Bridge Thermal Dilation Monitoring With Millimeter Sensitivity via Multidimensional SAR Imaging

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Abstract—The new generation of synthetic aperture radar (SAR) sensors is providing images with very high spatial resolution, improved up to the meter scale. Such a resolution increase allows more accurate monitoring capabilities by means of interferometric approaches. The use of higher frequency enhances the sensitivity of the system even to minute changes, such as thermal dilations. This phenomenon has an impact on the interferometric products, particularly on the deformation velocity maps, if not properly handled. Man-made structures, such as steel core bridges and specific buildings, may be very sensitive to thermal dilation effects. By extending the multitemporal differential interferometry SAR processing chains, in our case based on the multidimensional imaging (MDI) approach, an additional parameter related to temperature differences at acquisition instants, the thermal coefficient, can be accurately estimated. This parameter provides interesting perspectives in application to infrastructure monitoring: It brings information about the thermal behavior of the imaged objects. In this letter, we investigate the thermal response of the Musmeci bridge (Potenza, Italy), by experimenting the extended MDI approach on a real TerraSAR-X data set. Results highlight the possibility of such a technique to obtain measurements of the motion that is highly correlated with temperature, thus providing useful information about the static structure of bridges.

Index Terms—Multidimensional SAR imaging (MDI-SAR), SAR tomography, synthetic aperture radar (SAR), TerraSAR-X (TSX), thermal dilation.

I. INTRODUCTION

SYNTHETIC aperture radar (SAR) interferometry (InSAR) is a widely used technique that makes possible recovering the topographic profile with meter accuracy, by using coherent imagery. Furthermore, differential InSAR (DInSAR) and, particularly, multitemporal DInSAR have been proven to be very effective for monitoring the surface displacements [1], [2], pushing the use of SAR for environmental risk monitoring.

Multidimensional (4-D) SAR imaging (MDI-SAR) [3], [4] approaches use the phase and the amplitude information to provide an imaging also along the elevation and velocity directions of the backscattering properties of the scene. It uses all baselines of multitemporal data sets and therefore is specifically designed for the monitoring of structures at full resolution.

The new generation of X-Band high-resolution SAR sensors, such as the TerraSAR-X (TSX)/Tandem-X satellites and the COSMO-SkyMed constellation, contributed to a tangible improvement in the monitoring capabilities of interferometric techniques [5]: Among all other advantages, such as precise orbit determination and short revisiting time, this new class of SAR sensors delivers SAR data with a very high spatial resolution of up to 1 m compared to the medium (10–30 m)- and high (3–10 m)-resolution SAR systems available so far. These X-band SAR data provide much more details of single ground structures and, at the same time, much higher spatial density of monitored targets with respect to C-band sensors. Meanwhile, due to the reduced wavelength (~3.1 cm), they are more sensitive to small displacements, even those caused by thermal dilation of the imaged objects, which affects the phase signature [6], [7]. Thermal dilations have been observed also on DInSAR analysis of C-band data (i.e., ERS, ENVISAT, and RadarSAT) [8], [9]; however, their effects on X-band data stacks are more evident and critical, due to the increase of the deformation sensitivity, the increase of temporal sampling, and the observation on temporal span which can be often below one year; furthermore, the increase of spatial resolution allows one to better highlight the contributions of different features of ground structures.

In multitemporal interferometric processing [1]–[3], the effects of thermal dilation have clearly an impact on the final products, particularly on the deformation velocity estimates which, in the worst case scenario, can be strongly biased by the thermal-induced displacements [9]. In fact, large nonlinear thermal dilation effects lead to a mismatch of the received phase with the linear model typically assumed for the identification of persistent scatterers (PSs) and the extraction of the information relevant to the deformation motion, thus leading, depending on the processing scheme, to a significant decrease of the detection performances and/or to ambiguous velocity measurements, particularly on the structures exhibiting large thermal dilation effects. Therefore, the opportunity to investigate how structures are able to withstand weathering is of special importance, particularly in regions where the environmental conditions are harsh.

A strategy to mitigate problems associated with thermal dilation is the introduction of an additional seasonal (sine or temperature dependent) phase component within the processing.

Thermal dilation can be handled in MDI-SAR [10], [11] by extending the approach through the introduction of an additional unknown term, in addition to the classical residual topography and deformation mean velocity unknown parameters, i.e., the thermal coefficient which is related to the temperature differences at acquisition instants, leading to a mismatch of the received phase with the linear model typically assumed for the identification of persistent scatterers (PSs) and the extraction of the information relevant to the deformation motion, thus leading, depending on the processing scheme, to a significant decrease of the detection performances and/or to ambiguous velocity measurements, particularly on the structures exhibiting large thermal dilation effects. Therefore, the opportunity to investigate how structures are able to withstand weathering is of special importance, particularly in regions where the environmental conditions are harsh.

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difference between the acquisition instants. The inclusion of this term allows sensibly increasing the capability to detect targets affected by thermal dilation.

In this letter, we investigate the use of the extended MDI approach to monitor individual man-made infrastructures and, in particular, bridges. A real data set of TSX images over the city of Potenza (Italy) was acquired and processed. With respect to similar studies [7], first of all, here, we use an imaging technique that exploits both the amplitude and phase information. Compared to classical PS interferometry algorithms, which are based only on the use of the phase information, MDI allows a more accurate estimation of the scatterer parameters related to the height and to the deformation and better performances in terms of detection probability for a fixed false alarm probability [12]. Second, in addition to the spatial distribution of the deformation, we provide also plots of the temporal measurements that allow showing the possibility to achieve an extremely accurate monitoring of thermal-induced dilations, up to a sensitivity (standard deviation of the difference between the modeled and measured thermal components) on the order of $1 \text{ mm}$ in each deformation measurement. Finally, the characteristics of one of the analyzed bridge (Musmeci) provide peculiar thermal deformation response that do not allow the derivation of the structural thermal dilation coefficient as in [7]: Here, we rather emphasize the fact that radar measurements provide an indication on the whole response of the bridge from both the structural composition and the structural construction constraints.

II. FIVE-DIMENSIONAL IMAGING

Consider a collection of $N$ SAR images acquired at $t_n$ time instants, spatially separated from a reference acquisition by $b_n$, $n = 0, \ldots, N - 1$. The deformation signal of a scatterer at elevation $s$ is typically assumed to be composed of a linear and a nonlinear contribution. The 4-D imaging assumes the nonlinear contribution to be limited in extent to avoid the spread of the target peaks in the 2-D plane, given by the elevation/deformation mean velocity pair [3]. Indeed, thermal dilation can increase the nonlinear contribution component of the deformation signal and therefore affect the target detection. In order to account for such an additional component, the MDI technique is extended by introducing a new unknown term in the deformation model, namely, the thermal coefficient, related to temperature difference between acquisition instants.

Taking into account the thermal dilation signal, the deformation model for a fixed azimuth–range pixel at elevation $s$ and time $t_n$ can be extended to [7]

$$d(s, t_n) = v t_n + k T_n + d_{NL}(s, t_n)$$

where $v$ is the deformation mean velocity (in meters per second), $k$ is the thermal coefficient having the dimension of meters per kelvin, $T_n$ is the local temperature distribution at acquisition instants, and $d_{NL}(s, t_n)$ is the remaining nonlinear component of the deformation. Note that the estimated thermal coefficient is different from the coefficient of thermal expansion, which is related to a key physical property of materials and has the dimension of $(1/K)$.

MDI is commonly used within a two-step interferometric processing scheme in which the first step is aimed at estimating deformations and atmospheric phase delay components on a smaller (low resolution) scale [3]. In our processing chain, this step is typically carried out by using a small baseline subset (SBAS) approach [1] to avoid the impact of temporal and spatial decorrelation effects. After this phase calibration, the received signal $x_n$ at the $n$th acquisition, in any image pixel, may be written as the superposition of elementary contributions of the backscattering function $\gamma$ along the elevation $s$, exhibiting the deformation $d(s, t_n)$

$$x_n = \int_{\Delta s} \gamma(s, t_n) e^{-j2\pi \xi_n s} e^{-j4\pi^2 d(s, t_n)} ds.$$ (2)

By expanding the exponential deformation term in Fourier harmonics, we have [11]

$$x_n = \int_{\Delta s} \int_{\Delta v} \int_{\Delta k} \gamma(s, v, k)e^{-j2\pi(\xi_n s + \eta_n v + \zeta_n k)} ds dv dk$$ (3)

where $\gamma(s, v, k)$ is the backscattering distribution projection in the elevation/velocity/thermal dilation volume and

$$\xi_n = \frac{2b_n}{\lambda r_0},$$
$$\eta_n = \frac{2v}{\lambda}, \quad n = 0, \ldots, N - 1,$$
$$\zeta_n = \frac{2T_n}{\lambda},$$ (4)

are the spatial (1/m), temporal (in seconds per meter), and thermal (in kelvins per meter) frequencies, respectively, with $\lambda$ and $r_0$ being the system wavelength and the range of the target from the reference track. $\Delta s$, $\Delta v$, and $\Delta k$ are the scene extensions in the elevation, deformation mean velocity, and thermal dilation directions.

The discretization of the operator in (3) over a set of $M$ elevations/velocity/thermal coefficient bins over the domain of interest leads to the following linear problem:

$$x = A\gamma$$ (5)

where $x = [x_0, \ldots, x_{N-1}]^T$ is the vector collecting, for each pixel, the measured complex data, $\gamma = [\gamma_0, \ldots, \gamma_{M-1}]^T$ collects the values of the backscattering distribution at the $M$ discrete bins, and the superscript “T” stands for the transposition operator. Finally, $A = [a_0, \ldots, a_{M-1}]$ is the $N \times M$ system matrix collecting the $N$-dimensional steering vectors $a_m = \exp(j2\pi(\xi s_i + \eta v_j + \zeta k_l))$, where $m = 0, \ldots, M - 1$, $s_i, v_j$, and $k_l$ are the three parameters corresponding to the $m$th bin, $\xi = [\xi_0, \ldots, \xi_{N-1}]^T$, $\eta = [\eta_0, \ldots, \eta_{N-1}]^T$, and $\zeta = [\zeta_0, \ldots, \zeta_{N-1}]^T$.

A simple way to estimate $\gamma$ is by inverting, via a conjugate operator, the data to reconstruct an image that measures the distribution of backscattering in the elevation, velocity, and thermal coefficient domains

$$\hat{\gamma}(\hat{s}, \hat{v}, \hat{k}) = \arg \max_{(s, v, k)} x a^H(s, v, k)$$ (6)
where the superscript \( H \) stands for the Hermitian operator. Following this focusing stage, the detection for the presence of scatterers is carried out by evaluating a test statistic based on the intensities measured on the main peaks in the reconstructed scattering distribution [12]. With respect to this topic, it is important to note that the use of an imaging method allows one to take benefit also of the amplitude information for better PS detection performances [12]; moreover, in our approach, we follow a detection strategy which is based on a fixed false alarm probability that takes into account the increase of dimensionality of the imaging process. It should be also noted that possible correlations of the distribution of time and temperature may generate the occurrence of ambiguities between velocity and thermal coefficient. All these topics are addressed in detail in [11].

### III. EXPERIMENTAL RESULTS

The extended (temperature-dependent) MDI-SAR has been applied to a real data set, composed of 34 TSX strip-map mode (the standard acquisition configuration with about 3-m ground resolution) images, acquired during ascending passes of the satellite, over the city of Potenza (Italy). Almost all images are acquired with the minimum repeat cycle of the TSX mission of 11 days, from February 2010 to September 2011. The temperatures have been acquired by a meteorological station of the Institute of Methodologies for Environmental Analysis (IMAA) of the National Research Council (CNR).

The data set was calibrated for atmospheric phase component, estimated via the low-resolution multipass DInSAR approach in [13] before the application of the MDI processing. An extensive experimental and numerical investigation has been carried out on the Basento viaduct, in the town of Potenza (southern Italy), better known as the Musmeci bridge. The bridge, about 280 m long, is composed of four spans about 70 m long. In Fig. 1, an aerial view taken from the Bing Maps of the area under investigation and the schematic model of the bridge are shown. The bridge represents an important element of the infrastructural network, linking the city center to the Potenza–Scicignano highway, crossing the Basento river and the railway close to the main train station of the city.

In Fig. 2, the deformation mean velocity and the thermal dilation map of the area under investigation, estimated by means of the 5-D imaging, are shown. Most of the area is not affected by any linear deformation or thermal dilation. By contrast, the Musmeci bridge displays a remarkable thermal dilation with values ranging up to approximately 1 mm/K. Positive values indicate that positive temperature gradients induce displacements toward the sensor, while negative ones cause displacements away from the SAR sensor. Note that these values refer to the sensor line of sight (LOS). This means that a temperature variation of 1 K induces LOS displacements of up to 1 mm. It is important to note the high-resolution capability of the X-band TSX sensor: The resulting PS distribution allows achieving an excellent coverage of the edges of the Musmeci bridge.

Concerning the bridge, the thermal dilation map (distribution of the estimated thermal coefficient) indicates that it is sensitive with different spatial behavior to the temperature. Particularly, by referring to the red lines in Fig. 3 identifying the bridge segments (the three central ones are located approximately in correspondence of the three pillars, while the two external ones are located approximately in correspondence of the terminations of the bridge), an accumulation of the thermal dilation in the central part of each bridge span is evident.

In order to show how accurately the actual deformation time series, which includes also possible other (nonlinear) component, follow the expected thermal deformation time series, a temporal analysis of three scatterers distributed along the bridge, indicated by the letters A, B, and C in Fig. 3, has
Fig. 3. Same as Fig. 2, but with the overlay of the red lines indicating the bridge segments: The three central red lines are located approximately at the center of the three pillars; the two external ones identify approximately the position of the bridge terminations. Letters A, B, and C correspond to three scatterers, whose time series are shown in Fig. 4.

Fig. 4. Time series of the thermal deformation (in centimeters) of the three scatterers of the Musmeci bridge, whose position is shown in Fig. 3: (top) A, (middle) B, and (bottom) C. Radar measurements are reported as black diamonds, whereas red stars represent the deformation associated with the daily averaged temperature distribution. On the top annotations of each plot are reported (from left) the latitude and longitude coordinates of the analyzed scatterer, estimated thermal coefficient (in centimeters per kelvin), mean deformation velocity (in centimeters per year), measured correlation coefficient between the radar time series and the thermal component, and standard deviation of their difference, respectively. The right axis represents the daily averaged temperatures of red stars.

been carried out. Fig. 4 shows the comparison of the radar deformation time series (black diamonds) with the thermal dilation component (red stars), obtained by scaling the averaged temperatures with the estimated thermal coefficient. These plots clearly highlight the presence of a motion highly correlated with thermal dilation, thus providing an indication about the sensitivity of the system to the thermal component deformation at each epoch. In all cases, more than an excellent fit is achieved: The measured correlation coefficients between the radar time series and the thermal dilation component are well above the value of 0.9. The standard deviation of the difference between the radar time series and the thermal dilation component reaches an impressive value of about 1 mm at each epoch.

From a structural viewpoint, the Musmeci bridge uses Gerber beams, and the structure is defined in the civil engineering framework as a hyperstatic structure, that is to say that the number of constraints is greater than the number of degrees of freedom. A significant drawback of this typology of structure is the reduced tolerance to the thermal stress, since the high number of constraints tends to hinder the dilation. This consideration about the Musmeci bridge structure agrees with the measured thermal dilation. Note that the thermal dilation probably affects the bridge longitudinally. The presence of the pillars that lock the structure causes the accumulation of the thermal dilation along the spans, reaching its maximum values in their central part.

This effect is more deeply evidenced in Fig. 5, which displays the distribution of the estimated thermal coefficients along the southern flank of the Musmeci bridge. We modeled the spatial behavior of the thermal coefficient with a sinusoidal variation. The parameters (amplitude, period, and phase offset) of the sinusoidal model were estimated via a nonlinear least square optimization algorithm. In particular, the estimated periodicity was 72 m that is nearly the length of the bridge spans. The correlation between the thermal coefficient profile along the bridge and the estimated sinusoidal trend was 0.96. Note that the hyperstatic nature of the bridge implies a specific thermal dilation response which is fully captured by the SAR measurements: From the observed pattern, it is not possible to estimate the (linear) thermal dilation coefficient (1/K) following the approach in the appendix of [7] which requires specific construction constraints that allow a free expansion of the bridge on one side as in the case of the other bridge analyzed in the following.

A final analysis has been carried out for the scatterers located on the Musmeci bridge. Fig. 6 shows a scatter plot between the deformation caused by thermal dilation measured by the radar, obtained by subtracting the linear component from the total deformation, and the expected thermal dilation component obtained by scaling the temperatures with the estimated thermal coefficient. The colormap is set according to the density of the measures: The high density of measures accumulating around
the straight line confirms an optimal fit between the radar time series and the thermal dilation components.

A second interesting example is relevant to a bridge recently built and located at about 1 km west from the Musmeci bridge. In Fig. 7, the thermal dilation map superimposed on a Google Earth image is shown. In this case, the bridge exhibits a sudden discontinuity in the estimated thermal dilations. From further preliminary analysis, the discontinuity appears to be located on the junction between the ground and the bridge. Different from the previous case, the pillars do not act all as constraints; hence, thermal dilation is progressively distributed along the unconstrained bridge span.

**IV. Conclusion**

Data acquired by the newest high-resolution SAR systems contain a big amount of information. Particularly, the reduced wavelength provides higher sensitivity to small deformations of ground targets, such as those caused by thermal dilation effects. By properly modeling the measured signal, the thermal dilation becomes a new parameter that can be estimated from the data in modern multipass differential interferometry SAR processing. In this letter, we have investigated in particular the application of the multidimensional imaging technique, extended to account for the presence of thermal dilation. The analysis of the results obtained by processing a TSX data set has shown the possibility of this technique to achieve a millimeter sensitivity on a single deformation measurement and to infer the structures of bridges based on the measurement of their thermal dilation response.

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**References**


