The Time-Lapse Digital Elevation Models Difference for Change Detection of Earth's Topography

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Key words: DEM, Copernicus DEM, SRTM, DEM difference

SUMMARY

The Earth's topography changes continuously due to natural and anthropogenic processes, including erosion, seismic, tectonic displacements and volcanic activities, groundwater level changes, deformations due to mining operations, engineering projects, and construction of new buildings. In addition, the topography of the canopy of vegetation covering the Earth's surface is also on the move resulting from seasonal changes, growth or deforestation. Monitoring these changes is paramount for modelling underlying processes and planning purposes. Digital Elevation Models (DEM) is a contemporary method of representing the topography of the Earth's surface. While DEMs are an active research topic, relatively little attention from the research community has been offered to investigate the properties and utility of the difference of DEMs captured at some distant points in time. In this contribution, we investigate the properties of difference between two semi-global DEMs, i.e., the Shuttle Radar Topography Mission (SRTM) and the Copernicus DEM. Both DEMs were captured some 15 years apart. Therefore, besides typical measurement errors, their difference should contain a signal due to changes in the Earth's surface topography. To investigate the sensitivity level or the applicability of the DEMs difference for topography change assessment, we selected a few test sites representing various land cover types, including forest, agricultural land, subsiding mining area and bare ground. As found, visual inspection of the raster of DEMs difference does not reveal a small topography change. Therefore, we used spatial statistical methods to show these otherwise obscured changes in topography. We found that freely available DEMs can be used to study the Earth's surface topography change, providing that the time-lapse or the magnitude of the topography change is large enough. We point out that a crucial determinant of the sensitivity of the DEMs difference to topography change is the slope of the terrain.

SUMMARY (Polish)

Topografia Ziemi ulega ciągłym zmianom w wyniku procesów naturalnych i antropogenicznych, w tym erozji, sejsmiki, przemieszczeń tektonicznych i aktywności wulkanicznej, zmian poziomu wód gruntowych, deformacji spowodowanych eksploatacją górniczą, projektów inżynieryjnych, budowy nowych budynków. Ponadto topografia roślinności pokrywającej powierzchnię ziemi ciągle się zmienia w wyniku zmian sezonowych, wzrostu lub wylesiania. Monitorowanie tych zmian ma kluczowe znaczenie dla modelowania praw natury ale także planowania przestrzennego. Cyfrowe modele wysokościowe (DEM) to współczesna metoda odwzorowania topografii powierzchni ziemi. Chociaż DEM są aktywnym tematem badawczym, stosunkowo niewiele uwagi poświęcono zbadaniu właściwości i użyteczności różnic pomiędzy modelami terenu uchwyconych w pewnych odległych momentach w czasie. W tym artykule przedstawiamy badanie właściwości różnic między dwoma semi-globalnymi numerycznymi modelami terenu, tj. Shuttle Radar Topography Mission (SRTM) i Copernicus DEM. Oba DEM zostały zmierzone w odstępie około 15 lat. Dlatego też, poza błędami pomiarowymi, ich różnica pomiędzy nimi powinna zawierać sygnał ze względu na zmiany topografii powierzchni ziemi. Aby zbadać poziom wrażliwości lub zastosowanie różnicy DEM do oceny zmian topografii, wybraliśmy kilka poligonów badawczych reprezentujących różne rodzaje pokrycia terenu, w tym lasy, aktywne wulkany, tereny górnicze i tereny pustynne. Jak stwierdzono, inspekcja wizualna różnicy rastra DEMs nie ujawnia niewielkich zmiany topografii. Dlatego też, zastosowano przestrzenne metody statystyczne, aby ujawnić te niewielkie zmiany w topografii. Stwierdzono, że swobodnie dostępne DEM można wykorzystać do badania zmian topografii powierzchni Ziemi, pod warunkiem, że upływ czasu lub wielkość zmiany topografii jest wystarczająco duża. Zwrócono uwagę, że kluczowym wyznacznikiem wrażliwości różnicy DEM na zmiany w topografii jest nachylenie terenu.

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1. INTRODUCTION

Monitoring changes on the Earth's surface is the fundamental purpose of Remote Sensing (RS), which is extremely important for decision-makers to achieve the sustainability of natural processes on our planet. RS infers changes on the Earth's surface based upon analysis of the spectral properties of materials found on the Earth. The RS approach is the most widely used but not the only method available for the mentioned purpose. In a recent decade or two, a remote surveying method based on the synthetic aperture radar (SAR) data processed using interferometry (InSAR) have been investigated. These methods include the Permanent Scatterers InSAR (PsInSAR), and differential InSAR (DInSAR), which have been used to monitor the millimetre-level changes in topography. The InSAR approach has also been successfully used to develop semi-global Digital Elevation Models (DEM), including the Space Radar Topography Mission (SRTM) and Copernicus DEM (Coper).

A DEM was a snapshot of the topography when it was captured. Having another DEM captured sometime later will provide another snapshot of the topography, but it will include all the changes that occurred in the time lapsed between the acquisition of the DEMs. Therefore, a difference between the two DEMs should expose the changes to the topography. A little attention has been paid to investigating the utility of the difference of DEMs for monitoring topography change to date (Becek, et al., 2021). This project uses the difference between two DEMs to identify the location and assess the magnitude of change.

The rate of change of the Earth's topography depends on a few underlying geophysical or human-induced processes, land cover and properties of the Earth's top layer. It could be as low as a few millimetres to even hundreds of meters per year. The rate of change can be a local event or a widespread phenomenon. The change could be systematic or caused by a catastrophic event, such as a landslide, earthquake or forest fire. The wide range of topography/land cover characteristics makes the task challenging.

One of the peculiarities of the InSAR elevation data is that the DEM pixels over vegetation do not represent the Earth's topography. Nevertheless, in this contribution, we consider the InSAR DEMs as models of the Earth's topography, assuming that over vegetated areas, the difference between DEMs could mean a change to the properties of vegetation cover and not necessarily change to the topography. In other words, the difference between DEMs could indicate a change to the topography where pixels represent the bare Earth's surface or a change to land cover for all other pixels.

The magnitude of the elevation bias of InSAR elevations over vegetated areas depends on the canopy height and density of scatterers in the canopy (leaves). In addition, the bias depends on the frequency of the SAR instrument. The bias is more significant for the shorter wave, the X-band-based Coper model, than for the SRTM model. This effect must be accounted for while interpreting the DEMs difference.

This project aims to explore DEM's difference as a data source for change detection in topography/land cover. To this end, a few test sites exposed to different processes were selected, including Brunei Darussalam - vegetation change due to deforestation, Australia – aeolian processes, Bali voulcano water erosion, Brunei Darussalam – land cover change and Turkey – excavation/piling operations. As a master/slave, DEM, SRTM and Coper is used. The time-lapse between DEMs is about 15 years. A threshold method identifies the spatial extent and magnitude of change. The threshold is estimated based on the DEMs' accuracy. Another method for identifying local topography alternations is a majority filter for a given neighbourhood. The study results demonstrate the utility of the DEMs difference approach for change detection and suggest further studies in this direction, e.g., including other types of data in the topography change data model.

2. DATA AND METHOD

2.1 Study areas

2.1.1 Australia

A test field in Australia is located within the Gibson Desert Nature Reserve, a part of the Gibson Desert, Western Australia. The area is classified as an arid zone characterised by low annual precipitation. The topography features dunes, open plains, gentle hills and undulating laterite plains. The dominant vegetation is spinifex and low shrubs and trees. The topography is flat, ranging from 420 m to 469 m. The area is 13.5 km x 9.6 km in size. The Lat/long coordinates are (Top Left corner - TL) -24.604°/125.366° and (Bottom Right corner BR) -24.689°/125.5°. Figure 1 shows the landscape of the test area in the Gibson Desert Nature Reserve.

Figure 1. The landscape of the Gibson Desert Nature Reserve. Credit: spelio from guess, Australia, CC BY-SA 2.0 https://creativecommons.org/licenses/by-sa/2.0, via Wikimedia Commons.

The significant topography altering process is the wind which shifts and modifies dunes. The vegetation is insignificantly low, not dense and does not go through a significant phenological cycle.

2.1.2 Bali, Indonesia

The main features of the test site in Bali, Indonesia, are two volcanos, Mount Batur and Mount Agung. Mount Batur rises approximately 1717 m above sea level. The first recorded eruption occurred in 1804, and the last one occurred on July 7, 2000. The southeastern section of the caldera features the caldera lake, named after the volcano. The volcano walls are exposed to intense erosion that washes down soft material not protected by vegetation. Figure 2 shows the Mount Batur volcano, including the Batur lake inside the crater.

Figure 2. Inside of the Mount Batur volcano crater. The Batur lake is visible on the right-hand side. Credit: TropicaLiving - https://www.flickr.com/photos/tropicaliving/3662229028/.

The Mount Agung volcano is located southeast of Mount Batur and is the highest point on the island, reaching 3031 m. The last two eruptions of the volcano occurred in 2017 and 2019. One of the most devastating eruptions occurred in 1963/64. During that event, over a thousand people were killed. During 2000 and 2015, the nominating process that altered the topography was rainwater erosion. The Lat/Lon coordinates of the test site are (TL) -8.166°/115.306° and

(BR) -8.426°/115.6°. The test site is 36.1 km x 28.9 km in size. The site's elevation ranges from 0 m up to 3031 m a.m.s.l.

2.1.3 Brunei Darussalam

The test site in Brunei Darussalam covers the western part of the country, located on Borneo island. The Lat/Lon coordinates are (TL) 4.667°/114.275° and (BR) 4.466°/114.513°. The area is 26.3 km x 22.4 km in size—the northwestern corner of the area reveals the South China sea. Corresponding pixels to the sea area in the DEMs were flagged as NoData. The land is mainly covered by the wet tropical rainforest, except for an approximately 2.6 km wide coastal strip which is mainly urbanised. The area's climate is tropical wet, with precipitation spread throughout the year to approximately 4000 mm annually. The area's topography is featureless, ranging between 0 m and 80 m. The prominent land cover feature has been an object of exploitation and impacted by infrastructure development, including the construction of major highways and housing projects. There is no natural hazard except occasional forest fires led by the negligence of humans. Figure 3 shows a GoogleEarth® snapshot image of the test area.

Figure 3. The Northwest part of Brunei Darussalam is a test area. Credit: GoogleEarth® image.

2.1.4 Zonguldak, Turkey

The test site in Turkey is located in the Zonguldak district that borders the Black Sea to the north. The Lat/Lon coordinates of the test site are (TL) 41.538°/ 31.78° and (BR) 41.43°/31.957°. The terrain elevation ranges from 0 m to 594 m a.m.s.l. The area is mostly covered by mixed forest, except for the mainly urbanised coastal strip. There are active open peat mining or stockpiling operations, which are the major topography altering processes. Figure 4 shows an example of an open cut mining/and stockpiling operations located in the Zonguldak test site at Lat/Lon coordinates 41.484°/31.88°.

Figure 4. A fragment of the Zonguldak test site showing open peat/stockpiling operations. Source GoogleEarth image.

2.2 Data

2.2.1 Shuttle Radar Topography Mission (SRTM)

The first quasi-global digital elevation model, known as the Shuttle Radar Topography Mission (SRTM), was developed using the Synthetic Aperture Radar (SAR, band C). Data were collected during an 11-day mission of the Space Shuttle Endeavour in February 2000. The interferometry method was used to calculate the SRTM elevations (Farr & Kobrick, 2000),. Countless tests confirmed the assumed vertical accuracy of the SRTM data, e.g. (Rodriguez, Morris, & Belz, 2006). However, some tests confirmed that the vertical accuracy of SRTM is much higher and according to (Becek, 2013, it is approximately 2 m (one sigma) and represents the instrument- and environment-induced errors (Becek, 2008). An error model of DEM proposed by Becek (K. Becek 2008) is discussed further in the paper. The Lat/Long coordinates on the WGS84 datum of the SRTM data were projected using the UTM projection. The elevations are stored in a 16 bit signed integer format.

The SRTM data used in this project are version 3 and have the spatial resolution of one arcsec (30 m at the Equator and <30 m elsewhere). The resolution of elevation data is 1 m, and the vertical reference of the SRTM data is the EGM96 geoid model.

2.2.2 Copernicus

The most accurate global digital elevation data product is the Copernicus (further – Coper). Coper was developed using SAR, band X data captured by a satellite pair working as a tandem - TerraSAR-X and TanDEM (OpenTopography, 2022). The same interferometry method was used for SRTM production. Coper shares almost all features as its commercial version, the WordDEM™, except the spatial resolution of 1" vs 0.4". Elevation data a referenced to the EGM2008 geoid, and the horizontal reference is the WGS84 system. The geographic coordinates were projected to the corresponding UTM zone in the project. The elevations are stored in a 32-bit floating-point format, which eliminates the impact of the quantisation level of the elevation data. Overall, the instrument/environment-induced errors are less than 1 m (one sigma) (Becek, Koppe & Kutoğlu, 2016).

2.3 Method

To identify the location and the magnitude of topography change, a difference between two Coper *minus* SRTM is used (Equation 1):

$$d = Coper - SRTM \quad (1)$$

The vertical accuracy of DEM depends on three sources of errors. They are (Becek, 2008):

- environment-induced errors;
- instrument-induced errors, and
- target-induced errors.

The environment-induced errors are caused by the imprecision of the atmosphere model and the physical properties of the Earth's surface (low coherence). These factors could cause both systematic and random elevation errors. The instrument-induced errors are caused by imperfection of the SAR instrument and data required to perform the SAR interferometry estimations (e.g., the base length accuracy). These errors are random. The target-induced errors depend on the pixel size, slope of terrain and quantisation level or elevation reading's resolution. Equation (2) shows the variance of the target-induced error as a sum of the error caused by the slope and pixel size and the variance of the error caused by quantisation (Becek, 2008):

$$\sigma_T^2 = \frac{p^2 tan^2(s)}{12} + \frac{q^2}{12} \quad (2)$$

where *s* is the slope at a given pixel,
p is the pixel size, and
q is the quantisation level of the elevation readings.

In the case of the Coper/SRTM data pixel size $p = 30$ m, while the elevation reading's resolution $q = 1$ mm and $q = 1$ m for Coper/SRTM, respectively. For the Coper, the variance of the quantisation error is negligibly small (>10^{-6} mm). However, for SRTM, the variance is 1/12 m^2 (standard deviation = 0.289 m) which significantly contributes to the error budget of the SRTM data. Figure 1 shows the relationship between the vertical error of the SRTM due to the target and quantisation, the slope.

The variance of the vertical error of a DEM can be expressed as per Equation (3):

$$\sigma_{DEM}^2 = \sigma_E^2 + \sigma_I^2 + \sigma_T^2 \quad (3)$$

where the indices *E*, *I* and *T* indicate the variance of the environment-, instrument- and target-induced error sources.

Figure 5 shows a theoretical relationship between the target-induced and quantisation errors vs the slope calculated from Equation (3), assuming the SRTM parameters, i.e., pixel size of 30 m and quantisation level of 1 m.

According to several studies, the compound variance of the environment- and instrument-induced errors for SRTM and Coper is approximately 4.84 m^2 and 0.64 m^2 (one standard deviation of 2.2 m and 0.8 m) (Becek, 2013), (Becek, Koppe & Kutoğlu, 2016), respective. However, as far as the author is aware, there is no study of the impact of the environment-induced errors on the vertical accuracy of DEM.

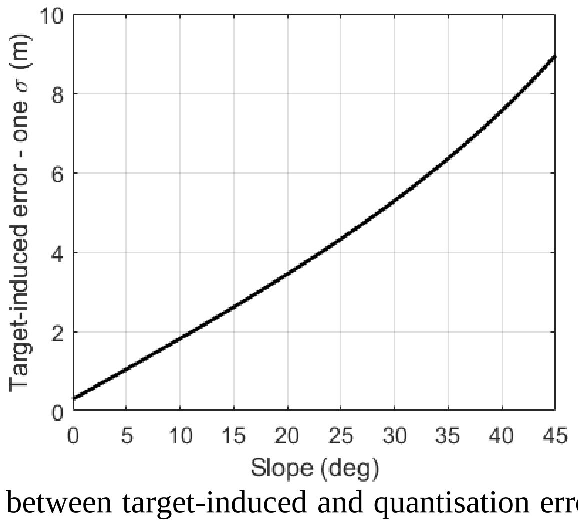

Figure 5. A relationship between target-induced and quantisation errors vs the slope. A pixel size of 30 m is assumed. The quantisation level is 1 m.

Referring to Equation (3), one can note that the accuracy of DEM is spatial dependent (varies from pixel to pixel according to slope). Hence, the question of how accurate is a DEM cannot be answered unless a particular value of slope and the pixel size is provided.

The standard deviation of a difference between two DEMs can be calculated using a well-known formula (assuming that both DEMs are uncorrelated) as per Equation (4):

$$\sigma_d = \sqrt{\sigma_{DEM1}^2 + \sigma_{DEM2}^2} \quad (4)$$

where σ_d is the standard deviation of the DEMs difference,
$\sigma_{DEM1/2}^2$ is the variance of the vertical error of the DEM_1/DEM_2.

For a flat pixel (slope = 0), assuming the standard deviation of the SRTM/Coper for a flat pixel is 2.2 m, and 0.8 m, the standard deviation of the difference is 2.35 m. However, for sloped pixels, the target-induced error term must be considered (Equations 2 and 3). Hence, for example, for a pixel with a slope = 10°, the standard deviation of the difference will be 3.18 m. In conclusion, the slope of the terrain determines the sensitivity of the DEMs difference to detect changes in the Earth's topography.

The topography changes are limited to small areas (small compared to landscape or regional scale). Using this spatial restriction, a few options are available to identify even small changes in topography, despite an apparent low accuracy of the DEMs difference. One of the possible methods is to compare a local histogram of the differences with a histogram for the entire DEM tile. This approach has already been used in the paper by Becek (Becek et al., 2021). The second method would be to use a dedicated filter, sometimes described as a zonal statistics filter", to identify a "concentration" of pixels with the majority of them having similar signs of the DEM difference. The following section demonstrates how these methods work on a few samples. ESRI ArcGIS software (version 10.8.1) was used.

3. RESULTS

This chapter summarises exploratory investigations of the topography changes of selected test sites. A thematic map and a histogram of the DEMs' differences are provided. The maps help to study the spatial context of the underlying forces causing the topography change, and histograms help study the changes' magnitude.

Figure 6 shows a raster of the topography changes in the Gibson Desert Nature Park. Extremely low annual precipitation in the area, flat terrain and lack of anthropogenic activities in the test site suggest that the wind triggered the changes in topography. Interestingly, the accretion is primarily present in the north to the northeast section of the site, suggesting prevailing wind directions. The map also confirms that the changes are not an artefact caused by the limited accuracy of the DEMs difference. A local averaging (7 by 7-pixel) filter was used to suppress the high-frequency noise. Looking at the histogram, one may learn that the magnitude of changes ranges from negative -2.27 m up to 2.08 m, suggesting that the accretion of the surface material almost perfectly balances the abatement. The low standard deviation of 0.54 m of the difference is a product of the flat terrain (slope = 0) and the low pass filter used.

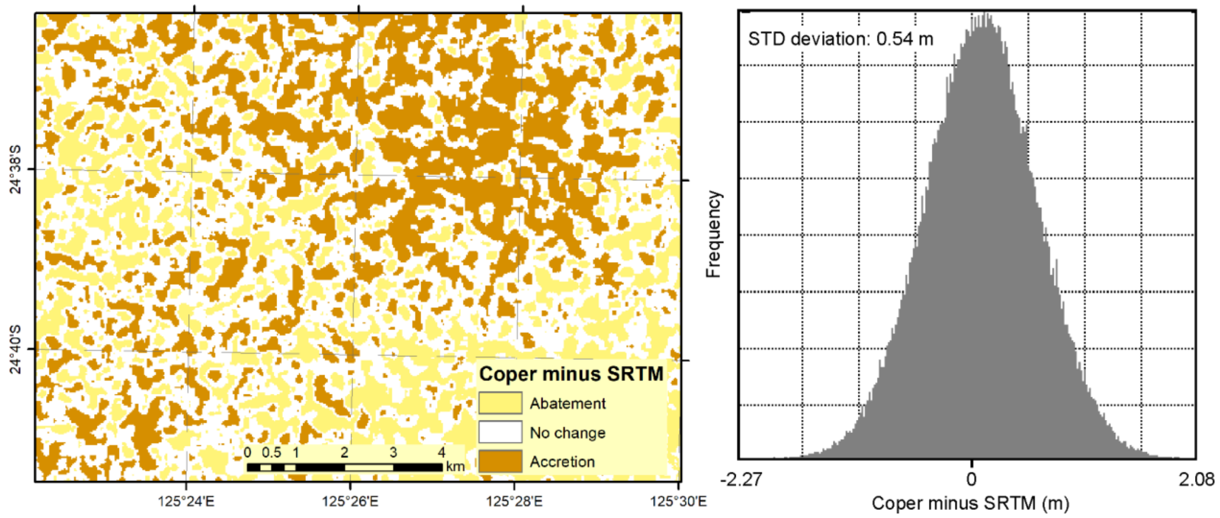

Figure 6. Raster of difference Coper *minus* SRTM over Australia's test sites. The discrepancies between both DEMs are caused by aeolian erosion. The accretion almost perfectly balances the abatement. A local averaging (7 x 7-pixel) filter was used, which suppressed the high-frequency noise.

Figure 7 shows differences for the Bali test site predominantly occupied by two active volcanos. No eruption event was witnessed in the area between 2000 and 2015. Hence, the prime topography alternation process is water erosion with specific spatial characteristics. The sides of the volcanos facing the ocean to the northwest are losing the material, while the sides exposed to the presumably milder condition from the southwestern direction accrete the volcanic material. Further specialised interpretation of the identified effect is required. A local averaging filter (7 x 7-pixel) was used to suppress the high-frequency noise. The histogram of the changes reveals some outliers that are probably due to a very steep but narrow caldera. However, most of the differences are "enclosed" in a Laplace-type of the probability distribution function with the standard deviation of 8.22 m which is justifiable, knowing that high slopes are present at the site. The symmetrical shape of the histogram suggests an insignificant or low vegetation cover.

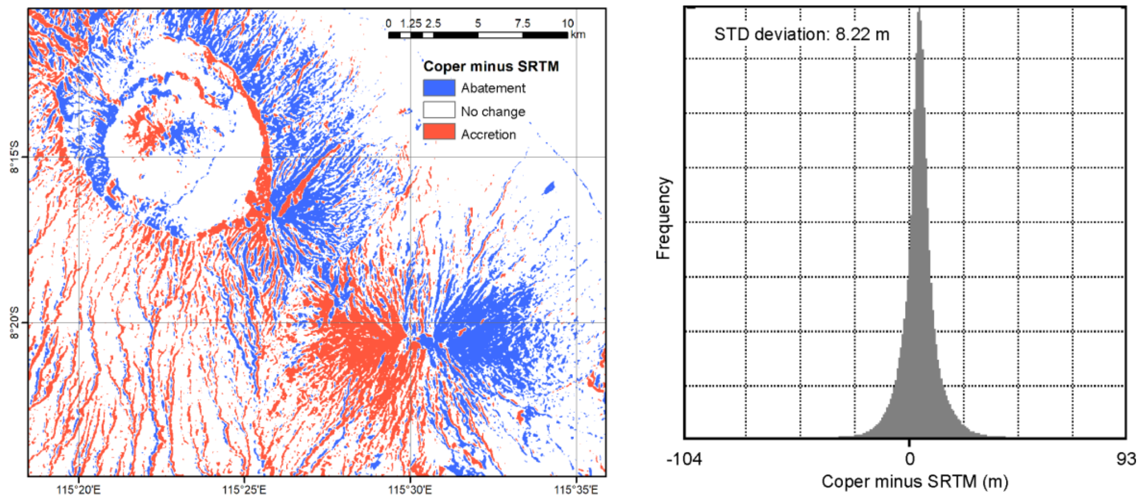

Figure 7. Raster of difference Coper *minus* SRTM over Bali's test sites. The water erosion processes cause discrepancies between both DEMs. Note accretion of the southwest slopes of the volcano and abatement on the northwest slopes, with the ridge of the volcanos forming a borderline between the accretion and abatement zones.

Figure 8 shows the topography alternations at Bruni Darussalam's test site. Most of the changes are caused by deforestation caused by infrastructure development projects (the west and north section of the country). A shape in the eastern part of the site is the tree harvesting concession area. The origin of the remainder of the changes is unclear. However, it is plausible that signs of forest depletion are caused due to global warming. Overall, 14% of the forest cover has been depleted or deforested. This figure corroborates other studies' estimates, implying that the deforestation or forest depletion rate is approximately 0.8% yr^{-1}.

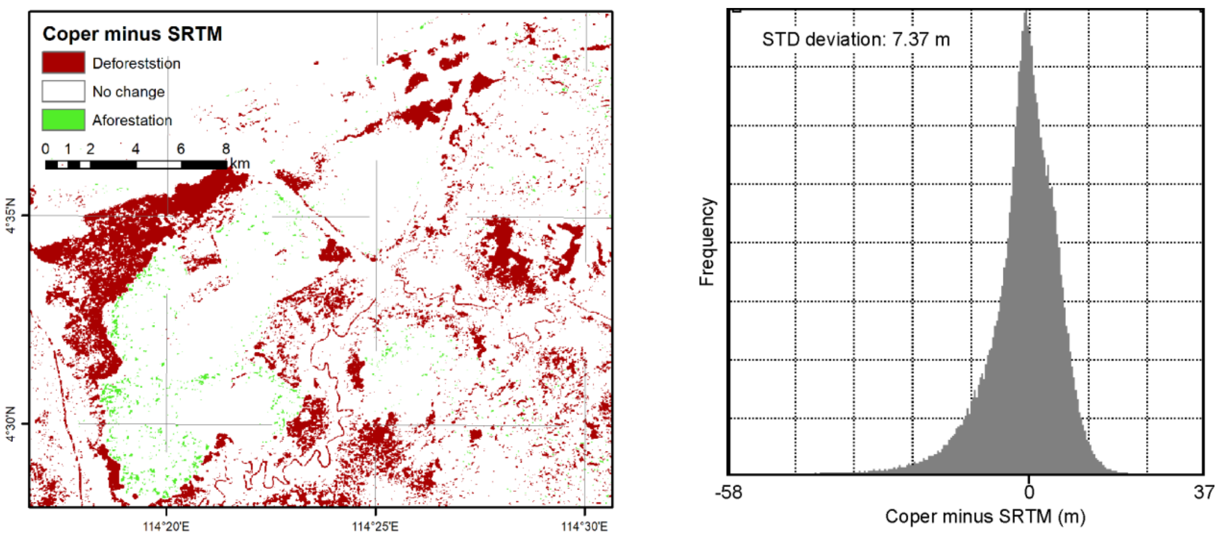

Figure 8. Raster of difference Coper *minus* SRTM over Brunei Darussalam's test sites. Land clearing processes cause discrepancies between both DEMs. Regrow of vegetation is minimal.

The histogram for the test site is asymmetrical. There are two factors controlling the asymmetry. First is the significant component of depleted or deforested pixels (negative difference). The second one is the different vegetation bias for the SRTM vs Coper models, i.e., the Coper model is always higher above forest than SRTM (positive difference). The raster in Figure 8 was produced by thresholding difference by one σ (7.37 m), i.e., "Deforestation" was selected for $d < -7.37$ m, while "No change" was assumed for $-7.37 < d < (7.37 + 4 \text{ m} = 11.37 \text{ m})$, where 4 m is the estimated vegetation bias difference between Coper and SRTM. For $d > 11.37$ m, the "Aforeststion" is assumed.

Figure 9 represents the topograph alternations at the Zonguldak test site. The processes responsible for the changes are the mining/excavation operations and stockpiling of the extracted or discussed material (e.g. ashes). The area is covered by mainly deciduous forest that is not exploited. The background of the map is the SRTM model. The map in Figure 9 was produced by thresholding difference using one σ (3.38 m), i.e., "Abatement" was selected for $d < -3.38$ m, while "No change" was assumed for $-3.37 < d < (3.37 + 1 \text{ m} = 4.37 \text{ m})$, where 1 m is the estimated vegetation bias difference between Coper and SRTM for the deciduous forest. For $d > 4.37$ m, the "Accretion" is assumed. The slightly asymmetrical histogram is due to more negative differences (Abatement > Accretion).

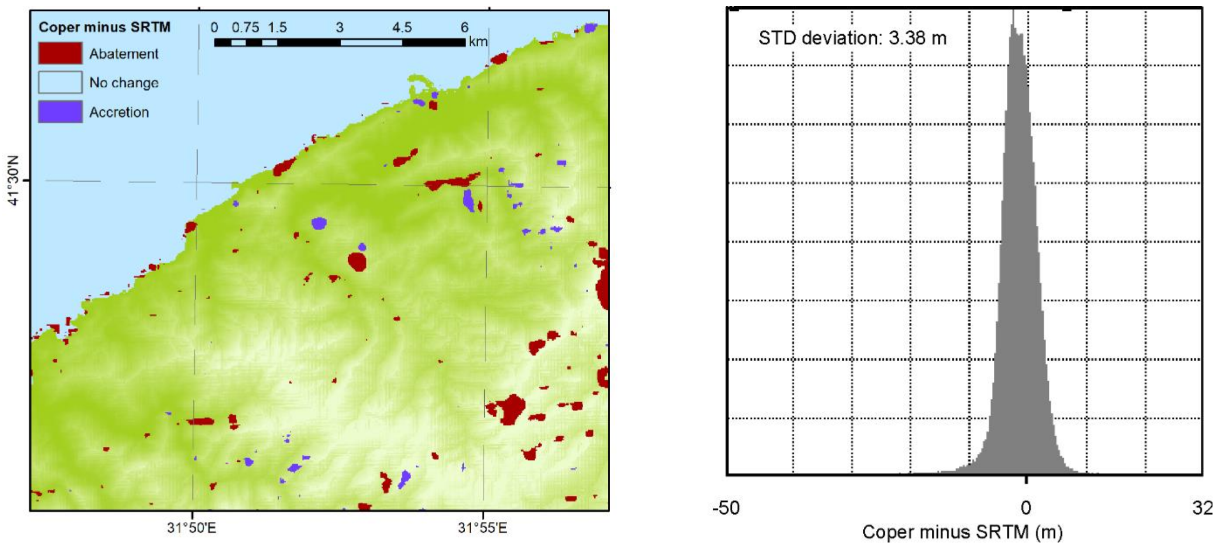

Figure 9. Raster of difference Coper *minus* SRTM over Zonguldak's test sites. The open cut mining/excavation and stockpiling operations are causing discrepancies between both DEMs.

4. DISCUSSION AND CONCLUSION

This study aims to demonstrate an alternative method to the spectral-based Remote Sensing methods or the InSAR-based deformation measurements to detect changes in topography or land cover. The proposed method uses the SRTM and the latest Copernicus model to calculate their difference. However, any DEM pair can be used, providing a sufficient time gap between them. In this case, the time-lapse between DEMs is about 15 years. Furthermore, a local averaging filter as a low pass filter is used to suppress the inherited errors of the DEMs, making it possible to detect changes in topography. In addition, a careful study of a histogram of the differences allows for identifying regions affected by the topography altering process. Finally, selected test sites allowed us to demonstrate that it is possible (at least qualitatively) to study the impact of aeolian erosion, water erosion, and anthropogenic forces changing the land cover or topography. As demonstrated, the method's sensitivity depends not only on the accuracy of instruments used to measure DEMs but also on the topographic feature of the terrain. The highest sensitivity of the method is acchived for flat pixels (slope = 0). Special procedures can be developed to address this constraint.

Overall, the presented method has the potential to beceome a method of choice for geoscientists studying the ever-changing Earth's cover and its topography.

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BIOGRAPHICAL NOTES

Kazimierz Bęcek (Senior Member, IEEE) received the Dipl.-Ing. (M.Sc.) degree in land surveying from the Wroclaw University of Agriculture, Wroclaw, Poland, in 1978, the PhD degree in geodesy from the Dresden University of Technology, Dresden, Germany, in 1987, with a computer simulation thesis of atmospheric refraction, and the D.Sc. (Habilitation) degree in remote sensing from the Dresden University of Technology, Dresden, Germany, in 2010, with a thesis on biomass representation in InSAR datasets. He is currently a Professor at the Wroclaw University of Science and Technology, Wroclaw, Poland. He worked with the School of Surveying, UNSW, Sydney, Australia, from 1989 to 1994, before joining a publishing house on the Gold Coast, Australia, in 1995, as the Head of the Cartography and Data Acquisition Department. He also worked for the Queensland state government and the Gold Coast City local government (both in Australia) from 1998. From 2003 to 2013, he worked with the geography department at the University of Brunei Darussalam, teaching Cartography, GIS, Photogrammetry, Remote Sensing, Geodesy, and Surveying. His research interests include mathematical modelling of environmental systems, including landslide monitoring, natural hazard mapping, and remote sensing methods for ecological studies. Dr Becek is a former Vice-President of the Brunei Institution of Geomatics.

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