), as well as the terms \( \cos(\phi_0^w) \) and \( \sin(\phi_0^w) \) are constant. Therefore, signal randomness is only due to \( \nu_x^w \) and \( \nu_y^w \). The discrete wavelet transform (DWT) can be seen as the addition of (weighted) random variables. By the central limit theorem, the weighted sum of identically distributed random variables can be approximated by a Gaussian distribution. Therefore, \( \nu_x^w \) and \( \nu_y^w \) are approximately Gaussian distributed. To test this, avoiding any interference from the phase \( \phi_0^w \), a constant slope producing 20 pixel fringes, corrupted with noise equivalent to a coherence \(|\gamma| = 0.6\), has been simulated. Table 1 shows a statistical test applied over the real part of the interferometric complex phase in the wavelet domain. As shown, since the useful signal is concentrated in the low frequency band (LL), the wavelet bands (HL, LH and HH) present a kurtosis close to 3 and the significance levels for the Kolmogorov-Smirnov (KS) test, assuming a Gaussian distribution, are high. These results demonstrate that \( \nu_x^w \) and \( \nu_y^w \) can be described by a Gaussian distribution. The same agreement is observed for any other value of \(|\gamma|\), and for the imaginary part of the complex interferometric phase in the wavelet domain. The LL band deserves special attention. In this case, there is signal content, the signal model will be represented by the real and imaginary parts of exp \( (j\phi_0^w) \) plus a Gaussian noise. Therefore, in this case, the amplitude \( \|\mu_1 + j\mu_2\| \) has a Rice distribution. This result is equally valid for the rest of the wavelet bands. The amplitude in the wavelet domain will be Rayleigh distributed for \(|\gamma| = 0\), in a particular space-frequency region, and Rice distributed for \(|\gamma| > 0\).

Table 1: Kurtosis and KS significance levels (Gaussian assumption) for real part of simulated complex interferometric phase ramp in wavelet domain

<table>
<thead>
<tr>
<th>Horizontal band (HL)</th>
<th>Vertical band (LH)</th>
<th>Diagonal band (LL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kurtosis</td>
<td>KS significance level (%)</td>
<td>Kurtosis</td>
</tr>
<tr>
<td>Scale 1</td>
<td>2.98</td>
<td>87.93</td>
</tr>
<tr>
<td>Scale 2</td>
<td>3.03</td>
<td>95.78</td>
</tr>
<tr>
<td>Scale 3</td>
<td>3.08</td>
<td>82.87</td>
</tr>
</tbody>
</table>

Complex interferometric phase signal model: The topographic model assumed previously (i.e. constant slope) does not take into account spatial details, which are important, for instance, in urban areas. Since no information is available about the distribution of the true topographic phase \( \phi_0^w \), an \textit{a priori} model for the spatial details is not available in the spatial domain. This drawback can be overcome in the wavelet domain. As mentioned in the preceding Section, the DWT can be interpreted as a weighted sum of random variables. Therefore, \( \text{DWT}_2D(N_0 \cos(\phi_0)) \) and \( \text{DWT}_2D(N_0 \sin(\phi_0)) \) can be supposed to be determined, as a first approximation, by a Gaussian distribution. Tests with real data (see Tables 2 and 3) show that wavelet statistics have kurtosis higher than 3. To take into account this deviation from Gaussian behaviour, a double stochastic model is proposed for the wavelet coefficients \( x \):

\[
p_x(x) = \int_0^\infty p_x(s) |s|^2 ds
d^n \text{d}x^2
\]

(5)

where \( p_x(s) \) represents the Gaussian distribution of the wavelet coefficients and \( p_x(c_2) \) is a generalised gamma distribution (GGD) modelling the variability of the variance through the phase image. \( p_x(x) \) cannot be obtained in a general form. Numerical integration of (5), see Fig. 1, indicates that \( p_x(x) \) can be assumed to be a GGD model. To test the validity of this model, two real interferometric phase images taken with the German sensor E-SAR from DLR have been employed. The first image is an X-band interferogram of Mount Etna (Italy) and the second one is an L-band interferogram of the Oberpfaffenhofen test site (Germany), were man-made structures are present. These two interferometric phases were filtered with the algorithm presented in [3], which is based on maintaining the spatial resolution. Tables 2 and 3 present the kurtosis and the KS test significance levels, assuming a GGD model, applied to the real part of the filtered complex interferometric...