Investigations on InSAR Data Processing Standard for Volcano Island Monitoring in Indonesia

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ABSTRACT:

In critical situations such as disaster and humanitarian relief, the reliable geospatial data will present an appropriate decision on a timely manner. As fundamental datasets, large-scale topographic maps are are mandatory in order to perform geospatial analysis for many societal challenges. Indeed, Large Scale Topographic Mapping in Indonesia shall be accelerated in an innovative and productive way to consider the production efficiency, especially for the geospatial data acquisition as its primary source. Interferometric Synthetic Aperture Radar (InSAR) data acquisition presents some advantages, especially in conjunction with the security clearance and global weather as some main constraints for the geospatial data acquisition. In terms of disaster preparedness and emergency response, radar interferometry techniques can play an important role by generating a Digital Elevation Model (DEM) as an input to Decision Support Systems (DSS). In addition, the techniques of differential Interferometric Synthetic Aperture Radar (D-InSAR) can provide the earth surface deformation from time series Radar Datasets.
A set of standards related to the InSAR data acquisition are essential, especially with regards to the improved sensors, and processing methods implemented by the worldwide space agencies nowadays. Hence, the precise definition of a standard is fundamental in order to prepare the InSAR data as one potential source of geospatial data and information, especially for LSTM data production. Generated time series of Digital Elevation Model (DEM) can identify the potential cause of 2018's Sunda Strait tsunami (Tampubolon, 2019). It was related with the increasing eruption activity of Anak Krakatau (Child of Krakatoa). From DEM analysis, the Volcanic mudflow material avalanche has been detected before the tsunami hit the coastal surrounding area.
In this paper, more advanced techniques was investigated by the combination between Time Series DEM Analysis and Ground Displacement detection. The focus on the integration between reliable TanDEM-X and up-to-date Sentinel 1A/B was proposed on another volcano island of Gamalama in Ternate. As TanDEM-X uses X-band as its medium wave, it can produce more reliable DEM as a reference data. On the other hand, Sentinel 1 uses C-band that can contribute to detect the ground deformation over the aforementioned volcano island. TanDEM-X uses a more robust and consistent approach to scan the earth surface by single data acquisition scheme, which is generally more accurate and reliable for the DEM generation. However, many factors influence the selection of a platform that can be best suited for radar interferometry. Initially, the German TanDEM-X Coregistered Singlelook Slant-range Complex (CoSSC) using bi-static InSAR approach has been implemented in order to generate DEMs comply with the LSTM specification in Indonesia. The basic principle is performing a simultaneous measurement of the same scene and identical doppler spectrum by using 2 sensors, thereby avoiding temporal decorrelation (DLR, 2012). Subsequently, the differential InSAR techniques by using Sentinel 1A/B has been performed in order to detect the ground deformation. Finally, tt can be shown that the reliable TanDEM-X data has increased the ground deformation resolution and accuracy in order to provide potential solution for disaster preparedness.

1. INTRODUCTION

The significant role of geospatial data to govern the country has been introduced since 2011 by the legislation about Geospatial Information in Indonesia. As planned, the act gives mandates the provision of large scale topographic maps up to the scale of 1:1,000. It is inevitable that large scale topographic mapping requires high resolution geospatial data sources. This type of data can support the national development e.g. related to disaster preparedness, detail spatial planning, etc. Unfortunately, in order to provide high resolution 3D geospatial data, large scale topographic mapping still relies on conventional airborne campaigns, which is in general a costly but not timely mapping project. The acquisition of topographic data has been nowadays not only limited to the conventional methodologies such as terrestrial survey, aerial photogrammetry and remote sensing technologies. The occurrences of disasters all over the world has increased the awareness of worldwide institutions to collect and use geospatial information in order to strengthen the capabilities to cope with disaster and to minimize human casualties. Especially in emergency situations up to date geo-information has to be provided timely, with high reliability and without bureaucracy obstacles. Geospatial data are mandatory in this case because they contain fundamental geospatial features especially of the earth surface (also called terrain) information with respect to its proper geometrical accuracies. During disaster and emergency situations, geospatial data can provide important information for decision support systems. As one instance of basic geospatial data, large scale topographic maps are essential in order to enable accurate analysis within quite a number of societal challenges. Recently, the utilization of geospatial data using topographic maps as a basic reference is mandatory to support accurate quick regional mapping in a scale of 1:5,000 in so called detailed spatial planning. The consideration between

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accuracy requirements and time restriction is selected as critical in this activity. Therefore, this paper outlines a utilization method of InSAR data by providing reliable DEM derived from linearized model and presents results of an investigation on the achievable results in Disaster Management (DM) application. In this case, the appropriate height reference determination has been performed through Geospatial Reference System of Indonesia (SRGI).

1.1 Volcano monitoring by InSAR techniques

InSAR techniques are the approach to measure earth surface as well as to monitor ground displacement (Anagnostou, 2023). The utilization of X-band SAR sensor increases the quality of measurements especially for DEM Generation purposes. In this case, the higher spatial resolution in cm level can be achieved and hence increase the ground deformation detection accuracy. As demonstrated by Tampubolon, 2019, the InSAR DEM and Differential InSAR (D-InSAR) are the major inputs to enable disaster preparedness. This data combination can provide the initial geospatial information as well as the object geometries without any knowledge as required in the conventional large scale topographic methods such as the 3D position of the surface or a set of Ground Control Points (GCP) in the worst case.

Since more than 20 years, InSAR sensors have shown the massive and progressive grows in the application, providing a basis to develop new alternative platforms for analyzing and monitoring earth surfaces. Among the available technologies, utilization of InSAR data indicates rising number of applications and innovations.

InSAR data as an alternative platform for geospatial data acquisition offers potentials because of its flexibility and practicability combined with low cost implementations. After all, the high resolution data collected from satellite platforms have the capabilities to provide a quick overview of one region. Nevertheless, there are some limitations that shall be taken into account in the InSAR data processing for topographic mapping.

In this paper, we present an approach satellite based data for topographic mapping which uses local reference to determine the height reference. The role of GCPs is reduced in our approach since its availability and accuracy are mostly problematic in the Indonesian region especially for disaster prone areas.

1.2 Research objectives and motivation

The main advantage of satellite-based data acquisition is the capability to enable on-demand very high resolution data collection which can be customized efficiently. In general, InSAR techniques require sensor orientation measured from orbital parameters in order to be able to determine absolute ground coordinates without any field GCP. Unfortunately, because of the inaccurate orbital parameters, it is generally difficult to perform reliable direct georeferencing on the InSAR platform.

Geospatial data collected from satellite platform are usually captured from high altitude. Under this circumstance, there normally is a significant occlusion surrounding the elevated objects such as high buildings, skyscrapers, towers, etc. This situation usually brings a tedious work in the data processing, especially during mosaicking tasks. However, these elevated objects can be useful if we use their 3D shapes and forms as a reference model to precisely extract image orientation parameters.

As already presented by Dong, 2020, the Ice, Cloud and Land Elevation Satellite (ICESat) can be used to calibrate the residuals in InSAR DEM generation. At this point, we are going further to use more accurate field GCPs as an input to adjust the main parameters in InSAR DEM generation i.e. height reference, absolute phase offset and baseline value.

In this paper, we want to demonstrate that an InSAR platform can deliver geospatial data with sufficient accuracy to be used for DEM generation by only using a minimum amount of GCPs. For this purpose, a direct georeferencing method has been selected as a potential solution to overcome the dependency from GCPs.

In this paper, we aim on extending the method of InSAR DEM generation to provide a sufficient accuracy for LSTM by only using a minimum amount of GCPs. For this purpose, a linearization of phase offset estimation has been selected as a potential solution to increase the height accuracy.

Our approach needs precise GCP data from GNSS measurements referring to the local height reference system. We also investigate the role of existing phase difference calculations into the height derivation method. Our main goal is to present a more robust approach for the DSM generation based on linear equations for providing above mentioned main parameters.

Our research also focuses on the comparison of different DEM references used for the absolute phase offset estimation. From this, we can select the proper DEM reference, which is adequate enough for our linear model. In order to evaluate the results, it is necessary to compare generated data with various geometric accuracies.

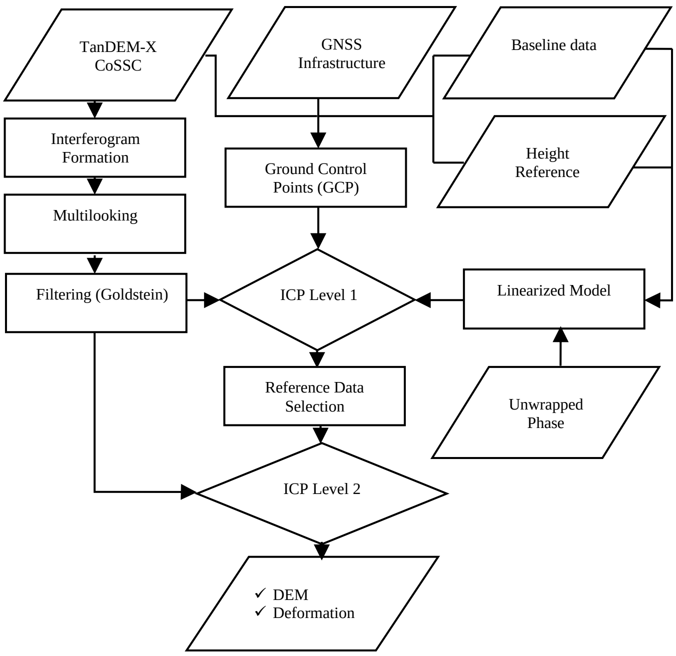

Figure 1. Research workflow

We assess our results not only based on the Check Point (CP) data but also based on airborne data equipped with digital medium-format photogrammetric camera as well as a sensor position/orientation measurement unit (Figure 1). The reference data has been selected based on the Independent Check Point (ICP) Level 1 result. The objective of ICP Level 1 is to assess the geometric accuracy for each dataset referring to the GNSS measurements.

Secondly, another objective of our investigations is to define a proper method for the DSM generation from TanDEM-X CoSSC data. A linear approach which allows for a consideration of GCP data has been chosen as an alternative way to derive a DSM with high accuracy.

1.3 Test area

Our test area around the volcano island of Gamalama has been selected because of the specific criteria of the island that can meet the investigation requirements. In addition, the availability of the reference data, including the geodetic reference network infrastructure also has been taken into account.

In general, the Area of Interest (AOI) is approximately a mountainous area of 134 km^2 which has the summit of 1700 meters above mean sea level (msl). The terrain condition of the Ternate City that also includes such as urban coastal area of building, trees, roads, etc. is classified as high undulated areas (see Figure 2).

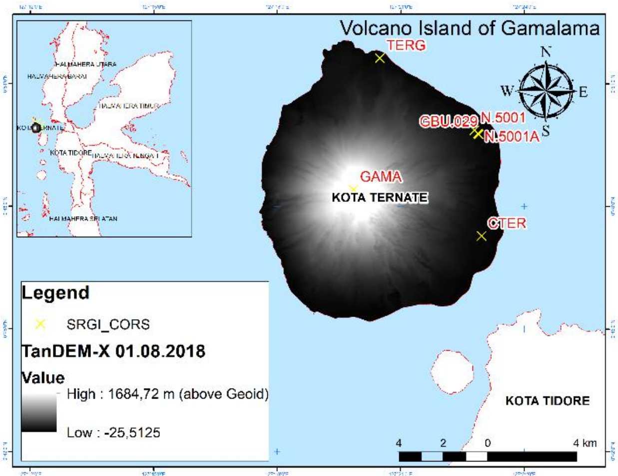

Figure 2. Area of Interest (Volcanic island of Gamalama)

2. RESEARCH METHODOLOGY

On-board georeferencing is defined as a method which provides the orbital parameters of the satellite platform only through integrated sensors (e.g. GNSS, IMU, INS) without any requirement of field GCP. This term is traditionally used in the context of processing aerial photogrammetric data (DLR, 2012) but recently also in conjunction with satellite technologies.

2.1 Data sources

The TanDEM-X Mission has produced a global uniform DEM in a resolution of 10-12 m in similar way as the SRTM global DEM in 2001, but with better height accuracy in a more up-to-date condition. For our AOI, TanDEM-X products i.e. Coregistered Singlelook Slant-range Complex (CoSSC) data have been used as a raw dataset to perform the DEM generation as well as the earth surface deformation detection using the interferometric approach (DLR, 2012).

To access the CoSSC data, there is a TanDEM-X data access service available only for scientific purposes with a limited AOI. For the AOI as depicted in Figure 2, there are currently 2 datasets available as included in **Error! Reference source not found.**. Unfortunately, the more recent data set is not available.

After the successful launch of the recent generation of German TerraSAR-X-add-on Digital Elevation Measurement (TanDEMX) satellite in 2010, the ongoing research by using TanDEM-X data was actively initiated by many mapping agencies especially for the DSM generation purpose. This project will hopefully provide the global uniform DSM in a resolution of 10-12 m in similar way as the SRTM global DEM in 2001.

Scene	Baseline/HOA (m)	Looking direction	Acquisition date
TDX-01	105.960 / -54.142	Descending	01-08-2018
TDX-02	134.047 / -44.058	Descending	28-11-2019

Table 1. Data specification

The requirement to comply with the High Resolution Terrain Information (HRTI) Level 3 accuracy of National Geospatial-Intelligence Agency (NGA) standard restricts the height measurement sensitivity. Indeed, the height of ambiguities (HOA) in Table **1** must be limited in the order less than 40 m (Krieger, 2005). However, it is normally difficult to fulfil this requirement as the HOA mostly depends on how accurate the baseline is measured. As a consequence, the baseline determination can not be determined without further improvement in the algorithm as it will be explained more comprehensive in 2.3.

2.2 Georeferencing method

There are two types of satellite georeferencing applied for this on-going research project:

- For indirect georeferencing of all satellite-based raw data, we use the geodetic and geodynamic control network of national reference system i.e. Indonesian Geospatial Reference System (SRGI);
- For direct georeferencing of the satellite data, we use a GPS IMU/INS on board as included in the orbital parameters.

Based on the previous investigation presented in (Tampubolon, 2020), the minimum amount of GCPs to deliver sub-meter level of accuracy are 3 for each CoSSC. From this context, we want to reduce the number of GCPs and only used three GNSS monitoring stations (TERG, GBU, CTER) as the GCPs instead. As depicted in Figure **2**, the distribution of the GCPs is also centralized in the perimeter of the test area because we want to reduce the GCP dependency in our approach as well.

The main reason to use GNSS monitoring station (Figure 3), as the GCPs in this project is to ensure the 3 D accuracy. Since the three aforementioned GNSS-points are also designed for the Continuous Operating Reference System (CORS) for the global monitoring service, the positional accuracy is in the range of millimeter level. Their 2 D positions as well as their height (above ellipsoid/msl using precise geoid model) can also be accessed freely via internet at http://www.srgi.big.go.id.

In addition, to confirm the results we visually inspect the generated DEM for each CoSSC data described above. For the purpose of independent validation of vertical accuracy, additional comparisons were conducted using different baseline in Phase Unwrapping (PU) step.

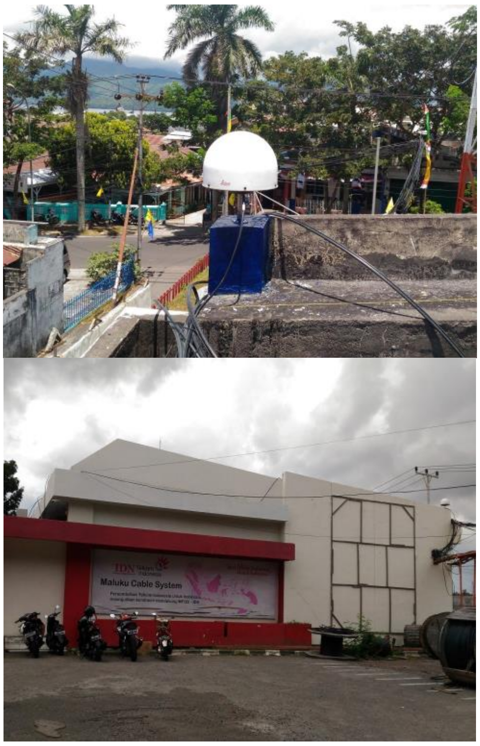

Figure 3. Geodetic Control (CORS) at Telkom office

2.3 DEM Generation

In this section, the workflow of the InSAR DEM generation for TanDEM-X CoSSC data is briefly described as depicted in Figure 3. Part 1 focuses on the phase unwrapping step as it iteratively improves the results by the output from Part 2 i.e. adjusted baseline value. Part 2 has the objective to convert the unwrapped phase into elevation/height as the final output to construct the DEM.

For the processing of the Radar interferometry data, we use the open source Sentinel Application Platform (SNAP) which is the next generation of the Next ESA SAR Toolbox (NEST) focusing on radar interferometry and polarimetry (Veci, 2016). SNAP desktop is already designed to deal with the TanDEM-X CoSSC (TDM). The steps for the IFSAR DEM generation using SNAP desktop are the following:

1. Interferogram formation of the CoSSC data (TDM format)
   This step provides an interferogram from the pair wise bi-static data acquisition. In order to get only the topographical phase, the flat earth phase must be subtracted.
2. Goldstein filtering
   The objective of the Goldstein filtering is to reduce the number of inaccurate fringes from the interferogram.
3. Multilooking
   The interferogram multilooking step is necessary to increase the positional accuracy of the intensity and wrapped phase by increasing the number of looking views of the CoSSC data. Normally, 2-5 looking views are the optimal solution to produce effective ground range pixels.
4. Export to SNAPHU (Statistical-Cost Network-Flow Algorithm for Phase Unwrapping)
   Currently, the complicated phase unwrapping built-in step is still not provided by the SNAP desktop. Nevertheless, SNAP has an export functionality to hand over the task to the SNAPHU platform.
5. Phase Unwrapping (PU) in SNAPHU
   Phase unwrapping using SNAPHU consumes a lot of Random Access Memory (RAM) during processing. Therefore as a rule of thumb, it is necessary to subset the whole area into a size of less than 20 Megabyte of Wrapped Phase Interferogram.
6. Unwrapped Phase to Elevation
   The Elevation (height) calculation in SNAP is mainly based on a DEM reference e.g. SRTM 1 Arc Second as an existing topographic phase reference. Hence, the absolute phase offset is determined by the DEM reference accuracy.
7. Geocoding
   The geocoding in SNAP considers the terrain correction as well as the input of Ground Control Points (GCPs) if available. However, only planimetric (X,Y) information from the GCPs can be taken into account in the geocoding step.

Figure 4. Tide monitoring station : Geodetic control (upper), tide gauges (lower)

The previous baseline phase offset estimation result using phase offset functions (POF) from (ISO, 2018) indicates a vertical accuracy in the level of sub meter by using X-Band data. This result motivates us to improve the vertical accuracy in TanDEM-X data by taking into account GCP/DEM Reference data in the subsequent linear phase offset estimation using SNAP desktop. For the accuracy assessment, we measure the RMSE of each generated point other than the reference area with the best available DEM (FGDC, 1998).

2.4 Differential Interferometric SAR (D-InSAR)

Differential IFSAR has been chosen in our approach by using a concept of time series measurements to model the earth surface deformation/displacement. This suits also the situation where accurate DEM reference and/or GCP are not available around the volcanic island of Ternate.

$$\Phi = \Phi_{flat} + \Phi_{height} + \Phi_{differential} \quad (1)$$

From equation (1), the differential phase component can be subtracted from unwrapped phase ($\boldsymbol{\Phi}$) if the flat earth phase and height phase are known (Richards, 2007). Afterwards the deformation (d) in meter from multi temporal datasets can be calculated using equation (2), where $\boldsymbol{\lambda}$ = wavelength in m (X Band).

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$$d = \frac{\lambda \, \Phi_{differential}}{4\pi} \quad (2)$$

3. RESULTS AND DISCUSSIONS

Our approach employs time series radar data in order to determine the preliminary analysis of recent Sunda Strait tsunami by performing GIS analysis on TanDEM-X data using toolboxes in ArcGIS desktop. Under International Charter on Space and Major Disaster, the available space-based data shall be collaboratively distributed by the participating agencies on a voluntary basis after the activation charter. This activation made available some post-disaster maps as well as the vector data immediately in a post disaster situation. In this paper, some of these GIS vector data are used to support GIS analysis in section 3.2.

3.1 Phase offset estimation

A DSM is a representation of the earth surface including manmade and natural structure above ground in three dimensional (3D) coordinates. The derived product of DSM which reflects the bare earth information is called Digital Terrain Model (DTM). In addition, the Ortho Rectified Imagery (ORI) can be produced as the ground projected object data by taking into account the DSM or DTM data.

With respect to the geometric accuracy, the National Standard for Spatial Data Accuracy (NSSDA) has been selected for geospatial positioning accuracy (FGDC, 1998). The main idea behind this method is the detection of blunders from a given data set and the derivation of a statistical model. In this case, Root Mean Square Errors (RMSE) can be used to estimate the absolute accuracy.

The RMSE can be calculated by the following equation (FGDC, 1998) for each corresponding object in the different datasets i.e. between the InSAR data (TanDEM-X) and the reference data (IDEM). The calculation focuses on the elevation aspect, for the reason of simplicity with high certainty. The accuracy is given at 95% confidence level. It means that 95% of the positions in the dataset will have an error with respect to true ground position that is equal to or smaller than the reported accuracy value.

For an appraisal, the produced DEM is compared directly with a similar DEM obtained by conventional DEM using Phase to Elevation offset in SNAP desktop. The comparison reveals that our approach can achieve 3 meters accuracy in vertical dimensions.

ICP Level 1 absolute accuracy assessment for the 2D (planimetric) and 3D (elevation) component has considered 10 checkpoints covering the test area provided from GNSS surveys as included in **Error! Reference source not found.**. For Direct Georeferencing (DG) from orbital parameters, we did not use any GCP, while for either Indirect Georeferencing (IG) or combined method we use 3 GNSS monitoring stations as GCPs. Since the DG method is not always free from the systematic errors such as GPS/INS-sensor misalignment, GPS time shift, phase offset, etc, the combined method using both GPS/INS data and GCPs is also applied. From ICP Level 1 assessment, we are convinced that our linearized model can be used as an appropriate algorithm for the DEM generation as well as for the D-InSAR displacement detection.

ICP Level 2 accuracy assessments have been done by using SRGI as the height reference data. The adjusted baselines from CoSSC metadata were validated against our linearized data model. To investigate the influence of the linear model algorithm in our approach the final assessment was performed in which the results from our approach were directly compared to the reference accuracy from direct georeferencing. However, as we see in Figure 5, the effect of phase discontinuities makes the generated DEM for the volcanic island, tilted away after the height calculation (upper part). To correct this problem, the preliminary condition about the zero height coastlines is added to the processing scheme (lower part).

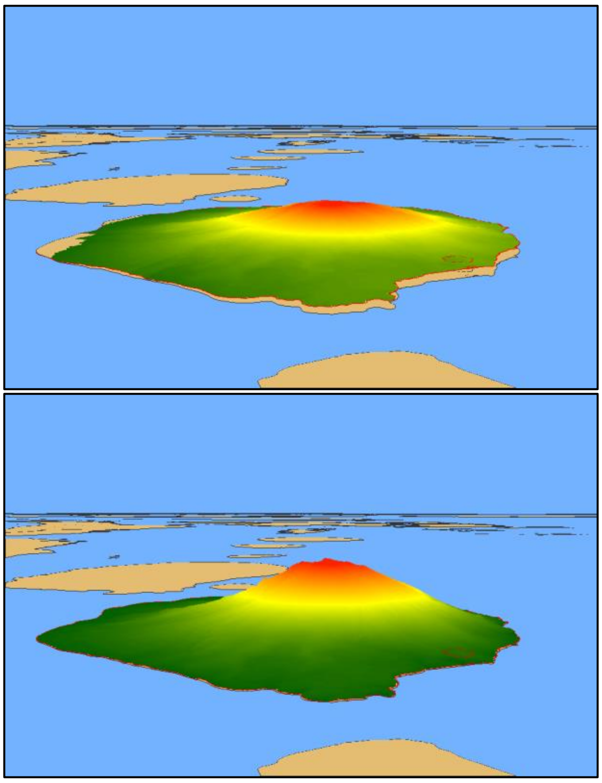

Figure 5. Implementation of linearized model algorithm (upper part: not corrected, lower part: corrected)

3.2 Ground Displacement analysis

As CoSSC format is a co-registered slave data to the master in a bi-static acquisition mode, the identification of the master dataset is mandatory. The TanDEM-X platform consists of two satellites namely TanDEM-X (TDX) and TerraSAR-X (TSX). For our datasets, we get the information from the included metadata that all the TDX data is a master data set.

By using multi temporal interferometric data processing between 2018 and 2019, the differential phase has been subtracted to calculate deformation using equation (2). As shown in Figure 6, the deformation tends to increase at the peak of the mountain

Gamalama in the range of more than 45 cm (indicated by red areas).

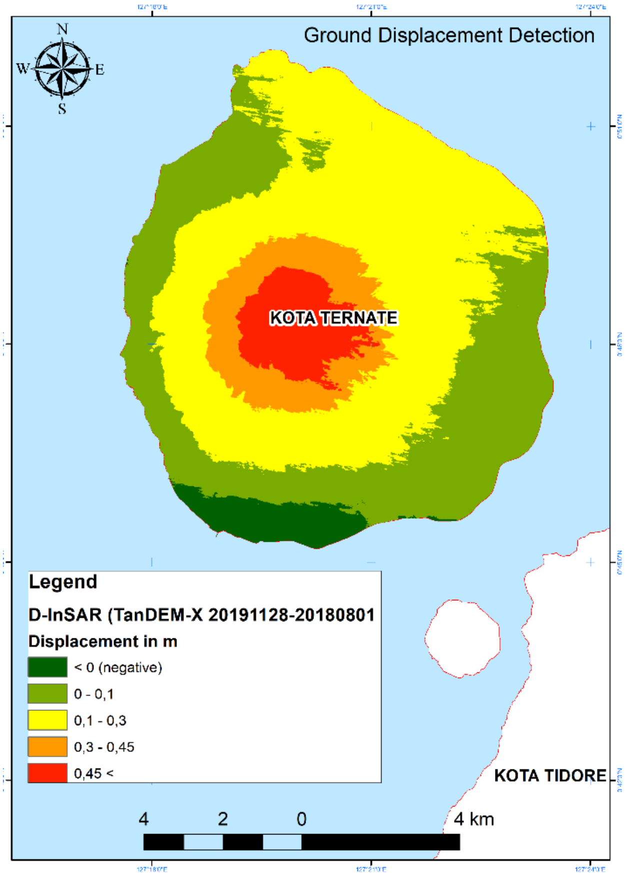

Figure 6. Ground displacements around volcanic island of Gamalama

On the other region of the volcano areas, the deformations were less significant in the range 0-30 cm (indicated by green-yellow areas). As indicated by the other volcanic island of Krakatoa (Copernicus Emergency Management Service, 2018), this negative movement in the southern parts of Gamalama probably will turn into an underwater landslide in the vulnerable area of Jambula (see Figure **7**).

Figure 7. Built-up area of Jambula

4. CONCLUSIONS

We have presented that up-to-date InSAR data, in this case TanDEM-X data, can contribute in DM system by enabling D-InSAR analysis. Despite the tidal and current wave factors is still not taken into account in our investigations, it is likely that the tsunami can be happened caused by the eruption activity of Mount Gamalama as depicted in Figure 7 and supported by the results of the investigations in chapter 3.1 and 3.2.

The earthquake occurrence detected by GEOFON is other system which must be integrated in the Tsunami Early Warning System (TEWS). As tsunami can be also triggered by the eruption activities, the aforementioned integration is a potential solution. That means, it is uncertain, but there are clear indicators that the underwater landslides of the volcano can cause the tsunami. Therefore, a bathymetric survey, as already planned in the near future by the responsible institution will probably map the underwater terrain condition.

Finally, an InSAR system is a potential technology to be used as a masterpiece of the TEWS not only by DEM Generation but also by differential IFSAR (D-InSAR) technique. D-InSAR must be applied especially in the active volcano island in order to monitor the deformation as a disaster preparedness.

ACKNOWLEDGEMENTS

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