

Mapping of ground surface deformations and its associated damage using SAR interferometry: a case study of the 2020 Masbate earthquake

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Abstract. The 2020 Masbate earthquake in the Philippines, with a moment magnitude 6.6, occurred on August 18, 2020. The earthquake dealt considerable damage to the surrounding areas. This study uses Sentinel-1 Interferometric Synthetic Aperture Radar (InSAR) to investigate earthquake-induced damages. Conventional repeat-pass InSAR is used to quantify the ground surface displacement along the radar line-of-sight (LOS). The InSAR technique shows ground surface displacements greater than 15 cm. This study also implements a two-step coherence difference analysis coupled with a statistical temporal coherence threshold to map and delineate the locations of damages associated with the earthquake. The InSAR-derived damage locations are consistent with the actual locations of damages, as reported from a field survey. This study confirms the effectiveness and accuracy of Sentinel-1 InSAR techniques for earthquake-induced damage mapping applications.

1 Introduction

Masbate is considered one of the seismically active regions in the Philippines, given that it rests upon a segment of the Philippine Fault. The fault exhibits a left-lateral strike-slip system that has been slipping at a rate of 33 ± 11 mm/yr at the northern Leyte segment, close to Masbate [1]. On August 18, 2020, a magnitude $M_W = 6.6$ earthquake struck the province of Masbate. The epicenter was located 7 km S29°E of the Municipality of Cataingan, with a depth of 21 km. The Philippine Institute of Volcanology and Seismology (PHIVOLCS) reported that 244 aftershocks occurred in the following day. The main shock registered as Intensity VII (Destructive) on the PHIVOLCS Earthquake Intensity Scale (PEIS) [2]. Damages caused by the earthquake include ground rupture, subsidence, liquefaction, structural damage, and even the collapse of minor structures.

Satellite-based remote sensing techniques are valuable for damage mapping applications due to global coverage and high spatial resolutions associated with satellite data [3]. Remote sensing using space technology, specifically Interferometric Synthetic Aperture Radar (InSAR) techniques, have successfully been used for different mapping applications such as post-war urban damage mapping [4], digital elevation model (DEM) generation [5], landslide investigation [6], and earthquake-induced damage mapping [7-9].

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The Philippines is still developing when it comes to the use of InSAR remote sensing techniques. Lack of freely available SAR data, complex data processing, and the small number of experts contribute to the limited studies involving InSAR in the Philippines. In 2016, the Sentinel-1 mission operated by the European Space Agency (ESA) reached its total operational capacity, and with it came the revolutionary availability of SAR data to the public. This milestone paved the way for the exponential growth of the remote sensing community and the development of new InSAR techniques for various Earth observation applications.

This study involves processing publicly available Sentinel-1 SAR data to map damaged areas and quantify the deformation caused by the 2020 Masbate earthquake. While repeat-pass InSAR has already been adapted as a method for change detection and surface displacement mapping, very few instances of delineating damaged areas using a coherence difference analysis have been carried out. This work seeks to promote remote sensing in the Philippines by exploring InSAR techniques for geohazard applications. This research also aims to open the field of civil engineering to the potential applications of satellite-based damage mapping, including structural health monitoring, post-disaster damage assessment, and disaster risk management and response.

2 Materials and methods

The study used Level-1 Single Look Complex (SLC) products with co-vertical (VV) polarization under the Interferometric Wide (IW) Swath mode of Sentinel-1. The data was acquired from the Alaska Satellite Facility (ASF). A total of 17 SAR acquisitions from an ascending flight path were acquired. Fifteen of these images were used to calculate the coherence difference threshold to refine the data [10]. Table 1 lists the Sentinel-1 product pairs used for the study.

Table 1. List of interferometric pairs including master and slave acquisition dates.

Pair No.	Master	Slave	Pair Type
01	2020/02/17	2020/02/29	Pre-Seismic
02	2020/02/29	2020/03/12	Pre-Seismic
03	2020/03/12	2020/03/24	Pre-Seismic
04	2020/03/24	2020/04/05	Pre-Seismic
05	2020/04/05	2020/04/17	Pre-Seismic
06	2020/04/17	2020/04/29	Pre-Seismic
07	2020/04/29	2020/05/11	Pre-Seismic
08	2020/05/11	2020/05/23	Pre-Seismic
09	2020/05/23	2020/06/04	Pre-Seismic
10	2020/06/04	2020/06/16	Pre-Seismic
11	2020/06/16	2020/06/28	Pre-Seismic
12	2020/06/28	2020/07/10	Pre-Seismic
13	2020/07/10	2020/07/22	Pre-Seismic
14	2020/07/22	2020/08/03	Pre-Seismic
15	2020/08/03	2020/08/15	Pre-Seismic
16	2020/08/15	2020/08/27	Co-Seismic

Figure 1 plots each interferometric pair's temporal and perpendicular baselines. The dataset used has a consistent temporal baseline of 12 days between SAR images and a maximum perpendicular baseline of 127 m. Small baselines, such as those associated with Sentinel-1 data, result in better coherence between image pairs. High coherence, in turn, produces more reliable ground surface deformation estimates.

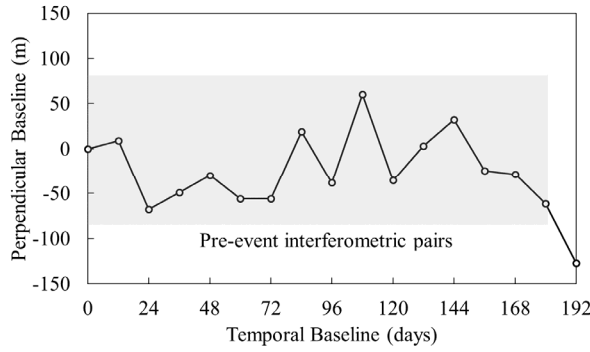


Fig. 1. Temporal and perpendicular baselines of interferometric pairs with respect to the first acquisition date.

SAR is a type of active imaging radar technology which allows image quality to be independent of sunlight and can operate regardless of weather conditions and cloud cover. The radar signal hits an object or target, is reflected at the device, and is recorded by a sensor. The reflected signal is called backscatter and is recorded as an image [11]. Each pixel of the backscatter image carries a complex number C , as seen in Equation 1 [12].

$$C = Ae^{i\varphi} \quad (1)$$

where A is the amplitude of the backscattered signal, φ is the phase, e is Euler's number, and i is the imaginary number $\sqrt{-1}$.

An interferogram is generated by pairing two SAR images, an interferometric pair. An interferometric pair consists of a master and a slave image. The value of each pixel in an interferogram is obtained by applying Equation 2 to each matching pair of pixels from the original 2 SAR images [12].

$$I = C_m C_s^* = A_m A_s^{i(\varphi_m - \varphi_s)} \quad (2)$$

where I is the interferogram pixel value, C_m and C_s are the pixel values of the master (m) and slave (s) images, respectively, and $*$ represents the complex conjugate of the number. The interferometric phase φ_{ip} , which is composed of different contributors, is obtained by subtracting the phase of the slave image φ_s from that of the master image φ_m , as seen in Equation 3.

$$\varphi_{ip} = \varphi_m - \varphi_s = \varphi_{elev} + \varphi_{defo} + \varphi_{flat} + \varphi_{atm} + \varphi_{noise} \quad (3)$$

where φ_{elev} is the topographic phase, φ_{defo} is the phase due to displacement or deformation, φ_{flat} is the flat-earth phase, φ_{atm} is phase due to atmospheric particles, and φ_{noise} is the phase due to errors in processing. The desired phase contributor may be isolated through interferometric processing. For change detection applications, this is typically φ_{defo} [13-14].

Interferometric coherence correlates amplitude and phase data between two SAR acquisitions within a specified pixel window. Computationally, the interferometric coherence γ is obtained using Equation 4 [15].

$$\gamma = \frac{|E(C_m C_s^*)|}{\sqrt{E(C_m C_m^*)E(C_s C_s^*)}} \quad (4)$$

where E represents the statistical expectation or mean value of pixels within the coherence window size. Coherence values of an interferometric pair range from 0 (out of phase) to 1 (in phase). Ground deformations and changes that occur between two SAR acquisition dates result in a loss of coherence. The coherence loss in the co-event image pair can be better isolated by subtracting the co-event coherence γ_{co} from the pre-event coherence γ_{pre} , resulting in the coherence difference γ_{diff} as seen in Equation 5 [10].

$$\gamma_{diff} = \gamma_{pre} - \gamma_{co} \quad (5)$$

In order to refine the coherence difference, a threshold is applied. Equation 6 shows the application of the two-step threshold method as discussed in [10].

$$[\gamma_{diff} > (\gamma_{diff(mean)} + 3\gamma_{diff(stddev)})] \cap (\gamma_{diff} \geq 0.25) \quad (6)$$

where $\gamma_{diff(mean)}$ and $\gamma_{diff(stddev)}$ is the mean coherence difference and standard deviation, respectively, per pixel of the pre-seismic stack. This threshold filters out pixels that exhibit low coherence values due to noise and background effects. Pixels with substantial coherence values will remain, isolating the pixels affected by the earthquake.

3 Results and discussion

The following section presents and discusses the results obtained from the repeat-pass InSAR and the coherence difference analysis. Figure 2 shows the co-seismic interferogram generated from the processed SAR data.

The color fringes of the interferogram depict the ground surface deformation between acquisition dates along the satellite's line-of-sight (LOS). Each color cycle signifies a deformation equal to half the radar wavelength. For Sentinel-1, one cycle represents a deformation of 2.8 cm in the LOS direction [16]. The regions with a very steep color gradient indicate more significant deformations than regions where the fringes are spread out over a larger area. Due to the presence of vegetated mountains on the northwest region of Cataingan and farmlands in villages and neighboring towns, intense phase noise (i.e., no visible fringes) is included in the interferogram.

Figure 3 shows the co-seismic LOS displacement map, as derived from the interferogram. Positive values indicate subsidence and westing, while negative values indicate uplift and easting. It should be noted that a pixel with a high coherence value of 0.99 was chosen and assumed to have not experienced any deformation. The deformation value of this pixel was then subtracted from the original displacement map to extract the displacement relative to this point. The map shows substantial uplift in the Municipality of Cataingan, northwest of the epicenter. The uplift continues north along the fault line, while the southern part of the island experienced minimal subsidence.

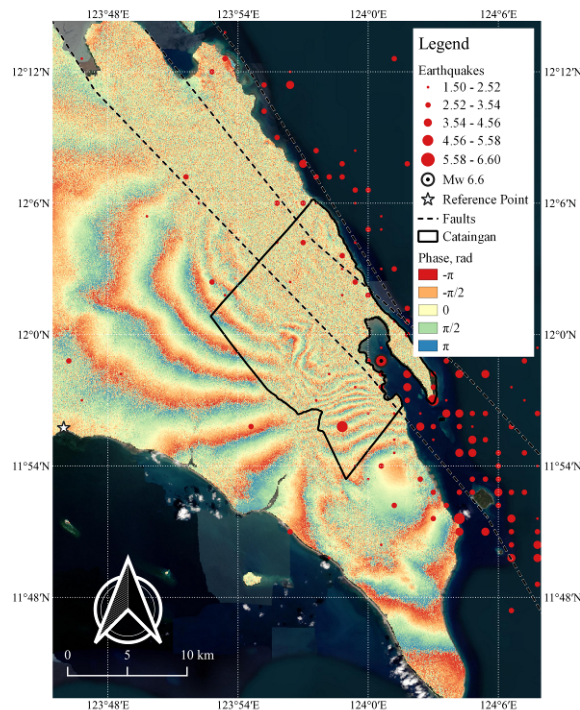


Fig. 2. Co-seismic SAR differential interferogram of Masbate province.

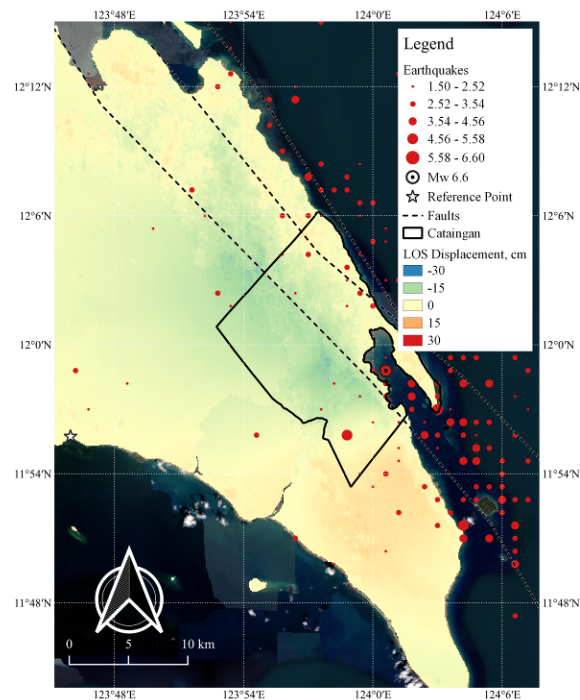


Fig. 3. Co-seismic LOS displacement map of Masbate province.

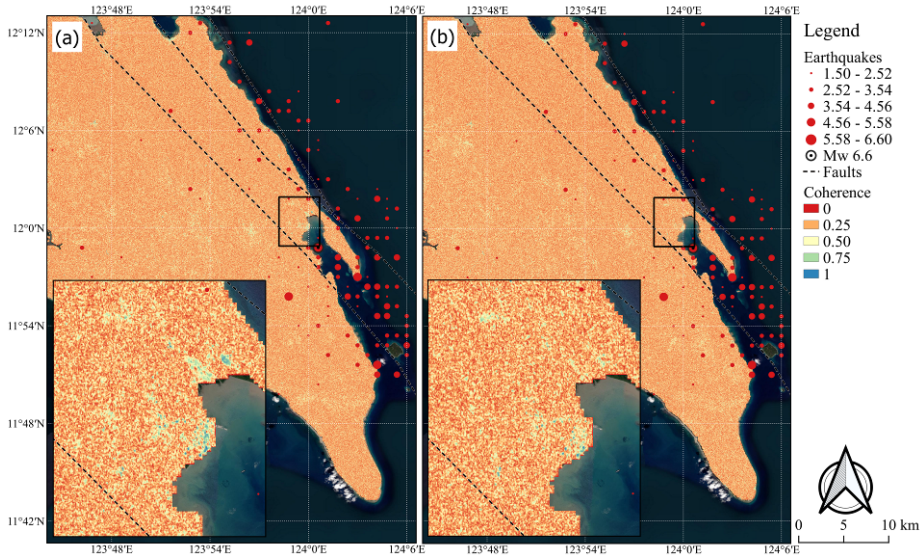


Fig. 4. (a) Pre-seismic (pair 15) and (b) co-seismic (pair 16) coherence maps.

Figure 4 shows the pre- and co-seismic coherence maps. The warmer (red) color indicates low coherence (i.e., vegetated areas showing complete decorrelation between images), while the cooler (blue) color indicates high coherence. Note that there was an observed decrease of approximately 10% in coherence between the pre-seismic and co-seismic pairs over Cataingan, as shown in the insets of Figure 4.

Figure 5 shows the coherence difference map after subtracting the co-seismic coherence from the pre-seismic coherence. The coherence difference γ_{diff} ranges from -1 to $+1$. Negative values indicate pre-seismic changes, while positive values indicate co-seismic changes.

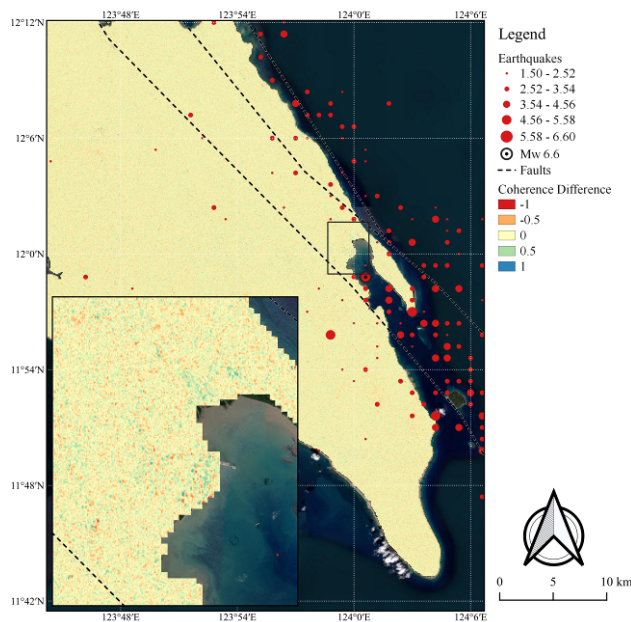


Fig. 5. Coherence difference map obtained from pre- and co-seismic coherence maps.

Figure 6 shows the final coherence difference map after applying the two-step threshold discussed above. After computing the mean and standard deviation of the pre-seismic coherence stack to extract a more reliable coherence baseline, the resulting threshold was then subtracted from the original coherence map. Furthermore, all pixels with a coherence value less than 0.25 were removed to obtain the pixels that experienced considerable coherence loss associated solely with the 2020 Masbate earthquake.

The final map also includes locations of earthquake-induced damages according to a field survey conducted by PHIVOLCS [17]. The coordinates of these areas were extracted from PHIVOLCS' report, georeferenced, and overlaid on the final coherence difference map. Note that the field-acquired locations of damages coincide with the processed pixels that indicate coherence loss.

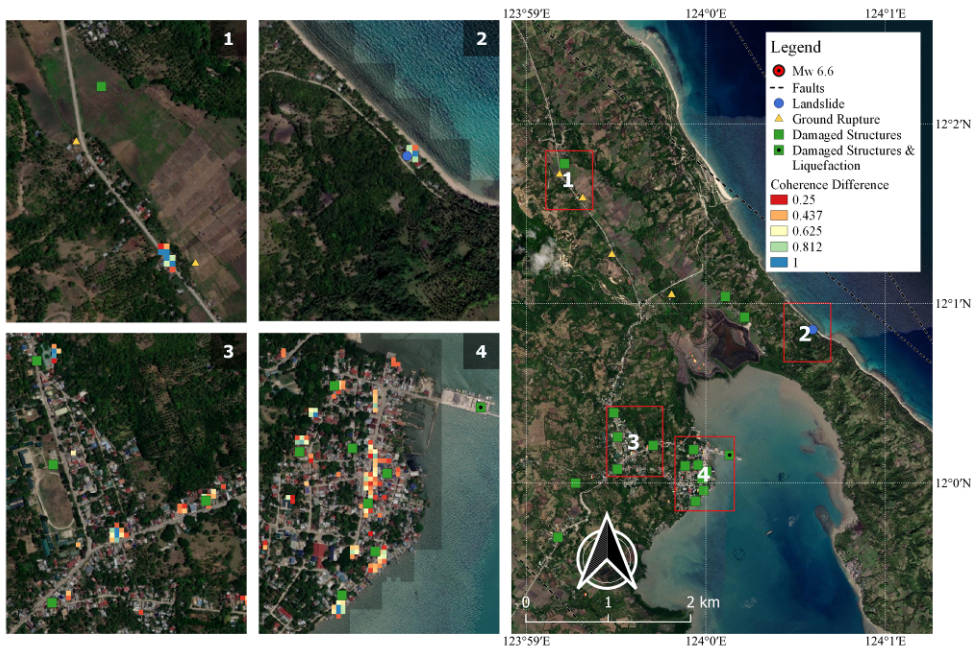


Fig. 6. Final coherence difference map including PHIVOLCS field survey damage locations.

4 Conclusions

Conventional repeat-pass InSAR was used to quantify ground surface displacements caused by the 2020 Masbate earthquake. A displacement map showing substantial uplift of more than 15 cm in areas surrounding the earthquake's epicenter was obtained using Sentinel-1 ascending data. Moreover, coherence difference analysis was carried out to map the damages associated with the earthquake. A coherence difference map was generated using pre- and co-seismic Sentinel-1 ascending images, to which a two-step threshold was applied to extract the pixels associated with damaged areas. The InSAR-derived results agree with the field survey damage locations. This study demonstrates the effectiveness and accuracy of Sentinel-1 medium-resolution SAR data for earthquake-induced damage mapping applications.

Future works will focus on the processing of Sentinel-1 descending data. The generated displacement map from this dataset will be combined with the ascending dataset to decompose the directional ground surface displacement, including horizontal displacement (east and west) and vertical displacement (up and down).

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