Digital Elevation Model (DEM) generation from Interferometric Synthetic Aperture Radar (InSAR) in Tropical Forest area in Indonesia

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Abstract

Interferometric Synthetic Aperture Radar (InSAR) technique is one of the most efficient ways to provide global digital elevation models (DEMs) due to its all-weather, all-day characteristics, and the automatic high-efficiency processing methods. ERS-1/2 tandem images pairs have been used in tropical forests in Central Kalimantan, Indonesia to generate DEM by applying InSAR technique. Derived DEM based InSAR has been assessed by comparing highly accurate independent ground check points collected using differential global position system (DGPS) with DEM elevation. Analyses of InSAR DEM accuracy indicate that DEMs with root mean square error (RMSE) of less than 5 m are possible in the study area and could meet many objectives of a global mapping mission. Applying adaptive filtering many times with a decreasing window size has a strong impact to reduce the number of residues, which can increase the phase unwrapping efficiency and that lead the final RMSE DEM accuracy to be less than 3 m.

Keywords: ERS, InSAR, DEM, DGPS, Tropical Forest, Adaptive filtering.

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الحصول على نموذج الأرتفاع الرقمي (DEM) من التقنية التداخلية للرادار ذو المستقبل المحاكي (InSAR) بمنطقة الغابات الأستوائية باندونيسيا

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الملخص

التقنية التداخلية للرادار ذو المستقبل المحاكي (InSAR) هي واحدة من الطرق الفعالة لتوفير تغطية عالمية لنماذج الارتفاعات الرقمية (DEM) نظراً لطرق المعالجة الآلية عالية الكفائة ولخصائصها بالعمل بكل الأحوال الجوية وعلى مدار اليوم. إن صور مزدوجات القمر الأوروبي (ERS1/2) استخدمت لمنطقة الغابات الأستوائية بمقاطعة كلمنتان الوسطى بأندونيسيا للحصول على خريطة الأرتفاعات الرقمية باستخدام التقنية التداخلية للرادار ذو المستقبل المحاكي. تم اختبار نموذج الأرتفاع الرقمي الناتج عن هذه التقنية بمقارنة نقاط تحكم أرضية عالية الدقة مأخوذة بنظام التموضع العالمي التفاضلي (DGPS) مع أرتفاعات نموذج الأرتفاعات الرقمية .أشارت تحليلات الدقة إلى أن خطأ متوسط تربيع بأقل من 5 مترهو أمر ممكن في منطقة الدراسة وهو ما يحقق العديد من أهداف التغطية العالمية لهذه الخرائط .إنّ تطبيق الترشيح المرن (الموائم) عدة مرات مع تخفيض أبعاد نافذة المرشح له أهمية كبيرة لتقليل عدد الرواسب وبالتالي زيادة فعالية عملية إزالة تغليف الطور وذلك يقود للحصول على خطأ متوسط تربيع لنموذج الأرتفاع الرقمي لأقل من 3 متر.

الكلمات المفتاحية: القمر الأوروبي ERS، التقنية التداخلية للرادار ذو المستقبل المحاكي، نموذج الأرتفاع الرقمي، نظام التموضع العالمي التفاضلي، الغابات الأستوائية، الترشيح المرن (الموائم).

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1. Introduction

In most regions where topographical data is simply non-existent or unavailable, generating digital elevation models (DEMs) from remotely sensed data can be the key to providing the required information. The interferometric synthetic aperture radar (InSAR) can be used to produce a highly accurate global DEM with its advantages in significantly less time and at significantly lower cost than other systems without the limitation of weather. There are a number of studies on the use of SAR interferometry data for DEM generation (Crosetto et al., 2008; Xinshuang et al., 2018; Shuai et al., 2018; Gao et al., 2017) and retrieval of terrain parameters (Rufino et al., 1998). However, InSAR DEMs still have some problems such as vegetation cover and the near- and far-range areas where elevation data appear rough (Jensen, 1998). For this reason, InSAR DEMs have relatively low precision and accuracy compared to other DEM sources such as LIDAR data.

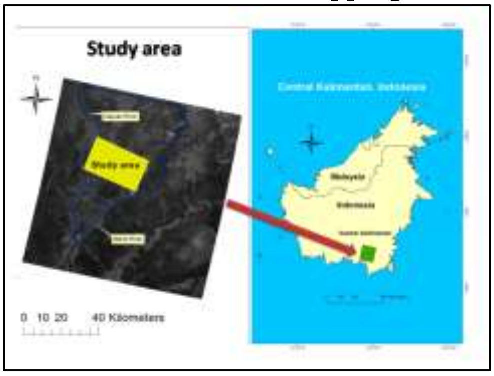
The digital description of the three-dimensional surface is important for several applications. DEMs have drastically changed the ways land surveyors and photogrammetrists collect elevation data for the production of contour maps. With the aid of DEMs, high quality contour maps can now be produced more quickly and economically. Planning and construction is one of the fields where DEMs are widely applied to different aspects, such as reconnaissance, design, construction and the maintenance of roads, railroads, airports, canals, dams, water reservoirs, pipe lines, power transmission lines and many others. Each of these applications could have different quality requirements. The quality needed for these applications is not high and their assessment methods will depend on how accurate the application needs to be.

Accuracy is the most important factor to be considered when a DEM is used. DEMs are used in a wide range of applications. Despite this fact, there is still a lack of quality control. A standard procedure for this kind of assessment as well as generally accepted specifications about the accuracy of DEMs does not exist (Ackermann, 1996). In 1997, the United States Geological Survey (USGS) proposed standards for the collection, processing and quality control of DEM data for the entry into the National Digital Cartographic Data Base (USGS, 1997). The International Cartographic Association (ICA) established a commission on spatial data quality which defined seven elements to describe the quality of data used in a GIS (Guptill and Morrison, 1995). Despite these efforts, quite a number of unsolved problems concerning the quality of spatial data still remain.

2. Study area

The study area (30 x 19 km) was chosen in the north west of Dadahup village in Central Kalimantan (figure 1).which is the biggest province on the largest island (Borneo) in Indonesia. The climate is tropical, hot and humid and 67% of the land is forest and woodland.

As a large part of Central Kalimantan is covered with tropical swamp forest, it is interesting to investigate how well an INSAR-derived DEM corresponds to the real terrain height in such areas. It should be possible to produce digital elevation models (DEMs) or slope maps from repeat-pass SAR interferometry over tropical forested terrain. It is also interesting to investigate how the accuracy of an ERS-derived DEM corresponds with RMS errors predicted in forest land cover in different forest area. Such DEMs may be useful for communication coverage, road and canal construction and flood mapping.



Figure(1): Location of the study area overlaid on ERS image

3. SAR data

The primary sources of available data for analysis in this paper were from the European Space Agency (ESA). Two ERS-1 and ERS-2 SAR data were acquired over Central Kalimantan in 2000 as it shown in Table 1.

By examining the data, it is clear that there is only a one day difference between the two acquisitions of the ERS-1/ ERS-2 pair. This small temporal difference gives advantages of high coherence and good height accuracy.

Table (1): List of ERS tandem data used in this study.

Sensor	Date	Track	Orbit	Frame	Par.B	Perp.B
ERS1	20000105	232	44308	3663	59	204
ERS2	20000106	232	24635	3663		

4. DGPS observations

A field survey was conducted to acquire ground control points. Differential GPS (DGPS) measurements were provided by two Leica SR20 GPS receivers. The SR20 GPS receiver is used as a high accuracy land surveying device, a powerful GIS data collector, or even a reference station. The files from the base and rover are transferred to the Leica Geo Office software, which computes corrected positions for the rover's file compared to reference station (static). For this measurement, ground control points (Figure 2) were divided into two sets of points, the first used as ground control points to calibrate the generation of DEMs during the processing steps and the second set of points are independent check points for accuracy assessment of the DEM after the processing steps are complete. Most of DGPS points were collected from the roads and stable areas where the heights have not changed between the time of image acquisition and the time of field data measurement.

The distribution of DGPS points was not perfectly distributed in terms of covering most of the study area, due to accessibility problems. Many areas were unreachable due to forest, heavy plantation or bad infrastructure facilities in the area.

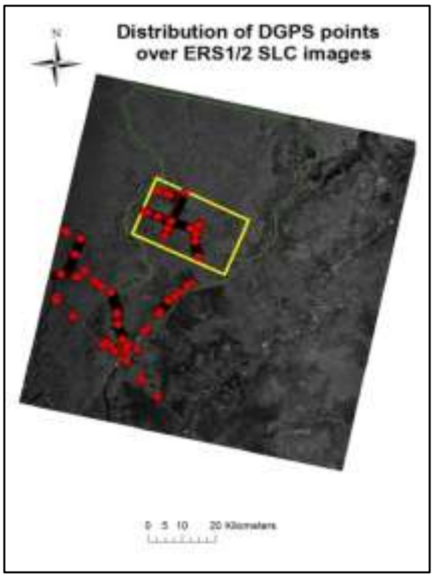


Figure (2): The distribution of DGPS points over ERS1/2 SLC images

5.Software environment

Gamma software, a product of Gamma Remote Sensing and Consulting AG, supports the entire processing from ERS raw data to products such as DEMs, displacement maps and coherence maps (Wegmuller and Werner 1997). ArcGIS10.3 software by Environmental Systems Research Institute (ESRI) and ERDAS 14 software were used for more analysis.

6. Data processing

Raw data were processed and transformed into a Single Look Complex (Slc) image format by ESA before distribution of SLC images. The entire InSAR process is outlined in Figure 3. The procedure that employed to generate a DEM includes the following stages: namely, image registration, interferogram calculation and filtering, phase unwrapping, elevation computation, and geo-coding.

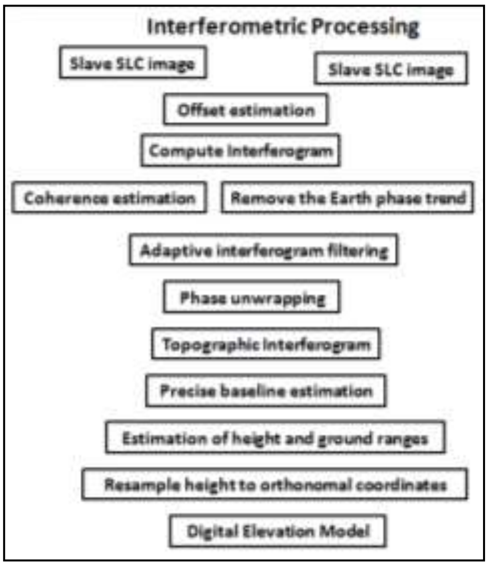


Figure (3): Schematic of steps in processing SAR data for interferometric applications

6.1 Co-registration and resampling

In this step the co-registration polynomial that describes the transformation of the slave to master image, which is subsequently used for the re-sampling of slave image to the master grid is determined.

6.2 Computation of interferometric products

In this step the complex interferogram and the coherence image (Figure 4) are generated. In addition, the phase noise is more serious where there is a terrain gradient, so the subsequent processing of interferogram need to be performed on removing the flat-earth phase and filtering.

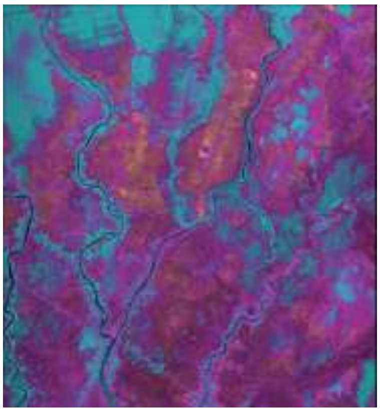


Figure (4): Coherence image derived from ERS-1/2 tandem pair acquired 5/6 October 2000 with backscatter intensity as background.

6.3 Phase Unwrapping method

This is the reconstruction of the original phase from the wrapped phase representation. Since the interferometric phase is wrapped modulo 2π, an integer number of 2π has to be added to recover the absolute phase difference. This can be done by adding a correct multiple of 2π to the interferometric phase for each pixel in order to obtain sequential phase values across the entire image. Branch Cut (BC) region growing algorithm has been applied (Figure 5).

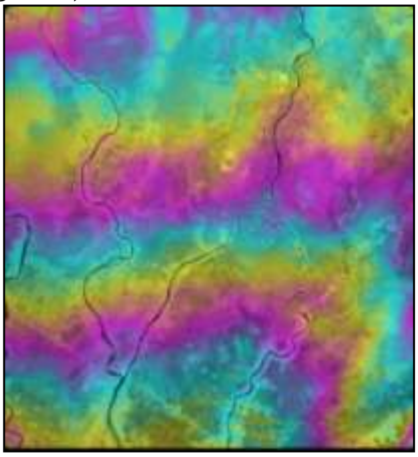


Figure (5): Unwrapped phase for the ERS-1/2 tandem image pair using MCF method with backscatter intensity as background. Phase displayed as 6π per colour cycle.

This method detects inconsistencies in the phase data, which cause errors in phase unwrapping. Critical areas such as areas of very low coherence or residues are identified and avoided in the phase unwrapping since the phase values are inaccurate and not useful for estimation of heights or displacements. The branch Cut algorithm consists of the following steps; masking low correlation areas, generation of neutrons to exclude regions of layover by generation of dense cuts, determination of residues, connection of residues through neutral trees, and unwrapping of interferometric phase.

6.4 Precise baseline estimation

Interferometric baseline is a vector pointing from the master to the slave orbit. The baseline information should be accurate if the unwrapped phase is to be used for the derivation of a height map. Refined baseline estimation is required using least squares fit for 39 of ground control points. Ground control points must be chosen in flat areas and should be spread over the entire image. Sometimes poor initial baseline estimation and poor selection of GCPs can lead to a non converting estimation. 39 ground control points have been used to improve the estimate of the interferometric baseline. Unfortunately, the distribution of the GCPs is not perfect due to limited access to many parts in Central Kalimantan, Indonesia. The field work covered most of all the accessible areas.

6.5 DEM Generation

Assuming that the interferometric phase is related to topography only, the unwrapped interferometric phase, together with the accurate baseline, is then used to derive the topographic heights and true ground ranges. The result is a height map in slant range/azimuth coordinates. The heights in SAR image coordinates were resampled to orthonormal coordinates (along track, cross track).

Geometric correction was applied to correct the spatial distortion using the Landsat images and all resulting images were stored in the Universal Transverse Mercator (UTM) projection system, zone 50 south. Finally, the DEM was extracted by the polygon that presents the study area.

Figure 6 shows the DEM generated by one tandem ERS pair in 2000 with spatial resolution (40x40 m). As the terrain is flat in the study area, the 40 m DEM can be suitable for this type of land relief in teams of keeping the topographic information and reducing the noise. This DEM has been derived by using an orbit method to calculate the interferogram and applying the Branch Cut unwrapping algorithm.

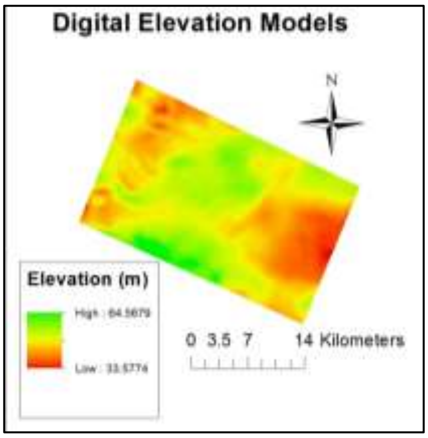


Figure (6): DEM has been derived by using InSAR technique

7. DEM accuracy assessment

Due to the lack of suitable reference DEMs, the quantitative evaluation of the result is often difficult. The main problem of this approach is the identification of ground features in both sources. In most of the cases, validation of the DEM has been done either by comparing with a DEM generated from other sources or from available topographic maps. The DEM validations were also carried out by ground surveyed data using GPS and total station (Dongchen et al., 2004). Contour maps were often used for the comparison with the interferometric data sets (Zebker and Goldstein, 1986). SRTM InSAR data has also been used for DEM generation and its validation.

the assessment of the quality of a digital elevation model is performed by using ground control points (GCPs). This approach is also a part of the standards for DEMs proposed by the United States Geological Survey (USGS, 1997). According to the National Digital Cartographic Data Base (NDCDB), a minimum of 28 points (20 interior and eight edge points) needs to be measured to determine the root mean square error (RMSE). In order to be suitable for this study, the test points have to fulfil the following requirements. They should be well distributed and representative for the terrain.

To compare the heights that were obtained by InSAR technique and DGPS check points, height in the study area were extracted from the DEM at the same locations where Kinematic GPS positioning sample were taken. Figure 7 presents the routes from which GPS height profile was extracted in study area, with the DEM of the site as background.

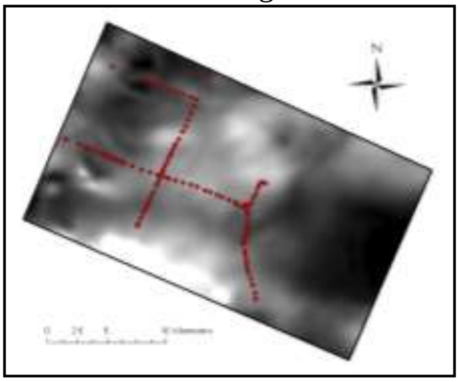


Figure (7): Distribution of check GCPs overlaid on InSAR DEM.

The accuracy assessment of the DEM has been carried out using 100 DGPS survey points. The most common practice to assess the accuracy of a DEM is to generate statistical measures, such as RMSE, mean error and standard deviation as its shown in table 2.

Table 2 shows the static information of InSAR derived DEM that has been assessed by comparing highly accurate independent check points collected using DGPS with DEM elevation

RMS errors of the InSAR DEMs being generated was less than 5 m. These results suggest that high resolution InSAR can meet the requirements of many applications in low relief areas, since it can capture small variations.

Table (2): Accuracy of InSAR DEM from DGPS check points

Min (m)	Max (m)	Mean (m)	St.dev (m)	RMSE (m)
0.03	16.56	3.49	3.08	4.66

Applying adaptive filtering many times with a smaller coefficient and decreasing window size (128, 64, 32, and 16) can reduce the complexity of the phase unwrapping problem and facilitate the unwrapping. The RMSE change resulting from applying adaptive filtering many times was

2.87 m as it shown in table 3. The quality of DEMs produced from ERS tandem pairs seems to be strongly affected by four issues; the offset estimation, interferogram computation, filtering and PU methods.

Table (3): Accuracy of Dadahup DEM from DGPS check points using Adaptive filter

Min (m)	**Max (m)**	**Mean (m)**	**St.dev (m)**	**RMSE (m)**
0.03	**6.10**	**2.44**	**1.51**	**2.87**

According to previous studies on the evaluation of DEM generated by ERS, the RMSE of approximately 16.9 m (Jayaprasad et al., 2008), 20 m (Rufino et al., 1998), 5 m (Zebker et al., 1994), 11.3 m (Baek et al., 2005) and 7 m (Al-harbi, 2009) can be achieved while RMSE predicted in forest land cover was around 18.7 m by Rufino et al. (1998) and 18.1 m and 5.1 m by Guritz et al. (1999).

That means that the accuracy was quite good for the whole area at least in terms of the requirements of small to medium scale topographic mapping. The InSAR DEM accuracy decreased only in very low coherence areas. Generally, the DEM of dense forest was successfully generated. Therefore, under favourable conditions, DEM with acceptable accuracy could be easily generated. However, this method was ideal in terms of comparing the DEM values by direct measurement using DGPS points.

The DEMs derived in this dense forest area, generally have slightly low RMS errors and better than those predicted in Hagberg and Ulander (1993) and Al-harbi (2009), which were 5 and 7 m respectively in open area. Obviously, the RMS errors in this study include very low coherence values which could affect RMS errors in a negative way.

The interferometric coherence is an important parameter determining how accurate the interferometric measurements are. Over forested terrain in the north of study area, the coherence is usually very low but it is still possible to make measurements.

Producing a digital elevation model with certain specifications in terms of accuracy already implies the decision about the usability for a specific application. It also shows that there is still a lack of specific requirements for DEMs from the user's side about the accuracy level needed for their application, since digital elevation models are often created for general use and not for a specific application.

A large number of parameters can be derived from DEMs for various purposes, at different scales and with different accuracy levels. Therefore, it is difficult to find a general quality measure which suits most of the potential applications. As stated by Ackermann (1996), there is no standard procedure for this kind of assessment and the accuracy of DEMs do not exist.

DEM error has only been measured at a limited number of survey points. Although these points represent a variety of terrain characteristics, only accessible locations can be surveyed and the most inaccessible areas could not be included. So the low coherence areas are not represented. Consequently, the largest errors are found in the low coherence areas.

8. Conclusion

The quality of the studied DEMs could satisfy the public and private sector intended applications such as cartographic mapping or installation of communication towers and global representation of terrain. Other applications that need more detailed representation such as civil engineering designs might need more accuracy and another source of data. LIDAR data might be another source and could give more accurate DEMS, but it is not widely available and it is expensive.

InSAR is one of the most efficient ways to provide global DEMs due to its all-weather, all-day characteristics, and the automatic high-efficiency processing methods. InSAR DEM supplies essential data for applications that are concerned with the Earth's surface and DEMs derived from survey data are accurate but very expensive and time consuming to create.

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