Abstract—In this letter, we propose a technique for selecting persistent scatterers (PSs) based on their polarization phase difference (PPD). We analyze a normalized PPD between HH and VV channels averaged over a temporal set of images and select pixels that demonstrate predominantly even or odd bounce scattering properties. We compare selected scatterers to PSs selected by applying an amplitude dispersion threshold as suggested by a standard PS interferometry (PSI) approach and show that both methods are complementary. However, the proposed approach can be potentially used on a small set of synthetic aperture radar (SAR) images, which can be beneficial in the early stage of data acquisition. We apply the proposed technique to produce a deformation map for the San Francisco region from six quad-pol RADARSAT-2 SAR images acquired during 2008–2009. The coverage and the precision of the produced deformation map are higher than if it was calculated with the standard PSI technique applied to the same data set.

Index Terms—InSAR, interferometry, persistent scatterers (PSs), polarization phase difference (PPD), synthetic aperture radar (SAR).

I. INTRODUCTION

DIFFERENTIAL synthetic aperture radar interferometry (DInSAR) is a technique for measuring ground deformation with a high spatial resolution and accuracy over a large area. The differential interferogram is calculated from two synthetic aperture radar (SAR) images acquired by the same or a similar satellite at two different times. The interferometric processing consists of the following steps: slave to master coregistration and resampling, interferogram formation, removal of topographic and Earth curvature phases, filtering, and phase unwrapping [17], [24]. The calculated interferogram is an image of the line-of-sight (LOS) deformation that occurred between the two acquisitions. This image often is contaminated with residual topographic and atmospheric noise [25]. At present, DInSAR is routinely used for mapping tectonic or seismic deformation [9], [26], [30], volcanic activity [5], [15], and various anthropogenic signals [25].

The quality of an interferogram is described by its coherence, which is the magnitude of a cross-correlation coefficient calculated for a master–slave pair of images. The coherence depends on a variety of parameters, including SAR wavelength, incidence angle, perpendicular baseline, and land cover. In a densely vegetated environment, the coherence generally is low, which prevents the formation of a high-quality interferogram and phase unwrapping. For these land cover conditions, a persistent scatterer (PS) interferometry technique is used instead [7], [8]. The PS approach is based on a selection of pixels that are dominated by a single strong scatterer within the pixel and which are consistent over a long period of time. These pixels are usually selected based on their amplitude or amplitude dispersion. Currently, PS interferometry (PSI) is an established technique that has proven successful for mapping ground deformation of various origins on a worldwide scale [6], [12], [13].

The standard PSI approach has also a few disadvantages. In order to confidently select PS pixels, it is necessary to have a large number of images. In general, the selection of PS pixels with a high degree of accuracy is possible only when at least 30 SAR images are available [8]. This is not always possible or desirable. Not only it is often difficult or expensive to acquire large numbers of images but also many images inevitably span large time periods, on the order of years to decades. Hazard estimates for volcanic or seismic monitoring, for example, often require the production of time series and deformation rates on short time frames, i.e., after the acquisition of only a few images. In addition, the selection of PS pixels is limited to those pixels that have a very high amplitude or a low standard deviation or satisfy both conditions. In some regions, the network of such PS pixels is very sparse, which limits the processing of such interferograms, particularly the phase unwrapping. A different group of the advanced DInSAR algorithms [1], [19] can be used to perform a time series analysis using a smaller number of images. However, these algorithms are generally not based on the PS approach and produce limited results in regions of low coherence.

The advantages of polarimetric DInSAR for mapping ground deformation were previously investigated in [22] for a ground-based quad-pol SAR sensor and in [20] for dual-pol TerraSAR-X. There, it was suggested that the calculation of coherence and amplitude dispersion for the selection of reliable pixels can be significantly improved in the case of polarimetric SAR data. In this letter, we demonstrate a technique that is able to select a large number of PSs from a small temporal set of SAR images by analyzing their copol phase difference [4], [16], [18], [28]. We designate these polarization phase difference scatterers (PPDSs). We successfully select pixels with predominant even or odd bounce scattering mechanisms and exclude pixels with diffusive scattering caused by interaction with vegetation. We also show that the majority of the PS pixels selected with the standard approach have primarily
even and odd bounce scattering mechanisms, suggesting that the two techniques are complementary. The proposed approach requires simultaneously acquired HH and VV SAR images with a preserved relative phase that are presently available from only a few satellites, such as RADARSAT-2, Advanced Land Observing Satellite Phased-Array-Type L-Band SAR, and TerraSAR-X. It is anticipated that the availability and usage of polarimetric data will improve in the future, and the technique proposed in this letter will become increasingly valuable for deformation mapping.

In this letter, we apply the proposed technique in order to produce a deformation map for a region along the northern Hayward Fault from six quad-pol RADARSAT-2 SAR images acquired during a nine-month time period from April 26, 2008, to January 15, 2009. In recent years, it has been determined that movement along this portion of the Hayward Fault is unlocked, dominated primarily by a creeping motion in the horizontal direction, while slow-moving landslides have been identified in the hills along the fault scarp [2], [3], [10], [11], [14], [31]. These results were produced from a selection of anywhere from 30 to 49 images for the PSI analysis over time periods that ranged from 1992 to 2001 [2], [10], [14]. In addition, [27], 13 stacked interferograms over the same period produced similar results for the west side of the Hayward Fault but were limited by the lack of coherence along the hills on the eastern side. Here, we employ this new PPDS technique to estimate the short-term time-dependent deformation in this region for better quantification of the tectonic structure and regional hazard estimates. The earlier results then can be compared with those from this new technique, which are acquired over shorter time periods and increased spatial details.

II. METHODOLOGY

In the standard PSI analysis, PSs are selected based on their amplitude dispersion, which is calculated as

\[ D = \frac{\sigma}{A} \]  

where \( \sigma \) is the standard deviation and \( A \) is the mean amplitude calculated for the same pixel of the coregistered set of SAR images. For a sufficiently large set of images, the pixels with \( D < 0.25 \) are said to be persistent and are selected for further processing, and pixels with \( D > 0.25 \) are excluded [8]. The polarization phase difference (PPD) \( \Delta \phi \) for each pixel is calculated in the following way:

\[ \Delta \phi = \phi_{HH} - \phi_{VV} \]

where \( \phi_{HH} \) is the phase of a wave transmitted and received in horizontal polarization and \( \phi_{VV} \) is the phase of a wave transmitted and received in vertical polarization. The extreme values of the PPD which are equal to either zero and \( \pm \pi \) correspond to deterministic odd and even bounce scatterers, e.g., scatterers with a predominant reflective mechanism [21], [29]. The PPD value diverges as the contribution from the diffusive scattering increases [4], [28]. The diffusive scattering from vegetation produces PPD values that are randomly distributed in \([- \pi, \pi]\). Thus, by selecting pixels with appropriate PPD values, it is possible to exclude pixels with a diffusive scattering mechanism caused by the interaction with vegetation.

The phase information of such pixels varies in an unpredictable way from one acquisition to another and, therefore, cannot be used for mapping ground deformation.

In this letter, we use the normalized PPD for the selection of reliable scatterers whose phase information carries consistent information. This can be done by calculating, for each pixel, a normalized average of absolute values of the PPD for a temporal set of SAR images and by selecting pixels with values close to zero and one

\[ \chi = \frac{\sum_{k=1}^{K} |\Delta \phi_k|}{K \pi} \]  

where \( K \) is the number of a SAR image used for processing.

This quantity ranges from zero to one where \( \chi = 0 \) corresponds to pixels with strictly odd bounce scattering and \( \chi = 1 \) corresponds to pixels with a strictly even bounce scattering mechanism. Furthermore, in order to exclude single-bounce pixels corresponding to a reflection from the water surface, as what occurred in the San Francisco images, it is recommended to set a threshold value on the pixel amplitude, which also excludes pixels with a large number of bounces (e.g., more than two). For example, it is possible to select only those pixels that have intensity values larger than the average value for the whole image. However, the threshold value will vary depending on the amount of water presented in the SAR image. Further analysis is required in order to determine the best method for the proper selection of the appropriate threshold values for \( \chi \) and it may be that this threshold value will depend on the type of land cover, satellite wavelength, incidence angle, and number of images available.

III. RESULTS

For this letter, we collected six fine quad polarization (FQ7) RADARSAT-2 images acquired on April 26, June 13, July 7 and 31, and December 22, 2008, and January 15, 2009, over a region along the Hayward Fault located northeast of San Francisco. The land cover in the area covered by this image consists of regions of dense vegetation, urban areas, and open water. The PPD reliable scatterers were selected with \( \chi \) less than 0.2 and greater than 0.8, and the average intensity was set at twice the mean intensity for the whole image. These results are shown in Fig. 1. In total, 252 000 single-bounce pixels and 69 000 double-bounce pixels were selected, which corresponds to about 1.34% and 0.37% of the total number of available pixels. For comparison purposes, the number of PS pixels selected based on the amplitude dispersion (less than 0.2) was equal to 176 000 or 0.94%.

Standard interferometric processing was performed on the images, and the topographic phase was removed using a 10-m National Elevation Dataset digital elevation model provided by the U.S. Geological Survey. In total, we created 15 differential interferograms with a maximum perpendicular baseline close to 400 m and time spans ranging from 24 days to approximately 9 months. Each interferogram was unwrapped, and all 15 interferograms were used to solve for the mean deformation rates and the residual topographic error for each pixel independently. Similar processing was performed for a set of images with the PS pixels selected based on the amplitude dispersion.
Fig. 1. Selection of reliable scatterers based on PPD and amplitude dispersion. (a) Single bounce. (b) Double bounce. (c) Single and double bounce. (d) Amplitude dispersion (less than 0.2). These images were acquired by right-looking SAR from descending orbit.

Fig. 2. Differential wrapped interferograms (full color range corresponds to $[-\pi, \pi]$, in YYYYMMDD format and $B_\perp$): (a) 20080426–20080613, $-156$ m; (b) 20080707–20080731, $68$ m; (c) 20081222–20090115, $18$ m; (d) 20080426–20090115, $-133$ m. These images were acquired by right-looking SAR from descending orbit.

The examples of the wrapped differential interferograms are presented in Fig. 2 (in YYYYMMDD format) with the corresponding values of the perpendicular baseline: Fig. 2(a) 20080426–20080613, $-156$ m; Fig. 2(b) 20080707–20080731, $68$ m; Fig. 2(c) 20081222–20090115, $18$ m; and Fig. 2(d) 20080426–20090115, $-133$ m. The interferograms spanning the last time period 20081222–20090115 and 20080426–20090115 [(c)–(d)] show a clear signal around the fault area. However, more images acquired recently have been required to classify the observed signal as the true ground deformation or...
to exclude water vapor or soil moisture related artifacts. Correspondingly, the mean deformation rates presented in Fig. 3 may not be the representative of long-term averages, in case of a nonlinear or short-term deformation processes.

For these six SAR images, acquired over a time period of less than 9 months, we were able to calculate the mean deformation rates with an accuracy close to 0.49 cm/year. The same quantity calculated for the PS pixels selected based on the amplitude dispersion is close to 0.54 cm/year. The mean deformation rates and standard deviation were estimated by applying linear regression [23] to the calculated time series, as described in [25]. This larger error in case of the standard PS analysis is probably due to the presence of unwrapping errors in individual interferograms resulting from the sparseness of the PS network.

In order to demonstrate that PPD can be used to describe the pixel reliability, we plotted the distribution of the pixels according to their amplitude dispersion and PPDs (see Fig. 4).

Only pixels with a high amplitude were considered since it is assumed that, for these pixels, the amplitude dispersion based on the six images is sufficiently accurate. According to this figure, the majority of the pixels with PPD values close to zero (odd bounce) and to one (even bounce scattering mechanism) also have a small amplitude dispersion. This suggests that both techniques (PS and PPDs) are complementary and can be used for cross validation, but the technique proposed in this letter can select reliable pixels even for a small set of available images.

IV. CONCLUSION

In this letter, we have presented a methodology for the selection of reliable scatterers based on their PPD. Those pixels with a normalized average of absolute values of the PPD close to zero and one are considered reliable because they are dominated by odd and even bounce scattering mechanisms. Diffusive scattering from vegetation produces pixels with the PPD randomly distributed in the \([-\pi, \pi]\) interval and with normalized average PPD values far from zero or one. Such pixels are excluded from the interferometric processing.

The analysis of the distribution of pixels according to their amplitude dispersion and PPDs has suggested that the majority of pixels that would be selected by a standard PS approach also have normalized PPDS values close to zero or one and, therefore, will be selected by the proposed technique also. However, as anticipated, the proposed technique has resulted in greater coverage. In addition, it expected that the method is more accurate, even for a smaller set of SAR images, although this will be evaluated further when at least 30 RADARSAT-2 images suitable for interferometric studies are available and when the amplitude dispersion can be considered a reliable parameter for the selection of the PS.

The proposed technique was used to compute the mean deformation rates for a region along the Hayward Fault.
northeast of San Francisco, which is partially covered by dense vegetation. We were able to achieve subcentimeter precision of the measured deformation rates, and the precision of each individual interferogram is high. The isolated signals near the Hayward Fault are visible, which possibly corresponds to those identified by [11] in a study of local hillslope motions that spanned 2 years and 17 images. In addition, the average horizontal deformation rates along each side of the fault compare favorably with those obtained by others [10], [14] despite the fact that their long-term averages are calculated for many more images (from 30 to 49) from a period exceeding ten years. Smaller scale differences may be the result of nonlinear or intermittent variation in the creep rate across the fault that are identifiable only over the shorter time periods in this letter, confirming that one of the primary strengths of this method is the ability to quantify motion over time periods on the order of one year with the accuracy of longer term PS-InSAR techniques. Future work will concentrate on determining the limits of spatial and temporal accuracy as a function of the number of available images. In addition, analysis for this particular region will be repeated when more SAR images are available, in order to better quantify these short-term variations.

ACKNOWLEDGMENT

Some images were plotted with the Generic Mapping Tools software.

REFERENCES