Assessing vertical accuracy of digital elevation model using flood line as a reference

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SUMMARY

Digital Elevation Models (DEMs) are used in many branches of geoscience as fundamental datasets for applications and studies. Therefore vertical/horizontal accuracy and precision characteristics are paramount. As established, the vertical accuracy and precision of DEM depend on the terrain characteristics (slope), pixel size, and environmental factors. In the case of global DEM, it might also depend on a geographic component. Several methods have been developed to assess the accuracy and precision of DEMs. These methods use features with known elevation and datasets, including higher accuracy benchmarks, roads, runways, and DEMs. In this contribution, we propose a novel approach to assess the accuracy and precision of a DEM. The idea is to use the horizontal feature of the water surface. The water surface intersects with the terrain along a line that, by definition, at any point possesses the same elevation. To demonstrate the approach, we selected the actual flood lines of the devastating floods in the Australian New South Wales state in February 2022. The flood lines can be identified using *in situ*, aerial photography, or satellite imagery. In this project, we utilised the Sentinel-1 Synthetic Aperture Radar (SAR) imagery to discriminate smooth surface water from the rough land surface, which was performed with a well-documented automatic procedure. However, some manual editing was required to eliminate insignificantly small polylines. Two global DEMs were selected for testing, i.e., the well-known Shuttle Radar Topography Mission (SRTM) and Copernicus DEM (COP) developed from the TerraSAR-X/TanDEM-X twin satellites. Statistical assessment of the differences between the DEMs pixels and the constant elevation of flood lines provided an opportunity not only to assess the accuracy of DEMs but also offered an inside look at the accuracy of the identification of the flood inundation using the SAR satellite imagery. This method can be utilised almost everywhere, because floods are a common hazard. Also, no reference data are required beyond freely available satellite imagery of the Copernicus Sentinel program or others.

Assessing vertical accuracy of digital elevation model using actual flood line as a reference

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1. INTRODUCTION

Digital Elevation Models (DEM) play a pivotal role as a fundamental reference data set in many branches of geosciences and beyond. Until the end of the last millennium, no consistent middle resolution (10 m – 100 m) elevation dataset of the entire Earth's topography existed. There were local (countrywide) topography datasets available. Still, it was beyond reasonable efforts to compile them into a single global DEM because of the inconsistencies of methods used to create them, cross-border legal challenges, security concerns, and politically motivated restrictions. This was one of the motivations and justifications for the Space Shuttle Radar Topography Mission (SRTM) program that NASA developed. The SRTM mission was flown in February 2000. Collected during the eleven-day mission of the Synthetic Radar Aperture data were processed using the InSAR method. The first version of the SRTM "digital elevation data product" – as NASA called it – started to be published on a continental basis in 2004 [7]. Many efforts were undertaken to assess the accuracy of the SRTM product. They were conducted by NASA [13] and several researchers, e.g., [3], [4], [9]. A few data sets were used for elevation reference, including road centerline transect captured using a GPS-equipped vehicle, benchmarks, ocean surface, DEM of higher accuracy and airport runways. The results of the studies consistently indicated that SRTM products achieved assumed accuracy characteristics. A quest for accurate modelling of the Earth's topography did not finish with developing new versions of SRTM. Based on the German twin satellite mission TerraSAR-X and TanDEM-X, a semi-global DEM – WorldDEM^{TM} - and based on it, the Copernicus DEM (COP) [2] was developed. Both models are subjects of the accuracy assessment using a novel method proposed in this paper. The proposed method uses the flood line as an elevation reference to test the vertical accuracy of SRTM and COP models. The flood line is extracted from two SAR images captured before and during the flood event. The two images are necessary to distinguish between existing and floodwater bodies. An image thresholding technique separated smooth water surface from rough land. A floodwater mask was further processed using the mathematical morphology of binary images that allowed the flood line or flood contours to be extracted. Subsequently, the flood lines were used as an equal-elevation reference line compared to the corresponding DEMs extracted elevations. Statistical analysis shows that the vertical accuracy characteristic of SRTM and COP matches the results conducted elsewhere, suggesting that the proposed method can be used in similar tasks elsewhere.

2. DATA and METHOD

2.1 Area of interest (AOI)

The area (and the flood) selected for study is located in New South Wales, Australia, more or less centred on the town of Grafton. The Clarence River system, discharging into the Pacific Ocean, is the main hydrographic feature of the landscape. The region is characterised by a humid subtropical climate, often receiving more than 300 mm of rain during summer. Grafton enjoys approximately 115.2 sunny days yr^{-1}. Like many other areas in New South Wales, heatwaves also affect it during the summer months [35].

The 2022 floods in eastern Australia were one of the worst recorded flood disasters in the country's history, with a series of floods occurring from February to April in south-east Queensland, Wide Bay-Burnett and parts of coastal New South Wales. The flooding resulted from a low-pressure system over the southern Queensland coast, which pulled moisture from the Coral Sea to the north, lifting it over the Queensland coast. As the system headed south, it developed into a low near the Central Coast of New South Wells and Sydney. In addition, there was a high-pressure area off New Zealand, that is a counter clockwise rotating high, which prevented the low-pressure system from drifting towards the Tasman Sea [11].

Rainfall totals exceeded values typical for this time of year. More than 30 locations in south-east Queensland experienced record rainfall totals of over 1000 mm, with some areas of Brisbane receiving close to annual average rainfall in just a few days. In Lismore, New South Wales, 181 mm were recorded in 30 minutes at one point [50].

According to the Insurance Council of Australia (ICA), the flood disaster between February and April 2022 in Queensland and New South Wales caused losses of approximately $4.8 billion [37].

Figure 1. Location of the Area of Interest.

2.2 Data

The Synthetic Aperture Radar (SAR) image captured by the Sentinel-1 satellite and two digital elevation models, i.e., the Copernicus Digital Elevation Model (COP) and the Shuttle Radar Topography Mission (SRTM), were used to perform the accuracy tests of both COP and SRTM models. The respective data sets employed in this study were downloaded from publicly accessible Internet servers.

2.2.1 Sentinel-1

The Sentinel-1 program consisted of twin satellites, launched in April 2014 and April 2016 [6]. However, in December 2021, a power anomaly in Sentinel-1B caused the satellite to stop functioning. Attempts to restore power to the sensor were unsuccessful, and the mission officially ended on 3 Aug 2022.

The Sentinel-1 satellites feature a C-band SAR instrument that ensures data collection in all weather conditions, day and night. This instrument has a spatial resolution of up to 5 m and a coverage of up to 400 km. The satellite orbits the Earth at an altitude of approximately 693 km on a heliosynchronous. The current revisit time (after the demise of the Sentinel-1B satellite) is around 12 days. The SAR instrument collects data in dual polarisation (HH+HV, VV+VH. Dual polarisation data is helpful for land cover classification and sea ice applications [15].

Sentinel-1 SAR mages were downloaded from the ESA website for 13 Jan 2022 and 2 Mar 2022. Detailed information about the images is presented in Table 1.

Table 1. Basic information about the Sentinel-1 imagery used in this study.

Acquisition date		13 Jan 2022	2 Mar 2022
Satellite		Sentinel-1A	Sentinel-1A
Product Mode		IW-GRDH	IW-GRDH
Orbit		Descending	Descending
Polarisation		Dual VV/VH	DV - Dual VV/VH
Pixel size		10 m	10 m
Coordinates of the scene			
Bottom Right	Lat	-31°12'01.61"	-31°12'1.91"
	Lon	154°43'46.66"	154°43'50.62"
Top Left	Lat	-29°5'16.88"	-29°5'17.18"
	Lon	152°35'18.05"	152°35'22.01"

2.2.2 Copernicus Digital Elevation Model

Copernicus DEM [2] represents the Earth's surface elevation, aboveground infrastructure and vegetation. This product is based on the TanDEM-X satellite mission. The Synthetic Aperture Radar Interferometry (InSAR) method developed the COP. The model is available in three versions: GLO-90, GLO-30, and EOG-10, with spatial resolutions of 90 m, 30 m, and 10 m, respectively. The EOG-10 is available to authorised users only. COP covers approximately 150 million km^2 of the land surface. The horizontal/vertical reference systems of COP are WGS84 and EGM2008. According to (Airbus 2020), the vertical accuracy of the COP is better than 2 m for slopes <20%. However, as several studies have proven, the accuracy of the COP is < 1 m (one sigma), e.g., [5].

2.2.3 SRTM

The Shuttle Radar Topography Mission (SRTM) data product [7] is a semi-global DEM developed using the InSAR method based on the C-band SAR data captured during the 11-day mission of the space shuttle Endeavour in February 2000. Over the years, SRTM has been modified few times. In this study, version 3, known as SRTM Plus or void-filled SRTM, was used. The current resolution of the SRTM is one second (approx. 30 m at the Equator). The vertical accuracy of the DEM significantly exceeds what was requested by the investor in the SRTM project, i.e., of 16 m absolute error at 90% confidence (RMSE) of 9.73 m worldwide. However, the vertical accuracy of the SRTM is approximately 2 m for flat surfaces, increasing with the pixel size and the slope of terrain [3], [13].

Both models contained a vertical bias over vegetated areas, depending on the vegetation density and crown shape ranging from 60 % – 80 % of the vegetation height.

2.3 Method

Two main data processing steps were performed towards the goal of this project:

- First, SAR images were used to identify the extent of the Grafton flooded areas. To do that, raster masks of water bodies were created from the reference image (13 Jan 2022) and the crisis image (3 Mar 2022. An intensity threshold was determined [12] using the histogram to identify the dark pixels in the VH intensity band, presumably representing a smooth water surface that specularly reflects microwaves away from the sensor. A pixel-by-pixel difference between both masks allowed us to identify and switch off the common dark pixels (ak water pixels). The remaining pixels represent the flood water pixels.

- Second, the flood water pixels mask found in the first processing step was subsequently processed using procedures based on the mathematical morphology of binary images and available as a set of tools in the MatLab [8] software package. This step aimed to identify outlines of the flooded areas and use them as contours. The flood contours were employed to extract the COP and SRTM elevations via raster operations, i.e., the Con function in ArcGIS Spatial Analyst ToolBox [1].

A detailed data processing workflow employed in this study is shown in Figure 2.

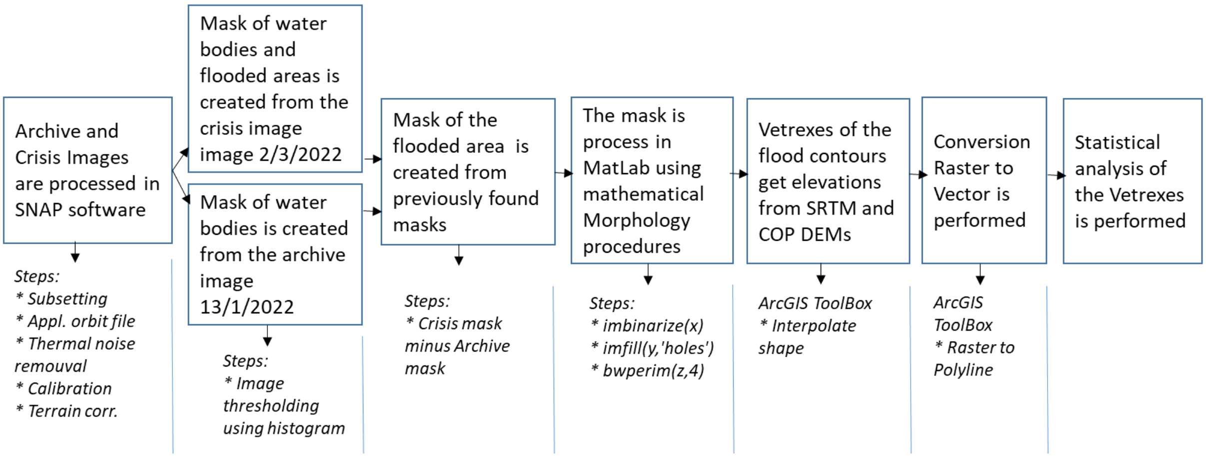

Figure 2. Data processing steps.

3. RESULTS

Figure 3 shows a map of the flood extent and the contours of the flooding.

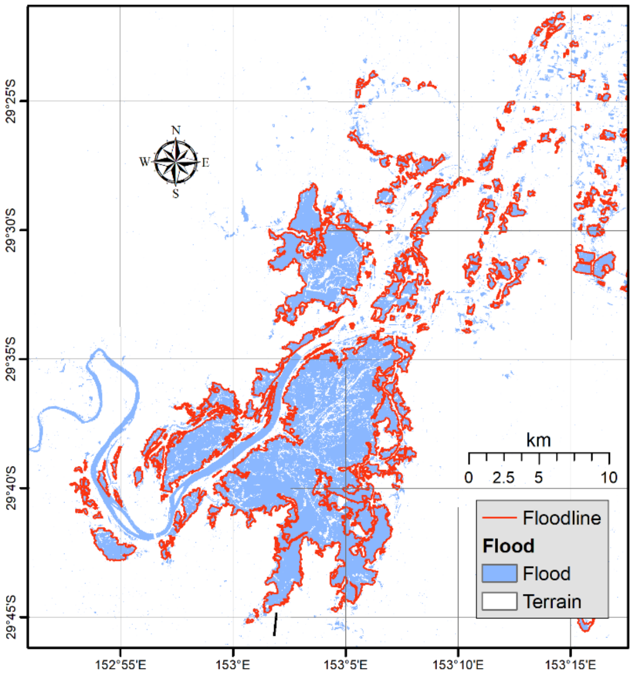

Figure 3. Flood extent and the flood lines used in this study.

The data processing steps lead to the identification of 209 contours. Each contour was made of docent vertexes. These vertexes were then used to interpolate the SRTM and COP elevations for them. The basic statistics for the vertexes are:

- The average vertexes/contour: 580.44
- The maximum vertexes: 28265

- The maximum vertexes: 112
- The standard deviation: 2069.6

The contours represented flooded areas were found at different levels. Figure xxx A and B shows a histogram of contour elevations for SRTM (A) and COP (B). The average elevation of the SRTM-derived contour elevation is 2.63 m. At the same time, for the COP, it is 1.85 m, indicating a vertical discrepancy between SRTM and COP of 0.78 m (SRTM is higher than COP). We have used the central line of the runway of the nearby Grafton airport to compare the SRTM and COP-derived cross-section. This method for the vertical accuracy assessment of DEM is known as the runway method [4]. We found that the SRTM runway elevation is 25.24 m, and the COP mean elevation is 25.52 m. This means that the SRTM elevation is 0.24 m lower than COP. The discrepancies are acceptable, considering the runway's surface is almost flat and free of obstacles. At the same time, flood contours are also found under vegetation where InSAR DEM models are subject to vegetation bias [5]. Figure 5 shows the SRTM and COP profiles of the runway. Both profiles follow the same trend (the runway); clearly, the COP model is smoother than the SRTM.

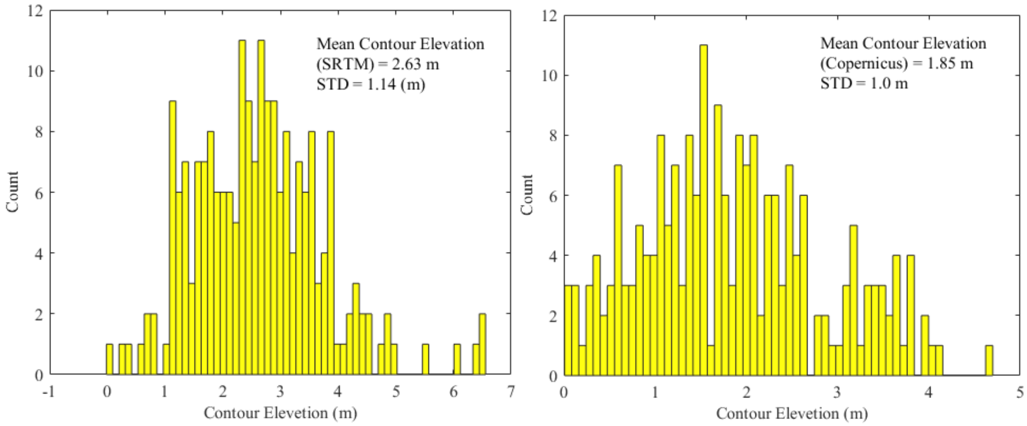

Figure 4. Histogram of contour elevations determined from SRTM (left panel) and COP (right panel).

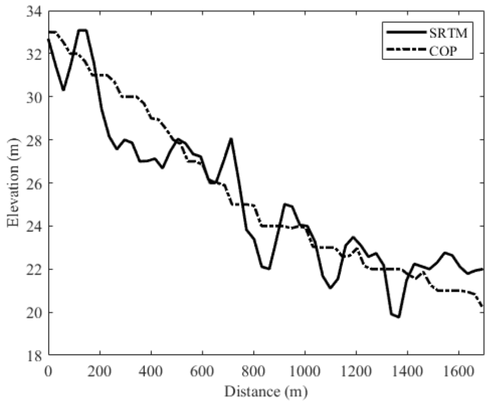

Figure 5. Profiles of the Grafton airport runway derived from the SRTM and COP models.

To assess the vertexes accuracy of COP and SRTM, the elevation of vertices was used. Figure 6 shows histograms of the standard deviation of elevation within a given contour. Assuming that the contour elevation is constant, the standard deviation of discrepancies in elevations of vertexes in a contour is due to the errors of the DEM from which the elevations were interpolated.

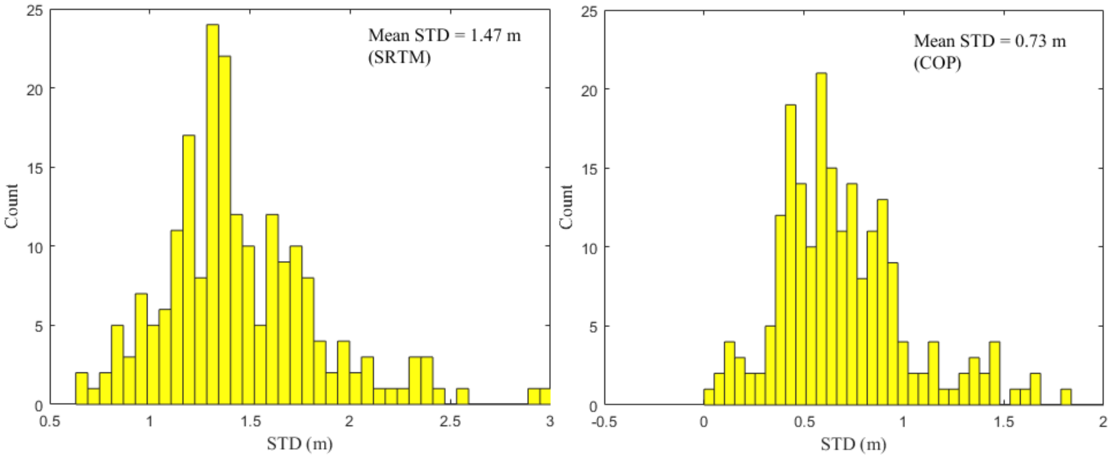

Figure 6. Histogram of vertexes' elevation determined from SRTM (left panel) and COP (right panel).

This further means that the relative vertical accuracy (one sigma) of SRTM is 1.47 m, and of COP is 0.73 m.

4. DISCUSSION

The vertical accuracy of a DEM depends on three statistically independent error sources. They are the instrument-, geometry- and environment-induced error sources [3]. The first error source is self-explanatory and can be controlled by selecting a more accurate instrument or method. The second source depends on the pixel size and terrain slope within a pixel. The third source is hard to model and is usually omitted or included in the first source. In the case of the proposed method, the second source equals 0 since the slope for any contour equals 0. This means that the results obtained here of 1.47 m and 0.73 m for SRTM and COP are caused by the instrument and environment-induced factors. In previous studies on the vertical accuracy of SRTM and WorldDEM^{TM} (derived from the same SAR data as COP), similar results were achieved, i.e., 1.55 m for SRTM [3] and 0.8 m for WorldDEM^{TM} [5].

The contours elevation identified and selected for the study indicates that the water started receding after reaching its summit on 28 Feb 2022 at a depth of over 14 m. This is because the highest recorded contour level identified on the 2 Mar 2022 image was approximately 6 m.

5. CONCLUSION

The proposed reference data derived from SAR satellite images for assessing vertical accuracy of DEMs of medium resolution (10 m to 90 m) produced results comparable with those obtained using other methods. The proposed method can be applied worldwide to floods or other water-related phenomena, e.g., dry lakes, frozen lakes, and glaciers, are more easily accessible than benchmarks, runways, or other anthropogenic features. Another feature of the method is that it does not require any *a priori* knowledge of the elevation of the reference contours.

The critical role of the mathematical morphology of binary images used in this project should also be mentioned. By applying a few pre-programmed procedures in a popular MatLab package [10], it was possible to extract the flood contours as reference data for the tests of the accuracy of the SRTM and COP DEMs.

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BIOGRAPHICAL NOTES

Kazimierz Bęcek received a Dipl.-Ing. (M.Sc.) degree in land surveying from the Wroclaw University of Agriculture, Poland, in 1978, the PhD degree in geodesy from the Dresden University of Technology, Germany, in 1987, and the D.Sc. (Habilitation) degree in remote sensing from the Dresden University of Technology, Germany, in 2010, He is currently a Professor at the Wroclaw University of Science and Technology, 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. He has also worked for the Queensland state government and the Gold Coast City local government since 1998. From 2003 to 2013, he worked at the University of Brunei Darussalam. From 2015 to 2019, he worked with the Geomatics Engineering Department at the Zonguldak Bülent Ecevit University, Türkiye. His research interests include mathematical modelling of environmental systems, including landslide monitoring, natural hazard mapping, and remote sensing methods for ecological studies.

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